CENTER FOR SPACE POLICY AND STRATEGY

DECEMBER 2020

SPACE AGENDA 2021

INFORMING THE FUTURE OF SPACE

AEROSPACE

Introduction

The space enterprise is engaged in one of the most transformative times in its history, as space becomes an increasingly democratized and contested environment.

In this emerging landscape, the strategies that secured the United States' leading role in space won't be enough to sustain leadership in the twenty-first century and beyond. We'll need new approaches, new concepts, and new ways of thinking about space to address the growing hostile threat to our ability to operate from space and realize the tremendous scientific and economic opportunities that development of space capabilities can bring down to Earth.

Space Agenda 2021 is a resource—developed by The Aerospace Corporation's Center for Space Policy and Strategy—that is meant to aid and inform U.S. leaders and policymakers as they confront critical decisions with long-lasting implications at this dynamic time. In the pages ahead, you'll find cutting-edge analytical insights on the pressing topics the incoming presidential administration and Congress will face over the next four years as they work to advance our nation's strategic interests as the world's preeminent space enterprise.

Through Space Agenda 2021, Aerospace provides in-depth research and informed context as the U.S. space enterprise positions itself to outpace the threat, expand the frontiers of our capabilities in space, manage growth in space traffic, and strengthen U.S. leadership in a time of immense change. We offer these ideas independently, not at the behest of any of the many government agencies that we support.

The topics covered in these 9 policy papers and 17 chapters cut across the whole of the space enterprise—from defense and intelligence to civil and commercial space—and speak to the growing coordination that will be needed to navigate the way forward. And the insights don't end here—two additional Space Agenda 2021 papers will be published in the coming months at www.aerospace.org/SA2021.

This effort is just one way The Aerospace Corporation is delivering on its vision to be *the nation's trusted partner, solving the hardest problems for the preeminent space enterprise.* Thank you for your support of Aerospace, and I look forward to the many informed conversations Space Agenda 2021 will help shape.

Steve Isakowitz
President and CEO
The Aerospace Corporation

Contents

Section 1 – Outpacing the Threat

Section 2 – Expanding Frontiers

Section 3 – Managing the Growth in Space Traffic

Section 4 – Leading in a Time of Change

Space Agenda 2021 Summaries

Section 1 – Outpacing the Threat

Developing a Foundational Spacepower Doctrine: Fostering an Independent Space-Minded Culture and Identity

The Space Force has taken a key step in establishing its doctrine, culture and identity by publishing the Spacepower Capstone Doctrine in August 2020. But specific choices yet to come that favor either space control or survivability will infuse the Space Force's culture and identity and shape the tools the Space Force provides the nation for decades.

A Roadmap for Assessing Space Weapons

Given advances in the space weapon capabilities of China and Russia, and the United States Space Force's priority to project military power in, from, and to space, the United States needs a new debate on the merits of fielding U.S. space weapons. Since the last debate, the strategic context has changed dramatically, invalidating many of the previous debate's core assumptions and primary alternatives. Thinking about space weapons cannot remain frozen in Cold War or post-Cold War era analysis and debates. The roadmap offered here will help the United States fully assess the merits of deploying space weapons, the best mix of space weapons, and how their development should be prioritized. The Department of Defense (DOD) cannot do it alone. The complexities of the issue require a whole-of-government approach with contributions from academia, industry, and other partners.

What Place for Space: Competing Schools of Operational Thought

The use of space is changing, with implications for U.S. national security. But there is not a consensus on how space is changing nor on how to best organize to achieve U.S. national security in space. This paper identifies six different schools of operational thought with different visions of what war will look like in the future leading to different technological and organizational preferences for how to prepare for those wars.

1. *Space Control First.* Drawing on traditional naval and air power thought, this school presumes we must gain space control first to allow all other uses of space to proceed.
2. *Enable Global Missile War.* This school presumes that precision-guided missiles, ballistic and hypersonic, are poised to fundamentally change how war is fought so long as space-based capabilities for surveillance, targeting, and navigation are available.
3. *Keep the Plumbing Running.* This school presumes traditional military operations remain dominant, though dramatically more effective because of space.
4. *Frictionless Intelligence.* This school presumes the value of space for gathering strategic intelligence supersedes all other uses.
5. *Nukes Matter Most.* This school presumes nuclear war is so terrible a possibility that space's role in commanding nuclear weapons must supersede all other uses.
6. *Galactic Battle Fleet.* A final school sees even grander long-term uses of space for national security, including space-based weapons that can strike anywhere in the world, defense of the planet from any threat originating elsewhere in the universe, and exploitation of key orbital "terrain" beyond geosynchronous Earth orbit. To respond, this school sees a need in the future for as yet unrealized technologies.

While few people belong completely in one school at the expense of all others, identifying distinct schools allows us to better understand the choices being made today about how to organize and fund space for national security.

Organizing for Defense Space: Balancing Support for the Joint Force and Independent Space Operations

The United States Space Force is arguably the largest restructure of U.S. defense space organizations since 1960. The reorganization also includes United States Space Command (USSPACECOM), the Assistant Secretary of the Air Force for Space Acquisition and Integration, and other new organizations. Being new, these organizations face many challenges—and how they address these challenges will define the tools that are available to senior political and military leaders for years to come. Despite the historic nature of the moment, there are lessons to be learned from these organizations' predecessors. Those lessons highlight that the greatest tension these organizations will face is how to balance the space-based needs of the joint force against independent military operations in, to, and through space.

Getting the Most Deterrent Value from U.S. Space Forces

As space becomes more crowded and contested it becomes ever more important to prevent a conflict in, directed toward, or from space. Without any actual experience of combat in space, however, we can only speculate about what role the space domain might play in a breakdown of deterrence and the start of a war. This inexperience with space's role in conflict complicates social science's already limited understanding of how wars begin and unfold—with their complex interplay of political goals, differing levels of commitment, the friction generated in any actual fighting, and the inherently flawed people (on all sides) making decisions. As the strategic environment changes, we must explore ways to strengthen the contribution of U.S. military space capabilities to deterrence while also enhance any advantages should deterrence fail. Focusing on the credibility of U.S. space capabilities in some narrow areas reveals steps that could be made to strengthen their deterrent value.

Noninterference with National Technical Means: The Status Quo Will Not Survive

The strategic context for U.S. national security space (NSS) activities will change if the 2010 New Strategic Arms Reduction Treaty (New START) expires in February 2021. Here we examine how this change would stress the NSS community's capabilities, assumptions, and habits, and is likely to present new challenges for maintaining stability in the space domain.

Leveraging Commercial Space for National Security

The increasing commercialization of space is presenting new opportunities for national security acquisition. Because of commercial developments in space-based weather; remote sensing imagery; radiofrequency collection; communications; positioning, navigation, and timing; and space situational awareness—among other areas—U.S. intelligence and defense agencies are considering alternatives to the traditional model of hiring contractors to develop bespoke capabilities. Some space capabilities could be treated like personal computers or passenger cars, which the government acquires as commodities from private companies rather than develops via contractors. Or space services could be treated like email clients or search engines, such as Microsoft Outlook or Google search, which the government licenses but does not own. In this new space era, U.S. space leadership will face many decisions over which acquisition model to use in a particular case. Given the potential of leveraging commercial services to accelerate the fielding of important capabilities and to preserve resources for quintessentially military capabilities, it behooves leadership to prepare for the analytic task of answering that question in many different mission areas, and to take the necessary steps to prepare to acquire commercial capabilities and services at scale for military applications. Our national security space enterprise and the commercial space sector are at critical junctures. National security leadership needs to consider the models it wants to use for its next-generation systems and business rules for how to balance them.

Continuous Production Agility: Future-Proofing the National Security Space Enterprise

The space sector is not immune to today's dizzying pace of change and constant technological disruption. The traditional, highly customized launch-on-need approach that allowed the United States to field the world's leading space capabilities during the twentieth century is ill suited to the new era of rapidly evolving threats and emergent opportunities. To stay in the race, the United States should shift toward modular national security space architecture, interoperability standards, and a launch-on-schedule production tempo to create agility, efficiency, and predictability. This will, in turn, encourage broad industry competition and provide frequent innovation opportunities.

Our national security space architecture can avoid competitive obsolescence by "future proofing" through regular introduction of new technologies. The proposed acquisition strategy, Continuous Production Agility (CPA), introduces modularity as a key element in the architecture. Modularity enables steady production flows for foundational space system elements while providing open doors for technology insertion or agility in response to threats. It simplifies the scope of rapid prototyping efforts and reduces the barriers to adaptation. While it requires more upfront engineering, it encourages lean and focused acquisition teams. And, especially important, it fosters a thriving and motivated ecosystem of space manufacturers and innovators.

The Future of Ubiquitous, Realtime Intelligence: A GEOINT Singularity

When assessing the trends of global connectiveness, commercial remote sensing from space, and advances in artificial intelligence (AI), the trends point toward a future where information and overhead imagery will become available to the general public in near-realtime. The rise of large constellations with remote sensing satellites and capabilities ranging from synthetic aperture radar imaging, nighttime imaging, and infrared imaging is a global phenomenon. Coupled with AI analysis, data from different sensors can be combined, processed and made useful for a specific user's needs on handheld devices worldwide. Large constellations of communication satellites and the rollout of 5G in metropolitan areas will provide the data pipeline needed to reach users globally at broadband speeds. A scenario, coined the Geospatial Intelligence (GEOINT) Singularity, is a future where realtime Earth observations with analytics are available globally to the average citizen on the ground providing a tremendous wealth of information, insight, and intelligence. Civil application could include identifying an empty parking spot from space or tracking autonomous vehicles in smart cities. These developments will likely not be contained within the U.S. but will be a worldwide phenomenon. The opportunities seem immense, but what would the availability of ubiquitous, realtime intelligence mean to the military operator and warfighter? The U.S. approach to commercial remote sensing has been to regulate and limit the imagery that can be taken from space, but international capabilities will not be so easily curtailed. Has the time come for the military operator to find better ways to hide, rather than tell someone not to look?

Space-Enabled Persistence and Transparency in the Arctic to Support Infrastructure and National Security Needs

The United States has maintained territorial claims and has advanced political, economic, national security, environmental, and cultural interests within the Arctic region since the 1867 acquisition of Alaska. The Arctic Council and the United Nations Convention on the Law of the Sea (UNCLOS) are avenues to engage our partners to promote a stable and secure Arctic. Commercial satellite data, including enhanced communications, navigation and timing, and remote sensing, will play a key role in establishing persistent situational awareness. It is through reliable and ubiquitous commercial satellite capabilities that the United States can meet its economic, national security, and environmental imperatives.

This chapter provides an overview of U.S. Arctic policy and national interests and describes how commercial satellite services can provide domain awareness to observe and adapt to the region's rapidly changing conditions. While geopolitical tension is rising in the Arctic, stakeholders will benefit from sharing satellite data with each other and the public. Sharing can enhance operations, establish greater transparency and accountability, and strengthen a common rule-based order.

Section 2 – Expanding Frontiers

To the Moon and Beyond: Challenges and Opportunities for NASA's Artemis Program

In just the next few months, multiple critical decisions will affect human exploration plans of the National Aeronautics and Space Administration (NASA). The FY21 budget cycle will shape significant aspects of the content and pace of NASA space programs and may make already ambitious exploration timelines unachievable. Even an extended continuing resolution, delaying the start of FY21 budget levels, could put current goals out of reach, as would flat funding levels. The continued effects of the novel coronavirus have already delayed progress on NASA programs in general, devastating the broad economy that furnishes the resources for NASA exploration activities. The outcome of the 2020 election may also affect the direction agencies and departments take from January 2021 onward.

The Trump administration has challenged NASA to return humans to the moon by 2024 with the goal of eventually sending astronauts to Mars.[1] To respond to the President's challenge, the NASA Artemis program has been established with the primary goal of landing the first woman and the next man on the surface of the moon before the end of 2024.[2]

The focus of this paper will be on NASA human exploration beyond low Earth orbit (LEO), specifically missions to the moon and beyond. In the following pages, a review of the path back to the moon, from the end of Apollo up until the present time, is provided. Recent exploration initiatives are explained, including the participation of the commercial sector. The importance of the Artemis program in the moon-to-Mars planning is discussed. The Findings section includes assessments of management and technical challenges, and policy points with opportunities highlighted in the closing section.

Cislunar Development: What to Build and Why

The current administration is seeking ways to facilitate and accelerate the evolution of space commerce. At the same time, the administration plans to pursue ambitious human exploration activities beyond low Earth orbit. Both of these objectives include a key role for infrastructure in cislunar space. The administration can serve both objectives through a concerted cislunar development program. Efforts are underway in areas such as space transportation and human habitats, but a sustainable, comprehensive space infrastructure requires much more. This paper highlights some proposed development scenarios and examines the components needed to form a coherent long-term strategy that delivers permanent, sustainable, purposeful, value-generating space activity.

Human Spaceflight Safety: Regulatory Issues and Mitigating Concepts

Commercial spaceflight offers significant benefits to society, the economy, and national security. Financial experts project that the global space economy could significantly grow over the next few decades.[3] However, spaceflight is also a risk-prone and capital-intensive endeavor. In fact, as Congress pointed out in the Commercial Space Launch Amendments Act of 2004, "Space transportation is inherently risky."[4] That assessment is certainly reflected in the historical human spaceflight safety record. This paper explores ways to address the issues associated with the rise of commercial human spaceflight.

Emerging Issues in New Space Services: Technology, Law, and Regulatory Oversight

Next-generation commercial on-orbit missions have started to include a variety of capabilities previously reserved only for governmental missions. These commercial endeavors range from radio-frequency collections and satellite servicing to planetary missions. Is the existing regulatory framework sufficient to provide oversight and compliance with our international obligations? This paper highlights some of the commercial missions starting to push the boundaries and looks at ways to address this exciting intersection between technology development, policy, and international treaties.

Public-Private Partnerships: Stimulating Innovation in the Space Sector

Governments seeking to expand their capabilities for satellite communications, navigation, Earth monitoring, exploration systems, and other space applications recognize the significant role that the private sector can play in delivering these capabilities at reduced cost and risk through public-private partnerships (P3s). The government sector generally wants to retain some level of control over key capabilities. P3s can provide significant advantages to government agencies by leveraging commercial efficiencies and innovation while sharing risk with the private sector in exchange for profits linked to performance. As space-related P3s proliferate for capital intensive projects and public-private data-sharing models, understanding key challenges and underlying economic arguments from real-world case studies can help lay the groundwork for future success.

Section 3 – Managing the Growth in Space Traffic

Space Traffic Management: The Challenge of Large Constellations, Orbital Debris, and the Rapid Changes in Space Operations

Big increases in space activity and new approaches to space operations necessitate organizational and technical changes to the way the United States and the world manage space traffic. Several key actions need to be taken to position the United States to lead these changes, ensuring a safe operating environment in space and enabling future growth.

Slash the Trash: Incentivizing Deorbit

There is likely to be a surge of satellites launched into space over the next decade, which means the risk of collisions in space will rise along with risks to the sustainability of the space environment from debris. How can the sustainability of the space domain be protected in a looming new era of increasingly congested space? How can the international space community reduce these risks and make them more manageable? One vital method is for satellite owners and operators to voluntarily comply with the already internationally agreed-upon guideline to deorbit satellites no longer than 25 years after the end of their mission. This paper outlines five distinct concepts to incentivize compliance with the “25-year rule” and provides a framework for analyzing the merits of each concept. It focuses on commercial satellites in low Earth orbit but could be applied more broadly.

Airspace Integration in an Era of Growing Launch Operations

Accommodating space launches in the National Airspace System (NAS) is burdensome, but at historical launch rates it is manageable. However, it is expected that launch rates will increase substantially, with the preponderance of that increase coming from commercial customers. This will require better integration of space launch activities in the NAS. This paper presents the issues and highlights potential conflicts between the “space side” and the “air side” that may call for intervention from high-level decisionmakers.

Light Pollution from Satellites

Commercial space companies, such as SpaceX, Telesat, OneWeb, and Amazon, have announced plans to launch large constellations of small satellites into low Earth orbit (LEO). As companies deploy more satellites in orbit in much larger numbers than in previous decades, this will become an issue in the next several years that requires leadership and decisionmaking by the U.S. administration—because there is currently no formal regulatory or licensing process addressing light pollution from space. The purpose of this paper is to provide an overview of an objective analysis performed by The Aerospace Corporation to inform leaders and decisionmakers on the issue.[5]

Cislunar Stewardship: Planning for Sustainability and International Cooperation

Space operations are expanding beyond the geosynchronous Earth orbit (GEO) to other parts of the Earth-moon system. As this trend continues, space operators will find preferred orbits and seek to leverage points of relative gravitational stability. These locations can enable lower-energy transits or provide useful parking places for various types of facilities (e.g., fueling depots, storage sites, and way stations with access to the lunar poles). As cislunar activity grows, a policy framework should be developed to promote the sustainability of operations in these locations. Motivated by lessons learned in space operations thus far, this paper discusses the need to extend best practices for debris mitigation (preventing its accumulation) to cislunar space lest we create a space debris mess in this valuable regime. Additionally, current international policy prevents spacefaring nations from removing space debris left by other actors. Significant policy adjustments are needed if debris remediation (removal of nonfunctional and potentially dangerous objects from useful orbits) is to become an effective complement to debris mitigation in cases where mitigation is not completely effective. Beyond the extension of current practices, significant future work remains in characterizing new orbital environments, monitoring their evolving use, and determining appropriate sustainability practices.

Developing a Sustainable Spectrum Approach to Deliver 5G Services and Critical Weather Forecasts

Fifth-generation (5G) wireless networks bring expectations of very fast, data intensive connectivity, with new capabilities that exceed today's 4G cellular networks. These 5G systems are the future of data connectivity, providing faster download speeds and more capacity to facilitate realtime general consumer and industrial applications. Implementation of 5G wireless networks will require the use of additional swaths of the radio spectrum.[*] Although 5G will utilize multiple frequency bands, the United States is working to permit new communications system uses of the spectrum in millimeter wave bands above 24 gigahertz (GHz) that are adjacent to key satellite remote sensing bands, making measurements of signals in that part of the electromagnetic spectrum critical for weather forecasts difficult to detect without comprehensive regulatory protection.

Section 4 – Leading in a Time of Change

Space Leadership in Transition

For generations, Americans have heard government officials, academics, technology pundits, and others talk about leadership in space. From this we can infer that space leadership has enduring importance. However, it seems to mean different things to different people. It also changes over time—space leadership today does not have the same characteristics and share the same priorities as in the days of Sputnik and Apollo. This paper discusses how we should characterize space leadership in the post-Cold War, twenty-first century context, and examines the hypothesis that the primary showcase for national space leadership for the foreseeable future will be cislunar space development.

Strategic Foresight: Addressing Uncertainty in Long-Term Strategic Planning

The space domain and the policy issues surrounding it provide a key opportunity for the application of strategic foresight. Space is an increasingly complex physical, political, economic, and threat environment, with significant and rising uncertainty. Many space systems involve capabilities that are on the bleeding edge of technological development in a field rife with surprise from both forward leaps and setbacks. Future uncertainty in space is not just about technology, however. The geopolitics of great power competition in space, rising questions about the civil and commercial regulatory environment, and the state of the space workforce all pose challenges for future planning due to complex interactions, long lead times, and high costs of miscalculation. Strategic foresight can help because it takes a holistic approach to considering and preparing for what is possible instead of relying on existing conditions and trends to predict the future. Long-term

[*] See FCC's FAST plan and the discussion of high-, mid-, and low-band spectrum: https://docs.fcc.gov/public/attachments/DOC-354326A1.pdf

vision is needed to navigate the toughest issues in space policy and help the United States proactively shape the path toward its preferred futures.

Space Game Changers: Driving Forces and Implications for Innovation Investments

The advancement of new space technologies, architectures, applications, and emerging business models will continue with many breakthroughs as well as some disappointments. A rapid and relentless pace of change requires timely analysis. This report offers a framework for government decisionmakers as they consider complex space sector innovation strategies and how best to prioritize investment decisions. The framework calls for recognizing innovations that offer market disruption for new users or applications, breakthrough capabilities, or incremental improvements and suggests a strategy for investment and risk management to advance these innovations to game changers that benefit civil, military, and national security interests. Ultimately, a portfolio management approach is needed across the whole-of-government to rationalize U.S. government investments in space innovation.

Defense Space Partnerships: A Strategic Priority

The United States has not fully leveraged its allies and defense partners in the space domain. This is partly due to significant obstacles, like classification and releasability, that have impeded more and deeper defense space partnerships. It also reflects the legacy of the Cold War, a period when space was dominated by a few major powers. A new space era is upon us. Allies and partners are developing significant space systems that can enhance U.S. capabilities. Concurrently, potential adversaries are developing weapons that could threaten U.S. and allied assets. The seriousness of the threat demands a more concerted and international approach. In this new space era, U.S. leadership should treat defense space partnerships as a strategic priority.

Space-Based Solar Power: A Near-Term Investment Decision

The concept of space-based solar power, also referred to as solar power satellites (SPS), has been evolving for decades. In 1968, Dr. Peter Glaser of Arthur D. Little, Inc. introduced the concept using microwaves for power transmission from geosynchronous orbit (GEO) to an Earth-based rectifying antenna (rectenna). Since then, technology has advanced on several fronts to remove some of the technological and economic barriers to practical full-scale implementation. U.S. decisionmakers are now facing a pivotal moment as several countries continue to invest in this promising, game-changing technology. This paper discusses the history of SPS, a few leading innovators, key functional components, and market applications. Ultimately, the United States must decide whether and how to invest in SPS to optimize the various operational, competitive, and societal benefits that this type of application offers to commercial, defense, and civilian markets.

References

1. Mike Wall, "US to Return Astronauts to the Moon by 2024, VP Pence Says," Space.com, March 26, 2019 (https://www.space.com/us-astronauts-moon-return-by-2024.html).
2. National Aeronautics and Space Administration, "Artemis Plan: NASA's Lunar Exploration Program Overview," *NASA.gov*, September 2020 (https://www.nasa.gov/specials/artemis/).
3. Jeff Foust, "Commerce Department to develop new estimate of the size of the space economy," *SpaceNews*, January 2, 2020 (https://spacenews.com/commerce-department-to-develop-new-estimate-of-the-size-of-the-space-economy/).
4. Public Law 108-492, Sec. 2(a)(12), December 23, 2004.
5. L. Riesbeck, R Thompson, J. Koller, "The Future of the Night Sky: Light Pollution from Satellites," March 2020 (https://aerospace.org/paper/future-night-sky-light-pollution-satellites).

Section 1
Outpacing the Threat

- Developing a Foundational Spacepower Doctrine: Fostering an Independent Space-Minded Culture and Identity
- A Roadmap for Assessing Space Weapons
- What Place for Space: Competing Schools of Operational Thought
- Organizing for Defense Space: Balancing Support for the Joint Force and Independent Space Operations
- Getting the Most Deterrent Value from U.S. Space Forces
- Noninterference with National Technical Means: The Status Quo Will Not Survive
- Leveraging Commercial Space for National Security
- Continuous Production Agility: Future-Proofing the National Security Space Enterprise
- The Future of Ubiquitous, Realtime Intelligence: A GEOINT Singularity
- Space-Enabled Persistence and Transparency in the Arctic to Support Infrastructure and National Security Needs

DEVELOPING A FOUNDATIONAL SPACEPOWER DOCTRINE: FOSTERING AN INDEPENDENT SPACE-MINDED CULTURE AND IDENTITY

Peter L. Hays, Russell Rumbaugh, and Michael P. Gleason

The Space Force has taken a key step in establishing its doctrine, culture and identity by publishing the Spacepower Capstone Doctrine in August 2020. But specific choices yet to come that favor either space control or survivability will infuse the Space Force's culture and identity and shape the tools the Space Force provides the nation for decades.

Introduction

The United States has a Space Force. Now what will the Space Force do? There are many ways to answer that question, from daily tasks to formally assigned missions. But nothing will be more important in shaping what the new service does to advance its efficacy than the Space Force's identity, culture, and doctrine. Space Force leaders themselves acknowledge the centrality of these factors. In his foreword to the *Spacepower Capstone Publication* (SCP) released in August 2020, Chief of Space Operations General Jay Raymond noted that the doctrine represents the Space Force's "first articulation of an independent theory of spacepower" and "answers why spacepower is vital for our Nation, how military spacepower is employed, who military space forces are, and what military space forces value."[1] General Raymond's foreword also notes:

> *Agility*, *innovation*, and *boldness* have always been the touchstone traits of military space forces. Today, we must harness these traits to pioneer a new Service and a new professional body of knowledge. This capstone doctrine is a point-of-departure toward that goal, not a final adjudication. Given the nascent state of spacepower theory, this publication will inevitably evolve over time as it is applied, evaluated, and refined. Therefore, military space forces are encouraged to read, critique, debate, and improve upon the ideas that follow."[2]

This chapter seeks to critique the SCP and offer suggestions for the next version by positioning the SCP within the broader evolution of thought about spacepower doctrine.

As the United States leverages space for military, commercial, and societal advantages and space becomes ever more democratized yet contested, everyone in the United States should care how the Space Force will defend this domain. How the Space Force sees itself and how it decides to fight will determine whether the Space Force delivers enduring strategic advantages, achieves goals the nation's leaders seek for space, or even becomes a liability. Once military organizations are settled into their ways, senior political and military leaders can find their tools—no matter how polished and refined—do not achieve the ends national leaders seek. The Space Force is currently establishing its identity, culture, and doctrine; these factors will be key in setting its priorities and explaining why it favors some missions over others. In essence, the next few years will be critical for all space forces and what they do for the country.

Defining Terms

To understand what the Space Force must build and how it will employ these systems, we must first define what we mean by doctrine, identity, and culture. Doctrine orients a military service and provides a foundation for further strategic and operational thought. Military doctrine is a formal set of beliefs that help to translate national security strategies and policies into specific military objectives, develop effective and efficient military strategies, and create the appropriate military organizations, systems, and operations for obtaining these objectives. In theory, doctrine could exist without or be drafted prior to an organization's creation, but in practice doctrine and organizations are almost always inextricably woven together. Historian I.B. Holley, Jr. emphasized these inherent links between doctrine and organizations in his concise definition of doctrine as "what is officially believed and taught about the best way to conduct military affairs."[3]

Identity and *culture* are more amorphous terms, centered on the things that distinguish one group from another, how group members categorize themselves, the social behavior and values of a group, and the contributions and achievements of the group. Distinct military identities and cultures arise from operational and social factors including shared perceptions, concepts, values, and behavior. It can be difficult for formal processes to be the primary drivers in shaping military identity and culture; new military identities can form rather quickly but it can be a generation-long process to develop or change the culture of a military organization.

Doctrine—like strategy itself—can be thought of as theory. Good doctrine will perform the primary roles of any theory: description, explanation, and prediction. When the members of a military service see the world through that doctrine, they have answers to basic operational questions and the service has a stronger foundation for a distinct identity and culture.

Main Drivers for Space Doctrine

Creation of the independent Space Force was the catalyst for the SCP, but space doctrine has been ripe for new developments for at least a generation. When space forces were a part of the Air Force, they got caught up in the doctrine, identity, and culture of that organization, itself a relatively new military organization. Now that the Space Force is independent it must seize every opportunity to balance and prioritize in its own doctrine all the different tasks and units it has inherited.

Early airpower advocates promulgated a simple, clear, and strongly held mantra: airpower is *inherently offensive*, *manifestly strategic*, *and should, therefore, be organized independently*.[4] These powerful ideas helped guide the United States toward creation of an independent Air Force in 1947 and drove Air Force decisions for decades. During most of the Cold War, the Air Force insisted that space and air formed a seamless operational domain which it defined as "aerospace," a position opposed by the rest of DOD that saw distinct space and air domains.[5]

Under the seamless aerospace concept, for decades the Air Force tended to "force-fit" space doctrine into the mold of air doctrine and argued that the three major airpower characteristics of speed, range, and flexibility applied equally well to spacepower when, in fact, speed and range mean very different things in space than in the air and spacecraft are among the least flexible of all today's military systems.

As the Cold War was ending, the Air Force began thoughtfully addressing many of the problems with the aerospace concept and the development of spacepower doctrine. Several of these improved approaches build from Dennis Drew's doctrine-tree model—the idea that doctrine should grow out of the soil of history, develop a sturdy trunk of fundamental doctrine, branch out into doctrine for specific environments, and only then attempt to sprout the organizational doctrine analogous to "leaves." Drew's doctrine tree metaphor provided a comprehensive way to critique the aerospace concept and the Air Force's earliest space doctrine as an attempt to grow leaves on a nonexistent branch.

Comparing the Lupton and Rumbaugh Spacepower Doctrine Typologies

Finding the airpower mantra and the aerospace concept to be inappropriate for developing spacepower doctrine, space officers searched for a better foundation to advance spacepower thought. One of the most influential examinations of these concepts is the four-part typology developed by Air Force Lieutenant Colonel David E. Lupton in his 1988 book, *On Space Warfare*.[6] He argued there were four schools on how the United States should use space: sanctuary, survivability, control, and high ground. The first two, sanctuary and survivability, emphasized space capabilities' role in supporting terrestrial forces. The *sanctuary* school argued that the critical strategic utility of space systems in providing capabilities including nuclear command and control, missile warning, and national technical means of verification (NTM) for arms control should not be endangered by developing capabilities that raise the risk of conflict outside of the atmosphere. *Survivability* acknowledged greater military use of space—and even the threat to space forces—but emphasized that space forces were subordinate to the other, terrestrial military missions they supported. Lupton's other two schools prioritized space forces. The third, the *control* school, held that space should be thought of like other military theaters of operation where the primary military objective is to gain control over the domain. "Control" implies an ability to maintain one's freedom of action while also having the ability to deny freedom of action to adversaries. The fourth school—*high ground*—goes even farther, holding that space has the potential to be the decisive theater of combat operations. Reasoning by historical analogy, the high ground school posits that just as holding the high ground is often the decisive factor in a land battle or as airpower often prevails over land and sea forces, in the future, space forces will dominate terrestrial forces.

Russell Rumbaugh's 2019 analysis on space doctrine schools of thought saw six distinct schools compared to the four from 1988, each of which has a different vision of war and therefore what role space forces will play.[7] Lupton's *control* translated directly into the s*pace control first* school, though it amended the school to give it decisive effects through the same logic that other domains, like air superiority or command of the sea, have followed: *If you do not win this domain first, you will lose the war.* Lupton's high ground school is captured in one variant of the *galactic battle fleet* school, though thirty years later, the promises of true terrestrial strike high-ground weapons remain technological dreams rather than operational realities. But this new taxonomy suggests another variant of Lupton's high ground school, *enable global missile war*, which relies on strikes by terrestrially based, precision-guided missiles enabled by space-based sensors and command and control. Today there is really no equivalent to Lupton's sanctuary school. With years of developments of space and four nations explicitly testing anti-satellite weapons, no one is seriously arguing space is not contested.[8] The big difference between the 1988 and 2019 schools is the greater split of Lupton's survivability school. The 2019 account posits three separate schools that stress the importance of space but still see it subordinate to other priorities: *Keep the plumbing running* emphasizes traditional terrestrial military forces; *frictionless intelligence* emphasizes strategic intelligence; and *nukes matter most* emphasizes the nuclear deterrence mission. All recognize the importance of space and rely on space forces but have unique priorities and demands on space forces.

Comparing and contrasting the two taxonomies highlights enduring challenges for Space Force's doctrine and mission priorities. Table 1 puts the 1988 schools on the left-hand column and the 2019 schools on the right-hand column. Within those columns are the value space systems provide, the preferred system characteristics, and the missions each school expects the various space forces to conduct in conflict. So arrayed, the table shows that many of the characteristics being pursued for today's spacecraft align with both Lupton's survivability and control schools (highlighted in yellow). As described above, few argue for a sanctuary approach. And while many advocates for high ground remain, the technology remains unready, leaving the principal tension between control and survivability.

<table>
<tr><th colspan="5">Table 1: What Various Schools of Thought Want from Space Forces</th></tr>
<tr><th>1988 Schools</th><th>Primary Value and Functions of Military Space Forces</th><th>Space System Characteristics and Employment Strategies</th><th>Conflict Mission of Space Forces</th><th>2019 Schools</th></tr>
<tr><td rowspan="2">Sanctuary</td><td rowspan="2">Enhance strategic stability
Facilitate intelligence gathering</td><td rowspan="2">Limited numbers
Earth-focused sensors most important</td><td rowspan="2">Limited
Survive nuclear war</td><td>Nukes Matter Most</td></tr>
<tr><td rowspan="2">Frictionless Intelligence</td></tr>
<tr><td rowspan="2">Survivability</td><td rowspan="2">Enhance strategic stability
Facilitate intelligence gathering
Force enhancement</td><td rowspan="3">Autonomous control
Attack warning sensors
Less vulnerable orbits
Maneuver
Space mission assurance
Defensive operations
Resilience
Disaggregation
Protection
Distribution
Proliferation
Diversification
Deception
Reconstitution
On-orbit spares
5Ds:
Deception
Disruption
Denial
Degradation
Destruction
Bodyguards and convoys</td><td rowspan="2">Force enhancement
Degrade gracefully
Fend off adversary attacks in order to preserve systems</td></tr>
<tr><td>Keep the Plumbing Running</td></tr>
<tr><td>Control</td><td>Fight in space</td><td>Space domain awareness
Space superiority
Offensive counterspace
Defensive counterspace</td><td>Space Control First</td></tr>
<tr><td rowspan="2">High Ground</td><td>Target terrestrial forces</td><td>Space-based comms and sensors to track, AI-enabled C2, and target Earth-based missiles</td><td>Targeting
Survive adversary attacks in order to preserve capability</td><td>Enable Global Missile War</td></tr>
<tr><td>Coerce terrestrial actors</td><td>Space-based Earth strike weapons</td><td>Decisive space-to-Earth strikes</td><td>Galactic Battle Fleet*</td></tr>
</table>

*Rumbaugh's Galactic Battle Fleet also encompassed a subschool that was less concerned about Earth-strike weapons as free maneuver space-to-space weapons, whether directed at natural, adversarial, or extraterrestrial forces.

Analogizing from Doctrine for Other Domains

Another longstanding and potentially rich source of insights for space doctrine is building from at least decades, if not centuries, of the best military thought on military operations at sea or in the air. Seminal theorists who developed important strategic frameworks on military operations in these two domains include Alfred Thayer Mahan, Julian Corbett, Giulio Douhet, Billy Mitchell, and John Warden.[9] Some of the key concepts that these theorists developed or applied to the air and sea domains are command of the sea, command of the air, shared sea lines of communication, land and sea interdependencies, choke points, harbor access, concentration and dispersal, and parallel attack.[10] Several of these strategic concepts have been appropriated directly through analogy into various strands of embryonic space theory; others have been modified slightly, then applied. For example, Mahan's and Corbett's ideas about command of the sea being normally in dispute, shared sea lines of communications between adversaries, and choke points have been applied directly onto the space domain. General maritime and airpower concepts that have been modified to help provide starting points for thinking about nascent space doctrine also include harbor access, command of the air, and sea control.

As discussed in recent books by John Klein and Bleddyn Bowen, however, much of our current thinking about space doctrine may overemphasize the analogous use of British Royal and U.S. naval experience and the application of military power within a single domain.[11] Specifically, the use of Alfred Thayer Mahan's seapower strategy and seeking the "decisive battle" has shaped much of our current thinking about spacepower.[12] This is problematic because it has led to an offensive dominant approach to spacepower doctrine and a perceived first-mover advantage in the space domain.[13] In contrast, Klein and Bowen advocate a more holistic and all-domain approach to space doctrine and strategy, building upon the works of past strategists such as Charles Callwell, Raoul Castex, B.H. Liddell-Hart, J.C. Wylie, and others. They believe space doctrine should include all instruments of national power and all-domain military operations in order to more accurately address the character of great power competition in space.[14] This perspective on the development of space doctrine provides new considerations regarding the "cosmic coastline" of current space operations, emphasizes space's significant contributions in supporting both terrestrial conflict and economic prosperity, while also providing insights for future conflict that may occur solely within the space domain.

Improving the Next Spacepower Capstone Publication

The Space Force deserves credit for recognizing the importance of doctrine to the new service and for delivering the SCP less than eight months after it was established. The SCP is a wide-ranging document that provides strong support for the importance of space to the United States and for creation of the Space Force. Unfortunately, however, it has less specific guidance regarding how military spacepower should be employed. It is undoubtedly appropriate for a capstone publication to avoid tactical details about employment of spacepower, but the SCP does not provide clear and comprehensive criteria for why it chose to incorporate, reject, or ignore existing operational- and strategic-level space doctrine. This approach did not provide a very strong foundation for the doctrinal content in the SCP or establish much of the framework needed to build the next levels. In practice, this shortfall will make it more difficult for the various space forces to act on General Raymond's charge to apply, evaluate, and refine the SCP.

Future versions of the SCP should build much more explicitly from existing doctrine in Joint Publication 3-14, *Space Operations*, and the Air Force's Annex 3-14, *Counterspace Operations*, as well as from the Lupton and Rumbaugh conceptual typologies. This is not to suggest that the next SCP should simply accept everything from existing doctrine and conceptual typologies, but without clear and replicable criteria for evaluating the existing foundations, only limited progress can be made. In particular, future versions should provide specific citations that extend or reject dialogue with previous work, rather than providing a long list of previous spacepower-related materials at the end but without references to these materials throughout the text. In the next version of the SCP, the Space Force should also consider interdependencies and the comprehensive and holistic strategic contributions of space capabilities. Such an approach may help the Space Force avoid stovepiped thinking and problems like the limitations the aerospace concept placed on Air Force thinking about space doctrine.

Doctrine is particularly important in space because we fortunately lack any experience with actual conflict in space to date. Experience and trial and error, therefore, cannot help the Space Force select which systems and missions to favor. Indeed, the SCP is likely to remain an important part of the Space Force's thinking and may play an outsized role in shaping the Space Force's missions, priorities, and capabilities, particularly if space remains a warfighting domain without actual warfare.

How Culture and Identity Flow from Doctrine

The chosen doctrine will also be infused throughout the organization by the culture and identity it favors. Edgar Schein, author of *Organizational Culture and Leadership*,[15] focuses on three "levels" of organizational culture, best visualized as a pyramid. The first, least substantive level is *observable artifacts*. Artifacts are tangible and visible to the outside community and include such things such as flags, emblems, uniforms, customs and courtesies, rituals and ceremonies, forms of address, jargon, songs, artwork, and myths and stories about the organization. Discussions on Space Force uniforms, rank, and its official song clearly belong in this level. The artifact level also includes architecture and technology, observed behavior, organizational processes, and structural elements such as charters, mission statements, and organizational charts. Although artifacts may be observable, that does not necessarily mean they are easily decipherable and meaningful to an outsider.

The first level is just the tip of the pyramid, however, and rests upon the second level, *espoused beliefs and values*. This level includes strategies, goals, philosophies, values, rules, embedded skills, habits of thinking, mental models, and shared meanings. The third, foundational level is *shared, underlying assumptions*, which are deeply embedded, taken-for-granted beliefs that are the essence of a culture but often difficult to perceive. Culture at this level, according to Schein, provides group members their basic sense of identity.

In a sense, doctrine has one foot in Schein's second level of organizational culture, and one foot in the third. Doctrine is one of the foundations on which strategy is based so it is reasonable to judge that doctrine may be placed more deeply in the second level of the organizational culture pyramid than strategy. But Lupton also notes that doctrine includes influential, unofficial beliefs that come in many levels of abstraction, putting the other foot in *shared, underlying assumptions*, Schein's third, taken-for-granted, foundational level of organizational culture.

In addition, Schein's three organizational culture levels align closely with Drew's doctrine tree metaphor discussed above. The Space Force's organizational culture should flow up from Drew's fundamental principles at the root of the tree, be informed by the beliefs found in environmental doctrine at the second cultural organizational level, and be particularized as appropriate for individual unit culture. This will help the Space Force develop an organizational culture and identity that dovetail with its doctrine, avoid overemphasis on less substantive observable artifacts, and avoid trying to grow leaves on a nonexistent branch.

Conclusion

While a very important step, a document alone is not enough because doctrine must be assimilated into how the members of the Space Force see their main missions and priorities. Doctrine must become part of their culture to help create a common and distinct identity. As a new organization, the Space Force faces several enduring challenges in building this doctrine, identity, and culture, not least because it has so many disparate responsibilities so critical to the nation. As a new organization, the Space Force will grow from its roots and incubate a distinct culture and identity. The doctrine it pursues will be one of the most important drivers of culture and identity—and once formed, they will shape every choice made within the Space Force. Space is ever more critical to the United States. Not just the U.S. military but all of U.S. society relies on space, which means all our nation's leaders must care how space is used militarily and defended. The Space Force was created for these purposes. The *Spacepower Capstone Publication*, along with the new service's culture and identity, will be primary drivers in forging the spacepower capabilities available to U.S. presidents and will answer basic questions about what the Space Force does.

References

1 Space Capstone Publication, *Spacepower: Doctrine for Space Forces* (Washington: Headquarters, United States Space Force, June 2020 (https://www.spaceforce.mil/Portals/1/Space%20Capstone%20Publication_10%20Aug%202020.pdf).

2 Ibid., emphasis in original.

3 Quoted in Lieutenant Colonel Dennis M. Drew, "Of Leaves and Trees: A New View of Doctrine," *Air University Review* 33 (January-February 1982): 41. See also I.B. Holley, Jr., "An Enduring Challenge: The Problem of Air Force Doctrine," The Harmon Memorial Lecture Series in Military History, No. 16 (Colorado Springs: USAF Academy, 1974).

4 David R. Mets, *The Air Campaign: John Warden and the Classical Airpower Theorists* (Maxwell AFB, Ala.: Air University Press, April 1999) provides an excellent overview of the development of this mantra by airpower pioneers.

5 See Lieutenant Colonel Peter Hays and Dr. Karl Mueller, "Going Boldly – Where? Aerospace Integration, the Space Commission, and the Air Force's Vision for Space," *Aerospace Power Journal* 15, no. 1 (Spring 2001): 34-49 on the aerospace concept and its stifling implications; and M.V. Smith, *Ten Propositions Regarding Spacepower* (Maxwell AFB, AL: Air University Press, October 2002), pp. 5-7 on the transverse region separating air and space that is approximately 60 miles wide and does not permit sustained aerodynamic or orbital flight.

6 Lieutenant Colonel David E. Lupton, USAF, (Ret.) *On Space Warfare: A Space Power Doctrine* (Maxwell AFB, AL: Air University Press, June 1988).

7 Russell Rumbaugh, "What Place for Space? Six Competing Schools of Operational Thought," The Aerospace Corporation, July 2019 (https://aerospace.org/paper/what-place-space-competing-schools-operational-thought-space).

8 Robin Dickey, "The Rise and Fall of Space Sanctuary in U.S. Policy," Aerospace Corp., September 2020 (https://aerospace.org/paper/rise-and-fall-space-sanctuary-us-policy).

9 Several of these individuals were quite prolific; the following list represents their best known works: Alfred Thayer Mahan, *The Influence of Sea Power upon History, 1660-1783* (Boston: Little, Brown, 1890); Julian S. Corbett, *Some Principles of Maritime Strategy*, ed. by Eric J. Grove (Annapolis: Naval Institute Press, 1988. First published 1911); Giulio Douhet, *The Command of the Air*, ed. by Richard H. Kohn and Joseph P. Harahan (Washington, D.C.: Office of Air Force History, 1983. First published 1921); William Mitchell, *Winged Defense: The Development and Possibilities of Modern Airpower -- Economic and Military* (New York: Dover, 1988. First published 1925); and John A. Warden III, *The Air Campaign: Planning for Combat* (Washington, D.C.: National Defense University Press, 1988). On the importance of these works see, Jon Tetsuro Sumida, *Inventing Grand Strategy and Teaching Command: The Classic Works of Alfred Thayer Mahan Reconsidered* (Washington, D.C.: Woodrow Wilson Center Press, 1997); Philip S. Meilinger, ed. *The Paths of Heaven: The Evolution of Airpower Theory* (Maxwell AFB, Ala.: Air University Press, 1997); and David R. Mets, *The Air Campaign: John Warden and the Classical Airpower Theorists* (Maxwell AFB, Ala.: Air University Press, April 1999).

10 John J. Klein, *Space Warfare: Strategy, Principles and Policy* (Abingdon: Routledge, 2006).

11 Brent Ziarnick, *Developing National Power in Space: A Theoretical Model* (McFarland and Company: 2015).

12 Peter Garretson, "A Historic National Vision for Spacepower," War on the Rocks, September 9, 2019.

13 Troy Endicott, "A Warrior's Mindset: Key to Winning in Space," Air Force Space Command, January 2017; John E. Hyten, "A Sea of Peace or a Theater of War: Dealing with the Inevitable Conflict in Space," Air & Space Power Journal 16, no. 3 (Fall 2002); and Pete Worden and John Shaw, *Whither Space Power?: Forging a Strategy for the New Century*, (Air University Press: 2002).

14 Bleddyn E. Bowen, *War in Space: Strategy, Spacepower and Geopolitics* (Edinburgh: Edinburgh University Press, 2020 and John J. Klein, *Understanding Space Strategy: The Art of War in Space* (London: Routledge, 2019). On the "misperception of offense dominance" in space see also LTC Brad Townsend, USA, "Strategic Choice and Orbital Security Dilemma," *Strategic Studies Quarterly* Vol. 14, no. 1 (Spring 2020): 64-90 https://www.airuniversity.af.edu/Portals/10/SSQ/documents/Volume-14_Issue-1/Townsend.pdf.

15 Edgar H. Schein and Peter A. Schein, *Organizational Culture and Leadership*, 5th Ed., (New York: Wiley, 2016).

A ROADMAP FOR ASSESSING SPACE WEAPONS

Michael P. Gleason and Peter L. Hays

Given advances in the space weapon capabilities of China and Russia, and the United States Space Force's priority to project military power in, from, and to space, the United States needs a new debate on the merits of fielding U.S. space weapons. Since the last debate, the strategic context has changed dramatically, invalidating many of the previous debate's core assumptions and primary alternatives. Thinking about space weapons cannot remain frozen in Cold War or post-Cold War era analysis and debates. The roadmap offered here will help the United States fully assess the merits of deploying space weapons, the best mix of space weapons, and how their development should be prioritized. The Department of Defense (DOD) cannot do it alone. The complexities of the issue require a whole-of-government approach with contributions from academia, industry, and other partners.

Introduction

A top priority for the new U.S. Space Force (USSF) is "Projecting military power in, from, and to space in support of our Nation's interests."[1] This includes applying lethal force in, from, and to space.[2] That new organizational imperative, traditional military preferences for offensive doctrines, and advances in competitor capabilities all raise the question of whether the United States will decide to field weapons in space. U.S. decisionmakers should carefully examine this most fundamental and critical of all space security issues to assess how deployment of weapons in space by any country, including the United States, will affect U.S. strategic interests.[3] Yet the United States has not had a robust public debate about the advantages and disadvantages of weaponizing space in almost 20 years. U.S. restraint carried the day then, but the threats and the strategic environment have changed a great deal since that era, leading to the need for a fresh examination.

This chapter aims to spark a renewed public debate on any upcoming decisions to station American weapons in space. Policymakers (and taxpayers) should understand thoroughly whether the United States requires space weapons to defend U.S. space infrastructure, to provide the U.S. an advantage in conflict, or to maintain strategic stability. The United States already has a large and varied arsenal of weapons that can attack different parts of adversary ground-based and space-based networks, helping to deter aggression or win a fight in space if deterrence fails. But if the United States decides deployment of space weapons is required, policymakers will need to decide the best mix of space weapons needed and decide which types of weapons should be prioritized in development and deployment. As discussed below, options include ground-based or space-based weapons; kinetic or non-kinetic weapons; weapons with reversible or non-reversible effects, and weapons in different orbits for different purposes. Choices should be informed with deliberate thinking about the consequences of those choices on deterrence, strategic stability, and the sustainability of the space domain. Decisions should also be consistent with U.S. treaty commitments, viewed as legitimate in international law, and ideally reinforce international norms of behavior. Today's space weapons debate should aim to identify the most effective ways to contribute to deterrence, maintain strategic stability in the absence of conflict, and achieve advantage in conflict if deterrence fails.

Space Weapons

Military satellites have been in use for decades for military communications, surveillance, navigation, and weather forecasting. While this was somewhat contentious in the initial years of the Space Age, since the 1960s the international community has generally accepted the U.S. position that these uses of military satellites are non-aggressive; i.e., peaceful uses of outer space. These military satellites are not considered weapons although they provide intelligence and enable military operations.[4] Up to the present day, spacefaring nations have refrained from employing weapons in space for hostile purposes although countries have deployed and tested weapons there.[5]

Space weapons can be divided into three main types: Earth-to-space, space-to-space, and space-to-Earth. They can be further sub-divided into kinetic and non-kinetic weapons with either temporary or permanent effects.[6]

Earth-to-space kinetic weapons include direct-ascent and briefly orbital antisatellite (ASAT) weapons with a warhead or projectile that directly strikes or detonates near the target spacecraft.[7] China, Russia, India, and the United States have tested such weapons. Kinetic weapons generally have permanent effects on a satellite and create space debris. *Earth-to-space non-kinetic weapons* include jammers, lasers, and cyber-attack methods, and their effects can be either temporary or permanent. Jamming a satellite's ability to communicate is temporary and localized, while lasers have the ability to create temporary effects, such as blinding a satellite, and permanent effects that may irreversibly damage satellite sensors. Several states have tested and deployed Earth-to-space non-kinetic weapons, including China, Russia, the United States, Iran, and North Korea. Many other countries now have residual kinetic and non-kinetic weapons-like capabilities that are inherent in the conventional technologies they have developed, such as missile defense interceptors and electronic warfare capabilities.

Space-to-space kinetic weapons include debris-creating, co-orbital ASAT weapons which may directly crash into a target satellite (damaging it or pushing it out of its orbit) or even explode near the target satellite. Space-based missile defense interceptors, if deployed, could target ballistic missiles as the they transit space, but would also have inherent ASAT capabilities. *Space-to-space non-kinetic weapons* include co-orbital jammers, high-powered microwaves, and lasers with temporary or permanent effects (as noted above). Spacecraft that are used to closely track and examine target satellites, and perhaps intercept signals and communications from such a target satellite, are not considered weapons for this discussion, although the behavior of such satellites may indicate hostile intent, and could possibly be used for destructive purposes even if the satellite was not intended to be a weapon.

Space-to-Earth kinetic weapons include exotic "Rods from God"-type concepts in which some sort of weapon is de-orbited from a carrier spacecraft to attack terrestrial targets that may be airborne, on land, or at sea. Arguably, the Soviet Fractional Orbital Bombardment Systems (FOBS), fielded operationally from the late 1960s until early 1980s, would also fit in this category, though the Soviets argued that it was Outer Space Treaty-compliant (and the United States agreed) because it executed a deceleration burn and, therefore, did not complete a full orbit.[8] *Space-to-Earth non-kinetic weapons* include high-powered lasers which might attack similar target locations on land and in the sea, or in the air, although penetrating the atmosphere may make this difficult. Space-based downlink jammers are also placed in this category. Again, effects can be designed to be temporary or permanent.

The Traditional Advantages and Disadvantages of Space Weapons

As has been discussed over the last several decades, space-based weapons have some material advantages over weapons based on land, in the sea, or in the air. First, if technologically and economically viable space-based weapons can be developed and deployed, any state that possesses them could have a significant advantage in a conflict against an adversary that relies on space capabilities. Since the last public debate about space weapons, the technical and economic feasibility of space weapons has increased. For example, space surveillance capabilities have dramatically improved and may better enable the ability to track, target and attack objects in orbit than in the past. A new class of launch vehicles is making it less difficult and less expensive to get objects to orbit. The arrival of highly capable smallsats and CubeSats and new forms of propulsion imply that space-to-space kinetic weapons are less expensive and less technologically risky than in years past. And lasers and high-powered microwave technological advances suggest the improved feasibility of space-to-space, non-kinetic space weapons. Space-to-Earth weapons remain the most speculative, but with the advent of proliferated Low Earth Orbit (LEO) constellations, even they may be more viable than in the past.

Space-based weapons, including space-based missile defenses and space-to-Earth weapons, offer enticing advantages in conflict. Space-to-Earth weapons could attack targets deep inside enemy territory without the same risk aircraft and cruise missiles have of being shot down. States possessing such capabilities would have enhanced ability to project power globally. Also, space-to-Earth and space-to-space weapons may provide a persistent (albeit less visible) presence and ability to respond to events rapidly across the globe—within minutes to hours as opposed to ships or aircraft that could take days before they are in position to attack a target.[9] Currently, intercontinental range missiles are the only weapon system with global reach and rapid response time.

Space-based weapons are potentially less vulnerable to traditional, kinetic methods of attack than terrestrial-based systems. Tracking and targeting a satellite or a weapon in orbit is a complex, high technology endeavor. While China, Russia, India, and the United States have demonstrated kinetic Earth-to-space weapons, and any nation with a sophisticated space program could develop such capabilities, space-based weapons remain relatively invulnerable to kinetic attack by less technologically sophisticated countries. In addition, space-to-space and space-to-Earth kinetic weapons would be difficult to defend against because their very high speeds and very brief flight times provide only an extremely limited window for warning and potential response options.

At a more strategic level, the USSF argues that space is the new high ground in modern warfare, providing a significant advantage in conflict.[10] Non-kinetic and kinetic Earth-to-space weapons provide the user an advantage by enabling targeting of adversary space support capabilities (and space-based weapons), imposing costs on the adversary to defend them and perhaps making the difference in who wins the war. The argument for space-to-space weapons—defensive and offensive—to control the high ground of space follows as well.[11] Others speculate that space weapons will be needed to protect commercial satellites and the flow of potential future wealth from mining the moon, asteroids, or other celestial bodies.[12]

Basing weapons in space, however, also has disadvantages in conflict. Even if a space weapon has self-defense capabilities, its defenses could be saturated by an adversary that can take multiple or sustained shots at it. Space-based weapons are also vulnerable to non-kinetic attacks, such as jamming or laser attacks. In addition, spacecraft follow highly predictable orbits, diminishing their ability to surprise an adversary and making them vulnerable to countermeasures. Maneuvering the space weapon reduces this weakness but might simultaneously reduce the weapon’s ability to fulfill its primary mission as its fuel is used up, shortening its mission life. Making the weapons less visible through techniques to reduce their visibility, making them appear as benign satellites to obscure that they are weapons, or distracting the adversary’s attention with decoys are a few of the ways to mitigate this disadvantage but also drive up the cost of the weapon. Even though the technical and economic feasibility of space weapons has improved over the last couple of decades, for the foreseeable future overall development, deployment, sustainment, and reconstitution of space-based weapons likely will be expensive compared to terrestrial-based weapon systems.

In addition, some argue that space weapons present broader geopolitical risks due to their potential effects on deterrence and strategic stability. Space capabilities have a close relationship to nuclear stability and the potential for escalation between great powers. Space weapons could therefore alter how decisionmakers calculate nuclear deterrence. Many of the visions of space-to-Earth weapons imagine them having incredible speed and accuracy tied to the ability to target any point on Earth with minimal or even no warning. At enough scale and with sufficient destructive effects, such attributes would threaten a first-strike capability; i.e., the ability to wipe out a target country's nuclear deterrent before it has a chance to launch a retaliatory strike. If so, nuclear deterrence may fail, a consideration that may outweigh all others. Similarly, some have comparable concerns about space-based ballistic missile defenses nullifying a country's nuclear deterrent and providing a nuclear first-strike incentive for the country that possesses such capability.

Earth-to-space weapons create concerns because targeting early warning satellites, strategic surveillance satellites, and nuclear command and control communication satellites could also be perceived as the immediate prelude to a nuclear first strike by an adversary, triggering a response on the nuclear escalation ladder. Even if space weapons do not fatally undermine nuclear deterrence, they still offer another path to rapid nuclear escalation.

Space weapons might upset strategic stability in other ways as well. Space is considered an offensive dominant arena, meaning it is materially easier and less costly to attack a satellite—including space-based weapons—than to defend a satellite. Earth-to-space and space-to-space weapons provide an offensive capability for attacking targets in space. Political scientists contend that war is more likely when the offensive is dominant—especially if it is difficult to distinguish between offensive and defensive weapons—and argue that there are strong incentives for striking first should a conflict appear inevitable.[13] Surprise attack is perceived as leading to large rewards. Space weapons provide a first-mover advantage for striking in space, but their speed could create crisis instability since decisionmakers—on all sides—will have very little time (perhaps only a handful of minutes) to decide what to do in the face of a sudden attack in space, creating a high risk of rapid escalation due to misunderstanding, miscommunication, and miscalculation.

Finally, the use of destructive, non-reversible kinetic Earth-to-space or space-to-space weapons would likely leave a persistent cloud of debris and pose a long-term (potentially decades or much longer) hazard to all satellites, including commercial and scientific satellites as well as satellites from non-adversary nations. Using weapons with non-kinetic, non-permanent affects would mitigate this risk.

The Previous Debate: Changes in Context, Assumptions, and Alternatives

A vigorous public discussion covering many of the factors discussed above flared during the last period in which the U.S. seriously considered the merits of space-based weapons, peaking around 2002 and waning a few years later.[14] But a lot has changed since then.

The earlier debate centered around two key alternatives: the first was whether the United States should deploy space-based weapons first—well before China or Russia would be capable of doing so effectively—in order to take a significant strategic leap ahead or, second, whether the United States should practice restraint in order to preserve strategic stability and not provoke China or Russia to react in kind. Those core alternatives are no longer operative. Since that era, China has deployed operational ground-based, direct-ascent, kinetic-kill ASATs and demonstrated co-orbital ASAT capabilities.[15] Russia has also tested ground-based, direct-ascent kinetic ASATs and appears to have tested in-orbit anti-satellite weaponry as well. The United States no longer gets to choose whether to leap ahead or to seek to inspire restraint among U.S. competitors. Indeed, today both China and Russia have the capability to station weapons in space and the June 2020 Defense Space Strategy states bluntly that China and Russia have already weaponized space.[16] While a future administration could revise U.S. strategy in space or attempt to secure new international agreements restricting space weapons, the U.S. has rung a bell that cannot be unrung by declaring space as a warfighting domain and by revealing some of what is known about potential adversaries' activities there. There will be implications on behavior by allies, adversaries, and third parties, as well as within the U.S. government.

As noted earlier, the new space weapons debate should inform decisionmakers on which space weapons, if any, contribute the most to deterrence and strategic stability, in the absence of conflict, while providing an effective means to achieve and maintain advantage in conflict. In addition to the factors outlined above, that debate requires due consideration of major changes in the strategic environment over the last 20 years.

The Strategic Space Environment in 2021

The strategic challenges in space presented by China and Russia, taken alone, may provide compelling reasons for the United States to deploy space weapons of its own. However, rather than basing a U.S. decision primarily as a reaction to China's and Russia's provocations, the United States should carefully consider the viability and effectiveness of space weapons for itself, bearing in mind the advantages and disadvantages outlined above and in light of the changes in the strategic environment identified below. Only then should the United States consider the best strategy and best mix of capabilities needed to respond to China's and Russia's space weapons. U.S. decisionmakers must weigh the considerations offered below when making decisions regarding space weapons.

China and Russia are great power competitors and space powers. The United States was far ahead of China 20 years ago in economic and military power, and in space capabilities. Today, China is a near-peer competitor with much more military power across the board than two decades ago and possesses significant space capabilities, including a variety of space launch vehicles, a wide array of modern satellites, and ASATs. China is asserting itself in its immediate region, the South China Sea, Taiwan, and Hong Kong as well as globally. Space systems are an integral part of China's ability to achieve its goals.

China has an extensive arsenal of Earth-to-space weapons, including operational communication, radar, and GPS jammers as well as Earth-to-space direct-ascent, kinetic-kill ASAT missiles to target satellites in LEO. In addition, in 2019, the Defense Intelligence Agency (DIA) said China was likely to deploy a ground-based laser weapon in 2020 to target the optical sensors of satellites in LEO, and have a more powerful laser by the mid-2020s that can damage the structural components of LEO satellites.[17]

Because of these extensive Chinese capabilities, from the moment they are placed in orbit, future U.S. space-to-space and space-to-Earth weapons in LEO will face potential attacks from these kinetic and non-kinetic capabilities. China is also likely developing kinetic ASATs capable of destroying satellites in geosynchronous orbit (GEO), so these vulnerabilities are not unique to LEO.[18] The potential benefit of U.S. deployment of space-based weapons and whether their fielding will contribute substantially to achieving and maintaining advantage against China will have to be carefully weighed in this light.

Like the United States, China has also tested satellites with technologies which could be used as space-to-space weapons. Technologies for on-orbit servicing, and rendezvous and proximity operations could serve dual-purpose roles as benign on-orbit servicing and inspection satellites or as space weapons.[19] U.S. defenses against these space-to-space capabilities might be placed on the ground, as noted above, or placed in space. The merits of placing U.S. ASAT weapons on the ground or in space, and the merits of relying on kinetic or non-kinetic options to defend against adversary space-to-space weapons should differ significantly between satellites in LEO, GEO, and other orbits and should therefore be debated separately.

The United States also should consider the possibility of China placing space-to-Earth weapons in orbit and debate the most effective means to counter them. At present, this threat remains highly speculative and no open-source examples of space-to-Earth weapons tests—kinetic or non-kinetic—exist. But the threat of space-to-Earth weapons to the United States from China should not be entirely dismissed.[20] The People's Liberation Army's (PLA's) 2013 *Science of Military Strategy*, (SMS) published by the PLA's top think tank and considered an authoritative, credible open source of PLA doctrine on military space, indicates the PLA has done the intellectual groundwork for fielding space-to-Earth weapons.[21] SMS identifies space-based attack operations against ground, sea surface, and targets in the air as a military space mission.[22] SMS also stresses development of new technologies to offset U.S. military advantages, including space weapons, that will leapfrog the United States in next generation defense technologies and give China asymmetric advantages.[23] Culturally, the Chinese put military strategists on a pedestal,[24] and as an authoritarian political system, military requirements and capability development more closely align with pronounced, authoritative strategy than is sometimes the case in the United States. The United States should consider the possibility of China developing space-to-Earth weapons and debate the best mix of capabilities to counter them should they appear.

While Russian resources are modest compared to China, the nation continues to develop high technology weapons systems under Vladimir Putin's authoritarian leadership. Since the last serious debate in the United States on deploying weapons in space, Russia has invested in and tested counterspace weapons, including worrisome systems it never developed even in the depths of the Cold War.

Russia has fielded Earth-to-space weapons (such as communication, radar, and GPS jammers) and in April 2020, Russia tested a direct ascent ASAT. In addition, in 2018, Russia began fielding a mobile ground-based laser weapon that the Russia Defense Ministry said could be used against satellites and is developing an airborne laser weapon system to use against space-based missile defense sensors.[25] As with the PLA ground-based ASATs, U.S. decisionmakers will need to take into account U.S. space-based weapons' potential vulnerability to these Russian capabilities and prudently evaluate their ability to provide substantial benefit, compared to terrestrial-based alternatives, against Russia.

Russia has also tested space-to-space kinetic weapons. In late 2017, a Russian satellite demonstrated the ability to get close to another satellite and fire a projectile at a very high velocity. In late 2019, a similar Russian satellite maneuvered provocatively close to a U.S. government satellite in LEO, and in July 2020 the same satellite that approached the U.S. LEO asset was observed firing a projectile.[26] U.S. options for achieving and maintaining space superiority in this scenario may include Earth-to-space, or space-to-space weapons with kinetic or non-kinetic effects. The merits and risks of each of these options should be debated and assessed thoroughly.

While the Soviets decommissioned their FOBS system after negotiating them away as part of the second Strategic Arms Limitation Treaty (notwithstanding the U.S. Senate's failure to ratify the treaty), at least the concept is back in the news. In March 2018, Russian President Vladimir Putin showed a graphic of the RS-28 Sarmat heavy ICBM placing a nuclear warhead on an orbital trajectory and descending on Florida. And although FOBS was a ground-based nuclear weapon system, it demonstrates Russia has long had the technological capability to successfully reenter targeted warheads from orbit.[27] In considering options for space-to-Earth weapons, the United States will want to evaluate whether it would be more or less secure on balance if they were widely fielded.

Based on the discussion above, the new debate should carefully weigh how U.S. space weapons would fare in a conflict with China or Russia in the face of the Chinese and Russian capabilities. It is reasonable to argue that U.S. space-to-space and space-to-Earth weapons would be exposed, at some level, to already existing Chinese and Russian Earth-to-space capabilities and nascent space-to-space capabilities. The United States will need to make significant investments to protect and defend U.S. space-based weapons. In comparison, U.S. Earth-to-space weapons would not be directly threatened by these Chinese or Russian capabilities but, instead, would be able to threaten Chinese and Russian space-based weapons and other space-based capabilities. With U.S. territory spanning almost 60 percent of the globe East to West (Maine to Guam), with territories from near the Equator to the Arctic Circle, and with bases around the world, U.S. Earth-to-space weapons should be able to rapidly reach LEO to defend U.S. satellites or threaten adversary satellites there. However, U.S. Earth-to-space weapons might not be so effective in scenarios at GEO and other orbits. In light of these considerations the new space weapons debate should consider the best strategy and best mix of U.S. space-based weapons and terrestrial-based weapons that gain the United States the most advantage and impose the most costs on Russia and China.

The new strategic environment presents additional complexities, however. As noted above, the space weapons debate has always included discussion of the affects space weapons could have on deterrence, and strategic stability. Those traditional concerns still exist and should be debated anew. However, the changes to the strategic context outlined next need to be added to the debate in order to more holistically inform decisionmakers of new potential strategic problems and dilemmas that deployment of space weapons could create.

The Outer Space Treaty, Arms Control Treaties, and Overflight. Fresh thinking is needed regarding the right of overflight as it pertains to space-based weapons. The 1967 Outer Space Treaty (OST)[28] and U.S.-Russia arms control treaties since the 1970s established the legitimacy of satellite overflight, but neither instrument provides unambiguous protection for space-based weapons in international law. The OST established the legitimacy of overflight when done for peaceful purposes. Even after the OST went into effect the Soviets argued that accepting "nonaggressive" military overflight as "peaceful" overflight did not mean they acknowledged the legitimacy of overflight that endangers their security.[29] With that in mind, it is difficult to argue convincingly that space-based weapons would be considered legitimate, peaceful, or nonaggressive uses of space. The OST does not ban conventional weapons from being placed in orbit, but neither does it provide any treaty protections.

Beginning with the 1972 Anti-Ballistic Missile (ABM) Treaty provision for noninterference with National Technical Means (NTM) and language repeated in several subsequent agreements, arms control treaties legitimized overflight of photo reconnaissance satellites and other types of satellites used to verify treaty compliance. The last of these arms control treaties, the 2010 New Strategic Arms Reduction Treaty (New START) currently in force between the United States and Russia is set to expire on February 5, 2021.[30] If that happens, formal prohibitions on interference with NTM also expire. U.S. decisionmakers should not reflexively assume the OST or U.S.-Russia arms control treaties would protect the legitimacy of overflight of space weapons, even in peacetime.

These two treaty-based protections for overflight helped establish a norm of unrestricted overflight that is broader than the treaties grant. In fact, the norm of unrestricted overflight has become so taken-for-granted that the presence of the norm is not even noticed. However, norms can shift suddenly, especially in response to a triggering event.[31] The new debate should evaluate if deploying space-to-space or space-to-Earth weapons might be a strong enough catalyst for nations to recalculate the norm's value given their national security interests.

For example, if an adversary put a space-to-Earth weapon that presented a grave threat to U.S. national security into an orbit that passed over U.S. territory tomorrow, adhering to the norm of unrestricted overflight means the United States would accept the situation, not protest, and only retaliate if the adversary took some sort of destructive action. But some political and military leaders—and opinion leaders—might reject acquiescing to such a grave new threat. The United States and the other countries overflown may have the right to challenge such a space-to-Earth weapon based on the UN Charter right to self-defense and the Law of Armed Conflict with its provisions on self-defense and anticipatory self-defense. On the other hand, in the analogous nautical sense, in some cases another country's warship may have a right to freedom of passage within a state's territorial waters. U.S. decisionmakers should work out what the U.S. strategy would be if China or Russia deployed space-to-Earth weapons first.

Space-to-space weapons produce similar concerns although the risk to the overflight norm is less straightforward since space-to-space weapons would not directly target a country's sovereign territory—but only its assets in orbit (although those, too, might be considered sovereign). In addition, the new debate should consider whether deploying any type of space-based weapon could weaken the right of overflight for other military satellites. Just deploying space-based weapons may mark all military satellites as targets, even in peacetime, since there is no guarantee that space-based weapons could be confidently distinguished from other military satellites. Today's debate should examine the indirect risks the deployment of space-based weapons might create for military and intelligence community intelligence, surveillance, and reconnaissance (ISR), communication, and other satellites.

Earth-to-space weapons would not raise questions about the overflight norm, but they do allow the countries that possess them to hold space-based weapons at risk even if a conflict has not started. When debating space-based weapons—along with the merits of each weapon type—the United States should evaluate how such systems—whether China's, Russia's or America's—might not be protected by the assumed right of unrestricted overflight. Without a full assessment, major decisions may be based on faulty assumptions and not result in the expected advantages for the United States.

The Expanding Gray Zone. U.S. policymakers and decisionmakers will also need to understand what effect deploying space weapons would have on gray zone activities. Gray zone tactics are the use of force or other means to achieve objectives while staying below the threshold of a conventional war.[32] Satellites have long been an integral part of gray zone activities. Fielding space-based weapons would add another dimension of ambiguity to such activities that the United States should consider when making space weapon deployment decisions.

As space becomes more congested with more countries and commercial entities in orbit and dual-use capabilities proliferate, threats increase and space becomes more contested with an expanded gray zone. Space is not immune from China's growing emphasis on its military-civil fusion (MCF) strategy in which China seeks to integrate military and civilian resources more effectively for military purposes. The employment of MCF in China's space activities focuses on using dual-use space capabilities militarily and portends China's use of gray, proxy forces in space, much as China's maritime militia of armed fishing vessels plays an influential role in asserting China's claims in the South China Sea.[33] Gray, proxy space forces could potentially challenge U.S. space-to-space and space-to-Earth weapons (as well as non-weapon space capabilities) without crossing the threshold that triggers a military response. Such a scenario would create difficult dilemmas for decisionmakers and disturb strategic stability.

In addition, if a U.S. space-based weapon is attacked in peacetime, either by gray or conventional forces, public attribution of the attack could be problematic. While U.S. military capabilities to attribute bad behavior in space have improved over the last 20 years, unless the attack is easily observable to many independent observers, public attribution may require release of sensitive information about U.S. satellites and the sources and methods used to attribute the attack. Commercial or partner unclassified space surveillance information about an attack might be shared with the public, but an adversary could potentially obscure the information and create doubt about its validity. In that way, since conflict escalation might need broad support by American politicians (and therefore the public), as well as allies and partners, the adversary may avoid significant retaliation in such a case. Furthermore, tempting adversaries to use gray zone tactics to challenge space-based weapons, without facing clear consequences, could weaken deterrence and disrupt strategic stability.

In total, this argues that all scenarios would have to be explored if a decision is made to field a classified space weapon. An analogy could be made to the risk associated with an alternative history in which the U.S. fielded submarine-launched nuclear missiles while attempting to hide the very existence of those submarines; if an adversary became aware of the threat and the submarines were fielded anyway, adversaries could have incentives to destroy the submarines on the presumption that the U.S. would not acknowledge the destruction.

For these reasons, the new debate on space weapons must evaluate the challenges gray zone activities (the new normal today) create for the viability and effectiveness of space weapons, and the risks gray zone activities produce for deterrence and strategic stability. Decisionmakers will need to decide the best mix of space weapons and decide which types of weapons should be prioritized in development and deployment while keeping the gray zone firmly in mind.

Way Ahead

The strategic environment has changed since we last had a national debate about deploying weapons in space. The United States should revisit the debate in the new era of great power competition and in light of the creation of U.S. Space

Command and the U.S. Space Force. This paper provides a roadmap for the new debate but does not fully assess all the factors introduced here and reaches no fully fleshed out conclusions. That is for the community to do now.

Today's debate should be informed by the debates of the past, but must be updated and based on a fresh analysis, new core assumptions, and an appreciation for new conditions. To avoid Russia and China imposing unnecessary costs on the United States, U.S. decisions on space weapons should not be made simply in reaction to China and Russia's space weaponization. U.S. decisions on space weapons require an exhaustive comparative analysis of the value to U.S. national security to develop, build, and deploy any type of space weapon and the downsides to such a decision. Is the United States better off with or without space weapons of any type? Indeed, the answer may not be binary. The analysis might lead to a conclusion that certain types of weapons or certain functions of such weapons are advantageous while others are not.

The United States should consider how deployment of space-based weapons might drive changes internationally in the interpretation of the OST right to peaceful uses of outer space and the norm of unhindered overflight. The status of U.S.-Russia arms control agreements and likely demise of treaty provisions for noninterference with overflight should also weigh on decisionmakers' minds. The United States should recognize space lends itself to gray zone approaches and consider how gray zone attacks against space weapons would be deterred. As well, we must bring back to mind the old concerns about the effect of space weapons on strategic stability. China and Russia face most of the same concerns discussed above. The question is, can the United States use such concerns and technologies to its advantage?

The increasingly congested space domain with ever more debris, more spacecraft, and more stakeholders may create additional dilemmas and trades for decisionmakers to balance. For example, how does a decisionmaker balance an increased risk of casualties (by not denying an adversary use of its space capabilities) with the risk that use of a debris-creating weapon in space may later cause the unintended destruction of friendly or third-party satellites, significantly increase the risk of operating in that orbit and surrounding regions of space for generations, or cause unknowable, harmful, tertiary effects? While current political tensions may make it unlikely in the near term, it is possible the United States, China, Russia, and other countries could find it in their mutual interest to agree to formally proscribe weapons that create space debris. The Geneva Conventions and their Additional Protocols regulate armed conflict and seek to limit its effects, providing an example of a framework for limiting conflict that extends into space. Mutual restraint in deployment and/or employment of debris-creating space weapons would reduce the indirect risk of indiscriminate, disproportionate harm to civilians or non-combatants, help preserve the sustainability of space environment, and temper decisionmakers' dilemmas. The community should continue to investigate ways to develop diplomatic instruments that would reduce the indiscriminate risks of debris-producing space weapons.

Further research and analysis in the areas identified in Table 1 should inform a new public debate on space weapons. Doing so will contribute to strategies to advance U.S. security and promote strategic stability.

The spotlight should be placed on countering China's capabilities first, since China is developing and deploying space weapons the most aggressively. The USSF and Department of Defense (DOD) cannot do it alone, however. The issues require a whole-of-government approach with contributions from academia, industry, and other partners. While the DOD and Intelligence Community (IC) should take the lead on evaluating the advantages and disadvantages of space weapons, for example, the Department of State (DOS) should take the lead on evaluating if space-based weapons are protected by the right of unrestricted overflight and investigating diplomatic avenues to reduce the risk of debris-producing space weapons. Then the DOS, working in close coordination with the DOD, should articulate U.S. positions in the international community in order to shape international opinion favorably toward the U.S. position. Likewise, the Department of Commerce (DOC) could play an important role in narrowing the gray zone with its civil space traffic management initiatives establishing international standards, guidelines, best practices, and norms of behavior for activities in outer space. The DOC will play a key part in bolstering stability and deterrence in space by working with commercial and international partners to shine light on non-standard or nefarious gray zone activities there.

Table 1: Areas for Further Research and Strategizing
1. Consider the advantages and disadvantages of U.S. space weapons given Chinese and Russian ASAT capabilities against potential U.S. space weapons. a. Separately weigh the relative advantages and disadvantages of each space weapon type, for each type of orbit, in the overall context of U.S. security. b. Review the various technologies available, determine potential asymmetries, and assess if these asymmetries are acceptable or can be offset in some way.
2. Evaluate if space-based weapons are protected by the right of unrestricted overflight and the effect on decisions if they are not protected.
3. Explore how space-based weapons can be protected against nefarious gray zone activities or how such activities can be deterred. a. Assess if potential gray zone vulnerabilities in space could weaken deterrence and stability.
4. Examine potential U.S. courses of action should China or Russia deploy space-to-Earth weapons first.
5. Gauge the indirect risks the U.S. deployment of space-based weapons might create for U.S. military and intelligence ISR, communication, and other satellites.
6. Investigate ways to develop diplomatic instruments that would reduce the indiscriminate risks of debris-producing space weapons.
7. Develop strategies for the U.S. to turn the concerns raised here to its advantage

Only by considering all these points can the United States make fully informed decisions about the deployment of space weapons, the best mix of space weapons, and how their development and deployment should be prioritized. Hopefully, the roadmap offered here will help inform and guide those decisions. Times have changed and the new era of great power competition means core assumptions, questions, and concerns about space weapons cannot remain frozen in Cold War or post-Cold War era analysis and debates. U.S. decisionmakers should make these choices consciously having weighed each of the considerations flagged here.

References

[1] Donald J. Trump, "Establishment of the United States Space Force," Presidential Memoranda, Space Policy Directive-4 (SPD-4), February 19, 2019 (https://www.whitehouse.gov/presidential-actions/text-space-policy-directive-4-establishment-united-states-space-force/).

[2] Headquarters United States Space Force*, Space Capstone Publication*, *Spacepower, Doctrine for Space Forces,* June 2020, p. 21.

[3] Barry Watts cautioned in 2001 that several paths toward space weaponization were "slippery slopes" and that it was conceivable U.S. leaders may perceive deployment of space-based weapons as a counter to China and Russia ground-based ASAT deployments without careful examination and without such deployment being "especially defensible." Barry D. Watts, "The Military Use of Space: A Diagnostic Assessment," Center for Strategic Budgetary Assessment, February 2001, p. 118.

[4] See Michael Krepon, Christopher Clary, *Space Assurance or Space Dominance: The Case Against Weaponizing Space*," The Henry L Stimson Center, 2003, pp. 28-36 for an extensive discussion on the distinction between space weaponization and space militarization. Also, Todd Harrison, *International Perspectives on Space Weapons*, CSIS, May 2020 (https://www.csis.org/analysis/international-perspectives-space-weapons).

[5] For example, Russia's Almaz military space station deployed in space in the 1970s with the R-23M Kartech cannon. Additionally, Russia deployed satellites in 2017 and 2020 that have a projectile-firing space weapon on-board. In July 2020, one of these satellites maneuvered closely to a U.S. satellite and was later observed firing a high velocity projectile. See "Russia conducts space-based anti-satellite weapons test," U.S. Space Command Public Affairs Office, July 23, 2020 (https://www.spacecom.mil/MEDIA/NEWS-ARTICLES/Article/2285098/russia-conducts-space-based-anti-satellite-weapons-test/).

[6] Todd Harrison, *International Perspectives on Space Weapons*, CSIS, May 2020.

[7] The Soviet Istrebitel Sputnikov (IS) ASAT launched into orbit, maneuvered near its target within an orbit or two, and then fired shrapnel toward the target satellite. It was tested multiple times from 1962 to 1982 and variants were operational until the end of the Cold War. See Brian Weeden, "Through a glass, darkly: Chinese, American, and Russian anti-satellite testing in space," *The Space Review*, March 17, 2014 (https://www.thespacereview.com/article/2473/1).

[8] Braxton Brick Eisel, "The FOBS of War," *Air Force Magazine,* June 1, 2005.

[9] Bob Preston, Dana Johnson, et al*, Space Weapons, Earth Wars*, RAND, 2002, and Headquarters United States Space Force, *Space Capstone Publication, Spacepower, Doctrine for Space Forces,* June 2020

[10] Headquarters United States Space Force*, Space Capstone Publication*, *Spacepower, Doctrine for Space Forces,* June 2020, p. 16.

[11] Everett C. Dolman, "Victory through Space Power," *Strategic Studies Quarterly*, Summer 2020, p. 8.

[12] Peter Garretson, "The purpose of a Space Force is a spacefaring economy," *The Hill*, June 2019 (https://thehill.com/opinion/technology/450519-the-purpose-of-a-space-force-is-a-spacefaring-economy).

[13] Robert Jervis, "Cooperation under the Security Dilemma," *World Politics* 30, no. 2 (1978): p. 211. Forrest Morgan, *Deterrence and First-Strike Stability in Space: A Preliminary Assessment,* RAND, 2010, p. 2.

[14] For example, see: Logsdon and Adams: *Space Weapons: Are they Needed?* 2003; Bob Preston, Dana Johnson, et al*, Space Weapons, Earth Wars*, RAND 2002; Michael Krepon and Christopher Clary, *Space Assurance or Space Dominance: The Case Against Weaponizing Space*, Stimson Center, 2003; Barry D. Watts, "The Military Use of Space: A Diagnostic Assessment," Center for Strategic Budgetary Assessment, February 2001. William Spacy, "Does the United States Need Space-Based Weapons?" Air University Press,September 1999. Everett Dolman, *Astropolitik: Classical Geopolitics in the Space Age*. London: Frank Cass, 2002.

[15] DIA "Challenges to Security in Space," January 2019, p. 21 (www.dia.mil/Military-Power-Publications).

[16] Department of Defense, Defense Space Strategy Summary, June 2020 (https://media.defense.gov/2020/Jun/17/2002317391/-1/-1/1/2020_DEFENSE_SPACE_STRATEGY_SUMMARY.PDF).

[17] DIA "Challenges to Security in Space Security" 20 (www.dia.mil/Military-Power-Publications).

[18] Assistant Secretary of State Christopher Ford, "Whither Arms Control in Outer Space? Space Threats, Space Hypocrisy, and the Hope of Space Norms," Remarks for CSIS Webinar, "Threats, Challenges and Opportunities in Space," March 2020. Also see Brian Weeden, "Through a glass, darkly: Chinese, American, and Russian anti-satellite testing in space," *The Space Review*, March 17, 2014 (https://www.thespacereview.com/article/2473/1). Even so, the Earth-to-space, direct-ascent ASAT threat is not as acute for GEO as LEO. A kinetic attack launched from Earth to GEO could take many hours to reach the target in GEO, providing time to detect the attack and counter it. In contrast, a kinetic attack from Earth to LEO may reach its target in just a few minutes, providing very little time to employ countermeasures.

[19] The U.S. government has argued for several years that space-to-space weapons are difficult to distinguish from peaceful satellites. Past arms control agreements like the Chemical Weapons Convention have addressed dual use technologies, so it is not necessarily impossible to govern such issues with a treaty.

[20] Harrison, *International Perspectives on Space Weapons*, 2020, p. 6.

[21] Mingda Qiu, *China's Science of Military Strategy: Cross-Domain Concepts in the 2013 Edition,* University of California San Diego, Department of Defense Minerva Initiative, September 2015, p. 2.

[22] Kevin Pollpeter and Jonathan Ray, "The Conceptual Evolution of China's Military Space Operations and Strategy," in Joe McReynolds (ed.), *China's Evolving Military Strategy*, Washington, DC: Brookings Institution Press, 2016, p. 262. SMS notes such attacks would employ laser, particle beam or kinetic energy weapons from space-based platforms.

[23] *Report to Congress of the U.S.-China Economic and Security Review Commission*, U.S. Government Printing Office, November 2019, p. 289. Also see Thomas G. Mahnken, *Secrecy & Stratagem: Understanding Chinese Strategic Culture,* The Lowy Institute for International Policy, 2011, p. 25, for a discussion on Chinese thinking regarding asymmetric weapons.

[24] Thomas G. Mahnken, *Secrecy & Stratagem: Understanding Chinese Strategic Culture,* The Lowy Institute for International Policy, 2011, 10, pp. 21-22. See also, Timothy L. Thomas, "The Chinese Military's Strategic Mindset," Military Review, November-December 2007, p. 52 and p. 55. And "7 Important Leaders of the Chinese Military," Norwich University Online, Oct 3, 2017, (https://online.norwich.edu/academic-programs/resources/7-important-leaders-of-the-chinese-military).

[25] DIA "Challenges to Security in Space," p. 29 (www.dia.mil/Military-Power-Publications).

[26] Sandra Irwin, "U.S. Space Command Again Condemns Russia for Anti-satellite Weapon Test," *Space News*, July 23, 2020.

[27] Air University, "Aerospace Commentary" (declassified 2014), Vol 1, No 2, Spring 1969, p. 17.

[28] Officially known as the "Treaty on the Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and other Celestial Bodies."

[29] See Michael Gleason and Luc Riesbeck, "Non-interference with National-Technical Means: The Status Quo Will Not Survive," Aerospace Corporation, January 2020, p. 4. Also see Maximilian Betmann, *The Political Origins of International Space Law*, Rheinische Friedrich-Wilhelms-Universitat Bonn, 2020, p. 47. Betmann explains that Soviet law scholars advanced a legal theory that accepted the principle of freedom of space in general, but limited it based on consideration of national security and opposing the idea that freedom of overflight meant that acts endangering the security, life and property of people on the Earth are permitted there. Eventually, with the 1972 ABM Treaty, the Soviets accepted the legitimacy of overflight for treaty verification purposes, but it is not clear if they (or Russia) ever accepted the legitimacy of overflight for purely warfighting purposes.

[30] Michael P. Gleason and Luc Riesbeck, "Non-interference with National-Technical Means: The Status Quo Will Not Survive," Aerospace Corporation, January 2020 (https://aerospace.org/paper/noninterference-national-technical-means-status-quo-will-not-survive).

[31] Harold Muller and Carmen Wunderlich (eds.), *Norm Dynamics in Multilateral Arms Control: Interests, Conflicts and Justice*, University of Georgia Press, 2013, p. 30.

[32] Raphael S. Cohen et al., *Peering into the Crystal Ball: Holistically Assessing the Future of Warfare*, RAND, 2020 (https://www.rand.org/pubs/research_briefs/RB10073.html?utm_source=WhatCountsEmail&utm_medium=National%20Security%20and%20Terrorism+AEM:%20%20Email%20Address%20NOT%20LIKE%20DOTMIL&utm_campaign=AEM:955488384).

[33] Mark Stokes et al., *China's Space and Counterspace Capabilities and Activities*, The U.S.-China Economic and Security Review Commission, March 30, 2020, p. 3; and Derek Grossman and Logan Ma, "A Short History of China's Fishing Militia and What It May Tell Us," The RANDBLOG (https://www.rand.org/blog/2020/04/ashort-history-of-chinas-fishing-militia-and-what.html).

CENTER FOR SPACE POLICY AND STRATEGY

JULY 2019

WHAT PLACE FOR SPACE: COMPETING SCHOOLS OF OPERATIONAL THOUGHT IN SPACE

RUSSELL RUMBAUGH
THE AEROSPACE CORPORATION

AEROSPACE

Summary

The use of space is changing, with implications for U.S. national security. But there is not a consensus on how space is changing nor on how to best organize to achieve U.S. national security in space. This paper identifies six different schools of operational thought with different visions of what war will look like in the future leading to different technological and organizational preferences for how to prepare for those wars. These schools are:

1. *Space Control First.* Drawing on traditional naval and air power thought, this school presumes we must gain space control first to allow all other uses of space to proceed.

2. *Enable Global Missile War.* This school presumes that precision-guided missiles, ballistic and hypersonic, are poised to fundamentally change how war is fought so long as space-based capabilities for surveillance, targeting, and navigation are available.

3. *Keep the Plumbing Running.* This school presumes traditional military operations remain dominant, though dramatically more effective because of space.

4. *Frictionless Intelligence.* This school presumes the value of space for gathering strategic intelligence supersedes all other uses.

5. *Nukes Matter Most.* This school presumes nuclear war is so terrible a possibility that space's role in commanding nuclear weapons must supersede all other uses.

6. *Galactic Battle Fleet.* A final school sees even grander long-term uses of space for national security, including space-based weapons that can strike anywhere in the world, defense of the planet from any threat originating elsewhere in the universe, and exploitation of key orbital "terrain" beyond geosynchronous Earth orbit. To respond, this school sees a need in the future for as yet unrealized technologies.

While few people belong completely in one school at the expense of all others, identifying distinct schools allows us to better understand the choices being made today about how to organize and fund space for national security.

Introduction

The use of space is changing, with implications for U.S. national security. Adversaries threaten U.S. space assets. Commercial industry offers new opportunities. Given widespread acknowledgement of these environmental changes, the president has proposed changes in the U.S. national security space enterprise, including a new U.S. Space Force, U.S. Space Command, and Space Development Agency. However, even as the U.S. national security enterprise reorganizes, there is not a consensus on how changes in the threat and commercial opportunities will affect the use of space for national security in the future. Different proponents identify different aspects of these changes as the most salient. These proponents therefore champion different solutions for how the U.S. government should reorganize national security space to adapt to those changes.

To provide a framework for understanding these differences, this paper bins many loosely associated and even competing ideas into a limited number of schools of thought on how the United States should operate in space to advance its national security. It identifies distinct schools based on their different views of war in the future and the technology and organization they see as necessary to prepare for that future vision. These schools each bring specific assumptions that lead to specific priorities.

This paper proposes six distinct schools of thought: Space Control First, Enable Global Missile War, Keep the Plumbing Running, Frictionless Intelligence, Nukes Matter Most, and Galactic Battle Fleet. Each of these schools is explored further in the following sections and Table 1 provides a summary of them. Together, these schools capture the bulk of contemporary thought on how the U.S. national security enterprise should operate in space.

Implications

This paper does not evaluate the merits of each school. But by comparing them next to each other in a like way, it clarifies what is at stake in decisions today about how to organize space. General John E. Hyten, commander of U.S. Strategic Command, said, "We're going to change the way we look at space. We're going to look at space and we're going to define our future, and we're going to treat space like a warfighting environment."[1]

How space is treated as a warfighting domain depends on which school dominates the new national security space organizations. Each of the schools of thought outlined in this paper has a coherent vision of future war, what space's role in that future war would be, what technology should therefore be pursued, and some institutional base to argue for its vision. The space community should be aware of how these visions intersect or conflict. Too often, because space involves a small number of high-dollar decisions, members of the space community focus on specific programmatic decisions, leaving unsaid the broader explanation of why one decision is favored over another; thus, divergent intellectual currents remain unexplored. Instead, proponents of each school should be aware of the arguments other schools are making and the vision on which those arguments are based. The public should be aware of the logic used by the people it has entrusted with national security space, and decisionmakers should be aware there are distinct schools of thought, how they relate to each other, and how the competing visions inform potential decisions. Only with such an awareness will the decisions being made today be fully informed.

This paper cannot answer which school of thought will shape the new space organizations. It does not even argue which school of thought should shape the organizations. But by describing the schools of thought in a common way, it provides a framework for understanding how each school of thought would shape the organizations differently than the others. Hopefully, in this time of change, this paper can serve as a resource to decisionmakers, practitioners and the broader public.

Caveats

Though this paper seeks to describe all the schools of thought relevant to how space achieves U.S. national security, it still is limited in its scope and claims. First, this paper only seeks to describe the different arguments for how space might be used for national security. There are many other uses of space, including commercial efforts, scientific exploration, and even shaping the destiny of mankind. However, the scope of this paper does not include those ideas despite their frequent relevance to national security. For example, advocates of commercial companies often argue their services or products can best fulfill a school's goals either through dedicated assets or as commodities purchased by the U.S. government.[2] Others argue for national security capabilities because they seek to harness those capabilities for broader social goals, as with weather satellites and GPS, and advocates of space exploration can often pursue similar technology as both they and the national security space enterprise require similar capabilities to achieve their goals.[3] While these topics are an important part of the space policy debate, these perspectives are not based on differing visions of the future of war and the role of space, so this paper does not include them.

Second, for analytic purposes this paper sets out stark distinctions between the different schools of thought—but in practice most people are not proponents of only one school and instead accept partial beliefs of multiple schools. Even the most ardent proponents of specific schools would not want the other schools' preferences completely neglected. At the least, proponents of all the schools often dream of yet more capability, which, if realized, would theoretically better be captured by the Galactic Battle Fleet school. For instance, Space Control First values satellites that can maneuver. If this maneuverability increases so much so that they act more like the spaceships of science fiction, that vision of war is better captured by the Galactic Battle Fleet school rather than the Space Control first school. Moreover, the United States has been able to leverage technology to achieve multiple schools' preferred capabilities in single programs. Ideally, these technological solutions will allow the United States to continue achieving the goals of multiple schools simultaneously. However, to better highlight differences between the schools, this paper draws the boundaries of each school sharply even if the lines blur in practice.

To explain the differences between the six schools, the following sections describe each school's vision of future war, the role of space in that war, its technological preferences and exclusions, and the organizations most commonly affiliated with the school.

Space Control First

The school of Space Control First presumes we must gain space control first to allow all other uses of space to proceed uncontested. In formal U.S. Air Force thought, space control is a part of "space superiority." But space superiority also connotes excellent space capabilities that support terrestrial forces, like cutting edge sensors and communications channels. Describing this school as Space Control First clarifies that while these supporting capabilities are important, they are secondary to securing space assets, potentially by targeting adversary space assets.

Vision of Future War

Space-based assets enable the U.S. military's operations in powerful ways. Military units can maneuver easily relying on space-based precision navigation and timing; they can communicate around the globe to coordinate action no matter where they are; and they have more accurate weather, imagery, and other sensor data than ever before. So enabled, today's U.S. military is more effective and lethal than any other force in history.

The Space Control First school emphasizes that space has become such a force multiplier, it will be an adversary's first target.[4] Because U.S. adversaries know our military is so empowered by space, the adversaries will target U.S. space capabilities to take that advantage away and potentially deter the United States from taking action. Proponents of this school, however, argue space capabilities up until now were able to make terrestrial forces so effective only because space has been assumed to be a "sanctuary." They point to China's and Russia's pursuits and fielding of a range of anti-satellite or counterspace weapons and argue space is not only no longer a sanctuary but instead a central battle area.[5]

Future war will then escalate along a spectrum from reversible attacks against satellites like lasing and jamming through irreversible attacks involving kinetic anti-satellite weapons. Potentially, this could escalate all the way to nuclear explosions to incapacitate space assets, with each step all the more likely because adversaries can tell themselves each action is less escalatory than a terrestrial action because there are no direct U.S. deaths stemming from hostile acts in space.[6] In the strongest version of this argument, escalation of hostilities in space may happen without any parallel escalation terrestrially.

Role of Space

This school sees space as the dominant asymmetric military capability. Without space assets, all other military capabilities degrade far enough to level the playing field or even give adversaries the advantage over the United States. Because of that dominance, space assets' most important mission is defending space assets.[7] Only once space assets are secure—even during a shooting war—can space properly support the rest of the U.S. military.

In this way, Space Control First follows the logic of other military specialties. For instance, Alfred Mahan in the nineteenth century argued that the correct role of a nation's navy was to defeat other navies because once done, the nation would have "command of the seas," allowing them to trade, transport, and even blockade or provide fire support from the uncontested sea.[8] So supported, the nation could achieve any other goal it had. In the 1990s, John Warden offered a version of this argument for fighter jets elevating "air superiority" from an operational circumstance to an organizing principle.[9] Warden argued that because the opportunities to target what the enemy valued were so great, yet these opportunities were contested only by the enemy's own fighters, those fighters should be the first priority of any war and all resources in war should initially be dedicated to U.S. fighters to destroy them. Once done, other military capabilities can be brought to bear. But until done, those other military capabilities will enjoy only degraded effectiveness anyway. Space Control First posits a similar logic for space. Without U.S. space assets, other military forces are dramatically less effective, so defending space assets must be the priority, potentially by attacking adversaries' own space systems that might threaten U.S. space assets.

As adversaries' own reliance on space increases, Space Control First also contains the logic that the United States can undercut adversaries by threatening their space assets, doctrinally termed *offensive space control*.

Technological Preferences

To defend U.S. space assets and potentially attack adversaries' threatening space systems, Space Control First prioritizes focusing on a smaller number of defendable satellites, enhanced spacecraft maneuverability, and exquisite custody of priority space objects. A smaller number of satellites makes it possible to equip each of the satellites with the capability to defend itself or dedicate distinct assets to the task. However, to keep the number of satellites low, each satellite must be capable of accomplishing multiple missions. Spacecraft maneuverability allows those assets to confuse and even evade an adversary's hostile actions, sometimes by capitalizing on advanced orbital mechanics. In the extreme, spacecraft maneuverability may allow offensive action. Spacecraft must be designed and orbited to maneuver more aggressively than stationkeeping requires, sometimes forcing tradeoffs with other capabilities, including sensors. Finally, space objects must be tracked much more closely than is done today if maneuvering and orbital mechanics are used to confuse, evade, or potentially even attack an adversary system. Today's space situational awareness is more focused on cataloging what is in space, presuming each object will likely follow the same orbit over its entire life. Maneuvering among these assets requires much more precise locations of key objects.

Some of these desired attributes share characteristics of traditional space assets. Economic reasons have driven reliance on a small number of highly capable satellites. All satellites must be maneuvered into orbit and kept on station in the face of radiation and other space weather. Many space assets have sensors to see out in space, across orbits, or down to the Earth. However, Space Control First requires exquisite versions of these capabilities to be effective according to its proponents.

"I also talked about a Space Warfighting construct which started with a CONOPS, having the ability to command and control, having space situational awareness, being able to go fast to develop the capabilities that we need to defend our constellations and critical partnerships.... Over the past year we have turned a construct into reality, and it all boils down to its [sic] just warfighting."

— General John Raymond
"National Space Symposium 2018
Keynote Address," April 17, 2018

Most Common Organizational Affiliation

Organizationally, the Space Control First school is most commonly associated with Air Force Space Command in Colorado, whose mission it is to operate most U.S. space assets, including defending them in the face of adversary action. With the creation of U.S. Space Command, these operational concepts will likely be more fully embodied even as Air Force Space Command retains its organize, train, and equip mission focused on acquiring space assets and training space operators. Both are likely

to be bastions of this school of operational thought. Proponents of the school often use the phrase "space is a warfighting domain" to emphasize space is not just a supporting capability but one under threat and with the ability to defend itself and potentially even strike back.

Enable Global Missile War

The school of Enable Global Missile War argues that the reconnaissance-strike revolution has matured and long-distance missile war is possible if space capabilities are harnessed.[10] Space-based assets could provide global targeting and command of U.S. missile strikes and warning and targeting of adversary missiles, both throughout their flight and on the ground before launch.

Vision of Future War

Since the rise of accurate missiles and the sensors to target them, advocates have been arguing "present-day military establishments will probably be superseded by new, far more capable means and methods of warfare."[11] In their view, traditional military units will not be able to survive in a battlefield swept by precision-guided munitions. Instead, advocates envision a war solely of long-range standoff weapons striking from afar targeted by long-distance yet very accurate sensors. Military units and tactics as currently known would be rendered obsolete. So far, however, the bolder claims of war based solely on long-range precision strikes by missiles have not been realized.[12]

The Enable Global Missile War school argues technological and commercial advances in space and artificial intelligence will finally make this way of war possible and it will inevitably be dominant because of its lethality. Proponents emphasize that global missile war is more likely than ever by pointing to adversaries emphasizing investment in long-range missiles. China may field more than 50 long-range, 100 medium- and intermediate-range, and more than 200 short-range missile launchers.[13] It also promoted its rocket forces to a full service in 2015.[14] Russia has long sought to harness long-range precision-strike, has invested in those capabilities in recent years, and is now fielding previously banned intermediate-range missiles.[15] To proponents, this means adversaries are already implementing the force structure to fight a global missile war.

Role of Space

This school sees space as the key to realizing this revolution. Only space can provide the global sensors and command and control to target, offensively and defensively, the long-distance missiles that can reach around the world and maintain their accuracy, including on the ground before they have even been launched. While today the U.S. military can field precision targeting and command and control in localized areas, it must first deploy forces into the area on traditional military systems, like ships and aircraft, and over longer distances, often relying on static targeting. Space, in contrast, could provide global, persistent, and dynamic coverage, making the only constraint the range of the missiles, which already have intercontinental range.

Technological Preferences

For space to fulfill the promise of global persistent and dynamic coverage, space assets must make significant jumps in capability from what is possible today. Today's space assets provide the widest geographic coverage, but that coverage is still not persistently global. This works when policymakers have already identified those regions they are most concerned about, but this lack of comprehensive coverage is unacceptable when an adversary might launch a missile from anywhere on Earth at any time. Today's space assets provide the broadest coverage by being able to revisit the same spot over and over for years, but that coverage remains intermittent—not an issue when policymakers only need to know if significant changes are occurring over days. However, this lack of constant coverage is unacceptable if one needs to know *exactly* where

> ***"The United States will pursue greater integration of attack operations with active and passive missile defenses. The United States will seek to use the same sensor network to both intercept adversary missiles after their launch, and, if necessary, strike adversary missiles prior to launch.... The exploitation of space provides a missile defense posture that is more effective, resilient and adaptable to known and unanticipated threats."***
>
> — Missile Defense Review, Department of Defense, January 2019, p. 35-36.

missile launchers are (given their ability to move every couple of hours). Today's space assets provide the greatest indication and warning of missile launches but still require integration with other sensors to track missiles throughout their trajectories.[16] While fine for defending known regions, to achieve truly global defense, space assets must be able to track—and maybe even target—missiles on their own. Other required advances may include spectral diversity, broader bandwidth, and higher frequencies.

Today, the most ardent proponents of this school argue proliferated low-Earth orbit constellations are the most likely avenue to field those technological capabilities. Proliferated constellations imagine hundreds if not thousands of small-size satellites orbiting the Earth. For these advocates, such numbers can be deployed only in low-Earth orbit. A priority technological preference is perfecting a communications network among a proliferated constellation to enable satellites to work together, exploiting their sensors and with greater command and control of the entire constellation. While there are alternatives in how space might enable global missile war, a proliferated low-Earth orbit solution is currently dominating the conversation.

Most Common Organizational Affiliation

Organizationally, this school is currently most closely associated with the Under Secretary for Research and Engineering, including the Missile Defense Agency and the Defense Advanced Research Projects Agency (DARPA), which report to the Under Secretary. A new organization, the Space Development Agency, has been created specifically to pursue space-based capabilities in line with the technological preferences of this school and also reports to the Under Secretary of Defense for Research and Engineering.

Table 1: A Framework for Understanding: Six Schools of Operational Thought in Space Today

School	Vision of Future War	Role of Space	Technological Preferences	Most Common Organizational Affiliation
Space Control First	Space-based conflict	The dominant military capability	Small numbers of defendable assets, maneuverability, and exquisite custody	Air Force Space Command
Enable Global Missile War	Long-range and lethal missiles sweeping away all other forces	Key to providing necessary sensor net	Persistent, global coverage; proliferated, low-earth orbit constellations	Under Secretary of Defense (Research and Engineering)
Keep the Plumbing Running	Traditional military units fighting like units	Empowering, but not decisive	Incremental improvement and availability	Military services
Frictionless Intelligence	Constant awareness of adversary activities not limited to wartime	The premier collection platform to populate the President's Daily Brief	High-quality sensors	Intelligence Community
Nukes Matter Most	Potential catastrophe of nuclear war	Critical to warning and command and control	Dedicated warning and hardening	U.S. Strategic Command
Galactic Battle Fleet	Threats to humanity beyond those known today	Superseding all existing weapons	Beyond what is possible today	No specific affiliation

Keep the Plumbing Running

The school of Keep the Plumbing Running recognizes how dependent modern military operations are on space-based positioning, navigation, and timing; communications; targeting; weather; and early warning. This school, though, prioritizes the military operations at land, sea, or air being supported by space capability.

Vision of Future War

As with the Space Control First school, this school embraces the idea that today's U.S. military is empowered by space. However, this school does not accept that being empowered by space has made space all important. Instead, it believes future war will transpire much as it has in the past: traditional military units like ships, soldiers, and planes will fight one another, sometimes in more technologically advanced ways but always with a local force-on-force fight determining tactical, operational, and even strategic outcomes.

While proponents acknowledge space creates new dependencies, they are unconvinced that the strategic calculus of war will be changed, especially after shooting starts. Space assets may be vulnerable to kinetic attacks. But the adversary's ground stations, the adversary's tanks and ships using space capabilities, and even an adversary's leadership and people are vulnerable to kinetic attacks. Moreover, post-World War II, a number of conflicts remained limited in scope—geographically, by weapon type, or by participants. Proponents in this school are skeptical that a terrestrial conflict will inevitably extend to space, that a conflict in space will stay contained in space, or that forces reliant on space are the only way to win a war.

This school lumps together many different visions of future war. They include those who think future wars will be decided on the high seas by large fleets, those who think wars will be decided by large land armies clashing on open plains or deserts, those who think future wars will be proxy wars involving irregular forces and stability operations, those who think future wars are unlikely to cross the threshold of open violence and instead involve constant low-level gamesmanship, and even those who think future wars will involve long-range strikes by conventional bombers. While these visions may conflict with each other, they agree on space's role: important, but not decisive.

Role of Space

This school sees space assets as important but supporting capabilities. The purpose of space assets is to empower other military capabilities.[17] Therefore, space assets should be built and operated in a way that best supports other parts of the U.S. military. At the least, operations of space assets should not hinder in any way operations of terrestrial assets. At the most, the funding of space assets becomes an opportunity cost that must be weighed against investing more in terrestrial assets. To advocates for other uses of national security space, prioritizing these terrestrial assets prevents the investment that might allow space assets to achieve fundamentally new capabilities.

Proponents of this school are not Luddites, however; they recognize how technological advances have changed the ways wars are fought, but they are skeptical these advances will mandate wars are only fought in a certain way. They are skeptical because they do not share assumptions made by other space schools of operational thought. While they acknowledge how much space-based assets empower units, they also see technological alternatives to those space-based assets. GPS-guided weapons are great, but laser-guided weapons also provide precision without requiring space assets. Space-based communications are important, but terrestrial networks can provide connectivity that allow greater access, more flexibility, and even greater bandwidth for localized fights. While they acknowledge that units are more effective using space-based assets, Keep the Plumbing Running proponents do not believe those units will stop fighting if they do not have access to space-based assets. Ships may not be able to target as accurately, but they will still search out and fight the adversary even if they cannot rely on space-based assets. Even when tank units are unclear of their own or the enemy's location, they will still seek to find the enemy and bring their organic firepower to bear. The war will go on, whether fought high-tech or not.

Technological Preferences

Technologically, this school prioritizes keeping existing space capabilities available and incrementally improving the capability. Today's U.S. military relies heavily on space. They therefore emphasize maintaining their access to existing space capability, which their other assets now use. Because that access already exists, this school can often presume space capability and not consider how to maintain it. These proponents often weigh in on technological preferences only when a capability seems endangered by a flawed acquisition program.

Despite their only occasional interest, proponents of this school do value advancing technologies in space. As the space age has matured, both militarily and commercially, essentially everyone can see the value of space-based capabilities. However, because they are concerned about balancing advancing space-based technology and the development and fielding of other terrestrial assets, proponents of this school can be skeptical of the value of unproven technologies, especially ones that require paradigm shifts. The fielding of GPS is a canonical case study. The eventual military users of the system were skeptical of the system, preferring to advance existing methods of navigation like inertial guidance.[18] Only when proven during the Gulf War did the broader military embrace GPS.

> ***"Army Maj. Gen. Daniel P. Hughes and Navy Rear Adm. Christian 'Boris' Becker stressed the importance of joint cooperation and incremental modernization to deliver systems that enable expeditionary operations by providing U.S. forces with resilient communications in the harshest environments [like]...urban, jungle or mountainous terrain."***
>
> — "Army, Navy leaders: New Technology, Joint Collaboration Advance Comms for Asia-Pacific," U.S. Army PEO C3T and U.S. Navy PEO C4I Public Affairs, February 12, 2015.

Most Common Organizational Affiliation

Organizationally, this school is most commonly associated with the military services. The military services all have visions of war that do not prioritize space, even as they rely on space-based assets. This school is affiliated with the legacy term "force enhancement," which emphasizes the role of space in making other forces more effective. The military services tend to think of space as a utility like plumbing, which will always be available for use given minimum investment needs are met. The groups most sensitive to this dynamic are the Army and Navy space cadres who interface between the Air Force space operators or acquirers providing the capability and their parent service using the capability.[19] Because it accommodates a broad range of visions in how future war might play out, this school includes a very large number of proponents with influential positions in Department of Defense decisionmaking.

Frictionless Intelligence

The school of Frictionless Intelligence represents the original national security mission for space.[20] It prioritizes space's ability to provide senior policymakers, particularly the president, intelligence of adversary activities. For this school, the ideal goal is being able to peer into adversaries' activities with no interference, confusion, or friction. Space capabilities offer unrivalled penetration and near-uncontested awareness of these activities, just as they did at the dawn of the Space Age.

Vision of Future War

Frictionless Intelligence focuses more on ensuring the president has insight into what other nations are doing than preparing for future wars. This may include investigating those nations' war preparations but also encompasses other activities such as diplomatic negotiations, economic investments, and staying apprised of cultural and political developments. For Frictionless Intelligence, the highest priority is on avoiding strategic surprise: a fundamental shift in a nation's role in the international system, whether an unexpected military move, technological advance, or societal change. Frictionless Intelligence argues the primary concern must be ensuring the senior-most U.S. policymakers are not taken by surprise and understand the context of their decisions.

While Frictionless Intelligence is wary of the increase in space threats, it is focused on constant awareness and not just wartime performance. Space threats to Frictionless Intelligence are chronic rather than acute and fit in the traditional understanding of spy-vs.-spy games of espionage and counter-espionage. Frictionless Intelligence is more concerned with an adversary's ability to deny and deceive than to destroy. While adversaries are harnessing technological advances to increase their denial and deception methods, these methods remain descendants of traditional efforts like hiding activities under cover.

Role of Space

Today, space still provides many of the advantages for collecting intelligence as it did in the early Space Age, making it critical to gather information on other nations' activities, intentions, and capabilities. In the 1990s, the military lamented its lack of access to the Intelligence Community's (IC's) space assets and the information they produced. These complaints—lodged at a time of depressed strategic competition—led to greater focus on leveraging intelligence space assets for military use and not just for strategic intelligence consumers. These efforts culminated in 1995's Presidential Decision Directive 35 that gave top priority to "supporting our troops and operations, whether turning back aggression, helping secure peace or providing humanitarian assistance."[21] Though the IC accepted this direction, the logic of the Frictionless Intelligence school continued to emphasize the importance of strategic intelligence to senior policymakers.[22] That priority remains the focus of the strongest strands of the Frictionless Intelligence school even as proponents acknowledge the need to fulfill other missions as well.

Technological Preferences

Because intelligence is best collected if the adversary does not fully understand U.S. capability, to protect those capabilities this school prioritizes secrecy over all other technological or operational concerns. The strongest advocates of this school may even accept degraded capabilities for other intelligence purposes, including supporting military operations in order to preserve the effectiveness of systems providing strategic information. Given these priorities, Frictionless Intelligence may unconsciously create technological barriers to sharing information gleaned from space systems.

"The Commission believes that ensuring a proper balance between strategic and tactical requirements—in terms both of the use of current NRO systems and of the design of future NRO systems—is a matter of utmost national security importance.... There also appears to be no effective mechanism to alert policy-makers to the negative impact on strategic requirements that may result from strict adherence to the current Presidential Decision Directive (PDD-35) assigning top priority to military force protection."

— "The NRO at the Crossroads," Report of the National Commission for the Review of the National Reconnaissance Office, November 1, 2000, p. 51.

Frictionless Intelligence further prioritizes advances in sensor capabilities to improve what can be collected in space; processing for better dissemination (albeit focused on intelligence collection and analysis rather than operational relevance); and unpredictability to limit adversaries' ability to counter these capabilities. Frictionless Intelligence is more concerned with how well a place is observed than with how often it is observed. Frictionless Intelligence also values global coverage less than localized coverage because it is most concerned with slow-developing trends, and systems can be retasked or even redesigned as the specific regions of focus change.[23]

In recent years, Frictionless Intelligence's priorities have not been in conflict with other schools' technological preferences because space assets have been so capable they can meet the priorities of both Frictionless Intelligence and other schools. However, Frictionless Intelligence does have distinct preferences and, if forced to choose, would prioritize secrecy and precision over other capabilities.

Most Common Organizational Affiliation

Organizationally, the school of Frictionless Intelligence is most commonly associated with the IC, which has responsibility for keeping senior policymakers informed, though it also has responsibility to other customers as well. The senior-most policymakers, however, stress the importance of the strategic information the IC provides, requiring the IC to prioritize that mission.

Nukes Matter Most

The school of Nukes Matter Most prioritizes over all other considerations the traditional contributions of space to nuclear deterrence such as missile warning, secure communications (even during nuclear conflict), and national technical means verification of arms control agreements.

Vision of Future War

Nuclear war remains the most catastrophic outcome of state-on-state conflict. Nuclear weapons have a destructive scale fundamentally different than all other uses of force and are tightly coupled to globe-spanning delivery systems. Though the world has experienced "only" two hostile uses of nuclear weapons 75 years ago, proponents of this school emphasize that as the most catastrophic—even if not the most likely—possibility, nuclear war should be the United States' top national security priority. Most proponents do not claim that its top-priority status means Nukes Matter Most should receive the greatest funding or even attention, nor do they dispute the greater likelihood of other visions of future war. But because of its catastrophic nature, proponents of this school argue that when a conflict or even tension between priorities arises, matters of nuclear war should take precedence.

Role of Space

Nuclear deterrence is the second original mission of national security space and remains dependent on space-based capabilities today. U.S. nuclear forces depend on space for indications and warning of an attack and for command and control to respond to an attack. Only space can provide the coverage—even in areas to which adversaries deny the United States access—necessary to monitor the potential start of a nuclear war. Only space can host the communications necessary to reach U.S. nuclear forces deployed around the world without a lengthy and visible support tail.

Space also plays a critical role in monitoring compliance with arms control agreements and setting the baseline for the United States' understanding of what and how a nuclear war might play out. When the United States and the Soviet Union first began agreeing to arms control, national technical means—the reconnaissance satellites—provided the ability to verify compliance when the two adversaries were unwilling to be more open with each other and remained skeptical of the other's motives.

Technological Preferences

As with other schools, Nukes Matter Most values technological advances across the spectrum of space capabilities. But this school makes technological demands on space assets other schools do not. It distinguishes itself from other schools because of how much it favors specific attributes like hardening against electromagnetic effects of nuclear weapons and dedicated warning of strategic nuclear attack within strict timelines. These attributes are demanding in design, often requiring sacrificing other capabilities. The other schools may resist those tradeoffs but Nukes Matter Most accepts them readily.

In recent years, the demands of Nukes Matter Most have not prevented advances in other areas. Secure satellite communications and missile warnings were extended to conventional, theater-based forces using the same platforms providing the secure, hardened nuclear war communications and the dedicated missile warnings. But many of these systems still favored the Nukes Matter Most school. Current plans involve separating satellite-based nuclear command and control from conventional and tactical command and control and giving them each dedicated systems. An entire new constellation of missile warning and tracking is being pursued, driven largely by the Enable Global Missile War school. As these programs develop, the overlap between the nuclear- and conventional-supporting systems may shrink. But as long as the nuclear-supporting systems meet the needs of nuclear deterrence, this school is not against other systems.

Most Common Organizational Affiliation

Organizationally, this school is most commonly associated with U.S. Strategic Command (USSTRATCOM), which has had the responsibility of preparing for and responding to nuclear war for almost 30 years. While both the Air Force and Navy provide nuclear forces and command and control, their systems all support other missions as well. Only USSTRATCOM is dedicated to nuclear deterrence. For the last 20 years, USSTRATCOM has been responsible for space operations as well, though in practice Air Force Space Command has dominated this conversation, not least because within USSTRATCOM nuclear deterrence has always taken precedence over space operations more broadly. With the creation of U.S. Space Command, USSTRATCOM is likely to focus even more narrowly on nuclear deterrence and how space systems support it. Nuclear war is, however, a catastrophic enough threat that USSTRATCOM often finds high-level support for its priorities, even if those senior levels do not spend the bulk of their time focused on nuclear deterrence.

> ***"Yet, deterrence depends not only on a modernized triad but also on survivable systems for decision-makers to understand the nature of a nuclear attack, and to command and control the response… The United States' strategic "thin line" is the communications network, much of it spaceborne, that connects our nuclear weapons, sensors and related systems to the president and his national security team."***
>
> — Admiral Dennis C. Blair (ret.)
> "Why the U.S. Must Accelerate all Elements of Space-based Nuclear Deterrence,"
> Defense News, February 7, 2019.

Galactic Battle Fleet

The school of Galactic Battle Fleet remains distinct because of its focus on scenarios requiring yet-to-be developed technology and applications, including space-based attack of terrestrial targets, planetary defense, and manned space combat. Proponents of this school in the near-term support other schools but always hope to advance longer-term goals as well.

Vision of Future War

The universe is unimaginably vast. It is possible a greater threat to humanity lurks in the far distances of space that will trump all of mankind's internecine conflict. Concerns about these possibilities motivate one variant of the Galactic Battle Fleet school. This threat might be natural, like planetary defense from a meteor or asteroid. Or the threat might be manmade, like an adversary exploiting Lagrange points or the moon to threaten activity in space.[24] Another manmade threat might be the need to regulate commerce in space with force, calling for a space coast guard, or even a need to militarily colonize space.[25] At the most extreme, it is a threat from the vast reaches of space not natural but from another intelligent species.[26]

Another variant imagines space weapons that supersede any existing weapons systems, even nuclear weapons. Space-based weapons that can strike terrestrial targets offer reach, lethality, and surprise unmatched by today's weapons.[27] For some proponents, the first nation to achieve such weapons will be able to force other nations to bend to their preferred political outcomes requiring the United States to pursue them.[28]

Whether proponents want mankind prepared for threats in or from the deep reaches of outer space or think space can force mankind to transcend its current divisions, they find common ground in envisioning national security outcomes driven by technologies well beyond existing forces.

Role of Space

Outer space is central to this school of thought. It is the limitless possibilities of space that open up new vistas—and threats—for mankind. It is space that will transcend our current geopolitical constraints.

Technological Preferences

Technology that will overwhelm today's forces is definitionally beyond what is possible today. This school's defining preference, therefore, is pursuing such technology. Because such technology is beyond what is possible, this school finds itself supporting the technical capabilities other schools are pursuing as a way station to new possibilities in

> ***"The Moon could be the ideal location to launch intercepting missions to hazardous asteroids. Hazardous asteroids could be slowed down to not hit the Earth, by ramming heavy spacecraft into them. This mitigation method is known as the kinetic impactor approach, and is considered to be the most technologically mature approach to mitigate hazardous asteroids."***
>
> — Thomas Drake Miyano
> "Moon-Based Planetary Defense Campaign,"
> Journal of Space Safety Engineering,
> Volume 5, Issue 2, June 2018.

space. Space Control First might generate enough maneuverability to make science-fiction-like spacecraft a possibility. Enable Global Missile War offers the possibility of a global sensor and command and control net that can be retrofitted with Earth-striking space weapons. Frictionless Intelligence and Nukes Matter Most have already provided the political support to advance technology beyond the dreams of early space visionaries.

Most Common Organizational Affiliation

There is no single organizational home for this school. Some proponents are attached to scientific or research organizations as they push technology, though they often favor solely peaceful uses of such technology and underestimate the security threats proponents of this school. Some proponents are too troubled by the political demands of existing organizations to hold an affiliation. Because of these dynamics, one sign of this school's proponents is their dissatisfaction of existing organizations, even those dedicated to space. Proponents often identify themselves by emphasizing that the grandest visions of space will not match existing organizations, and so future space organizations should be organized differently. One common proposal is to use naval ranks to distinguish Galactic Battle Fleet organizations from existing Air Force- or Army-based rank structures.[29]

This school matters organizationally because it provides a near-constant push for change as it seeks to transcend today's order. Yet this school has few immediate goals to be gained, making it a potential partner for all other schools in pursuing organizational change, resources, or new technology.

Conclusion

These six schools of operational thought capture most of the ideas being advanced today in the debate about organizing national security space. Space Control First focuses on an unmanned war in space. Enable Global Missile War presumes the sweeping away of old modes of war with the arrival of a reconnaissance-strike complex. Keep the Plumbing Running insists on continuity in how wars are waged, albeit ever more empowered by space. Frictionless Intelligence and Nukes Matter Most concentrate on already traditional roles for space. And, finally, Galactic Battle Fleet envisions space changing mankind's future completely.

By considering these ideas as discrete schools, this paper better identifies the assumptions each makes about how wars of the future will transpire, what role space will play, and what technologies and organizational structure should thus be pursued. Because the assumptions and implications in each of these categories differ, each school would organize and fund national security space differently. Conversely, when decisions are made about how to organize or fund national security space, those decisions will likely favor or hurt the schools unequally. Sometimes decisions can achieve multiple schools' preferences, but at other times a decision will force a choice among the schools' preferences. Today, proponents of each school are jockeying to see their visions and preferences dominate.

But this jockeying of ideas is not clear to many. Proponents of schools may not fully understand the assumptions and arguments of other schools. They may not appreciate how best to accommodate or contest the arguments being made by proponents of other schools. Decisionmakers themselves may not understand how proposals they are considering tie back to assumptions each school is making. Also, if proponents of each school cannot help decisionmakers understand, decisions may be made in a vacuum. Decisionmakers may not realize they are choosing an option that is based on assumptions with which other decisionmakers do not agree. In the worst-case scenario, decisionmakers may seek compromise among the proponents only to choose a solution that achieves none of the schools' goals and leaves national security space worse off than if any one school was supported.

This paper offers a framework for clarifying where the schools of thought are competing with each other. It clarifies the assumptions each school makes and the implications of those assumptions. By doing so, this paper hopefully helps everyone involved in the debate about how space should be organized and funded regardless of their own preferred school of thought.

Space is an area of utmost importance to everyone, yet it is a field dominated by a small group of experts, who themselves are divided on what is most important about space in achieving U.S. national security. The better those divisions are understood, the better the nation can prepare for the future when making choices about how to organize and fund space.

Acknowledgments

Thanks to Dr. Michael P. Gleason for his continuing engagement with the ideas in this paper and to Michael A. Leon and Erin Ryan for their invaluable reviews. As an external reviewer, Ben Friedman's incisive comments are also appreciated.

References

1 General John Hyten, U.S. Air Force, "John H. Glenn Lecture on Space History," June 13, 2018.

2 An extreme version of commercial developments fundamentally changing US national security space is James Clay Moltz, "The Changing Dynamics of Twenty-First-Century Space Power," *Strategic Studies Quarterly*, Spring 2019.

3 National Research Council, "The Global Positioning System: A Shared National Asset," The National Academies Press, 1995.

4 Adam P. Jodice and Mark R. Guerber, "Space Combat Capability . . . Do We Have It?," *Air & Space Power Journal*, November–December 2014

5 "Challenges to Security in Space," Defense Intelligence Agency, February 2019.

6 General John Hyten, U.S. Air Force, "Questions and Answers," Mitchell Institute Breakfast Series, June 20, 2017.

7 B. T. Cesul, "A Global Space Control Strategy," Air & Space Power Journal, November-December 2014

8 Alfred Thayer Mahan, *The Influence of Sea Power on History*, 1890.

9 John Warden, *The Air Campaign*, Air University Press, 1989.

10 For a discussion of the reconnaissance-strike complex concept, see Thomas Mahnken, *Technology and the American Way of War Since 1945*, (Columbia University Press: 2008), pp. 176-177.

11 Andrew Krepinevich, "The Military-Technical Revolution: A Preliminary Assessment," Prepared for the Office of Net Assessment, July 1992, p. 1.

12 Barry Watts, "The Evolution of Precision Strike," Center for Strategic and Budgetary Assessments, 2013 and Michael O'Hanlon, "A Retrospective on the So-Called Revolution in Military Affairs, 2000-2020," Brookings Institution, 2018.

13 "Ballistic and Cruise Missile Threat," National Air and Space Intelligence Center in collaboration with Defense Intelligence Ballistic Missile Analysis Committee, June 2017.

14 Michael S. Chase, "PLA Rocket Force Modernization and China's Military Reforms," Testimony Before the U.S.-China Economic and Security Review Commission, February 15, 2018.

15 Roger McDermott and Tor Bukkvoll, "Russia in the Precision-Strike Regime: Military Theory, Procurement and Operational Impact," Norwegian Defence Research Establishment, August 2017 and Matthew Schwartz, "Russia Says It Will Build New Missile Systems Within 2 Years," NPR, February 6, 2019.

16 "Elements: Sensors," Missile Defense Agency website, https://www.mda.mil/system/sensors.html, accessed April 2019.

17 "Army Space Support as a Critical Enabler of Joint Operations," AU.S.A Background Brief No. 97, December 2003.

18 Glenn Kent, "Thinking About America's Defense: An Analytical Memoir," RAND: 2008, p. 189-91.

19 Chadwick D. Igl, Candy S. Smith, Daniel R. Fowler, and William L. Angermann , "568 Balls in the Air: Planning for the Loss of Space Capabilities," Joint Force Quarterly 90.

20 Walter McDougall, …the Heavens and the Earth: A Political History of the Space Age, (New York: Basic Books, 1985), chapters four through ten. Also see Peter Hays, "Struggling Towards Space Doctrine: U.S. Military Space Plans, Programs, and Perspectives During the Cold War," Tufts University Fletcher School of Law and Diplomacy, unpublished dissertation, 1994, p. 61-79.

21 William J. Clinton, "Remarks by the President at the 50th Anniversary of the Central Intelligence Agency," press release b the White house, Office of the Press Secretary, September 16, 1997.

22 "IC21: The Intelligence Community in the 21st Century," Staff Study, U.S. House of Representatives Permanent Select Committee on Intelligence, June 1996.

23 John Kringen, "Rethinking the Concept of Global Coverage in the U.S. Intelligence Community," Institute for Defense Analyses, NSD-5491, May 2015.

24 G. Harry Stine, *Confrontation In Space*, (Englewood Cliffs, NJ: Prentice-Hall, Inc. 1981) and

25 For space coast guard, see Cynthia McKinley, "The Guardians of Space: Organizing America's Space Assets for the Twenty-First Century," Aerospace Power Journal, Spring 2000 and Michael Sinclair, "Model a Space Force on the Coast Guard," U.S. Naval Institute Proceedings, September 2018. For a military role in space colonization, see Konrad Szocik, Tomasz Wójtowicz, and Leszek Baran, "War or peace? The possible scenarios of colonising Mars," Space Policy, November 2017.

26 Travis Taylor, Bob Boan, R.C. Anding, and T. Conley Powell, An Introduction to Planetary Defenes: A Study of Modern Warfare Applied to

Extra-Terrestrial Invasion, (Brown Walker Press: 2006).

[27] Jonathan Shainin, "Rods from God," *New York Times Magazine*, December 10, 2006 and Robert Preston, Dana J. Johnson, Sean J. A. Edwards, Michael D. Miller, Calvin Shipbaugh, *Space Weapons, Earth Wars*, (RAND: 2002).

[28] Everett Dolman, *Astropolitik: Classical Geopolitics in the Space Age,* (Frank Cass: 2002).

[29] Jacqueline Klimas, "Trump to approve lean Space Force," *Politico Pro*, February 18, 2019.

ORGANIZING FOR DEFENSE SPACE: BALANCING SUPPORT FOR THE JOINT FORCE AND INDEPENDENT SPACE OPERATIONS

R. Russell Rumbaugh, Peter L. Hays, and Michael P. Gleason

The United States Space Force is arguably the largest restructure of U.S. defense space organizations since 1960. The reorganization also includes United States Space Command (USSPACECOM), the Assistant Secretary of the Air Force for Space Acquisition and Integration, and other new organizations. Being new, these organizations face many challenges—and how they address these challenges will define the tools that are available to senior political and military leaders for years to come. Despite the historic nature of the moment, there are lessons to be learned from these organizations' predecessors. Those lessons highlight that the greatest tension these organizations will face is how to balance the space-based needs of the joint force against independent military operations in, to, and through space.

Introduction

The U. S. Space Force is the first new military service created in 70 years and is arguably an even larger restructuring of national security space than the creation of a separate agency for satellite reconnaissance in 1960. While the biggest, this reorganization is not the first and likely will not be the last. Most of these reorganizations have sought to balance the needs of the joint force, which relies on space to achieve the military effectiveness it enjoys today, against the value of a domain-focused organization for developing independent military options in, to, and possibly even from space. In the next few years, that tension is likely to come to a head as the new space organizations define their doctrine, role, and organization.

The United States leverages space for military, commercial, and societal advantages.[1] As space becomes ever more democratized yet contested, everyone in the United States should care how the new organizations shift the balance between supporting the joint force and pursuing independent options. Once military organizations are settled into their ways, senior political and military leaders can find their tools—no matter how polished and refined—do not achieve the ends national leaders seek.[2] The new space organizations are building and establishing their priorities now and in so doing, inevitably will favor some missions over others. Thus, the next few years will be critical for the new space organizations to truly define what they are and what they do for the country.

U.S. Space Force. Despite its historic creation, the U. S. Space Force still faces challenges, some of which may be informed by how its antecedents dealt with similar tensions. Drawing from those experiences, the U. S. Space Force will be successful if it can build a cohesive single organization dedicated to space that meets the needs of military space's many users, effectively balancing requirements for force enhancement and space control.

The clearest predecessor of the U.S. Space Force is Air Force Space Command (AFSPC), created in 1982.[3] The Air Force had become the military service responsible for most military space programs by the early 1960s.[4] Most of these programs were secret research and development efforts and the Air Force considered air and space a single operational area doctrinally.[5] As a result, space efforts then were not organized around space as a separate domain, but instead were owned by multiple commands in a more functionally aligned way. With the demise of Air Defense Command in 1977, the growth of military space capabilities created an opportunity with the creation of AFSPC to organize space in one place separate from the research and development community.[6] For the first time, AFSPC was focused on the space domain, not any particular function.

Those supported by space did not accept the separation of space capabilities easily. It took more than a decade to consolidate space activities under AFSPC. AFSPC inherited Air Defense Command's early warning radars.[7] Then, AFSPC took over Strategic Air Command's weather satellites in 1983; in 1985, the Satellite Test Facility from Systems Command; in 1987, the ground-based satellite control network; in 1990, launch systems; and in 1991, the Air Force's astronaut program was transferred to AFSPC.[8] By the early 1990s, space itself seemed a mission with an organization dedicated to it. No longer was it a supporting capability spread throughout the force.

The end of the Cold War stalled that refocus on space as a domain for action itself. The first Gulf War showed how much the joint force could leverage space to be the most effective military force in the world and possibly in history.[9] Once proven, everyone in the DOD wanted space to provide "force enhancement" and saw AFSPC's role as providing that support.[10]

Additionally, AFSPC took responsibility for the ground-based intercontinental ballistic missiles (ICBMs) that had belonged to Strategic Air Command. This merger gave two small communities a scale equivalent to other Air Force communities, including providing the two career fields a better promotion pyramid.[11] To some, it was also a consolidation of missions in response to the argument that ICBMs belonged in a space organization because they transited space.[12]

But the merger never quite brought the cultures, let alone missions, together.[13] Instead it blurred whether space could achieve decisive effects itself, while being perceived as simultaneously diluting sufficient focus on safe nuclear operations.[14] The Rumsfeld Commission report of 2001 restarted the conversation by recommending sharper delineation of space organization, though it stopped short of recommending a separate service.[15] When the commission's chairman, Donald Rumsfeld, became Secretary of Defense, AFSPC took control of building as well as operating satellites with the transfer of Space and Missile Systems Center from Air Force Materiel Command.[16] Finalizing this era, in 2008 the ICBMs were organizationally split back out from space activities, once again leaving the space domain as AFSPC's mission.[17]

The next decade sharpened the focus on the space domain, eventually leading to the U.S. Space Force as an independent service. First, a distinct space budget was mandated in law—virtually in 2008 and completely in 2015.[18] Then in 2017, the House Armed Services Committee proposed a Space Corps within the Air Force.[19] After more negotiations on how to best organize defense space, the U.S. Space Force was formally established within the Department of the Air Force in 2019.

Embedded in the sixty years of evolution described in the last few paragraphs is a running fight about whether space should be organized separately to focus on a fight in space itself or whether space capabilities' main purpose is to support the rest of the joint force, as discussed in the previous section.[20] The U.S. Space Force will now have the dominant role in allocating how dollars are invested for space. Will it favor those capabilities focused on military action in space independent of other efforts or those capabilities that support the joint force? Will the other military services trust the Space Force to provide capabilities on which they depend? Or will they develop their own space-based capabilities, just as the U.S. Navy always maintained its own ultra-high frequency satellite program to support its submarines, or even non-space-based alternatives, or just as the U.S. Army developed attack helicopters when it feared it could not depend on the Air Force to provide it air support?

Now that the Space Force is independent, it will be successful if it can address this tension and achieve a cohesive culture and mission that also serves the many parts of the U.S. military—and even U.S. society—that are dependent on space.

U.S. Space Command. SPACECOM has clearer antecedents than the Space Force but also faces the core tension the Space Force faces. SPACECOM will be successful if it can provide independent strategic options in space while remaining a critical part of U.S. global operations.

A unified space command has long been one option to focusing on space while still weighing joint force equities. In the late 1950s, the Chief of Naval Operations, Admiral Arleigh Burke, proposed such a command to address intense interservice rivalry between the Army and Air Force.[21] When the Air Force was planning to create AFSPC in the 1980s, some of the concerns and equities the other services had regarding space roles and responsibilities were reawakened. Some of the original planners for AFSPC expected it would become a specified command—an operational command responsible for DOD-wide operations but controlled and manned by only one service.[22] Recognizing space's wider value, the services insisted on creating a command for all joint operations, which led to the creation of the unified U.S. Space Command in 1985.[23]

Independent space operations remained subordinate for the next couple of decades. When the Gulf War highlighted what capabilities space could provide, the joint force sought to better leverage space, which was reflected in giving command of SPACECOM to General Chuck Horner, a fighter pilot who had overseen the air campaign in the Gulf War.[24] Ironically, Secretary Rumsfeld's ascension worked against independent space options despite his heading the Rumsfeld Commission. The September 11th attacks drove a need for a greater homeland defense mission, which in 2002 resulted in the separation of North American Aerospace Defense Command from SPACECOM to form U.S. Northern Command (NORTHCOM).[25] The space mission was merged into U.S. Strategic Command (STRATCOM) in Omaha as NORTHCOM stayed in Colorado Springs.

In the last few years, despite being submerged in STRATCOM, independent space operations gained ground. Operational command was reenergized as the Combined Space Operations Center (CSpOC) in 2018.[26] In 2015 the Joint Interagency Combined Space Operations Center was created to better interface with intelligence community space operations and was later renamed the National Space Defense Center (NSDC).[27] In 2017, AFSPC was dual-hatted as the Joint Force Space Component Command to direct both the CSpOC and NSDC.[28]

Ironically, all of these changes may have culminated in the creation of the U.S. Space Force. In contrast, SPACECOM's main focus may be on supporting the joint force rather than independent space operations.[29] Despite the likelihood that the Space Force will provide nearly all of DOD's capabilities that operate 100 kilometers above the Earth, which is designated as SPACECOM's geographic domain, SPACECOM has been kept as a separate organization and SPACECOM is to draw forces from *all* the services, not just the Space Force.[30] An Army general—not a Space Force general—is the first non-dual-hatted SPACECOM commander.[31]

Will SPACECOM become the organization that champions space's support of the joint force? What will be the relationship between the two four-star generals— the SPACECOM commander and the Space Force's Chief of Space Operations? Will it become adversarial as each becomes the champion for competing visions of what space should do? How will SPACECOM support the joint force if the Space Force focuses ever more on capabilities to conduct independent activities in space? Will SPACECOM serve as a champion for space as STRATCOM serves as one for nuclear weapons? Will the resourcing process within DOD respond to these calls? Will Congress? Will the other geographic combatant commands see SPACECOM's support as critical or will they feel they should have direct control of space assets?

As with the Space Force itself, SPACECOM must balance the demands of providing options in space independent of other military forces and enhancing the joint force's lethality. SPACECOM will have to do so even as it relies for most of its capabilities on a single service—the U.S. Space Force.

Assistant Secretary of the Air Force for Space Acquisition and Integration. Along with the Space Force, the fiscal year 2020 defense authorization bill also created the position of assistant secretary of the Air Force for Space Acquisition and Integration (SA&I).[32] The individual confirmed for this new position is to be responsible for all architecture and integration of the Air Force for space systems and programs, chair the Space Force Acquisition Council (more on this below), become the Department of the Air Force service acquisition executive with responsibility for space systems and programs by October 1, 2022, and oversee and direct the Space Rapid Capabilities Office, the Space and Missile Systems Center, and the Space Development Agency. Just as the Space Force and SPACECOM must balance the dual roles of space (independent missions and missions to support the joint force), SA&I will be successful if he or she can serve as a locus for DOD-wide space efforts while also being an integral partner of the Space Force.

SA&I has 30 years of clear precedent that shows how difficult it is to serve as a single authority over the institutional side of space. While the Goldwater-Nichols Reform Act of 1986 successfully made DOD operationally more joint, the DOD has never been as successful in coordinating the acquisition and institutional side.[33] Space has long been one of the clearest examples of this dynamic.[34] Every part of DOD depends on space but organizational seams keep many programs and responsibilities fragmented, particularly those for programming space budgets, prioritizing between air and space programs, and synchronizing deployment of space, ground, and service-procured user equipment.[35]

The DOD tried to create just such an organization in the 1990s. Facing congressional frustration with several major space programs, the department created the deputy under secretary of defense for space and the related space architect in 1995.[36] Tasked to integrate space policy, architecture, and acquisition, these offices found that, despite their high-level tasking, they could not force other department components to conform, usually resulting in guidance that was unobjectionable to all stakeholders at the expense of clarity.[37] Worse, the deputy under secretary position did not survive the 1990s budget downturn that saw the office dissolved as an efficiency measure.[38]

In 2004, the Air Force tried again by implementing several major recommendations from the Rumsfeld Space Commission by establishing a National Security Space Office to staff the architect and integration roles.[39] This office lasted until 2010, when the executive agent for space staff was transferred from OSD back into the Air Force secretariat and a new Defense Space Council was created as a forum where the principals of each stakeholder could come together to make coordinated decisions.[40] In 2015, a new position, the principal DOD space advisor, was created with enhanced authorities, a more robust staff, and the intent to provide more centralized direction and oversight of DOD's newly mandated dedicated space budget.[41] But by 2017, the commander of STRATCOM recommended doing away with all these organizations and Congress did so in the fiscal year 2018 defense bill.[42]

Embedded in each of these organizational changes is the challenge of balancing support for the joint force against independent space operations. When SA&I's predecessors sought to prioritize space as an independent area for action, the other military services and other oversight bodies used their authorities to undermine centralized control of space.[43] When SA&I's predecessors sought to represent the joint force's equities, the space organizations saw them as interlopers.[44]

How will SA&I balance these tensions? Will SA&I use its service acquisition executive authority to prioritize independent space capabilities or support for the joint force? Will SA&I become the civilian spokesperson for independent space capabilities including as chair of the Space Acquisition Council? Or will SA&I become the DOD's point person in emphasizing space's critical supporting role using the Space Acquisition Council to force the space-focused organizations to incorporate needed support functions?

SA&I will be successful if it is seen both as a civilian champion of independent space capabilities and as the representative of the rest of the DOD in ensuring space's role supporting the joint force. In doing so, SA&I will in turn shape how the Space Force and SPACECOM see their role in maintaining the balance between these two missions.

Other Organizations. The fiscal year 2020 defense bill also created an assistant secretary of defense for space policy (ASD(SP)) and DOD created a Space Development Agency (SDA), while all the reorganizations have left the intelligence space agencies outside of Space Force. These organizations, too, represent enduring tensions in overseeing and balancing between independent space options and supporting the joint force, while also providing strategic intelligence.

ASD(SP), like SA&I, builds on the many efforts to create a civilian to oversee and deconflict competing needs for defense space. DOD currently has a deputy assistant secretary of defense for space policy, one level down from the new statutory position.[45] Because ASD(SP) is not part of the Department of the Air Force but part of the Office of the Secretary of Defense (OSD), it might represent the joint force perspective even more than SA&I.[46] Alternatively, it might come to be the champion of independent space options throughout DOD, potentially even goading Space Force and SPACECOM into greater independent options. The emphasis on maintaining space superiority in the Defense Space Strategy Summary released in June 2020 may indicate OSD is leaning slightly more toward independent options than support to the joint force.[47]

SDA represents the fruition of one solution to the defense space organization problem. Many have proposed a defense agency over the years to capture the joint nature of space.[48] Usually, these proposals have presumed a supporting role like the Defense Logistics Agency though some imagine it more like the Missile Defense Agency.[49] The Missile Defense Agency and its predecessors are defense agencies, but with an operational focus. Though sometimes seen as a place to acquire space equipment differently, SDA has primarily taken on a distinct mission from Space Force and SPACECOM, focusing on tracking long-range missiles on the ground and in the air, and on creating a space-based communications network fast enough to make that data actionable.[50] SDA is slated to become part of the U.S. Space Force no later than fiscal year 2023 and—depending partly on whether it has proven the military capability it is pursuing—may remain semi-independent, may revert to a distinct approach to acquisitions, or may be subsumed completely within other Space Force organizations.

Finally, the recent changes reaffirmed a formal split between defense and intelligence space. The presidential directive explicitly exempted intelligence space agencies from being part of Space Force.[51] While that decision maintains the status quo, it also leaves intact a perennial challenge: how to balance the different missions of defense and intelligence space against the value from integrating the architecture and programs of all national security space programs.[52] Keeping intelligence and defense space separate means the balance will stay tipped toward differentiation even as the intelligence community and Space Force work to better ensure unity of effort, particularly in times of conflict in space.[53] While the manner in which scarce resources are allocated between strategic intelligence and intelligence support for military operations will always require balancing, this organizational differentiation emphasizes that the focus of the next few years will likely be on balancing support for the joint force and independent space missions.

Conclusion

The U.S. Space Force and its related organizations are the greatest changes to defense space institutions in half a century. These new organizations have advantages many of their predecessors did not have. They are more unitary, more senior, and created at a time when space enjoys high-level support and attention. Each of these new organizations faces the central challenge of balancing support for the joint force against independent space options. How each seeks to address this balance will depend on how and where the other new space organizations also seek to achieve that balance.

While their creation alone is significant, they remain nascent organizations that will face many of the same challenges their predecessors faced, and their success is not guaranteed. By learning lessons from past efforts to address the tension between independent space operations and supporting the joint force, senior leadership can potentially improve the coherence and effectiveness of U.S. space capabilities for the coming decades. If the leadership of the country does not watch how the new organizations develop, they may find the organizations have chosen paths at odds with leadership's goals for space.

References

1 Robert Wilson, Michael Gleason, Samira Patel, and Luc Riesbeck, "The Value of Space," The Aerospace Corporation, May 2020.
2 Adam Grissom, "The Future of Military Innovation Studies," Journal of Strategic Studies, Vol. 29, No. 5, 2006.
3 Earl Van Inwegen, "The Air Force Develops an Operational Organization for Space," in R. Cargill Hill and Jacob Neueld, *The U.S. Air Force in Space: 1945 to the Twenty-First Century*, (USAF History and Museums Program: 1998).
4 David Spires, "The Air Force and Military Space Missions: The Critical Years, 1957-1961), in R. Cargill Hill and Jacob Neueld, ed. *The U.S. Air Force in Space: 1945 to the Twenty-First Century*, (USAF History and Museums Program: 1998).
5 David Bradburn, "Evolution of Military Space Systems," in R. Cargill Hill and Jacob Neueld, *The U.S. Air Force in Space: 1945 to the Twenty-First Century*, (USAF History and Museums Program: 1998) and Frank W. Jennings, "Genesis of the Aerospace Concept," Air Power History, vol. 48, no. 1, 2001.
6 Rick Sturdevant, "The United States Air Force Organizes for Space: The Operational Quest," in Roger B. Launius, ed. Organizing for the Use of Space: Historical Perspectives on a Persistent Issue, (American Astronautical Society History Series, Vol 18: 1995).
7 Joshua Boehm with Craig Baker, "A History of United States National Security Space Management and Organization," Prepared for the Commission to Assess United States National Security Management and Organization, 2000.
8 Tony Tunyavongs, "A Political History of the Establishment of Air Force Space Command," *Quest*, Vol. 9, Issue 1, 2001, p. 39-40.
9 David Spires, *Beyond Horizons: A Half Century of Air Force Space Leadership*, (Air Force Space Command: 1998), p. 243-270).
10 Frank Gallegos, "After the Gulf War: Balancing Space Power's Development," in Bruce DeBlois, ed. *Beyond the Paths of Heaven: The Emergence of Space Power Thought*, (Air University Press: 1999).
11 Kevin McLaughlin, "Military Space Culture," Prepared for the Commission to Assess United States National Security Management and Organization, 2000 and Georges Vernez, "Improving the Development and Utilization of Air Force Space and Missile Officers," (RAND: 2006).
12 Jamie Varni et al, "Space Operations: Through the Looking Glass (Global Area Strike System)," A Research Paper presented to Air Force 2025, August 1996, p. 14-15.
13 Thomas Deppe, "Why American Needs ICBMs Contributing to Air and Space Power and Strategic Deterrence," *High Frontier*, Vol. 2, No. 4, August 2006.
14 Adam Hebert, "Strike Command Steps Up," *Air Force Magazine*, June 1, 2010.
15 Benjamin Lambeth, *Mastering the Ultimate High Ground*, (RAND: 2001), p. 67-71.
16 "Historical Overview of the Space and Missile Systems Center," Space and Missile Systems Center Historical Office, 2003, p. 5-6.
17 Amaani Lyle, "Air Force stands up Global Strike Command," Air Force Public Affairs, August 7, 2009.
18 Michael B. Donley, "The Challenges of Space Management and Organization," Remarks at the National Space Symposium, Colorado Springs, Colo., April 13, 2010.
19 House Report 115-200 to accompany National Defense Authorization Act for Fiscal Year 2018, p. 267.
20 David E. Lupton, *On Space Warfare: A Space Power Doctrine* (Air University Press, 1988) and R. Russell Rumbaugh, *What Place for Space: Competing Schools of Operational Thought in Space* (The Aerospace Corporation: 2019).
21 David Spires, "The Air Force and Military Space Missions: The Critical Years, 1957-1961), in R. Cargill Hill and Jacob Neueld, ed. *The U.S. Air Force in Space: 1945 to the Twenty-First Century*, (USAF History and Museums Program: 1998), p. 40.
22 Earl Van Inwegen, "The Air Force Develops an Operational Organization for Space," in R. Cargill Hill and Jacob Neueld, *The U.S. Air Force in Space: 1945 to the Twenty-First Century*, (USAF History and Museums Program: 1998), p. 142-3.
23 Tony Tunyavongs, "A Political History of the Establishment of Air Force Space Command," *Quest*, Vol. 9, Issue 1, 2001, p. 39-40.
24 David Spires, *Beyond Horizons: A Half Century of Air Force Space Leadership*, (Air Force Space Command: 1998), p. 243-284.
25 Edward Drea et al, H*istory of the Unified Command Plan: 1946-2012*, Office of the Chairman of the Joint Chiefs of Staff Joint History Office, 2013, p. 81-87.
26 "Combined Space Operations Center established at Vandenberg AFB," Joint Force Space Component Command Public Affairs, July 19, 2018.
27 Phillip Swarts, "The JICSpOC is dead; Long live the National Space Defense Center," *Space News*, April 4, 2017.
28 John Raymond, "Fiscal Year 2019 Priorities and Posture of the National Security Space Enterprise," Testimony before the House Armed Services Committee Strategic Forces Subcommittee, March 15, 2018.

[29] Rachel Cohen, "Army General Auditions for Top SPACECOM Job," *Air Force Magazine*, July 28, 2020.
[30] Theresa Hitchens, "Milley to OK New Unified Command Plan; Defines SPACECOM's Roles," *Breaking Defense*, August 26, 2020.
[31] Terri Moon Cronk, "Space Command Leadership Changes Hands," DOD News, August 21, 2020.
[32] P.L. 116-92, National Defense Authorization Act for Fiscal Year 2020, Sec. 956.
[33] James R. Locher III, "Has It Worked?—The Goldwater-Nichols Reorganization Act," *Naval War College Review*, Vol. 54 (2001), No. 4.
[34] James Jay Carafano, "America's Joint Force and the Domains of Warfare," Heritage, October 4, 2017.
[35] "Defense Space Acquisitions: Too Early to Determine If Recent Changes Will Resolve Persistent Fragmentation in Management and Oversight," Government Accountability Office, GAO-16-529R, July 27, 2016.
[36] Joshua Boehm with Craig Baker, "A History of United States National Security Space Management and Organization," Prepared for the Commission to Assess United States National Security Management and Organization, 2000.
[37] Joan Johnson-Freese and Roger Handberg, "Searching for Policy Coherence: The DOD Space Architect as an Experiment," *Joint Force Quarterly*, Summer 1997.
[38] "Organizational Changes Initiated, but Further Management Actions Needed," General Accounting Office, GAO-03-379, April 2003.
[39] Michael Donley, "The Challenges of Space Management and Organization," Remarks at the National Space Symposium, Colorado Springs, Colo., April 13, 2010.
[40] "FACT SHEET: National Security Space Strategy DOD Initiatives," Department of Defense, 2011.
[41] Deputy Secretary of Defense Memorandum, "Designation of the Principal. DoD Space Advisor," October 5, 2015.
[42] John Hyten, "Thoughts on National Security Space Organization," January 2017 and Public Law 115-91, National Defense Authorization Act for FY2018, sec. 1601.
[43] Government Accountability Office, "Challenges in Aligning Space System Components," GAO-10-55, October 2009.
[44] James B. Armor, Jr., "The Air Force's other blind spot," *The Space Review*, September 15, 2008.
[45] "Remarks by Vice President Pence on the Future of the U.S. Military in Space," August 9, 2018.
[46] Senate Report 116-48 to accompany the National Defense Authorization Act for Fiscal Year 2020, p. 298.
[47] Office of the Secretary of Defense, "Defense Space Strategy Summary," June 2020.
[48] Kevin Kruse et al, "United States Space Management and Organization: Evaluating Organizational Options," Prepared for the Commission to Assess United States National Security Management and Organization, 2000, p. 181.
[49] Christina Chaplin, "Defense Space Acquisitions: Too Early to Determine If Recent Changes Will Resolve Persistent Fragmentation in Management and Oversight," Government Accountability Office, GAO-16-592R, July 27, 2016, p. 57.
[50] Sandra Erwin, "Space Development Agency wants to demonstrate hardware before merging with Space Force," *Space News*, June 18, 2020.
[51] Space Policy Directive-4: Establishment of the United States Space Force, February 19, 2019.
[52] "Report of the Commission to Assess United States National Security Space Management and Organization," January 11, 2001, p. 90-94.
[53] Space Policy Directive 4: Establishment of the United States Space Force, February 19, 2019.

GETTING THE MOST DETERRENT VALUE FROM U.S. SPACE FORCES

Michael P. Gleason and Peter L. Hays

As space becomes more crowded and contested it becomes ever more important to prevent a conflict in, directed toward, or from space. Without any actual experience of combat in space, however, we can only speculate about what role the space domain might play in a breakdown of deterrence and the start of a war. This inexperience with space's role in conflict complicates social science's already limited understanding of how wars begin and unfold—with their complex interplay of political goals, differing levels of commitment, the friction generated in any actual fighting, and the inherently flawed people (on all sides) making decisions. As the strategic environment changes, we must explore ways to strengthen the contribution of U.S. military space capabilities to deterrence while also enhance any advantages should deterrence fail. Focusing on the credibility of U.S. space capabilities in some narrow areas reveals steps that could be made to strengthen their deterrent value.

Background

Russian and Chinese efforts to field antisatellite (ASAT) weapons represent serious threats to U.S. national security and complicate U.S. deterrence efforts. According to the U.S. Defense Intelligence Agency (DIA), China's People's Liberation Army (PLA) already has operational ground-based ASAT weapons to destroy satellites in low Earth orbit (LEO), and the PLA has military units dedicated and trained to use them. In addition, China may already have a limited capability to use laser systems against satellite sensors, will likely deploy a ground-based laser weapon operationally before the end of 2020, and within the next ten years may have lasers powerful enough to damage satellites themselves, not only satellite sensors.[1] China is also developing advanced on-orbit capabilities which could serve as inspection and repair satellites or co-orbital weapons. Dedicated counterspace electronic warfare and jamming weapons also threaten U.S. space capabilities and cyber-attacks are a threat in space, just like in other domains.[*] While reflecting different priorities and investment decisions, Russian efforts generally mirror Chinese development of counterspace weapons.

The vulnerability of U.S. military, intelligence, and partner satellites to these threats weakens the United States' conventional deterrence abilities and potentially undermines the U.S. nuclear deterrent. Conventionally, Russia and China see their space attack capabilities as a means to level the battlefield with the U.S. military. U.S. military and intelligence satellites, as well as the commercial satellites the U.S. military uses, are critical to the modern American way of war. But if

[*]For a more detailed discussion see *A Roadmap for Assessing Space Weapons*, also from CSPS.

those satellites can be destroyed or at least disrupted, Russian and Chinese terrestrial forces may perceive a narrower disadvantage and those nations may be more willing to start a war.

U.S. space capabilities enable U.S. nuclear deterrence strategy by gathering and delivering intelligence on adversaries' nuclear weapons dispositions, verifying Russian compliance with nuclear arms control agreements, providing the United States with warning of a nuclear attack, and providing U.S. decision-makers with tight command and control of U.S. nuclear forces. If attacking those satellite capabilities is perceived as a way to prevent the United States from responding to a nuclear attack, nuclear deterrence may be undermined. Moreover, even if the adversary attacks U.S. satellites only in pursuit of limited, regional objectives, the United States may perceive itself to be under strategic attack.

Worryingly, space is perceived as an offensive dominant arena, meaning it is considered materially easier and less costly to *attack* a satellite than to *defend* a satellite. Political scientists contend that war is more likely when the offensive is dominant—especially if it is difficult to distinguish between offensive and defensive weapons as is the case with space—and they argue that there are strong incentives for striking first should a conflict appear inevitable.[2] Surprise attack is perceived as leading to large rewards, fueling a first-mover advantage for striking in space. But the speed with which events can happen in space leads to the potential for crisis instability since decisionmakers—on all sides—will have very little time (perhaps only a few minutes) to decide what to do in the face of a sudden attack in space. In short, perceived weaknesses in the ability of space forces to protect themselves can lead to a broader breakdown in deterrence.

An exploration of deterrence theory fundamentals can serve as a guide on how to mitigate some of these weaknesses and strengthen the deterrence value of U.S. military space capabilities while contributing to achieving advantage should deterrence fail.

Fundamentals

Deterrence is a psychological concept intended to prevent undesired behavior and activity. As detailed in the study of nuclear deterrence, there must be at least two actors in the deterrence calculus and there are two basic approaches: deterrence by punishment and deterrence by denial.[3] Each approach emphasizes different concepts of operations and favors different capabilities and architectures. An integrated approach is ideal, but trades between the two approaches make a fully integrated approach difficult. Punishment attempts to deter undesired behavior by credibly threatening to punish assailants with overwhelming force or other punitive action in retaliation for an aggression. The punishment need not be in the same domain or region as the initial attack; it may not even need to be a military response. The December 2017 *National Security Strategy of the United States of America* sends a deterrence by punishment message where it states:

> The United States considers unfettered access to and freedom to operate in space to be a vital interest. Any harmful interference with or an attack upon critical components of our space architecture that directly affects this vital U.S. interest will be met with a deliberate response at a time, place, manner, and domain of our choosing.

Under this threat, actors may be deterred from undesired behavior if they conclude that the costs of the behavior outweigh the benefits. Denial, by contrast, attempts to deter undesired behavior by leading actors to conclude that they will be unable to achieve the objectives they seek from their behavior. Denial requires effectively responding in the same time and place as the attack.

To prevent a breakdown in deterrence, both punishment and denial require that the actor attempting to deter undesired behavior is perceived as possessing needed capabilities, is credible in exercising those capabilities under threat of counter-retaliation and potential escalation, and has successfully communicated its capabilities and credibility to the actors it intends to deter.

Table 1: Requirements for One Actor to Deter Another Actor
Be perceived as possessing required capabilities
Be perceived as credible in exercising those capabilities and in possessing the willingness to suffer counter-retaliation and escalation
Be able to successfully communicate capabilities and credibility to those being deterred

The study of deterrence reveals many complexities and nuances associated with the *concept* of deterrence which could lead to a breakdown in *actual* deterrence, including:

- Differing perceptions of undesired behavior, rationality, and credibility
- Divergent ways different cultures allocate values to cost-benefit analyses
- Philosophical differences in understanding causation

These are not addressed here so the focus can remain on the issues particular to deterrence in the space domain and how a breakdown in general deterrence may follow several paths flowing from these peculiarities. Demonstrating the credibility of U.S. capabilities is at the core of the issue and is key to getting the most deterrent value from U.S. space forces.

The Credibility of U.S. Attribution of Attacks in Space

To deter, the United States must be able to attribute an attack on its satellites. Attribution refers to the ability to determine the actor(s) responsible for creating certain effects and, in many space scenarios, can be difficult to determine. Space has a wide range of naturally occurring phenomena such as micro meteoroids and geomagnetic storms which can interfere with satellite operations in ways that can be hard to distinguish from interference intentionally caused by human actions. We also have limited fidelity about many ongoing space activities, satellite systems, and their orbital locations. Moreover, the amount of and dangers posed by debris continue to grow and pose problems. Accounting for the effects of debris that is too small to track but still large enough to damage or disable a satellite presents one of the most daunting attribution challenges. Finally, many space capabilities can be used for military, civil, and commercial purposes. These growing dual-use entanglements make it difficult to identify individual space actors or single uses of space capabilities, complicating attribution and leading to several potential paths to a broader breakdown in deterrence.

A key challenge for strategists is to identify ways for the United States to demonstrate its capability to attribute malicious behavior in space in light of these problems. The adversary should perceive that it will be caught.

Table 2: Attribution Difficulties in Space
Distinguishing natural phenomenon from intentional interference
Limited fidelity about space activities and sensor limitations
Space debris that is too small to track but still can cause damage
Dual-use entanglements

A *deterrence by punishment* strategy has more stringent attribution requirements. To justify a punitive response elsewhere, an actor must have defensible evidence of what happened that it is willing to share with allies and the public. If an adversary is confident that its responsibility for an attack may be obscured or unattributable—quite possible in space with all the attribution difficulties noted above— the adversary may calculate that it can avoid retaliation for the attack and get away with a *fait accompli*. Therefore, for deterrence by punishment to be most credible, the adversary must perceive that it will *not* be able to escape responsibility for an attack in space due to the United States' inadequate ability to confidently attribute the attack.

Table 3: Attribution, Punishment, and Space
Possess the most stringent attribution requirements
Shape an adversary's perception of the United States' capability to confidently attribute an attack
Have the need to share some amount of attribution information to get domestic political/allied support for retaliation
Have the need to reveal, to some degree, U.S. decisionmaking processes for retaliation

However, an adversary's mere *perception* of attribution is not sufficient. Since conflict escalation might need broad support from American opinion leaders and the public as well as support from allies and commercial partners, attribution information likely needs to be credible and available to share with this broad range of stakeholders.

If the United States decides to emphasize a deterrence by punishment strategy for attacks on its space assets, it will have to communicate, to some extent, its criteria and decisionmaking processes for deciding to retaliate. The United States provides such insights about its nuclear deterrence strategy in the public release of how information on a nuclear attack warning flows to the president, about how much time the president has to make a decision, and how the president gives the command to retaliate. But the United States, by necessity, also must keep some aspects of its nuclear capability secret to ensure it is effective; if too much is exposed, an adversary could exploit that knowledge. As with nuclear deterrence, senior decisionmakers will have to balance what to share and what to keep secret.

In contrast, *deterrence by denial* emphasizes the ability to absorb an attack at the time and place it occurs, so rapid, precise attribution of an attack in space may appear relatively less important. However, the line between deterrence by denial and punishment is blurry at best. Strategists might assume that if the threat of denial fails, they still have the threat of punishment to wield. In essence, the threat of punishment usually backstops a denial deterrence strategy. If that is the case, it leads to the notion that both denial and punishment strategies require the same attribution strategy.

An effective attribution strategy will drive the spectrum of technologies, architectures, and decisionmaking processes needed to maintain deterrence. Even with near-perfect technologies for understanding what is happening in space, without a comprehensive attribution strategy for space, many of the attribution challenges outlined above would remain.

The Credibility of U.S. Denial, Space Mission Assurance, and Resilience Efforts

The United States must also ensure that adversaries know U.S. space capabilities can withstand attacks. Weak links make for tempting, first-strike targets and can lead to a breakdown in deterrence no matter where the capabilities physically reside. Increasing satellite and space architectural resilience and defenses can make space a strong link that discourages rather than tempts attack. For the past decade, the Department of Defense has attempted to strengthen deterrence by advancing the concepts of denial, space mission assurance (SMA), and resilience.[4] This approach moves beyond the Cold

War nuclear warfighting context of the deterrence by punishment and denial concepts and focuses on the space domain and today's security dynamics.

Denial, SMA, and resilience approaches for strengthening space deterrence are closely related but there are some distinctions that can be drawn to sharpen these concepts. The goal of denying adversaries the objectives they seek from their space attacks or undesired behavior can be achieved by reducing reliance on space capabilities, developing alternative means of providing these capabilities (perhaps not space-based), or creating resilient space architectures. Alternative concepts of operations (CONOPS) and enhanced training can acceptably reduce Joint Force reliance on space capabilities in some cases. In other cases, such as the positioning, navigation, and timing (PNT) capabilities provided by the Global Positioning System (GPS), there currently is no comprehensive alternative and this places a premium on ensuring delivery of this critical capability or fast-tracking development of an alternative.

Active and passive defense measures such as decoys, escorts, or convoy approaches could be used to strengthen denial capabilities. One interesting historical precedent for covertly strengthening defense capabilities is the "Q Ship" approach, whereby decoys for high-value satellites would be designed to lure adversaries into attacks that could be countered by active defenses. This and other active defense approaches could deter adversaries from attempting attacks. Options include the range of resilience approaches: disaggregation, diversification, deception, protection, proliferation, and distribution. Ongoing commercial programs and plans to deploy very large constellations of low-Earth orbit satellites can be leveraged and should dovetail nicely into the DOD's efforts to enhance resilience.

Credibly communicating the resilience of U.S. space capabilities to a potential attacker and convincing them that it will be unable to achieve its objective is a sticky problem, however. To derive deterrent value from the resiliency of U.S. space capabilities, decisionmakers have to decide the right balance between demonstrating space capabilities' robustness (and/or spotlighting alternative means to accomplish terrestrial military missions), while keeping capabilities' strengths hidden in order to surprise an adversary in conflict, disrupt its plans, and win the fight.

Table 4: Difficulties for Deterrence by Denial in Space
Credibility: Balancing communicating satellite resilience to adversary while maintaining the ability to surprise the adversary if deterrence fails
Credibility: Balance communicating alternatives that enable system resilience without identifying targets for the adversary if deterrence fails
Overemphasis on warfighting could lead to deterrence failure
Overemphasis on deterrence could lead to warfighting failure

As with attribution, decisionmakers must grapple with this tension between the need for transparency and the need for secrecy. Overemphasizing secrecy may allow more warfighting options, but it also might leave a path open for deterrence failure. On the other hand, overemphasizing transparency to signal adversaries might make a war harder to win. Decisionmakers will need to choose their path carefully.

Conclusion

This paper focuses on only a few–but important–areas that would strengthen the overall deterrent value of U.S. space forces and serves as a guide on how to mitigate some weaknesses. It finds that strengthening the deterrent value of U.S. space forces requires a degree of transparency that could weaken the nation's hand should deterrence fail, creating difficult dilemmas for decisionmakers. A thorough assessment of these tensions is in order.

U.S. space strategists need to develop a comprehensive attribution strategy that will cement the adversary perception that the United States has overcome the challenges outlined above. The strategy should define the technologies and decisionmaking processes needed to close this possible path to deterrence failure. It also needs to consider what technical details and other attribution information and data can be appropriately released to the public, or released only to a narrow group of leaders that, in some cases, must include trusted allies and key commercial providers.

To strengthen denial, U.S. strategists should also consider how to best communicate directly or indirectly to potential adversaries the resilience of U.S. capabilities—for example, through public release of information, or demonstrations, or via diplomatic channels. The United States may simply hope its reputation is enough to make credible its ability to attribute attacks or withstand attack—but hope is not a strategy.

References

1 Defense Intelligence Agency, "Challenges to Security in Space," January 2019 (https://www.dia.mil/Portals/27/Documents/News/Military%20Power%20Publications/Space_Threat_V14_020119_sm.pdf).

2 In his foundational analysis on differing perceived attributes of the security dilemma, Robert Jervis calls the situation where actors believe offensive capabilities are dominant and it is difficult to distinguish between offensive and defensive capabilities "doubly dangerous." See "Cooperation Under the Security Dilemma," *World Politics*, Vol. 30, No. 2 (Jan 1978): 167-214.

3 See for example Thomas Schelling, "Arms and Influence," Yale University Press, New Haven, CT, 1966; and Glenn Snyder "Deterrence and Defense," Princeton University Press, Princeton, NJ, 1961.

4 Office of the Assistant Secretary of Defense for Homeland Defense & Global Security, "Space Domain Mission Assurance: A Resilience Taxonomy" (Washington: Office of the Secretary of Defense, September 2015).

CENTER FOR SPACE POLICY AND STRATEGY

JANUARY 2020

NONINTERFERENCE WITH NATIONAL TECHNICAL MEANS: THE STATUS QUO WILL NOT SURVIVE

MICHAEL P. GLEASON AND LUC H. RIESBECK
THE AEROSPACE CORPORATION

AEROSPACE

Summary

The strategic context for U.S. national security space (NSS) activities will change if the 2010 New Strategic Arms Reduction Treaty (New START) expires in February 2021. Here we examine how this change would stress the NSS community's capabilities, assumptions, and habits, and is likely to present new challenges for maintaining stability in the space domain.

Introduction

The 2010 New Strategic Arms Reduction Treaty (New START) currently in force between the United States and Russia is set to expire on February 5, 2021. When that happens, formal prohibitions on interference with national technical means (NTM) of verification expire along with limits on U.S. and Russian nuclear arms. This will mark a significant change in the strategic context within which U.S. national security space forces operate. U.S. space forces' resources will be taxed, and the stability of the space domain will face new risks.

The United States needs a comprehensive strategy to address these challenges. This paper introduces a thought experiment to identify the key factors that should be considered when such a strategy is formulated. It does this by contemplating four alternative futures. Each alternative future assesses the implications of New START's expiration for the U.S. national security space enterprise and for the strategic stability of the space domain. No alternative future foresees the existing status quo surviving after New START expires.

Table 1: Reasons NTM Are Not Defined or Identified
Protect sources of sensitive information
Protect methods used to gather information
Permit maximum flexibility in what means to use
Create uncertainty about specific capabilities to deter cheating
Allow for new technologies

What are National Technical Means of Verification and why are they important?

Formal prohibitions on interference with NTM of verification began with the 1972 Anti-Ballistic Missile (ABM) Treaty between the United States and the Soviet Union. Subsequent arms control treaties also included protections for NTM satellites used to verify treaty compliance.

However, the systems and sensors that constitute NTM for treaty verification have never been defined in the text of the arms control treaties or in the treaty negotiating records.[1] The United States and Russia have preferred to keep the precise definition and identity of NTM purposefully ambiguous for the following reasons: to protect the sources of sensitive information; to protect the methods used to gather such information; to permit maximum flexibility in what methods are used to gather information; to create uncertainty on the other side about specific capabilities being used as a deterrent against cheating; and to allow flexibility to introduce new technological innovations.

NTM for treaty verification may include sensors based on the ground, on aircraft, or even underwater.[9] However, arms control experts consider satellites the most important type of NTM. Indeed, many different types of satellites may be considered NTM.[10] For example, various types of photoreconnaissance satellites and synthetic aperture radar satellites collect detailed imagery of things on the ground, such as inter-continental ballistic missiles (ICBMs) and aircraft. Other satellites detect electronic signals, which may provide insights into a missile's or missile launcher's performance.[11] U.S. missile launch warning satellites such as Defense Support Program (DSP) and Space-Based Infrared System (SBIRS) spacecraft detect the intense heat generated by a missile launch and may be considered NTM since they monitor Russian ICBM and submarine-launched ballistic missiles (SLBM) launch tests and can thereby reveal their capabilities.[12]

New START states:

"For the purpose of ensuring verification of compliance with the provisions of this Treaty, each party undertakes:

(a) to use national technical means of verification at its disposal in a manner consistent with generally recognized principles of international law;

(b) not to interfere with the national technical means of verification of the other party operating in accordance with this article; and

(c) not to use concealment measures that impede verification, by national technical means of verification, of compliance with the provisions of this treaty."

Substantively the same language has been included in preceding nuclear arms control agreements (no longer in force), including the 1972 Anti-Ballistic Missile (ABM) Treaty[2], the Interim Agreement on Offensive Arms (SALT 1)[3], the 1979 SALT II Treaty[4], the 1987 Intermediate-range Nuclear Forces (INF) Treaty[5], and the 1991 START I Treaty[6]. The 1996 Comprehensive Test Ban Treaty (CTBT), which the United States has signed but not ratified[7], and the multilateral Conventional Forces in Europe (CFE) Treaty[8] also use substantively the same language. However, Russia has unilaterally "suspended" its participation in the CFE Treaty.

The lack of clarity around which space systems are considered NTM of verification also suggests that other satellite systems that aid in the detection of treaty violations can be considered NTM for treaty purposes. For example, the nuclear detection capability of global positioning satellites (GPS), which detect the flash and radiation of nuclear detonations, may be considered NTM for verification of compliance with the Limited Test Ban Treaty (LTBT) and the Comprehensive Test Ban Treaty (CTBT).[13] Furthermore, the CTBT's International Monitoring System (IMS) is part of a verification regime detecting nuclear explosions and includes a global infrastructure for satellite communications from IMS stations to an international data center (IDC), which processes and distributes data to state parties. In that regard, even commercial telecommunication satellites may be considered NTM for treaty verification.[14]

In this milieu of purposeful ambiguity, the United States and Russia extended the ban on interference to be effectively a de facto ban on interfering with the entire national security space constellation of the other.[15] In short, for treaty verification purposes NTM include all military and intelligence satellites, broadly defined. Despite this intentional vagueness concerning what NTM are, arms control treaty language for the last 50 years has consistently included protections for NTM because they remain critical to the overall compliance verification process and for detecting cheating against treaty requirements.

Arms control treaties have long included protections for NTM satellites used to verify treaty compliance.[16] As such, noninterference with NTM has always been linked tightly to arms control, forming a key component of the strategic context in which U.S. and Russian behavior in space has taken place for nearly five decades.

Since prospects for New START's extension are dim, consideration should be given to what the change in strategic context may entail. For example, New START's expiration could have negative implications for the legitimacy of NTM overflight. The formal prohibition on interference with NTM of verification, beginning with the 1972 ABM Treaty, was key to establishing NTM overflight legitimacy. The Eisenhower administration began the process of legitimizing overflight by not objecting to Sputnik's overflight of the United States. Indeed, many observers believe that NTM overflight was legitimized in Russian minds with the launch of Sputnik, but that is not completely true.[17] Overflight was considered legitimate when done for peaceful purposes. However, while the United States asserted that peaceful means "nonaggressive" beginning in the early 1960s, the Soviets did not recognize that definition and continued to object to overflight of "spy" satellites as a form of espionage. In 1962, the Soviet Union submitted to the United Nations a "Draft Declaration of Basic Principles Governing the Use of Outer Space," which asserted "use of artificial satellites for the collection of intelligence information in the territory of foreign states *is incompatible with the objectives of mankind* in its conquest of outer space [emphasis added]."[18] Some Soviet officials continued to object to U.S. spy satellite overflights into the late 1970s, even after the ABM Treaty came into force.[19]

The Outer Space Treaty (OST) prescribes broad principles rather than detailed regulations. The most relevant obligations regarding noninterference are found in Article IX: "In the exploration and use of outer space…States Parties to the Treaty…shall conduct all their activities in outer space…with due regard to the corresponding interests of all other States Parties to the Treaty."

This obligation is significantly less explicit than the prohibitions against interference with NTM in New START and its predecessor agreements. Even so, many scholars take the view that intentional interference with the satellite of another country would run afoul of this "due regard" obligation.

Article IX also requires "appropriate international consultations" rather than outright prohibiting activities that would cause interference. However, it would be surprising if a State targeting NTM carried out advance consultations with the target State, and failure to conduct such consultations would constitute a breach of Article IX.

The dispute resolution mechanism in either of these cases is not defined, however, making these OST protections less clear and specific compared to the bilateral noninterference protections in New START.

Eventually, with the ABM Treaty, the Soviets accepted the legitimacy of NTM overflight for treaty verification purposes, but it is not clear if they (or Russia) ever accepted the legitimacy of overflight for intelligence collection. For example, in 1979, a member of the Institute of State and Law of the USSR Academy of Sciences argued that NTM overflight activities are unlawful if they go beyond treaty compliance monitoring to gather information for intelligence purposes.[20] Although the United States consistently rejected these objections, the United States also kept U.S. spy satellites' existence secret from 1962 until 1978, when President Carter publicly acknowledged the existence of photo-reconnaissance satellites in the context of their importance as NTM for monitoring arms control agreements.[21]

With this history in mind, the current trends and rhetoric toward a conception of space as a warfighting domain may also contribute to undermining NTM overflight's legitimacy in international law, since the U.S. position from the 1960s—that overflight is a "peaceful use" of outer space—is difficult to reconcile while avowedly preparing for warfighting in, through, and from space. Again, the Soviet Union accepted the "nonaggressive" definition for what peaceful use means *only in connection with NTM use to verify compliance* with arms control treaties. But Russia's continued acceptance of that definition in lieu of New START and in the face of a more aggressive U.S. posture in space should not be taken for granted. Indeed, active interference with NTM might not be considered illegitimate when NTM are used for finding, tracking, and fixing targets in a crisis or conflict. And perhaps other countries also will begin to question the legitimacy in international law of NTM overflight.

Four Alternative Futures

As a thought experiment, consideration of four alternative futures helps predict how the strategic context will be different when New START expires. The scenarios represent a spectrum of possibilities. They are (a) *noncodified*, bilateral mutual restraint; (b) *codified*, bilateral mutual restraint; (c) *multilateral* restraint; and (d) *no* mutual restraint. These are by no means the only potential futures—many variations are possible—but the alternatives offered here serve to highlight some key challenges.

Each alternative future contemplates two key issues: changes in demand on U.S. NTM collection capabilities when New START is no longer in force and how the strategic stability of the space domain may be affected. Borrowing from a recent definition of what strategic stability means in the nuclear context, strategic stability in space is the *peacetime* management of strategic relationships to avoid conflict extending into space. Strategic stability is facilitated through processes, mechanisms, and agreements, which, combined with the deployment of military forces, minimize any incentive for first-use of offensive space capabilities.[22] When these instruments for managing strategic relationships erode, are absent, or are misapplied, the likelihood for miscommunication, misunderstanding, and miscalculation leading to conflict increase. There is less crisis stability and, in turn, less strategic stability.

To subjectively assess how strategic stability of the space domain may be affected, each scenario evaluates how the legitimacy of NTM overflight might be affected; how interference with NTM may increase (or not); how the end of legally binding U.S.–Russian prohibitions on interference with NTM may shape other nations' attitudes, beliefs, and behavior in space; how military space control strategies might be influenced; and how the cumulative effect of these factors influences crisis stability. Table 2 captures the differences among the scenarios and compares them to the current status quo, with the light green color indicating no expected change in the status quo for that factor under each scenario.

Scenario A: Noncodified, Bilateral Mutual Restraint

In Scenario A, the United States and Russia each decide separately that it is in their national interest to continue current practices regarding noninterference with NTM, even in the absence of a bilateral agreement and without direct, bilateral engagement on the issue. Overall, they decide unilaterally that exacerbating tensions in the space domain is not in their national interest.

Nevertheless, as Table 2 illustrates in light pink, Scenario A still presents new challenges for the U.S. national security space community and is not conducive to the stability of the space domain. First, the United States will have to rely, to the greatest degree in a generation, on space-based observations to persistently track Russia's strategic nuclear forces when New START provisions for onsite inspections of Russia's nuclear forces end. Regular bilateral warhead counts, notifications, exhibitions, and telemetric and information data exchanges will also end with New START's demise. As a result, demand on NTM for tracking Russian nuclear weapons development, testing, and deployments will intensify. Commercially available space-based remote sensing imagery may augment NTM but will not be a substitute for NTM exquisite capabilities. With competing requirements for limited NTM resources, such as monitoring China, North Korea, Iran, and terrorist organizations, any decisions to shift attention and scarce resources to more persistently track Russian nuclear forces impose an opportunity cost.[23] Furthermore, the end of prohibitions on concealment at ICBM and SLBM test ranges will make the task of monitoring Russian nuclear developments from space more complicated as Russian denial and deception efforts surrounding test ranges intensify. NTM satellite systems, ground systems, and the workforce will need to be scaled to accommodate these new strategic requirements.

Challenges for the stability of the space domain in this scenario are more nuanced but also differ from the status quo. In this case, NTM overflight's legitimacy in international law is not challenged by either party and the incidence of interference between the United States and Russia remains at the same level as the current status quo, as reflected in light green in Table 2, Scenario A. However, the loss of the sole legally binding treaty-based prohibition on interference with NTM between the two traditional major space powers could negatively shape the attitude, beliefs, and behaviors of other nations regarding interference. Although the United States and Russia practice noncodified, bilateral mutual restraint in this scenario, other countries such as China may see an opening to practice less restraint themselves once interference with NTM is no longer explicitly proscribed anywhere in international law. The U.S. national security space community and U.S. diplomats may have to make additional efforts to counter such an impression.

Similarly, international efforts to develop norms of behavior for responsible use of outer space may lose momentum should the two leading space powers abandon their clear, legally binding restraint. Why make the effort internationally to develop nonlegally binding, voluntary "rules of the road" when the two traditional major space powers abandon existing, legally binding treaty constraints? Likewise, the lack of a U.S.-Russia agreement may have a chilling effect on the development and implementation of international, voluntary Transparency and Confidence Building Measures (TCBMs) for space.

While U.S. and Russian space forces practice noncodified, bilateral mutual restraint in routine, peacetime operations in this scenario, the space domain at large will be less stable because in a crisis, or in the gray zone between peacetime and conflict, the threshold for initiating active interference will be lower due to the absence of the usual treaty check on military offensive space operations. In other words, military commanders will not be delayed by their staff judge advocate lawyers raising treaty compliance issues. In addition, the lack of an agreement to drive regular dialogue between the United States and Russia, either military-to-military or between diplomats, also makes the strategic environment less stable. In combination with accelerated planning for warfighting in space, such an environment raises the chances of miscommunication, misunderstanding, and miscalculation. For these reasons, even noncodified mutual restraint will lead to a comparatively less stable space domain.

Treaties, conventions, and other types of agreements that are in force (signed and ratified by participating states) are considered "legally binding" agreements between governments in international law. In contrast, unratified instruments are considered "nonlegally binding" agreements between governments in international law. Such agreements are still politically binding, and, while breaching such an agreement may increase political tension, breaches are not considered violations of international law. Examples of nonbinding agreements may include voluntary guidelines and norms, codes of conduct, and other instruments such as nonbinding memorandums of understanding (MOUs) and memorandums of agreement (MOAs).

Table 2, Scenario A, illustrates that ultimately, noncodified mutual restraint dampens some negative impulses, but also presents some concerns. NTM overflight remains legitimate, and the level of interference remains at status quo levels. However, the demand for NTM collection rises along with the difficulty of observing Russia's nuclear weapons development, testing, and deployments. The stability of the space domain weakens due to the undermining of existing processes for developing international norms of behavior and TCBMs for space, the risk that other countries feel less restrained in the absence of U.S.–Russia formal restraint, and the fact that military forces face a lower threshold for initiating the first-use of offensive space control capabilities, resulting in less crisis stability.

Scenario B: Codified, Bilateral Mutual Restraint

In Scenario B, the United States and Russia sign a bilateral agreement to continue noninterference with their respective space-based NTM. This bilateral, noninterference agreement stands on its own, unconnected to other arms control treaties. Since prospects for new, broader arms control treaties are dim, noninterference with NTM by itself provides the basis for a narrower agreement and provides a way forward in preserving stability in the space domain.

A bilateral agreement between the United States and Russia that simply prohibits interference with NTM is feasible, given that all it does is maintain the status quo as it has been since the 1970s. Moreover, the United States finds the agreement meets U.S. prerequisites to enter into a new arms control agreement as required in the 2010 U.S. National Space Policy; i.e., such an agreement must be equitable, effectively verifiable, and enhance the national security of the United States and its allies.[24] Also, the Russians find it difficult to argue convincingly against reestablishing the 50-year-old status quo in space. Indeed, the United States, chided internationally for years over its opposition to the Russian "No First Placement of Weapons in Outer Space" (NFP) initiative and the Russian and Chinese draft "Treaty on the Prevention of Placement of Weapons in Outer Space, the Threat or Use of Force Against Outer Space Objects" (PPWT), could offer an agreement on noninterference with NTM as an alternative to Russia and, eventually, to China and the international community. A formally ratified agreement may be difficult to achieve, given the troubled nature of the current U.S.–Russia strategic relationship and with the high hurdle of U.S. Senate consent. If so, such an arrangement might be accomplished through a nonlegally binding MOU that does not necessitate ratification.

As in Scenario A, the collection requirements for tracking Russia's nuclear forces grow due to the lack of onsite inspections, while at the same time the Russian concealment of their activities makes monitoring their nuclear forces more challenging. However, the stability of the space domain would be unaffected in Scenario B, and the challenges arising from the increasing contested nature of the space domain would not be exacerbated. The bilateral U.S.–Russian agreement means NTM overflight's legitimacy in international law would not be challenged by either party, and the incidence of interference between the United States and Russia would remain at the same level as the current status quo (reflected in light green in Table 2, Scenario B).

Contrary to noncodified mutual restraint outlined in Scenario A, a new formal U.S.–Russian agreement reduces the impetus for China, India, and other countries to change their attitudes, beliefs, and practices regarding interference with NTM. This finding is based on a key assumption that runs throughout all the scenarios: that the United States and Russia, as the traditional space powers, influence what other countries consider legitimate, acceptable behavior in space. It is reasonable to predict that more antagonistic behavior in space by the United States and Russia will likely lead to more antagonistic behavior in space by other nations and a less stable space domain. Conversely, U.S.–Russian mutual restraint, especially codified bilateral mutual restraint, will ideally shape the strategic environment toward restraint among all spacefaring nations and build a more stable space domain. The international community's development of norms of behavior for outer space will be shaped correspondingly.

The United States and Russia approach space control activities more cautiously than in Scenario A, due to the codified agreement raising the threshold for initiating active interference with the others NTM. The agreement also drives regular dialogue between the United States and Russia, further supporting stability. The opportunity for miscommunication, misunderstanding, and miscalculation remains at today's level, as well as the level of risk to crisis stability.

The United States and Russia, as the traditional space powers, influence what other countries consider legitimate, acceptable behavior in space.

The Scenario B row in Table 2, with six of the seven columns showing light green (status quo), reflects the idea that a bilateral, codified, noninterference agreement between the United States and Russia is as close to maintaining the status quo as possible. Despite increased demand for NTM collection and the difficulty of observing Russian nuclear weapons development, the stability of the space domain remains at status quo levels. The bilateral noninterference agreement bolsters existing processes for developing international norms of behavior and TCBMs for space, and there is no change from the status quo regarding the risk of first-use of offensive space operations capabilities, keeping crisis stability level.

Scenario C: Multilateral Mutual Restraint

In Scenario C, multilateral mutual restraint could develop along a couple of paths. A bilateral agreement between the United States and Russia, as outlined in Scenario B, could be widened to include other countries. With the United States and Russia setting the example, other countries would be welcome to sign on. Alternatively, in the interest of global strategic security, the United Nations Security Council (UNSC) five permanent members (P5) could move to formalize prohibitions on interference with space-based NTM.

A group of like-minded nations, such as the United States, the United Kingdom, and France could provide the impetus for a wider agreement or a UNSC resolution that proscribes interference with NTM. The UNSC's interest in maintaining international peace and security and reducing the chance of miscalculation leading to war could drive the development of this alternative. UNSC resolutions carry the force of codified, international law so such a UNSC resolution would carry great weight. In either case, the Russians would find it difficult to argue convincingly against simply reestablishing the 50-year-old status quo in space as such an agreement would do. Presented as an alternative to the Russian NFP initiative and the PPWT, an NTM noninterference proposal might gain traction within the international community.

As in Scenarios A and B, even if one of these paths came to fruition, the demands on NTM for tracking Russia's nuclear forces would still grow and be more difficult than today. Any path to multilateral restraint in Scenario C, however, strengthens space domain stability more than Scenario B (as reflected by the predominately dark green cells in the Scenario C row of Table 2). In this scenario, NTM overflight legitimacy is not questioned and the amount of interference remains as expected given the status quo. However, other countries' attitudes, beliefs, and practices regarding interference with NTM are shaped toward more restraint, driven by the combined diplomatic signaling and subsequent political impetus created by the United States, Russia, and other countries acting in concert. Scenario C also fosters an environment conducive to norms development and the establishment of TCBMs for space.

A multilateral agreement significantly raises the stakes for taking offensive space control actions, as military commanders would have to check with their staff judge advocate lawyers to weigh the implications of violating a multilateral agreement or a UNSC resolution (i.e., international law) before initiating offensive space operations. In turn, crisis stability is strengthened since the increased decision time raises the threshold for military action and reduces the opportunity for miscommunication, misunderstanding, and miscalculation.

The Scenario C row in Table 2 illustrates how multilateral mutual restraint improves stability in space compared to the status quo. Stability improves due to the multilateral agreement creating new, broad processes and mechanisms that reduce the risk of miscalculation leading to crisis. Also, the multilateral agreement accelerates processes for developing international norms of behavior for space. And the threshold for first-use of offensive space control capabilities is raised, resulting in improved crisis stability.

Scenario D: No Mutual Restraint

Scenario D is the most pessimistic scenario on the spectrum of possible futures. In this scenario, the United States and Russia each decide separately that it is in their national interest to disregard restraint. Each begins interfering regularly with each other's NTM satellites, even in the absence of crisis or conflict, undermining the stability of the space domain and eventually even threatening strategic nuclear stability. Scenario D contemplates a new era where the entire concept of noninterference with space-based NTM is rendered obsolete due to various factors, including (a) the lack of an arms control treaty that provides legitimacy in international law for NTM overflight;[25] (b) the availability of commercially available, ubiquitous, space-based remote sensing; (c) the fact that the United States and other countries now identify space as a warfighting domain; (d) rising tensions and mutual distrust between the United States and Russia; and (e) China's and other countries' growing assertiveness in space.

In this unrestrained scenario, highlighted in dark red in Table 2, the U.S. national security establishment faces increasing challenges in tracking Russian nuclear arms. Demand on NTM surges with the end of New START onsite inspections, data exchanges, and notifications. At the same time, fulfilling NTM collection requirements becomes especially difficult as unrestricted Russian denial and deception activities accelerate and interference grows. In turn, U.S. confidence erodes in regard to its understanding of Russian nuclear forces. In such a future, the United States and Russia face the danger of miscalculation leading to greater risk of nuclear conflict.

Even in the absence of crisis or conflict, as the United States and Russia alter their operations toward routine, everyday interference with NTM, it follows that China, India, and other countries also feel less restrained compared to the status quo. They alter their attitudes, beliefs, and practices in a very negative direction as interference with space-based NTM is no longer proscribed by any treaty, the international legitimacy of NTM overflight is weakened, and they mirror U.S. and Russian changes of behaviors in space. Hence, Scenario D also represents the demise of good faith efforts to develop norms of behavior for outer space. In this scenario, an unfettering of offensive space operations amplifies the risk that miscommunication, misunderstanding, and miscalculation could lead to confrontations spinning out of control, making crisis management much more difficult.

Scenario D in Table 2 portends a future with no mutual restraint and deviates the furthest and most dramatically from the current status quo. Tracking Russia's nuclear forces becomes increasingly difficult. The stability of the space domain deteriorates severely due to the absence of mutual restraint and the degradation of existing processes for developing international norms of behavior for space. The danger of miscommunication, misperception, and miscalculation swells along with the risk of conflict quickly extending into space. Current threats to stability in the space domain are greatly exacerbated, resulting in its full destabilization.

Table 2: A Thought Experiment—Analysis of the Four Alternative Futures

	NTM Collection Requirements	Stability of the Space Domain						Disruptive Policy Change Opportunity
	Amount and Difficulty	Overflight Legitimacy	Interference with NTM	Shaping 3rd Country Behavior	Norms Development	Space Control Aspects	Crisis Stability	
A. Noncodified bilateral, mutual restraint	Increase amount	Status quo	Status quo	Less restraint	Discouraged	Formal check removed	Difficult	Yes[2,3]
B. Codified bilateral, mutual restraint	Increase amount	Status quo	Status quo	Status quo	Status quo	Status quo	Status quo	Yes[1]
C. Multilateral mutual restraint	Increase amount	Status quo	Status quo	More restraint	Encouraged	Greater check	Improvement	Yes[1]
D. No mutual restraint	Increase amount and difficulty	Delegitimized	Large increase	Much less restraint	Unattainable	No check	More difficult	Yes[2,3]

1. Break synergistic relationship between arms control agreement and noninterference with NTM.
2. The United States begins calling out bad behavior by attributing interference to shape strategic environment and bolster deterrence.
3. The United States reveals its NTM spacecraft to enable attribution of interreference and to bolster deterrence.

Disruptive Policy Changes

As the end of New START approaches, U.S. national security decisionmakers will have the opportunity to make some disruptive policy changes, shaping the post-New START strategic context toward or away from the scenarios laid out above. For example, Scenario B and Scenario C depend on breaking the symbiotic relationship between noninterference with NTM of verification and U.S.–Russia arms control agreements. U.S. decisionmakers will have to decide if negotiating a new bilateral or multilateral NTM noninterference agreement that stands on its own (i.e., unconnected to other arms control treaties) will encourage stability in the space domain and be in U.S. interests.

Enabling the bilateral or multilateral agreements on which Scenario B and C are based may also require decisionmakers to identify NTM satellites. As noted earlier, the United States and Russia have preferred to keep the precise definition and identity of NTM purposefully ambiguous. Nevertheless, reaching a separate agreement on noninterference with NTM seems more likely if specific satellites, on all sides, are identified as NTM. That does not mean specific NTM spacecraft capabilities would need to be revealed, but removing the ambiguity over which satellites are NTM might be judged worthwhile in order to proactively shape the future strategic context in space.

Today, deterring aggression in space is more important than ever, so decisionmakers might also judge that revealing the identity of NTM spacecraft may strengthen deterrence, benefiting stability in space across all four future scenarios. In September 2019, during a discussion on space and deterrence, the commander of U.S. Air Force Central Command, Lieutenant General Joseph Guastella, implied that some senior leaders need to make tough decisions about which NTM capabilities should be revealed in order to make deterrence credible, explaining that adversaries have to know about one's capability to be deterred by it. "At some point," he said, "we have to reveal some things."[26]

Table 3: Potential Disruptive Policy Changes Post-New START
Negotiating a standalone NTM noninterference agreement
Revealing the identity of NTM satellites
Publicly attributing interference with U.S. satellites

In parallel, New START's end may provide the United States the opportunity to reconsider the current policy of not attributing interference against U.S. satellites. The current reasons for not publicly attributing incidences of interference has been the concern that attributing interference may divulge U.S. technological capabilities. Also, attributing interference could subject the United States to criticism by other countries. Senior leaders will need to weigh those concerns and balance them against the needs of the alternative futures. For example, decisionmakers may judge that such a policy change makes a lot of sense in the context of verifying compliance with the notional agreements on which Scenarios B and C are based. In addition, General Guastella noted that a key component of deterrence is being able "to call them out" when an adversary acts threateningly. He said, "Attribution has kind of become the new deterrence." In that light, New START's end could provide a catalyst for the U.S. government to set in place a new policy for the public attribution of attacks on, and interference with, U.S. government satellites—for the sake of deterrence—even in lieu of any noninterference agreement.

Public attribution of bad behavior could also shape the strategic environment by reinforcing noninterference as an international norm of behavior. Indeed, the national security space enterprise could follow in the vein of the cybersecurity community, in which incidences of cyber interference and attacks are publicly "named and shamed" comparatively aggressively.

New START's end presents an opportunity for decisionmakers to carefully weigh updating a half century's worth of entrenched security space policy. The cost-benefit calculus of the current policies and strategies, which have held over that period, may need to be recalculated with the end of New START and the increasingly contested nature of the space domain.

Conclusion

The strategic context for U.S. national security space activities is about to change with the expiration of New START. This change will stress the national security space community's capabilities, assumptions, and habits, and is likely to raise new risks for the stability of the space domain. U.S. national security space leaders should proactively consider the challenges and opportunities this looming change in the strategic environment presents, and act now to develop a comprehensive post-New START strategy.

Each alternative future contemplated how the demand on U.S. NTM collections would increase when New START is no longer in force and how the stability of the space domain would be affected in that scenario. In all foreseeable cases, demand on NTM collections increases. In Scenario A, if key assumptions ring true, the stability of the space domain would be marginally worse than today. In contrast, Scenario D shows that if NTM overflight legitimacy is broadly challenged, space stability will be significantly worse than today. On the other hand, Scenarios B and C show that a formalized mutual restraint agreement may prevent stability in space eroding at a greater pace than the status quo. Importantly, all scenarios represent clear opportunities for U.S. policymakers to proactively shape the new strategic context with a variety of disruptive policy changes. With the growing threats to the stability of the space domain presented by China and Russia and the increasingly contested nature of the space domain, the national security space community should consider how the demise of New START may exacerbate these challenges.

Acknowledgments

Thanks to Russell R. Rumbaugh for his continuing engagement with the ideas in this paper and to Dr. Josef S. Koller, Dr. James Vedda, Dr. Rebecca R. Reesman, and Dr. Mark A. Williams for their invaluable reviews. As external reviewers, David A. Koplow's, Brian Israel's, and Dr. Joan Johnson-Freese's international law and policy points are also greatly appreciated.

References

[1] Richard A. Scribber, Theodore J. Ralston, William D. Metz, "The Verification Challenge: Problems and Promise of Strategic Nuclear Arms Control Verification," The American Association for the Advancement of Science, 1985, 48.

[2] Treaty Between the United States of America and the Union of Soviet Socialist Republics on the Limitation of Anti-Ballistic Missile Systems (ABM Treaty), May 26, 1972.

[3] Interim Agreement Between the United States of America and the Union of Soviet Socialist Republics on Certain Measures with Respect to the Limitation of Strategic Offensive Arms (Interim Agreement), May 26, 1972.

[4] Treaty Between the United States of America and the Union of Soviet Socialist Republics on the Limitation of Strategic Offensive Arms (SALT II), June 18, 1979.

[5] Treaty Between the United States of America and the Union of Soviet Socialist Republics on the Elimination of Their Intermediate-Range and Shorter-Range Missiles (INF Treaty), Dec. 8, 1987.

[6] Treaty Between the United States of America and the Union of Soviet Socialist Republics on the Reduction and Limitation of Strategic Offensive Arms (START I), U.S.-U.S.S.R. July 31, 1991.

[7] David A. Koplow, "An Inference about Interference: A Surprising Application of Existing International Law to Inhibit Anti-Satellite Weapons," Georgetown University Law Center, 790. [Hereinafter "Koplow."]

[8] Treaty on Conventional Armed Forces in Europe (CFE Treaty), Nov. 19, 1990.

[9] "Monitoring Technologies: How they Work," CTBT Organization Preparatory Commission. https://www.ctbto.org/verification-regime/monitoring-technologies-how-they-work/hydroacoustic-monitoring/

[10] Peter L. Hays, United States Military Space, Into the 21st Century, 2002, 57. https://apps.dtic.mil/dtic/tr/fulltext/u2/a435077.pdf [Hereinafter "Hays."]

[11] Koplow, 772-773.

[12] Koplow, 772.

[13] Koplow, 773; and implied in Hays, 56.

[14] "The Global Communications Infrastructure," CTBT Organization Preparatory Commission. https://www.ctbto.org/verification-regime/the-global-communications-infrastructure/; and Koplow, 773.

[15] Ambassador Roger G. Harrison, Space and Verification, Volume 1: Policy Implications, Eisenhower Center for Space and Defense Studies, 2010; and Koplow, 772.

[16] Hays, 57.

[17] Stuart A. Cohen, "The Evolution of Soviet Views on SALT Verification: Implications for the Future, in *Verification and SALT: The Challenge of Strategic Deception,* Edited by William C. Potter, Westview Press, Boulder Colorado, 1980, 55. [Hereinafter "Cohen."]

[18] Hays, 69-71.

[19] Richard A. Scribber, Theodore J. Ralston, William D. Metz, "The Verification Challenge: Problems and Promise of Strategic Nuclear Arms Control Verification," American Association for the Advancement of Science, 1985, 48.

[20] Cohen, 72.

[21] Steven J. Dick, Roger D. Launius, Editors, "Critical Issues in the History of Spaceflight," NASA, 2006, 228.

[22] Ernest J. Moniz and Sam Nunn, "The Return of Doomsday: The New Nuclear Arms Race—and How Washington and Moscow Can Stop It," Foreign Affairs, September/October 2019, 151. https://www.foreignaffairs.com/articles/russian-federation/2019-08-06/return-doomsday

[23] Vince Manzo, *Nuclear Arms Control Without a Treaty? Risks and Options After New Start*, CNA IRM-2019-U-019494, 2019, 41. https://www.cna.org/CNA_files/PDF/IRM-2019-U-019494.pdf.

[24] National Space Policy of the United States of America, June 28, 2010, 7. https://history.nasa.gov/national_space_policy_6-28-10.pdf

[25] Hays, 57-58.

[26] Theresa Hitchens, "Declassifying Space Threats, US Capabilities For Stronger Deterrence: AFCENT," Breaking Defense, September 9, 2019. https://breakingdefense.com/2019/09/declassify-space-threats-us-capabilities-for-stronger-deterrence-afcent/

LEVERAGING COMMERCIAL SPACE FOR NATIONAL SECURITY

Jamie Morin and Robert S. Wilson

The increasing commercialization of space is presenting new opportunities for national security acquisition. Because of commercial developments in space-based weather; remote sensing imagery; radiofrequency collection; communications; positioning, navigation, and timing; and space situational awareness—among other areas—U.S. intelligence and defense agencies are considering alternatives to the traditional model of hiring contractors to develop bespoke capabilities. Some space capabilities could be treated like personal computers or passenger cars, which the government acquires as commodities from private companies rather than develops via contractors. Or space services could be treated like email clients or search engines, such as Microsoft Outlook or Google search, which the government licenses but does not own. In this new space era, U.S. space leadership will face many decisions over which acquisition model to use in a particular case. Given the potential of leveraging commercial services to accelerate the fielding of important capabilities and to preserve resources for quintessentially military capabilities, it behooves leadership to prepare for the analytic task of answering that question in many different mission areas, and to take the necessary steps to prepare to acquire commercial capabilities and services at scale for military applications. Our national security space enterprise and the commercial space sector are at critical junctures. National security leadership needs to consider the models it wants to use for its next-generation systems and business rules for how to balance them.

Introduction

In May 2020, U.S. astronauts launched into orbit aboard a commercially procured rocket for the first time in history.[1] The launch was both a direct manifestation of, and a metaphor for, the dramatic growth we have witnessed in the commercial space sector in the last decade. This growth is largely due to rising private investment, lower technical barriers to entry, and conscious choices by government to permit commercial activity in previously restricted areas. Private investment in startup space firms increased from less than $500 million per year from 2001 to 2008 to roughly $2.5 billion per year in 2015 and 2016.[2] Satellites are getting smaller and cheaper; launch costs have fallen.

In this new space era, increasing commercialization extends to national defense, with private companies offering services such as space situational awareness, responsive launch, synthetic aperture radar, and hyperspectral imagery that used to be exclusively carried out by the governments of major powers. In other areas, such as in communications and electro-optical imagery, private companies have been engaged for decades but are now fielding systems in quantities that dramatically surpass those of the U.S. military and intelligence community. Based on Seradata's Spacetrak subscription database, Figure 1 shows the number of active satellites in orbit from 2005, 2010, 2015, and 2020.[3] As shown in the figure, satellites owned by U.S. private companies are driving much of the increase in satellite activity.

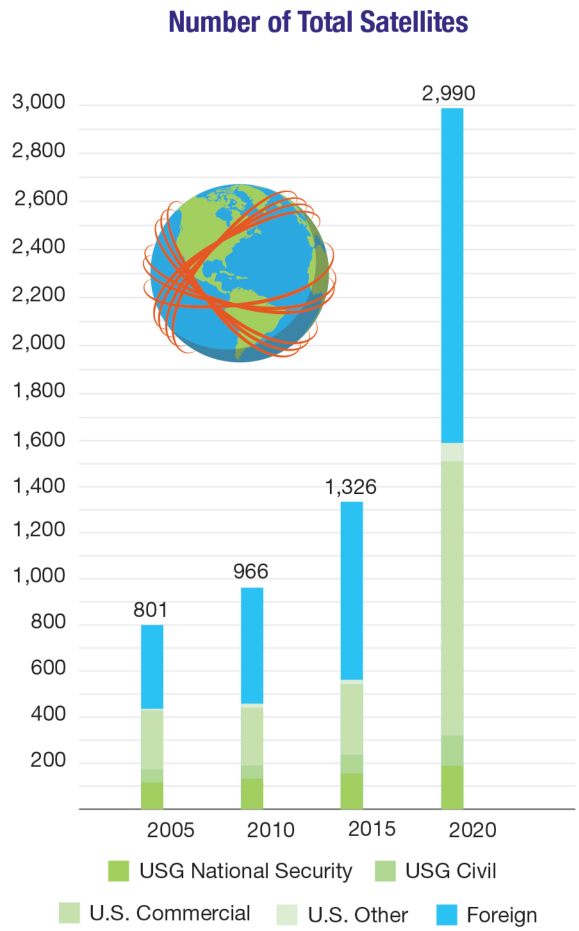


Figure 1: Satellites by owner, from 2005 to 2020.

Three Models of Space Acquisition and Hybrids

The increasing commercialization of satellite technology with defense applications presents serious opportunities for defense acquisition. It also places pressure on the traditional model of hiring contractors to develop bespoke capabilities for government programs. But conceiving of the changes as offering a binary choice of make-versus-buy is overly narrow and could lead to missed opportunities. It is more productive instead to think of the democratization and commercialization of space as offering a spectrum of opportunities to leverage commercial capabilities.

Over time, some space capabilities could be treated like personal computers or passenger cars, which the government acquires as commodities from private companies rather than develops via contractors. Or space services could be treated like email clients or search engines, such as Microsoft Outlook or Google search, which the government licenses but does not own. Table 1 lists these three broad models but, in the emerging environment, acquisition approaches are likely to be less frequently a pure manifestation of one of these models and instead a hybrid that combines the different models to meet different parts of the need.*

In this new space era, U.S. space leaders will find themselves considering the latter models more frequently in multiple capability areas, and likely will shift further toward the latter approaches to take advantage of ongoing and future commercial developments. Currently, U.S. national security space leadership is seeking to reduce the cost of providing basic capabilities on which the national leadership, the joint force, and the nation as a whole rely in order to free up resources for addressing potential adversaries' efforts to deny those capabilities to the United States. In this environment, programmatic options that rely on commercial and hybrid architectures to provide some degree of capability may enable the national security space community to shift investment to next generation bespoke systems, and these options may also deliver novel capabilities.

* For more information about the defense acquisition models, please see Karen Jones and Geoffrey Reber's chapter in the Space Agenda 2021 titled, "Continuous Production Agility: Future Proofing the National Security Space Enterprise," September 17, 2020 (https://aerospace.org/policy/space-agenda-2021).

Table 1: Three Models for Defense Acquisition	
Name	**Description**
1. Traditional (Developmental Programs of Record)	Hiring contractors to develop custom-made capabilities
2. Commercial Off -the-Shelf	Procuring existing commercial hardware, which the government would own and operate, including for government-unique purposes
3. Purchased Services	Procuring services from commercially owned and run space and ground systems (including potentially in a Services Oriented Architecture or Infrastructure as a Service)

Shifting Balance Among Models

Some areas in commercial space activity that have national security applications have progressed substantially in recent years. Notable examples include remote sensing or Earth observation, satellite communications, and space situational awareness. U.S. national security space acquisition has been shifting to leverage some of these commercial capabilities. This includes defense and intelligence agencies contracting with commercial companies for capabilities and services as well as promoting concepts that would integrate commercial and government systems.

Remote Sensing/Earth Observation. Remote sensing satellite capabilities are advancing significantly, both qualitatively and quantitatively. Commercial systems now comprise a large share of remote sensing satellites. Based on data from Seradata, about 270 of the 620 remote sensing satellites in orbit are privately-owned, about 200 of which are owned by U.S. companies. In contrast, about 50 are owned by the U.S. military or intelligence agencies.[4] Figure 2 shows, from 2005 to 2020, the evolution in the quantity of U.S. commercial remote sensing satellites in comparison to remote sensing satellites owned and operated by U.S. defense and intelligence agencies. While the number of U.S. national security assets has stayed relatively flat, the number of commercial systems has jumped dramatically – nearly tripling from 2005 to 2010, nearly quadrupling from 2010 to 2015, and nearly quintupling from 2015 to 2020.

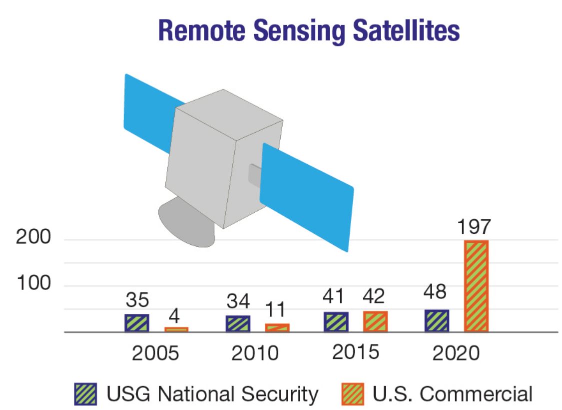


Figure 2: Remote sensing satellites by owner, from 2005 to 2020.

The large number of commercial remote sensing satellites is due, in part, to companies offering traditional electro-optical imagery (digital pictures) with high revisit rates (being able to take imagery of the same location frequently), which can help companies monitor changes on the ground to make informed decisions. Commercial providers have realized that excellent temporal resolution (revisit rates) can be complementary or in some cases more valuable than high spatial resolution. To achieve this capability, companies are deploying large numbers of small or midsized satellites. Planet, for example, achieved a 150-satellite constellation in 2018 with the goal of being able to take an image of the entire Earth each day.[5] Maxar is working on its next generation constellation called WorldView Legion, which reportedly will be able to revisit some locations on Earth up to 40 times per day.[6] Other remote-sensing satellite companies, such as BlackSky and SatRevolution, are also seeking to deploy large satellite constellations for electro-optical imagery.[7]

And the rise in commercial remote sensing is not limited to just electro-optical. Companies such as PredaSAR Corp, Iceye, Umbra Lab, and Capella Space are developing commercially-owned synthetic aperture radar satellites, which can take imagery of the Earth through different atmospheric conditions during the day and at night.[8] Maxar and other firms market infrared imagery.[9] HawkEye360 and Aurora Insight are two examples of companies that offer satellite-based radiofrequency collection services, which—by detecting and geolocating a range of radiofrequency emitters—could be valuable for transportation tracking and search and rescue, among other applications.[10] A slew of companies are also proposing hyperspectral remote sensing satellite systems, technology that could theoretically identify chemical composition, which might help agricultural conglomerates better decide what crops to plant in which fields but also can be used to spot a camouflage tarp hiding a weapon system.[11]

The surge in activity and improvement in quality is contributing to what we have called a "GEOINT Singularity"—the potential for the "convergence, and interrelated use, of capabilities in artificial intelligence, satellite-based imagery, and global connectivity, where the general population would have realtime access to ubiquitous intelligence analysis."[12]

As of late, U.S. national security elements have been leveraging more of these commercial remote sensing ventures. Maxar, Planet, and BlackSky have contracts in place for their data with an intelligence agency.[13] In 2019, HySpecIQ was awarded an intelligence contract for a commercial hyperspectral imaging study.[14] In June, Capella Space announced a cooperative research and development agreement with the National Geospatial Intelligence Agency (NGA), the first such agreement for commercial synthetic aperture radar data, and has received contracts from the Navy and the Air Force.[15,16,17] Another intelligence agency recently established a Commercial Systems Program Office that will oversee procurement of commercial imagery.

Perhaps more so than any other satellite service capability, remote sensing epitomizes the rapid commercialization of previously tightly held government national security technology, allowing national security organizations around the world to use the third model: buying commercial services rather than simply designing their own capabilities. That many world-leading companies are based in the United States provides an advantage to the U.S. and its allies.

Space Situational Awareness. Space situational awareness capabilities have historically been primarily owned by major government powers. A 2018 Institute for Defense Analysis report says: "Until recently, the United States Department of Defense (DOD) was the only organization in the world—outside perhaps Russia—to develop high-fidelity space situational awareness information."[18] But in recent years, commercial players have been more involved in developing space situational awareness capabilities for purchase. LeoLabs established a space radar in New Zealand in 2019 that allows it to track objects as small as two centimeters in low Earth orbit.[19] Numerica offers commercial space situational awareness services, and it receives data from more than 130 optical sensors positioned worldwide. These are just two examples of a burgeoning industry trying to fill a need for commercial companies to monitor and track their satellites.

U.S. defense organizations are seeking to exploit these commercial projects. The Air Force has collected information from several commercial space situational awareness companies as it experiments with how to integrate a wide variety of data sources. According to a report from *Breaking Defense,* Assistant Secretary of the Air Force Will Roper said that the Air Force was receiving information from LeoLabs, Numerica, ExoAnalytic Solutions—which can track objects in geosynchronous orbit using optical and passive radio frequency telescopes—and Rincon, a commercial network using passive radio frequency telescopes.[20,21,22] The Air Force is not the only government customer for these companies: on its website, ExoAnalytic Solutions also notes that it has been "committed to developing technologies for the U.S. Missile Defense Agency to enable robust missile defense architectures."[23]

As commercial solutions improve, DOD will have more options for integrating and using more commercial space situational awareness data. In some case, the companies, such as LeoLabs, are only selling their data, not their radars or telescopes, which might push the department to rely more on the third model of purchasing capabilities as a service.

Communications. Satellite communications are perhaps the richest place for defense agencies to leverage commercial capabilities. The vast majority of communications satellites are owned and operated by private companies. Based on data from Seradata, there are approximately 1,570 communications satellites in orbit, about 1,040 of which are U.S. systems. Of the U.S. satellites, about 960 are owned by private companies and 50 are owned and operated by the U.S. military and intelligence community. Figure 3 shows, from 2005 to 2020, the evolution in the quantity of U.S. commercial communication satellites in comparison to communication satellites owned and operated by U.S. defense and intelligence agencies. As is the case with remote sensing satellites, the number of U.S. military and intelligence community-owned assets has stayed relatively flat while the number of U.S. commercial systems has increased dramatically.

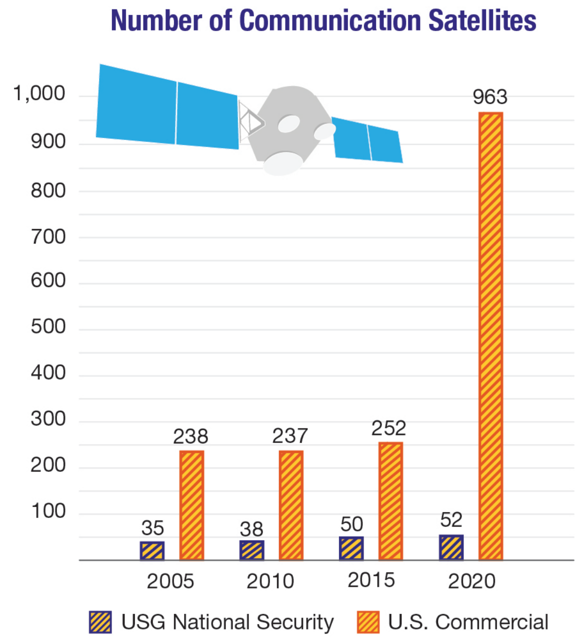


Figure 3: Communications satellites by owner, from 2005 to 2020.

Even these large numbers may see geometric growth in the next few years. Multiple companies, including SpaceX and Amazon, have filed requests to launch hundreds or thousands of small communications satellites. This would represent a transformation in the level of activity we have grown accustomed to in space. For example, SpaceX has announced plans to launch 40,000 satellites for its Starlink constellation, far exceeding the about 3,000 active satellites of all kinds currently in orbit.[24] (This scale of increase would also create a need for space traffic management services far beyond those currently in use.[25])

The Department of Defense has contracted for some of its satellite communications needs for years.[†] But today the DOD is exploring new ways to capitalize on this explosion of commercial communications satellites, including in its "Fighting Satcom" operational vision released in 2020.[26] In it, the Space Force refers to Fighting Satcom as collectively using military satellite communications and commercial satellite communications, as a single enterprise, in a contested environment. While traditional commercial satellite communications are more susceptible to jamming and interference than military communications, a more diverse set of capabilities complicates adversaries' planning and investment. This ambitious vision will entail acquiring services from commercial entities in addition to acquiring unique military capabilities and commercially derived capabilities like the Wideband Global SATCOM system, thus pushing toward a hybrid of the first, second, and third acquisition model.

Other Capabilities and Services. Remote sensing, space situational awareness, and satellite communications are just three examples of the broader commercialization of space and the associated opportunities it brings to national security. Positioning, navigation, and timing (PNT) is another area where there are many players. To name just a few, Draper Laboratory offers alternative navigation technologies to GPS; The Aerospace Corporation (Aerospace) has demonstrated another GPS-independent positioning technology; CTSi and L3 Technologies developed an enhanced link navigation system that could be used in the absence of GPS; and Iridium uses communication links to provide satellite time and location services.[27,28,29] Like PNT, space-based weather has long been dominated by government-owned capabilities, but commercial providers are emerging. Companies such as Spire, GeoOptics, and PlanetiQ use small satellites in low Earth orbit to develop profiles of moisture and other properties of the atmosphere.[30]

[†] The Defense Information Systems Agency (DISA) has for decades contracted to gain additional bandwidth from commercial providers. "Satellite Communications: Strategic Approach Needed for DOD's Procurement of Commercial Satellite Bandwidth," Government Accountability Office, GAO-04-206, December 2003 (https://www.gao.gov/new.items/d04206.pdf).

The possibilities extend beyond simply satellites. For ground stations, for instance, Kongsberg Satellite Services and Amazon both offer access to a ground network of locations and antennas across the globe.[31,32] The first director of the Space Development Agency (SDA), Fred Kennedy, said that for its proposed proliferated satellite constellation the agency was looking to acquire commercially off the assembly line, espousing the second acquisition model, not just for the satellites but for an array of capabilities: "If I can buy payloads, if I can buy ground command and control software, hardware, user equipment, if we could get user terminals from the commercial side, then I can maybe do minimal ruggedization and put [it] on ships, planes, Humvees, you name it. That's big," said Kennedy.[33] The SDA architecture now includes elements from all three models, and explicitly embraces hybrid approaches which build on strengths of each. The opportunities for using commercial systems span the full range of capabilities and services.

Advantages and Risks in Acquiring More Commercial Services

Realizing the potential of commercial systems for national security acquisition—relying on the latter acquisition models—will pose advantages and risks. For several space capabilities, the advantages of using commercial capabilities are significant enough that U.S. space leadership should seriously consider embracing more risk.

Quicker Acquisition and Technology Refresh Versus Giving Up Control. A big advantage of buying off-the-shelf capabilities or services is saving time. As Aerospace has previously reported, "Under the current approach, it can take more than 10 years to develop, build, and launch highly complex space systems."[34] Where they exist, buying off-the-shelf capabilities or services could enable circumvention of the lengthy requirements, contracting, and development process.

A related advantage of using commercial capabilities is rapidly incorporating new technology. Steve Jobs famously said, "People don't know what they want until you show it to them." This completely flips the traditional government development and acquisition model, which begins with users identifying a gap in capabilities, defining specific requirements of a materiel solution to close that gap, hiring a contractor to develop a system to meet those requirements, and then procuring that bespoke system. While there are many areas where that model is still appropriate, the democratization of space technology means that there are an increasing number of areas where that kind of commercial development logic can apply to the government and even national security capabilities. National security agencies may not know which technologies to pursue until they are available and demonstrated. Buying commercial capabilities and services allows them to take advantage of technological maturation rather than try to predict which technologies may mature or force them to mature through direct government investment.

A trade-off in cutting lengthy requirements definition and procurement processes is that the government will have less control over the exact parameters of the capabilities it buys and will have to rely on what it can buy. And in cases in which the government uses the third model—buying services, not capabilities—it will have even less control over the system. Further, some of the companies that the government may want to use may be foreign. For example, according to the data from Seradata, roughly 27 percent of the commercial remote-sensing satellites in orbit are owned by foreign companies.[35] Many U.S.-domiciled technology firms raise funds from a global investor base, which may include both innocuous passive investors and more problematic players. Acquiring more from commercial industry in a globalized economy will require appropriate vetting of companies and their products, done in a way that does not raise unreasonable obstacles to new players.

But the risks should not dissuade us from using these alternative models, even if problematic companies are off-limits. Quicker acquisition offers huge advantages. It would create more agility in our enterprise, generate potential savings, and allow us to adapt our national security space architecture to the threats as they evolve. In the past, the gap between commercial and government capabilities was so large that it was worth waiting to develop something exceptional; the shift to commercial advantage is accelerating and will likely continue to do so.

Undefended Assets Versus More Resiliency. A critique of acquiring commercial capabilities for defense purposes is that they will not be as protected as military systems. We would not ideally bring a cruise ship to a naval battle, for instance, though many ocean liners were pressed into service as troop transports in World War I and World War II and several were sunk. However, incorporating more commercial systems could actually enhance the overall resiliency of a network or capability. All else equal, more satellites would be more resilient to an attack than a comparable attack on fewer satellites. And in areas like communications, more diversity of spectrum and waveform creates more challenges for an adversary looking to obstruct communications. This is part of the rationale and theme underlying the Fighting Satcom concept for satellite communications. By integrating commercial and military communications capabilities, our forces would have more assurance that they have global connectivity even in contested environments where one or more signals are denied or degraded.

Construct for Considering Which Acquisition Model to Use. In considering the value of commercial systems in producing an architecture that is resilient as a whole, it is also important to consider the capabilities where governments ought to retain maximal control, and those are the military capabilities directly tied to the use of violence. For instance, if the United States were to adopt one or more forms of space weapons (e.g., weapons from ground-to-space, space-to-space, or space-to-ground), the third capability acquisition model (services) would be extremely problematic, and the applicability of the second model (commercial off-the-shelf) would also be limited.[‡] Such capabilities should warrant serious reflection and debate, and likely would be considered through a more traditional requirements process.

As noted, acquiring off-the-shelf capabilities or services entails a certain level of risk; for capabilities directly tied to violence, the appetite for risk should be much lower. While governments may buy simpler weapons systems like firearms based on commercial developments, more complex weapons capabilities are much more likely to be custom-made to reflect precisely what the government wants. This is particularly true in uncharted areas where civilian weapon analogues are unavailable, like satellites. Additionally, while some private companies have been willing to sell militarily-relevant services like communications or imagery to the government, some may be reticent to be directly engaged in the kill-chain, much less to directly sell lethal effects; therefore, drawing a sharp line at capabilities tied to violence could also help with commercial cooperation. But while weapons get much of the attention when it comes to equipping and operating a military, in the real world beans are often as important as bullets; for many capability areas, the advantages of commercial resiliency are likely to outweigh any risk.

Figure 4 diagrams the spectrum of options for acquiring military space capabilities, showing which capabilities would be appropriately procured under more traditional models (blue) versus the second model of acquiring commercial capabilities (yellow) and the third model of acquiring services from commercially owned capabilities (orange). Moving left to right, the space capabilities shift from the innocuous (e.g., ground stations and weather satellites) to force enhancement (e.g., tactical intelligence and communications in the kill chain) to direct force application (e.g., space-to-Earth weapons, Earth-to-space weapons, and space-to-space weapons, potential capabilities most closely tied to the use of violence). The figure gradually shifts from orange to yellow to blue (least control with acquisition approach three to most control with acquisition approach one), but the three colors are interspersed throughout because the acquisition model for any particular capability will depend not just on whether it is tied to violence but also on the options for that capability or service from commercial companies – which will often raise capital and make investments based on an ability to serve a market that reaches well beyond government purchasers.

[‡] There are areas where the U.S. government and its contractors do employ private companies in areas closely tied to the use of violence, including private security firms in war zones, but this model has multiple problematic aspects, especially if extended to space.

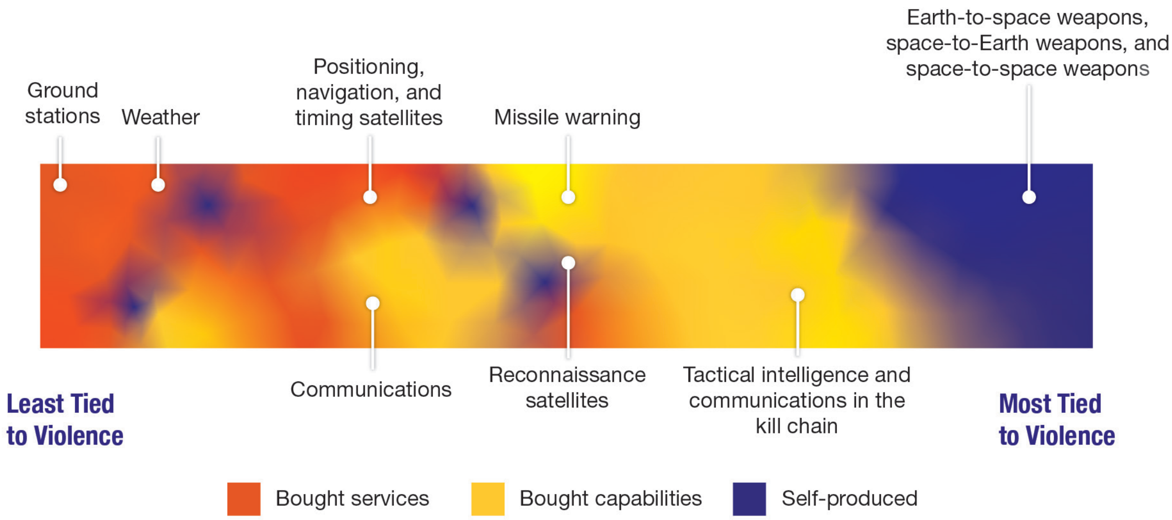


Figure 4: Spectrum of Acquisition Approaches for Space Capabilities

Still, acquiring non-commodity commercial technology is a tricky matter for the federal government, where there are strong legal requirements for competition in contracting. There are well-understood acquisition pathways for buying mundane supplies, and also for buying bespoke technology. The in-between areas are harder because specifying the decision criteria can be tantamount to picking the winner of the competition. The Department of Defense's troubled cloud computing services contract competition is a cautionary tale here; multiple companies sued the department and concerns of political interference loomed over the process.[36]

A Way Ahead

U.S. space leadership will face many decisions that are essentially about considering which acquisition model to use in a particular case. Given the potential of leveraging commercial services to accelerate the fielding of key capabilities and preserving resources for quintessentially military capabilities, it behooves leadership to prepare for the analytic task of answering that question in many different mission areas, and to take the necessary steps to prepare to acquire commercial capabilities and services at scale for military applications.

This issue has received senior-level attention. In 2019, General John Raymond said: "And I see [our partnerships with commercial industry] as a big growth area going forward. We have a commercial integration cell on the floor at the Combined Space Operations Center. I see great, great steps ahead in being able to leverage this."[37] The U.S. Space Force seems intent on pushing for hybrid architectures with commercial partner services playing a growing role.

Driving towards the latter acquisition models may require further changes in organizations. Traditionally, users who might be most interested in what the commercial capabilities and services could deliver to them today do not have money. In the Defense Department, acquirers—who have the money—are organized to design and build stuff, not buy services. The commercial integration cell at the Combined Space Operations Center and intelligence community offices aimed at acquiring commercial products are a good start to bridging this gap, as are cooperative research and development agreements, which allow agencies to explore opportunities for deeper partnerships and commitments with commercial players. The Defense Department should continue these efforts and revisit whether its organizational models need to adjust to better leverage commercial developments.

In a democratized space environment, for most defense applications, leadership should start by first looking to the non-traditional acquisition models and leaning more heavily on commercial capabilities. This includes the capabilities mentioned above as well as others—space weather, meteorology satellites, perhaps even missile warning. The list goes on. After looking at the more commercial models, leaders will likely find that capability gaps remain—but they may well require only narrower solutions, and in some cases the gaps may simply be acceptable given the faster timelines for adopting commercial technology.

Our national security space enterprise and the commercial space sector are at critical junctures. Our space leadership needs to consider the models it wants to use for its next-generation systems and business rules for how to balance them.

References

[1] Michael Sheetz, "SpaceX launches two NASA astronauts to space for the first time in historic US mission," *CNBC,* May 30, 2020 (https://www.cnbc.com/2020/05/30/spacex-launches-two-nasa-astronauts-to-space-for-the-first-time.html).

[2] Matthew Weinzierl, "Space, the Final Economic Frontier," *Journal of Economic Perspectives,* (Volume 32, Number 2), Spring 2018, pages 173-192 (https://pubs.aeaweb.org/doi/pdfplus/10.1257/jep.32.2.173).

[3] SpaceTrak, Seradata, (https://www.seradata.com/products/spacetrak/).

[4] Ibid.

[5] "NASA Evaluates Commercial Small Sat Earth Data for Science," *National Aeronautics and Space Administration (NASA),* October 4, 2018 (https://www.nasa.gov/press-release/nasa-evaluates-commercial-small-sat-earth-data-for-science/).

[6] Anusuya Datta, "DigitalGlobe reveals plans for WorldView Legion; to be made by MDA's SSL," *Geospatial World*, February 26, 2017 (https://www.geospatialworld.net/blogs/digitalglobe-reveals-plans-for-worldview-legion/).

[7] Sandra Erwin, "Satellite imagery startups to challenge Maxar for big government contracts," *SpaceNews*. June 6, 2019 (https://spacenews.com/satellite-imagery-startups-to-challenge-maxar-for-big-government-contracts/).

[8] Debra Werner, "PredaSAR to send 48 satellites into initial radar constellation," *SpaceNews,* June 18, 2020 (https://spacenews.com/predasar-48-satellites/).

[9] See, for example, "Short Wave Infrared," (https://www.digitalglobe.com/products/short-wave-infrared).

[10] James A. Vedda and Josef Koller, "Commercial Radio Frequency Collections from Space," The Aerospace Corporation, March 2020 (https://aerospace.org/paper/commercial-radio-frequency-collections-space).

[11] Adam Keith, "Is hyperspectral the next Earth observation frontier?" *SpaceNews,* March 30, 2019 (https://spacenews.com/op-ed-is-hyperspectral-the-next-earth-observation-frontier/).

[12] Josef Koller, "The Future of Ubiquitous, Realtime Intelligence: A GEOInt Singularity," The Aerospace Corporation, Center for Space Policy Strategy, August 8, 2019 (https://aerospace.org/paper/future-ubiquitous-realtime-intelligence-geoint-singularity).

[13] Sandra Erwin, "Satellite imagery startups to challenge Maxar for big government contracts," *SpaceNews*, June 6, 2019 (https://spacenews.com/satellite-imagery-startups-to-challenge-maxar-for-big-government-contracts/).

[14] Nathan Strout, "Intel agency will test hyperspectral images from industry," *Defense News,* September 23, 2019 (https://www.defensenews.com/battlefield-tech/space/2019/09/23/intel-agency-will-test-hyperspectral-images-from-industry/).

[15] Debra Werner, "NGA signs research and development agreement with Capella," *SpaceNews,* June 25, 2020 (https://spacenews.com/capella-nga-crada/).

[16] Debra Werner, "Capella to supply U.S. Navy with airborne imagery," *SpaceNews,* May 13, 2020 (https://spacenews.com/capella-navy-airborne-contract/);

[17] Debra Werner, "Capella wins Air Force small business contract," *SpaceNews,* November 21, 2019 (https://spacenews.com/capella-wins-air-force-small-business-contract/).

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

[19] Theresa Hitchens, "LeoLabs' New Radar Tracks Tiny Space Debris," *Breaking Defense,* October 14, 2019 (https://breakingdefense.com/2019/10/leolabs-new-radar-tracks-tiny-space-debris/).

[20] Ibid.

[21] "Numerica awarded U.S. Air Force contract for real-time satellite tracking," *Geospatial World,* July 19, 2019 (https://www.geospatialworld.net/news/numerica-u-s-air-force-contract-real-time-satellite-tracking/).

[22] "ExoAnalytic Solutions and NorthStar Earth & Space join forces to combat growing space debris threat, protect satellites in orbit," *PR Newswire,* April 1, 2019 (https://www.prnewswire.com/news-releases/exoanalytic- solutions-and-northstar-earth-amp-space-join-forces-to-combat-growing-space-debris-threat-protect-satellites-in-orbit-889592952.html).

[23] Missile Defense, ExoAnalytic Solutions (https://exoanalytic.com/missile-defense/).

[24] Jackie Wattles, "SpaceX moves ahead with Starlink satellite launch amid pandemic," *CNN*, April 22, 2020 (https://www.cnn.com/2020/04/22/tech/spacex-starlink-satellite-launch-scn/index.html).

[25] Jamie Morin, "Four Steps to Global Management of Space Traffic," *Nature,* March 5, 2019 (https://www.nature.com/articles/d41586-019-00732-7).

[26] U.S. Space Force, "United States Space Force Vision for Satellite Communications," January 23, 2020 (https://www.spaceforce.mil/Portals/1/SATCOM%20Vision%20Paper.pdf).

[27] Sandra Erwin, "No GPS? No problem, there are increasingly more options," *SpaceNews,* July 24, 2018 (https://spacenews.com/no-gps-no-problem-there-are-increasingly-more-options/).

[28] Space Foundation, "Commercial PNT System Augments GPS," *The Space Report* (https://www.thespacereport.org/resources/commercial-pnt-system-augments-gps/).

[29] Theresa Hitchens, "NGA to Tap Commercial Data on Military Targets," *Breaking Defense,* April 3, 2020 (https://breakingdefense.com/2020/04/nga-plans-first-commercial-contracts-for-military-geoint/).

[30] Andrew Freedman, "Weather company with tiny satellites inks deal with NASA, top European agencies to improve forecasts," *The Washington Post*, June 25, 2020 (https://www.washingtonpost.com/weather/2020/06/25/spire-satellites-weather-forecasting/).
[31] Ground Station Services, Kongsberg Satellite Services, (https://www.ksat.no/services/ground-station-services/).
[32] Amazon AWS, (https://aws.amazon.com/about-aws/global-infrastructure/regional-product-services/
[33] Sandra Erwin, "Exclusive interview with the Space Development Agency's Fred Kennedy: 'How we do things in space has to change," *SpaceNews,* April 8, 2019 (https://spacenews.com/exclusive-interview-with-the-space-development-agencys-fred-kennedy-how-we-do-things-in-space-has-to-change/).
[34] Project Thor Team, "Outpacing the Threat With an Agile Defense Space Enterprise," The Aerospace Corporation, September 2019 (https://aerospace.org/sites/default/files/2019-09/Aerospace_OutpacingThreat_09242019.pdf).
[35] Union of Concerned Scientists, Satellite Database, updated as of April 1, 2020 (http://ucsusa.org/org).
[36] Meg Anderson, "Pentagon Awards $10 Billion Contract To Microsoft over Front-Runner Amazon," *NPR*, October 26, 2019 (https://www.npr.org/2019/10/26/773706177/pentagon-awards-10-billion-contract-to-microsoft-over-front-runner-amazon).
[37] Center for Strategic & International Studies, "A Conversation with General Raymond," November 18, 2019 (https://www.csis.org/analysis/conversation-general-raymond).

CONTINUOUS PRODUCTION AGILITY: FUTURE-PROOFING THE NATIONAL SECURITY SPACE ENTERPRISE

Karen L. Jones and Geoffrey S. Reber

The space sector is not immune to today's dizzying pace of change and constant technological disruption. The traditional, highly customized launch-on-need approach that allowed the United States to field the world's leading space capabilities during the twentieth century is ill suited to the new era of rapidly evolving threats and emergent opportunities. To stay in the race, the United States should shift toward modular national security space architecture, interoperability standards, and a launch-on-schedule production tempo to create agility, efficiency, and predictability. This will, in turn, encourage broad industry competition and provide frequent innovation opportunities.

Our national security space architecture can avoid competitive obsolescence by "future proofing" through regular introduction of new technologies. The proposed acquisition strategy, Continuous Production Agility (CPA), introduces modularity as a key element in the architecture. Modularity enables steady production flows for foundational space system elements while providing open doors for technology insertion or agility in response to threats. It simplifies the scope of rapid prototyping efforts and reduces the barriers to adaptation. While it requires more upfront engineering, it encourages lean and focused acquisition teams. And, especially important, it fosters a thriving and motivated ecosystem of space manufacturers and innovators.

Background

Today, substantial foreign, military, and commercial investments have blunted U.S. historical leadership in space and competitive edge. The number of foreign reconnaissance and remote sensing satellites has tripled (from 100 to 300) in the last 10 years. And within areas where the United States still leads, China and Russia are gaining. The National Air and Space Intelligence Center concluded that new technology deployed by these potential adversaries was unprecedented.[1] While striving to catch up to U.S. space capabilities in areas such as communications, reconnaissance, and positioning, China and Russia are also aggressively pursuing new electronic warfare, directed energy, kinetic weapons, and cyberattack capabilities that threaten U.S. space capabilities. Space is now an actively contested domain.

In March 2018, then Deputy Secretary of Defense Patrick Shanahan asked The Aerospace Corporation (Aerospace) to look at how U.S. space systems can outpace the emerging threat. Three months later (July 2018), Aerospace responded with a briefing titled, "Creating an Agile Space Enterprise." To continue to outpace our adversaries, Aerospace recommended a strategy called *Continuous Production Agility* (CPA), which is designed to realign space acquisition for speed, adaptability, and resilience. The keys of CPA are increased production, a modular open systems architecture design and contracting approach, and enhanced competition.[2] By shifting to a continuous production approach and opening the space system architecture, the DOD can more readily field new capabilities or respond to counter-space efforts while combining the energy and ingenuity of the new entrants to the U.S. space industry with the deep expertise of the traditional defense space players.

Since proposing this new strategy, considerable progress has been made to support the overall CPA vision across various classes of spacecraft and the United States Space Force's (USSF's) alternate acquisition strategies:

- **Small spacecraft.** The National Security Space (NSS) community has reimagined several of its constellations, looking at synergies with low Earth orbit (LEO) spacecraft constellations that already reflect varying degrees of modularity and/or high-volume production (e.g., Starlink and OneWeb). Additionally, new nano-satellite form factors for rapid prototyping (e.g., the Air Force Research Lab's Mycroft and Aerospace's HIVE) have also received innovation, research, and development funds.

- **Hosted payload opportunities.** The Space and Missile Systems Center (SMC) has revived its payload hosting strategy to take advantage of excess power and weight capabilities of large commercial vehicles. A modular and standardized payload interface specification would accelerate these hosted payload opportunities.

- **Medium size "combat capable" spacecraft.** Studies of future space systems routinely find that some NSS user requirements can only be met effectively by mid-sized spacecraft in orbits above LEO. Industry responders to the March 2019 "SMC Modular Enterprise Spacecraft Bus Procurement" request for information validated Aerospace's assessment that these needs could be met by modular/scalable spacecraft designs to accommodate NSS strategic missions.[3] This enterprise spacecraft bus would fall within a "sweet spot" or range of mass and power values that currently includes medium Earth orbit (MEO), geostationary Earth orbit (GEO), polar and high Earth orbit (HEO) satellites. To generate CPA opportunities for these systems, SMC encouraged the formation of a working group in September 2019, bringing together vehicle and payload manufacturers to develop open bus (platform) to payload interface descriptions.

- **USSF acquisition authorities.** Aerospace provided recommendations to the Air Force to help inform a May 2020 report to Congress on USSF alternate acquisition authorities. While the USSF continues to take shape, its largest acquisition organization reorganized into SMC 2.0 before the end of 2019. The new structure emphasizes an enterprise approach and encourages partnerships, innovation, and cultural shifts to respond to the new space environment with speed.

What Is CPA and Why Use It?

Dynamic Space System Acquisitions. CPA shifts the architecture of space systems into elements that can be dynamically integrated into the broader NSS architecture and coevolved. Some of these elements can be commercial off-the-shelf (COTS), some can require specialization for National Security Space, and some elements can be purchased as services (e.g., ground station as a service). This modularity opens the doors for innovation and multisided platform network benefits (see sidebar). It also creates opportunities for production efficiencies through reuse of platform elements and/or proliferation of modules across systems.

Establishing modular platforms and breaking down engineering and manufacturing silos makes sense in today's fast-paced and budget-constrained world. From automobiles to personal computers to telecommunications, the commercial sector has already discovered that modular platforms with interoperable interfaces minimize development costs and provide advantages to the consumer. For the defense community, modular architecture is written into law, with 10 U.S.C. 2446a requiring that all major defense acquisition programs be designed and developed using modular open standards architecture (MOSA). Applying MOSA principles, the DOD space enterprise can break out of the high value asset procurement model that has yielded expensive and sometimes vulnerable systems. Instead, an agile, higher volume space production concept will deliver modular buses and payloads that can rapidly evolve. (see Figure 1).

Ultimately, CPA's virtuous cycle of lower incremental costs and more frequent launches further reduces unit costs and feeds the cycle again. Moreover, CPA's shorter acquisition cycles allow for frequent prototyping and testing. And, as opportunities emerge, successful prototypes are inserted into the architecture.

CPA Introduces Multisided Platform Benefits

Multisided platforms refer to technologies or products that create "network effects" or value primarily by facilitating interactions between two or more participant groups. A widely cited 2009 study, "Platforms, Markets and Innovations," refers to these participants as "core components," which are primarily stable, and "complementors," which are encouraged to vary. CPA's multisided platform is a good example of an "industry platform" where the core components (space bus providers) and complementors (payload innovators) combine to "create novelty without developing a whole new system from scratch."[4]

Whole of Government. The term whole of government is popular these days. It refers to working under a shared mission toward a joint goal to maximize appropriate resources in a collaborative effort. This term is applicable to the space sector and is referenced in the July 2020 White House report, "A New Era for Deep Space Exploration and Development," wherein the National Space Council calls for a cooperative approach within the U.S. government (USG) and with other spacefaring nations:

> The important supporting roles of the Departments of State, Defense, Commerce, Transportation, Energy, and Homeland Security in space exploration and development are among the major reasons the United States takes a whole-of-government approach to its space activities.…
>
> The challenge in this new era is not simply to achieve what others cannot but to provide opportunities for others to partner with us.[5]

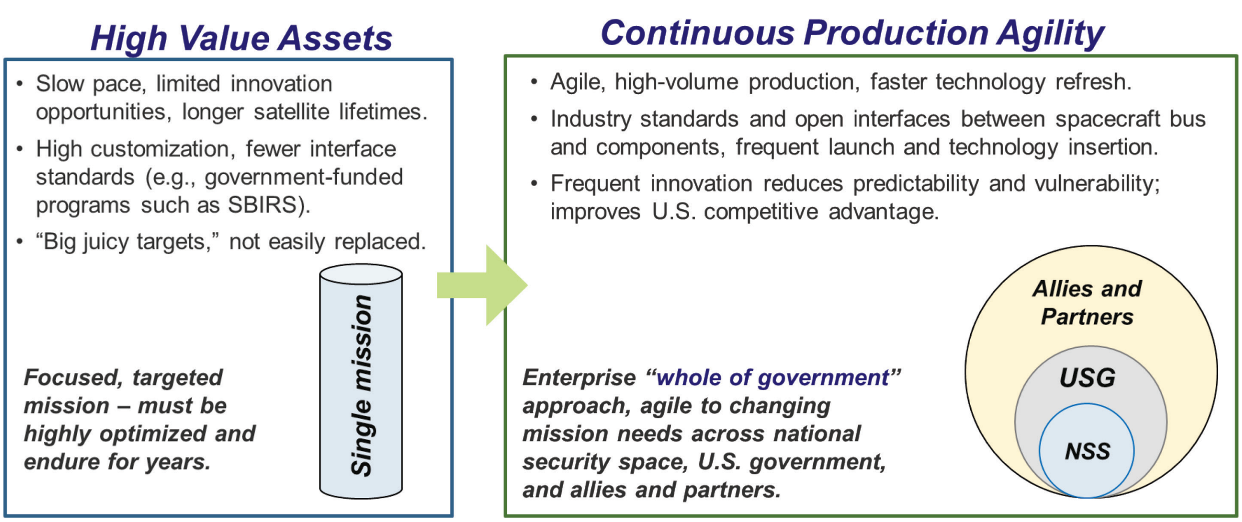


Figure 1: Operational Paradigms. *CPA addresses a rapidly evolving and changing threat environment. CPA's modular approach allows each generation of satellite to remain relevant for a longer time period by allowing frequent technology insertion from an ecosystem of payload providers. The same frequency of insertion opportunities can also invite broader participation for shared missions across the NSS government agencies, civil government agencies, and multinational partners.*

Whole-of-government wider interests can translate into multiple customers on the same production line or even on the same satellite. CPA embraces this concept, allowing a wider range of customers and missions by replacing stovepiped space systems with a modular architecture and an ecosystem of developers. While whole of government is a laudable goal, specific acquisition strategies will continue within the NSS community that will not rely on a CPA approach. Still, the trend is for greater use of modular open systems for sharing architectures and inviting a larger group of participants.

Beyond defense-related missions, a modular and scalable platform with a range of payload options could meet various USG missions or could support shared missions with allies and partners. For instance, SMC satellites that are in GEO are well known for short production runs, and some experts still do not believe that they are suitable for mass production.[6] Extensibility across orbits has been validated by industry request-for-information responses, and an open architecture can likewise support partners such as the National Aeronautics and Space Administration (NASA), the National Oceanic and Atmospheric Administration (NOAA), and other USG stakeholders. A modular bus with a range of compatible payloads serving wider interests improves economies of scale. Such an approach is consistent with CPA's whole-of-government approach to maximize the government's buying power.

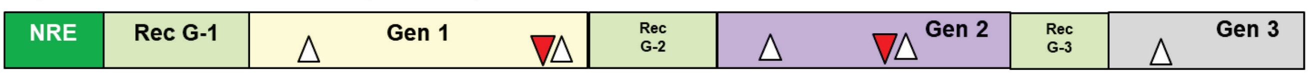
Finally, a whole-of-government approach must also stretch across acquisition strategies. The CPA strategy should fit and complement the larger acquisition framework, including balancing capital expenditures (CapEx) and operating expenditures (OpEx):

1. **Services-Oriented Architecture (SOA)** – Leveraging the full suite of commercially available and appropriate on-demand satellite services, and the growing trend toward infrastructure as a service (IaaS) for ground stations, launch sites, network operation centers, and cloud services and analytics. This approach offers the ability to rapidly access existing services and infrastructure while minimizing CapEx. Over time, SOA will increase OpEx as USG becomes a subscriber for more services.
2. **Commercial Off-the-Shelf (COTS)** – Acquiring existing commercial hardware offerings that can perform the mission, potentially augmented with limited government-unique technology. Advantages are rapid access and use of heritage systems. With time, more of these COTS space systems are also developing modularity for both LEO and GEO. This will allow for increased technology insertion and customized missions within certain constraints.
3. **Continuous Production Agility (CPA)** – Creates a foundation for an ecosystem of payload innovators and bus providers. By executing a high-volume, launch-on-schedule plan, lower unit costs can be achieved. While the cumulative CapEx could exceed that of a locally optimized program of record, the incremental nature of CPA ideally allows reduced capital exposure for any one design. This allows more frequent evolution to incorporate emerging capability or respond to threats. Also, both SOA and COTS solutions can be compatible with CPA and can serve to further lower CapEx and improve time to market. Modular open interoperability standards result in reduced costs when looking across the whole of government.
4. **High Value Assets / Programs of Record** – Focused, targeted missions requiring highly optimized designs that must endure for longer periods. Allows for highly customized, high-performance missions.

Prioritization of Incremental Delivery over Launch-on-Need. CPA proposes a high-tempo, launch-on-schedule strategy to deliver an entire operational constellation over a short period (targeting five years for most constellations) and to replenish the constellation on a schedule-certain basis. The additional quantity of satellites drives steady demand and incentivizes industry to make capital investments in manufacturing capability for efficiency and speed. This is a significant change from the more traditional, customized, and lower volume launch-on-need approach. CPA requires more upfront capital investment in terms of nonrecurring engineering costs for high-volume production design. The idea is that over time, this investment pays off in terms of reaching lower unit costs and increased generational extensibility. Extensibility is essential, as modular elements are more readily changed, and more frequent technology insertion allows each fielded system to stay relevant to evolving needs. Figure 2 compares the two operational paradigms, launch-on-need versus launch-on-schedule, and the advantages of each.

The CPA is a suitable strategy for those missions that require agility, speed, and technology relevance, where a modular platform can be introduced.

A: Current Approach – Launch-on-Need: Less frequent technology insertion. Launches are based on replacing failures or expiring satellites. New technologies are typically introduced with new satellite generations. Satellites are often designed as long life "Class A" satellites and experience fewer failures. They also require more time to manufacture.



B: CPA Approach – Launch-on-Schedule: A modular open systems architecture allows for continuous production improvement and frequent technology insertion. Higher upfront NRE costs and reduced recurring costs associated with later generations are due to greater investment in modular architecture and capital infrastructure needed to produce high satellite volumes. High degree of modularity also allows for rapid production.

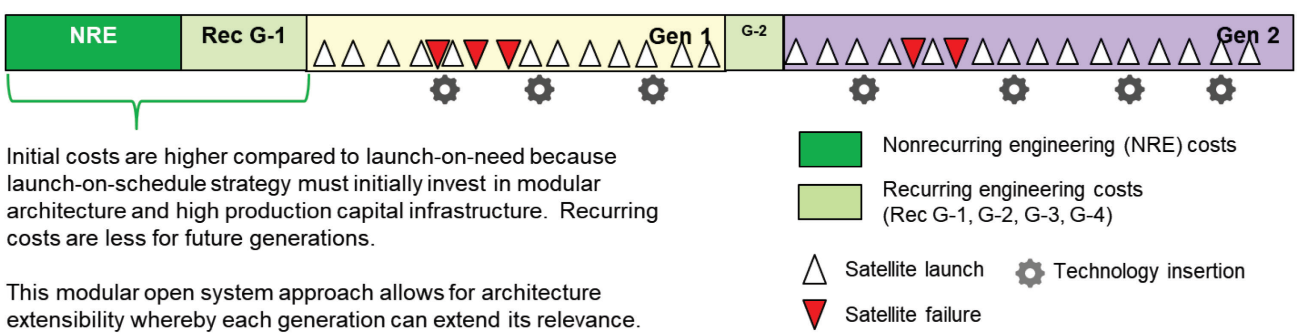


Figure 2: Comparing Launch Tempo Alternatives for Fixed Performance. *Provides a comparison of the traditional (Figure 2A) launch-on-need versus and (Figure 2B) launch-on-schedule. Both approaches can meet similar mission performance requirements. However, launch-on-schedule results in increased technology insertions and development cycles and requires greater upfront capital investment. Longer term, the payback is greater agility and decreased recurring costs due to modular architecture design benefits. Under the CPA approach, each generation of satellite can stay relevant for longer due to a more open architecture which allows new payloads to be introduced.*[7]

A Modular and Scalable Platform for Multiple Missions and Adversarial Threats. The satellite industry is ripe for reinvention. Instead of focusing on building a highly customized satellite from the ground up, the CPA strategy calls for configuring mission-specific payloads to a modular space bus platform. Figure 3 describes how the space enterprise can compress integration time by opting for a modular architecture. Just as the Evolved Expendable Launch Vehicle (EELV) standard interface specification (SIS) decoupled the launch vehicle design from its payloads, a SIS separates evolution of payloads from their spacecraft "buses." This provides for agile pairing of payloads to buses and for innovative solutions for either to smoothly bridge the development gap into operational systems.

This strategy is consistent with USSF efforts to leverage DOD's MOSA policy and move toward rapid prototyping and agile acquisition. Figure 3 also shows that CPA can work well with both COTS and SOA acquisition approaches by allowing those commercial payload and bus providers with compatible interfaces to become part of the ecosystem of potential solutions. Compatible COTS approaches may work particularly well with CPA for the smallsat class of satellites characterized best by proliferated LEO spacecraft such as in the Starlink and OneWeb constellations.

CPA will also shift NSS test and operations practices. Space testbed platforms, such as X-37 and the Long Duration Propulsive ESPA (EELV Secondary Payload Adapter) ring, have already created regular opportunities for on-orbit test. An open and modular vehicle architecture will allow advanced payloads (or platform) solutions to be developed at their natural

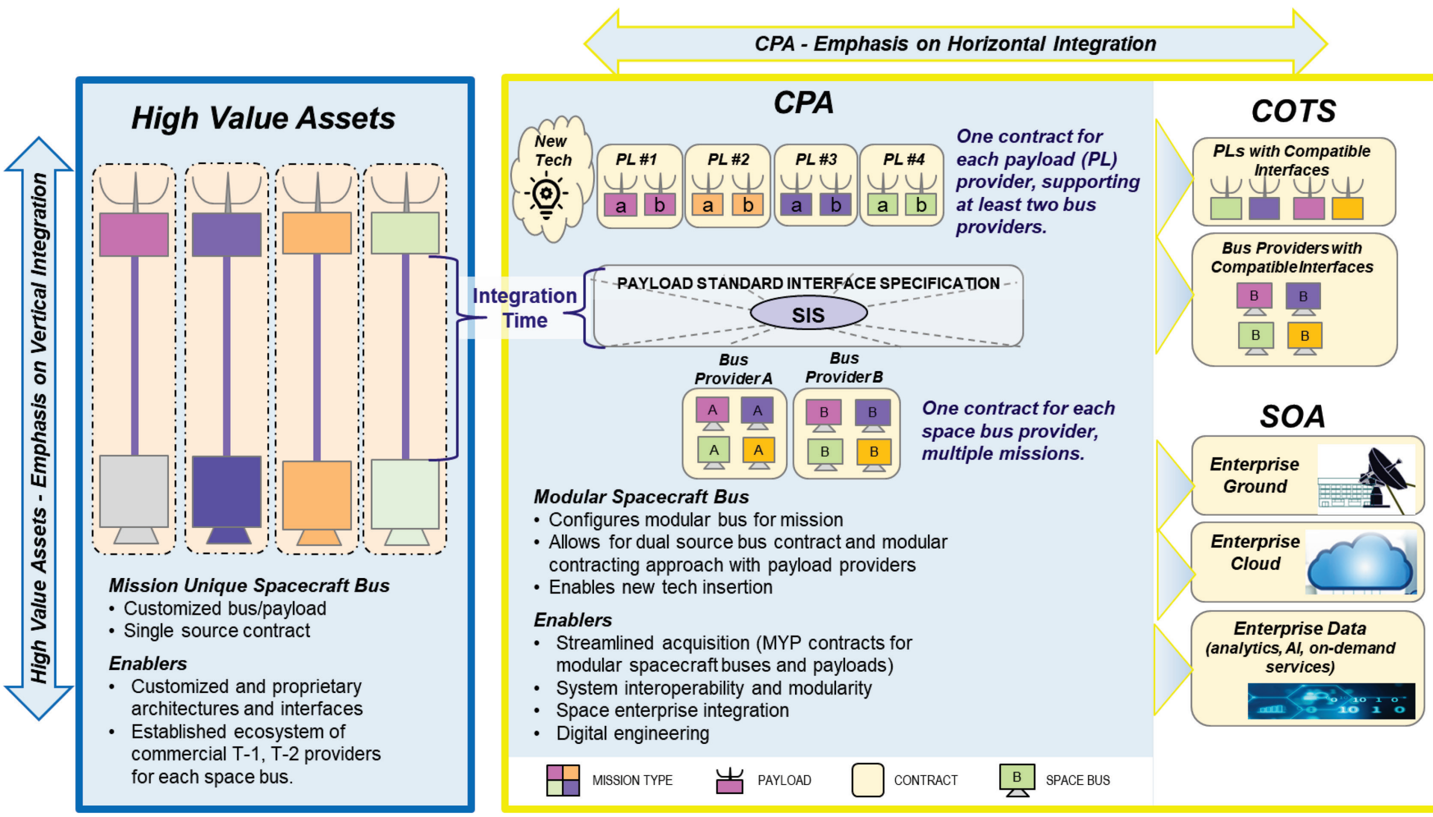


Figure 3: High Value Assets vs. CPA. *CPA initiates a sweeping change from the traditional "High Value Assets" model by breaking down stovepipes and separating spacecraft bus designs from payload designs to achieve efficiencies through higher volume production. The higher production quantity lowers the per-unit platform production cost, even when including non-recurring engineering (NRE). In addition, standard and open government-facilitated spacecraft bus-to-payload interfaces will yield a greater variety of bus-payload pairings (e.g., the multi-sided platform architecture increases potential connections and attracts new participants, or "positive network effects") and enable regular technology insertion opportunities to outpace the threat. Also, standard interfaces enable the government to own the technical baseline and minimize the potential for technology or vendor lock-in.*[8]

pace, tested in place, and then inserted into operational constellations. Extensible platforms, supplemented by digital twins* and model-based systems engineering (MBSE) capabilities provide operators with training assets for tactics, techniques, and procedures development. The digital twin frees the payload innovators, spacecraft bus providers, and various integrators and program managers from the physical realm, allowing common visualization, including conceptualization, comparison, and creative collaboration capabilities.[9]

Industry Reinvention

Enhancing the Speed to Market: Responding to Competitive Threats. The automotive industry has successfully applied the use of platforms to produce product families since the 1960s. Sometimes these single platforms, the core automobile framework and its underbody, can extend beyond one car manufacturer.[10] For instance, in July 2020, Fisker Automotive announced a platform-sharing arrangement with Volkswagen (VW) to use VW's modular electric vehicle platform, known as Modular Electric Drive Matrix (MEB). According to the July 2020 investor presentation, the MEB platform will allow Fisker to "enter the market in approximately half of the time and with costs substantially reduced relative to a vertically integrated business model." The MEB presentation also notes that "multiple vehicles can be produced on the same platform, which will enhance the speed to market and meaningfully reduce the cost and risk of future product offerings." [11]

By leveraging the existing VW modular vehicle platform, car designer Henrik Fisker avoided the non-recurring engineering costs in producing his own electric vehicle platform. Fisker and other automotive manufacturers are now adopting a horizontal integration business model to avoid the huge capital investments in chassis platform manufacturing and expensive production delays that have haunted Tesla.[12] The space sector can adopt this type of strategy for responding to ever-changing adversary threats, saving time to orbit and reducing costs. Shifting from a vertically integrated and "High Value Asset" architecture to an open and modular CPA strategy can help the space enterprise realize greater economies of scale with a greater diversity of system designs (see Figure 3).

Extensibility of the CPA Standard Interface Specification (SIS). Already disruptive new space startups are embracing modular architectures. Examples include:

- NanoAvionics (Lithuania) – Standardized flight-proven 6U (six-unit) CubeSat modular satellite bus, scalable to 12U and 16U form factors.[13]

- Maxar (Canada) – Legion Class satellite platform built with a modular architecture that can scale to meet a variety of mission requirements.[14] Maxar has year 2021 launch plans for Earth imaging satellite constellation WorldView Legion and for Swedish mobile broadband provider Ovzon.

- NovaWurks (Los Alamitos, California) – Developer of the Hyper Integrated Satlet (HISat), a GEO-qualified flight-proven satellite platform that is modular and scalable to various payload missions.[15]

---

*A digital twin is a dynamic digital representation of a physical system. The twin is continually updated as the physical system undergoes various changes throughout its testing, operations, and maintenance lifecycle. The concept of digital twin was introduced during a 2003 Product Lifecycle Management course by Michael Grieves.

Much like VW's scalable MEB platform, which can provide the underlying electric vehicle platform for a compact sports car or larger utility truck, modular spacecraft can contribute to a range of space mission areas and will have scalability built into their design. The end vision of the modular bus is an open architecture for space vehicles to support a variety of payload modules and missions.

What Do We Mean by Modularity and Scalability?

Modularity is the grouping of components, logically or physically, with well-defined interfaces to simplify integration, upgrades, and/or changing out elements. CPA argues for modularity within space vehicles, especially between payloads and a bus platform (e.g., attitude determination and control, command and data handling, structure, and thermal), between space and launch vehicles, and at space-to-ground links.

Scalability is the ability to change, add, or remove components within an architecture, such that it can be tailored to address a wide range of capabilities and missions. For example, adding propellant tanks for missions where propellant capacity needs to be scaled up. Or swapping a low accuracy sensor for a high accuracy one.[16]

Future-Proofing Space: Opportunities for Decisionmakers

For those situations where national security space requires increased agility and technology relevance, CPA provides key benefits, including frequent technology insertion, production efficiency, mission flexibility, and support for key industrial base capabilities. Most high-tech commercial companies face the same strategic imperative: to introduce new technologies effectively and often or face competitive obsolescence. The space sector faces a similar challenge. The DOD and national security space enterprise can prepare for adversarial and competitive threats by leveraging modularity and frequent launch rates to support space asset adaptability and space industrial base sustainability.

Opportunities exist for decisionmakers within the context of CPA.

Recommendations

- **Embrace a whole-of-government approach.**
  - **Fit across NSS – Enterprise Integration.** Space responsibilities for the NSS enterprise are spread across multiple organizations. For those missions that require agility, speed, and increased technology relevance, the NSS should adopt a strong CPA enterprise integration approach based on an open architecture.
  - **Fit with partners.** CPA could extend well beyond NSS to USG civil space. In a world where the ability of a single nation or a small group of nations to drive a global agenda has faded significantly, CPA can provide opportunities for allies and international partners to maximize resources to meet joint goals.
  - **Fit within the full spectrum of acquisition options.** Decisionmakers should consider a range of levers to provide stability to the space industrial base and to ensure best value for mission budget. CPA can support a range of acquisition strategy options, including use of COTS solutions and service-oriented architecture elements.
- **Ride the operational and cultural paradigm shift by breaking down a previously monolithic, requirements-driven system into manageable phases.**
  - **Development ecosystem.** Accept the reality that government is no longer the driver for all space system innovations. Increasingly, government's role is shifting to a focus on fostering a healthy market and adding limited government-unique capabilities. Use collaborative design spaces/testbeds (e.g., emulating Silicon Valley garage or modern "plug fests"). Nurture an ecosystem of payload innovators. Ensure regular, rapid prototyping of all elements. Emphasize industry consensus standards, and a modular, open framework to lower both the risks of technology transition and barriers to entry.

- **Steady Procurement.** Create a virtuous cycle by placing space vehicles on a production footing using extensible bus platforms, with a regular rhythm for payload flights and technology upgrades.

- **Deployment.** Continue to emphasize open, modular architecture to allow for smooth technology insertion into operational systems and responsiveness to evolving needs.

- **Align USSF acquisition authorities for MOSA and CPA.**

  - **Long-term planning and flexibility across missions and NSS enterprise.** The NSS organizational structure should be complemented by funding and authority that allows for confident long-term planning. This could be enabled by reallocation of budget dollars within the USSF to fund extensible/modular architecture elements supporting multiple missions and to ensure integration across the NSS, with the goal to move toward a flexible architecture for the NSS space enterprise.

Recently, the Air Force's Report to congressional defense committees on space acquisition identified several opportunities which are worthy of serious consideration, though their viability will depend on shared trust between DOD and Congress.[17] These opportunities include:

- **Efficient Space Procurement.** Take "an evolutionary block-upgrade approach to production satellites, sometimes referred to as *Efficient Space Procurement*." The combination of block buys and incremental funding help smooth out budget spikes in procurement[18] and provide a steady, more efficient demand signal to industry.

- **Define "useable end items" to encourage open architecture and innovation.** Authorize USSF to determine that key components of a modular space vehicle architecture, like a modular satellite bus or various peripherals that could be attached to it, constitute "usable end items" for federal budgetary purposes This would encourage the "pursuit of open architectures, innovation, robust supply chains, and greater commercial and international partnering opportunities."[19,†]

Conclusion: "What got us here, won't get us there"

What earned the U.S. dominance in space in the twentieth century won't keep the U.S. ahead in the twenty-first century. By shifting from highly integrated and locally optimized space system designs to a modular and open space architecture, USG buyers can harness domestic production capability and American ingenuity to stay ahead. A modular architecture allows acquisition centers to shift the expensive platform capabilities into production contracts and to focus development dollars for technology maturation and rapidly evolving payloads. This decoupling provides for agility in response to threats and opportunities. The combination of a steady production demand signal and agile design, termed *Continuous Production Agility*, creates a virtuous cycle of industrial capacity, ingenuity, flexible fielding, and new opportunities to seed the next generation of advanced space capability.

Acknowledgments

Considerable recognition goes to Aerospace senior leadership, who spearheaded and socialized Project Thor and the related CPA concept. We would also like to express our gratitude to Major General (ret) Susan Mashiko, who provided helpful review and comments.

[†]DoD Financial Management Regulation (DOD 7000.14R) "requires the total estimated cost of a complete, military useable end item or construction project [be] funded in the year in which the item is procured." Exceptions to this policy require Secretary of Defense approval in order to avoid incremental funding or budgeting an item in one fiscal year that would depend on a future year's funding to complete procurement. For MOSA applications in space, the challenge is that many modular elements may not have military utility by themselves.

References

[1] National Air and Space Intelligence Center (NASIC), Competing in Space; December 2018.
[2] Karen L. Jones, *Continuous Production Agility (CPA): Adapting at the Speed of Relevance*, The Aerospace Corporation, March 2020.
[3] FedBizOpps Issue #6314; "SMC Modular Enterprise Spacecraft Bus Procurement Request for Information"; March 6, 2019.
[4] Annabelle Gawer; "Platforms, Markets and Innovation"; University of Surrey; December 2009.
[5] White House National Space Council, "A New Era for Deep Space Exploration and Development," July 23, 2020.
[6] Sandra Irwin, "Air Force space buyers trying to make change happen," *SpaceNews*, June 30, 2020.
[7] Jones, 2020.
[8] Jones, 2020.
[9] Michael Grieves; "Digital Twin: Manufacturing Excellence through Virtual Factory Replication"; March 2015.
[10] Jesus Lambon et al; "The Impact of Implementation of a Modular Platform Strategy in Automobile Manufacturing Networks"; Governance and Economics research Network (GEN) and Universidade de Vigo; January 2015.
[11] Spartan Energy Acquisition Corp., July 2020 (https://www.sec.gov/Archives/edgar/data/1720990/000121390020017291/ea124083ex99-3_spartanenergy.htm).
[12] Ibid.
[13] NanoAvionics, "Nano-satellite buses" (https://nanoavionics.com/nanosatellite-buses/).
[14] Maxar, "Spacecraft Platforms" (https://www.maxar.com/products/spacecraft-platforms).
[15] NovaWurks (https://www.novawurks.com/company/).
[16] Ryan B. Burke, Nishant Prasadh, *Combat Bus Reference Designs – Concept Design Center Study*, Aerospace report number TOR-2020-01247, The Aerospace Corporation, June 10, 2020 (for U.S. government and government contractors only).
[17] United States Space Force, "Alternative Acquisition System for the United States Space Force," May 2020.
[18] Ibid.
[19] Ibid.

CENTER FOR SPACE POLICY AND STRATEGY

AUGUST 2019

THE FUTURE OF UBIQUITOUS, REALTIME INTELLIGENCE: A GEOINT SINGULARITY

JOSEF S. KOLLER
THE AEROSPACE CORPORATION

AEROSPACE

Summary

When assessing the trends of global connectiveness, commercial remote sensing from space, and advances in artificial intelligence (AI), the trends point toward a future where information and overhead imagery will become available to the general public in near-realtime. The rise of large constellations with remote sensing satellites and capabilities ranging from synthetic aperture radar imaging, nighttime imaging, and infrared imaging is a global phenomenon. Coupled with AI analysis, data from different sensors can be combined, processed and made useful for a specific user's needs on handheld devices worldwide. Large constellations of communication satellites and the rollout of 5G in metropolitan areas will provide the data pipeline needed to reach users globally at broadband speeds. A scenario, coined the Geospatial Intelligence (GEOINT) Singularity, is a future where realtime Earth observations with analytics are available globally to the average citizen on the ground providing a tremendous wealth of information, insight, and intelligence. Civil application could include identifying an empty parking spot from space or tracking autonomous vehicles in smart cities. These developments will likely not be contained within the U.S. but will be a worldwide phenomenon. The opportunities seem immense, but what would the availability of ubiquitous, realtime intelligence mean to the military operator and warfighter? The U.S. approach to commercial remote sensing has been to regulate and limit the imagery that can be taken from space, but international capabilities will not be so easily curtailed. Has the time come for the military operator to find better ways to hide, rather than tell someone not to look?

Introduction

The industrial revolution marked a major turning point in history: almost every aspect of daily life was influenced in some way. Our society has been undergoing a similar revolution from a mass production society to an information society where the line between physical systems, data, and cyber becomes ever more blurred. Advances in AI are influencing our behavior, and interactions between humans and machines are becoming indistinguishable. [1]

Here, we discuss how advances in AI, satellite-based sensing and imaging, and an increasingly connected world enable a society with realtime access to global information, services, and intelligence at its fingertips. Whether such a future is real, or even achievable, is not debated here, but the trend is real. For the purpose of this discussion, the term *GEOINT Singularity*[2] is defined as ubiquitous intelligence available to the general public[3] in realtime (Figure 1). We cover advances in

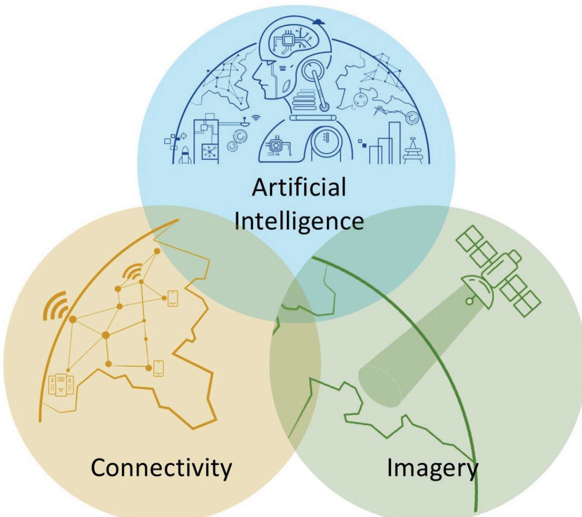


Figure 1: GEOINT Singularity. *GEOINT Singularity is the convergence, and interrelated use, of capabilities in artificial intelligence, satellite-based imagery, and global connectivity, where the general population would have realtime access to ubiquitous intelligence analysis.*

three areas—remote sensing data, artificial intelligence, and global connectivity—as enabling factors for a GEOINT Singularity. The focus here is on the effect on military operators and warfighters but acknowledges the privacy concerns of people around the world. Overhead imagery available to all (including governments) may certainly raise such privacy concerns. Some argue that the surprise attacks of the past are gone and that it is getting more difficult to stage an attack in a world that is becoming more transparent.[4] However, denial and deception (D&D) and disinformation techniques applied at appropriate levels will be key in military operations in a future of global realtime intelligence.

GEOINT Singularity is a hypothetical concept and, while we may certainly approach it, we may not actually reach it. There are several reasons why this could be so:

- Demand may not be sufficient for a commercial market providing access to remote sensing analytics in realtime on a global scale.
- The recipient of data may always experience a time lag to account for the time it takes to receive, analyze, and distribute data and analytics.
- Obtaining realtime analytics may be too cost prohibitive for a general user.
- Bridging the digital divide by deploying large constellations of communication satellites may only shift the divide to one side but not completely close the gap between those who have and have not.

Nevertheless, the trends are clear: proliferation of remote sensing space systems providing continuous monitoring; advancements in AI to analyze large data sets and provide analytics; and global communication and connectiveness, making such analytics accessible to a general user, are discussed in the following sections.

Artificial Intelligence, Machine Learning, and Deep Learning[5]

Often terms such as *machine learning* and *artificial intelligence* are used interchangeably. However, there is a distinction between these terms and they can be thought of as subsets of each other. **Artificial intelligence** (AI) is the overall umbrella term describing a branch of computer science studying the capability of a machine to imitate human intelligent behavior by performing tasks that typically require a human to perform such as visual perception, speech recognition, and complex decisionmaking. **Machine learning** is a particular method in the field of AI that provides computers the ability to learn without being specifically programmed for a particular task. Particular algorithms process input data and desired outcomes attempting to minimize prediction errors, for example, through a neural network algorithm. The more training data provided to the algorithm, the better (typically) the algorithm is in predicting the desired output. **Deep learning** is a subset of machine learning where the term "deep" refers to an increased number in hierarchies and layers in a neural network, providing it with ability to learn more complex relationships between input and output data.

Major Trends Leading to a GEOINT Singularity

Commercial, Space-Based Remote Sensing

In previous years, there was a clear trend to improve resolution of space-based platforms. However, the trend to continuously increase resolution seems to have slowed down, just like the well-known Moore's law has slowed from the original doubling of transistors on an integrated circuitry board every 12 months to now 24 months due to physics limitations. Today, companies are competing increasingly on multispectral capabilities, nighttime sensitivity, infrared, synthetic aperture radar (SAR) capabilities, and on revisit time. Recent commercial initiatives focus on decreasing revisit time by building constellations of satellites with a variety of capabilities instead of a single satellite. Companies seem to have concluded that it is more cost effective and profitable to launch a large number of small satellites rather than to invest in a few, heavy Earth-observation platforms like WorldView 3 (imaging at 0.31 meters resolution) from DigitalGlobe (now part of Maxar).[6] Planet, a U.S. company operating a constellation of Earth-observing small satellites, certainly adopted that early on with a mission statement to "image the entire Earth daily." Today, Planet has reached its goal by operating the world's largest constellation of small satellites with approximately 150 orbiting platforms.[7] Compared to WorldView 3, Planet images at coarser resolutions of 5, 3, and 0.72 meters (depending on the platform). This section provides just a few examples of remote sensing companies.

Planet is likely to see competition. EarthNow[8], a Seattle-based company backed by SoftBank, Airbus, Bill Gates (Microsoft), and Greg Wyler (OneWeb and O3b Networks) plans to launch about 500 small satellites offering video coverage with "live and unfiltered" footage of almost anywhere on Earth.[9] The company plans to provide the footage to smartphone applications with little time delay to track illegal fishing, animal migration patterns, and forest fires. Other possible applications include mapping and guiding traffic flows through a "smart city" and realtime media reports of events happening in remote sites. Military operators should pay attention. EarthNow intends to sharply reduce design and production costs by using an upgrade of the basic satellite platform and assembly-line manufacturing techniques already devised by OneWeb. The company says that by incorporating substantial computing power on each platform, called "the Model T of spacecraft," it will provide more timely and useful video images than its rivals. Even though each satellite would collect colossal quantities of data—far too much to send back to Earth in realtime—the software would be able to process it all onboard and only send back data that individual users want to see.

Live Earth[10], another example, is a Utah-based company built around advancements of optical sensor technology with the purpose of expanding the capabilities and uses of geostationary remote sensing systems. The plan is to offer instant access to live, continuous imagery of events on Earth. The imagery would not be as highly resolved as with an equivalent system in low Earth orbit, but instead emphasizes the unique attributes of a geostationary orbit for continuous monitoring. The proposed applications include natural disaster relief, maritime awareness, and national security. In particular, defense and intelligence customers, according to the Live Earth website, would benefit from intelligence on the movement of hostile forces.

While EarthNow and Live Earth are both U.S.-based companies and appear to have prominent backers with deep pockets, the international market also presents some competition. SatRevolution[11], a Polish company funded by the European Commission, is planning to develop a realtime Earth observation constellation. The satellite would reach a resolution of 0.5 meters using a 6U CubeSat with a deployable telescope. The company plans to launch 82 satellites achieving realtime electro-optical imaging with a revisit time of less than 1 hour. Possible applications include crisis response, environmental monitoring, smart city support, logistics, and traffic monitoring. The imager would consist of a hyperspectral imaging detector with adaptive optics and onboard AI processing. The first satellite on orbit is scheduled for 2019 (full operational constellation by 2023) with a four-hour revisit time and "realtime" capability by 2026. SatRevolution (being a Polish company) would not be subject to U.S. regulation and could image and sell information as they wish, subject to Polish and European law and regulation. Imaging in different spectral bands, including short-wave infrared imaging (SWIR), nighttime, or with synthetic aperture radar (SAR), as compared to imaging with increasing revisit frequencies, may not be the only concerns to the national security community and ultimately the military operator. Enter Data Analytics.

Data Analytics

Combining information from various spectral domains that provide complementary insights, or even with data from online records (Twitter, Facebook, and Instagram, for example), as well as using advanced analytics, deep learning, and AI in general will truly be a game changer. Remote sensing satellites produce vast amounts of data. So much data, in fact, that in 2017 the former director of the National Geospatial-intelligence Agency (NGA), Robert Cardillo, said that in about 5 years the agency would be dealing with "a million times more" data and in 20 years would need to employ 8 million analysts to handle the load.[12] The solution to this trend is automation in the form of AI. While the more traditional remote sensing companies, such as Maxar, Planet, and Spire pursue both hardware in space and analytics on the ground, other companies such as Ursa and Descartes Lab focus on data analytics alone.

The company Ursa Space Systems, headquartered in Ithaca, New York, recognized the disconnect between information-rich satellite data and those who could really use it. Ursa and its founder, Adam Maher, realized that there is a plethora of data already available and decided on a different approach rather than building SAR satellites. Ursa has been quite successful in analyzing existing data and making it usable for customers. For example, Ursa has developed a proprietary algorithm using data purchased from SAR satellite operators to analyze and estimate global strategic petroleum reserves. Typically, stockpiled petroleum reserves are officially reported by nations but are often deliberately inaccurate. Ursa can help investors understand what exactly is in storage. Typically, low storage means high demand, and high storage means an oversupply and a potential price drop. There is an interesting aspect to this company from a regulatory perspective. Since Ursa is simply purchasing global data and not actually operating satellites, it is not subject to the U.S. regulatory framework. Moreover, while some national security stakeholders may want to restrict U.S.-based SAR companies from selling specific data, Ursa and other companies can purchase data from non-U.S. companies. Such a restriction on U.S.-based data could be inconsistent with a national policy designed to enable the competitiveness of the U.S. space sector.

Similar to Ursa, Descartes Lab, a company, headquartered in Santa Fe, New Mexico, is focusing on data analytics rather than building hardware. They view the increase and diversity of data as a resource. To harness the power of multiple, complementary data sources and enable global-scale computation, Descartes Lab built a "data refinery" to clean up datasets and developed a platform with deep learning and other AI capabilities. Using SAR data, for example, the company has built models to identify new construction sites on the ground regardless of weather conditions. It can also identify agricultural field boundaries and automatically classify the crop growing in each field. Descartes Lab, according to a major new outlet, has been noted as a promising startup to watch among a list of companies "breaking industry barriers".[13]

Artificial Intelligence and Machine Learning

Technology trends are advancing, and there are indications that a "sixth wave of innovation" is coming. The Russian economist Nikolai Kondratiev first postulated the major cycles of innovation in 1925. The five initial major economic cycles have been defined as the industrial revolution; the age of steam and railways; the age of steel and electricity; the age of oil, cars, and mass production; and the age of information and communication. Each wave lasted from 40 to 60 years and consisted of alternating periods between high and slow sector growth.

The sixth cycle is postulated by some as an increase in resource efficiency.[14] A new wave would be heralded by massive changes in the market, societal institutions, and technology that all reinforce each other and are centered around connected intelligence with new devices, new applications, new business models, and new services. Space-based commercial remote sensing services that create massive datasets, joined by AI for analysis and product development, will be just one aspect of the innovation wave. Current prices for electro-optical data are around $5/km^2 image and prices are dropping at a rate of 3 percent to 5 percent per year according to EuroConsult.[15] New lower-cost data is expected to challenge current high prices as the electro-optical imaging supply is anticipated to expand rapidly in the coming years, increasing the supply. Some economists claim that this will add to competition and make it possible for supply to start outstripping demand. However, new markets have opened up as data-hungry AI has become more established and demand has increased. Further strengthening the trend is a noticeable shift from investment in new satellite operations to investment into new service companies aiming to exploit data based on change detection and predictive analysis.

Artificial intelligence, and deep learning in particular, hold the promise of enabling mass usage of satellite imagery services similar to how Geographic Information Systems (GIS) enabled the satellite remote sensing business to provide value to consumers 15 years ago.[4] GIS will continue to play a role as a foundation in storing, manipulating, and managing spatial data, similar to cell phone service as a foundation to providing the connectivity for apps on a smartphone. However, given the magnitude of data produced, AI will provide the analytics that sifts through the myriad satellite-based information, incorporate data from a variety of sources, and may even be used for on-orbit processing. NGA has been focusing on bringing automation to its geospatial analysis for some time, lamenting the fact that for all of its ability to amass satellite and other data, parsing that data often comes down to human analysts having to search images and videos in a time-consuming manual process.

General investments in AI are continuously growing. According to ABI Research,[16] the number of businesses adopting AI worldwide will increase significantly from 7,000 this year to 900,000 in 2022, with investments in AI growing at a rate of 4.5x. The future will make machine learning algorithms the norm for developing user applications rather than the subject of science fiction movies. Recent advancements in machine learning are significant. While complex algorithms have been limited to big tech companies like Google, Amazon, and Microsoft, today AI is becoming more affordable through a variety of open source software that allows building advanced self-learning systems.

Big data and machine learning are a match made in heaven. Machine learning without training data is impossible and training requires a lot of data. The more complex a machine learning algorithm gets, the more training data it requires. Last year, for instance, NGA collected more than 12 million images and produced over 50 million indexed observations.[17] AI has a great appetite for more data and will be the primary consumer of the immense increase in available data in the future.

While today the U.S. may still be a leader in AI, China is catching up. Years ago, IBM Watson began as a research project and first attracted headlines as the algorithm that beat human contestants in the TV show *Jeopardy*. Today, Watson is used across many sectors around the world to boost revenue and efficiency, and even save lives. However, China may soon be leading the development of AI. A few years ago, Chinese technology entrepreneurs were focused on repeating (and copying) Western success stories. Today, China is determined to be the tech industry leader in AI. In 2018, the total global investment into AI-focused startups amounted to $15.2 billion worldwide—of which China accounted for nearly half of that—while the United States' investment reached only about 38 percent.[18]

Global Connectivity

Many have postulated that global connectivity and advanced networking will drive the development of new products and services. Next generation technologies such as 5G, low Earth orbiting satellite constellations, and meshed networks will support data-hungry consumers and bridge the digital divide. For example, OneWeb, founded in 2012, started with financial support from companies including Airbus, Coca Cola, Qualcomm, and Virgin Group. The mission statement of OneWeb is to bridge the global digital divide by operating a global network of satellites in low-Earth orbit. In the summer of 2017, OneWeb received approval with an FCC license[19] to access the U.S. market with 720 satellites and service customers. The first six demonstration satellites launched in 2019.

Competition for global connectivity comes from SpaceX's Starlink, which also received FCC approval[20] but for over 12,000 satellites for a space-based Internet communication system. In particular, SpaceX plans to place several shells of satellite constellations in Earth orbit. Deployment of these constellations will take decades and estimated costs are nearly $10 billion, as Gwynne Shotwell, president and COO of SpaceX, stated in a TED Talk in May 2018. Terrestrial competition will come from 5G suppliers worldwide.

Certainly, the trend of increasing global connectivity with broadband services is clear. Global communication networks, whether space-based or terrestrial, promise to deliver data, analytics, and intelligence to a user worldwide. While these global communication networks target the general public as a customer, they often rely on government as an anchor tenant to make the costly endeavor financially feasible. Communication traffic from the public and potentially from military operators will be routed through the same networks making them opportune targets for deliberate disruption. The events of Ukraine in 2014 and Georgia in 2008 suggest that communication networks can break down quickly.

In addition to space-based and terrestrial-based networking advancements, access to intelligence, data, and analytics comes in the form of apps on smartphone devices. In 2014, Ericsson's annual global connectivity report predicted that by 2020, 90 percent of the world's population aged over 6 years will have a mobile phone. In June 2019, the Ericcson report[21] assessed that mobile broadband providers will service over 9 billion subscriptions worldwide by 2024 indicating the people will have multiple mobile broadband devices and multiple subscription (Figure 2). Note the worldwide population forecast for that time is around 8.1 billion people[22].

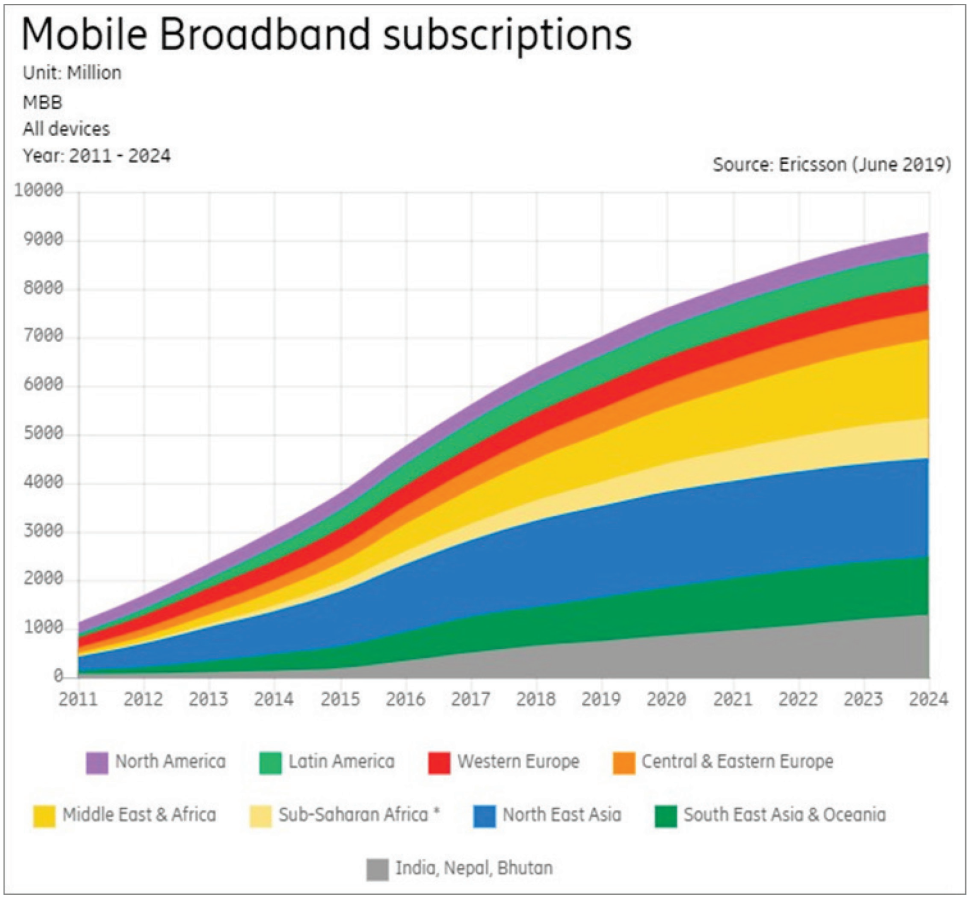


Figure 2: Ericsson Prediction. *Past and future broadband mobile subscriptions as of June 2019.*

Combining the described trends of (1) increasing imaging data supply through new satellite companies entering the field, (2) advancing AI, and (3) increasing global connectivity, the trend toward satellite-based information available in realtime to the general consumer is real—the GEOINT Singularity. While experts agree that increased commercialization of satellite-based remote sensing is leading to more global transparency, the effects on national security and military operations remain under debate. Some argue that the increased transparency will increase the predictability of adversaries: staging areas for surprise attacks in the physical domain will become difficult. Of course, this is a double-edged sword. The question remains: As we trend toward more global transparency, how can a policymaker assist military operators to still maintain the benefit of surprise? Traditionally, this has been attempted through licensing and license restrictions.

The U.S. Regulatory Framework for Commercial Remote Sensing

The U.S. framework for licensing commercial remote sensing systems was implemented through the National and Commercial Space Programs Act (2010) and the Land Remote Sensing Policy Act (1992), which state that no U.S. person or entity may operate a remote sensing space system without a license that has been authorized and granted by the Secretary of Commerce. The responsibility to license is currently delegated to the Administrator for the National Oceanic and Atmospheric Administration (NOAA). In addition to the legal framework provided by law, additional specifics are provided through the Code of Federal Regulations (CFR) in 15 CFR Part 960 and policies such as the National Space Policy of 2010 and NSPD-27, which is partially classified.[23] By law, the Secretary of Commerce can only grant a license that complies with all applicable international obligations (determined by the Secretary of State) and all national security concerns of the United States (determined by the Secretary of Defense). This is where interagency discussions take place. The Office of the Secretary of Defense will tend to advocate to satisfy national security concerns, and the Office of the Secretary of Commerce will tend to promote commercial competitiveness. Notable license conditions include resolution limits over Israel, traced back to the Kyl-Bingaman Amendment, and resolution limits of electro-optical imaging[24] at 25 cm. In addition to resolution limits, every license has a provision allowing for the U.S. government to invoke "shutter control." According to general license provisions, shutter control is invoked during periods of exceptional circumstances to meet significant concerns about national security or foreign policy and requires a licensee to limit data collection and/or distribution at specific times and in specific geographic areas. However, the discussion is shifting given the tasks laid out in Space Policy Directive 2 (SPD-2)[25] and the recently published Notice of Proposed Rule Making by NOAA in May 2019.[26]

A Comprehensive Risk Assessment Framework

When license conditions are determined through an interagency coordination process, in particular those pertaining to national security, the stakeholders evaluate risks and benefits. The risks to national security from overhead imagery and information being disseminated broadly can be wide ranging: adversaries could track the movements of U.S. and allied military equipment, detecting patterns of training and operations; hyperspectral imaging can identify chemical compositions; short-wavelength infrared imaging can see through clouds; and SAR sensors can image at night. When determining risks to national security, one can define it as the risk of being seen or detected. The risk of an operation being detected during a specific time depends on two variables: the operation or mission occurring at a specific time and a satellite remote sensing system looking at the specific time in the specific direction with the right sensor (i.e., an observation occurring). Together, the operation and the observation provide the risk of detection as shown in Figure 3.

In order to reduce the risk of detection, the military operator can either choose not to operate or maneuver during a given time or to somehow control the observation. Shutter control is an option to limit the observation and thereby minimize the risk of detection. The process for requesting shutter control or limiting an observation is time consuming and has to progress from a military operator to the Chairman of the Joint Chiefs Staff, to the Secretary of Defense, and to the Secretary of Commerce, who then notifies the company operating the satellite. Nevertheless, it is important to keep in mind that such restrictions only apply to U.S. entities operating in space and do not apply to high-altitude pseudo satellites (HAPS; i.e., balloons) or international space companies and foreign

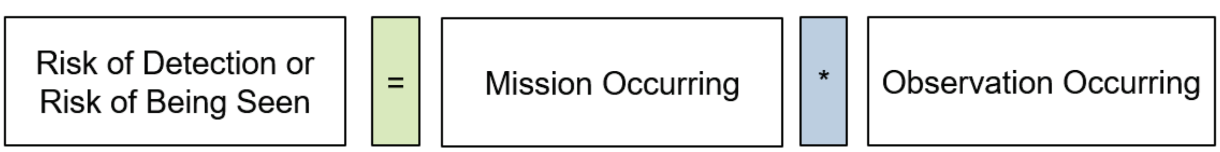


Figure 3: Risk of Detection. *The risk of detection can be summarized in two components: the risk from an observation occurring and the chances of a mission being conducted.*

governments. Diplomatic mechanisms exist for the U.S. government to request shutter control and other provisions specifically through space cooperation agreements, but those mechanisms remain largely untested and some say an untested capability is not a capability.

Capabilities of satellite remote sensing systems are not constant but continuously improve in various aspects. When assessing risks to national security, simplified here as *risk of detection*, the process of determining appropriate license conditions and the need for limiting observation traditionally only takes into account the known capabilities of past and existing space systems. This often leads to the statement that "policy lags behind capabilities." While it may not be possible to account for specific capabilities of planned and proposed systems because they may or may not become reality, the national security community should not be deterred from taking trends into account when assessing the risks to national security.

In consideration of the broader context, the risk of detection by limiting an observation comprises several components, out of which only one can be regulated—the U.S. commercial satellite remote sensing sector—whereas, imaging from high altitude platforms and by foreign nations cannot. Commercial imaging capabilities are certainly increasing, not just domestically but globally. In the changing world of increasing imaging capabilities, the risk of detection by observation could only be held constant (at best) if regulations are increased and strengthened. However, this would be inconsistent with domestic policies of advancing competitiveness of the U.S. commercial sector. Often the risk from unregulated capabilities (international commercial and governmental, HAPS) is neglected and license conditions are imposed based on domestic commercial platforms, as if the risk would only be from the domestic sector alone (Figure 4). However, imposing stricter regulations may provide a false sense of security because the growth of international capabilities is neglected. On the other hand, increasing regulation is free of charge and has no immediate cost imposed on those who advocate for it. This is a true "regulatory paradox" in the commercial remote sensing market.

Options to Break the Regulatory Paradox in Commercial Remote Sensing

Instead of increasing U.S. remote sensing regulation, other mitigation techniques will have to be found that also support maintaining U.S. commercial competitiveness. Options to reduce the risk of detection to the military operator could

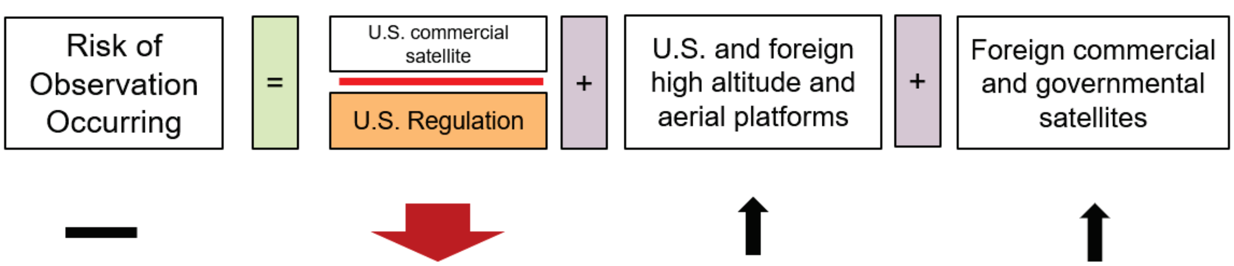


Figure 4: Risk of Observation. *In order to keep the risk of detection by observation steady (at best), regulatory restriction would have to increase and become more restrictive at the same time that international and domestic, unregulated capabilities are becoming more available. However, the U.S. government tends to lessen restrictions imposed on U.S. companies to enable competitiveness in the remote sensing market, which leads to an overall increase in the risk of detection. As restrictions decrease and international capabilities increase, military operators have no choice but to accept the additional risk or develop countermeasures and new doctrine.*

include limiting the advancements on data analytics, artificial intelligence, and global connectivity to maintain a certain opaqueness and element of surprise. However, those may not be viable in Western societies where the freedom of information is valued, and free markets and innovation are high priorities identified in national policies. Some argue that the risk of detection is already assumed in existing military doctrine, although how much risk is unclear.

If increasing regulation is not a good choice, what remains is to improve D&D and disinformation techniques to maintain the advantage or element of surprise. Surprise is one of the nine fundamental principles of warfare, described in the U.S. Army Field Manual.[27] Surprise is to strike the enemy at a time or place or in a manner for which they are unprepared. Surprise can decisively shift the balance of combat power. By seeking surprise, forces can achieve success well out of proportion with the effort expended. The U.S. Army field manual notes that rapid advances in surveillance technology and mass communication make it increasingly difficult to mask or cloak large-scale marshaling or movement of personnel and equipment. However, the manual does not appear to offer a solution.

Nearly 20 years ago, a thesis titled "The End of Secrecy" by Lt. Col. Beth Kaspar (U.S. Air Force), discussed the implications of transparency to U.S. military competitiveness and recommended a variety of activities ranging from innovating new doctrine and developing fast decisionmaking processes to integrating camouflage, concealment, and deception both vertically and horizontally into military operations. In her thesis, Lt. Col. Kaspar stated, "DoD should go back to basics and actively incorporate deception into all organizational levels and all levels of warfare". [28]

Typical denial and deception techniques, such as camouflage, are well known to military operators and warfighters. However, when approaching a GEOINT Singularity, traditional denial and deception techniques may not be sufficient and will have to be advanced in ways that cope with frequent and continuous observations in various bands of the electromagnetic spectrum. Fewer or no time windows will exist without a satellite passing over or other capabilities that could detect an activity. Conceptual D&D methods dealing with reducing transparency and maintaining an element of surprise are listed in Table 1; specific methods and programs of D&D are beyond the scope of this unclassified discussion.

Table 1 illustrates a number of potential active and passive measures that could be incorporated and taken during peace time or during times of heightened risks to national security. Active measures could be reserved for conflict situations against adversaries and may be inappropriate to use against assets operated by friendly governments or the U.S. private sector. Passive measures could be used at any time as they would not harm or negatively affect the operation of a remote sensing system. Note that none of these measures attempt to slow down the three trends towards a GEOINT Singularity but instead provide independent ways and means to permit a military operator to complete a mission while remaining undetected.

The approach of improving D&D techniques instead of regulating the domestic commercial satellite remote sensing sector bears several advantages, which include:

- Improving D&D techniques against domestic commercial capabilities will likely also advance those techniques against foreign military capabilities.

- Reducing the regulatory burden will permit the domestic commercial remote sensing sector to remain innovative and competitive on a global scale.

Table 1: Active and Passive Measures. Mitigating risks of detection from a military operator's perspective is dependent on the remote sensing capabilities and wavelength domain of the space remote sensing system and can be divided into active and passive measures.

	Active Measures (likely reserved for extreme situations)	Passive Measures
Electro Optical (EO) (visual spectrum)	♦ Jamming sensor ♦ Jamming communication links ♦ Lasing sensors ♦ Cyber defense methods ♦ Misinformation	♦ Lower emission and reflectivity ♦ Operate at night ♦ Operate under clouds ♦ Reduce size ♦ Exploit time delays ♦ AI spoofing ♦ Mimic innocuous activity
Synthetic Aperture Radar (SAR)		
Short-Wave Infrared (SWIR)		
Hyperspectral Imaging (HS)		

- Supporting increased innovation in the field of commercial remote sensing, artificial intelligence, and global communication will provide new capabilities for the nation, including for national security purposes.
- Using commercial imaging can be used to support public messaging without revealing the capabilities of governmental systems.

The advancements of new D&D (Table 1) may appear costly at first. However, it should be evident that simply placing remote sensing license restrictions is not free either. Remote sensing license restrictions simply delay the cost to a later time when existing D&D methods have become ineffective due to the growth of foreign remote sensing capabilities.

At the same time Lt. Col. Kaspar called for new doctrine to deal with increased transparency, The RAND Corporation published a book about the "leading edge of global transparency" and highlighted policy issues with international security case studies in a world of increased transparency.[4] Both reports recognized and predicted a further increase in global transparency almost 20 years ago and called for innovative doctrine to handle the increased transparency. It is unclear, however, how much military doctrine improved and integrated new D&D to keep up with the trend toward global transparency.

Conclusion

The general public may have increased privacy concerns when approaching the GEOINT Singularity, but military operators should be working now to mitigate the implications of the general public having access to ubiquitous intelligence in realtime. Traditionally, the national security community attempted to maintain a certain level of opaqueness or surprise by limiting commercial space-based imaging through regulation. However, that approach has provided a false sense of security and neglected developments that are not under U.S. regulatory control such as foreign commercial imaging companies and advancements of foreign military capabilities. A broader framework for assessing the risks to the military operator within the looming GEOINT Singularity has been proposed here, and the advantages of improving denial and deception techniques at a tactical and operational level have been discussed.

Strengthening U.S. remote sensing regulation only applies to the domestic commercial sector and can be summarized as a "don't look" approach. Given the advancements in the three critical areas of artificial intelligence, global connectivity, and satellite imagery, a different approach focusing on denial, deception, and misinformation to maintain the element of surprise may be more appropriate and more future-oriented.

References

[1] Amazon's Alexa, Google's Assistant, and Apple's Siri are just the beginning. For example, Google made headlines in 2018 by demonstrating how its Google Assistant could make a restaurant reservation on your behalf. The restaurant was real, but the "person" making the call was an AI system able to interact with humans on the phone.

[2] Adopted from: C. Herring, J. Googasian, S. Truitt "The Geo Singularity", USGIF Jan 2019.

[3] Information could be provided free of charge with a hidden revenue generation business model, where customers don't pay for a service but revenue comes from advertising or a paying customer.

[4] John C. Baker, Kevin M. O'Connell, Ray A. Williamson (2001) "Commercial Observation Satellites – At the Leading Edge of Global Transparency", The RAND Corporation

[5] https://skymind.ai/wiki/ai-vs-machine-learning-vs-deep-learning

[6] Physics limitations are certainly a factor: due to the Rayleigh Criterion, a telescope has a theoretical resolution limit based on the diameter of the lens or mirror.

[7] Anna Esher (2018) "Inside Planet Labs' new satellite manufacturing site", Techcrunch, https://techcrunch.com/2018/09/14/inside-planet-labs-new-satellite-manufacturing-site/.

[8] https://earthnow.com/

[9] EarthNow Press release (April 2018), https://earthnow.com/

[10] https://liveearthimaging.net/

[11] https://satrevolution.com/

[12] Robert Cardillo, GEOINT 2017 Remarks, https://www.nga.mil/MediaRoom/SpeechesRemarks/Pages/GEOINT-2017-Symposium.aspx

[13] CNBC Staff Writer (2018) "CNBC unveils its annual list of 100 promising start-ups to watch", https://www.cnbc.com/2018/10/09/cnbc-unveils-its-list-of-100-promising-startups-to-watch-in-2018.html.

[14] Moody, J. B.; Nogrady, B. (2010). The Sixth Wave: How to succeed in a resource-limited world. Sydney: Random House. ISBN 9781741668896.

[15] Sima Fishman (2018) "Earth Observation: State of Play and Future Prospects" https://www.nesdis.noaa.gov/CRSRA/pdf/AACRES_meeting_2018_Euroconsult.pdf.

[16] ABI Staff Writer (2017) "ABI Research Forecasts Almost One Million Businesses Worldwide Will Adopt AI Technologies by 2022", https://www.abiresearch.com/press/abi-research-forecasts-almost-one-million-business/.

[17] NGA Staff Write (2018) "Remarks as prepared for Robert Cardillo, Director, National Geospatial-Intelligence Agency", https://www.nga.mil/MediaRoom/SpeechesRemarks/Pages/GEOINT-2018-Symposium-.aspx.

[18] James Vincent (2018) "China overtakes U.S. in AI startup funding with a focus on facial recognition and chips", https://www.theverge.com/2018/2/22/17039696/china-us-ai-funding-startup-comparison.

[19] FCC Staff Writer (2018) "FCC Grants Oneweb Access To U.S. Market For Its Proposed New Broadband Satellite Constellation", https://www.fcc.gov/document/fcc-grants-oneweb-us-access-broadband-satellite-constellation.

[20] FCC Staff Writer (2018) "FCC Authorizes SpaceX to Provide Broadband Satellite Services", https://www.fcc.gov/document/fcc-authorizes-spacex-provide-broadband-satellite-services.

[21] https://www.ericsson.com/en/mobility-report/mobility-visualizer

[22] https://population.un.org/wpp/DataQuery/

[23] Vedda, James (2017) "Updating National Policy on Commercial Remote Sensing", Center for Space Policy and Strategy, The Aerospace Corporation. 10.13140/RG.2.2.14869.93925.

[24] Sarah Scoles (2018) "How the Government Controls Sensitive Satellite Data", https://www.wired.com/story/how-the-government-controls-sensitive-satellite-data/.

[25] Presidential Memoranda, Space Policy Directive – 2, Streamlining Regulations on Commercial Use of Space, Issued on May 24, 2018

[26] Notice of Proposed Rule Making for the "Licensing of Private Remote Sensing Space Systems", RIN 0648-BA 15, https://www.federalregister.gov/documents/2019/05/14/2019-09320/licensing-of-private-remote-sensing-space-systems

[27] U.S. Army Field Manual 100-5: Operations, Chapter 2: The Fundamentals Army Operations.

[28] LtCol USAF Beth M Kaspar, "The End of Secrecy – Military Competitiveness in the Age of Transparency", Maxwell Air Force Base, Alabama, 2000.

SPACE-ENABLED PERSISTENCE AND TRANSPARENCY IN THE ARCTIC TO SUPPORT INFRASTRUCTURE AND NATIONAL SECURITY NEEDS

Karen L. Jones and Lina M. Cashin

The United States has maintained territorial claims and has advanced political, economic, national security, environmental, and cultural interests within the Arctic region since the 1867 acquisition of Alaska. The Arctic Council and the United Nations Convention on the Law of the Sea (UNCLOS) are avenues to engage our partners to promote a stable and secure Arctic. Commercial satellite data, including enhanced communications, navigation and timing, and remote sensing, will play a key role in establishing persistent situational awareness. It is through reliable and ubiquitous commercial satellite capabilities that the United States can meet its economic, national security, and environmental imperatives.

This chapter provides an overview of U.S. Arctic policy and national interests and describes how commercial satellite services can provide domain awareness to observe and adapt to the region's rapidly changing conditions. While geopolitical tension is rising in the Arctic, stakeholders will benefit from sharing satellite data with each other and the public. Sharing can enhance operations, establish greater transparency and accountability, and strengthen a common rule-based order.

Introduction

The area north of the Arctic Circle (66.3° latitude) includes vast expanses of ocean, ice, and land masses. Surface air temperatures in the Arctic are rising at twice the rate of the rest of the planet, resulting in widespread permafrost melting.[1] Melting sea ice has cleared two major sea routes for increased maritime traffic (see Figure 1), and harbors have become available year-round for shipping, resource extraction, and industrial development.

As both allies and potential adversaries have expanded their activity, protecting U.S. interests in the Far North has become increasingly complex. National security, cooperation, and environmental sustainability are enduring objectives from the past five administrations. More recently, a June 2020 Presidential Memorandum requires *persistent* Arctic domain awareness and directs an assessment to ensure a strong presence in the Arctic, including using operational means such as space systems, sensors, command and control, data transfer capabilities, and intelligence assets,[2] which could be provided by space-based services. This operational persistence underpins the DOD's Arctic Strategy (2019), which aims to provide a secure and stable region and a rule-based order, respecting both national sovereignty and constructive engagement.[3]

Fortunately, the polar region is developing at a time when the burgeoning commercial space industry can provide persistent space-enabled connectivity, navigation, and increased surveillance. A combination of strategically aligned commercial satellites, in a variety of orbits, can provide the coverage necessary to step up to national security, industry, and environmental challenges.

Arctic Governance

Various conventions and rules of order create the basis for Arctic governance. The most prominent are a binding framework for nations' ocean rights and responsibilities known as the United Nations Convention on the Law of the Sea,[5] and an intergovernmental forum, the Arctic Council.

United Nations Convention on the Law of the Sea (UNCLOS). In 1994, the United States along with the other seven members of the Arctic Council agreed that UNCLOS provided sufficient governance due to the fact that much of the Arctic is ocean. The United States has not ratified UNCLOS but abides by it.[9] UNCLOS establishes territorial boundaries, facilitates international coordination, and promotes peaceful, equitable, and efficient utilization and conservation of ocean resources and the marine environment.[10]

Arctic Council. The Arctic Council is an intergovernmental forum that encourages cooperation, coordination, and interaction among the Arctic States, indigenous communities, and other Arctic inhabitants on sustainable development and environmental protection.[11,12] Additionally, the council looks to the United Nations' Sustainable Development Goals as a guiding framework for sustainability.

The United States is one of eight members of the Arctic Council along with Canada, Denmark, Finland, Iceland, Norway, the Russian Federation, and Sweden. These eight "Arctic States,"[13] all with land inside the Arctic Circle, are permanent members

Figure 1: The Arctic Region. *The smaller red circle (81°3') is the maximum latitude beyond which a geostationary satellite (GEO) is unable to provide coverage because it is below the local horizon. Operationally, a GEO satellite's limits are several degrees lower due to receiver noise from atmospheric refraction, frequency interference due to Earth's thermal emission, line-of-sight obstructions, and signal reflections with ground structures at approximately 75°.*[4]

Organizational Alignment to Optimize Arctic Strategy

The Arctic will require military strategic and operational integration among all U.S. forces operating in the region. Yet the region is currently split between two combatant commands: U.S. Northern Command (USNORTHCOM) and U.S. European Command (USEUCOM). A single authority could facilitate and streamline other countries' engagement with the United States.[6] The trend appears to be pointing to further consolidation. During 2011, the Unified Command Plan removed a portion of the Arctic region from the U.S. Pacific Command (USPACOM) area of responsibility (now USINDOPACOM).[7] More recently, in December 2019, Senator Dan Sullivan (R-Alaska) introduced a bill (S. 3080), "Strategic Arctic Naval Focus Act," which addresses the need for strategic placement of military assets in the Arctic. Among other things, the bill calls for "the establishment of the position of Deputy Assistant Secretary of Defense for the Arctic tasked with optimizing the Unified Command Plan for the Arctic and other overarching strategies for the Arctic region." [8]

of the Arctic Council, which was established by the 1996 Ottawa Declaration to promote cooperation, coordination, and interaction. In addition, mid-latitude countries normally not associated with the Arctic such as China, India, and Singapore, are accorded Observer status.[14]

The pace of growth of human activity in the Arctic is astounding, and the scramble to gain access to the region's resources has reached a fevered pitch. Recently, during a May 2019 Arctic Council meeting, U.S. Secretary of State Mike Pompeo noted, "We're entering a new age of strategic engagement in the Arctic, complete with new threats to the Arctic and its real estate, and to all of our interests in that region."[15]

U.S. Policy Responses

The United States has defined its strategic and commercial interests through a series of policy statements, each building on previous documents to address the changing environment and geopolitics. Despite the steady building of Arctic policies there is "a lack of operational articulation," according to Troy Bouffard, University of Alaska Fairbanks instructor and Arctic Security expert. Bouffard notes further "let's get serious – current policies leave room for too much interpretation which could result in pulling resources from other global mission sets. An operational plan (OPLAN) is needed as an actionable catalyst, otherwise DoD could potentially shift funding from current missions when trying to resource unfunded capabilities for the Arctic."[16]

Table 1: National Arctic Policies Across Three U.S. Administrations. Policies build on common themes of national security, cooperation, and environmental sustainability.

Key National Policies	Priorities
National Security Presidential Directive 66/Homeland Security Presidential Directive 25 (Bush 2009)	Addresses national security and homeland security needs and calls for: ◆ Environment and natural resource conservation and management ◆ Strengthening institutions and cooperation ◆ Greater involvement of indigenous communities
National Strategy for the Arctic Region (Obama 2013)	Responds to challenges and economic opportunities: ◆ Advances security interests and evolves infrastructure and capabilities ◆ Pursues stewardship to protect the Arctic and conserve its resources ◆ Strengthens international cooperation through bilateral relationships and multilateral bodies, including the Arctic Council ◆ Advances collective interests such as shared Arctic state prosperity, environmental protection, and regional security
U.S. Coast Guard Arctic Strategic Outlook (2019)	Establishes three lines of effort crucial to achieving long-term success: ◆ Enhance capability to operate effectively in a dynamic Arctic domain ◆ Strengthen the rules-based order ◆ Innovate and adapt to promote resilience and prosperity
DOD Arctic Strategy (2019)	Describes a secure and stable region, where: ◆ Interests are safeguarded and homeland is defended ◆ Nations work cooperatively to address shared challenges ◆ Reliance on a rules-based order is emphasized

Key National Policies	Priorities
Memorandum on Safeguarding U.S. National Interests in the Arctic and Antarctic Regions (Trump 2020)	Safeguards national interests and emphasizes a persistent polar presence: ◆ Requires a fleet of polar security icebreakers and cutters by 2029 ◆ Establishes fleet acquisition program ◆ Directs basing assessments for two national and two international locations ◆ Supports maximum use of additional capabilities such as "unmanned aviation, surface, and undersea systems; space systems; sensors and other systems to achieve and maintain maritime domain awareness; command and control systems; secure communications and data transfer systems; and intelligence-collection systems"[17]
The Department of the Air Force Arctic Strategy (2020)	Articulates the Air Force's role in the Arctic, including efforts to optimize Air and Space Force capabilities, including: ◆ Enhancing missile defense ◆ Exploring new surveillance and communications technologies ◆ Updating regional infrastructure

Moving to a Persistent Arctic Presence. During June 2020, the White House issued a memorandum, "Safeguarding U.S. National Interests in the Arctic and Antarctic Regions," which is, in part, a response to Russia's and China's increasing presence in the Far North. The White House memorandum calls for a review of the United States' requirements for icebreaking capabilities in the polar regions, with the goal of getting a fleet in place by 2029. The Trump administration emphasized *persistence* to retain a strong security presence with allies and partners.[18] Beyond expanding the nation's Arctic maritime fleet, space system capabilities are needed to support persistent domain awareness. Joint Publication 3-14, *Space Operations*, notes that "Most space-based intelligence collection capabilities consist of multiple satellites operating in concert, or supplemented by other sensors, when continuous surveillance of an area is desired."[19] This type of persistence is possible through a combination of commercial low Earth orbit (LEO), highly elliptical orbit (HEO), and geostationary Earth orbit (GEO) satellites.

Commercial Systems for Disparate Stakeholders and Multinational Collaboration. Following the White House memorandum, the Air Force issued its own Arctic Strategy in July 2020, which outlines an approach for collaboration with the Joint Force, international allies, and partners to protect U.S. sovereignty and national security interests. The Air Force Arctic Strategy calls for greater investments in command, control, communications, intelligence, surveillance, and reconnaissance (C3ISR), as well as in space operations and missile defense.

While defense-focused satellite systems are customized and only available to DOD stakeholders, commercial systems provide a more open means to cooperate and collaborate for other critical missions.

Seamless Data and Connectivity. During a rollout of the new Arctic Strategy, Air Force Gen. Dave Goldfein emphasized a strong data strategy and investment in networks that operate "seamlessly."[20] Given Gen. Goldfein's comment, one must consider the commercial satellite sector's progress in closing the infrastructure gap to seamless connectivity (see section "Communication and Connectivity," below). Eventually Far North stakeholders will have access to the same cloud-hosted services on which lower latitude counterparts have relied, including data storage, predictive analytics, and various enterprise solutions for logistics and supply chains. Cloud-based commercial solutions are leading the way for collaboration for emergency and natural disaster operations, which often require a massive amount of data originating from various organizations and devices.

Great Power Competition – China and Russia

China – Polar Silk Road. As part of a larger strategy to increase access to global natural resources, China's president Xi Jinping stated that China would encourage enterprises to build infrastructure and conduct commercial trial voyages, paving the way for Arctic shipping routes that would form a "Polar Silk Road."[21] China is also increasing its operational presence by using and constructing icebreaking vessels and supporting a growing number of research efforts, which could fortify a military presence in the Arctic Ocean.[22] China sees potential future economic benefits in the development of the Arctic and has undertaken an aggressive diplomatic and economic effort to establish a foothold in the Arctic region."[23]

Many mid-latitude countries[24] have gained permanent observer designation at the Arctic Council, whereby they can observe the work of the council and contribute at the of working group level. China goes a step further and has declared itself a "near-Arctic state," which is an informal self-designation not recognized by Arctic Council members, including the United States.[25,26]

Russia – Growing Military and Industry Presence. Unlike China, Russia has a long-established stake in the Arctic region and has significantly increased shipping through the Northern Sea Route (NSR), a Europe-to-Asia shipping passage which is 3000 miles shorter than an alternate route through the Suez Canal. Russia has asserted and exceeded its maritime regulatory authority across the entire NSR (approx. 3,500 miles) and views the NSR as an internal waterway (see Figure 2). The rest of the Arctic community, however, views the NSR as an international passage since only portions of the route flow through Russia's internal waters.[27] Similarly, the United States has long disputed Canada's sovereign claims to the Northwest Passage. Therefore, any Freedom of Navigation Operation (FONOP) with Russia could unintentionally open the door to a similar territorial dispute with our ally, Canada.[28, 29]

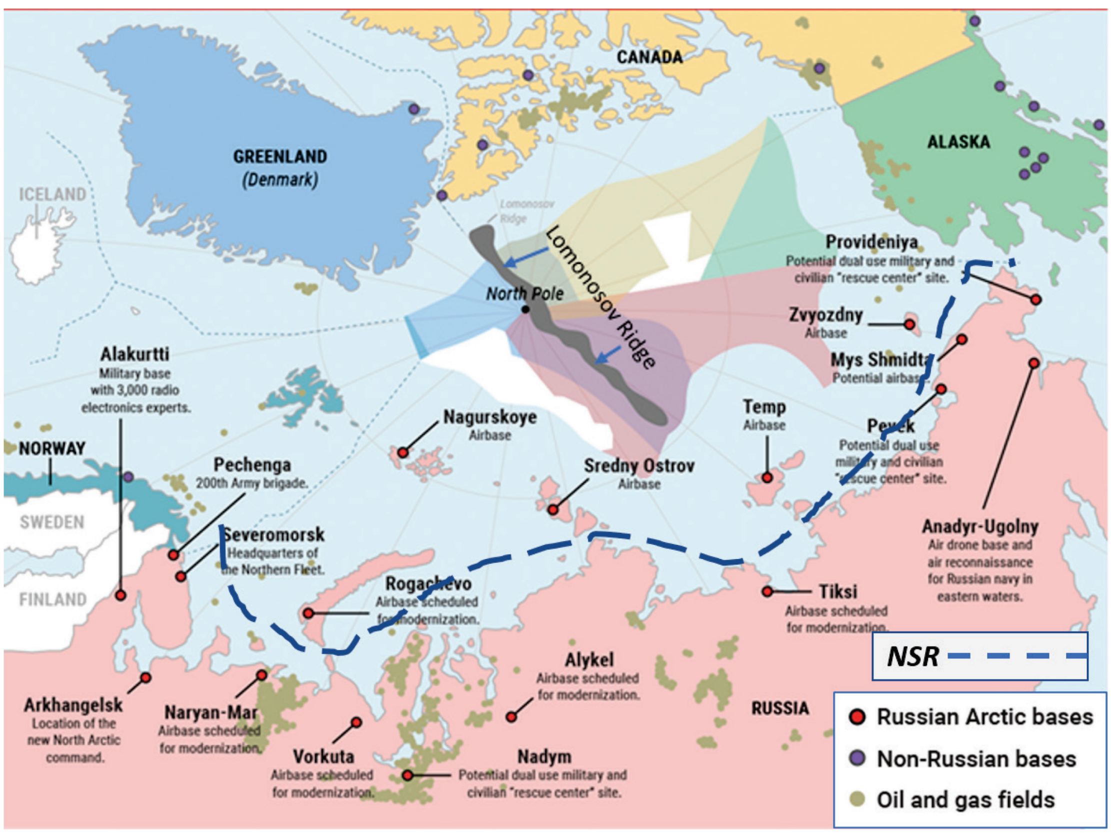


***Figure 2: Arctic Countries, Military Installations, and Landmarks.**[30] Map shows key Russian military and maritime installations, as well as the Lomonosov Ridge trending northwest and southeast across the North Pole. This ridge represents an ongoing scientific dispute regarding continental shelf geography and territorial claims between Russia, Denmark, and Canada.*

Regardless of disputed sovereign claims to the NSR, Russia's activities are proportionate to its enormous territory (Figure 2) and economic resources in the Arctic region. Still, concerns remain. In July 2019, Air Force General Terrence O'Shaughnessy, commander of U.S. Northern Command, noted that "if you look at the northern approaches through the Arctic, that's a key avenue of approach that we have to be able to defend." He also identified cruise missiles by way of the Arctic "as one of the biggest threats that we face."[31]

Russia's military defense investments in the Arctic are aimed at protecting its territory and controlling the NSR. Russia has increased its military infrastructure and activity around the Arctic Ocean by refurbishing old airfields and establishing new military bases along its Arctic coastline. Existing and planned networks of air defense and coastal missile systems, early warning radars, rescue centers, and a variety of sensors are pivotal to Russia's military ambitions.[32]

In March 2020, Vladimir Putin unveiled "Arctic 2035," a 15-year plan calling for increasing the local population's quality of life and accelerating economic development through improved infrastructure and technology. As the Arctic's most significant stakeholder in terms of land, this plan will advance Russia's "persistence" in the region. Economic measures include boosting private investment in key energy projects on the Arctic shelf and paying Russians who want to relocate to the north.[33]

Typically, Arctic Council discussions focus on cooperation, natural resources, sustainability, and environment. However, in May 2019, Secretary of State Pompeo delivered a blunt message to Arctic Council members during a meeting in Finland, where he countered Beijing's territorial aggression in the Far North, asking, "Do we want the Arctic Ocean to transform into a new South China Sea, fraught with militarization and competing territorial claims?"[37]

A comparison to the South China Sea is apropos and crucial in understanding Chinese strategy. China has imposed domestic laws to supplant international law to limit the rights of foreign vessels, preferring to base its claim on historical rights rather than distance to its land territory per the UNCLOS.[38] China's rejection of UNCLOS in the South China Sea has fueled circumspection and fear that China will wedge itself into the Arctic region and play by its own rules. This suspicion could be extended beyond matters of territorial claims to fishing rights as well.

China and Russia Cooperation and Tension. Both Chinese ambitions and Russian territorial claims and strong military presence in the Arctic are even more concerning as these two countries collaborate across diplomatic, economic, and security areas.[34] For example, Russia remains a top source for Chinese energy imports and China has demonstrated a financial commitment to Russia's energy economy. This symbiotic relationship between Russia and China is a marriage of convenience, not trust. Recently, for instance, Russia arrested a well-known Russian scientist for allegedly sharing classified information with China.[35] Despite lack of full trust, the Arctic Institute notes that "there is a growing interdependence" between Russia, who needs capital investments in infrastructure, and China, who needs commodities.[36]

Increasing Space Capabilities in the Arctic

As the United States grows more concerned about its strategic rivals, China and Russia, interest is increasing in creating a "force presence," which would include rebuilding the United States' polar security icebreakers and cutters, adding a deep-water arctic port in Alaska, and hosting military exercises. As part of this increasing commitment, the United States has continued to host military exercises. From a civilian perspective, connectivity is critical to the residents of Alaska to engage in commerce, e-medicine, and distance learning. In referencing affordable satellite connectivity for Alaskans, senator Lisa Murkowski noted that "this has a potential for transformational opportunities for us."[39]

Access to Denied Areas. Satellites are a practical option to consider in the Arctic because they provide global coverage and enable access to otherwise denied areas. Space-based assets provide timely, persistent, and objective coverage, which can support requests for continuous operations, scheduled interactions, and emergency requests.

"Unlike the rules for aircraft overflight, there are no overflight restrictions for spacecraft in outer space. Therefore, space-faring nations benefit from unrestricted space overflight. This characteristic makes space-based ISR, remote sensing, SATCOM, and PNT more responsive than terrestrial alternatives." [40]

Arctic stakeholders such as ship operators, scientists, Arctic residents, teachers, public safety, medical professionals, and industry will be able to benefit from these new commercial developments, which will allow greater connectivity options with some satellite operators offering broadband speeds.

Communication and Connectivity. Historically, simple store and forward constellations, such as Gonets (Russia) and Argos (France), served the polar regions using narrowband, unidirectional communications for scientific, environmental, and meteorological purposes. By the late 90s Iridium Communications introduced global satellite communications that provided coverage to both poles. Few new satellite services to the region were introduced until recently. Within the past two years, a flurry of new commercial satellite offerings has expanded in the Far North, providing a range of services across LEO, GEO, and HEO.

LEOs. Incumbent operator Iridium replenished its global constellation, Iridium NEXT, to provide voice and data communications, although Iridium does not offer broadband speeds (25 Mbps and higher, as defined by the FCC). In 2018, three new small satellite players entered the market: Kepler, Hiber, and Fleet Space, all targeting the Internet of Things (IOT) or machine-to-machine (M2M) markets.

New proliferated LEO (pLEO) operators, such as OneWeb and SpaceX "Starlink," are introducing satellites in polar or near-polar orbit. OneWeb has 72 satellites in high inclination orbit, which could provide broadband capabilities for an interested buyer. Although OneWeb filed for Chapter 11 bankruptcy, it now appears that the Indian mobile network operator along with the government of the United Kingdom will take a significant equity share in return for providing $1 billion in new funding for the global constellation of broadband satellites.[41]

Far North GEO Coverage. The current generation of GEO high-throughput satellites (HTS) can also support high latitude regions, including a significant portion of the Arctic, with large amounts of capacity concentrated in small areas, using high power, multiple spot beams, and frequency reuse. Pacific Dataport (Anchorage, Alaska), for instance, is launching two GEO HTS for coverage of Alaska and the surrounding Arctic region, with the first satellite scheduled for launch in July 2021 and a second satellite launch in 2023. These GEOs will provide full coverage of Alaska with a minimum beam pointing elevation angle of 10 degrees[*] and Arctic coverage well beyond Alaska for land, maritime, and aero services (up to 80 degrees North latitude, depending on the application). The two satellites will provide backup capacity and signal diversity for each other.[42]

HEO and Hosted Payloads. Space Norway, owned by the Norwegian government, is cooperating with commercial satellite operator Inmarsat and the Norwegian Ministry of Defense to offer mobile broadband coverage to civilian and military users in the Arctic. Two HEO satellites are scheduled to be launched in late 2022. The ground station will be established in Norway, and both satellites will provide full coverage from 65 degrees North. Each of the two satellites will carry multiple payloads and the system is scheduled to be operational for at least 15 years, with users able to switch between current GEO satellites and the HEO satellites.[43] Among the various payloads will be the U.S. Space Force's stopgap Arctic

---

[*]The elevation angle refers to the angle between the beam pointing direction of the antenna (e.g., satellite dish) toward the satellite and the local horizontal plane.

communications system known as Enhanced Polar System Recapitalization (EPS-R). This system will fill a vital gap for defense operations in the Arctic region.[44]

Observation. Polar orbiting satellites in LEO circle the planet every 90 minutes and have fields-of-view spanning hundreds of miles. GEO satellites can also view parts of the Arctic region up to a practical limit of 75 degrees. Together, GEO and LEO space capabilities can provide situational awareness for air, land, and maritime domains. The market momentum provided by commercial space providers offers Far North stakeholders a range of technical options as they seek to navigate, communicate, and maintain persistent situational awareness over the region.

Operational and Tactical Response

Space-based capabilities provide the ability to quickly surge and reallocate assets when there is an emergency or crisis. Space operations are especially useful for coordination across multiple stakeholders and nationalities that must work together (see Table 2) across Arctic critical mission areas.

Table 2: Arctic Missions. Persistent commercial satellite imaging, continuous connectivity, and open data sharing will enable cooperation and magnify transparency in the Arctic region.

Arctic Missions	Benefits to Increased Transparency
National Security	Imaging satellites can share data with both allies and adversaries regarding military exercises and to surveil for trespassing.
Border Patrols and Sovereignty Protection	Sharing images and data along national borders will allow observation and enforcement of border security and access to territories and natural resources.
Passage Assistance and Management	Sharing imagery, data, and communications to ensure safe passage for ships in the Northern Sea Route, Northwest Passage, and other areas.
Fisheries Monitoring	Sharing information on fishing activities to encourage compliance. Imaging satellites can provide cost-effective solutions to support fisheries management bodies, fishing moratoriums, and ensure ocean sustainability.
Environmental and Oil Spill Response	A multilateral treaty ratified by Canada in 2014, *Marine Oil Pollution Preparedness and Response in the Arctic*, aims to increase cooperation and coordination among Arctic countries. Commitments include mutual assistance and information exchange to improve oil spill response success.
Search and Rescue	*The Arctic Search and Rescue Agreement*, ratified by all Arctic Council countries and entered into force in 2013, calls for coordination, cooperation, and response between all Arctic nation coast guards.

Open data is structured, machine readable, open licensed, and well maintained.[45] Open data is a key enabler for data sharing, which allows for increased government transparency and accountability.[46] Sharing data between governmental agencies and nations will be a game changer as scientists continue to monitor global climate change and as governments focus on increased cooperation across a range of Arctic missions.

Opportunities for Decisionmakers

The fallout from the COVID-19 pandemic will introduce unique fiscal challenges, including a worldwide decline in military spending.[47] During this period of rapid change, Russia, China, the United States, and NATO allies will assert their territorial, economic, and military interests. It is, therefore, a pivotal time to support affordable and persistent satellite capabilities for communications, connectivity, navigation, and observation. The United States space enterprise can start by considering the following opportunities:

- **Emphasize open, available, and shared systems for multi-partner cooperation.** Commercial satellite services offer open and readily available systems for responding to missions that require multinational interoperability, and multistakeholder cooperation.

  - **Open solutions.** The Air Force Arctic Strategy calls for greater investments in areas such as C3ISR, space operations, and missile defense. Beyond secure and protected defense-focused satellite systems, more open and available systems are needed for emergency response. These missions require joint, multi-national capabilities to prepare and respond to large-scale disasters (natural and man-made), coordinate readiness with allies and partners, and plan for rescue and personal recovery.[48]

  - **Ready access.** Defense systems often require 15- to 20-year acquisition cycles. Decisionmaking and design/production processes alone can take 5 years, on average, to mature a concept, gain stakeholder validated requirements, and establish an acquisition program, and another 7.5 years, on average, to reach first launch.[49,50] By contrast, contracting with a commercial space provider to develop and operate communications, navigation, and remote sensing services could entail a couple of years instead of close to a decade, which is the amount of time government programs often need.[51]

  - **Optimize networks, data sharing, and cloud connectivity.** Arctic stakeholders can optimize communication paths through network convergence and interoperability standards. Enterprise cloud connectivity for polar region customers (commercial, civil, and military users) will also drive efficiencies and allow remote Arctic business locations and operations to become more integrated and central.

- **Update the U.S. relationship with our Arctic allies to integrate an evolving Arctic Strategy.** The United States has a unique relationship with Canada for mutual deterrence, defense, and space operations. It is now a propitious time to update our space alliances and partnerships to address the new Air Force Arctic Strategy, including optimizing combined space capabilities, exploring new surveillance and communication capabilities (including commercial solutions), and updating regional infrastructure.

  Canada's combined space operations with the United States includes Sapphire orbital space surveillance and RADARSAT Earth observation. As a partner, Canada participates with the United States in the following programs: Space Situational Awareness (SSA); Wideband Global SATCOM; North American Aerospace Defense Command (NORAD) Command, and missile warning, maritime warning, and positioning, navigation and timing capabilities.[52] To ensure that our longstanding relationship with our northern neighbor remains strong, the United States and Canada should jointly operate all domain Arctic awareness for security and stability applications.[53] The United States should continue to promote and expand the enduring defense relationship with Canada via NORAD and bolster strategic messaging to enhance deterrence. On the civil front, the Alaska Domain Awareness Center (ADAC) works as a collaboration hub for safety, security, and crisis response and should be further resourced.

- **Engage and incentivize the commercial sector.** Expanding commercial space capabilities can provide the rapid access, reach, and domain awareness to advance our political, economic, national security, environmental, and cultural interests as an Arctic nation. Now is the time for policymakers to examine how government can encourage commercial ventures, perhaps as a committed customer, anchor tenant, or seed investor, to support critical mission areas and to improve the lives of the people in the Far North region.

Looking Forward

The Arctic region will continue to grow in strategic importance for commercial, national security, and environmental interests at a time when space assets are poised to respond to a range of challenges and needs across private sector, civil, and defense interests. This is a unique time in the space sector as commercial space is proving its resilient capacity to provide open and hybrid architectures across a range of orbital regimes. Emerging ubiquitous networking options and open data sharing will usher in a new age of greater persistence, transparency, and cooperation. By strengthening our international Arctic partnerships, particularly with Canada, and fully leveraging our commercial satellite-based assets, the United States can build Arctic awareness, enhance Arctic operations, and strengthen a common rule-based order. Good actors can be recognized, bad actors can be exposed, and rules can be enforced.

References

[1] E. Osborne, J. Richter-Menge, and M. Jeffries (eds.), Arctic Report Card 2018, https://www.arctic.noaa.gov/Report-Card.
[2] Memorandum on Safeguarding U.S. National Interests in the Arctic and Antarctic Regions (https://www.whitehouse.gov/presidential-actions/memorandum-safeguarding-u-s-national-interests-arctic-antarctic-regions/).
[3] DOD Arctic Strategy, June 2019, p 2.
[4] Tomas Soler, David W. Eisemann, "Determination of Look Angles to Geostationary Satellites," NOAA – National Geodetic Survey.
[5] United Nations Convention on the Law of the Sea of 10 December 1982 (https://www.un.org/depts/los/convention_agreements/convention_overview_convention.htm).
[6] Unified Command Plan, 2017 Change 1, May 24, 2019, p.11.
[7] Daniel Kochis, James Di Pane, "Designating EUCOM Lead Combatant Command in the Arctic Will Better Protect U.S. Interests," The Heritage Foundation, December 17, 2017.
[8] S.3080 - Strategic Arctic Naval Focus Act of 2019 (https://www.congress.gov/bill/116th-congress/senate-bill/3080/text).
[9] Hoogensen, 2020. Routledge Handbook of Arctic Security, p. 156.
[10] United Nations (https://www.un.org/depts/los/convention_agreements/texts/unclos/unclos_e.pdf).
[11] Arctic Council (https://arctic-council.org/en/about/).
[12] The Arctic Council was founded with the "Declaration of the Establishment of the Arctic Council" in Ottawa, Canada in 1996 – referred to as the "Ottawa Declaration."
[13] Arctic Council (https://arctic-council.org/en/).
[14] Ibid.
[15] Somini Sengupta, "United States Rattles Arctic Talks with a Sharp Waring to China and Russia," *New York Times*; September 13, 2019.
[16] Webinar interview and discussion with Troy Bouffard and authors; August 7, 2020.
[17] Memorandum on Safeguarding U.S. National Interests in the Arctic and Antarctic Regions (https://www.whitehouse.gov/presidential-actions/memorandum-safeguarding-u-s-national-interests-arctic-antarctic-regions/).
[18] Ibid.
[19] Joint Publication 3-14, "Space Operations," April 10, 2018.
[20] Valerie Insinna, "Armed with a New Arctic strategy, the Air Force Seeks Increased Connectivity in the Region," *Defense News*; July 21, 2020.
[21] Reuters – Business News; "China Unveils Vision for 'Polar Silk Road' across Arctic," January 26, 2018.
[22] DoD Report to Congress: Military and Security Developments Involving the People's Republic of China 2019, p.114.
[23] J. Daooy, "The Arctic: Securing the High Ground," National Security Institute, December 2019, p. 21,
[24] Non-arctic States, The Arctic Council (https://arctic-council.org/en/about/observers/non-arctic-states/).
[25] AsiaNews.it, "Research and Development: China and Russia on the Arctic Silk Road," May 20, 2019.
[26] The Department of Defense Arctic Strategy, June 2019, retrieved from https://media.defense.gov/2019/Jun/06/2002141657/-1/-1/1/2019-DOD-ARCTIC-STRATEGY.PDF, p.5.
[27] Matthew Melino, Heather Conley; CSIS; "The Ice Curtain: Russia's Arctic Military Presence," 2020.
[28] David Auerswald, "Now is the Not the Time for a FONOP in the Arctic," War on the Rocks; October 11, 2019.
[29] Department of Defense Arctic Strategy, p. 4.
[30] With permission from: Malte Humpert/The Arctic Institute (7 July 2020); Col. Michael J. Forsyth who further adapted with additional landmarks, "Why Alaska and the Arctic are Critical to the National Security of the United States." Military Review, January-February 2018, Lina Cashin, The Aerospace Corporation further adapted landmarks.
[31] Russ Read, "NORTHCOM Commander Warns the Arctic is an 'Avenue of Approach' for Russia," *Washington Examiner*, July 22, 2019.
[32] Office of the Under Secretary of Defense for Policy; "Report to Congress Department of Defense Arctic Strategy," June 2019.
[33] "Russia Unveils Arctic Ambitions With 2035 Strategy," *Moscow Times*, March 6, 2020.
[34] Department of Defense, "Indo-Pacific Strategy Report: Preparedness, Partnerships, and Promoting a Networked Region," June 1, 2019.
[35] Mary Ilyushina, "Russia accuses leading Arctic researcher of spying for China," *CNN*, June 17, 2020.
[36] Christopher Weidacher Hsiung, "The Emergence of a Sino-Russian Economic Partnership in the Arctic?" The Arctic Institute; May 19, 2020.
[37] Blake Hounshell, "Pompeo Aims to Counter China's Ambitions in the Arctic," *Politico*, May 6, 2019.
[38] Sarah Lohschelder, "Chinese Domestic Law in the South China Sea," Center for Strategic and International Studies
[39] Senator Lisa Murkowski; "The U.S. Air Force Arctic Strategy, Alaska, and the New Arctic: A Conversation with Alaska's Senator"; The Wilson Center, Webcast, September 14, 2020.
[40] Joint Publication 3-14, Space Operations, April 10, 2018, p. I-4.

[41] Caleb Henry, “British Government and Bharti Global buy OneWeb, Plan $1 Billion Investment to Revive Company,” *SpaceNews*, July 3, 2020.
[42] Interview with Bruce Kraselksy, Legal, Regulatory, Strategic Planning with Pacific DataPort, June 28, 2020.
[43] Space Norway (https://spacenorway.no/home/).
[44] Nathan Stout, “Space Force’s Stopgap Polar Communications System Passes Another Milestone,” *C4ISRnet*, July 10, 2020.
[45] Lewis Wynn-Jones, “Is There a Difference Between Open Data and Public Data?” September 2019.
[46] Mariel John Borowitz, “Open Space: The Global Effort for Open Access to Environmental Satellite Data,” Massachusetts Institute of Technology, 2017.
[47] Marcus Weisgerber, Global Defense Spending Decline Expected as Nations Deal with Coronavirus,” Defense One, April 28, 2020.
[48] “Department of the Air Force’s Arctic Strategy,” July 21, 2020.
[49] Lorrie A. Davis, *Pre-Contract Award Study Schedule Study,* TOR-2016-01191, The Aerospace Corporation, February 2016, limited distribution.
[50] Jacqueline M. Wyrwitzke, *Why Does It Take So Long?* Aerospace Report Number TOR-2018-00183, The Aerospace Corporation, October 2017, limited distribution.
[51] “L3Harris developing a constellation of small spy satellites for U.S. Air Force,” *SpaceNews* (https://spacenews.com/l3harris-developing-a-constellation-of-small-spy-satellites-for-u-s-air-force/).
[52] Michael Gleason, Charity Weedon; “Alliance Rationales & Roadblocks: A U.S. – Canada Space Study,” April 2018. (https://aerospace.org/sites/default/files/2018-05/US-Canada_0.pdf).
[53] Nancy Teeple interview, July 29, 2020, Adjunct Assistant Professor and Research Associate, Department of Political Science, Royal Military College of Canada , Fulbright Canada Research Chair in Peace and War Studies, Norwich University, Vermont.|

Section 2
Expanding Frontiers

- To the Moon and Beyond: Challenges and Opportunities for NASA's Artemis Program
- Cislunar Development: What to Build and Why
- Human Space Flight Safety: Regulatory Issues and Mitigating Concepts
- Emerging Issues in New Space Services: Technology, Law, and Regulatory Oversight
- Public-Private Partnerships: Stimulating Innovation in the Space Sector

TO THE MOON AND BEYOND: CHALLENGES AND OPPORTUNITIES FOR NASA'S ARTEMIS PROGRAM

Angie P. Bukley

In just the next few months, multiple critical decisions will affect human exploration plans of the National Aeronautics and Space Administration (NASA). The FY21 budget cycle will shape significant aspects of the content and pace of NASA space programs and may make already ambitious exploration timelines unachievable. Even an extended continuing resolution, delaying the start of FY21 budget levels, could put current goals out of reach, as would flat funding levels. The continued effects of the novel coronavirus have already delayed progress on NASA programs in general, devastating the broad economy that furnishes the resources for NASA exploration activities. The outcome of the 2020 election may also affect the direction agencies and departments take from January 2021 onward.

The Trump administration has challenged NASA to return humans to the moon by 2024 with the goal of eventually sending astronauts to Mars.[1] To respond to the President's challenge, the NASA Artemis program has been established with the primary goal of landing the first woman and the next man on the surface of the moon before the end of 2024.[2]

The focus of this paper will be on NASA human exploration beyond low Earth orbit (LEO), specifically missions to the moon and beyond. In the following pages, a review of the path back to the moon, from the end of Apollo up until the present time, is provided. Recent exploration initiatives are explained, including the participation of the commercial sector. The importance of the Artemis program in the moon-to-Mars planning is discussed. The Findings section includes assessments of management and technical challenges, and policy points with opportunities highlighted in the closing section.

Introduction

There has recently been a proliferation of new space companies and legacy organizations offering new and innovative launch vehicles, small but capable spacecraft, instruments, and other space-enabled products, services, and capabilities. These new technologies and systems, coupled with NASA's now decade-long demonstrated success in incorporating commercial efforts, point to the commercial sector having a strong potential to impact the path upon which NASA embarks to realize its human space exploration goals. Commercial space companies are foreseen to play a significant role in returning U.S. astronauts to the moon and on to Mars.

The administration has directed that both international and private sector partners be included in pursuing the moon and Mars exploration goals.[3] How the implementation of international and commercial partnerships and collaborations will be accomplished, along with the associated challenges, is still taking shape. Planning program milestones for the lunar return, as well as what we do on the moon after we return, requires that key decisions be made now and in the very near future. Areas of particularly high importance include refining the Artemis integration plans and the concept of operations for lunar surface missions. What we can leverage from lunar exploration, especially in the realm of extended surface operations on another planet, which humans have never done, must be objectively assessed in terms of how the experience and common elements transfer to exploring Mars and beyond.

The elements comprising the Artemis architecture are already under development. The Space Launch System (SLS) and the Orion Multi-Purpose Crew Vehicle (Orion) represent significant agency investments in the overall NASA portfolio of 25 major projects. A major project is defined as one with a lifecycle cost of over $250 million. Major projects comprise by far the majority of the NASA budget.[4] According to the U.S. Government Accountability Office (GAO) report on NASA, published in April 2020, the current portfolio continued to experience significant cost and schedule growth this year, as it has over the last three years, with performance expected to continue degrading. Cost growth for 2020 is approximately 31 percent over baseline and has been increasing steadily since 2017. NASA is doing slightly better this year than last in terms of launch delays, with the average delay being 12 months, rather than 13.

Given NASA's track record of cost and schedule overruns,[5] the GAO findings show that both SLS and Orion have underreported their cost growth. The Artemis I launch date has yet to be firmly established, which likely means additional cost increases and schedule delays as it slips further into the future.

The Path Back to the Moon

Since the final mission of the Apollo program in 1972, the United States has initiated three major programs aimed at returning humans to the moon and beyond. In 1989, on the 20th anniversary of the Apollo 11 landing, George H.W. Bush announced what came to be called the Space Exploration Initiative (SEI).[6] This initiative comprised three major elements, including constructing the Space Station Freedom (announced by President Ronald Reagan in 1984), returning to the moon "to stay," and sending humans to explore Mars. Following the president's announcement, Richard Truly, then the NASA Administrator, directed the agency to embark on a 90-day study[7] to ascertain what such a program would cost and how long it would take to realize. The bottom line was that the estimated cost of the program would be approximately $500 billion spread over 20 to 30 years. The NASA cost estimate caused consternation in both Congress and the White House, both of which were critical of the plan.[8] The SEI ended in 1993 under the Clinton administration. However, the plan to build a space station evolved into what is now the International Space Station (ISS), which includes participation from Russia, Japan, Canada, and the European Space Agency.

The second major U.S. program meant to return humans to the moon was established during the George W. Bush administration. The Constellation Program[9] was a response to the goals set out in the Vision for Space Exploration (VSE),[10] which was announced by President Bush in January 2004, partially in response to the Space Shuttle Columbia disaster as well as to foment enthusiasm for space exploration. It is important to remember that the VSE also set the goals of completing the ISS and retiring the Space Shuttle by 2010, and developing a new Crew Exploration Vehicle, or CEV (now Orion), by 2008.

The goals of the Constellation Program were essentially the same as those set out in the SEI; however, the first goal became completing the International Space Station by 2010. The program also aimed to send humans back to the moon no later than 2020, with the ultimate goal of sending a crewed vehicle to Mars. The NASA Authorization Act of 2005 was based on the results of the Exploration Systems Architecture Study,[11] led by then NASA Administrator Michael Griffin. The act reshaped the goals laid out in the VSE with Constellation initiated in 2005. The launch vehicles were named Ares, the crew vehicle was called Orion (which continues today), and Altair would be the vehicle taking astronauts to the surface of the moon. The Constellation Program was cancelled after the 2009 Augustine Committee concluded that the program was behind schedule and could not be completed without a significant injection of additional funding. President Obama made the decision to cancel the program, which was terminated in October 2010, when he signed the NASA Authorization Act of 2010.[12]

In 2011, the super-heavy lift Space Launch System (SLS), which replaced the Constellation Ares V, was initiated. SLS was to replace the Space Shuttle as the NASA flagship vehicle, carrying both crew and cargo. The path for planned SLS evolution is shown in Figure 1. It represents the largest development of a space launch system undertaken by NASA since the beginning of the Space Shuttle program nearly 50 years ago. Congress mandated that SLS is to follow the design of Ares V and make use of Space Shuttle heritage components, which significantly constrained its design, but also provided continuity for work at various NASA centers and contractors. Development of the Orion crew vehicle continued, and Constellation morphed into the Exploration Systems Development (ESD) program that was working towards again landing humans on the moon by the late 2020s.[13]

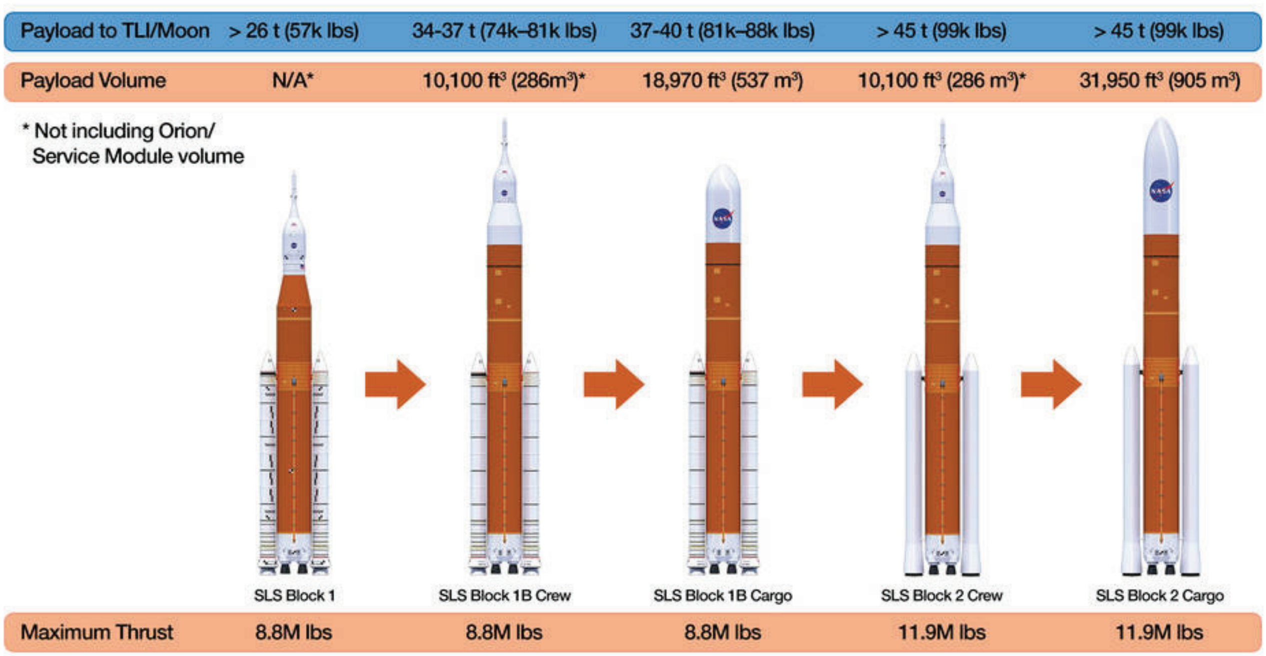


Figure 1: Planned evolutionary path for SLS Block 1 through Block 2 Cargo. *The first copy of Block 1 is in test with a new expected launch date no sooner than November 2021. (Courtesy of NASA)*

Recent Exploration Initiatives

The Trump administration has been relatively active in the domain of space policy. The National Space Council (NSpC), established by the George H. W. Bush administration in 1989 as a modified version of the earlier National Aeronautics and Space Council (1958–1973), was re-established by the Trump administration by Executive Order in 2017.[14] Chaired by the Vice President, the NSpC functions primarily as a policy development body. Civil, commercial, national security, and international space policy matters are all handled by the NSpC, the members of which are cabinet-level officials supported by a small staff and the Users' Advisory Group, which comprises non-government experts. The NASA Administrator also sits on the Council. Working with the NSpC, the administration issued four Space Policy Directives in its first three years and a National Space Strategy in March 2018.

The Next Moon-Mars Program is Officially Endorsed and Accelerated. On December 11, 2017, the Trump administration issued a Presidential Memorandum, referred to as Space Policy Directive-1 (SPD-1), with the subject line "Reinvigorating America's Human Space Exploration Program." SPD-1 amended Presidential Policy Directive-4 of June 28, 2010 (National Space Policy) by replacing the paragraph beginning "Set far-reaching exploration milestones" with the words:

> Lead an innovative and sustainable program of exploration with commercial and international partners to enable human expansion across the solar system and to bring back to Earth new knowledge and opportunities. Beginning with missions beyond low-Earth orbit, the United States will lead the return of humans to the Moon for long-term exploration and utilization, followed by human missions to Mars and other destinations.

The seeds were thus planted for the next exploration missions to the moon and on to Mars. The SPD-1 document endorsed the ESD program with the goal of sending humans to the moon by 2028. The first mission, which would be an uncrewed swing around the moon comprised of the Orion, the European Service Module (ESM), and the SLS, was known as Exploration Mission-1 (EM-1). That mission would be followed by EM-2, a crewed mission that would again make a pass around the Moon and return to Earth. EM-3 would be humans on the Moon. It should be noted that the ESD budget was capped at $3 billion per year.

About 15 months later, on March 26, 2019, Vice President Pence surprised almost all concerned when he announced to the crowd at the NASA Marshall Space Flight Center, during the fifth meeting of the NSpC, that the U.S. would land "the first woman and the next man" on the surface of the moon by 2024. He further stated that getting there by 2028 "is not good enough" and that "we can do better than that." The lunar exploration program was summarily kicked into high gear. In May 2019, the name Artemis, twin sister of Apollo, was chosen for the program.

Artemis

The Artemis program is marching forward to fulfill the goals set out in SPD-1 on an accelerated schedule, returning humans to the moon and eventually to Mars. Specifically, the program is to land humans on the moon by 2024, create a sustainable human presence by 2028, and proceed towards the ultimate goal of exploring Mars in the 2030s. Artemis leverages the elements that were under development during ESD, including the SLS, Orion, and the Exploration Ground Systems (EGS).[15] The missions planned under ESD were renamed Artemis I, Artemis II, and Artemis III. The Artemis system architecture now comprises the Orion crew vehicle (Figure 2), the SLS, Gateway, the Exploration Ground Systems, the Human Landing System (Figure 3), and advanced Artemis Generation spacesuits.[16] Implicit in the architecture is the ESM, which will be integrated with Orion for all three of the Artemis missions on the books. The program will leverage the Commercial Lunar Payload Services (CLPS) program in which commercially provided lunar landers transport various types of payloads to the lunar surface as well as potentially placing them in lunar orbit. CLPS plans to eventually deliver an unpressurized lunar rover to the lunar surface, as well.

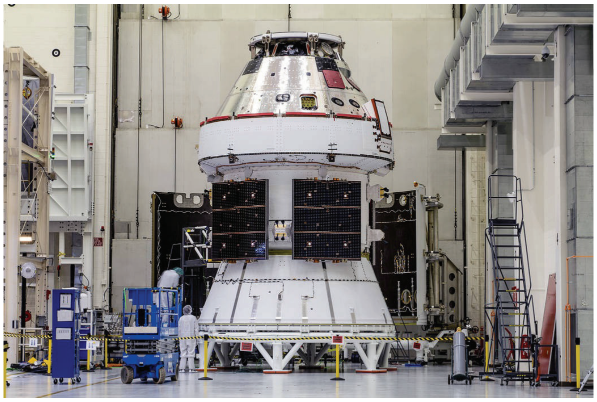


Figure 2: Orion crew vehicle with solar panels attached.
(Courtesy of NASA)

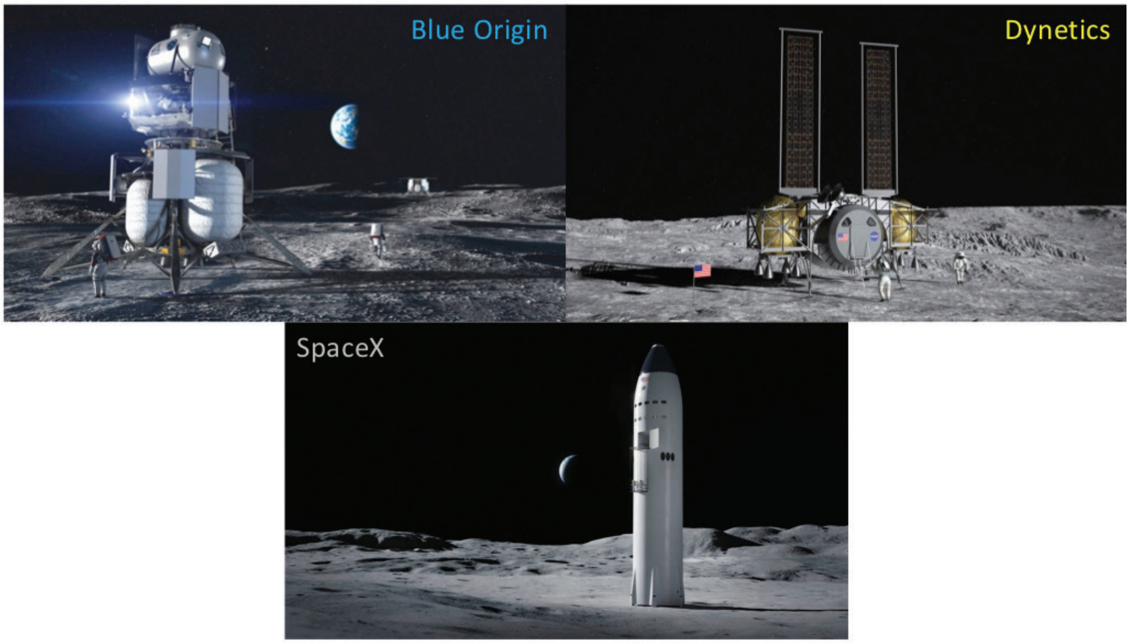


Figure 3: The three selected concepts for the Human Landing System. *(Courtesy of NASA)*

Both Orion and SLS have been in development since well before SPD-1 was issued as they are derivatives from the Constellation Program. Gateway (Figure 4), a lunar orbiting outpost formerly known as the Deep Space Gateway and then renamed the Lunar Orbiting Platform-Gateway in 2018, has been under study in one form or another since NASA made public a plan for a cislunar station in 2012 called the Deep Space Habitat. The development of these elements has not been without challenges.

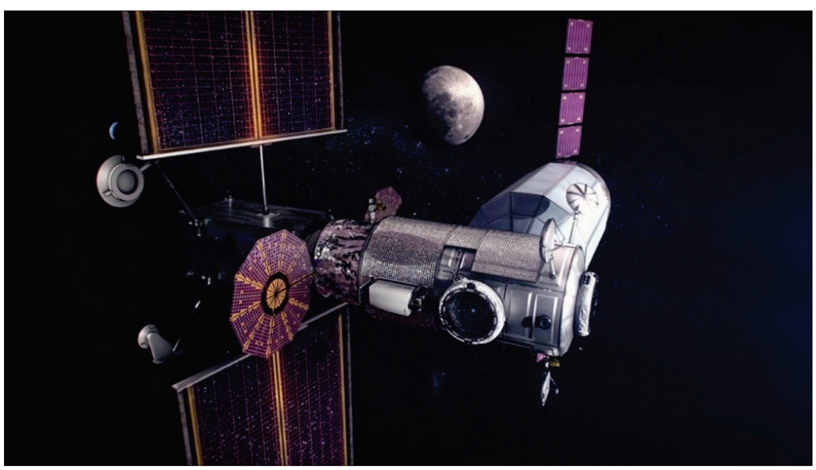


Figure 4: Concept artwork of the initial Gateway configuration comprising the Power and Propulsion Element (PPE), Habitat and Logistics Outpost (HALO), and a notional HLS. *(Courtesy of NASA)*

Artemis System Architecture Elements. Referring to the collection of elements that will comprise the Artemis missions as an architecture is an overstatement because a formal Artemis systems engineering and integration (SE&I) plan is missing.[17] The SLS and Orion implementation efforts have been underway for quite some time, as has the ground systems development. These elements, which are systems in themselves, have been on independent development tracks with their own SE&I at the piece-part hardware element level. The elements are being brought together in a bottoms-up fashion loosely tied together with 18 requirements at the NASA Headquarters (HQ) Human Exploration and Operations

Mission Directorate (HEOMD) level, which were selected based on synchronization points where hardware elements come together. There is essentially no SE&I plan associated with integration of all of these elements into one functioning system of systems.

Table 1 provides short descriptions of the NASA-developed Artemis architecture elements along with the development status of each based on the GAO 2020 report and reports on the SLS and Orion recently published by the NASA Office of Inspector General.[18,19] The information in the table provides a recent snapshot of the Artemis elements status.

The Artemis Accords. The Artemis Accords,[20] issued in May 2020, are intended to establish a means for safe and cooperative development of space resources. Because international partnerships will play a key role in achieving a sustainable and robust presence on the moon while preparing to conduct a historic human mission to Mars, such an agreement is necessary. There will be numerous international and private sector players conducting missions and operations in cislunar space; therefore it is critical to establish a common set of principles to govern the civil exploration and use of outer space. Space agencies joining NASA in the Artemis program will do so by executing bilateral Artemis Accords agreements, which will describe a shared vision for principles, grounded in the Outer Space Treaty of 1967, to create a safe and transparent environment which facilitates exploration, science, and commercial activities.

The Artemis Accords are similar to the Intergovernmental Agreements (IGA) that were executed between the U.S. and the international partners on the ISS.[21] NASA desires that all of the ISS partners participate, including Canada, Japan, Russia, and the countries in the European Space Agency (ESA). The Artemis Accords have been developed in consultation with the U.S. Department of State to cover operations *on the lunar surface*. The administration argues that the 10 principles in the accords are grounded in the 1967 Outer Space Treaty and that they cover the following:

- Peaceful purposes
- Transparency
- Interoperability
- Emergency assistance
- Registration of space objects (applies to Earth orbit as well as at the moon)
- Release of scientific data (in a timely manner, for free)
- Protecting heritage
- Space resources (extraction and utilization allowed)
- Deconfliction of activities (operate with due regard, establish safety zones)
- Orbital debris and spacecraft disposal

The accords are meant to cover activities on the surface of the moon, so the international partners involved with Gateway are not expected to abide by them. Russia is already pushing back on the U.S. position that companies should have rights to space resources. In fact, NASA had hopes for Russia to provide an airlock for Gateway, but the country has declared that it will not be participating in the Artemis moon program. "For the United States, this right now is a big political project. With the lunar project, we are observing our American partners retreat from principles of cooperation and mutual support," said Dmitry Rogozin, head of Roscomos (the Russian space organization), in an interview translated by CNBC.[22] Rogozin further stated that Russia and China intend to lead the development of a lunar science base. China is apparently reviewing preliminary studies for a crewed lunar landing mission in the 2030s with the possibility of the construction of an outpost near the lunar south pole with international cooperation.[23]

Table 1: Summary of the Artemis Architecture Elements					
Heritage	**Status**	**Original FD Estimate**	**Current FD Estimate**	**ABC or Initial Estimate**	**Cost Through FY2020**
SPACE LAUNCH SYSTEM (Marshall Flight Center)					
Ares V from the Constellation program, Space Shuttle	• Contracts awarded to Boeing, Northrop Grumman, and Aerojet-Rocketdyne in 2011-2012. • Boeing Core Stage is in testing at the NASA Stennis Space Center. • Northrop Grumman completed the Shuttle-derived solid rocket motor boosters for Artemis I; now working on motors for Artemis II. • Aerojet-Rocketdyne upgraded and tested the 16 RS-25 Space Shuttle engines in inventory. • The Interim Cryogenic Propulsion Stage (ICPS) derived from the Delta IV cryogenic second stage delivered to KSC. • A complete SLS Block 1 unit has not yet been integrated.	Artemis I November 2018	Artemis I November 2021	$9.7B	$18.6B

Table 1: Summary of the Artemis Architecture Elements

Heritage	Status	Original FD Estimate	Current FD Estimate	ABC or Initial Estimate	Cost Through FY2020
ORION (Johnson Space Center)					
Constellation Crew Exploration Vehicle (conceptualized in 2005)	• Original contract with Lockheed-Martin initiated in 2006 for $3.8B • Three successful test flights: Pad Abort-1 in May 2010 at White Sands tested Launch Abort System; Exploration Flight Test-1 December 2014 (launched on a Delta IV, two Earth orbits); and Ascent-Abort (AA-2) in July 2019 tested the launch abort system and other Orion subsystems. • Artemis I unit in testing; work proceeding on Artemis II unit	Original construction goal was 2008	Artemis I vehicle is in test, Launch November 2021	$6.2B (2012)	$13.7B ($18.7B since 2006)
EXPLORATION GROUND SYSTEMS (Kennedy Space Center)					
Saturn V, Shuttle, ESD	• Infrastructure to support different kinds of spacecraft and rockets that are in development, including the Artemis launches and commercial • Upgrading Launch Pad 39B, the crawler-transporters, the Vehicle Assembly Building (VAB), the Launch Control Center's Young-Crippen Firing Room 1, mobile launcher (ML), and other facilities • EGS ready to support Artemis I launch as soon as November 2020	Schedule follows Artemis I launch date	Schedule follows Artemis I launch date	$2.8B	$3.3B

Table 1: Summary of the Artemis Architecture Elements					
Heritage	**Status**	**Original FD Estimate**	**Current FD Estimate**	**ABC or Initial Estimate**	**Cost Through FY2020**
HUMAN LANDING SYSTEM (Marshall Space Flight Center)					
New Designs	• July 2019 MSFC named lead center for developing Lunar Landers (HLS) • Using Broad Agency Announcement for procurement for design and development by U.S. companies • Three companies selected April 2020 (Blue Origin, Dynetics, and SpaceX), three different concepts, total value of the three contracts is $967M to initiate the work[24]	2024	Schedule follows Artemis III	Project just initiated	~$18B through 2024 based on 2021 PBR
GATEWAY (Johnson Space Center)					
2012 Deep Space Habitat; 2017 Deep Space Gateway; 2018 Lunar Orbiting Platform-Gateway (Gateway)	• PPE - Contract awarded to Maxar Technologies May 2019.[25] PPE under direction of Glenn Research Center. $375M, but already increasing.[26] • First U.S. commercial provider for Gateway Logistics Services - contract awarded to SpaceX in March 2020.[27] • HALO contract awarded to Northrop Grumman June 2020. $187M.[28] • Planned International Cooperation with Canada (robotic arm), Japan (habitat and research capacity), and the European Space Agency (refueling and communications hardware).	PPE and HALO launched together November 2023 on commercial launch vehicle	TBD	Project just initiated	~$2.3B through 2024 based on 2021 PBR

Table 1: Summary of the Artemis Architecture Elements					
Heritage	**Status**	**Original FD Estimate**	**Current FD Estimate**	**ABC or Initial Estimate**	**Cost Through FY2020**
ARTEMIS GENERATION SPACE SUITS (Johnson Space Center)					
Extra-vehicular Mobility Unit (EMU) – Shuttle and ISS; Exploration EMU (xEMU) – ISS 	• Exploration Extra-Vehicular Activity (xEVA) comprises the Artemis Generation Suits, vehicle interfaces, and tools. • Suit based on xEMU which has been in development to replace LEO suits, which are 40 years old. • NASA is doing an "in-house" build at JSC – Jacobs is the contractor building the suits as Government Furnished Equipment. • After the first 10, an RFP will be issued for competitive procurement • xEMU originally funded from ISS budget – now funded from Gateway.	November 2023	TBD	Unknown	Development cost estimated to be between \$300M and \$500M

Notes:

a. FD is flight date.
b. ABC is the Agency Baseline Commitment or the original estimated budget.
c. Cost through FY2020 is what has been committed in real-year dollars.
d. The lead NASA centers are indicated parenthetically.

Moon to Mars

One of the defining characteristics of the Artemis program is the push to use experience gained on the surface of the moon to inform the technologies, operations concepts, and policies that will be needed to explore Mars beginning as early as the 2030s. This is important to ensure successful Mars missions, as there are limitations to existing analogs or other opportunities from which relevant experience can be gained.

The NASA Human Research Program (HRP) is prioritizing research to address the top five hazards to crew during spaceflight.[29] These include:

1. **Space radiation**, which increases cancer risk.
2. **Isolation and confinement**, which can cause sleep loss, cardiac desynchronization with work overload leading to performance degradation.
3. **Distance from Earth**, which means that detailed forward planning and exploration systems self-sufficiency are of paramount importance.
4. **Reduced gravity environment**, which will range from zero-g en route to 0.38 g on the surface of Mars, the effects of which are not well understood for longer surface stays.
5. **Hostile and closed environments**, which is a result of the environment inside the spacecraft and surface modules, including things like temperature, humidity, atmospheric composition and pressure, noise, lighting, and space available.

NASA and other space agencies have undertaken robotic missions to Mars to better understand the Martian environment. In fact, three missions just launched in July 2020 including the Perseverance rover mission from the U.S., which includes the Ingenuity helicopter; the Hope orbiter developed by the United Arab Emirates and launched by Japan; and the Chinese Tianwen-1, comprising an orbiter, lander, and rover. Altogether a total of 55 attempted robotic missions have been sent to Mars by eight nations, 28 of which were successful. From those successful missions, much has been learned about the planet. However, there is still much more to learn before humans set foot on the Martian surface.

NASA is now working on the development of six key technologies[30] required to send humans to Mars. More powerful propulsion systems are required to take humans there and back again more quickly, thereby reducing radiation, isolation, and physiological risks from low gravity, among others. Propulsion options may include nuclear electric and nuclear thermal propulsion systems. Another key technology is a deployable entry, descent, and landing system, which has an inflatable heat shield that will provide the protection required upon entering the Mars atmosphere but will not take up as much mass and volume on the space vehicle as would a rigid heat shield. The next generation spacesuit, the xEMU, is being developed for exploring both the moon and Mars. The spacesuit is basically a custom mini-spacecraft for one person that provides all the life support systems needed to sustain and protect the astronaut. A Martian pressurized rover, which will serve as both a habitat and a means of transportation, is also being investigated. Nuclear surface power systems are also under study and development to provide efficient and reliable power systems for lunar and Martian surface operations. Finally, laser communications systems are being developed to manage the large amounts of real-time information and data, including high-definition images and video feeds that are anticipated.

A New Era for Deep Space Exploration and Development. On July 23, 2020, the White House and National Space Council released a document titled *A New Era for Deep Space Exploration and Development*[31] that lays out a new vision, an ambitious and sustainable strategy, and a definition of the role of government for U.S. space exploration. The document includes a plan to take the U.S. from working in LEO to exploring the moon and Mars as well as addressing the potential for deep space science studies. Emphasis is placed on involving commercial and private sector companies, research laboratories, universities, and international partners.

This clearly represents a movement towards a whole-of-government approach to space exploration and utilization that incorporates the timely insertion of private enterprise. For example, the commercialization and privatization of LEO activities, if successful, would free up funds for government agencies to forward the country's exploration initiatives and allow for extending government-supported space activities into cislunar space and to the moon. In due course, commercialization and privatization of human activities on the moon would then allow shifting government resources and support to living and working on the surface of Mars.

Findings

These findings are based on the information gleaned from the references cited coupled with input from NASA and Artemis experts, most of whom are former NASA officials, program managers, or scientists. The findings are divided by general subject area into programmatic and management challenges, technical challenges, and policy points.

Programmatic and Management Challenges. Based on past and current GAO and NASA IG assessments it is clear that more management attention could be directed to large programs. No doubt exacerbating the present situation in human exploration is the fact that HEOMD at NASA HQ has undergone a change in leadership three times in a little over a year. With each change of leadership comes a reorganization and reassignment of senior leaders, which takes time to resolve.

According to several experts interviewed, the Artemis program seems to be missing a strong and informed management structure that includes high-level planning functions (such as site selection boards, operations practices, flight techniques, training, the mission build sequence, control boards, system integration, and other key functions) as well as the science advisory structure. NASA management might well revisit what was required to successfully execute the Apollo missions. It is sobering to realize that the average age of the civil servants in Mission Control when Apollo 11 splashed down was 26, while Flight Director Gene Kranz had not yet reached the age of 36. The average age of NASA civil servants when Space Shuttle Atlantis launched in May 2009 was 47. Now, many experienced NASA personnel with significant "corporate knowledge" and honed management skills are retired or near retirement. Furthermore, the emphasis at NASA over the last four decades has been on operations (e.g., Space Shuttle and ISS) with the vast majority of NASA personnel being operations specialists who are more familiar with sustainment activities rather than the development of new systems. These factors lead to another management challenge regarding the transition from an operations and sustainment mode to a mission design, build, fly, and execute mode. The task that lies ahead is daunting in its complexities and would benefit from taking onboard the lessons learned during Apollo to optimally leverage state-of-the-art technology for successfully revisiting the moon and going beyond.

One NASA expert interviewed argued that the program to return Americans to the moon has been underfunded by at least $1 billion per year since the early days of ESD. In addition, the NASA budget is not stable year to year and the mission portfolio changes from administration to administration. Artemis is the third attempt to return Americans to the moon since Apollo. Regarding funding and affordability, it is unlikely that NASA can execute Artemis while continuing to fund the ISS and LEO operations at approximately $4.5 billion per year. [32,33]

Another challenge is associated with the competition amongst the NASA Centers. The main NASA-developed Artemis elements are being loosely coordinated by NASA HQ and managed out of three different centers: Marshall, Johnson, and Kennedy. The other seven centers are providing various levels of support, some managing the development of major element subsystems. (See Table 1.) This could be problematic in light of the fact that there is no overall integration plan for Artemis at the HQ/HEOMD level.

Many costs associated with Artemis are hidden, intentionally or not, as a result of the changes from Constellation to ESD to Artemis. One interesting case, as related by an individual close to the program, is that of the xEMU. Because the EMUs onboard the ISS are approaching 40 years old and experiencing all the pains associated with aging, with maintenance becoming extremely challenging, development of the xEMU began and was funded under various lines in the ISS budget. When it recently became obvious that a space suit for lunar surface operations will be needed well before 2024, the xEMU development oversight and funding was moved from ISS to Gateway to be part of the Artemis program. It has now morphed into the xEVA, which also requires the development of Gateway and HLS vehicle interfaces (donning and doffing racks, for example) and tools that the astronauts will use on the moon. With the costs of the xEMU and xEVA intertwined between two different programs spread under different funding lines and spanning more than 10 years so far, determining the actual cost will be challenging.

According to two interviewees, NASA might well consider rethinking the acquisition strategy for planned Mars missions. An honest assessment of whether the SLS is the right rocket for the mission should be undertaken. The SLS production tempo is not designed to support the two to three Block 2 launches per year needed to provide the six to eight launches required for **one** Mars mission. Block 2 is not yet under development and the need for Block 1B is already in question.

Technical Challenges. The ESD program began already constrained by Congress to use Ares V as the basis for the SLS, but without the more powerful upper stage. The Ares V was constrained to use shuttle heritage hardware. This has resulted in limitations on SLS capability. SLS development has also been fraught with numerous technical and manufacturing issues leading to schedule degradation and budget overruns.

A former NASA program manager indicated that the technical problems are further exacerbated because an Artemis systems integration plan has not been developed. In fact, said former program manager stated that the three main elements under the purview of three different NASA centers (SLS, Orion, and EGS) are expected to "self-integrate." That is, the three different management teams are to cooperate to ensure a successful integration without the benefit of an overall SE&I plan. This situation will lead directly to technical challenges if the three systems are brought together without any overarching integration plan. What happens if the interfaces are incorrect or other conflicting requirements emerge? Obviously, that would mean additional schedule pressure and increased cost.

Other technical concerns resulting from program management challenges include the lack of a concept of operations (CONOPS) for Artemis III lunar surface EVAs. According to an expert familiar with the Artemis program, the CONOPS and logistics for the 2024 mission are still unknown. Specifically, the space suits do not fit in the Orion spacecraft with the crew onboard, so there needs to be a plan for how to get them to the moon. Do they come in the HLS? Will there be a separate logistics module quickly developed to support Artemis III? It is known that the Orion will need to dock with the HLS. If the suits are not carried up in the HLS, then somehow, the astronauts will need to get the suits onboard. Given that three concepts for the HLS are being considered and nothing has yet been built, it seems that now HLS is pacing the run-up to the 2024 boots on the moon target date. There are a significant number of technical hurdles to jump to make that date. From a technical point of view, first landing in the 2028 timeframe is much more realistic, according to several experts interviewed for this paper.

Policy Points. How space exploration initiatives evolve hinges on policy decisions and implementation. The National Space Council is setting the broader U.S. space policy with this administration paying significantly more attention to space and space exploration than any in the recent past. However, perhaps the space policy decisionmakers need to take a step back with respect to space exploration and exploitation and ask a few basic questions. *Why go? What are we trying to do? What is the economic motivation for exploring the Moon and Mars? How do we achieve sustainability? How can we maximize the productivity of our time on the Moon? How can we maximize the productivity of our time on the moon? Why the accelerated timeline?* Fast does not equal sustainable. Establishing artificial deadlines forces decisions to be made. They may not be the right decisions at the end of the day if sustainability is a critical objective.

One lunar exploration expert emphasized that sustainability is a strong function of being able to harvest the needed resources for a self-sustaining lunar base. There are mountains of legal and policy challenges that need to be surmounted, and the Artemis Accords are a first step. Working through these challenges will no doubt take as much or more time than that required for the technology to develop.

From a policy perspective, there are questions regarding how to smoothly transition from LEO to exploration as well as how to incorporate lessons learned from the bumpy transitions that occurred between Apollo and the Space Shuttle Program, and then between Shuttle and the Commercial Crew Program (CCP). Specifically, in the transition from Apollo to Shuttle, significant numbers of jobs were lost with a not inconsequential economic impact. Then, when the Shuttle program ended in 2011, Kennedy Space Center was downsized and more jobs were lost, profoundly affecting the economy of the Florida's Space Coast. After Shuttle, there was a transition to the Commercial Crew Program, but that brought only modest, delayed relief to the Space Coast workforce because the program was four years behind schedule.

Another consideration during these transitions is to ensure that what is left behind remains sustainable as things move forward. Looking even farther ahead, policies need to be in place to ensure a graceful transition from sustainable moon to exploring Mars followed by sustainable Mars. NASA has seemed to struggle with transitions, according to several of the experts interviewed.

It is clear that moving to a full-up Artemis effort will likely mean not being able to support operations in LEO at the current level. Even though NASA managed to maintain the Shuttle program while developing the ISS (which depended on the Shuttle for its construction), it is not clear that without additional budget allocations both sustaining the ISS and developing Artemis at the desired pace is possible. Funding for the ISS, Commercial Resupply Services (CRS), CCP, spaceflight support, and commercial development now totals close to $4.5 billion per year.

There are two main activities to be executed on the moon: a) surface operations for sustainability and habitation that map directly to Mars exploration, and b) exploration of the lunar surface followed by development of a self-sustaining base of operations. This will take more funding than is currently committed. According to one expert, if the ISS support cost can be dropped to about $1 billion per year, then lunar exploration becomes more feasible in the immediate timeframe. A policy change coupled with clear direction to NASA to commercialize and significantly reduce the cost of LEO operations, including the ISS, are needed for current exploration plans to succeed.

The Artemis Accords are garnering praise as being a good vehicle for clarifying the interpretation of international legal principles, according to one of the experts interviewed. There are also those who are not pleased and think that turning commercial enterprise loose to exploit resources off planet is problematic. Even though currently limited to supporting the European Service Module and contributing to Gateway, there is still a fair amount of international interest in participating in Artemis, particularly from Canada, Japan, and ESA. Interest is also being expressed by the United Arab Emirates, Australia, and South Korea. As already mentioned, Russia has opted out and plans to work with China.

Building on the recently released New Era document that promotes a whole-of-government approach to space exploration, NASA and the USSF signed a memorandum of understanding on September 21, 2020.[34] The first paragraph in the background section of the document reads:

> NASA and relevant precursor organizations of the USSF share a long history of mutually beneficial cooperation that contributes to the Parties' respective civil and defense roles. Such cooperation was built on synergies in certain operational capabilities and in research and development activities in science and technology. With the historic establishment of the USSF as a new branch of the Armed Forces in December 2019 and with NASA's Artemis Program under way to land the first woman and next man on

the Moon by 2024, NASA and USSF hereby reaffirm and continue their rich legacy of collaboration in space launch, in-space operations, and space research activities, all of which contribute to the Parties' separate and distinct civil and defense endeavors.

Eleven cooperative areas are specified, including space domain awareness, near-Earth object detection, cislunar operations, search and rescue, launch support, safety standards and best practices, fundamental scientific research, interoperable space communications, and workforce sharing. This marks an important policy step in the collaborative exploration and exploitation of cislunar space. Indeed, there are commonalities among space exploration, development, and security that provide strong incentives for coordination and collaboration.

Opportunities

In spite of the management, technical, and policy challenges facing America's return to the moon and moving forward to Mars exploration, there are many opportunities ripe for exploitation. The Artemis program is different from previous programs in that it is pulling on the commercial sector to develop some of the key program elements. There are, in fact, already opportunities for the commercial sector, including CLPS, launch services, HLS, and Gateway modules. The use of commercial launch providers is foreseen in all of the architectures for operations in cislunar space and lunar surface exploration and operations.

Significant attention is now on in-situ resource utilization (ISRU) for sustaining lunar bases and refueling launch vehicles. The harvesting of water ice, heavy metals, and helium-3 are activities that would be ripe for commercial development if there is a market for those resources on the moon. Studies on ISRU and resource harvesting have been ongoing for decades. Already, companies focused on off-planet resource harvesting have come and gone. The Artemis Accords were developed to provide a framework in which these sorts of operations can be executed commercially. It seems that the government and commercial sector are in synch. Now it is time to work out if there is any "there" there.

Another *potential* market is building and launching spacecraft from the moon for exploration beyond cislunar space. *If* the resources to do this are present and *if* they can be processed in-situ, then launching spacecraft becomes much easier. There is no atmosphere, so no fairing is required. The lunar gravity well is much weaker than that of the Earth, therefore much lower thrust would be required, resulting in reduced vibrations and a less harsh launch environment. That is, *if* a way to produce spacecraft on the moon at a sufficiently attractive price point can be found. Assuming, of course, that sustainable operations and functional ISRU are possible.

Perhaps the biggest question of all is whether or not there can be a lunar-based economy. For private enterprise in space to succeed, there needs to be a value proposition and business plans to identify the needs to be filled. Just what is the next "killer app" for NASA and the commercial space enterprise? Hopefully the answers will be revealed in the coming decades as cislunar exploration marches onward.

NASA leadership, at least at a high level, is thinking of something more than just boots on the moon. They are laying out a vision that ties together Gateway with a cislunar transportation infrastructure enabling a sustained lunar presence and serving as a launching pad for Mars. Forward thinking is crucial to the success of Artemis. The leadership of NASA is enthusiastically and optimistically looking to the future.

References

[1] Mike Wall, "US to Return Astronauts to the Moon by 2024, VP Pence Says," Space.com, March 26, 2019 (https://www.space.com/us-astronauts-moon-return-by-2024.html).

[2] National Aeronautics and Space Administration, "Artemis Plan: NASA's Lunar Exploration Program Overview," *NASA.gov*, September 2020 (https://www.nasa.gov/specials/artemis/).

[3] Donald J. Trump, "Presidential Memorandum on Reinvigorating America's Human Space Exploration Program," December 11, 2017 (https://www.whitehouse.gov/presidential-actions/presidential-memorandum-reinvigorating-americas-human-space-exploration-program/).

[4] Government Accountability Office, Report to Congressional Committees, NASA Assessments of Major Projects, GAO-20-405, April 2020 (https://www.gao.gov/products/GAO-20-405).

[5] Government Accountability Office, NASA Lunar Programs: Opportunities Exist to Strengthen Analyses and Plans for Moon Landing, GAO-20-68, December 19, 2019 (https://www.gao.gov/products/GAO-20-68).

[6] National Aeronautics and Space Administration, "The Space Exploration Initiative," *NASA.gov*, October 19, 2010 (https://history.nasa.gov/sei.htm).

[7] National Aeronautics and Space Administration, "Report of the 90-Day Study on Human Exploration of the Moon and Mars," *NASA.gov*, November 1989 (https://history.nasa.gov/90_day_study.pdf).

[8] Steven Dick, "Summary of Space Exploration Initiative", *NASA.gov*, accessed July 20, 2020 (https://history.nasa.gov/seisummary.htm).

[9] John F. Connolly, "Constellation Program Overview," *NASA.gov*, October 2006 (https://www.nasa.gov/pdf/163092main_constellation_program_overview.pdf).

[10] National Aeronautics and Space Administration, "Vision for Space Exploration," *NASA.gov*, March 1, 2012 (https://history.nasa.gov/sep.htm).

[11] National Aeronautics and Space Administration, "NASA's Exploration Systems Architecture Study," *NASA.gov*, November 2005 (https://www.nasa.gov/exploration/news/ESAS_report.html).

[12] Joel Achenbach, "NASA budget for 2011 eliminates funds for crewed lunar missions," *Washington Post*, February 1, 2010 (https://www.washingtonpost.com/wp-dyn/content/article/2010/01/31/AR2010013101058.html).

[13] National Aeronautics and Space Administration, "Exploration Technology Development Program," *NASA.gov*, October 22, 2008 (https://www.nasa.gov/directorates/esmd/aboutesmd/acd/technology_dev.html).

[14] Executive Office of the President, "Executive Order 13803: Reviving the National Space Council," *FederalRegister.gov*, June 30, 2017 (https://www.federalregister.gov/documents/2017/07/07/2017-14378/reviving-the-national-space-council).

[15] National Aeronautics and Space Administration, "Exploration Ground Systems," *NASA.gov*, accessed June 20, 2020 (https://www.nasa.gov/sites/default/files/atoms/files/fs-2018-01-047-ksc-egs_program_fact_sheet.pdf).

[16] Erin Mahoney, "A Next Generation Spacesuit for the Artemis Generation of Astronauts," *NASA.gov*, October 8, 2019 (https://www.nasa.gov/feature/a-next-generation-spacesuit-for-the-artemis-generation-of-astronauts).

[17] NASA Headquarters staffer who wishes to remain anonymous.

[18] NASA Office of Inspector General, "NASA's Management of Space Launch System Program Costs and Contracts," IG-20-012, March 10, 2020.

[19] NASA Office of Inspector General, "NASA's Management of the Orion Multi-Purpose Crew Vehicle Program," IG-20-018, July 16, 2020.

[20] National Aeronautics and Space Administration, "The Artemis Accords: Principles for a Safe, Peaceful, and Prosperous Future," *NASA.gov*, accessed August 3, 2020 (https://www.nasa.gov/specials/artemis-accords/index.html).

[21] Marcia Smith, "NASA Unveils 'Artemis Accords,'" *SpacePolicyOnline.com*, May 15, 2020 (https://spacepolicyonline.com/news/nasa-unveils-artemis-accords/).

[22] Yelena Dzhanova and Michael Sheetz, "Top Russian space official dismisses NASA's moon plans, considering a lunar base with China instead," *CNBC.com*, July 15, 2020 (https://www.cnbc.com/2020/07/15/russia-space-chief-dmitry-rogozin-dismisses-nasas-moon-program-considering-china-lunar-base.html).

[23] Echo Huang, "China lays out its ambitions to colonize the moon and build a 'lunar palace,'" *Quartz*, April 26, 2018 (https://qz.com/1262581/china-lays-out-its-ambitions-to-colonize-the-moon-and-build-a-lunar-palace/).

[24] Marcia Smith, "Three Winning Bids for NASA's Human Landing System," *SpacePolicyOnline.com*, July 11, 2020 (https://spacepolicyonline.com/news/three-winning-bids-for-nasas-human-landing-system/).

[25] Karen Northon, "NASA Awards Artemis Contract for Lunar Gateway Power, Propulsion," *NASA.gov*, March 16, 2020 (https://www.nasa.gov/press-release/nasa-awards-artemis-contract-for-lunar-gateway-power-propulsion).

[26] Doug Messier, "Lunar Gateway's Power & Propulsion Element Faces Cost Increases," *ParabolicArc.com*, May 29, 2020 (http://www.parabolicarc.com/2020/05/29/lunar-gateways-power-propulsion-element-faces-cost-increases/).

[27] Sean Potter, "NASA Awards Artemis Contract for Gateway Logistics Services," *NASA.gov*, April 2, 2020 (https://www.nasa.gov/press-release/nasa-awards-artemis-contract-for-gateway-logistics-services).

[28] Katherine Brown, "NASA Awards Northrop Grumman Artemis Contract for Gateway Crew Cabin," *NASA.gov*, June 8, 2020 (https://www.nasa.gov/press-release/nasa-awards-northrop-grumman-artemis-contract-for-gateway-crew-cabin).

[29] National Aeronautics and Space Administration, "How Investing in the Moon Prepares NASA for First Human Mission to Mars," *NASA.gov*, accessed July 22, 2020 (https://www.nasa.gov/sites/default/files/atoms/files/moon-investments-prepare-us-for-mars.pdf).

[30] Loura Hall, "6 Technologies NASA is Advancing to Send Humans to Mars," *NASA.gov* , July 20, 2020 (https://www.nasa.gov/directorates/spacetech/6_Technologies_NASA_is_Advancing_to_Send_Humans_to_Mars).

[31] White House National Space Council, "A New Era for Deep Space Exploration and Development," July 23, 2020 (https://www.whitehouse.gov/wp-content/uploads/2020/07/A-New-Era-for-Space-Exploration-and-Development-07-23-2020.pdf).

[32] National Aeronautics and Space Administration, "FY 2020 Explore: Budget Estimates Briefing Book," *NASA.gov*, accessed July 22, 2020 (https://www.nasa.gov/sites/default/files/atoms/files/fy2020_summary_budget_brief.pdf).

[33] National Aeronautics and Space Administration, "FY 2021 President's Budget Request Summary," *NASA.gov*, accessed July 22, 2020 (https://www.nasa.gov/sites/default/files/atoms/files/fy2021_congressional_justification.pdf).

[34] National Aeronautics and Space Administration, "Memorandum of Understanding Between the National Aeronautics and Space Administration and the United States Space Force," September 21, 2020 (https://www.nasa.gov/sites/default/files/atoms/files/nasa_ussf_mou_21_sep_20.pdf).

Image courtesy of NASA

CENTER FOR SPACE POLICY AND STRATEGY

APRIL 2018

CISLUNAR DEVELOPMENT: WHAT TO BUILD—AND WHY

JAMES A. VEDDA
THE AEROSPACE CORPORATION

Abstract

The current administration is seeking ways to facilitate and accelerate the evolution of space commerce. At the same time, the administration plans to pursue ambitious human exploration activities beyond low Earth orbit. Both of these objectives include a key role for infrastructure in cislunar space. The administration can serve both objectives through a concerted cislunar development program. Efforts are underway in areas such as space transportation and human habitats, but a sustainable, comprehensive space infrastructure requires much more. This paper highlights some proposed development scenarios and examines the components needed to form a coherent long-term strategy that delivers permanent, sustainable, purposeful, value-generating space activity.

Springboard to the Solar System

In a 2006 speech, John Marburger, the science advisor to President George W. Bush, addressed the long-term rationale for spaceflight by saying that it boils down to "whether we want to incorporate the solar system in our economic sphere, or not… At least for now, the question has been decided in the affirmative."[1] Since that statement, slow but steady progress has been made across three presidential administrations, including the realization that multipurpose infrastructure in cislunar space[2] is a prerequisite for ambitious long-term scenarios of space exploration and development.

In December 2017, a memo from President Trump (referred to as Space Policy Directive 1) changed one paragraph in the 2010 National Space Policy, directing U.S. government agencies (particularly NASA) to

> lead an innovative and sustainable program of exploration with commercial and international partners to enable human expansion across the solar system and to bring back to Earth new knowledge and opportunities. Beginning with missions beyond low-Earth orbit, the United States will lead the return of humans to the Moon for long-term exploration and utilization, followed by human missions to Mars and other destinations.[3]

Meanwhile, the administration's revived National Space Council was devoting much of its effort to promoting and accelerating U.S. space commerce. The commercial sector has been linked for many years to the nation's exploration ambitions; its role in "incorporating the solar system into our economic sphere" has yet to be fully defined, but its highest value proposition may be development of multipurpose cislunar infrastructure in advance of the interplanetary journeys that may follow. The Trump administration and subsequent U.S. leadership may determine that the best way to achieve human expansion into space while building a space economy is by focusing on cislunar development through a combination of government programs and industry partnerships.

Space efforts spanning more than a half-century have shown that large capital outlays, long development cycles, high technical risk, and potentially unstable long-term funding commitments can be expected in such endeavors. But as with large terrestrial projects, the resources invested in space infrastructure pave the way for a multitude of missions that can use it to satisfy critical needs such as transportation, communications, energy, water, and waste management.

All space sectors—civil, commercial, and national security—share common needs for space infrastructure that will serve their missions and allow them to loosen, or even sever, the lifeline that has so far kept them dependent on Earth for all operations and support functions. The long-term reliability of that lifeline comes into question if it can offer little or no hands-on support to space systems needing attention at locations far from Earth.

Resources invested in space infrastructure pave the way for a multitude of missions…

Visions for cislunar development have been proposed by public and private stakeholders in spacefaring countries. None are comprehensive; typically, projected scenarios focus on a small subset of components needed to accomplish a particular function, such as space transportation or human habitats. There is healthy competition among solutions to some critical needs, but others receive less attention, and so far, no credible, widely accepted architecture has emerged. This indicates a need to take a step back in the planning process: before we start bending metal for an uncoordinated assortment of infrastructure elements, we need to agree on a set of common goals and objectives. Although this has been pursued internationally for many years, consensus remains elusive.

Planners understand that space infrastructure projects should be designed for broad applicability, beyond a single mission or short-term series of missions for a single agency, or even a single country (in contrast to the Apollo paradigm). However, more needs to be done to reach agreement on what the development of cislunar space should seek to achieve and what steps need to be taken, in what order, and at what pace.

A Few Examples

Cislunar activity in the next generation and beyond will be both human and robotic, government and nongovernment. For the moment, the precise mix of humans and robots, and their particular affiliation, is less important than the aggregate value derived from enterprises in cislunar space for security, the economy, scientific research, and international relations. There is no shortage of ideas, but there is insufficient agreement on steps—and funding mechanisms—leading to a comprehensive, value-generating space architecture that would allow us to "incorporate the solar system in our economic sphere." Some recent and intriguing ideas include:

- **NASA's Lunar Orbital Platform—Gateway.** Formerly Deep Space Gateway, this project envisions a crew-tended spaceport in lunar orbit for staging missions to the lunar surface and deep space. Gateway would consist of a small habitat, a power and propulsion bus, a docking system, and an airlock. Serviced by logistics modules, it could accommodate research activities as well as crews in transit.[4] Essentially, this is a smaller version of the International Space Station placed at a more distant location, and should be able to take advantage of many technical and operational lessons learned from that program.

  Gateway is one of the systems NASA hopes to build and test as it prepares for missions beyond cislunar space, particularly Mars. The deep-space environment around the moon provides a testbed for human missions headed elsewhere in the solar system. For these early building-block missions, Earth is conveniently located just days away, rather than weeks or months. The Gateway concept was associated with NASA's cislunar plans for more than a year before it was first incorporated in the president's budget request in February 2018.[5] If it is funded by Congress and brought to fruition, it will be a key element of early cislunar architecture, one piece of a much larger effort.

- **European Space Agency (ESA) Moon Village.** Johann-Dietrich Woerner, Director General of ESA and leading spokesman for the Moon Village concept, explains that the term "village" in this context does not mean "a development planned around houses, some shops, and a community center." Rather, it is "a community created when groups join forces without first sorting out every detail, instead simply coming together with a view to sharing interests and capabilities." So far, it is "neither a project nor a program."[6]

Participation in the Moon Village may take the form of robotic or human activities in scientific research, technological development, and even tourism. Activities could include placement of a radio-telescope on the far side of the moon, where interference from Earth transmissions would be blocked; experimentation with new technologies, such as in-situ manufacturing; exploitation of lunar resources; and creation of a base for testing and deploying human spaceflight systems aimed at destinations elsewhere in the solar system.

ESA has begun discussions with China regarding collaboration on the Moon Village concept.[7] This could have implications for U.S. participation in the project if it comes to fruition.

- **Space Resources Luxembourg.**[8] This is an industrial policy rather than a strategic plan for the development of cislunar space. It sets an example for other countries that are willing to take a chance on the future of a space economy by presenting a friendly political and regulatory climate. By opening its doors to space mining and resource utilization companies, "Luxembourg provides a unique legal, regulatory, and business environment enabling private investors and companies to explore and use space resources…. Luxembourg aims to play a leading role in the exploration and utilization of these resources." The country recently enacted legislation granting property rights to extracted resources from celestial bodies.[9]
- **ULA Cislunar-1000.**[10] United Launch Alliance, the most experienced U.S. launch provider, has a long-term vision for cislunar activity, based on its own transportation technology currently in development. "Thirty years from now, 1,000 people could be living and working in the space around Earth and the moon—waking up in commercial habitats, prospecting on the moon, and even harnessing power from solar power satellites for consumption on Earth." ULA believes that "the technology for a cislunar transportation system will exist early in the next decade." ULA has recognized that "there is some economic incentive to spur the creation of the first elements of infrastructure needed for a self-sustaining cislunar economy." The company expects this incentive to show results in the near term: "Developments of commercial industries in space are quickly demanding more than the ISS can provide. This includes frequent (months or better) access, return of goods, production facilities and the ability to work with dirty and risky processes. New facilities designed to support commercial activities in space are needed."
- **Space Industrialization.**[11] Blue Origin founder Jeff Bezos believes that "over the next few hundred years, we need to move our heavy industry off-planet. Our Earth will be zoned residential and light industrial." But he is not simply dreaming about something that may happen long after he is gone. "I'm using my resources to put in place heavy-lifting infrastructure so the next generation of people can have a dynamic, entrepreneurial explosion into space. I want thousands of entrepreneurs doing amazing things in space."
- **Cislunar Space Next.**[12] For many years, lunar scientist Paul Spudis has advocated a high priority for exploration of the moon and exploitation of its resources. "The real debate is not about launch vehicles or spacecraft or even destinations; it is about the long-term purpose of our space program…. A cost-effective, sustainable human spaceflight program must be continuous, incremental, and cumulative. Our space program must continually expand our reach, creating new capabilities over time. Moreover, it should contribute to compelling national economic, scientific, and security interests."[13]
- **On-Orbit Servicing.** In early 2016, Orbital ATK signed Intelsat as the first customer for its on-orbit servicing program,[14] which will extend the life of aging satellites by attaching a module to replace their propulsion systems. On-orbit repairs are also contemplated. The president of the Space Logistics LLC subsidiary, which is responsible for this effort, says the company believes "there's a real market for space logistics." The first mission for Intelsat is scheduled for 2019, and a second is planned for 2020. (Orbital ATK is active in another area related to cislunar development: the company received an award in NASA's NextSTEP program to study the design of a cislunar habitat derived from its Cygnus spacecraft.[15]) A competitor, the Space Infrastructure

Services division of Maxar Technologies, has a contract with communications satellite operator SES to perform on-orbit refueling to extend the life of a satellite in a mission scheduled for 2021.[16]

- **Global Exploration Roadmap.** The most inclusive effort leading to a cislunar architecture is being undertaken by the International Space Exploration Coordination Group (ISECG), a coalition that includes NASA, ESA, and the civil space agencies of Australia, Canada, China, France, Germany, India, Italy, Japan, Russia, South Korea, Ukraine, and the United Kingdom. ISECG has its roots in a 2007 collaboration called "The Global Exploration Strategy: Framework for Coordination."[17] The group released its first Global Exploration Roadmap in September 2011,[18] with updates in August 2013[19] and January 2018.[20] The Global Exploration Roadmap is an evolving effort to apply collective wisdom to a reasonably comprehensive vision. As civil space agencies, the ISECG members are keen on advancing science projects and human spaceflight programs. As a result, the primary emphasis is on development of space transportation architecture and human habitation systems. But they also recognize the importance of other aspects of space architecture: capabilities and infrastructure for off-Earth operations, research on planetary defense, orbital debris management, and the role of commercial entities as they create new markets that bring benefits to all humankind. Inspiring the public is also a priority.

  The ISECG approach to the Global Exploration Roadmap appears to be a welcome recognition that exploration and development go hand-in-hand; that robust, versatile, and sustainable space infrastructure must be built; and that benefits to Earth, through new markets and solutions to global problems, must be produced to justify the investment. To realize their long-term goals, all participants will need to contribute brainpower, work, and funding. Government risk-sharing and other incentives are needed to bring in private-sector contributors along with the individual and collective efforts of nations.

  Despite some refreshing words about capabilities-driven planning, however, the Global Exploration Roadmap still has the trappings of a destination-driven strategy.[21] As it has been structured so far, all roads lead to Mars, which is referred to as the "horizon" goal. This narrowing of the parameters of space exploration and development—real or perceived—carries the risk that the endeavor could be seen as an expensive prestige activity, an elaborate series of scientific field trips, or otherwise lacking long-term societal value.

Long-Term Expectations

Between now and mid-century, some predictions are a safe bet. Geosynchronous equatorial orbit will continue to be valuable. The number of operational satellites in Earth orbit, the number of different space operators, and the quantity of orbital debris all will increase. There will be a greater variety of marketable space applications, going beyond communications, navigation, and remote sensing. The forecast through 2050 gets murkier if we try to estimate the exact amount of growth in these areas, the balance between human and robotic activity, and the relative proportions of governmental and nongovernmental activity. We are compelled to rely on the safest answer to such questions: it depends.

In addition to today's familiar applications, the cislunar work environment of tomorrow may include activities for which the moon is a hub of activity. This would naturally follow from:

- one or more scientific research outposts on the moon, especially if they are populated all or most of the time;
- the extraction, processing, and use of extraterrestrial resources, primarily from the moon at first but eventually from asteroids as well;
- the use of the moon and lunar orbit as training ground and staging points for deep-space missions;
- demand for propellant storage depots in various cislunar locations (e.g., to fuel on-orbit servicing vehicles or deep-space missions) using propellants derived from lunar ice deposits;
- employment of large multipurpose orbiting platforms that would benefit from the use of lunar materials in their construction or resupply (e.g., solar power satellites, lab/manufacturing/habitat "industrial parks").

All of these drivers are accompanied by variables that affect the amount and type of traffic in cislunar space. For example:

- How many people will be needed on orbit to support this activity, and how frequently will they rotate back to Earth? This will be dependent on the evolving state of the art in life-support systems and in robotics and human-machine interfaces. Cislunar space is small enough to permit extensive use of teleoperations.
- What solutions will be employed to mitigate the cost of access to orbit? Small numbers of large, partially reusable boosters? Larger numbers of small reusable boosters? Some of both? What will be the mix of single-mission vs. multi-mission launches?
- Will there be any geopolitical obstacles to cooperation among cislunar spacefarers? Which spacefaring entities will be friends and allies, and which will be potential adversaries? How much will the entities involved attempt to conduct in-space surveillance of each other? Will terrestrial conflict prompt decision-makers to consider disruption, destruction, or hostage-taking of cislunar operations?

It is reasonable to project that in the next 20 to 30 years, global efforts in cislunar space will aim to:

- use the unique characteristics of space—such as microgravity, vacuum, high-intensity solar exposure, and isolation from Earth—to produce useful knowledge and products;
- harvest and process extraterrestrial materials and energy resources;
- build sophisticated structures in Earth orbit and in the vicinity of the moon;
- build installations on the moon, constructed to the greatest extent possible with local materials.

Success in these endeavors could produce the following results by mid-century:

- construction and operation of advanced structures that minimize their dependence on supply lines from Earth;
- aggregation of space structures into industrial parks at locations deemed valuable for their proximity to space resources, relatively stable gravitational points ("Lagrange" or "libration" points), or other attributes;
- realization of significant contributions to the terrestrial economy (through raw materials, energy, and manufactured products for use in space and on Earth) and security (through more comprehensive and accurate space surveillance and better intelligence gathering).
- Improvements in stewardship of the Earth regarding both its environment/ecosystem and planetary defense against impact threats.

Multipurpose Space Infrastructure

The rockets and spacecraft for carrying people and cargo from Earth to cislunar space are perhaps the most visible and familiar parts of a potential cislunar infrastructure. They are, however, just part of the picture. The segments of a hypothetical system that will serve all cislunar operators—the utilities that will make the system work—include a number of diverse functions and capabilities, such as:[22]

- **Inter-orbital transportation.** In the coming decades, in-space transportation could have a renaissance comparable to the experience of automobiles, ships, and aircraft in the 20th century. This will produce a wide variety of craft that are sized and specialized for particular tasks. Just as terrestrial vehicles come in an assortment of shapes and sizes, so will future space vehicles that travel between low Earth orbit, geosynchronous orbit, lunar orbit, and Lagrange points. With the ability to change orbital planes and altitudes, they will drop off and retrieve many kinds of payloads and will carry robots and humans to locations where they are needed.
- **On-orbit servicing.** If we are serious about living and working in space for the long haul, we are not going to discard our hardware every time it breaks down or runs out of propellant. Cislunar operators are going to learn how to refill the tank, replace the gaskets, and generally take actions to extend a system's life and upgrade its capabilities. This has to become routine, unlike the elaborate and expensive Hubble Space Telescope repair missions. As much as possible, the job should be done with automated or teleoperated robots. Demonstrating the robotics should be straightforward—satellite servicing will be done in a structured environment (human-made

devices working on each other), and teleoperation is an option throughout cislunar space. Such demonstrations already have begun at NASA and DARPA,[23] multiple private-sector developers are planning demonstrations by 2020,[24] and as noted earlier, two companies already have commercial contracts for on-orbit servicing.

- **Standardization.** If retrieval, repair, and refueling of space hardware is to occur, it will be facilitated by interoperability. Establishing industry standards and common interfaces will enable broad participation by a global community of space system developers. Multinational lunar activity also would benefit from a globally accepted lunar reference coordinate system, as well as emplacement of logistics and support services on the moon, such as emergency response resources and supply warehouses.

Manufacturers may need incentives to redesign their space hardware to be serviced by robots....

Manufacturers may need incentives to redesign their space hardware to be serviced by robots using common interfaces. This should be achievable at the current stage of development, since spacecraft and component manufacturers around the world are already employing standardization to service global markets. It should be a relatively simple matter to settle on standard grappling fixtures so that satellites can be captured safely and efficiently by service vehicles. Also needed are standard ports for fuel and other fluids, electric power, and data transfer. Replacement of old or malfunctioning parts could be done with modular components. Once these standards are in place, they can be carried over to modular assembly of large platforms. Orbiting fuel depots can be among the platforms benefitting from standardization. Just like terrestrial gas stations, all manner of space travelers should be able to pull up to the pump, interface their credit information, and neatly fit the dispenser nozzle into their own tank.

- **Fuel storage.** An internal NASA study in 2011 assessed the use of a fuel depot in low Earth orbit that would fill up the final stages of missions bound for the moon or points beyond, enabling a reduction in launch mass. This would require development of cryogenic fluid management, storage, and distribution systems. The study's rough cost estimates purported to show significant cost savings compared to using a government-developed heavy-lift rocket that carried all of its fuel at launch. Further analysis is required to determine whether the depot concept makes economic sense in the broader scheme of space development.

  Ultimately, the preferred locations for orbiting fuel depots may be beyond low orbit, and may get their fuel supplies from sources other than Earth. Their best customers may come from the inter-orbital traffic throughout cislunar space (for example, satellite servicing bots and reusable orbital transfer stages), with less-frequent visits from deep-space missions needing a fill-up on their way out.

- **Energy collection and distribution.** Cislunar operations will need power generation, storage, and distribution systems to satisfy their energy demands at widely dispersed locations. We have yet to determine the appropriate balance between solar, nuclear, and fuel-cell power sources, and which particular designs are best in each of these categories. Studies at NASA and elsewhere have suggested that a large power generation system (e.g., solar power satellites) could beam energy to orbiting platforms, lunar outposts, or the surface of the Earth. NASA and its partners have not conducted, or even initiated, a pilot project to demonstrate this capability in space, which must precede efforts to scale up to a sufficient size.

  During NASA's Constellation program, it was suggested that Earth-generated power might be transmitted to satisfy the demands of lunar operations. If such long-distance transmissions are contemplated, future testing and experience may lead to placement of generation facilities at other cislunar locations (such as Lagrange points L4 or L5) to provide power to facilities in the lunar neighborhood. Collaboration across sectors and among international partners will improve the political, technical, and economic feasibility of such a grand system.

- **Other space utilities.** If operations throughout cislunar space become routine, there will be a need for dedicated communications and navigation services like the ones we are accustomed to on and around Earth. Existing services are aimed at serving Earth, so additional systems are needed to serve other parts of cislunar space, where operators of all types will need secure, reliable, and scalable communications to support mission needs. Similarly, operators will need position, navigation, and timing capabilities like GPS. Growing cislunar operations cannot depend on research facilities like NASA's Deep Space Network to provide all that is needed.

  Another essential utility is space weather forecasting. Human crews living and working in high orbits or on the moon need timely warnings and analyses of solar activities that could have dire effects on their health and their technical systems. Ideally, they should have real-time links to the warning systems to avoid any delays in alerts relayed through Earth. Future human activities spread across cislunar space will have threat-determination and risk-mitigation needs that differ from the International Space Station, and may not have the luxury of around-the-clock monitoring by teams of technicians.

- **Extraterrestrial resources.** Another essential element of sustainable, long-term cislunar operations will be on-site resource extraction and utilization. Science fiction writers and real-world space planners at NASA and elsewhere have been talking about this for decades, but we are still at an early point in the learning curve for lunar and asteroid mining. How would terrestrial mining methods need to be modified for the task? Should materials be refined on site, or in a separate orbiting facility? What kinds of final products will benefit from these materials? Will the products only be used in space, or will they be marketable on Earth? These and other questions need answers before attempting something like what was suggested in the Constellation program: "Construct facilities and manufacture hardware, materials, and other infrastructure growth products and capabilities from lunar resources, to improve the productivity of lunar operations."

  Recent evidence suggests that large deposits of water ice exist in permanently shadowed craters near the poles of the moon. Before we set up a lunar economy based on use of that ice for water, oxygen, and rocket fuel, the deposits need to be located precisely and their extent has to be estimated more accurately. (For example, is the ice in large, contiguous blocks, or thousands of tiny deposits?) Then we need to figure out how to "mine" the ice in extremely harsh conditions using an appropriate mix of humans and machines. Once extracted, the ice must be transported to a facility for processing, to turn it into potable water or to separate the hydrogen and oxygen. All of this must be demonstrated before we can count on lunar ice as a critical element in the cislunar infrastructure. The resources and expertise to accomplish this will not come from NASA alone, but from some combination of U.S. government agencies, the private sector, and international partners.

We are still at an early point in the learning curve for lunar and asteroid mining….

- **Materials processing and manufacturing in space.** Although not strictly a space utility or service, an important component of "living off the land" in space is likely to be microgravity materials processing. From the space shuttle missions of the 1980s through today's experiments on the International Space Station, there has been considerable attention devoted to attempts to discover previously hidden properties of materials, take advantage of processes and conditions not available on Earth, and begin the evolution of component manufacturing in space (for example, using additive manufacturing). The research effort has always been insufficient because access to lab space on orbit is extremely limited and very expensive. As a result, the basic research phase has stretched out, and questions about which processes result in useful products, how those processes might be scaled up to industrial production levels, and whether any of this can be turned into a viable business plan remain unanswered. A key component of the economic future in space is moving away from complete reliance on Earth for materials processing and manufacturing.

Conclusion

Investment in cislunar development makes sense as a strategy for realizing stated national objectives of boosting U.S. space commerce and exploring the solar system. Priorities for the near to medium term (through mid-century) include developing the technologies, processes, expertise, and infrastructure for:

- utilizing the unique characteristics of space, such as microgravity, vacuum, high-intensity solar exposure, and isolation from Earth, to produce useful knowledge and products;
- harvesting and processing extraterrestrial materials and energy resources;
- building progressively more sophisticated structures in Earth and lunar orbits;
- building installations on the moon, constructed to the greatest extent possible with local materials;
- advancing robotic technology to minimize the need for human presence in activities that are hazardous, remote, or readily automated and to provide direct assistance to humans when required.

Broad, multi-mission application of space infrastructure is integral to cislunar development; however, much of the value of a cislunar architecture program could be lost, and its political durability jeopardized, if it is exclusively linked to limited missions that may fail to offer credible and widely accepted justification for their long-term value.

References

[1] John Marburger, keynote speech to the American Astronautical Society's 44th Robert H. Goddard Memorial Symposium (Greenbelt, MD, March 15, 2006); http://www.spaceref.com/news/viewsr.html?pid=19999.

[2] Cislunar, for the purposes of this paper, refers to the space inside the moon's orbit, lunar orbits, and Earth-moon Lagrange points.

[3] Donald J. Trump, memo on "Reinvigorating America's Human Space Exploration Program" (Dec. 11, 2017); https://www.whitehouse.gov/the-press-office/2017/12/11/presidential-memorandum-reinvigorating-americas-human-space-exploration.

[4] Kathryn Hambleton, "Deep Space Gateway to Open Opportunities for Distant Destinations," NASA Journey to Mars website (April 4, 2017); https://www.nasa.gov/feature/deep-space-gateway-to-open-opportunities-for-distant-destinations.

[5] NASA, "FY 2019 Budget Estimates" briefing (Feb. 12, 2018); https://www.nasa.gov/sites/default/files/atoms/files/nasa_fy_2019_budget_overview.pdf.

[6] Jan Woerner, "Moon Village: A vision for global cooperation and Space 4.0," European Space Agency website (2016); http://www.esa.int/About_Us/Ministerial_Council_2016/Moon_Village.

[7] "China and the European Space Agency discuss collaborating on a human outpost on the moon," *Los Angeles Times* (April 26, 2017); http://www.latimes.com/world/la-fg-china-esa-moon-village-20170426-story.html.

[8] http://www.spaceresources.public.lu/en.

[9] Jeff Foust, "Luxembourg adopts space resources law," *Space News* (July 17, 2017); http://spacenews.com/luxembourg-adopts-space-resources-law/.

[10] Bernard F. Kutter, United Launch Alliance, "Cislunar-1000: Transportation supporting a self-sustaining Space Economy," paper presented at AIAA Space 2016 (Sept. 13–16, 2016); http://www.ulalaunch.com/uploads/docs/Published_Papers/Commercial_Space/Cislunar-1000_Transportation_AIAA_Space_2016.pdf.

[11] Jillian D'Onfro, "Jeff Bezos thinks that to save the planet we'll need to move all heavy industry to space," *Business Insider* (June 1, 2016); http://www.businessinsider.com/jeff-bezos-on-blue-origin-and-space-2016-6.

[12] http://www.cislunarnext.org.

[13] http://www.spudislunarresources.com/Cislunar.pdf.

[14] Jeff Foust, "Orbital ATK signs Intelsat as first satellite servicing customer," *Space News* (April 12, 2016); http://spacenews.com/orbital-atk-signs-intelsat-as-first-satellite-servicing-customer/.

[15] Jeff Foust, "A New Chapter for Antares and Cygnus," *Space News* (Oct. 24, 2016, pp. 15-16).

[16] Sandra Erwin & Caleb Henry, "Orbital ATK lands second Intelsat satellite servicing deal," *Space News* (Jan. 4, 2018); http://spacenews.com/orbital-atk-lands-second-intelsat-satellite-servicing-deal/.

[17] ISECG, "The Global Exploration Strategy: Framework for Coordination" (April 2007); http://www.globalspaceexploration.org/wordpress/wp-content/uploads/2013/10/Global-Exploration-Strategy-framework-for-coordination.pdf.

[18] ISECG, "The Global Exploration Roadmap" (Sept. 2011); http://www.globalspaceexploration.org/wordpress/wp-content/uploads/2013/10/GER_2011.pdf.

[19] ISECG, "The Global Exploration Roadmap" (Aug. 2013); http://www.globalspaceexploration.org/wordpress/wp-content/uploads/2013/10/GER_2013.pdf.

[20] ISECG, "The Global Exploration Roadmap" (Jan. 2018); https://www.globalspaceexploration.org/wordpress/wp-content/isecg/GER_2018_small_mobile.pdf.

[21] For a more thorough discussion of the contrast between capabilities-driven and destination-driven strategies, see James A. Vedda, *Choice, Not Fate* (Xlibris, Dec. 2009) and *Becoming Spacefarers* (Xlibris, June 2012).

[22] This discussion is derived from a NASA Office of Exploration spreadsheet from December 2006 identifying 160 activities that could follow a return to the moon, and from James A. Vedda, *Becoming Spacefarers*, Chapter 11 (Xlibris, June 2012).

[23] Caleb Henry, "NASA's Restore-L contract nudges SSL closer to in-orbit servicing," *Space News* (Dec. 6, 2016); http://spacenews.com/nasas-restore-l-contract-nudges-ssl-closer-to-in-orbit-servicing/.

[24] Caleb Henry, "MDA Corp. (nearly) ready to take another run," *Space News* (Dec. 5, 2016, pp. 21-23).

HUMAN SPACEFLIGHT SAFETY: REGULATORY ISSUES AND MITIGATING CONCEPTS

Josef S. Koller and George C. Nield

Commercial spaceflight offers significant benefits to society, the economy, and national security. Financial experts project that the global space economy could significantly grow over the next few decades.[1] However, spaceflight is also a risk-prone and capital-intensive endeavor. In fact, as Congress pointed out in the Commercial Space Launch Amendments Act of 2004, "Space transportation is inherently risky."[2] That assessment is certainly reflected in the historical human spaceflight safety record. This paper explores ways to address the issues associated with the rise of commercial human spaceflight.

Introduction

Since the dawn of the space age, the United States has conducted 381 rocket launches with a person onboard (see Table 1). Four of those flights ended in tragedy: an X-15 in 1967, Space Shuttle Challenger in 1986, Space Shuttle Columbia in 2003, and SpaceShipTwo in 2014. That works out to be a fatal accident rate of approximately one percent. The fatal accident rate for commercial airlines has steadily improved over the last several decades, but in 2003, the year Columbia was lost, the rate was approximately one fatal accident for every million flights,[3] meaning that the risk of human spaceflight today is more than 10,000 times greater than the risk of flying on a commercial airliner. If we want to reap the full benefits of human spaceflight in the future, whether it be for exploration, scientific research, business, or tourism, we will need to find ways to improve the safety of those operations.

The Federal Aviation Administration (FAA) is currently under a moratorium that prohibits the issuing of regulations to protect the health and safety of crew and spaceflight participants; however, the moratorium is scheduled to end in October 2023.[4]

Table 1: Human Spaceflight Accident Statistics*		
Program	**Flights**	**Fatal Accidents**
X-15	199	1
Mercury	6	0
Gemini	10	0
Apollo	15	0
Space Shuttle	135	2
SpaceShipOne	6	0
SpaceShipTwo	9	1
Commercial Crew	1	0
Total	**381**	4

*The overall U.S. fatal accident rate is approximately one percent.

Projected Near-Term Activity

The United States is currently in the midst of a major transformation in how we operate in space. Over the next decade, there are plans for five different kinds of human spaceflight missions, four of which will be courtesy of private industry, rather than the government. The five categories are: suborbital commercial spaceflights that take off from and land at the same location, either for research purposes or for space tourism; commercial missions to low Earth orbit (LEO); NASA missions to the moon in support of the Artemis Program; commercial missions to the moon; and commercial point-to-point missions for high-speed, long-distance transportation. Some of these activities might be too ambitious to achieve over the next decade; however, they should still be taken seriously given the significant investments being made in this sector.

- ***Suborbital Commercial Spaceflights.*** Virgin Galactic's SpaceShipTwo has twice completed piloted missions that exceeded 50 miles in altitude as part of the testing required prior to the start of commercial space tourism operations.[5] Meanwhile, Blue Origin has conducted a number of suborbital missions with its New Shepard reusable launch vehicle, and flights carrying people are expected to begin within the next 12 months.[6] Although specific launch schedules have not been announced, both Virgin Galactic and Blue Origin may start regular commercial operations at a pace of about one flight every 1-2 months at first, gradually working up to approximately one flight per week over the next few years.

- ***Commercial Missions to LEO.*** On May 30, 2020, SpaceX successfully launched two NASA astronauts to the International Space Station (ISS), using a Falcon 9 rocket and a Crew Dragon spacecraft, as part of the Demo-2 certification test flight.[7] NASA will be scheduling post certification missions with SpaceX every 6-12 months that will carry four astronauts to and from the ISS.[8] Boeing is planning to conduct a test flight of its Starliner capsule on an Atlas V rocket in late 2020.[9] A crew flight test mission for Boeing will likely take place in early 2021, and if successful, would also be followed by post certification missions every 6-12 months.[10] Separately, NASA recently issued an interim directive that will allow private astronauts to make short-duration visits to the ISS, where they will be able to conduct either commercial or marketing activities.[11] In response to this directive, SpaceX recently completed an agreement with Axiom to carry private astronauts to the ISS in the second half of 2021.[12] In addition, SpaceX has signed an agreement with Space Adventures to fly customers to LEO on a free-flyer mission in late 2021 or early to mid-2022.[13]

- ***NASA Missions to the Moon.*** Artemis 2 is planned to be the first mission of the Space Launch System and Orion to carry crew, and will include a lunar fly-by. It is currently scheduled for 2023.[14] Artemis 3, currently scheduled for 2024, will be the second Artemis mission to carry crew, and will incorporate the use of a commercially developed lunar lander to allow NASA astronauts to touch down near the south pole of the moon.[15]

- ***Commercial Missions to the Moon.*** SpaceX has announced a plan to fly a space tourist on a flight around the moon, using the Starship, as early as 2023.[16] Whether that flight becomes the first in a series of commercial missions, or whether it ends up being a one-of-a-kind vehicle demonstration, remains to be seen.

- ***Commercial Orbital or Sub-orbital Point-to-Point Flights.*** Richard Branson has long spoken of his desire to operate the world's first commercial "spaceline," and Virgin Galactic recently signed a Space Act Agreement with NASA to study high-speed, long-distance transportation.[17] Although some believe that the technology necessary for conducting hypersonic flights may be a long way off, it is certainly possible that we will see some initial capabilities demonstrated in the next 10 years. As one possible example, according to Elon Musk, the Starship system that SpaceX is developing to fly astronauts to the moon and to Mars would also have the capability to fly hundreds of people from one side of the Earth to the other in less than an hour. Although many are skeptical about the ambitious development schedule, SpaceX is planning to have such a system flying by 2022.[18]

Moratorium on Human Spaceflight Regulations

As mentioned previously, the FAA is currently under a moratorium from Congress that prohibits the issuing of regulations intended to protect the health and safety of crew and spaceflight participants; however, that limitation is scheduled to expire in October 2023.[19] The moratorium was originally put in place in 2004, and was to last for eight years. The rationale was to make sure that government regulations would not stifle the industry before adequate experience had been gained to inform the development of an appropriate set of regulations. When Scaled Composites won the XPRIZE in 2004 by becoming the first private company to launch people to the edge of space, it was assumed that suborbital commercial spaceflights would begin soon afterward. At that point, the expectation was that sufficient data could be gathered by 2012 to allow the FAA to institute at least some top-level regulations. With the delay in commercial flights, Congress extended the moratorium—first until 2015, and then later until 2023, although the development of voluntary industry consensus standards was encouraged. Unfortunately, very little progress has been made in the development of industry standards, and since it is possible that Congress will decide to extend the moratorium once again, there is little incentive for industry to focus on standards development.

An alternative viewpoint is that the United States now has 59 years of experience in human spaceflight, which should be sufficient for the community to come to a consensus on what kinds of top-level safety characteristics would be desirable. Even though most of that spaceflight experience has been gained by NASA, the resulting data has been shared. With the continuing success of the Commercial Crew Program, both SpaceX and Boeing have had an opportunity to perform "clean sheet" vehicle designs, while still taking advantage of lessons learned and technical feedback from the government. If the FAA were to craft true "performance-based" regulations, rather than prescriptive ones, it should be able to avoid a situation in which the regulations limit the use of innovation and new technologies by commercial developers.

Should an accident occur before the moratorium expires, it is likely that the FAA (or perhaps some other government agency) would be directed to assume regulatory responsibility for commercial human spaceflight, even though it may not be prepared to do so. To mitigate that risk, several options should be considered in order for the FAA to prepare for the task of regulating commercial human spaceflight: (1) revising legislative language on requiring a presidential commission on accident investigations, (2) using a safety case approach for performance-based regulation, and (3) establishing a collaborative framework to create safety guidance and best practices.

Mitigation Options

Update Mishap Investigation Requirements. In response to the Space Shuttle Columbia accident, Congress included language in the NASA Authorization Act of 2005 that required the president to establish an independent, nonpartisan commission to investigate any incident that results in the loss of a space shuttle, the ISS or its operational viability, any other U.S. space vehicle carrying humans that is owned by the federal government or that is being used pursuant to a contract with the federal government, or a crew member or passenger of any space vehicle described in that section of the Act.[20] Although these provisions may have been appropriate for the space shuttle era, they have definitely outlived their usefulness and are not a good fit for the current commercial environment.

To illustrate the point, suppose that a Virgin Galactic flight of SpaceShipTwo or a Blue Origin flight of New Shepard, in addition to carrying several civilian space flight participants, is also carrying a small NASA experiment as part of a contract with the government. Should such a mission have a problem that results in the loss of the vehicle, even if there are no fatalities, the Act requires the establishment of a presidential commission to investigate the loss. Similarly, suppose that during a flight of the SpaceX Crew Dragon or the Boeing Starliner that is carrying NASA astronauts to the ISS, the space vehicle experiences an anomaly that results in the activation of the Launch Escape System. Suppose further that the capsule is rocketed to safety and lands in the water under parachutes, with the crew being rescued, but due to high winds and waves in the area, the capsule sinks (as occurred in Gus Grissom’s Mercury flight). According to the Act, a presidential commission would be required to investigate the matter. Although each of these hypothetical events would be serious and very unfortunate, it is not clear that they would warrant the time, expense, and inevitable slowdown of human spaceflight activities that would almost certainly result from a presidential commission.

The Act also specifies that no employee of the federal government shall serve as a member of the commission, nor can a member have, or have pending, a contractual relationship with NASA.[21] Such restrictions may make it very challenging to find knowledgeable and experienced members for the commission.

Based on those considerations, the Aerospace Safety Advisory Panel noted in its 2018 Annual Report, “Language in the NASA Authorization Act of 2005 requiring a Presidential Commission for independent investigations must be reviewed and revised, especially as we are on the cusp of reinitiating U.S. launch of our astronauts.”[22]

The Safety Case Approach. Government regulations are typically described as either being prescriptive or performance-based. When the original safety requirements for the Eastern and Western Ranges were crafted by the Air Force during the early days of the space age, most were very prescriptive, specifying precisely how the flight safety systems were to be designed, tested, inspected, and operated. There are a number of advantages to such an approach. For example, the contractor knows exactly what the government expects the company to do, and it is relatively easy to conduct inspections that will determine whether or not the government requirements have been met. The disadvantage of a prescriptive approach is that it becomes very difficult, if not impossible, to incorporate new technologies or innovative approaches, since they are usually not mentioned in the regulations. In recent years, performance-based regulations have become much more popular. With this approach, the government specifies what the end objective is, rather than how to achieve that objective. In general, performance-based requirements are more accommodating of new approaches and new technologies. The downside of this approach is that the contractor may not understand exactly what the government is looking for, and how to demonstrate that its system satisfies the stated requirements. The government, in turn, may have a more difficult time determining whether its requirements have been met.

One promising approach to implementing performance-based regulations is known as the *safety case methodology*. The safety case methodology is already being used by the United Kingdom’s Ministry of Defence, which defines a safety case as "a structured argument, supported by a body of evidence that provides a compelling, comprehensible, and valid case that a system is safe for a given application in a given environment."[23] To implement a safety case approach, the FAA could allow launch license applicants to choose between complying with existing regulations, or following an alternate process, which would fully implement a performance-based regulatory philosophy, along with the requirement for the launch operator to accept the responsibility for operating safely, and the necessity to advocate for safety. The alternate process would consist of a voluntary audit of the applicant's safety and risk management program, followed by the development of a safety case in which the applicant would present evidence, in the form of engineering analysis and test data, showing how public safety would be protected.

In terms of who would conduct the safety audit, the FAA could either conduct the safety audit and safety case assessment itself, or obtain the support of a knowledgeable, experienced, and independent third party to carry out those responsibilities.

A Collaborative Framework: A Space Safety Institute. The Space Safety Institute (SSI) is an organizational concept that has been discussed and promoted over the last few years.[24] It could overcome the challenges associated with performance-based regulatory approaches by mitigating some of the side effects.

For example, the SSI could be a non-profit, public-private partnership (or a similar construct) that would provide space safety expertise and support to both government and industry. Participation could be open to all interested stakeholders, including vehicle developers and operators, insurance underwriters, professional society representatives, researchers, and academia. The SSI could be administered by an independent and objective engineering organization or a federally funded research and development center (FFRDC), which would be supported by subject matter experts from partner research laboratories and academia as needed. A list of potential products and services is provided in Table 2, along with examples of various topic areas.

Table 2: Space Safety Institute Products and Services

Examples of Products and Services	Examples of Topic Areas
Independent Assessments	Launch and Reentry
Licensing Support	Rendezvous and Proximity Operations
Standards and Best Practices	Human Spaceflight Safety
Research and Technology Development	Space Situational Awareness
Infrastructure, Tools, and Data	Space Debris Mitigation
Space Traffic Management Services	Cyber Security Implementation
Safety Education and Training	Space Safety Data Sharing

An SSI would provide two major benefits to stakeholders: 1) Serve as an objective third party auditor and evaluator in reviewing "safety case" proposals prepared by launch license applicants; and 2) provide a collaborative framework that could support the development of much-needed industry consensus standards, and on a much faster pace than is possible today.

Conclusion

The 1920s are sometimes referred to as the "Golden Age of Aviation." During that period, there was plenty of barnstorming and air races, and Charles Lindbergh made his non-stop flight across the Atlantic. Perhaps someday, the 2020s will be referred to as the "Golden Age of Commercial Space." But this time, rather than a definition based on the feats of daredevil pilots and wing-walkers, perhaps that distinction will be earned based on partnerships and collaboration, and a renewed focus on improving space flight safety.

References

[1] Jeff Foust, “Commerce Department to develop new estimate of the size of the space economy,” *SpaceNews*, January 2, 2020 (https://spacenews.com/commerce-department-to-develop-new-estimate-of-the-size-of-the-space-economy/).

[2] Public Law 108-492, Sec. 2(a)(12), December 23, 2004.

[3] Aviation Safety Network, “Fatal Accidents Per Million Flights 1977-2017,” (https://www.aviation-safety.net/graphics/infographics/Fatal-Accidents-Per-Mln-Flights-1977-2017.jpg).

[4] Federal Aviation Administration, “Report to Congress: FAA Evaluation of Commercial Human Space Flight Safety Frameworks and Key Industry Indicators,” October 2016, p. 7 (https://www.faa.gov/about/plans_reports/congress/media/CSLCA_Sec111_Report_to_Congress.pdf).

[5] Meghan Bartels, “Virgin Galactic Reaches Space Again, Flies Test Passenger for 1st Time,” *Space.com*, February 22, 2019 (https://www.space.com/virgin-galactic-powered-flight-february-2019.html).

[6] Jackie Wattles, “Jeff Bezos's Blue Origin launches 12th test flight of space tourism rocket,” *CNN.com*, December 11, 2019 (https://www.cnn.com/2019/12/11/tech/blue-origin-jeff-bezos-new-shepard-test-flight-scn/index.html).

[7] Jeff Foust, “Crew Dragon in orbit after historic launch,” *SpaceNews*, May 30, 2020 (https://spacenews.com/crew-dragon-in-orbit-after-historic-launch/).

[8] NASA New Release 20-076, "NASA Announces Astronauts to Fly on SpaceX Crew-2 Mission to Space Station," July 28, 2020 (https://www.nasa.gov/press-release/nasa-announces-astronauts-to-fly-on-spacex-crew-2-mission-to-space-station).

[9] Michael Sheetz, “NASA and Boeing aim to redo Starliner spacecraft test later this year after investigating failures,” CNBC, July 7, 2020 (https://www.cnbc.com/2020/07/07/nasa-and-boeing-aim-to-redo-starliner-spacecraft-test-later-this-year.html).

[10] Stephen Clark, “Safety panel concerned about quality control on Boeing crew capsule,” *Spaceflight Now*, July 27, 2020 (https://spaceflightnow.com/2020/07/27/safety-panel-concerned-about-quality-control-on-boeing-crew-capsule/).

[11] NASA, “NASA Interim Directive (NID) on Use of International Space Station (ISS) for Commercial and Marketing Activities,” June 16, 2019 (https://www.nasa.gov/sites/default/files/atoms/files/nid_8600_121_tagged.pdf).

[12] Michael Sheetz, “SpaceX signs deal to fly 3 space tourists to the International Space Station late next year,” CNBC, March 5, 2020 (https://www.cnbc.com/2020/03/05/spacex-axiom-deal-to-fly-three-space-tourists-to-iss-in-late-2021.html#:~:text=a%20space%20hotel.-,Houston%2Dbased%20start%2Dup%20Axiom%20has%20signed%20a%20deal%20with,and%20a%20Falcon%209%20rocket).

[13] Tom Shelley, “Space Adventures Announces Agreement with SpaceX to Launch Private Citizens on the Crew Dragon Spacecraft,” Space Adventures news release, February 18, 2020 (https://spaceadventures.com/space-adventures-announces-agreement-with-spacex-to-launch-private-citizens-on-the-crew-dragon-spacecraft/).

[14] Philip Sloss, “NASA studying practice rendezvous options for Artemis 2 Orion,” *NASA Spaceflight*, June 25, 2020 (https://www.nasaspaceflight.com/2020/06/nasa-rendezvous-options-artemis-2-orion/).

[15] NASA press release, “NASA Names Companies to Develop Human Landers for Artemis Moon Missions,” April 30, 2020 (https://www.nasa.gov/press-release/nasa-names-companies-to-develop-human-landers-for-artemis-moon-missions).

[16] “Elon Musk unveils first tourist for SpaceX ’Moon loop,’” BBC, September 18, 2018 (https://www.bbc.com/news/science-environment-45550755#:~:text=Elon%20Musk's%20company%20SpaceX%20has,journey%20by%20humans%20since%201972).

[17] Darrell Etherington, “Virgin Galactic is partnering with NASA to develop supersonic point-to-point air travel,” *TechCrunch*, May 5, 2020 (https://techcrunch.com/2020/05/05/virgin-galactic-is-partnering-with-nasa-to-develop-supersonic-point-to-point-air-travel/).

[18] Tariq Malik, “Elon Musk Says SpaceX’s Giant Mars Rocket Could Fly Passengers Around Earth,” *Space.com*, September 29, 2017 (https://www.space.com/38314-elon-musk-spacex-mars-rocket-earth-travel.html).

[19] Federal Aviation Administration, “Report to Congress: FAA Evaluation of Commercial Human Space Flight Safety Frameworks and Key Industry Indicators,” October 2016, p. 7 (https://www.faa.gov/about/plans_reports/congress/media/CSLCA_Sec111_Report_to_Congress.pdf).

[20] National Aeronautics and Space Administration Authorization Act of 2005,” December 30, 2005 (https://www.congress.gov/bill/109th-congress/senate-bill/1281).

[21] Ibid.

[22] Aerospace Safety Advisory Panel, “Annual Report for 2018,” 2019, p. 30 (https://oiir.hq.nasa.gov/asap/documents/2018_ASAP_Report-TAGGED.pdf).

[23] “Acquisition Safety and Environmental Management System,” Ministry of Defense, January 31, 2020 (https://www.asems.mod.uk/guidance/posms/smp12).

[24] Tereza Pultarova, “Indepdendent body proposed to ensure commercial spaceflight safety,” *SpaceNews.com*, April 26, 2019 (https://spacenews.com/independent-body-proposed-to-ensure-commercial-spaceflight-safety/).

EMERGING ISSUES IN NEW SPACE SERVICES: TECHNOLOGY, LAW, AND REGULATORY OVERSIGHT

Josef S. Koller, Rebecca Reesman, and Tyler Way

Next-generation commercial on-orbit missions have started to include a variety of capabilities previously reserved only for governmental missions. These commercial endeavors range from radio-frequency collections and satellite servicing to planetary missions. Is the existing regulatory framework sufficient to provide oversight and compliance with our international obligations? This paper highlights some of the commercial missions starting to push the boundaries and looks at ways to address this exciting intersection between technology development, policy, and international treaties.

Overview and History

The commercial sector is developing a spectrum of on-orbit capabilities. Some of them are commercial versions of capabilities previously operated only by governments, but others are completely new. These capabilities will help to satisfy a range of needs, including inspection and maintenance of satellites, debris mitigation, science and exploration missions, and more. However, the government offices involved with regulating space are still working to update their processes and rules to better support these industries. The following section provides some examples of space activities that are starting to approach a fuzzy boundary of regulatory oversight and international obligations. The paper concludes with a list of actions that would ensure the U.S. space sector remains at the forefront by providing transparent regulation where needed, guidelines where regulation would be premature, use commercial capabilities for government missions, and invest in targeted R&D efforts.

Existing Regulatory Framework

Even as the commercial sector grows, it remains the job of governments to ensure safe and responsible behavior in space. Specifically, Article VI of the Outer Space Treaty of 1967 states, "The activities of non-governmental entities in outer space, including the moon and other celestial bodies, shall require authorization and continuing supervision by the appropriate State Party to the Treaty."[1] The manner of any derived regulation is not directly determined in the Outer Space Treaty of 1967; it is up to individual states to determine how best to regulate their space industry while adhering to the treaty. In the United States, the regulatory authorities are within the Federal Communications Commission (FCC), the Federal Aviation Administration (FAA) of the Department of Transportation, and the National Oceanic and Atmospheric Administration (NOAA) of the Department of Commerce.

FCC. The role of the FCC is to ensure communications and spectrum use in space do not interfere with terrestrial communications or other space-based communications; it also provides requirements for orbital debris mitigation in the licensing process.[2] The FCC is becoming increasingly important as more large satellite constellations in low Earth orbit (LEO) stress spectrum allocations. In some circumstances it has also become the "regulator of last resort" for novel commercial concepts that do not fit neatly into other agencies' jurisdiction, since nearly all satellite activity requires spectrum. The FCC issues licenses to operators and launch providers for the use of spectrum to communicate with their launch vehicles and satellites, as well as for any other use of spectrum such as ranging and broadcasting.

FAA. The FAA regulates commercial space transportation to ensure safety of launch and reentry. It does not have the responsibility to regulate U.S. government launches or commercial on-orbit activities; however, it *does* have the authority for integrating the launch and reentry of both government and commercial systems into the existing air traffic system. Around the time of a launch, the airspace must be restricted to ensure that there are no collisions with airplanes.[3]

NOAA. NOAA regulates space-based remote sensing operations. Prior to the May 2020 release of the *Rules on Private Remote Sensing Space Systems*, if a system were capable of imaging the Earth, it required a license; now there are exceptions to this rule, including imaging for the purpose of mission assurance.[4] Prior to the release of the May 2020 rules, NOAA had its own debris mitigation guidelines; however, NOAA now defers to the FCC on debris mitigation rules.

Fuzzy Regulatory Boundaries

Rendezvous and Proximity Operations with Satellite Servicing. The practice of rendezvous and proximity operations (RPO) has existed since the Gemini and Apollo programs, though it has mostly been employed by government spacecraft, not commercial systems. RPO generally refers to orbital maneuvers in which two spacecraft arrive at the same orbit and approach at a close distance. This rendezvous may or may not be followed by a docking procedure. On-orbit servicing is an activity that utilizes RPO and possibly docking maneuvers to employ a spectrum of capabilities. A widely agreed-upon definition of RPO does not exist, but the term generally includes non-contact support such as inspection, orbit modification and maintenance, refueling and commodities replenishment, upgrade, repair, assembly, and debris mitigation.[5]

No national or international policies explicitly regulate RPO. Article VI of the Outer Space Treaty of 1967 requires governments to provide authorization and continuing supervision of nontraditional activities, to include many proposed RPO activities. The treaty's Article VII establishes that a party that launches or procures the launching of an object into outer space is liable for the object or its "component parts" in air or in outer space.[6] The Liability Convention of 1972 expands upon the principles of liability for damage caused by space objects introduced in Article VII of the Outer Space Treaty of 1967.[7]

On-orbit activities such as communication, spectrum usage, and debris mitigation strategies require approval from the FCC. A couple of commercial companies pioneering the on-orbit servicing market are working to gain regulatory approval in a relatively ad hoc manner. Northrop Grumman's Mission Extension Vehicle (MEV) received approval from NOAA and the FCC to perform rendezvous, proximity operations, and docking with Intelsat-901 as a demonstration.[8]

Non-Earth Imaging. The scope of authority to regulate non-Earth imaging (NEI) is confusing and not easily spelled out. Some have even argued that the Department of Commerce does not have legislative authority to regulate NEI.[9] The language in the Land Remote Sensing Policy Act (51 U.S.C. 60121)[10] on regulatory authority refers to the ability to license private remote sensing space systems. In response to questions regarding this authority over NEI satellites, the Department of Commerce states, "the plain language of the Act requires a broader scope than simply intentional Earth imaging."[11] Referencing 15 CFR Part 960, NOAA defines the phrase *remote sensing space system* as "any device, instrument, or combination thereof, the space-borne platform upon which it is carried, and any related facilities capable of actively or passively sensing the Earth's surface."[12] The word *capable* is interpreted by the Department of Commerce as permitting the inclusion of NEI satellites; while their purpose is not Earth imaging, NEI systems have the capability to image the Earth.[13]

On May 20, 2020 a new rule was released by the Department of Commerce clarifying that instruments used primarily for mission assurance or other technical purposes were among the exceptions to the license requirements for Earth imaging and non-Earth imaging.[14] This would also specifically exclude the licensing of private remote sensing systems that are beyond Earth's orbit including the moon and Mars. Yet nation states are ultimately responsible for commercial activities through the Outer Space Treaty Article VI provision. If commercial space remote sensing activity extends beyond Earth orbit, some form of authorization will be required for the United States to remain consistent with our international obligations.

Space Object Ownership Issues for Active Debris Removal. Active debris removal (ADR) is the process of removing space objects ranging from small pieces of debris to large defunct satellites. The debris removal vehicle may dock with the object to retrieve it or deploy some other form of technology to guide the object out of orbit to burn up in the atmosphere. Studies conducted by The Aerospace Corporation, NASA, and the European Space Agency (ESA) revealed that the amount of debris, assuming no additional space objects are launched, will steadily rise assuming a collision rate of every ten years.[15] LEO continues to be the site of the most space traffic and thus, the location most at risk from debris collisions. Most models show[16] that efforts to mitigate the creation of debris are no longer enough and more active solutions are needed.

ADR must deal with legal issues related to the removal of debris that is not owned by the debris removal entity. At minimum, permission from the owner and the supervising nation would be required. Some questions include: can states remove debris of other states, or debris of unknown origin, without permission? How can we ensure that objects being removed are, in fact, debris and not active satellites? Should there be an international body charged with oversight of debris removal or a national clearing house to track debris removal permissions? Given those open questions, ADR will likely focus initially on intra-state activities.

Commercial Planetary Missions and Planetary Protection. Historically, only national and international space agencies have had the technological and monetary means to send satellites and probes to other planetary bodies. This is changing as companies like SpaceX develop their own Mars missions. The rise of commercial interplanetary missions will elevate the already-challenging issue of planetary protection with guidance provided through the COSPAR Planetary Protection Policy, an international, science-based guidance and standard framework. Planetary protection refers to "managing contact between terrestrial life forms and organic material from celestial bodies as it relates to adversely affecting the scientific study of these bodies, called forward contamination." Additionally, it refers to the opposite—protecting the Earth from outside contamination.[17] These issues will need to be properly accounted for as we look to send humans back to the moon and on to Mars. Eventually, they will return to Earth. However, astronauts cannot be doused in chemicals, baked at high temperatures, or irradiated to remove any foreign organism.[18]

Experts in this field have provided a number of recommendations to the U.S. government regarding planetary protection guidance for commercial companies involved in the development of interplanetary missions. Objectively the most important recommendation is the need to establish a regulatory authority for commercial companies with plans to visit other planets. This authority would be to ensure the proper planetary protection standards are maintained before and during the mission.[19] Diversifying the classifications of regions on the surfaces of celestial bodies would be important and would allow for areas of biological importance to be protected while others to be less so. For example, the poles of the lunar surface should be relatively protected due to the presence of water; however, the rest of the moon is barren and may not require as much, if any, protection.[20]

Going forward, it is important to create standards by which humans are held accountable, while also allowing for the exploration of space and search for life on other planets.

Space Flight Safety. In order for space tourism to become commonplace, there must be serious conversations about space flight safety. The FAA is currently under a congressionally initiated moratorium that prohibits the issuing of regulations to protect the health and safety of crew and space flight participants, which was intended to allow the infant industry of commercial space flight to develop prior to regulation. This moratorium is currently scheduled to end in October 2023, but Congress could adjust this date.

Since 2006, the FAA has had regulations in place to ensure that space flight participants are made aware of risks and that they are provided with the minimum safety standards to prevent death upon entry into space.[21] If space tourism is going to be a common occurrence in the future, spacecraft must be adapted for participants who do not meet the physical qualifications of a professional astronaut. Should an anomaly occur during a commercial space flight, it is likely that the FAA would be directed by congressional oversight committees or the administration to immediately assume regulatory responsibility.

Commercial Radio-Frequency Collection. Space-based commercial radio-frequency (RF) collection systems are designed to detect and geolocate a range of RF signals from emitters of interest, such as handheld radios, maritime radar systems, automated information system beacons, very small aperture terminals, and emergency beacons. The detected signals can also be processed and analyzed to produce information about spectrum use in a particular region or about the emitters themselves. Emerging commercial operators believe there is a market among governments, industry users, and nonprofits for the information they produce. Although these companies disclaim any interest in intercepting and examining the content of message traffic, the potential for such operations raises concerns in national security circles because these services represent the first wave of non-government entities conducting such collections from space on a global scale. For decades, the U.S. government operated on the assumption that uncooperative RF collection from space (as opposed to regular communication satellites) was a government-only activity. That assumption is simply no longer valid. In addition, the Department of Commerce has decided that commercial RF collections are not included under the definition of a commercial remote sensing regulatory framework. Thus, space companies pursuing such activities operate in space without a license requirement except for what is necessary to launch and to receive a spectrum allocation to communicate with the spacecraft.

Export. Satellite companies often have to deal with export control laws which are designed to prevent the spread of sensitive technologies to foreign actors. There are two sets of regulations: International Traffic in Arms Regulations (ITAR) and Export Administration Regulations (EAR). ITAR is under the jurisdiction of the Department of State and seeks to control items, information, or activities that could be used for military purposes; it operates under the assumption of denial. EAR is under the jurisdiction of the Department of Commerce and controls items and technologies that could be applicable to commercial or military use. RPO, for example, can include a mix of ITAR and EAR technologies and services. Given that spacecraft rendezvous and docking frequently utilize cameras for the terminal phase, it is possible that some imagery collected during this phase of a servicing mission could provide satellite design information to the servicer that would fall under export control regulations.

Ways Forward and Conclusion

This paper described several examples where space activities are likely approaching regulatory boundaries in the near future. Some may require further study, some may benefit from a regulatory framework, and some may call for guidelines and best practices. Following are several actions the U.S. government could take to help the emerging spectrum of on-orbit capabilities flourish, enable both industry and government to operate in space more efficiently and effectively, and fulfill the nation's international obligations.

- **Provide technically informed and enabling regulations.** The current uncertainty created by an ad hoc approval process for many of these activities makes it difficult for commercial companies to develop new business opportunities and get them funded. There is a tradeoff between industry's desire for clear regulations that provide certainty for potential investments versus those that can nimbly address emerging businesses, which would likely be broader. Given the pace with which new ideas are emerging for space business, it is likely that an approach that demands a separate regulatory framework for each type of capability would be too slow; instead, a framework that provides a reasonable level of regulatory certainty for all novel on-orbit activities would be best. The current lack of a clear path forward increases difficulty in closing business cases and securing investors.

- **Develop guidelines and best practices with broad participation.** Activities that are too premature for regulation would benefit from clear guidelines and norms of behavior. A mixture of precedents and industry consensus efforts helps to drive norms of behavior, leading to many important outcomes. It improves the interoperability of systems such that platforms owned by different stakeholders can all interface with each other. This in turn improves flight safety. If a spacecraft deviates from established norms, it will stand out—making it easier to identify bad actors. This will also help with issues related to space traffic management, and more.

- **Focus on commercial capabilities as a service to government missions.** The U.S. government should include the use of commercial on-orbit capabilities when designing its future space architecture. Historically, satellites were large, pristine platforms that were launched in their final form and expected to operate for ten years or more. Current discussions focus on switching to smaller, shorter-lived satellites to increase agility. However, there is also a range of options in between that could employ on-orbit capabilities. It is important to understand the range of capabilities to better assist both the government and the commercial market. When exploring the tradespace, there should be consideration for what capabilities should be government-owned and operated versus provided to the government as a service. The U.S. government should look to maximize its role as the customer.

- **Fund critical R&D investments.** The U.S. government should continue to fund research and development projects related to furthering on-orbit capabilities. Small business grants and R&D investments are a way to help small businesses with innovative ideas enter the market.[22]

These actions would help ensure that the United States will remain at the forefront of space activities, promote domestic businesses, and not only fulfill international obligations but, perhaps more importantly, provide leadership in an increasingly democratized, global domain.

References

[1] United Nations, Treaty on the Peaceful Uses of Outer Space, the Moon, and Other Celestial Bodies, 1967, Article VI (https://www.unoosa.org/oosa/en/ourwork/spacelaw/treaties/outerspacetreaty.html).

[2] Federal Communication Commission, “Report and Order and Further Notice of Proposed Rulemaking” (https://docs.fcc.gov/public/attachments/FCC-20-54A1.pdf).

[3] Department of Transportation, “Human Space Flight Requirements for Crew and Space Flight Participants” (https://www.govinfo.gov/content/pkg/FR-2006-12-15/pdf/E6-21193.pdf).

[4] Department of Commerce, “Licensing of Private Remote Sensing Space Systems,” 15 CFR Part 960 (https://www.govinfo.gov/content/pkg/FR-2020-05-20/pdf/2020-10703.pdf).

[5] Joshua P. Davis, John P. Mayberry, and Jay P. Penn, “On-Orbit Servicing: Inspection, Repair, Refuel, Upgrade, and Assembly of Satellites in Space,” The Aerospace Corporation, (https://aerospace.org/sites/default/files/2019-05/Davis-Mayberry-Penn_OOS_04242019.pdf).

[6] Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies, January 27, 1967.

[7] Convention on International Liability for Damage Caused by Space Objects, September 1972; (http://www.unoosa.org/oosa/en/ourwork/spacelaw/treaties/introliability-convention.html).

[8] Henry, Caleb, “FCC begins approval of Orbital ATK satellite-servicing mission for Intelsat-901,” *SpaceNews*, 2017 (http://spacenews.com/fcc-begins-approval-oforbital-atk-satellite-servicing-mission-for-intelsat-901/).

[9] James Lee, ”Comments of Maxar technologies Inc.“ (https://downloads.regulations.gov/NOAA-NESDIS-2018-0058-0041/attachment_1.pdf), June 10, 2020.

[10] Title 51 – National and Commercial Space Programs Act, Subtitle VI – Earth Observation, Chapter 601 – Land Remote Sensing Policy, Subchapter III – Licensing of Private Remote Sensing Space Systems, Section 60121 – General Licensing Authority.

[11] National Environmental Satellite, Data, and Information Service, National Oceanic and Atmospheric Administration, Department of Commerce, Proposed Rule ”Licensing of Private Remote Sensing Space Systems “(https://www.federalregister.gov/documents/2019/05/14/2019-09320/licensing-of-private-remote-sensing-space-systems), July 15, 2019.

[12] Commercial Remote Sensing Regulatory Affairs, ”Frequently Asked Questions” (https://www.nesdis.noaa.gov/CRSRA/generalFAQ.html).

[13] Ibid.

[14] Department of Commerce, ”Licensing of Private Remote Sensing Space Systems,“ Sub-part A § 960.2(b), (https://s3.amazonaws.com/public-inspection.federalregister.gov/2020-10703.pdf), May 20, 2020.

[15] European Space Agency, “Active Debris Removal.“ (https://www.esa.int/Safety_Security/Space_Debris/Active_debris_removal).

[16] Inter-Agency Space Debris Coordination Committee, Working Group 2, “Stability of the Future LEO Environment,” Action Item 27.1, IADC-12-08, Rev. 1, January 2013.

[17] Thomas H. Zurbuchen, “NASA Response to Planetary Protection Independent Review Board Recommendations,“ NASA, October 17, 2019. (https://www.nasa.gov/sites/default/files/atoms/files/planetary_protection_board_report_20191018.pdf).

[18] Center for Space Policy and Strategy, “What is Planetary Protection and Why Should We Care?“ Vimeo.com, The Aerospace Corporation, (https://vimeo.com/438990780), July 23, 2020.

[19] Thomas H. Zurbuchen, “NASA Response to Planetary Protection Independent Review Board Recommendations,“ NASA, October 17, 2019. (https://www.nasa.gov/sites/default/files/atoms/files/planetary_protection_board_report_20191018.pdf).

[20] Ibid.

[21] Department of Transportation, “Human Space Flight Requirements for Crew and Space Flight Participants,” 75644 (https://www.govinfo.gov/content/pkg/FR-2006-12-15/pdf/E6-21193.pdf).

[22] Jeff Foust, ”Orbit Fab gets award to test satellite refueling technology,“ Space News, (https://spacenews.com/orbit-fab-gets-award-to-test-satellite-refueling-technology/; https://spacenews.com/olis-robotics-space-applications/), March 31, 2020.

CENTER FOR SPACE POLICY AND STRATEGY

APRIL 2018

PUBLIC-PRIVATE PARTNERSHIPS: STIMULATING INNOVATION IN THE SPACE SECTOR

KAREN L. JONES
THE AEROSPACE CORPORATION

Summary

Governments seeking to expand their capabilities for satellite communications, navigation, Earth monitoring, exploration systems, and other space applications recognize the significant role that the private sector can play in delivering these capabilities at reduced cost and risk through public-private partnerships (P3s). The government sector generally wants to retain some level of control over key capabilities. P3s can provide significant advantages to government agencies by leveraging commercial efficiencies and innovation while sharing risk with the private sector in exchange for profits linked to performance. As space-related P3s proliferate for capital intensive projects and public-private data-sharing models, understanding key challenges and underlying economic arguments from real-world case studies can help lay the groundwork for future success.

Background

A public-private partnership (P3) is an arrangement between a public body or agency (federal, state or local) and a private sector entity to deliver a collective good—a beneficial facility, product, capability or service for use by the public. Both parties commit to shared risk and investment in an agreement where risks and rewards are shifted to the private entity.[1] Each P3 has unique characteristics to accommodate the requirements and operational styles of different organizations as they pool their interests over a defined term. As former NASA Administrator Michael Griffin has expressed it, "Developing public-private partnerships is an art form. It is all about the deal and all stakeholders must have skin in the game."[2] There are many reasons why government decision-makers may turn to a P3 to fill a public sector need. The government might be seeking to provide better public services by introducing commercial sector know-how, innovation or efficiencies. Perhaps the public sector lacks the capacity or bandwidth to deliver services or infrastructure in a timely manner. Or maybe, the government faces budget constraints and prefers to reduce upfront capital exposure. Ideally, a P3 provides a win/win whereby the government partner receives private capital investment, innovation or know-how and the private partner reaps profits.

This paper:

- explores reasons why public sector space stakeholders may want to pursue a P3 model for delivering services, infrastructure, and innovation
- proposes a phased approach for strategizing, planning, and implementing P3 delivery models along with guiding principles of neutrality, transparency, accountability, and governance.
- examines case studies, including successful and less than ideal P3 scenarios (e.g. where the government gives up too much control or where the private sector assumes too much risk), and offers lessons which can guide future decision-makers to develop better P3 delivery models.

Both the Obama and Trump administrations emphasized the importance of private investment when considering how to provide a public or collective good such as critical infrastructure. This emphasis extends to space as the National Space Policy of 2010* and the National Aeronautics and Space Act of 1958† (as amended) support the use of P3s to meet the U.S. government's objectives to promote a robust and competitive commercial space sector.

P3s are traditionally associated with public infrastructure such as toll roads, wastewater treatment, and public buildings. However, innovative partnerships, drawing upon the strengths of both government and commercial companies, address a broad range of sectors well beyond transportation, including space. This variety explains why P3s have no single, widely accepted recipe for success.

P3: Key Objectives

When a public-sector entity considers a P3 arrangement, it should articulate the objectives. Within the space sector this could include:

- Mission Support—to advance science, space exploration, or national security and defense.
- Functional Support—such as communications, Earth observation, space logistics.
- Technology Advancement—such as prototyping or developing new technologies.
- Space Industrial Base—to promote a competitive and robust commercial space sector

Traditional public infrastructure projects are structured across a range of P3 project delivery models to provide functional support—from operation and maintenance to concession agreements (see Figure 1). By contrast, space industry P3 delivery models typically include various arrangements for sharing risk and know how through cooperative research, Space Act Agreements (SAAs), or longer term development agreements. The current emphasis appears to be leveraging commercial sector innovation and agility (see Figure 2). Perhaps over time the space sector will introduce more traditional P3 functional support models such as:

- **Example: Future Low Earth Orbit (LEO) Modules/ Habitat ("Concession" P3 Model).** NASA could potentially apply a concession arrangement to replace the ISS with one or more commercial modules. The space module(s) could be owned by the U.S. government and designed, built and operated by one or more commercial companies for a specific period of time. Several commercial companies, including Axiom Space, Bigelow Aerospace and NanoRacks, have already expressed interest in the provisioning of space modules to replace the existing International Space Station (ISS). Note that if these commercial modules were ***owned***, built, operated and maintained by the commercial sector then this would shift the business model from a P3 model to full privatization.
- **Example: Future Space Tug ("Design, Build, Finance & Maintain" P3 Model).** A "space tug" satellite could be built and financed by the commercial sector. The P3 agreement could guarantee the space tug a certain amount of business over a specified period of time. Near the end of life, the space tug could revert to being wholly owned by the commercial company, thereby offloading "end of life" risk such as responsibilities for decommissioning and de-orbiting. In return, the commercial sector, could attract additional revenue streams from other customers for as long as practical before end of life disposal.

For now, however, the space sector is undergoing rapid change, and it makes sense that government/commercial sector research and innovation collaborations are popular. In considering applicability to the space sector, planners should be aware of the need to configure each P3 to accommodate the needs, abilities, resources, and objectives of the parties involved. Planners should also be aware of P3s' mixed record of success.

* The National Space Policy of 2010 encourages federal departments and agencies to: actively explore the use of inventive, nontraditional arrangements for acquiring commercial space goods and services to meet United States Government requirements, including measures such as public-private partnerships, hosting government capabilities on commercial spacecraft, and purchasing scientific or operational data products from commercial satellite operators in support of government missions.

† 51 USC § 20112(a) notes that the Administration shall: (4) seek and encourage, to the maximum extent possible, the fullest commercial use of space; and (5) encourage and provide for Federal Government use of commercially provided space services and hardware, consistent with the requirements of the Federal Government.

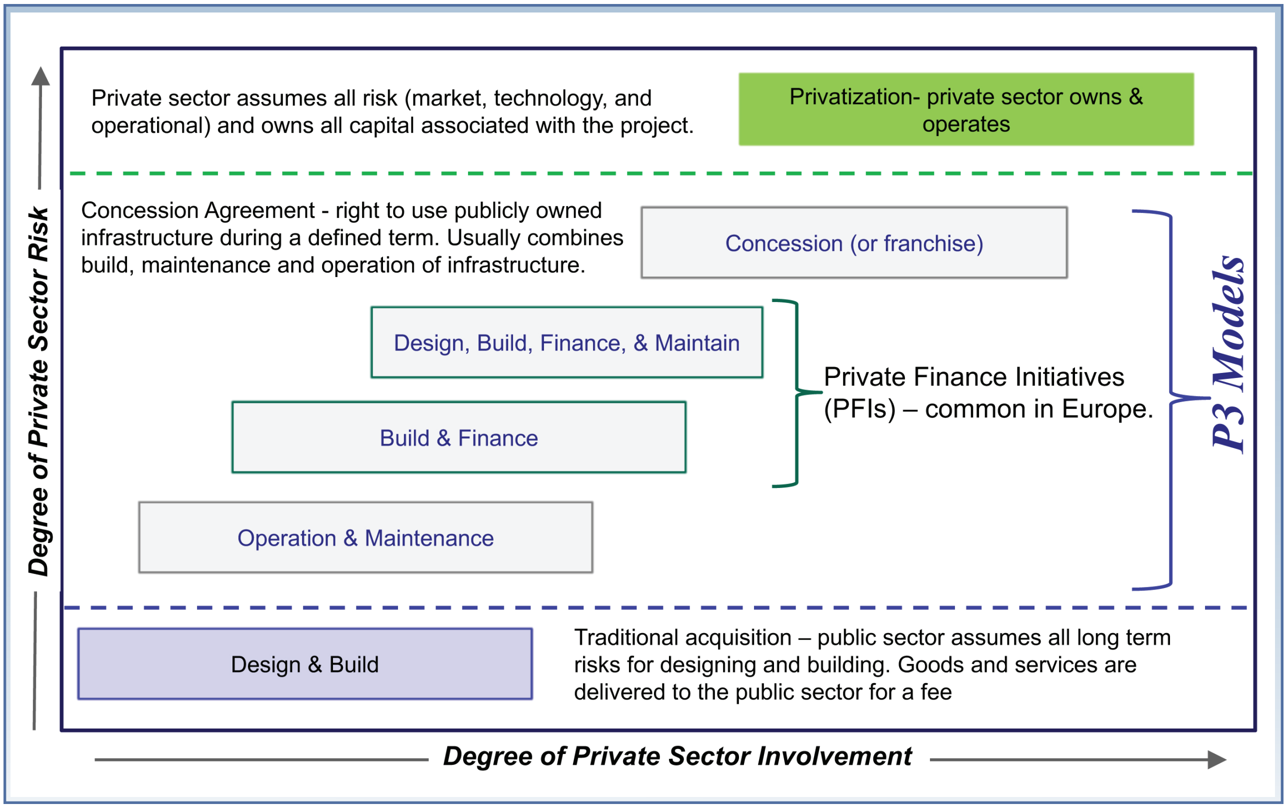


Figure 1: Traditional Public Infrastructure Sector: P3 project delivery models range from private sector design and build to full privatization. Source: Adapted from the Canadian Council for Public Private Partnerships.

P3: Key Strategies

Typically, P3s are pursued by governments for the following reasons:

- **Efficiency Gains.** Improve operations management and leverage the profit-driven efficiencies that the private sector offers in terms of schedule, costs and experience – including state of the art technology.
- **Reduce Life Cycle Costs.** Seek the lowest cost alternatives over the lifecycle of an asset. Attain Value for Money (VfM)*
- **Transfer Risks.** Operational and project execution risks are transferred from the government to the private sector which is often better able to contain costs and manage key milestones on schedule.

* Governments often apply Value for Money (VfM) analysis to determine whether a P3 makes sense. VfM compares the net present value of the life-cycle procurement cost if the project were to be funded, financed, built, operated, and maintained by the public sponsor (the "Public Sector Comparator") with the net present value of the likely private bid under the P3 option (the "shadow bid").

In addition to the above three public sector goals which are applicable to almost any industrial sector, the space sector recognizes the importance of P3s to meet certain strategic space imperatives:

- **Innovation and Technology "Spin-Ins."** P3 models can be structured to encourage innovation. Historically the space industry has spun off new technologies such as precision GPS, memory foam, and digital camera sensors. Now the space sector is attracting investors from other industries and realizing the benefits of "spin-in" technologies such as cloud computing, 3D printing, and artificial intelligence. NASA is currently seeking game changing technologies for a range of applications (see "NASA Tipping Point Space Technologies," page 8).
- **Alignment with Space Policy Goals.** The National Space Policy of 2010[3] encourages the use of P3s to promote a "robust commercial space industry." NASA is now encouraging entrepreneurship, catalyzing commercial space development, and strengthening the

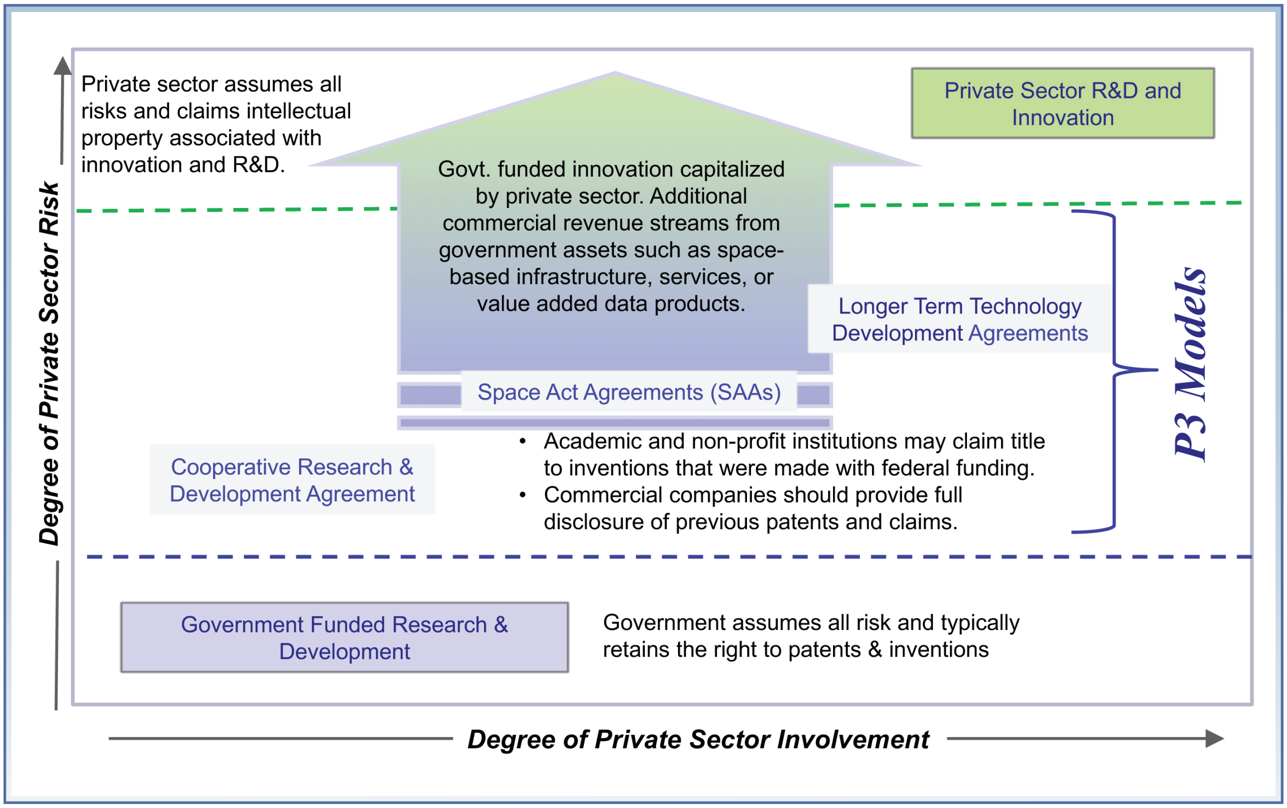


Figure 2: Space Sector P3 Delivery Models: The space sector is focused on sharing innovation and risk with the private sector. There is a fluid range of risk and participation between the public and private sector. Various types of cooperative grants, space act agreements, and long term development agreements have the potential to "spin-off" additional revenue streams for the commercial sector. This may also include sharing or assigning intellectual property or data rights to the private sector for further capitalization.

U.S. space industrial base through public-private partnerships.

The private sector pursues P3s for the following reasons:

- **Return on Investment (ROI).** In exchange for taking on public sector risk, the private sector can expect a return on investment (ROI). Typically, the higher the risk then the greater the expected ROI.
- **Gain Competitive Advantage.** Leverage commercial technologies and intellectual property through a P3 arrangement to mature and advance the technology and gain market traction with key public sector customers.
- **Create Additional Revenue Streams.** The private sector has the ability to create additional revenue streams from unique government assets such as space-based infrastructure, services, or data. For instance, a private sector company, such as Accuweather, repackages large amounts of National Weather Service (NWS) weather data and adds value-added services and analytics for a fee to the private sector. Another example is the potential for launch providers to use the same launch vehicles that might serve NASA missions to carry tourists to space. A productive co-existence is possible between private sector profit interests and public sector mission needs.

> ***"Government must understand what motivates industry and assume an MBA perspective—what is acceptable in terms of risk, payback, and overall capital investment?"***
>
> *—Michael Griffin, former NASA Administrator*

P3: Key Elements

The term "Public-Private Partnership" is often used, incorrectly, as interchangeable with traditional private sector procurement contracts, causing many in both the public and private sector to confuse the issues. The key elements of a P3 model are different from a traditional procurement model in the following ways:

- **Funding.** Public funds are not dispersed at outset. Instead, a P3 private partner receives periodic payments based upon reaching specific milestones, perhaps tied to technology maturation, technological advancement, or a contractual formula.
- **Duration.** P3s often extend beyond construction or deployment and often include operations and maintenance.
- **Requirements.** Performance versus Design. P3s should focus on performance rather than design requirements. Performance requirements are based upon stakeholder expectations and define what needs to be accomplished to meet the objectives of the project. There is often less potential for a commercial partner to innovate and optimize when striving to meet overly specific design details.
- **Risk Allocation.** Traditional procurement risk is borne by the public sector. P3s, on the other hand, offer a way for risk to be shared with the private sector.

Intellectual Property and Data Rights

What are the provisions for intellectual property rights for the results of joint research or a P3? The answer: it depends. However, NASA's Human Exploration & Operations Mission Directorate notes that a critical success factor for the Commercial Orbital Transportation Services (COTS) program using a Space Act Agreement (SAA) implementation, is the ability for private companies to "get their ROI" or return on investment. These private sector rights to intellectual property can help reap substantial commercial contracts downstream. NASA notes that:

> When engaging in a public-private partnership, it can be important for the commercial partner to retain ownership of the products and be able to sell to a broader market. In this case, forfeiting the government's rights to intellectual property was a key component of establishing the PPP.[4]

A case-by-case analysis is required to determine whether work to be performed by the Partner (which could be commercial, academic or other) under the SAA is being performed for NASA (as opposed to being performed by the commercial partner for its own benefit). If the Partner is not performing work under the SAA for NASA, but is instead participating in the collaborative activities for its own benefit, then NASA's title-taking authority does not apply. Even under those situations where NASA's title-taking authority applies, there are waiver provisions. And NASA "liberally grants waivers to SAA partners for commercializing the waived invention." Since NASA is entitled to a government purpose license of the technology, they do not give up much by allowing these waivers.

P3s have several common elements, including leveraging the strengths of the public and private sectors, appropriate risk transfer, transparent and flexible contracts and alignmentof policy goals.

—Findings and Recommendations of the Special Panel on Public-Private Partnerships, Committee on Transportation & Infrastructure, U.S. House of Representatives, January 2014

Beyond patents, the U.S. space enterprise is progressing towards data sharing models to leverage public sector assets in space and the commercial sector's ability to provide customized value-added data products. There are many examples which are beyond the scope of this paper. However good examples include weather enterprise data sharing; the National Geospatial Agency's more recent interest in sharing historical sensor data with commercial start-up companies; and a potential future partnership between commercial Space Data Association and a federal civil entity which could assume authority.

Proposed Process: Strategize, Plan, Implement, and Share

P3s have received considerable attention, including in national policy, as a potential solution to the ever-present

NASA Tipping Point Space Technologies

NASA's Space Technology Mission Directorate (STMD) "Tipping Point" solicitation is designed to work with the private sector within certain strategic thrust areas across a wide range of technology readiness levels. The idea is to create a "sustainable pipeline" across a range of technology maturity levels. A technology is considered at a tipping point if an investment in a demonstration of its capabilities will result in a significant advancement of the technology's maturation, high likelihood of infusion into a commercial space application, and ability to successfully bring the technology to market.

Recently, NASA partnered with eight U.S. companies to advance small spacecraft and launch vehicle technologies that are on "the verge of maturation." The results were fixed-priced contracts including milestone payments tied to technical progress and require a minimum 25 percent industry contribution. Technologies could address robotics, in-space manufacturing and assembly of spacecraft, small spacecraft propulsion systems, small satellite launch systems, etc.

Source: https://www.nasa.gov/directorates/spacetech/solicitations/tipping_points

triad of space development challenges: high cost, high risk, and long lead-times. But P3s are not a magic tool that eliminates these challenges. Rather, they provide an avenue for better managing the challenges using the best qualities offered by each participant. A successful outcome is dependent on applying these qualities effectively and consistently. The following proposed planning steps can contribute to a successful P3 structure::

- Determine how the partnership is expected to improve the cost, schedule, or performance of a space system or service.
- Clearly identify the scope and roles of the P3 partners.
- Introduce a decision framework supported by lessons learned (failures and successes) that realistically represents risks, contingencies, and stakeholder requirements.
- Based upon the decision framework, balance stakeholder needs and expectations to optimize benefits and fairly allocate risks for all participants.
- If a viable solution is evident, develop a contract acceptable to all parties.

Although each P3 is different, there are lessons to be learned from the collective experience of such arrangements across different sectors of activity. The lessons apply to varying degrees based on the nature of the potential P3, with a short-term P3 to sponsor a conference or run a prize competition likely requiring less stringent review than one that has open-ended financial liability or mission risk. Several lessons and supporting examples are presented below.

Throughout the P3 lifecycle (see Figure 3), decision-makers should focus on the following principles:

- **Neutrality.** Value for Money (VfM) should be calculated without bias and result in an estimation which does not artificially inflate or deflate P3's value under various scenarios.
- **Transparency and Accountability.** Government decision-makers should establish a structure and process for P3 screening, VfM analysis, and ongoing management and oversight. These well established best practices will go a long way toward engendering trust with public stakeholders and P3 partners. OMB Circular A-11[5] also requires that federal agencies submit non-routine financing proposals (such as P3s) for review of scoring impact to evaluate the overall value.
- **Governance.** While not discussed in detail here, appropriate checks and balances should be established during the different stages of the P3—from project approval through implementation. A P3 should be properly structured to avoid any real or perceived conflicts of interest during planning, project delivery and regulation.

1 ***Strategize. Market Assessment, Forecast, and Business Model Concept***

NGA Case Study—Calibrate Investment to Fit Budget and Contract Risks: The National Geospatial Agency (NGA) Enhanced View (EV) Program, a ten-year public-private partnership between the U.S. Government (USG) and Digital Globe and GeoEye. Each company was awarded a $3.55 billion agreement. The agreement had a ten-year term, consisting of nine one-year options exercisable by NGA, and subject to congressional appropriations and the right of NGA to terminate or suspend the contract at any time. Unfortunately for GeoEye, in 2012 NGA decided to terminate its agreement due to funding constraints and in 2013 GeoEye was acquired by Digital Globe.

Lessons Learned: Before agreeing to a major, long-term partnership, government should conduct a comprehensive review of a commercial partner's business plan including market forecast, market risk, related cost and revenue projections for all parties. Commercial companies should calibrate their expectations to fit budget and contract realities or seek greater upfront commitments. Avoid having critical missions depend on private business models that are overly optimistic or uncertain.

EELV Case Study—Conduct Independent Due Diligence and Market Studies: The Evolved Expendable Launch Vehicle (EELV) Program, a partnership of the U.S. Air Force, Boeing, and Lockheed Martin, with SpaceX added in early 2016. The U.S. Air Force (USAF) started the EELV program during the 1990s to assure access to space for DoD and other U.S. government payloads and to make government space launch more affordable and reliable. During the mid-1990s when initial EELV discussions and planning occurred, the space industry was expecting a large international market for commercial satellites, particularly large communication satellite constellations, and therefore, for launch vehicles.[6] The winning contractors would gain "an enhanced competitive position in the international launch vehicle market from DoD's investment in the program." However, these market projections proved to be wildly optimistic. In fact, several large LEO satellite constellations conceived in the 1990s never launched or went bankrupt shortly after the satellites launched. During a hearing for FY2017 Budget Request for National Security Space, General John Hyten noted that after 92 launches since EELV inception only 14 "in the entire history of the program" were for the commercial sector and emphasized "that is why it is a public/private partnership because the commercial sector is not there right now."

As of early 2018, there are several new planned "mega-constellations" (e.g., OneWeb, SpaceX, and LeoSat) and

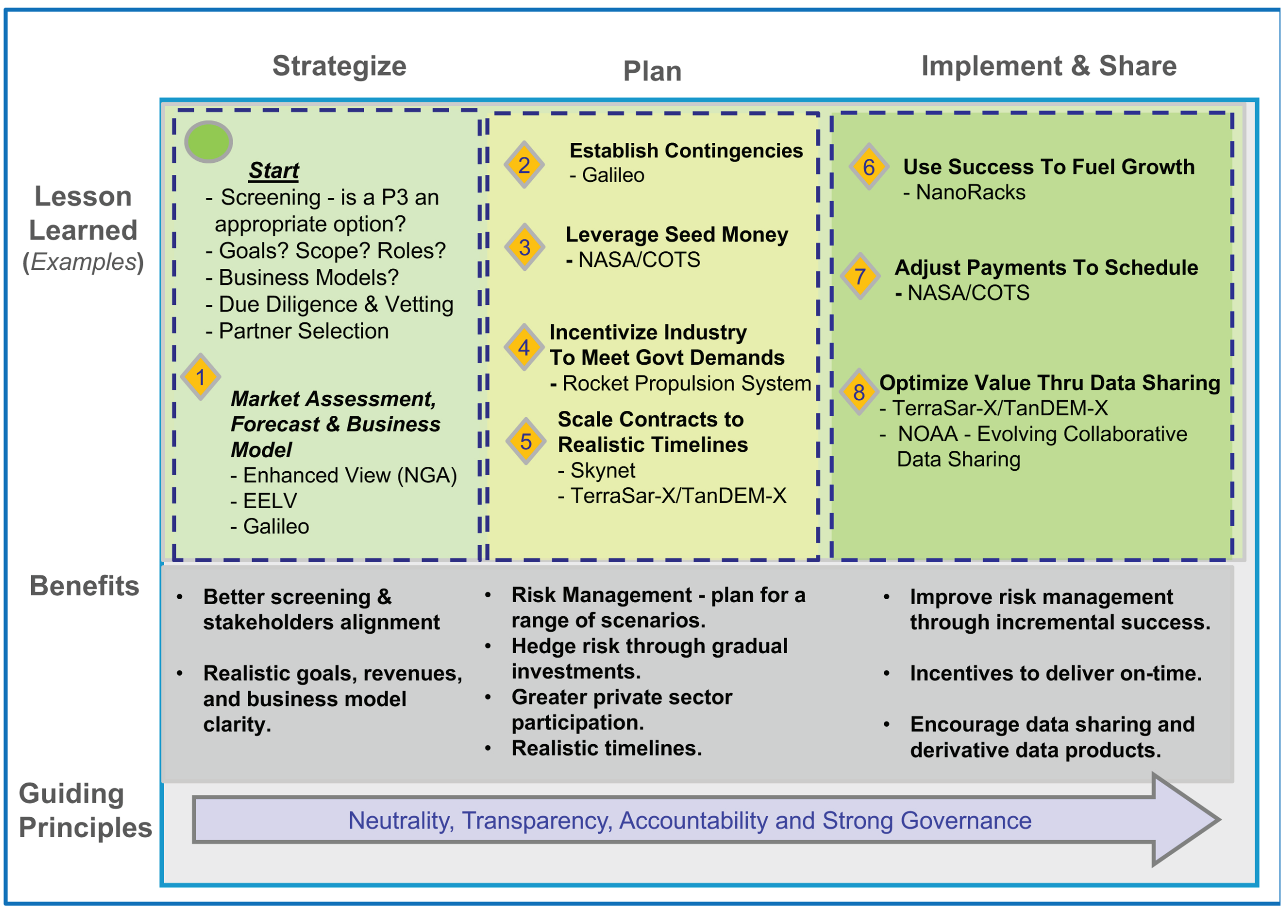


Figure 3: Lessons Learned Through P3 Case Studies. Each diamond represents a specific P3 space sector case study discussed below.

these constellations might help to "close the business case" for new launch-related P3 investments. However, if these constellations do not materialize the resulting commercial satellite and launch market pressures could potentially jeopardize space P3 business cases in even tangentially related areas.

Lessons Learned: Government should seek to understand the industry partner's business case and conduct an independent due diligence to validate demand forecasts and cost of launch services in a limited market. Likewise, industry must understand its own risks and limitations for market capture when investing in development of launch systems and establishing a partnership with the government.

Galileo Case Study—Creating a Shared Vision: The Galileo Satellite Navigation System involved a collaboration of the European Union, the European Space Agency, and an industry consortium of eight companies called "European Satellite Navigation Industries" which was tasked with developing and building the satellites and components for the ground segment.[7] The partnership, based upon a cost and risk-sharing contract, planned to construct, deploy, and operate a constellation of 30 navigation satellites. Industry was to incur two-thirds of the deployment costs and all of the operating costs. The public committed to all of the development costs and the remaining one-third of the deployment costs.[8] The consortium and EU entered the partnership with different ideas on how the satellite constellation could be used to generate revenue. In addition to the challenges of competing with the U.S.'s free GPS navigation signals, value-added commercial services to bolster private revenues were uncertain, which created rifts in negotiations. The private sector partner withdrew from its Galileo funding commitments in 2007 and subsequently the EU assumed responsibility for the construction of the Galileo positioning system. Galileo's early history struggling with P3 development highlights the critical need for business model clarity early during the formation of P3 partnerships. Without such clarity, it is unlikely that the private sector is willing to assume any risk.

Lessons Learned: During the early stages of P3 conceptualization it is important to create a shared vision or framework for project goals. This will serve as the benchmark to ensure the realization of joint objectives, clarify business models and projected revenue streams. Also identify key assumptions and conduct sensitivity testing.

2 *Plan: Establish Contingencies*

Galileo Case Study—Changing Requirements: The Galileo Satellite Navigation System's original partnership was terminated in 2007 by the public sector after negotiation breakdowns and considerable schedule delays. Political decisions occurring on a shorter timeframe than the project duration created strain on the partnership as the terms of the contract were altered.[9] This caused considerable delays because of ongoing conflicts over work distribution. While political pressures are unavoidable in dealing with democratic governments, future partnerships may do better to agree on fixed terms and strong upfront commitments, with contingencies in place for changes in funding or unforeseen technical challenges.

Lessons Learned: Establish contingencies for changing requirements.

3 *Plan: Leverage Seed Money for the Development of a Private Sector Capability and Select Two or More Partners to Encourage Competition and Hedge Risk*

NASA/COTS Case Study—Investing in Partners: NASA's Commercial Orbital Transportation Services for International Space Station (ISS) activity, provided by SpaceX, Orbital ATK, and Sierra Nevada Corporation. The partnership, based upon a cost and risk sharing contract, calls for industry to develop, own, and operate their own space transportation systems for first generation resupply contract. NASA leveraged seed money, with commercial partners funding over 50%. Pay-for-performance fixed milestone payments helped control cost and minimize schedule delays. SpaceX invested 53% and the U.S. government invested 47% for the development and demonstration of a commercial transportation system; and Orbital invested 58% and the U.S. government invested the remaining 42%.[10]

NASA's interest in enhancing competition among existing commercial partners offers distinct advantages, including: competitive pricing, a broader base of innovation and lower market risk if one commercial partner leaves the market. The NASA COTS program is just one more example where space sector P3s introduce somewhat unique market dynamics compared to more traditional infrastructure P3s. In a highway project, for example, the government partner is less compelled to broaden the competitive base of potential commercial partners because the existing public infrastructure market is already broad with many buyers and sellers.

Lessons Learned:

- Federal agencies use P3 arrangements to essentially act as a "venture capitalist." Early seed funding allows the project to grow. Once the project is operating well, the government can step back.
- A portfolio with multiple partners offers a blend of different capabilities, and helps provide a balanced approach to technical and business risks.[11] Moreover healthy competition encourages cost efficiencies and often better products.

4 ***Plan: Incentivize Industry to Meet Government Demands***

RPS Case Study—Strengthening Strategic Capabilities: Rocket Propulsion System (RPS), a collaboration involving the U.S. Air Force, SpaceX, and Orbital ATK.

As part of the Air Force plan to transition away from Russian RD-180 propulsion systems, the Air Force established the RPS program to facilitate the development of propulsion systems that would enable two or more domestic, commercially viable launch providers to meet national security space requirements. In early 2016, the Air Force awarded Other Transaction Authority contracts (OTAs)* to four providers (Aerojet Rocketdyne, Orbital ATK, SpaceX, and ULA) for development of booster and upper stage engines. "OTAs have proven effective as a vehicle for public-private partnership (PPP) to bring down cost."[12] All U.S.-based P3 examples (NGA, NASA, and USAF) were developed using OTAs for cost and risk sharing.

The P3 OTAs required that winning companies contribute at least one third of the total development cost for each of the projects. The RPS program has proven successful; all four providers have made significant progress on their propulsion systems. The RPS program demonstrates that government funding combined with industry investment is an effective way to develop strategically important domestic capabilities to meet stringent DoD demands.

Lessons Learned: P3s can be designed to incentivize industry to meet the more stringent demands of a government partner and strategically reduce foreign reliance on key strategic capabilities – such as access to space.

5 ***Plan: Scale contracts to realistic timelines and extended success.***

Skynet Case Study—Realistic Timelines: The Skynet 5 satellite communications project, a partnership of the United Kingdom (U.K.) Ministry of Defense (MoD) and Paradigm Communications, involves a 20-year contract signed in 2003 for service delivery of a secure military telecommunications network, with the provision to sell spare capacity to select foreign governments and NATO. An unintended consequence of a 20-year deal between the commercial sector, Airbus, and the U.K. MoD is that the MoD may have ceded too much control. The MoD is now short on expertise and resources in the sector, and it is likely the ministry will appoint a contractor to help set requirements and undertake other tasks. While longer contract terms may be required to make more capital-intensive P3s viable, the risks associated with lock-in to long-term deals could be accentuated by the potential move to shorter satellite life spans. Paul Estey, executive vice president of engineering, manufacturing and test operations at SSL noted that "the 15-year model is obsolete… There's so much change going on in the telecomm business that we'll have to refresh payloads much faster than 15 years."[13]

Lessons Learned: Avoid commitments that are longer than technology refresh cycles or that cede too much control and put at risk needed government expertise.

---

* **Other Transactional Authority**
Title 10, United States Code (U.S.C.), section 237lb allows the Department of Defense (DoD) to enter into transactions for prototype projects using a legal instrument other than a contract, grant, or cooperative agreement. This legal instrument, known as an "other transactions" agreement (OTA) allows defense agencies and other federal agencies to negotiate terms and conditions specific to their project. OTAs are often used for P3 arrangements and offer flexibility which can help agencies attract commercial partners.

Section 845 of the FY1994 National Defense Authorization Act (NDAA) requires industry to provide at least one-third of the funding for OTA projects. Doug Loverro, Deputy Assistant Secretary of Defense for Space Policy, noted that DoD is "encouraging our OTA industry partners to contribute at a level higher than one-third. Even at a one-third contribution, however, the Department is receiving an excellent return on its RPS investments. The ultimate incentives for those investments is clearly access to the future National Security launch market, which CAPE estimated at $80B in 2013." *(Source: March 15, 2016; NDAA FY 2017; Subcommittee on Strategic Forces; Hearing on FY 2017 Budget Request for National Security Space).*

TerraSAR-X/TadDEM-X Case Study—Incentives for Extended Success: Germany's DLR Space Administration partnered through a cost and risk-sharing contract with Airbus Defence and Space GmbH and subsidiary Infoterra GmbH/Airbus DS Geo GmbH. Airbus's "twin" satellites TerraSAR-X and TanDEM-X produce images using a synthetic aperture radar (X-band) with one-meter resolution providing accurate digital elevation models. The lifetime of the German Earth observation satellites, TerraSAR-X/TanDEM-X, was intended to be approximately 5-7 years, but it has been 10 years since the launch of TerraSAR-X and it is still flying and producing valuable data for scientists as well as the commercial sector. The success of this P3 is partially predicated on the contract's ability to scale with the mission's longevity. The private sector, Airbus, assumed some of the initial risk of developing and deploying the satellites, but is now rewarded with even more data and longer-term cash flows than were expected.[14]

Lessons Learned: Scale contracts to the mission's longevity and provide incentives to commercial sector if satellites exceed expected lifetime. Set up distribution channels across the partnership base to fully exploit government sector and commercial sector demand for both primary and value-added products.

6 *Implement: Use Success to Fuel Incremental Growth*

Nanoracks Case Study—Incremental Growth: Nanoracks provided in-orbit services to NASA and the International Space Station (ISS) through a cost and risk-sharing contract. NanoRacks hardware was funded by private investors, with no funding from the U.S. government. Nanoracks developed a "pay-back" to NASA for use of onboard resources on the ISS. NanoRacks incrementally grew from basic research racks on ISS to a CubeSat pod deployer to the first-ever private airlock system on ISS.

The International Space Station has served as a powerful management and test bed for how the government and private sector can undertake space exploration together. Both sides contribute what they do best. In NASA's case, that is resources and hardware already paid for by the taxpayer and available for further utilization. In NanoRacks' case, that is the capital and expertise in attracting and working with customers in a cost-efficient manner.—Jeffrey Manber, CEO NanoRacks LLC

Lessons Learned: Incremental growth through success. Developing a close working relationship with the government partner can help to establish longer-term project growth.

7 *Implement: Carefully Structure Technical and Financial Milestones and Measure Success Criteria for Meeting Milestones*

NASA/COTS Case Study—Structure Milestones: NASA prepared a detailed Lessons Learned Report of COTS (April 2017)[15] and specifically called out the following areas for further improving key project metrics and milestones – including:

- Establish both technical and financial milestones.
- Link progress payments to specific milestones.
- Develop milestone performance success criteria with more specific detail.

In addition to the above lessons learned, Michael Griffin, former NASA administrator, noted that "the entire deal was thrown out of balance" because NASA did not adjust payments when SpaceX's and Orbital's launch schedules were deferred.[16] In an audit report (June 13, 2013) NASA's Office of Inspector General recommended that NASA should reduce future financial risk and "ensure that contractual agreements for the commercial cargo providers are updated to reflect the lead times required to meet any revised launch dates. If launch dates slip, NASA should adjust contract work plans to ensure that the authorized lead times and NASA payments reflect the revised schedules.[17]

Lessons Learned: Adjust payment schedules to reflect schedule slippage. Sometimes the delivery of goods or services is delayed. It is important that the government partner monitor delivery schedules and adjust payments.

8 *Implement: Optimize Value through Data Sharing and Additional Market Channels*

TerraSAR-X/TanDEM-X Case Study—Optimizing Market Channels: The P3 agreement between DLR and Airbus lays out clear marketing channels to fully exploit the market demand for data products. The government partner, DLR, provides SAR data to the scientific community, while the commercial partner, Airbus, exclusively distributes to the commercial sector through its GEO-Information division – including providing value-added products including 3D urban simulations and Digital Elevation Models.

Weather Data Sharing Case Study—Evolving Data Models: Weather data, based upon value-added services and analytics, could be provided for fee to the public and private sector. Conrad C. Lautenbacher, CEO, GeoOptics, Inc.[18] noted that the environment is right for a productive co-existence and synergy between the commercial and government weather stakeholders due, in part, to three key drivers:

1. Small & Nano Satellites - the commercial sector has ushered in the significant advantages of small and nano satellites to perform mission critical functions – including lower costs, greater resilience and increased agility.
2. Private Weather Data "Swim Lane" - the need for weather data extends well beyond public safety which has long been the traditional swim lane for government. Private sector weather data customers, such as airlines, utilities, commodity investment companies, TV stations, and Internet users often need different customized products.
3. Broader acceptance and commitment to private sector participation to provide new technologies and weather solutions. The *Weather Research and Forecasting Innovation Act of 2017,* Public Law 115-25 (April 18, 2017) was designed to "expand commercial opportunities for the provision of weather data." The new law (Section 302 (d) (3) includes a provision requiring NOAA to "determine whether it is in the national interest to develop a governmental meteorological space system... if a suitable, cost-effective, commercial capability is or will be available."

Lessons Learned: Data can be shared between the public and private sectors based on its intended application. Both public and private sector parties should agree to how the data is disseminated such that each can benefit without hurting the other.

Comparing P3 Experiences Internationally

Lessons learned will continue to accumulate as the space sector continues to leverage commercial sector know-how and capital for space projects on a global basis. P3s are already well established in the areas of satellite telecommunications, satellite imagery, and space transportation. It is reasonable to expect other P3 relationships to emerge over time, such as weather, space situational awareness, and space traffic management.

As demonstrated by some of the examples discussed above, Europe has significant experience with public-private partnerships – often referred to as Private Finance Initiatives (PFIs) – see Figure 1. In general, the U.S. is less experienced with PFIs, a subset of P3s. This is due in part to the U.S.'s well-established municipal bond market of approximately $3.7 trillion, of which a vast portion is allocated for public infrastructure financing.[19] When the Federal, state and local governments can borrow from private capital markets at lower rates than private partners in potential P3s, there is a financial hurdle that limits P3 viability. However, P3s are rapidly gaining traction within the space sector as NASA, NOAA, and others become more familiar with how to engage the commercial sector.

The U.S. civil and defense space sectors are becoming increasingly familiar and adept with OTAs. The OTA vehicle has proven effective for building partnerships with industry, reducing both time and acquisition costs, creating a more commercial friendly environment, and avoiding some requirements of the traditional Federal Acquisition Regulations (FAR) which can be daunting to commercial companies unaccustomed to contracting with the government.

The experience of Russia's space industry with P3s offers an interesting contrast. While the U.S. has made significant progress "privatizing" the space sector and establishing successful public-private partnerships such as NASA's COTS program, Russia's efforts are somewhat spotty. After the collapse of the Soviet Union in 1991, the Russian aerospace industry was partially privatized and made progress through public-private partnerships. However, between 2009 and 2017, the Russian space sector experienced a troubling series of launch failures. Ostensibly to address these failures as well as to consolidate and improve efficiency, the Russian government began to "re-nationalize" the space sector.

Russia's interim privatization of some of its space industry allowed the Russian military industrial base to benefit from public-private partnerships, at least for a while. According to retired Brigadier General Bruce McClintock, one rationale for shifting the sales of Russia's RD-180 engine to a commercial company may have been "the intent to gloss over the Russian government connection." Ultimately a "culture of patronage prevailed" and commercial companies established during the 1990s and 2000s, never separated far from the Russian government, returned to government control.[20] Perhaps they could be referred to as Potemkin P3s.

Conclusion

The space economy, once the sole domain of wealthy countries, has rapidly transitioned to a complex ecosystem of public and private entities. Along the way, government and commercial sectors have learned by doing, recognizing and incorporating key successes and lessons learned from past partnerships. Stakeholders must sort through a myriad of complexities, conflicts, and contingencies to shape an acceptable agreement. Most stakeholders recognize that this process is more art than science. Yet there is potential to achieve greater efficiency without sacrificing transparency and accountability by utilizing a decision framework supported by a broad understanding of past experiences in multiple sectors. As the space sector engages in more P3s, more lessons will emerge as partners strategize, plan, and implement. In the meantime, the following lessons, from the case studies discussed above, should continue to resonate with future P3 arrangements:

- The government partner must conduct a comprehensive review of a commercial partner's business plan including market projections, market risk, and related cost projections. These factors may impact the ability to reliably deliver on time and within budget. Avoid business models that are overly optimistic or uncertain.
- Create a shared vision among stakeholders.
- Establish contingencies for changing requirements.
- Strategically leverage seed money for private sector development and encourage healthy competition by selecting multiple partners.
- Use the partnership to incentivize industry to meet the more stringent demands of the government partner.
- Scale contracts to the mission's longevity and extended success. Be wary of commitments that are longer than technology refresh or capital reinvestment cycles.
- Use success to fuel incremental growth and to build longer term trusted partnerships with commercial sector partners.
- Carefully structure technical and financial milestones and measure success criteria for meeting milestones, including adjusting payment schedules to reflect any slippage.
- Optimize value through shared data agreements between the public and private partners – focusing on a range of intended applications and niche markets.

P3s will continue to test traditional approaches to space acquisition and operations. They can demonstrate significant advantages such as improving delivery schedules, quality of service, and innovation. Capital-intensive P3s will continue to experience successes and failures as both the public and private sector become more adept at crafting optimal arrangements. The future also holds great promise for public-private data-sharing models as this type of arrangement will begin to spur innovation and extract the most utility from space-derived data products.

Acknowledgements:

The development of this policy paper benefited from the insight provided by the following individuals: Conrad C. Lautenbacher, CEO, GeoOptics and former administrator of NOAA; Michael D. Griffin, former NASA Administrator; Jeffrey Manber, CEO NanoRacks; Wolfgang Duerr, Airbus Defense & Space; and Bruce H. McClintock, Founder and CEO of Zenith Advisors Group. The paper also benefited from the expertise or research provided by Aerospace colleagues including: Lina Cashin, James Vedda, Mick Gleason, David Eccles, Jeffrey M. Hanley, Nicholas Perlongo, Bruce Mau, Francesco Bordi, and Mark P. Jelonek.

References

[1] Syracuse University; Public-Private Partnerships: Benefits and Opportunities for Improvement Within the United States; 2017. http://eng-cs.syr.edu/wp-content/uploads/2017/04/P3Report.pdf

[2] Interview with Michael Griffin, April 24, 2017.

[3] Barack Obama, "National Space Policy of the United States of America," June 28, 2010 (https://www.nasa.gov/sites/default/files/national_space_policy_6-28-10.pdf).

[4] NASA - Human Exploration & Operations Mission Directorate Chief Knowledge Officer "Lessons Learned Report of Commercial Orbital Transportation Services (COTS); April 2017.

[5] OMB Circular No. A–11 "Preparation, Submission and Execution of the Budget"; Executive Office of the President; Office of Management and Budget; July 2017.

[6] U.S. Government Accountability Office "Access to Space: Issues Associated with DoD's Evolved Expendable Launch Vehicle Program," GAO/NSIAD-97-130, July 1997.

[7] The original consortium had eight members, among them Alcatel Alenia Space (France), Thales (France), Fimeccanica (Italy), EADS Astrium (UK and Germany), and Galileo Sistema y Servicios (Spain).

[8] Masafumi Hashimoto, *Public-Private Partnerships in Space Projects: An Analysis of Stakeholder Dynamics*, Massachusetts Institute of Technology, 2009.

[9] Stefan Barensky, "Galileo Public-private Partnership Crashes to Earth," *Politico*, May 9, 2007.

[10] NASA, Commercial Orbital Transportation Services: A New Era in Spaceflight, NASA/SP-2014-617, February 2014, p. 95 (https://www.nasa.gov/sites/default/files/files/SP-2014-617.pdf).

[11] NASA, Commercial Space Transportation, "COTS Final Report" (https://www.nasa.gov/content/cots-final-report).

[12] Air University, Maxwell AFB, AL; Fast Space: Leveraging Ultra Low-cost Space Access for 21st Century Challenges; December 22, 2016.

[13] Kendall Russell, "Satellite Manufacturers Stress Collaboration to Overcome Industry Challenges," *Via Satellite*, March 9, 2017.

[14] German Space Agency, "Excellence in Space: 10 Years of TerraSAR-X," June 2017 (http://www.dlr.de/dlr/en/desktopdefault.aspx/tabid-10081/151_read-22816/#/gallery/27214).

[15] Commercial Orbital Transportation Services (COTS): Lessons Learned for Commercial Capability Development Partnerships (April 2017).

[16] Interview with Michael Griffin, April 24, 2017.

[17] NASA Office of Inspector General, "Commercial Cargo: NASA's Management of Commercial Orbital Transportation Services and ISS Resupply Contracts," Report No. IG-13-016, June 13, 2013 (https://oig.nasa.gov/audits/reports/FY13/IG-13-016.pdf).

[18] Phone interview with Conrad C. Lautenbacher, June 25, 2017.

Section 3
Managing the Growth in Space Traffic

- Space Traffic Management: The Challenge of Large Constellations, Orbital Debris, and the Rapid Changes in Space Operations
- Slash the Trash: Incentivizing Deorbit
- Airspace Integration in an Era of Growing Launch Operations
- Light Pollution from Satellites
- Cislunar Stewardship: Planning for Sustainability and International Cooperation
- Developing a Sustainable Spectrum Approach to Deliver 5G Services and Critical Weather Forecasts

SPACE TRAFFIC MANAGEMENT: THE CHALLENGE OF LARGE CONSTELLATIONS, ORBITAL DEBRIS, AND THE RAPID CHANGES IN SPACE OPERATIONS

Marlon E. Sorge, William H. Ailor, and Ted J. Muelhaupt

Big increases in space activity and new approaches to space operations necessitate organizational and technical changes to the way the United States and the world manage space traffic. Several key actions need to be taken to position the United States to lead these changes, ensuring a safe operating environment in space and enabling future growth.

Introduction

Activities in space are rapidly changing. Order-of-magnitude or more increases in satellites, numerous new players from satellite operators to tracking data providers, and entirely new missions like satellite servicing are seriously stretching conventional approaches to safe space operations. The United States needs to lead in the development and implementation of good space traffic management to ensure that safe space operations practices are followed by all operators in a domain that is intrinsically international. To do this, the United States must:

- Clearly establish organizational authorities and required resources for a national approach to space safety, addressing the technical and organizational challenges this requires.
- Establish mechanisms for international coordination and cooperation with government and commercial entities.
- Develop clear definitions of nationally "acceptable" levels of safety and risk to enable development of thorough and justifiable norms of behavior and performance-based rules to encourage innovation while ensuring safe space operations.

The rapid advances in space operations offer many new opportunities and a number of challenges. The United States needs to be a leader in meeting these challenges to maximize the opportunities.

This paper highlights key actions for implementing effective space traffic management and safe space operations. These actions will assist the space community in establishing the organizational and technical capabilities needed to develop safe space practices.

Space Traffic Management. The term *space traffic management* (STM) has a range of definitions. Space Policy Directive-3, National Space Traffic Management Policy (SPD-3) signed by the President on June 28, 2018,[1] focused on laying out U.S. policy directions and defined STM as “the planning, coordination, and on-orbit synchronization of activities to enhance the safety, stability, and sustainability of operations in the space environment.” STM focuses on activities that facilitate safe operations in space both now and in the future. Considerations of safe space operations are growing in importance as the level of space activity increases and as new actors arrive in an increasingly democratized Earth orbit.

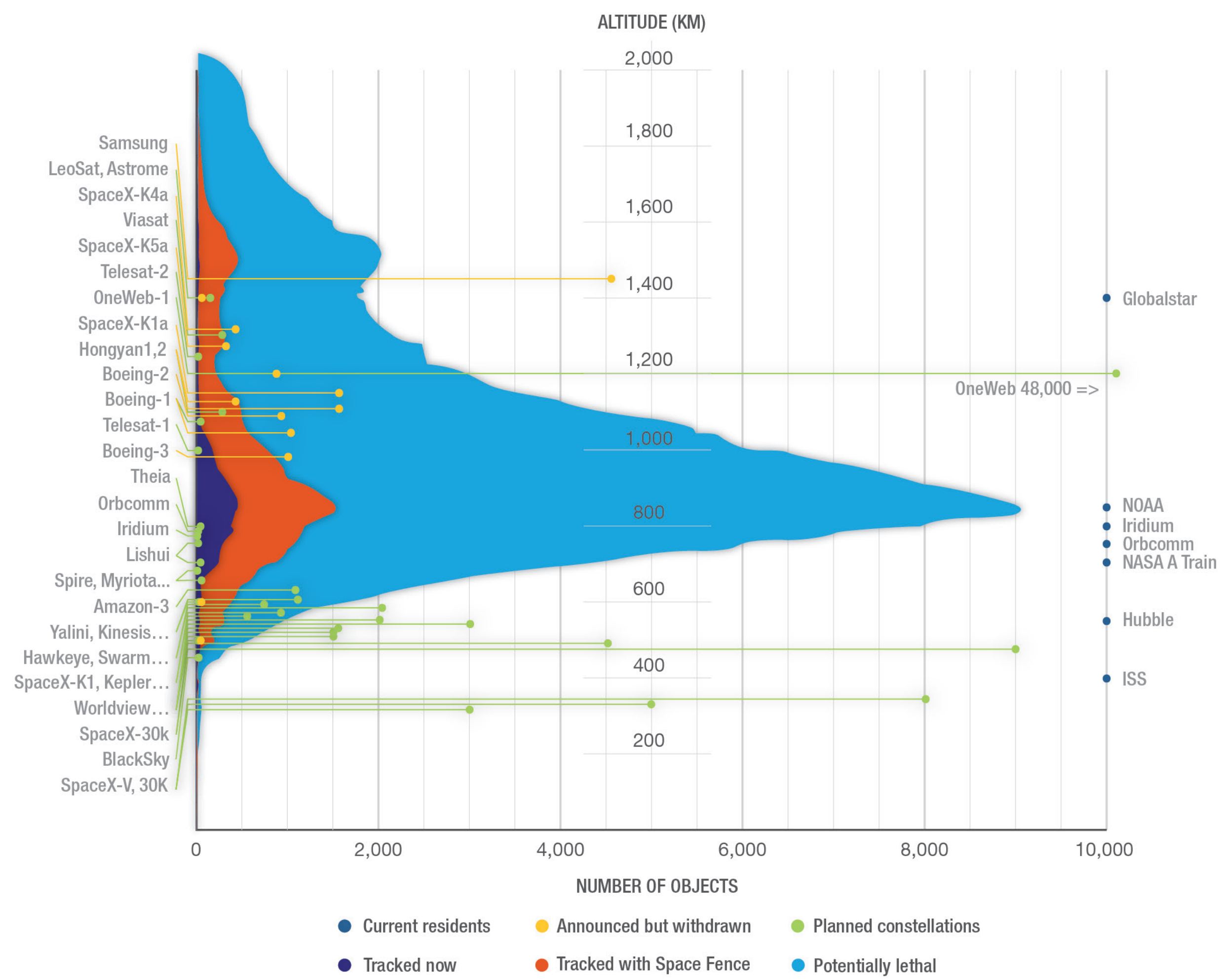
Space was originally thought of as a “big sky” where interactions between satellites were very unlikely. There were only a few satellite operators, and they could operate “Wild West” style with few rules and fewer consequences. The challenge now is that space is becoming more crowded with order-of-magnitude increases in commercial activity, greatly expanded numbers of satellite operators, both organizationally and internationally, and numerous organizations having launching capabilities. With that increased and diversified activity, having structure and norms of behavior for operating in space becomes critical to ensure safe operations for everyone.

In the United States and internationally, safe operations in space are governed by few regulations. The Outer Space Treaty of 1967 and associated treaties provide some basic international structure for operating in space, including definitions of ownership and responsibility but little in the way of practical operations structure. On June 21, 2019 United Nations Committee on the Peaceful Uses of Outer Space (UN COPUOS) adopted a preamble and 21 guidelines for the long-term sustainability of space.[2] These voluntary guidelines represent practices that would improve the safety of space operations. The guidelines cover a wide range of topics, including the importance of national regulations and what to include in those regulations, the promotion of information sharing, encouragement of operations safety practices like collision avoidance, and promotion of safety-related research.

Orbital debris mitigation is one of the subsets of STM where there has been more success at generating guidelines, best practices, and standards both within the U.S. and in the international community. Within the United States, the Orbital Debris Mitigation Standard Practices (ODMSP) were recently updated[3] and contain rules followed by U.S. government organizations. Organizational standards such as NASA’s Standard 8719.14[4] and Air Force Instruction 91-202[5] describe debris mitigation requirements in more detail. For U.S. commercial space systems, the Federal Communications Commission (FCC), Federal Aviation Administration (FAA), and National Oceanic and Atmospheric Agency (NOAA) all include debris mitigation requirements as part of their licensing processes. Internationally, the Inter-Agency Space Debris Coordination Committee (IADC) has developed and revised consensus guidelines.[6] The International Organization for Standardization (ISO) includes international standards for debris mitigation.[7] Other nations have their own debris mitigation rules or, as in France, legal requirements for debris mitigation.

Currently, the Combined Space Operations Center (CSpOC) under the U.S. Space Force’s Space Operations Command (formerly the 14th Air Force) has the responsibility to track objects on orbit for the nation. Because of its capabilities in this role, as well as the risk of collision as highlighted by the debris-generating 2009 collision between the active Iridium 33 and inactive Cosmos 2251 satellites, CSpOC also has taken on the task of providing conjunction warnings for operational satellites from around the world. Other organizations also contribute to space safety: e.g., the NASA Goddard Spaceflight Center Conjunction Assessment Risk Analysis (CARA) team provides collision warnings predominantly to NASA satellites using data provided by the CSpOC, and space agencies in other countries actively follow risks to their own satellites.

Space activity and space operations are undergoing one of the largest changes since the beginning of the space age.[8,9,10] The substantial increase in commercial space activity, including participation from around the world, is both crowding and democratizing space—pushing the quantity and nature of space operations well beyond the traditionally government-dominated activity of the past, and challenging existing processes. With the advent of large constellations of hundreds or thousands of satellites, the number of operational satellites may increase by an order of magnitude or more over the next decade. The development of small satellites, including CubeSats, has opened up space to a whole range of organizations that previously would have been unable to afford satellites. These include universities and even high schools. The democratization of space means that there will be significantly more operators than in the past and many will have relatively little experience in space. This diversity of space operators also includes an expansion of international operators outside of the traditional spacefaring counties adding to the complexity of coordinating space activities, requiring a broader-than-traditional U.S.-centered approach to ensure safe space operations practices are followed.



Significantly increased launch traffic and expanded space tracking capabilities will increase both the number of objects in space and the number of objects that can be tracked and need to be avoided. The plot above illustrates both changes.

The plot shows the number of objects by altitude. The purple region on the left shows what is currently tracked by the Air Force Space Surveillance System. This includes both active satellites and debris. The orange region shows the distribution of objects with the improved tracking capabilities of the Air Force Space Fence. The blue region shows the distribution of potentially mission-ending objects down to 1 cm in size. Improved tracking capabilities beyond Space Fence will reveal more of this currently untracked region.

The dark blue dots on the right illustrate the altitude locations of some existing systems. The green and yellow dots show proposed commercial constellations and their possible operational sizes. Although not all of these proposed systems will be launched the scale of the increase in the number of active satellites these systems represent can be seen.

The large increases in the numbers of operational satellites and the number of tracked objects provide challenges for implementing an efficient system for safe space operations and space traffic management.

New classes of missions are being developed, including on-orbit servicing, mission life extension, and active disposal at end of life, which involve a servicing spacecraft rendezvousing with a customer satellite to provide the requested service. The range of orbits for operational use is also expanding to include elliptical and inclined geostationary orbits, medium Earth orbits, and cislunar space, which have seen only modest use in the past. New modes of operation are also being developed. Along with rendezvousing with other satellites, operators are employing extensive use of low-thrust propulsion and non-propulsive maneuvering techniques like changing satellite orientation to change the effects of atmospheric drag. These new capabilities allow frequent and autonomous station keeping and collision avoidance, but also complicate satellite tracking and maneuver coordination. All of these changes make tracking and maintaining awareness of the space environment more difficult and add to the challenges of safe space operations at a time when the United States' approach to STM is changing.

Space Surveillance in the Context of STM. The U.S. STM organizational structure is in transition. In 2018, SPD-3 stated that the U.S. Department of Commerce (DOC) would take over the public STM role from the Air Force to allow the Air Force to focus on its primary mission—and having a civil agency lead the nation's STM efforts might also facilitate international and commercial cooperation. This transition required action from Congress to define and allocate the responsibilities between organizations and provide the associated funding to the DOC.

Although two or more bills have been introduced in Congress to transition STM responsibilities to a civil agency, to date none has been enacted into law. There is still discussion at the congressional level about whether the DOC or another civil agency should take on the U.S. STM responsibilities (in late August, a congressionally mandated independent report from the National Academy of Public Administration endorsed the DOC taking on the STM role).[11] The DOC has assigned this role to its Office of Space Commerce but cannot fully execute the needed programs to complete the civil transition until Congress acts. The agency will need to create the required organizational and technical structure to take on the role. This leaves the United States in an extended transitional period which is occurring while space activities are rapidly changing. If the space operations changes occur before the nation has clear organizational, technical, and regulatory structures in place, implementing an effective STM strategy will be significantly more complex.

While there is a growing consensus on the need to transition STM to a civilian agency,[12] an inability to legislate the decision on which agency or to resource that agency to execute the mission keeps the mission in the Department of Defense. Moving forward on the assignment of responsibility of and funding for STM is recognized by many space operators as critical to enable the United States to progress in advancing STM capabilities and safe space operations, both within the nation and in coordination with international entities.

Key Action 1. **Establish the identity of the entity that will provide basic space situational awareness and STM services to all satellite operators and provide the resources and authorities to do so.** Critical changes in space operations are underway. The government needs to be in a good position to maintain safe space operations through the changes. There are differences between the various candidate organizations that are significant, but the pace of change in space operations means that the decision is needed soon. Much technical work is needed to establish a civil space traffic management capability. Operating in space is an intrinsically global endeavor as the location and operation of satellites literally spans the globe. As such, one of the primary needs of a U.S. STM agency is to facilitate information gathering and sharing. It must also facilitate the associated coordination of activities, such as collision avoidance, that the collected data enables and are required for effective STM. Once a civil agency is chosen, one of its major tasks will be determining how to orchestrate the required data flow and coordination activities.

Key Action 2. **U.S. leaders should work with international counterparts to harmonize global STM practices and regulations.** Space is an intrinsically global environment, so bad actors affect all users of space.

The area of space surveillance, or keeping track of where things are and where they are going in space, is rapidly changing. Historically only a few government agencies around the world were capable of systematically tracking objects in orbit. For the United States, this was the Air Force. Recently the number of countries tracking space objects has been expanding. In addition, a number of countries have been increasing their capabilities either individually, such as Australia and Japan, or in cooperation as seen with the European Union Space Surveillance and Tracking (EUSST) consortium, which as of 2020 consists of eight member states.[13]

In parallel with government expansion of tracking capabilities, several commercial companies including LeoLabs, Numerica Corporation, and ExoAnalytics have developed their own space object tracking capabilities. These systems, both radar and optical, can collectively observe low and high-altitude orbits and represent an entirely new set of non-government players in space surveillance.

One of the big changes in space operations is the dramatic increase in the number of commercial satellites, surpassing those of government entities. Very often, satellite operators will have detailed knowledge of their satellites' orbits as well as foreknowledge of orbit maintenance and repositioning maneuvers. If shared, this information can add a whole new level of accuracy to the orbit knowledge for these satellites. The Space Data Association currently uses orbit data provided by its satellite operator members to perform collision avoidance assessments for its members' satellites.

It should be noted that more data is not necessarily better data. A civil agency responsible for STM will need to develop techniques to validate, calibrate and incorporate all of these data sources, and to integrate them with traditional U.S. Space Force-generated data. The integration of beneficial data sources is needed in order to have a full and accurate picture of what is going on in space; this is the first critical step to effective STM.

There are numerous challenges associated with effective data integration, the first being organizational. Even using data from within the U.S. government will present difficulties, especially when considering the differences between data management in a military vs. a civil organization as well as "ownership" issues. The civil agency will also need to develop data sharing relationships with allied space surveillance systems and work out the data sharing protocols that will be needed for routine exchange of information within constraints of operating internationally.

Commercial tracking data providers present a different set of challenges: they generate tracking information for profit, so a mechanism is needed to enable the civil agency to use the data for its purposes while still allowing the commercial companies to sell to other users. New mechanisms will also need to be developed to incorporate commercial satellite operator data into the civil agency's STM system. This is particularly important as commercial operators launch systems with large numbers of satellites and for those who are planning frequent orbit adjusts or station-keeping maneuvers. Without a process for rapidly incorporating and disseminating STM service data, it will not be possible to maintain safe space operations in the dynamic environment of the near future.

One of the primary STM-related tasks for which tracking information is used is to provide conjunction warnings. The paths of satellites are projected into the future, typically a few days to a week. Times are identified where there are particularly close approaches which might result in collisions. Future collisions cannot be absolutely determined because there are uncertainties in predicting where objects on orbit will be. Reducing these uncertainties limits the false alarm rate for potential collisions and makes for a more effective collision avoidance system.[14]

Although more tracking information can reduce the uncertainties, the utility of the tracking data and how much it adds to the overall knowledge of a satellite's orbit, is dependent on several factors beyond accuracy. The approaches for combining ground-based sensor data, space-based data, and data from satellite operators are different as are the combination of different sensor types like radar and telescope information. All of this adds to the difficulties that must be overcome by a civil STM agency to develop an efficient collision avoidance system.

Key Action 3. **Once authorized and funded, the STM organization's leadership should partner with commercial data and service providers, satellite operators, and international organizations to combine data and develop a set of services that meet the basic needs of space operators.** Many new data sources are being developed with the potential to greatly increase space safety. Data needs for safer space operations include:

- **Very accurate and timely data on all objects of sufficient size to seriously damage or destroy a satellite or damage a launching vehicle.** More complete data is required to provide basic space safety services in an increasingly crowded and dynamic space environment.

- **Warning messages to operators must be clear, consistent, and accurate.** Improved data quality would decrease false alarms and increase safety of flight.

Orbital Debris Mitigation and Management

One of the areas within the scope of STM that has received the most attention both nationally and internationally is orbital debris mitigation. The United States developed its Orbital Debris Mitigation Standard Practices (ODMSP) in 2001. The 2010 National Space Policy and subsequent directives[15] require U.S. government organizations to comply with the ODMSP. Exceptions to meeting the best practices require approval at the department or agency level, giving debris mitigation compliance high visibility. In November 2019, ODMSP was updated per guidance in SPD-3 and included many more quantitative requirements that had previously been included in the NASA Standard and Air Force Instructions.

Internationally, the Inter-Agency Space Debris Coordination Committee (IADC), a group of the 13 primary national and international space agencies, provides technical insight into the debris problem. The IADC developed a set of mutually agreed-upon debris mitigation guidelines in 2002, updated in 2007 and again in 2020. In 2010 the International Standards Organization (ISO), which includes both government and commercial participation, developed a debris mitigation standard (ISO 24113), which was updated in 2019. In the summer of 2019, the United Nations Committee on the Peaceful Uses of Outer Space agreed to 21 guidelines for improving safe space operations. Each of these organizations includes a different subset of the space operations community. In all of these cases the guidelines or rules are non-binding. Individual countries have decided to adopt aspects of IADC guidelines into their own national-level rules or laws or have required the application of ISO standards to contracts.

One of the major challenges with space is that poor debris mitigation practices can quickly affect all space operators. The Chinese anti-satellite test in 2007 generated more than 3,000 trackable objects and hundreds of thousands of untrackable but hazardous debris. That debris has resulted in numerous conjunctions and some collision avoidance maneuvers for other operators and may also be the source of some small debris that has impacted active satellites. It is in the best interest of the United States to disseminate its guidelines and best practices for debris mitigation to the other spacefaring nations if for no other reason than to protect U.S. assets.

There is no one international organization or document that controls the behavior of all nations with respect to debris mitigation, making distribution of norms a challenge. Effectively dissemination of debris mitigation best practices will require the United States to engage with international partner organizations to broadly influence thinking on debris mitigation issues. A similar situation exists for STM as more best practices are developed. Without a single international organization with broad responsibilities, a distributed approach will be required. Currently, U.S. influence is exerted through active participation in IADC working groups, via the Department of State at the United Nations and other organizations, and via interactions at international conferences and forums such as ISO.

Techniques have been developed to better understand the effects of space activities on the orbital debris environment and therefore on future space activities. These capabilities exist both in the United States and in other nations and make it possible to generally understand what types of actions need to be taken to move the evolution of the debris environment in a particular direction. The major component that is missing is *how much* of each of these actions needs to be taken.

There are currently no clear limits defining what is and is not acceptable with respect to the effects of the orbital debris environment on space operations. Current rules are typically based on individual organizational decisions rather than broader purposeful choices as to what is an acceptable consequence or risk. Without this specificity, it is possible to point in a preferred direction (e.g., limit the growth of debris) but not provide more specific instructions on what needs to be done to direct actions toward the specific goals and effectively balance cost and benefit. Without a more definite decision on what is "acceptable" it would be easy to either do too much, which will create excess costs now, or too little and create significant costs in the future when space systems are forced to operate in an unacceptable debris environment. This issue will become a problem in other STM-related areas as development of best practices advances. Purposefully choosing what is "acceptable" will enable the United States to clearly define the required levels of and types of activities needed to keep the debris environment within "acceptable" limits. It will also provide concrete and justifiable targets for which the nation can advocate with the rest of the spacefaring nations.

Key Action 4. **Establish definitions of nationally "acceptable" thresholds for orbital debris and space safety consequences.** A clear understanding of where the lines need to be drawn for effects on operations, such as conjunction frequency, will enable consistent regulations.

Once the "acceptable" limits are defined, mechanisms need to be developed for monitoring, increasing, and perhaps eventually enforcing compliance. Producing new treaties with direct requirements for adherence will be very difficult, as illustrated by the long development time and incomplete success of the non-binding UN COPUOS Guidelines for the Long-Term Sustainability of Outer Space Activities. Other mechanisms exist including IADC, leading by example, use of international standards like ISO, encouraging voluntary rule adoption like the Space Safety Coalition (SSC), and encouragement techniques like the World Economic Forum Space Sustainability Rating.[16]

Within the United States, the commercial regulatory structure for debris mitigation, which is more developed than other facets of STM, is distributed among a number of organizations including the FCC, FAA, and the DOC. As the level of commercial activity increases, it will be important to streamline the U.S. debris mitigation regulatory processes.[17] As the U.S. civil STM capabilities develop, coordinating the debris mitigation regulatory structure with the STM organization will also be necessary, since there is significant overlap between debris mitigation and safe space operations. An inefficient system will hamper U.S. companies when competing with the rest of the world.

Key Action 5. **Organize and streamline the U.S. regulatory structure for debris mitigation.** A more efficient regulatory system coordinated with other STM-related efforts will ensure the United States remains a location of choice for commercial space operators.

Space Safety Regulations for Future Space Operations

The rapid pace of change in the space industry necessitates both the rethinking of organizational and regulatory approaches to space operations. Focusing on what needs to be done for safe space operations—performance, rather than specifically on *how* to do it—will provide greater flexibility and encourage new approaches to operating safely. The use of performance-based regulations versus prescriptive rules will enable innovation especially from commercial endeavors. It will also place emphasis on the need for sound technical justification for rules and more technically complex capabilities to assess compliance. In order to support effective performance-based regulations, supporting technical justification and substantiating data are critical. Essentially, the justification explains why specific performance goals are set and what they accomplish. More sophisticated assessment capabilities are also needed to evaluate new approaches and determine if a proposed solution meets requirements.

The regulations will need to be applicable both to individual satellites as has been done historically, and to large constellations of satellites. Aggregated risks from individual constellations can far exceed individual satellite requirements.[18] An illustration of this approach is in the 2019 ODMSP with reference to limiting reentry risk from a whole constellation. Flexible, well-substantiated debris mitigation practices will be far easier to propagate into the international community, which is essential for any successful efforts to mitigate the risk from the orbital debris environment.

Key Action 6. **Establish performance-based, technically justifiable rules based on the "acceptable" consequences and then disseminate globally**. It is essential that best practices be followed by all space operators, and rules need to be flexible enough to accommodate the rapid pace of technology change while still resulting in the desired outcomes.

Key Action 7. **Establish technical expertise to provide the knowledge to develop effective rules and to evaluate the diverse implementations of those rules by space operators.** This capability is necessary to develop and enforce performance-based rules.

Conclusion

Space operations are changing rapidly and will have profound effects on how and by whom space is used. The implementation of norms of behavior for safe space operations is critical for ensuring effective use of space in the future. The United States needs to be a leader in the effort to guarantee that space operations remain unimpeded by risks to operations. Seven Key Actions have been discussed to establish the organizational and technical capabilities needed to develop safe space practices and effectively disseminate them to the space community. Establishing these capabilities will allow the United States to guide the development of global space traffic management in this rapidly changing environment.

References

[1] Space Policy Directive-3 National Space Traffic Management Policy (https://www.whitehouse.gov/presidential-actions/space-policy-directive-3-national-space-traffic-management-policy/).
[2] Guidelines for the Long-term Sustainability of Outer Space Activities (https://www.unoosa.org/res/oosadoc/data/documents/2018/aac_1052018crp/aac_1052018crp_20_0_html/AC105_2018_CRP20E.pdf).
[3] U.S. Government Orbital Debris Mitigation Standard Practices, November 2019 (https://orbitaldebris.jsc.nasa.gov/library/usg_orbital_debris_mitigation_standard_practices_november_2019.pdf).
[4] NASA Standard 8719.14 (https://standards.nasa.gov/standard/nasa/nasa-std-871914).
[5] AFI 91-202 (https://static.e-publishing.af.mil/production/1/af_se/publication/afi91-202/afi91-202.pdf).
[6] Inter-Agency Space Debris Coordination Committee Space Debris Mitigation Guidelines (https://www.iadc-home.org/documents_public/file_down/id/4204).
[7] ISO 24113: Stokes, H., Y. Akahoshi, C. Bonnal, R. Destefanis, Y. Gu, A. Kato, A. Kutomanov, A. LaCroix, S. Lemmens, A. Lohvynenko, D. Oltrogge, P. Omaly, J. Opiela, H. Quan, K. Sato, M. Sorge, and M. Tang, "Evolution of ISO's Space Debris Mitigation Standards," 1st International Orbital Debris Conference, Sugar Land, TX, December 2019.
[8] Space Traffic Management in the New Space Age, Muelhaupt, Sorge, Moring, Wilson, Journal of Space Safety Engineering (2019) 80-87.
[9] Glenn E. Peterson, Marlon E. Sorge, William H. Ailor, Space Traffic Management in the Age of New Space (https://aerospace.org/paper/space-traffic-management-age-new-space).
[10] Jamie Morin, "Four steps to global management of space traffic," *Nature*, March 5, 2019 (https://www.nature.com/articles/d41586-019-00732-7).
[11] National Academy of Public Administration, "United States Department of Commerce: Space Traffic Management," (https://www.napawash.org/studies/academy-studies/united-states-department-of-commerce-office-of-space-commerce), August 19, 2020.
[12] "Space Traffic Management," A Report by a Panel of the NATIONAL ACADEMY OF PUBLIC ADMINISTRATION for the United States Department of Commerce (https://www.napawash.org/studies/academy-studies/united-states-department-of-commerce-office-of-space-commerce).
[13] European Union Space Surveillance and Tracking (https://www.eusst.eu/).
[14] Peterson, Sorge, McVey, "Tracking Requirements for Space Traffic Management in the presence of Proposed Small Satellite Constellations," 69th International Astronautical Congress, Bremen Germany, October 2018.
[15] Barack Obama, "National Space Policy of the United States of America," PPD-4, June 28, 2010 (https://aerospace.org/sites/default/files/policy_archives/National%20Space%20Policy%2028Jun10.pdf).
[16] Rebecca Reesman, Michael P. Gleason, Slash the Trash: https://aerospace.org/paper/slash-trash-incentivizing-deorbit
[17] Marlon E. Sorge, Commercial Space Activity and Debris Regulation (https://aerospace.org/paper/commercial-space-activity-and-debris-regulation).
[18] William H. Ailor, "Large Constellation Disposal Hazards," Center for Space Policy and Strategy, The Aerospace Corporation, 2019.

CENTER FOR SPACE POLICY AND STRATEGY

APRIL 2020

SLASH THE TRASH: INCENTIVIZING DEORBIT

REBECCA REESMAN, MICHAEL P. GLEASON, LAYLA BRYANT, AND COLLEEN STOVER
THE AEROSPACE CORPORATION

AEROSPACE

Summary

There is likely to be a surge of satellites launched into space over the next decade, which means the risk of collisions in space will rise along with risks to the sustainability of the space environment from debris. How can the sustainability of the space domain be protected in a looming new era of increasingly congested space? How can the international space community reduce these risks and make them more manageable? One vital method is for satellite owners and operators to voluntarily comply with the already internationally agreed-upon guideline to deorbit satellites no longer than 25 years after the end of their mission. This paper outlines five distinct concepts to incentivize compliance with the "25-year rule" and provides a framework for analyzing the merits of each concept. It focuses on commercial satellites in low Earth orbit but could be applied more broadly.

Introduction

Since the Space Age began more than 60 years ago, almost 9,000 satellites have been placed in orbit, with about 5,150 still there and about 2,207 of those still operational as of October 2019.[1] In 2019, commercial companies proposed satellite constellations ranging from around 1,000 to 30,000 satellites each, totaling 46,000 or more new satellites in orbit over the next decade. This potential rise in the number of satellites in such a short period of time means the risk of collisions in space will rise. The resulting space debris, along with the new vehicles themselves, will affect the overall sustainability of the space environment. While it is unlikely that all the planned satellites will be launched, we are on the cusp of a fundamental change in the space environment.

Some satellites function for decades but many cease to be useful after only months or a few years. "Dead" satellites, or satellites that have reached end-of-mission life, can remain in valuable and densely populated orbit regions and present major risks to the space environment—all related to debris. Dead satellites can collide with other satellites—dead or alive—generating debris.[2] Additionally, a dead satellite can break up when old batteries or leftover propellant explode, creating a cloud of expanding space debris. The bigger the satellite, the more debris that can be produced from an explosion or a collision. Debris is dangerous to both satellites still performing their mission and to other debris objects. Similarly, debris does not discriminate between targets from the commercial or government sector.

For decades, the international community has been aware of the growing risk to orbital operations caused by space debris. One of the most important principles created internationally is from the Inter-Agency Debris Coordination Committee (IADC) and is drawn from the 2002 *IADC Space Debris Mitigation Guidelines*, which recommends that satellite operators should remove spacecraft and orbital stages from useful and densely populated orbit regions no longer than 25 years after mission completion.[3] It started as a 25-year guideline that has been incorporated into some regulation and, hence, is often colloquially referred to as the "25-year rule." This rule helps operators be responsible users of space by protecting and sustaining the operational environment for all users.

Analysts and scientists argue that the simplest and most efficient way to mitigate the growth of space debris is for satellite operators to increase the rate of compliance with the 25-year rule. Unfortunately, compliance rates have been poor,[4] and there is growing need for drastic improvement. In addition to the imminent boom in the number of satellites, an increasing diversity exists in both the size and capability of satellites and satellite constellations. The current approach will not scale to the expected increases from satellite constellations consisting of hundreds or thousands of satellites. Nor does the current approach account for the short mission lives of CubeSats, which represent a growing sector of the satellite industry. In fact, a 2015 NASA report found that one out of every five CubeSats launched between 2003 and 2014 violates international deorbiting guidelines.[5] The projected increase in collision risk could be mitigated by complying with the 25-year rule and reducing the overall number of years in orbit after the end-of-mission life, especially when considering relatively short mission lifetimes.

Commercial satellite owners and operators need better incentives to comply with the 25-year deorbit rule and reduce the overall number of years that dead satellites occupy the most crowded orbits. Five distinct concepts to incentivize voluntary compliance to deorbit and a framework for evaluating them or any other voluntary deorbit concept are discussed herein.

Deorbiting a Satellite from LEO

This discussion focuses on low Earth orbit (LEO) satellites, but similar concepts could be applied to other orbits. Satellites in LEO are used for remote sensing, Earth observation, human spaceflight, and more. LEO is the most crowded orbit.

Satellite operators use two primary means to deorbit a satellite from LEO. Satellites below 600 km will naturally deorbit within 25 years due to drag from the atmosphere. This is very efficient for operators since they do not have to take any action or incur any costs; however, it still poses a risk to other satellites in operation as the unguided satellite passes through lower altitudes.

On the other hand, satellites above 600 km generally do not deorbit naturally within the 25-year time frame and require direct action to comply. In fact, this is where the greatest concentration of LEO satellites resides—from 800 to 1,000 km.[6] Complying with the 25-year rule generally requires a guidance system and the use of thrusters or deployment of a drag enhancement device to lower the orbit. Satellites are not required to have this capability and controlled reentry comes with costs. Many satellites can complete their mission without these capabilities and without the added expense in terms of satellite complexity, weight of thrusters and propellant, or drag enhancement devices. Designing a satellite with such added weight and complexity simply to crash it into the atmosphere at the end of

> An ***uncontrolled reentry*** is when a spacecraft's orbit naturally decays through lower orbits until reentry. The reentry location is undetermined beforehand and poses possible risk to people and property if components survive reentry. This is more the case for upper stages than for satellites.
>
> A ***controlled reentry*** is when the spacecraft fires its thrusters to place it on a trajectory to avoid objects in lower orbits and reenter—usually in an unpopulated region in the South Pacific.
>
> Controlled reentry is the preferred means to deorbit but requires functioning guidance and control systems with thrusters.

its mission provides no direct gain for the owner or operator in terms of accomplishing the satellite's mission or in generating revenue. Meanwhile, some satellites have thrusters and propellant to enable their functionality and make them profitable. Using the propellant to deorbit—to crash and burn—then, reduces the profit made from that satellite. Without economic or other incentives for timely, controlled reentry, operator compliance with the 25-year rule for orbits above 600 km will likely remain low. See Figure 1 for how long it typically takes satellites to naturally deorbit as a function of their altitude.

Benchmark Guidelines

Space activities occur in an inherently international context. The 1967 United Nations (UN) Outer Space Treaty[7] establishes that all states are equally free to use space and have the right of freedom of access to space. It also establishes that no state can claim sovereignty over any part of space and prohibits the testing and placement of weapons of mass destruction in space. As of January 2019, 132 countries have either ratified or signed the treaty.

The 1972 UN Space Liability Convention[8] makes a country liable for damage caused by objects launched from its soil. As of January 2019, 116 countries have either ratified or signed the treaty. Many of them developed corresponding domestic licensing regulations with varying levels of attention given to mitigate debris and reduce chances of collisions. For example, the *U.S. Government Orbital Debris Mitigation Standard Practices* established in 2001, and updated in 2019, has a 25-year deorbit rule similar to the French *Space Operations Act* from 2010. Both the U.S. guideline and the French law state that a satellite or launcher element shall reenter the Earth's atmosphere no more than 25 years after its end of mission date naturally or by performing a controlled reentry.[9]

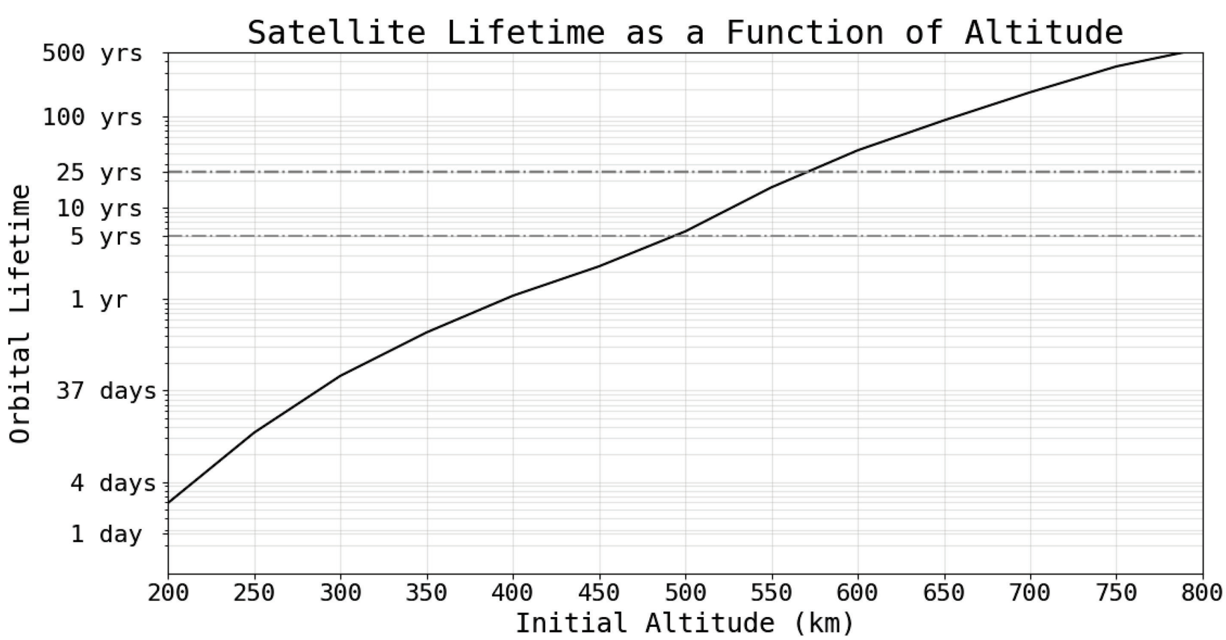


Figure 1: Approximate time it takes a satellite to naturally decay given a starting altitude. *Specific reentry times depend on size and other parameters.*

As mentioned previously, the IADC debris guidelines came into being in 2002 and were used as a basis for the 2007 UN Space Debris Mitigation Guidelines. In 2019, the International Organization for Standardization (ISO) issued standard 24113, which aims for a 90 percent disposal success rate. Important to note is that these most recent attempts to limit debris are *nonbinding* agreements, and organizations and governments are encouraged to use them when mission planning. At a minimum, they are politically binding. Besides the Outer Space Treaty and the Liability Convention, there are no international, legally binding agreements that restrict or mandate actions in space, including deorbiting.

Although scholars are divided on the topic, high value, widely used regions of space such as LEO could be viewed in economic terms as a *common pool resource*.[10] Common pool resources are typically defined as goods that are "rival," meaning that one actor's consumption of the good prevents another from also consuming it, and which are relatively "non-exclusive," meaning that it is costly to prevent others from consuming them. Key orbital regimes can be susceptible to overuse, where all stakeholders will have diminished benefits if each pursues maximum activity at minimum cost in their own narrow self-interest, largely due to the increased risk of collisions creating debris that will reduce the statistical life of other missions. The Outer Space Treaty gives all states equal rights to access space and conduct missions there. Classic examples of common pool resources in the economic literature are open ocean fish stocks and underground water sources that cross borders.

Existing international treaties and guidelines, as well as domestic laws, have been useful in avoiding some of the classic tragedies of the commons in space but may not be sufficient. With large increases in activity planned in LEO, considering additional methods to effectively manage that orbit is timely. Indeed, many satellite companies desire an international solution to develop and enforce end-of-mission requirements according to a 2015 report on space debris.[11] Interviews with more than 80 commercial satellite operators show they understand the consequences of overuse and indicate that companies might be willing to bear some costs to maintain the space environment. The commercial satellite sector functions like other commerce in a competitive global marketplace; that is, it crosses borders and is incentivized by maximizing profit. A single country cannot set deorbit requirements without potentially losing commerce to other countries as owners and operators seek to avoid the higher costs of compliance (e.g., shorter mission life, satellite propellant, thrusters, and complexity) by moving elsewhere. This also encourages new spacefaring countries to not regulate as heavily or follow costly, voluntary international norms as they try to attract space commerce to their shores. Analyzing key orbital regimes through a common pool resource lens provides some ideas on several paths forward.

A Framework for Evaluating Voluntary Compliance Concepts

Scholars, most notably Elinor Ostrom, have shown that a consistent set of design elements matter greatly in the design of successful management regimes for common pool resources.[12] This paper suggests that Ostrom's framework is applicable to incentivizing deorbit within the 25-year rule parameters.[13] Table 1 represents a subset of Ostrom's design elements that are most relevant to incentivizing voluntary compliance with the deorbit rule. This set of design elements informs the framework for assessing incentivizing concepts.

Table 1: Common Pool Resource Management: Most Applicable Design Elements

- All stakeholders affected by the management regime are allowed to participate in its rulemaking.
- Penalties for rules violations exist to minimize cheating and free-riders. Penalties for violations should start very low but progressively become stronger if a user repeatedly violates a rule.
- A mechanism for rapid, low cost, dispute resolution exists, and is considered credible by stakeholders.
- Participants are not locked into participating in the management regime. They could exit the management regime if desired. Similarly, they may rejoin when they perceive it to be in their interest.
- Costs are distributed fairly.
- The condition of the resource is monitored by those that are considered credible by stakeholders. Such an entity may include users and other stakeholders.
- Users of the resource are monitored for compliance with the rules by a monitor considered credible by the users. Users and other stakeholders may provide this monitoring function.
- The fairness of resource allocation, management decisions, and dispute resolution are monitored by those considered credible by the users. Users and other stakeholders may provide this monitoring function.
- Good communication among stakeholders is a prerequisite because it facilitates trust and increases cooperation among participants.
- Complete, accurate, and timely information sharing among stakeholders is crucial for verifying all the elements of a resource management regime.

With these design elements in mind, the framework for evaluating voluntary compliance concepts consists of four categories:

1. ***Control*** – the ability of satellite owners and operators to have a significant level of control over the development, monitoring, and enforcement of rules in the pursuit of space sustainability. Bringing owners and operators into the management and rule-making process increases their understanding and support for the rules and further reduces pushback when it comes to enforcing them. Stakeholders may also be free to exit the system, for example, if they feel cheated.

2. ***Financial*** – the economic cost. Satellite owners and operators are more likely to comply if it would lead to reduction in cost. However, economic cost also refers to costs being fairly distributed among owners and operators, "a level playing field" so to speak. As Ostrom points out, stakeholders are much more likely to comply with deorbit rules if the costs are spread fairly. Managing progressively more severe penalties for repeated violations is also important.

3. ***Social*** – the reputation among stakeholders and peers. When managing common pool resources, elements that improve a stakeholder's reputation can be key. Ostrom argues that when participants' reputations are known to others, the likelihood of cooperation increases.[14] Social capital applied in this context refers to the public, potential investors, and customers having a positive impression of a satellite company. Social capital can be built with peers, the media, investors, governmental entities, or the public at

large. Owners and operators who show a commitment to sustain space and protect future endeavors in space can reap direct benefits in terms of increased investment, positive "brand" recognition and media coverage, and increased public and governmental support. Alternatively, both government and commercial operators who damage the space environment for other users may be socially, reputationally, (and financially) castigated. States ultimately carry the responsibility to "authorize and continuously supervise" commercial activities as required by the Outer Space Treaty (Article 6), so a state's reputation in the international community is also at stake.

4. ***Rules*** – Minimization of the burden for stakeholders to comply is fundamental to any *voluntary* incentivized compliance system. Rules can come from governmental or organizational entities—even a voluntary system should not overly burden participants. Thus, this is different from *Control*, which tells who (government, private markets) is making the rules. In terms of government-imposed rules, if the country in which owners or operators are based has a lengthy, expensive licensing process, they might seek to move their companies to a country with more lenient rules. Owners and operators often recognize the need for some governmental regulation or rules in order to create regulatory certainty with their investors. Striking the right balance is the trick.

Five Concepts to Incentivize Deorbit

There are several models for managing common pool resources, starting with either direct government management or private market alternatives. Private markets are created when governmental authorities parcel out a common pool resource at the start, then allow a marketplace to develop in which private stakeholders can pursue their self-interest within government-defined rights and enforcement of contracts.

However, Ostrom argues that many successful common pool resource management institutions are a rich blend of "private-like" and "public-like" institutions. They are neither exclusively private institutions or markets nor completely government institutions. She refers to these blended institutions as *clubs*.[15] A club (or consortium, cooperative, or coalition) can include both private and governmental stakeholders who are free to join so long as they abide by the rules and may leave at any time. It should be noted that these also require a "government hand" to create the conditions that allow such clubs to be implemented and lend legitimacy to their authority. Using these approaches, five concepts to incentivize voluntary compliance with the 25-year deorbit rule are outlined here. While not an exhaustive list, it shows a range of concepts using these models. The concepts are not mutually exclusive—a combination of them could be considered to yield the best result—but they will be examined separately.

Assumptions

The following assumptions (in no particular order) were applied to the management concepts:

- All concepts are technically feasible (i.e., they use existing technologies).
- Concepts can use existing international treaties or laws; however, new structures may be needed and could be implemented using regular international negotiation channels.
- Concepts can begin as domestic constructs; however, they may be extended internationally.
- Concepts may require development of domestic policy, rules, regulations or legislation.

1. Direct Government Management

The current model involves direct management by governments and governing bodies that voluntarily abide by international agreements and guidelines and then shore them up with domestic laws, licensing procedures, and enforcement. This domestic enforcement can come from governing bodies such as that from the European Space Agency that requires companies with whom they contract to follow ISO standard 24113, which includes the 25-year rule. Nations will often create more stringent guidelines, using the standards as a starting point.

The current model is unevenly distributed around the globe. Since not all spacefaring countries have the same laws, a risk exists to "race to the bottom," where the nation with the least environmentally responsible regulations becomes the home of choice for space operators, similar to how Liberia or Panama became the preferred countries for registering ocean-going vessels.

2. Mandatory Satellite Collision Insurance

Presently, satellite insurance serves to lessen the owner's and operator's financial risk for launch plus one year on orbit. However, working to extend this private insurance market to include collision risk would encourage voluntary debris mitigation compliance. Launch-providing countries could require collision insurance for the entirety of a satellite's time on-orbit and provide incentives to "good steward" companies. Similar to good driver discounts for auto insurance, satellite collision insurance would incentivize satellites to deorbit in a timely manner to reduce collision risk with higher premiums for those owners and operators that do not comply. For operators that deorbit well *before* the 25-year mark, insurance companies may offer even lower premiums. This is especially important for reducing the number of overall years that a satellite is on orbit and benefits operators of CubeSats with very short mission lives. This could lead to a financial incentive for satellite companies since space insurance is the third highest program cost to satellite operations after satellite and launch services.[16]

A requirement for on-orbit insurance is already being explored. The 2008 French Space Law contains an insurance requirement for on-orbit risks. In 2018, the United Kingdom passed the *Space Industry Act*. Section 38 of the act requires holders of on-orbit operations licenses to have third-party liability insurance. However, insurance typically does not go past launch plus one year on orbit since this period has the highest rate of incidents for satellites. For this model to be financially equitable all spacefaring nations must adopt concurrent insurance requirements for all commercial satellite operators.

3. Industry Consortium

An industry consortium (or club, as Ostrom would call it) is a bottom-up approach that creates buy-in from stakeholders and enables voluntary, consensus-based standards, guidelines, and best practices for safe deorbiting. A successful industry consortium needs participation from major companies that own and operate the majority of commercial satellites around the world to foster equity and support for the system. This concept also offers some degree of social benefit to member owners and operators as well as perks of membership. Membership is voluntary, so it offers a degree of control as well.

There are several analogous efforts in the works that could function as a model for building a space industry consortium. The Consortium for the Execution of Rendezvous and Servicing Operations (CONFERS)[17] is actively trying to create industry consensus standards and norms of behavior for on-orbit satellite servicing. The Space Safety Coalition is taking a lead in protecting the sustainability of the space domain. The Space Data Association shares information on orbital positions and notifies commercial and government members of collision risk. Multiple consortia can coexist, covering a broad spectrum of activities. Governments, governing bodies, and major operators could provide funding or regulatory frameworks and contract enforcement mechanisms to enable new consortiums and to assist in the development and legitimization of their charters.

4. Sustainability Rating, Certifications, and Awards

An independent, unbiased entity that awards participants with a space sustainability rating could also incentivize voluntary deorbiting. The awarding entity, which may be a consortium**,** could provide space sustainability ratings, certifications or awards to owners and operators that comply or favorably exceed best practice guidelines and rules. Similar models are used to incentivize environmentally sustainable practices across many industries such as the airlines, construction, fashion, home furnishings, and food. Voluntary compliance creates buy-in, establishes credibility, and offers social capital and reputational benefits to adopters, without forced regulation, although there may be membership dues, branding fees, and other associated costs associated with this concept. In the long run, sustainability ratings might contribute to the development of positive norms of behavior.

In May 2019, the World Economic Forum (WEF) designated a consortium of companies, universities, and agencies to develop a system to rate the sustainability of space systems to incentivize responsible behavior in space.[18] As with other concepts, this offers a platform to incentivize deorbit *before the 25-year rule* for added reward, which will further reduce the number of years in orbit post-mission.

5. Deorbit Year Trading Scheme

Under this concept, a privatized market is set up so that satellite owners and operators can trade "credits" with each other. Credits are earned by deorbiting satellites earlier than an established time cap with compliance being monitored by an international entity. Credits could be used toward future deorbit years or, if a satellite owner or operator could not deorbit within the caps, they could either "buy" credits from other owners and operators in a regulated marketplace or be penalized. This concept requires both government regulation to establish the rules and international cooperation to create the marketplace, verify deorbits, and establish dispute resolution procedures.

A slightly different approach would function like a bottle deposit. In this formulation, a satellite owner puts funds in escrow that will only be returned upon successful and timely deorbit. If the satellite fails and is stranded past a predesignated time, a third party may collect the deposit by deorbiting the spacecraft; i.e., active debris removal. Commercial companies like Astroscale are already pursuing active debris removal methods as a business service. This concept may be more successful on a domestic or regional level since the financial management on an international level would be very complex.

Similar to the "cap and trade" carbon trading concept for offsetting climate change, a deorbit year trading scheme would create an economic, market-

Additional Considerations

Regardless of which incentivizing concept, or combination of concepts, is employed, it should be as adaptable and flexible as possible. It needs to adapt to macro changes in technology—relevant on timescales of 10-plus years. It also needs flexibility to account for different technological approaches implemented by owners and operators.

Customized deorbit guidelines are an example of added flexibility that can be based on parameters such as expected lifetime, altitude, inclination, mass, ability to maneuver, and other characteristics. They also allow owners and operators to be innovative and efficient when developing deorbit plans. This could be a timely approach given the likely proliferation of large constellations and nonmaneuverable CubeSats.

based incentive for satellite owners and operators to deorbit satellites before the deorbit deadline. The Kyoto Protocol and Paris Accords on Carbon Dioxide emissions offer ideas and lessons for the implementation of analogous trading schemes. It should be noted that for this concept to promote a level playing field, governments from around the world would need to work together to establish an international deorbit rule trading market.

Concept Assessment with the Proposed Framework

The four metrics in the framework—control, financial, social, and rules—can be applied in different ways to assess the concepts. Example ideas of how to utilize them are presented below. Note: The concepts laid out here are not prescriptive and, thus, can only be assessed so far and relative to each other.

Figure 2 shows how two of the metrics—rules and (owner/operator) control—can create a useful tradespace to evaluate how to balance government requirements with owner and operator leadership and control. The current model, Direct Government Management, located in the top left of the figure, is highly regulated and has low stakeholder control. In the United States, owners and operators are given the opportunity to comment on rulemaking such as the Federal Communications Commission's 2018 call for comments on rules to mitigate space debris.[19] However, industry must ultimately comply with government-imposed domestic deorbit rules and regulations to launch from the United States. The exact locations of the other concepts are dependent on specific implementation designs. Figure 2 highlights the regions in which they would likely reside.

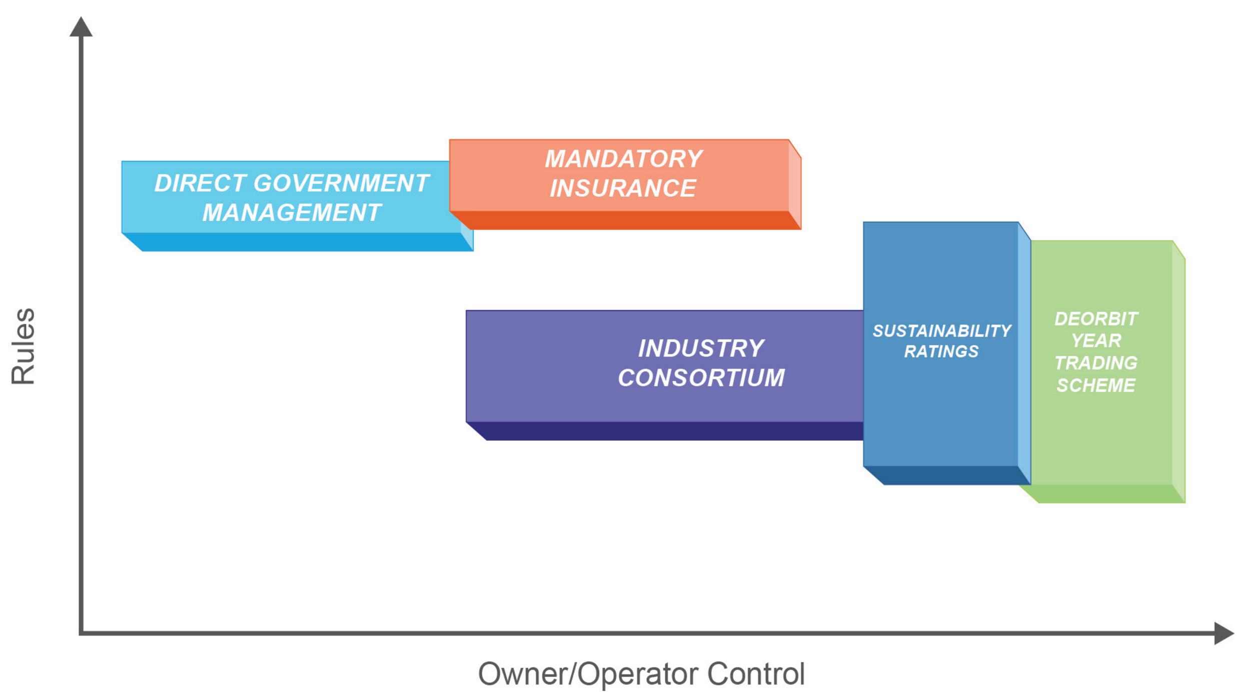


Figure 2: Example assessment of the rules-control tradespace.

Figure 3 is an example of how to explore the range of a single metric. Both Direct Government Management and Mandatory Insurance offer little opportunity for building social capital. With insurance, the social capital would be indirect. An improved owner and operator deorbit track record would improve a company's reputation as a secondary benefit to lower insurance costs. A Consortium could incentivize compliance via peer (social) pressure. Membership in a given Consortium could be viewed as a positive status and offer exclusive benefits. For example, the Space Data Association offers its members improved access to collision avoidance data and screening of flight plans. With the Trading Scheme, owners and operators who are frequently able to sell deorbit year credits would gain a positive reputation, which would be an incentive to comply. However, like Mandatory Insurance, the gain in social capital would be a secondary benefit in comparison to the primary motive of reduced expenses. This creates a positive feedback loop with the economic cost incentive as mentioned for previous designs.

Figure 4 is an example of exploring a particular aspect of one of the metrics—the fairness of the cost burden. The current model of Direct Government Management is less likely to have fairly distributed costs due to the potential for an unlevel playing field by which owners and operators based in different countries with different regulations pay different associated costs.[20] Likewise, consistent domestic enforcement and penalties for noncompliance are unclear creating uncertainty for owners and operators about the fairness of potential penalties. Consortiums can require fair cost burden sharing to the participating members, but, ultimately, the costs will depend on the rules decided on by the consortium. A Trading Scheme allows for the most flexibility and stakeholder control over costs.

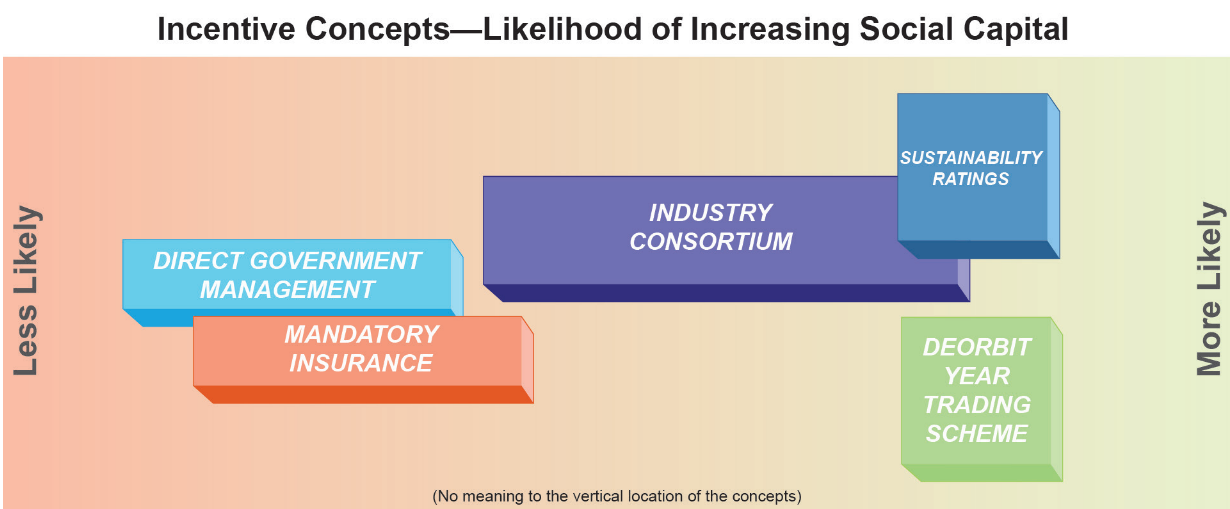


Figure 3: Example of assessing the concepts using one of the metrics. *The concepts are relatively scored based on how likely they would increase the social capital of owners/operators. There is no meaning to the vertical location of the concepts.*

Incentive Concepts—Stakeholder Perception of Cost Fairness

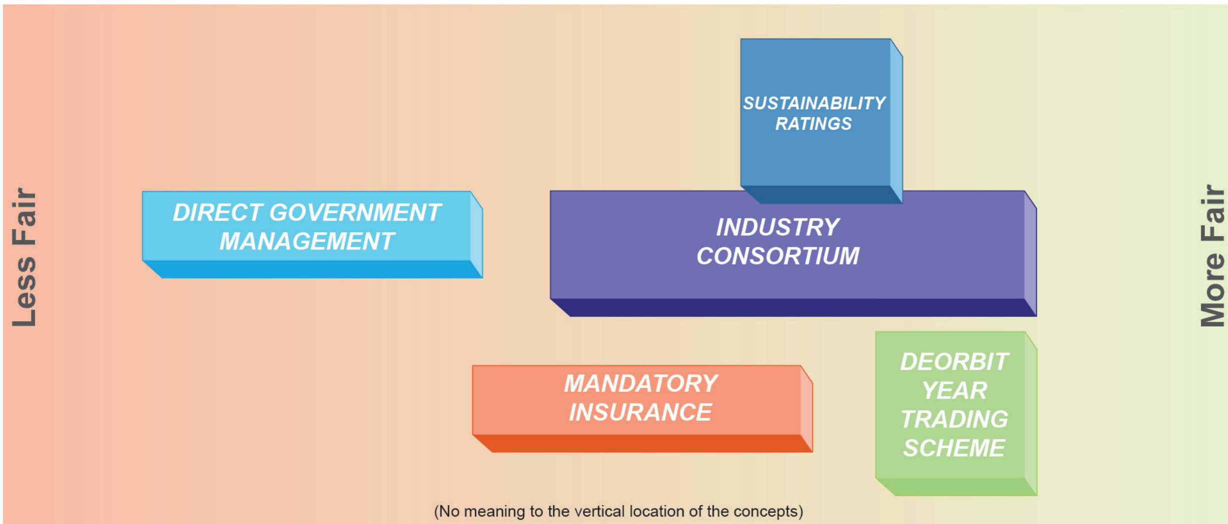


Figure 4. Example of assessing an aspect of one of the metrics. *How fair are stakeholders likely to feel the cost burden of the concepts are relative to each other? There is no meaning to the vertical location of the concepts.*

Conclusion

Each of the concepts outlined above have merit, and there is no need to pick just one to implement. A hybrid approach is likely the best approach. The main objective is to sustain the space environment for current and future users, commercial and government, by lessening the chance of debilitating collisions, especially in the useful, already crowded LEO. Voluntary compliance to the 25-year rule or more stringent deorbit rules is the most logical choice since space operations are done on an international scale, beyond borders and individual governments. When considering space through a common pool resource lens, the free market and financial incentives play a role but are balanced with necessary regulation and oversight. Any voluntary compliance concept, be it collision insurance, an industry consortium or a sustainability rating system, will still need some level of government involvement. Commercial space is at an exciting time in history, and, to continue on this socially and financially beneficial curve, our shared resource must be carefully managed to keep it safe and productive for all users.

Acknowledgments

The authors would like to thank the following people for their help in completing this paper: Marlon Sorge, Steve Jordon Tomaszewski, Ted Muelhaupt, and Roger Thompson of The Aerospace Corporation, and Chris Kunstadter of AXA XL.

References

[1] European Space Agency, "Space Debris by the Numbers," https://www.esa.int/Our_Activities/Operations/Space_Safety_Security/Space_Debris/Space_debris_by_the_numbers

[2] The U.S. Space Surveillance Network currently tracks more than 20,000 pieces of space debris down to approximately 10 cm. The U.S. Space Force's Space Fence was recently turned on and will track even smaller objects, likely resulting in five times as many trackable objects.

[3] Gleason, M., and T. Cottom, "U.S. Space Traffic Management: Best Practices, Guidelines, Standards, and International Considerations," The Aerospace Corporation, August 2018. https://aerospace.org/sites/default/files/201808/CottomGleason_U.S.%20Space%20Traffic%20Management_08272018.pdf

[4] "ESA's Annual Space Environment Report," 17 July 2019. https://www.sdo.esoc.esa.int/environment_report/Space_Environment_Report_latest.pdf

[5] Peterson, G., A. Jenkin, M. Sorge, and J. McVey, "Effects of CubeSats on Collisions and Long-Term Debris Growth in Near-earth Environment," IAC-A6.2.3x32388, 67th International Astronautical Congress, Guadalajara, Mexico, 26-30 September 2016.

[6] Interview with Marlon Sorge, June 2019.

[7] Officially known as the "Treaty on the Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and other Celestial Bodies"

[8] Officially known as the "1972 Convention on International Liability for Damage Caused by Space Objects"

[9] "The French Space Operations Act," Presentation. 2008. UN Office of Outer Space Affairs. http://www.unoosa.org/pdf/pres/lsc2009/pres-04.pdf

[10] The question of whether common pool resource economics apply to scarce orbital regimes is distinct from the political and legal question of whether space itself constitutes a "global commons," a position that the U.S. government has not historically accepted. See, for example, Henry Hertzfeld, Brian Weeden, Christopher Johnson. "How Simple Terms Mislead Us: The Pitfalls of Thinking about Outer Space as a Commons." IAC-15 - E7.5.2 x 29369]

[11] Tam, W., "The Space Debris Environment and Satellite Manufacturing," Walden University. 2015. https://pdfs.semanticscholar.org/a90d/20a5a824b639f0688bdbfd0ceb2e2120a37c.pdf

[12] Ostrom, E., "Beyond Markets and States: Polycentric Governance of Complex Economic Systems." *American Economic Review,* Vol 100, No. 3, June 2010: 12-13.

[13] Hertzfeld, H., B. Weeden, and C. Johnson, "How Simple Terms Mislead Us: The Pitfalls of Thinking about Outer Space as a Commons." IAC-15 - E7.5.2 x 29369, p.11.

[14] Ostrom, E., "Beyond Markets and States: Polycentric Governance of Complex Economic Systems." *American Economic Review,* Vol 100, No. 3, June 2010: 15.

[15] Ostrom, E., "Governing the Commons: The Evolution of Institutions for Collective Action," Indiana University, Cambridge University Press, 1990, p.14.

[16] Schenone, R., "Space Insurance Update 2019," International Union of Aerospace Insurers. https://iuai.org/IUAI/Study_Groups/Space_Risks/Public/Study_Groups/Space_Risk.aspx

[17] CONFERS homepage. https://www.satelliteconfers.org/

[18] Foust, J., "Consortium to develop "space sustainability" rating system." *SpaceNews.* 7 May 2019. https://spacenews.com/consortium-to-develop-space-sustainability-rating-system/

[19] https://www.fcc.gov/document/fcc-launches-review-rules-mitigate-orbital-space-debris-0

[20] In 2018, Swarm Technologies, a Silicon Valley Startup, flew four picosatellites on an Indian Polar Satellite Launch Vehicle. The FCC had not approved their application a month earlier, but they launched from India anyway. This event garnered much outrage from the space community as it highlights the lack of consistent regulation across international borders.

AIRSPACE INTEGRATION IN AN ERA OF GROWING LAUNCH OPERATIONS

Robert M. Unverzagt

Accommodating space launches in the National Airspace System (NAS) is burdensome, but at historical launch rates it is manageable. However, it is expected that launch rates will increase substantially, with the preponderance of that increase coming from commercial customers. This will require better integration of space launch activities in the NAS. This paper presents the issues and highlights potential conflicts between the "space side" and the "air side" that may call for intervention from high-level decisionmakers.

Background

"Space launch" is a broad category, covering orbital launch of satellites, suborbital launch of payloads (and soon tourists), vertical launch of rockets, horizontal launch of aircraft carrying rockets, flyback of boosters, etc. There are even emerging concepts involving catapults (SpinLaunch) and evacuated tubes (the Thor launch system from 8 Rivers) being proposed for space launch. Therefore, any methods to increase space launch integration into the NAS will not be one size fits all. For example, processes (filing a flight plan) and technology (such as Automatic Dependent Surveillance-Broadcast, or ADS-B) could prove feasible for better integrating suborbital space tourism flights (which has been likened to "suborbital aviation") into the NAS but prove infeasible for rockets launching satellites to orbit.

This paper focuses primarily on vertical launch of rockets to orbit, which is likely the hardest space launch modality to integrate into the NAS for a few reasons:

- Vertical launches of rockets generally occur from fixed launch sites, which limits flexibility. A system such as Northrop Grumman's Pegasus or Virgin Orbit's LauncherOne, carried aloft by an aircraft to a location where the rocket is dropped and launched for its flight to orbit, has a degree of freedom to choose a drop location to minimize impact to the NAS (within mission requirements). Similarly, ABL Space Systems is developing a ground-based launch system that could potentially be deployed to locations that also minimize such impact. That being said, these launch systems are relatively "small" and generally do not present a growing trend for orbital launch .

- The fixed site in the United States with the greatest space launch activity—the combined Cape Canaveral Air Force Station (CCAFS) and Kennedy Space Center (KSC) in Florida—affects airspace heavily traveled by commercial aviation.

- Space launch to orbit results in a larger “footprint” compared to suborbital systems. The instantaneous impact point track (where a rocket would land on the ground if its thrust were terminated during flight) for an orbital launch system extends from the launch site to the point where the system achieves orbital velocity (over 17,000 miles per hour). This track is thousands of miles long, whereas suborbital systems have a much shorter impact point track.

- The reliability of suborbital space tourism vehicles is anticipated to be higher than that of space launch systems. The demonstrated reliability percentage of launch-to-orbit systems is in the mid-to-high 90s, while suborbital space tourism systems are striving for (and should achieve) much greater reliability.

Current Process

To date, space launch has been *accommodated* in the NAS rather than *integrated*. That is, a launch operator determines a launch day and time based on mission needs and secures a launch window from the relevant range authorities, regardless of the impact on the NAS. (There are some exceptions for certain holiday periods, but, generally, impact on the NAS is not a consideration for space launch operators.) Hazard areas are identified by the launch provider and reported to range safety authorities; the Federal Aviation Administration (FAA) issues a notice to airmen (NOTAM), defining Special Activity Airspaces (SAAs) to alert aircraft pilots of potential hazards due to launch activities (such as flight of the launch vehicle itself, hardware jettisoned from the launch vehicle, or debris in the event of vehicle breakup/explosion). These hazard areas can cover the airspace over many hundreds of square miles and last for substantial periods of time (hours), again depending on mission needs.

The Changing Launch Landscape

The kind of accommodation described above is burdensome, but, at launch rates of approximately 20 per year (from CCAFS, for example), it is manageable. In addition, most space launches have historically been for government customers, so acceptance of this process by other users of the NAS has had an aspect of “for the greater good.” It is anticipated, however, that launch rates could increase substantially, with the preponderance of that increase accommodating commercial customers (see Figure 1). This increase speaks for the need of better integration of space launch activities in the NAS.

In addition to the potential increase in launch cadence, there are efforts underway to shorten the readiness timelines for launch systems to achieve a “responsive” launch capability. Recent efforts along these lines include the Defense Advanced Research Projects Agency (DARPA) Launch Challenge and the Rapid Space Launch Initiative (RSLI) from the Air Force’s Space and Missile Systems Center. An outcome of such schedule compression has implications for the existing process. NOTAMs are often published well in advance of space launches, which provides planning time by other users of the NAS. As the ability improves for launch operators to provide “responsive” launch, the lead time available for providing NOTAMs will decrease.

While the focus of this paper is orbital space launch, it should be noted that there are a dozen FAA-licensed spaceports in the United States, only a few of which are currently active but more are being proposed and developed. The “infrastructure” for more spaceflight is getting in place, pointing to an expectation of increased demand on usage of the NAS, not only for orbital launch from CCAFS.

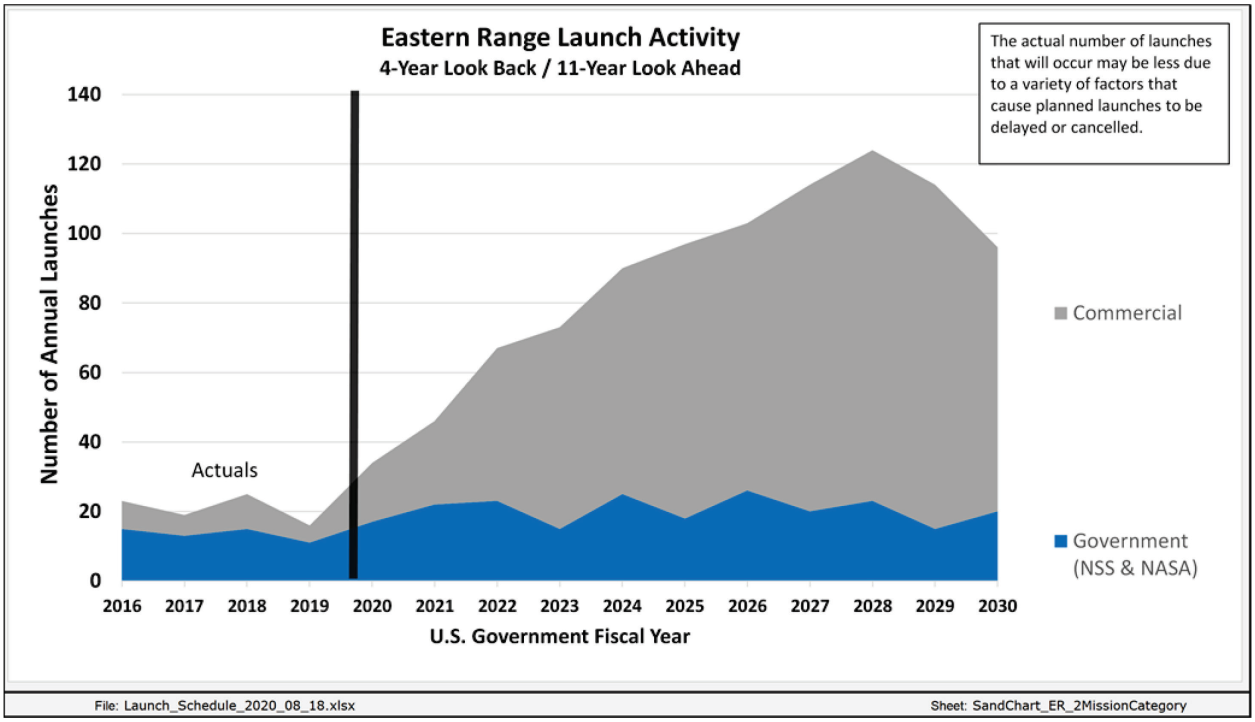


Figure 1: Eastern Range Launch Activity. *Derived from several data sources as of August 18, 2020, in particular Federal Communications Commission (FCC) filings for planned satellites, which telegraph a large potential increase in future launch rates. A description of the methodology used to derive this upper-bound launch demand can be found in the paper by Grant Cates et al.,* Launch Uncertainty: Implications for Large Constellations *(The Aerospace Corporation, Center for Space Policy and Strategy, November 2018).*

Considerations in Integrating Space Launch into the NAS

The process described above (segregating airspace for space launch activities) has a history dating back to the early days of spaceflight and is a valid risk management approach that has successfully protected the uninvolved public from space launch mishaps. Integration of space launch into the NAS must maintain this excellent safety record, protecting not only people on the ground but also users of the NAS. Any integration strategy must recognize characteristics of orbital space launch that constrain the solution space. This is particularly relevant given the existing infrastructure and operational procedures involved with managing use of the NAS. These characteristics fall into the broad categories of launch timing, launch system reliability, and launch trajectories.

Launch Timing. An obvious way to minimize the impact of space launch on the NAS would be to limit space launch opportunities to times when the affected portions of the NAS are relatively unused, perhaps between 1:00 a.m. and 4:00 a.m. local time. Such an "integration" of orbital space launch into the NAS is more procedural than technical; that is, it would follow the current process.

This sort of accommodation is not possible since launch times are not determined arbitrarily but are calculated to meet very specific needs. Launch times are driven by mission requirements with limited flexibility to move them into time frames with less air traffic. For example, launches of cargo or crew to the International Space Station (ISS) must launch at a specific time on a given day to rendezvous with the station (an "instantaneous launch window"). Similarly, satellites often have a specific time they need to reach their orbital destination for phasing with other satellites or to meet other mission needs. Generally, launch vehicles have limited ability to accommodate a suboptimal launch time. Therefore, an integration strategy of limiting space launch to "quiet" times in the NAS is not achievable since orbit mechanics generally dictate launch times for orbital space launch.

A feasible option might be to limit the duration of launch windows. Launch providers generally plan for the longest launch window possible within their capabilities and mission requirements in order to have the greatest likelihood of launching if issues arise during the launch countdown. For this reason, certain launches might have launch windows that are hours long, which obviously have a greater impact on the NAS than an instantaneous launch window. This area is ripe for study to determine where air and space equities can both be accommodated, determining the tradeoff of launch window duration versus the probability of successfully launching and the impacts on air traffic. It's important to realize that this is not just a "scheduling" issue; there can be significant cost considerations on the part of the launch provider and satellite payload for a missed launch opportunity.

Launch System Reliability. *Aerospace* is used to describe both air and space activities. There are certainly great similarities: many companies service both the air and space markets; advanced materials and technology are used in both; there is overlap in many technical skills used for both; etc. It is easy, therefore, to view space launch rockets as something akin to just "bigger airplanes." Even a first-cut engineering look might lead one to believe in a near-equivalence of airplanes and rockets in terms of expected reliability; a large passenger jet is roughly the same size as a medium-lift space launch rocket, and both expend roughly the same amount of energy in carrying out their missions.

However, other considerations drive expected reliability for the two systems to be much more different than their apparent similarity. A simple thought experiment provides some insight into why orbital space launch rockets would be less reliable than aircraft. Regarding the energy expended in carrying out their missions, an international aircraft flight might take 10 hours whereas a space launch mission might take 12 minutes to reach low Earth orbit. This reframes the comparison as a *power* consideration, not an *energy* consideration—rockets are at least tens of times more powerful than aircraft per pound (using admittedly simplistic "thought experiment" values). This has sometimes been described as "the tyranny of the rocket equation"; when the mass of a rocket is increased, the amount of fuel required increases exponentially, so it is unattractive to beef up rockets for higher reliability.

In addition, rockets are, in general, single-use items (though this is changing as some launch systems have successfully incorporated reusable elements). A system designed to survive its operating environment once obviously will be less physically robust than one required to survive thousands (or even tens of thousands) of times, even considering periodic maintenance. It remains to be seen how "design for reuse" will affect the reliability of launch vehicle hardware, but given that the number of intended reuses of systems flying or in development is in the tens of uses one would not expect an increase in reliability of orders of magnitude.

These considerations lead one to see notionally that space launch rockets would be inherently less reliable than aircraft—a lighter, more powerful machine would be expected to be less reliable than a more robust, less powerful machine. And the result of this thought experiment is substantiated by the actual flight record (the aforementioned demonstrated reliability of space launch systems being in the mid-90-percent range) and the reliability expectations of those responsible for acquiring launch services.

As an example, the probability of "loss-of-crew" that NASA's Commercial Crew Program levies on its commercial providers is 1 in 270, with a greater risk of "loss-of-mission" of 1 in 60. For comparison, FAA Advisory Circular (AC) 25.1309-1A describes aircraft target levels of safety being an average probability per flight hour for catastrophic failure conditions of 1×10^{-9}; that is, functionally not anticipated to occur during the entire operational life of an aircraft type. While the numbers laid out here are not directly comparable (one being a risk per mission and the other being a risk rate per hour), the difference in the orders of magnitude is striking and shows the very different design philosophies of aircraft and rockets. Given this, rockets cannot be treated just like aircraft in the NAS as normal operations assume a high level of intrinsic reliability of the craft.

Launch Trajectories. To reach orbit, space launch systems are required to put their payload up 100 miles or more with enough horizonal velocity to remain in orbit. The "up" is the easier part of the problem, requiring a few thousand miles per hour; the harder part is the approximate 17,000 miles per hour to be added horizontally. At the thrust levels available for rockets, it takes hundreds of miles for that horizontal velocity to be achieved. In addition, the down range distance the vehicle would travel if the thrust were terminated extends for thousands of miles, which results in SAAs covering very large areas (see Figure 2).

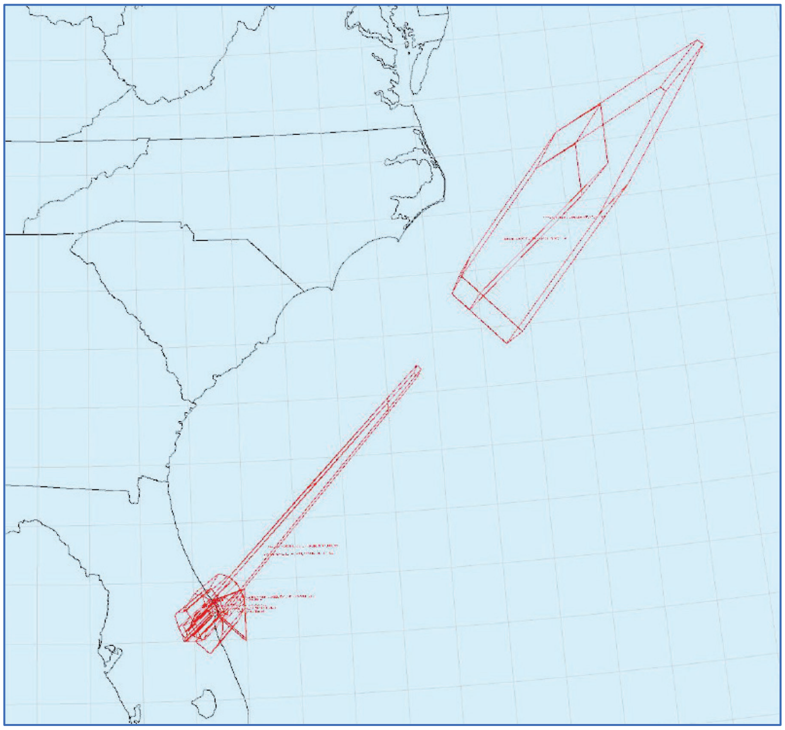


Figure 2: The SAAs for a SpaceX Falcon 9 launch on March 1, 2013. *From the FAA report, "SpaceX Falcon 9/Dragon Operations NAS Impact and Operational Analysis."*

Further, to maximize performance to orbit, hardware is often jettisoned from launch vehicles during ascent when no longer needed (for example, payload fairings that are not needed once the air is sufficiently thin, depleted solid rocket motor casings, etc.). These jettisoned bodies travel down through the NAS.

A further consideration involving space launch rockets is that they are not controllable in that they cannot react to situations that would require evasion to avoid a collision. They are, of course, guided by control laws to reach their orbital destination, but they cannot sense any other users of the NAS. Aviation use of the NAS presumes a level of ability to react to changing conditions in the NAS to maintain safety; short of self-destruction, rockets do not generally have this ability.

Where Does This Leave Us?

Given the physical characteristics described above, which pose barriers to space launch rockets achieving the level of reliability expected of aircraft using the NAS, it would appear that integration of space launch into the NAS would be virtually impossible; for all real purposes, one must assume that a rocket will fail during flight. The current process of segregating airspace to protect against such a failure has worked for decades, but the anticipated increase of launch rates necessitates improvements to this concept of operations to minimize the impact on the NAS. While total integration of space launch rockets as "just another user" of the NAS would appear to be impossible given the differences in the systems, improvements can be made in the areas of situational awareness, data exchange, and automation to minimize the impact of space launch on the NAS.

One area in need of improvement is data sharing between launch providers and the managers of the NAS. The current process to "release" the SAAs created for space launch relies on manual operations; that is, relevant air traffic control authorities monitor whether a launch has occurred, the launch has been scrubbed for the day, or the launch time has been delayed to later in the launch window, etc. They then use existing communication capabilities to effect airspace management changes. The FAA's Space Data Integrator (SDI) project aims to automate much of this process (see the fact sheet on the FAA website). By incorporating information directly from launch providers into the air traffic control system, SAAs can be released more expeditiously. Such increase in situational awareness would improve the coordination of space launch activities with other users of the NAS. And while operational integration of orbital space launch into the NAS might never be fully possible, there is no reason why full data integration cannot occur. Indeed, any operational integration is predicated on data integration, so any advancement will require this and should be advocated to decisionmakers and pursued.

Existing technology (such as ADS-B) employed by such users of the NAS should be investigated for potential use in orbital space launch. While some characteristics of orbital space launch might be outside the operating range of such technology (due to rockets' speed, acceleration, altitude, etc.), assessments should be made to determine how such technology could facilitate space launch integration into the NAS, and promising research lines should be pursued.

The SAAs presented in Figure 2 make certain assumptions about failure modes and debris generation. While safety of the NAS users is paramount, it is conceivable that such failure and debris modeling might be *too* conservative; that is, larger areas than necessary might be segregated for orbital space launch. Given that there is essentially no cost to using conservative assumptions in such analyses, since impact on the NAS is not a consideration, erring on the side of safety is to be expected. Research into evaluating and improving such modeling might bear fruit in reducing both the area and time affected by such segregation. For example, high-altitude aircraft with high-quality optics (such as NASA's WB-57 aircraft with its DyNAMITE imagery system) could carry out observation campaigns of launch vehicle hardware jettisoned during flight. This would provide data to anchor and validate modeling, potentially allowing the size of SAAs to be reduced while maintaining equivalent levels of safety.

Carrying out such an imagery campaign (as an example) brings up the consideration of the cost of such research activities versus the potential benefit of reduced impact on the NAS. Aircraft users of the NAS are currently incurring costs due to space launch, in time and fuel spent avoiding SAAs. What is an acceptable expenditure to reduce SAAs by, say, 50 percent in area and time span, and what is the anticipated benefit to other users of the NAS? Who would shoulder the cost of such activities? Such questions point to the critical part of integration of space launch in the NAS: continuing dialogue between all the stakeholders, representing both air and space. As mentioned earlier, increasing space launch integration into the NAS will not be one-size-fits-all due to the different modalities of space launch. In fact, some of the categories of space launch (such as suborbital tourism launches) might have more in common with commercial aircraft operators and have similar equities with which they would be concerned. For this reason, representatives of all spaceflight modalities should be included in any discussions regarding integrating space access into the NAS.

While not a space launch concern, spaceflight often includes reentry of space hardware, both intentional and random. Unless the hardware is "designed for demise" as it reenters the atmosphere, it will transit the NAS and become another user with its own set of integration challenges. If the proliferated LEO constellations described in FCC filings come to fruition, the number of reentries could greatly increase. Given this, any discussions of integrating space access into the NAS should include relevant satellite operators whose systems could potentially enter the NAS from above.

This paper focuses on the technical considerations in integrating space launch into the NAS without addressing other mechanisms to foster integration. For example, given that the NAS is a resource with competing claims from the "air side" and the "space side," one idea would be for users to explicitly pay for its use. For space launch, this might be a fee paid to the FAA for each launch attempt. This fee could be determined based on the area of the NAS affected, duration of usage, etc. With "skin in the game," launch providers would be motivated to minimize their impact on the NAS. Such nontechnical mechanisms to foster integration should certainly be investigated by all stakeholders.

Conclusion

In 1949, the 81st U.S. Congress promulgated the first launch safety policy: "From a safety standpoint, [launch vehicles] will be no more dangerous than conventional airplanes flying overhead." This guiding principle has resulted in the safe regime we enjoy today (codified in Air Force and FAA regulations, AFSPCMAN 91-710 and 14 CFR Part 400, respectively), at the increasing expense of affecting other NAS users. While the technical characteristics of orbital space launch make full integration into the NAS challenging, there are avenues of investigation that could reduce the impact of orbital space launch on the NAS.

LIGHT POLLUTION FROM SATELLITES

Josef S. Koller, Roger C. Thompson, and Luc H. Riesbeck

Commercial space companies, such as SpaceX, Telesat, OneWeb, and Amazon, have announced plans to launch large constellations of small satellites into low Earth orbit (LEO). As companies deploy more satellites in orbit in much larger numbers than in previous decades, this will become an issue in the next several years that requires leadership and decisionmaking by the U.S. administration—because there is currently no formal regulatory or licensing process addressing light pollution from space. The purpose of this paper is to provide an overview of an objective analysis performed by The Aerospace Corporation to inform leaders and decisionmakers on the issue.[1]

Background

The logic behind the large constellation architecture is to take advantage of advancements in automation and miniaturization achieved in the past two decades to quickly build and operate several thousand satellites. These "smallsats" are comparatively inexpensive, faster to produce, and can be more readily replaced and upgraded. Should they all achieve orbit, the proposed commercial large-constellation satellites launched could total well over 17,000, distributed primarily between low and very low Earth orbits by the end of the 2020s[2] and could surpass 50,000 in the following decade.[3] The scale of these planned constellations combined is more than twenty times the current satellite population in orbit.[*]

Despite the potential benefits from the proposed proliferated LEO (pLEO) constellations (sometimes referred to colloquially as mega-constellations) and the recent public discussion on this topic, the aggregate effects of light pollution from such constellations remain underexamined in an objective way. If not carefully considered and mitigated at the design stage, optical reflective emissions of satellites may have a negative impact on astronomical research, undercutting investments made in astronomy by national governments, universities, and private foundations around the world.

Astronomers can compensate for general light pollution by locating their telescopes in dark places, but they cannot site their telescopes to avoid satellites except by placing them in space themselves (like the Hubble Space Telescope and the forthcoming James Webb Space Telescope). Stop-gap measures and temporary fixes already exist for when a single satellite passes through the field-of-view (FOV) of a telescope. Astronomers and telescope operators, however, stress that a continued lack of high-level coordination on mitigation strategies will make satellite light pollution and radio frequency emissions an increasingly difficult problem to tackle as architectures shift toward large constellation models. The present

[*] For comparison, fewer than 9,000 payloads have been put into orbit in the past 62 years.

concerns of the astronomy community and others over the contribution of reflectivity by pLEO constellations to overall light pollution are part of this larger, under-studied set of concerns that merit further interdisciplinary and objective research.

Satellites' Contribution to Light Pollution

The brightness of an object in space, such as a planet, a satellite, or a star as viewed in the night sky from Earth's surface is described as its apparent magnitude, with larger numbers indicating fainter objects. For astronomers with ground-based telescopes, brighter apparent magnitudes of satellites result in bright streaks of light across the exposures captured by their equipment (a satellite streak or track)—the same way a headlight from a car might appear as a streak of light across a long-exposure photograph taken by a camera at night. A similar effect is caused by airplane lights in the night sky. Depending on the apparent magnitude and the duration of the exposure, these satellite streaks in exposures are forcing astronomers to throw out some portions of their data at what they are warning could be an unsustainable rate.

The apparent magnitude of a satellite in space varies based on multiple factors such as the observer's position on the Earth's surface, the altitude and specific orbit of the spacecraft, and the angle between the sun, satellite, and observer in addition to the satellite's reflectivity. When viewed from the ground, satellite brightness can also vary by time of year as regions experience shorter periods of night during the local summer. On the Earth's surface, the terminator defines a moving line that separates the side of the Earth illuminated by the sun from its dark side. Shortly after sunset, there is a period of twilight when the sky is still illuminated by the sun. Astronomical twilight ends when the center of the sun is 18° below the local horizon, which usually indicates the time at which astronomical observations can begin. The observation window ends when the sun again is 18° below the horizon prior to sunrise. Satellites, because of their altitude, can still be sunlit and visible to a telescope even when the location of the telescope is in "astronomical night" conditions. As the observer location rotates deeper into the night, satellites are in Earth's shadow and do not reflect sunlight. The interference period (satellites being illuminated) is longer for satellites at higher altitudes and, at geosynchronous Earth orbit (GEO), generally lasts the entire night—although because they are so much farther away, they appear dimmer to the observer. Satellites at lower altitudes are brighter but have less impact because they move into Earth's shadow earlier than satellites at higher altitudes.

Orbiting spacecraft have generated optical interference for decades—most of them quite predictably. For example, the original Iridium constellation had predictable flares of specular reflection, visible to the naked eye, with a consistency that enabled them to be predicted down to the second. The timing of such flares has historically been tracked and published on the nonprofit Heavens Above website. Timing and observing them has become a hobby for some, and satellite watching can be inspirational for children and the general public.

Other types of interference are continuously provided by airplane lights as well; astronomers regularly find streaks of blinking lights in images throughout the night, which turn out to be emanating from aircraft. Interference with star trackers on lower-altitude satellites may be possible but is deemed unlikely due to the short exposure time and algorithms of these devices. Human navigators will also be able to quickly separate a LEO satellite from a star due to the former's fast movement across the night sky.

Streaks generated by large numbers of reflective satellites in LEO effectively create light pollution from space for astronomers attempting to observe dim stars in our own or distant galaxies. They make up a small and uncontrolled portion of the wider light pollution problem affecting astronomers. A 2016 American Association for the Advancement of Science (AAAS) study found that more than 80 percent of the world and more than 99 percent of U.S. and European populations live under light- polluted skies, and that the Milky Way is hidden from more than one-third of humanity.[4]

The low apparent magnitude (greater brightness) of satellite reflections in a telescope's FOV, which can be caused by both specular (direct, mirror-like reflections, which cause short flares or glints) and diffuse (indirect) reflection (which causes the longer streaks), degrades the quality of the exposures it captures. In extreme cases, they may even temporarily "blind" sensor pixels capturing the images. For astronomers, that interference can impede their ability to capture long-duration exposures of deep space. When interviewed, Johnathan McDowell, an astrophysicist at the Harvard-Smithsonian Center for Astrophysics and staff member at the Chandra X-ray Observatory, said, "On a technical level, when an image is ruined, we throw out one, with the understanding that the next will be fine."

Most satellites need some form of surface coating to protect them from exposure to extremes of the space environment, including harmful radiation.[5] Satellites often produce the largest signals (both visible or near-infrared reflected and thermal emitted signatures) because of the large surface area of solar arrays relative to the cross-sectional area of the body of the satellite. While the solar arrays of very small satellites do not typically have large surface areas, many glints and thermal signatures are dominated by the effects of reflected or emitted light from their arrays.

Modeling and Simulation of Optical Interference

To model the effects of satellite reflection of sunlight, Aerospace used the mathematical description of the optical assembly to determine the apparent magnitude of a satellite with respect to an observing ground site. The most influential parameters are the size, shape, and attitude of the spacecraft; the angle between the sun, satellite, and observer; and the reflection coefficients of the surfaces. All of these factors would need to be included in a detailed analysis to determine precise interference from a single object. Our purpose here is to define the periods when interference is possible without descending into the specifics of a particular satellite and orbit. To simplify the numerical results, we modeled hypothetical constellations at 500 km and 1,200 km to illustrate the tradeoff between altitude and illumination. Specific simulations of proposed constellations are available upon request.

To determine all possible geometries where the assumptions and constraints combine to create optical interference, we create a spherical grid at a specific altitude above the observer. Our chosen observer location is Cerro Pachón, Chile, the site of the Rubin Observatory and the Large Synoptic Survey Telescope (LSST). We also included a constellation of 1,296 satellites at 50degrees inclination evenly distributed with 36 orbital planes and 36 satellites per plane in order to provide a sample of the fraction of satellites visible at certain times. We performed two simulations (summer vs. winter) to illustrate seasonal effects and the length of astronomical night.

For satellites orbiting at 500 km altitude (1,200 km in simulation 2) and during long winter nights, the results show that the observatory can have up to 4 hours (8 hours in simulation 2) of illuminated satellites in the night sky split almost evenly at each end of the night. The period of possible interference begins at the end of astronomical twilight (the first collection opportunity) with approximately 40 satellites (100 in simulation 2) illuminated. About 63 percent (80 percent) of the sky can contain illuminated satellites. At one hour into the night operations, approximately 28 percent (58 percent) of the sky can still receive solar reflections from passing satellites. Two hours (four hours) after astronomical twilight, the site has rotated into Earth's shadow enough that both altitudes are no longer illuminated.

During the short summer night, the illumination of both the 500 km and the 1,200 km shell never completely ends although the number of illuminated satellites drops significantly.

In summary, Aerospace's simulations show that the number of illuminated satellites and the areas change throughout the night, leaving varying portions of the sky free from interference. It is technically feasible to predict the position of each illuminated satellite and implement the information into astronomical scheduling and optimization routines. However, doing so may lead to an overall reduction in time available to the observatory and may also become impractical at some point.

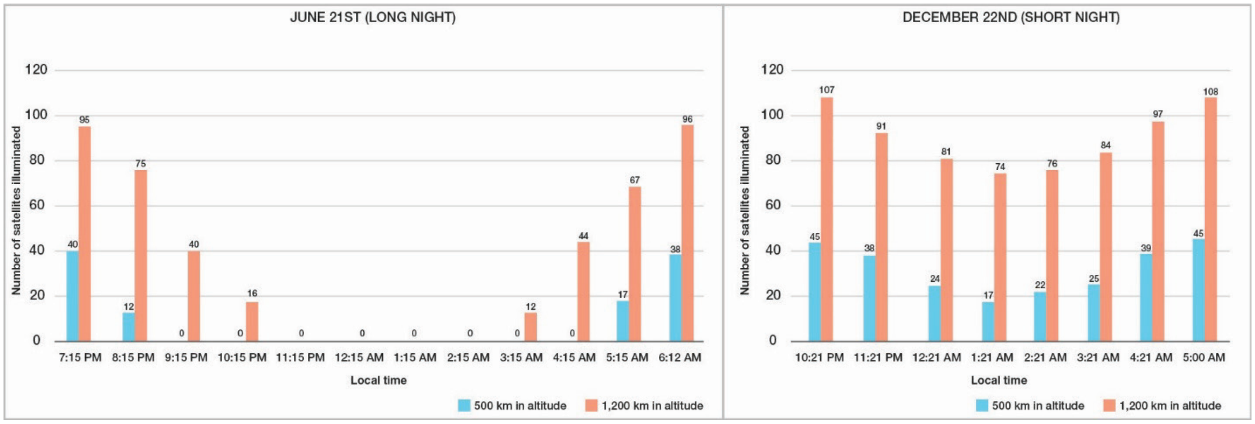


Figure 1: Summary of Tables 2 and 3 with number of satellites illuminated during a long winter night (June 21, left) and short summer night (December 22, right). Blue bars illustrate the number of satellites illuminated at 500 km, and orange bars show the number of satellites at 1,200 km altitude.

Current Mitigation Efforts

Astronomers already employ methods to dampen the severity of ground-based light pollution in their observations. Astronomers must therefore rely on other mitigation strategies to decrease optical interference from satellites. Many algorithms can stitch together multiple exposures taken over specific intervals and digitally combine them to "erase" current levels of satellite streaks. However, particularly for short- and medium-duration exposures, streaks can still compromise some data beyond the point of use; still, this "stitching" (sometimes called a "track-and-stack" approach) has proved useful as a stop-gap measure to retain as much raw data as possible from each night of measurements.

Mitigating the effects of satellite streaks gets tougher when applied to larger telescope systems, which are sensitive enough to see fainter satellite streaks. Researchers using these systems take multiple exposures of a section of the night sky and median-filter them, discarding those with streaks and averaging the rest. However, each exposure has an opportunity cost in the form of sensor read-out noise. This is why five separate 10-minute exposures are not equal to one 50-minute exposure; in the first instance, there are *five* samples of read noises to account for instead of only one. Also, reading out an image takes time, adding to the overhead and allocation of observation time requirement. When planning the logistics of operating large telescopes, it becomes a question of balancing this "cost" in read noises. This illustrates why satellite streaks during long-duration exposures can have a substantial impact on data collection efforts; while it may be possible, it could also become impractical to carefully time one hundred 1-minute exposures in between periods of interference. To add to the challenge, bright satellites can cause saturation in some pixels, with charge spilling over and "blooming" into the rest of the image. However, using the "track-and-stack" approach on a pixel-by-pixel basis could be an alternative.

As skies have grown more polluted with a variety of light sources, state and local governments, as well as grassroots organizations, have started to push back. The International Dark Sky Association (IDSA), for instance, is a nonprofit organization advocating for the preservation of the night sky and providing guidance and education to regulators on how to mitigate light pollution from terrestrial sources. For example, IDSA is working with the public, city planners, legislators, lighting manufacturers, parks, and protected areas to provide and implement smart lighting choices. Astronomers have voiced growing concern as early as the late 1990s, when the first satellite constellations were initially proposed. Current proposals for large constellations have created even greater apprehension.

According to the National Conference of State Legislatures, at least 18 states have laws in place to reduce light pollution, which are mostly limited to outdoor lighting fixtures installed on the grounds of a state building or public roadway.[6] In 2015, the Environmental Protection Agency (EPA) administrator, Gina McCarthy, said that light pollution is "in our portfolio" and that the agency is "thinking about it." To date, EPA has no official regulation on light pollution.[7] A recent article highlighted that the EPA has provided the Federal Communications Commission (FCC) with a categorical exclusion since 1986, arguing that such activities do not impact the environment and thus do not require a review.[8] It can be argued, however, that the time has come to address light pollution at the national level.

Table 1: Possible Mitigation Approaches	
Astronomers	**Satellite Operators**
◆ Optimize observation schedules to avoid satellites ◆ Apply "stitching" and median-filter algorithms	◆ Apply special coating or paint to lower reflectivity ◆ Modify orbit placement and satellite orientation

Astronomers, however, have found that much of the diligence, investment, and preparwation to shield equipment from ground-based light pollution is being undercut by a lack of regulatory coordination around mitigating satellite light pollution and reflections from above. This is of particular concern for wide-field telescopes taking long exposures. "A substantial increase in number of satellites in LEO will certainly change the operations of major ground-based telescopes," confirmed McDowell. Facilities, such as the Large Synoptic Survey Telescope (LSST)[9] currently under construction in Cerro Pachón, Chile, and the Panoramic Survey Telescope and Rapid Response System (Pan-STARRS), located at the Haleakala Observatory in Hawaii, perform observations that will help scientists better understand deep space, the nature of dark matter, and how the Milky Way was formed. However, the telescopes also search for undiscovered near-Earth objects (NEOs). The LSST alone will be able to detect between 60 percent and 90 percent of all potentially hazardous asteroids (PHAs) larger than 140 meters in diameter, serving a key warning function for planetary defense against potential impact threats.

A "Wake-Up Call"

In May 2019, the commercial space company, SpaceX, launched the first 60 satellites belonging to its Starlink LEO constellation, which will eventually have 1,584 satellites orbiting at a 550 km altitude. Since then, SpaceX has continued to add sets of approximately 60 satellites with several launches and the numbers keep rising.[10] Directly following each launch, several videos of clearly visible "trains" of the spacecraft in preliminary orbits enroute to their final orbital positions and orientations were uploaded to social media, and confused local citizens even filed numerous reports of UFOs in the areas where the satellite trains were visible.[11]

Though the brightness of the spacecrafts' reflection at the time they were observed (within the few days following launch) are not representative of their brightness once in their final positions, the videos[12] nevertheless contributed to renewed discourse on the effect of space commercialization on astronomical research and society more generally.

The International Astronomical Union, the world's largest international association of local and regional chapters of professional astronomers, issued a statement following an early launch,[13] depicting a photo of a telescope's FOV obstructed by light streaks from Starlink satellites. The picture was taken early on as the satellites made their way into their final orbits, noting in the image caption that the density of satellites is significantly higher in the early days after launch and that the satellite brightness would diminish as they reach their final orbital altitude. The statement urged constellation "designers and deployers as well as policy-makers to work with the astronomical community in a concerted effort to analyze and understand the impact of satellite constellations."

The good news is that multiple stakeholders involved in this issue are increasing their communication with each other. Notably, at a recent American Astronomical Society (AAS) conference, LSST Chief Scientist Dr. Tony Tyson remarked, "…we find that SpaceX is committed to solving this problem."

Looking Ahead

Despite the preparation and investments already made to mitigate ground-based light pollution for wide-field and long-exposure telescopes, the impact of light pollution of satellite constellations is currently not given consideration at the federal or international level.

Thanks to institutions like the International Telecommunications Union (ITU), radio astronomers are equipped with both policy protections in the form of regulation and a forum to challenge any harmful interference with their observations. For instance, many satellites broadcasting signals must redirect or cease such signals when passing over radio astronomy facilities. However, as of today, researchers in optical astronomy have no such recourse; unlike other risks and hazards (such as orbital debris concerns) associated with pLEO constellations , no formal regulatory or licensing process currently exists for constellation operators to demonstrate their strategy for mitigating the adverse impacts of reflectivity in their license applications.

An organized avenue for coordinated discussion on guidelines and mitigation strategies among stakeholders is needed to address the wider concerns of the optical astronomy community. Other aspects of managing the risks of pLEO constellations are already discussed at interagency, national, and international fora, such as the Inter-Agency Space Debris Coordination Committee (IADC), which has worked for nearly three decades to negotiate and form mutually agreed-upon mitigation guidelines preventing the widespread proliferation of orbital debris. The IADC is tasked with "consideration of space sustainability effects from deploying large constellations of satellites" at the federal level, but satellite light pollution is outside the scope of IADC.[14]

Groups like the AAS and the International Astronomical Union (IAU) already act as representatives of the larger astronomy community, working to express optical interference concerns to regulators. Other, more collaborative avenues may prove more appropriate; to ensure allied and multi-national coordination, for example, regulators could look to successful models that resulted in progress for other space sustainability issues, such as within the United Nations working group on the "long-term sustainability of space."

Conclusion

From a U.S. policy perspective, pLEO constellations—both governmental and commercial—will provide novel services and benefits to their users. As more satellites are launched, and industry players continue to develop norms of operation in LEO, astronomers will want a larger role to play in wider constellation management and space safety coordination considerations. Operators of such constellations face an opportunity to get ahead of the issue by working with stakeholders to consider strategies for mitigation of optical reflectivity and albedo reduction. Regulators, astronomers, and industry should be in communication about their respective operational needs to explore options for building optical interference mitigation into existing constellation licensing application processes.

In the years to come, information sharing and cooperation could help facilitate the creation of industry best practices and standards to ensure the long-term sustainability of both ground-based astronomy and LEO constellations. This is an important issue and approach for the administration to foster and facilitate.

References

1 L. Riesbeck, R Thompson, J. Koller, "The Future of the Night Sky: Light Pollution from Satellites," March 2020 (https://aerospace.org/paper/future-night-sky-light-pollution-satellites).

2 Thierry Dubois, "Eight Satellite Constellations Promising Internet Service from Space," *Aviation Week & Space Technology*, December 2017 (https://aviationweek.com/space/eight-satelliteconstellations-promising-internet-service-space).

3 Caleb Henry, "SpaceX submits paperwork for 30,000 more Starlink satellites," *Space News*. October 15, 2019 (https://spacenews.com/spacexsubmits-paperwork-for-30000-more-starlinksatellites/).

4 Fabio Falchi, et al., "The new world atlas of artificial night sky brightness," *Science Advances*, Vol. 2, No. 6, June 10, 2016.

5 SPC Surface Treatments, "Metal Plating on Satellites: The Benefits of Light Reflection" (https://www.sharrettsplating.com/blog/metalplating-satellites-benefits-light-reflection/).

6 National Conference of States Legislatures "States Shut Out Light Pollution," May 23, 2016 (https://www.ncsl.org/research/environment-and-natural-resources/states-shut-out-light-pollution.aspx).

7 Daniel Chaitin, "EPA Chief: Light Pollution 'in our portfolio,'" *Washington Examiner,* December 30, 2015 (https://www.washingtonexaminer.com/epa-chief-light-pollution-in-our-portfolio).

8 Jonathan O'Callaghan, "The FCC's Approval of SpaceX's Starlink Mega Constellation May Have Been Unlawful," *Scientific American*, January 16, 2020 (https://www.scientificamerican.com/article/the-fccs-approval-of-spacexs-starlink-mega-constellation-may-have-been-unlawful/).

9 National Science Foundation, "About LSST" (https://www.lsst.org/about).

10 For a list of Starlink satellite launches, see https://space.skyrocket.de/doc_sdat/starlink-v1-0.htm.

11 Anthony Cuthbertson "UFO Reports surge after Elon Musk launches SpaceX Internet satellites," *The Independent*, May 28, 2019 (https://www.independent.co.uk/lifestyle/gadgets-and-tech/news/ufo-sightings-elonmusk-spacex-internet-satellites-starlink-spacea8933411.html).

12 Marco Langbroek, "SpaceX Starlink Objects train 24 May 2019" (https://vimeo.com/338361997).

13 "IAU Statement on Satellite Constellations," June 3, 2019 (https://www.iau.org/news/announcements/detail/ann19035/).

14 NASA Public Affairs Representative, email correspondence, August 22, 2019.

CENTER FOR SPACE
POLICY AND STRATEGY

JUNE 2020

CISLUNAR STEWARDSHIP: PLANNING FOR SUSTAINABILITY AND INTERNATIONAL COOPERATION

GEORGE E. POLLOCK IV AND JAMES A. VEDDA
THE AEROSPACE CORPORATION

AEROSPACE

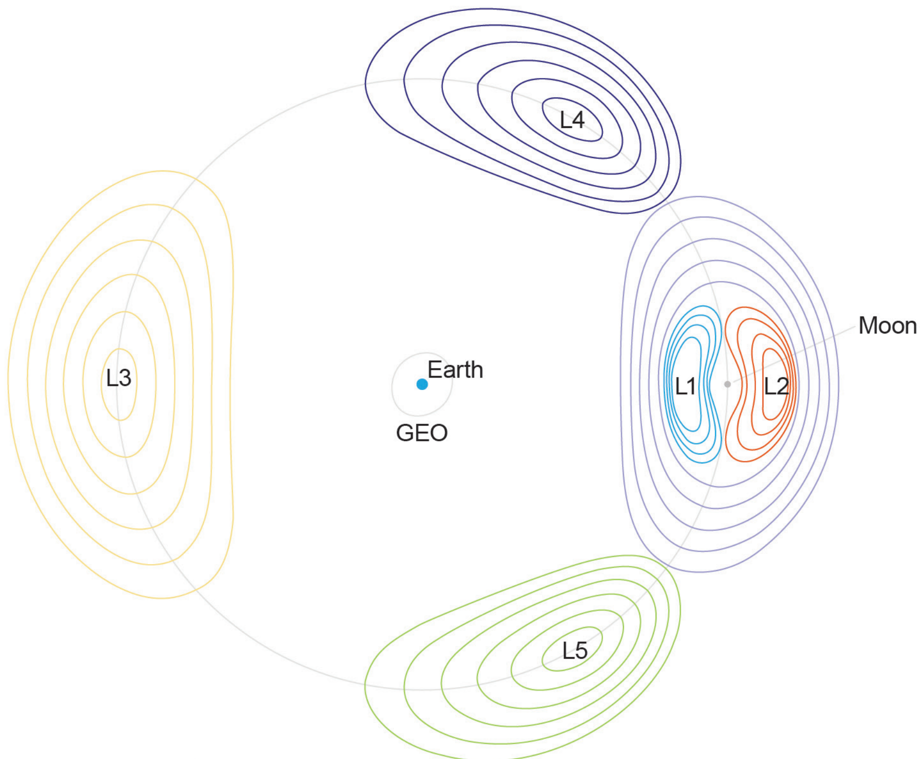
Summary

Space operations are expanding beyond the geosynchronous Earth orbit (GEO) to other parts of the Earth-moon system. As this trend continues, space operators will find preferred orbits and seek to leverage points of relative gravitational stability. These locations can enable lower-energy transits or provide useful parking places for various types of facilities (e.g., fueling depots, storage sites, and way stations with access to the lunar poles). As cislunar activity grows, a policy framework should be developed to promote the sustainability of operations in these locations. Motivated by lessons learned in space operations thus far, this paper discusses the need to extend best practices for debris mitigation (preventing its accumulation) to cislunar space lest we create a space debris mess in this valuable regime. Additionally, current international policy prevents spacefaring nations from removing space debris left by other actors. Significant policy adjustments are needed if debris remediation (removal of nonfunctional and potentially dangerous objects from useful orbits) is to become an effective complement to debris mitigation in cases where mitigation is not completely effective. Beyond the extension of current practices, significant future work remains in characterizing new orbital environments, monitoring their evolving use, and determining appropriate sustainability practices.

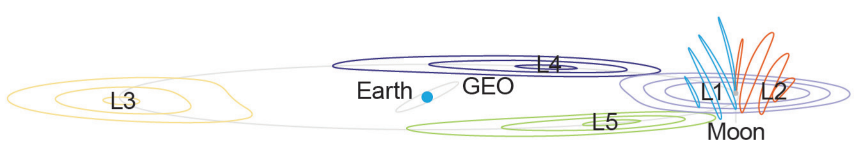
Why is Cislunar Space Important?

Between now and mid-century, some basic assumptions about the state of space operations are reasonable. Geosynchronous Earth orbit (GEO) will continue to be valuable and actively used. The number of operational satellites, especially in low and medium Earth orbits (LEO and MEO), will increase. Space operators will become more numerous and more diverse. Orbital debris will continue to be a significant concern. Most relevant for purposes of this paper, a greater variety of cislunar orbits will be used for an assortment of space applications, including communications, navigation, space domain awareness, scientific remote sensing, and human exploration.

There may be aggregation of space structures into industrial parks at locations deemed valuable…



These orbits reside in the plane of the moon's orbit around Earth and are depicted in an Earth-moon rotating frame. The blue orbits about L1 and the orange orbits about L2 stay on the near and far sides of the moon, respectively, while never actually encircling the moon. The orbits about L3 are centered at a point opposite the moon. L4 and L5 orbits lead and trail, respectively, the position of the moon in its orbit.



Halo orbits (examples shown here in blue and orange about L1 and L2, respectively) exhibit motion above and below the moon's orbit plane, which enables visibility to the lunar poles. L2 halo orbits offer a unique location for a communication relay, with continuous visibility to both Earth and the far side of the moon.

Illustration of several types of cislunar orbits: halo and Lyapunov orbits about the five Lagrange points; distant retrograde orbits.

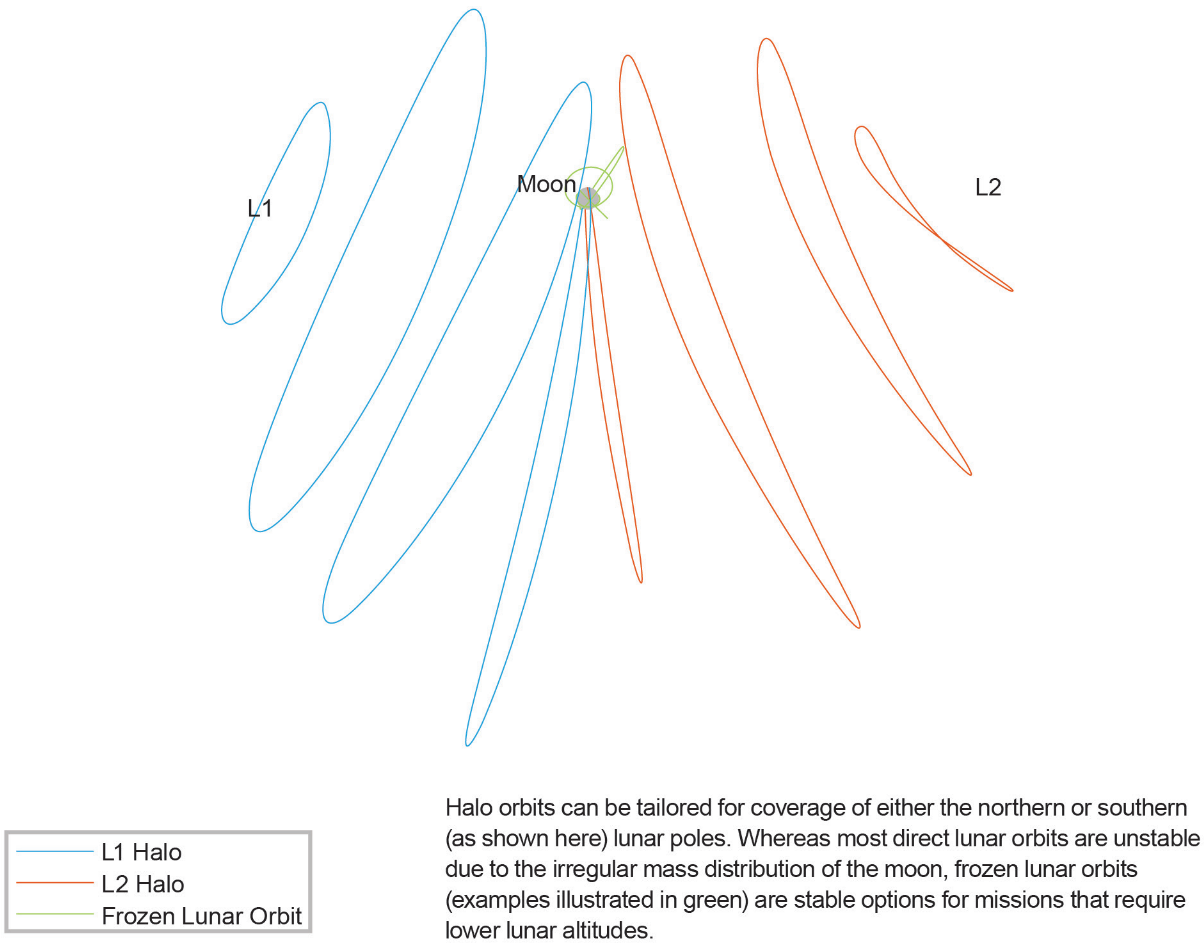


Illustration of example L1 and L2 halo orbits and frozen lunar orbits.

In addition to today's familiar applications, the cislunar environment of tomorrow may host some combination of the following:

- Next-generation multi-purpose orbiting platforms for use as labs, manufacturing facilities, and habitats
- Propellant storage depots
- Research outposts on the moon
- Extraction, processing, and use of extraterrestrial resources
- Training and support for deep space missions

Efforts to stimulate a space economy could result in sophisticated structures in various orbits designed to take advantage of the unique characteristics of the space environment, such as microgravity, vacuum, high-intensity solar exposure, and isolation from Earth, to produce useful knowledge and products. There may be aggregation of space structures into industrial parks at locations deemed valuable for their proximity to space resources, relatively stable gravitational points ("Lagrange" or "libration" points), or other attributes.

These activities all have the potential to be realized in less than a human lifetime. The scope and complexity of these developments may challenge spacefaring actors to be good stewards of this emerging enterprise and preserve it for the generations to come.

Lessons from Space Operations to Date

Spaceflight experience in orbits nearer to Earth offers both positive and negative lessons that can help to avoid unsustainable practices in cislunar space. As space activities ramped up in the 1960s and 1970s, no policy framework governed debris mitigation and disposal in the most frequently used orbits. In GEO, for example, many spacecraft were disposed in orbits that continue to cross the operational orbit. These defunct satellites impose a permanent burden of monitoring and tracking for safe operation, and they are prone to breakups and collisions that yield numerous untrackable debris pieces.

Since those early decades, several methods of spacecraft disposal have been used to mitigate debris. At the completion of a mission, a spacecraft could be:

- **Placed into a long-term storage orbit**. The most common example of this is relocation of expired satellites from the GEO belt to higher (super-synchronous) disposal orbits.

- **Sent into Earth's atmosphere for reentry**. Satellites in LEO can gradually reenter on their own due to orbital decay caused by atmospheric drag. If properly equipped and fueled, they can be commanded to reenter using onboard propulsion systems. For any vehicles that are intended for destructive reentry, the U.S. government's Orbital Debris Mitigation Standard Practices (ODMSP) impose a threshold on the allowable likelihood of pieces surviving to Earth's surface causing human casualties.

- **Actively removed**. An owner/operator may retrieve a spacecraft and remove it from orbit. Spacecraft components may be salvaged or recycled. To date, this has been done very rarely and only for demonstration purposes. Operational employment of active debris remediation faces many technical, economic, and legal hurdles. For example, the current regulatory framework does not allow any actor other than the original owner or launching state to remove an object from orbit.

Today's U.S. orbital debris mitigation standards are the result of a gradual evolution that began with NASA and the Department of Defense (DOD) in the 1990s. The standards originally were built around four objectives:

1. Control of debris released during normal operations

2. Minimizing debris generated by accidental explosions during and after mission operations

3. Selection of safe flight profiles and operational configurations to limit the probability of creating debris by collisions

4. Post-mission disposal of space structures to minimize impact on future space operations[1]

Once established in December 2000, the U.S. guidelines proved influential on global best practices. The U.S. government proposed the guidelines to the international community through NASA's participation in the Inter-Agency Space Debris Coordination Committee (IADC), an organization founded in 1993 that currently includes the world's most active civil space agencies. The IADC published its own version of the guidelines in

2002.[2] The essential elements are the same as the U.S. version, plus it contains additional background information, definitions, and some technical details. The IADC presented this version to the U.N. Committee on the Peaceful Uses of Outer Space (COPUOS), which deliberated on it for five years before issuing its own version,[3] which was endorsed by the U.N. General Assembly a few months later.[4] Once again, the COPUOS version retained the same essential elements. The U.N. document states that nonoperational space objects "should be disposed of in orbits that avoid their long-term presence" in the heavily populated LEO or GEO regimes. (Other orbital regimes are not mentioned.) Note that the process from U.S. outreach to U.N. endorsement took seven years even though there is broad agreement about the need to mitigate orbital debris. Plans to establish or change international laws and norms must factor in long lead-times, even for issues that appear noncontroversial.

The U.N. Working Group on Long-Term Sustainability of Outer Space Activities under COPUOS undertook related sustainability issues. Its multi-year work plan approved in 2011 sought to identify best practices in a variety of areas designed to keep space accessible and usable for all nations.[5] Its guidelines on space debris and space operations largely mirrored the U.N. Space Debris Mitigation Guidelines and suggested practices in data sharing. No guidelines were proposed for space debris removal.[6]

In November 2019, the U.S. government updated its debris mitigation guidelines,[7] as directed by Space Policy Directive-3.[8] The update, which replaces the original December 2000 guidance, makes clarifications and adds specificity to orbit descriptions and collision probability estimates. A greater variety of orbits between LEO and GEO are addressed, as well as new satellite disposal options. The new guidelines specify a goal of 90 percent success for post-mission disposal and encourage even higher success rates for large constellations.

Space domain awareness (SDA) beyond GEO stretches an already challenged capability.

There is also acknowledgment of emerging activities, such as various types of proximity operations. All these changes are important steps to better stewardship of orbital space, but none of them specifically address activities beyond GEO and its graveyard orbit.

The process of developing, promoting, and institutionalizing debris mitigation best practices took the better part of a decade, and effective implementation is an ongoing process. This implies that planning for expansion to the full cislunar environment should begin now, so space operators are ready to employ best practices for debris mitigation and remediation as activity beyond GEO grows and diversifies.

What Will Be Different in Cislunar Operations?

The operational environment in the cislunar region is different than that found in LEO, GEO, or other regions where humans have operated spacecraft, so we must be cautious in extrapolating our experience. Just as GEO has a slower speed and longer orbital path from that found in LEO, the cislunar environment is different from either of these. Sunlight is essentially perpetual, with rare passages through Earth's or the moon's shadow. The radiation environment is more intense than LEO, since cislunar orbits are largely outside of Earth's magnetic bubble. The volume of cislunar space is vastly larger and distances from Earth-based sensors much farther, so the tracking of objects is much more difficult. Similarly, the relative speed of an encounter with a neighboring cislunar object will be different than in other orbit regimes. We must adapt our expectations and our best practices for this new environment.

For many cislunar orbits, orbit periods can be measured in days, and the volume of space traversed is larger than the congested LEO regime near Earth. Collision risk from debris depends on the density of the debris and the frequency of encounters with the debris. Therefore, the collision risk with other cislunar spacecraft may be relatively small in many cases. However, we should learn from the early missions to GEO with respect to disposal practices. Early GEO satellites often were disposed in place, leaving the orbital inclination to drift, which has resulted in twice daily passages of the GEO belt to this day, decades after their retirement. Had the ODMSP and other nations' similar practices been in place in the 1960s, far fewer wayward dead satellites would transit the highly valuable GEO belt today. Foresight can prevent similar disposal regrets for important cislunar orbits.

High above Earth, but still in the Earth-moon system, the combination of Earth and moon gravity yields orbits whose behavior differs substantially from objects directly orbiting Earth. Many of these orbits are unstable, and small changes in initial conditions can lead to widely varied resulting trajectories. Some of the unstable orbits (e.g., halo orbits) are slow to diverge, such that actively controlled objects can efficiently maintain an orbit that enables specific mission applications. Still other orbits (e.g., distant retrograde orbits) can enable objects—even without active control—to persist in a stable orbit for decades to centuries. Many of the particularly useful orbits exist about the five Lagrange points, or points of gravitational equilibrium. Their natural mission utility will attract increasing use, and the complex dynamical behavior motivates a rigorous approach to traffic management, including debris mitigation and remediation.

Debris shed or objects discarded in cislunar orbits can meet a variety of fates, including passing near or even colliding with operational vehicles, impacting the lunar surface, and departing the Earth-moon system entirely. Achieving a desired long-term orbit in these orbital neighborhoods is challenging, particularly due to the gravitational perturbation from the sun. Therefore, researchers have begun examining the criteria that determine the behavior of objects in orbits that may see frequent use, such as the near rectilinear halo orbit planned for the Lunar Gateway.[9,10]

Space domain awareness (SDA) beyond GEO stretches an already challenged capability. Current ground-based and Earth-orbiting SDA sensors cannot provide the coverage or the sensitivity needed to robustly detect, track, and monitor spacecraft-sized objects at the lunar distance. To address these shortfalls, space-based SDA systems could be added in the Earth-moon system and their data integrated with that from ground-based systems. The limited capacity of SDA sensors for tracking cislunar objects motivates robust spacecraft disposal practices, so scarce sensor time is not redirected to monitor retired vehicles.

What Could Be Done to Advance Cislunar Stewardship?

In general, the provisions of multilateral space treaties apply to space operations anywhere. However, specific rules and recommended practices to date have been aimed at orbital regimes within the GEO arc. There is no agreement, for example, on how multiple operators will share orbits around Lagrange points. It would be an unsound practice to wait—as we did in the early space age—until the most valuable orbits become crowded before we define protected regions, devise space traffic management protocols, and establish norms for debris mitigation and disposal practices. For example, the region near the Earth-moon L1 Lagrange point is likely to emerge as a high-traffic "strait" transited by most vehicles passing between Earth and the moon. A sustainability plan for the L1 region could include traffic management among resident L1 orbit vehicles and others transiting the space.

The cislunar orbits that require sustainability plans should be informed by at least two principal factors: the utility of the orbit, which likely will correlate strongly with the future volume of traffic there, and the stability of the orbit, which governs the longevity of debris that are generated in that vicinity. Examples of orbits with high potential utility include Lyapunov and halo orbits about the five Lagrange points (including the sub-type of near rectilinear halo orbits as is planned for NASA's Lunar Gateway), distant retrograde orbits, and frozen lunar orbits. The distant retrograde orbits and frozen lunar orbits are among the most stable of these orbits. Useful orbits in the Earth-moon system should be evaluated relative to the need to establish cislunar protected regions where spacecraft operators may not dispose of their space systems.

There is no agreement, for example, on how multiple operators will share orbits around Lagrange points.

New disposal options may become available for high-orbit applications, and the traditional disposal options enumerated earlier may have new factors to consider in cislunar orbits:

- **Long-term storage orbit.** Finding suitable disposal orbits in the cislunar environment and ensuring they can be achieved is an area of ongoing study. This option necessitates detailed analysis of orbital stability over decades to centuries, in the presence of perturbative forces, in addition to determining the likelihood of a sufficiently accurate final maneuver to enter the disposal orbit.

- **Reentry into Earth's atmosphere.** This option will be common for returning crew or cargo vessels. For other vehicles operating in the lunar vicinity, atmospheric reentry may not represent an affordable option as it can be quite costly to return objects to Earth.

- **Active removal.** As noted earlier, space system operators will need to overcome a variety of technical, economic, and legal hurdles to retrieve spacecraft and remove them from orbit. If cislunar operations prompt a market for salvaged or recycled spacecraft components, this may provide incentives to overcome the hurdles. However, the vast area involved and the greater distance from Earth are likely to increase the challenges compared to active removal efforts in LEO and GEO.

- **Crash into the moon.** This option invokes planetary protection issues (i.e., preventing contamination of celestial bodies) and safety considerations for lunar surface operations planned by several countries and nongovernment entities. Most low lunar orbits are unstable, so objects left there will commonly crash into the moon unless deliberate action is taken to use an alternate disposal option.

- **Send into heliocentric escape.** Perhaps the "cleanest" option, space vehicles can be sent away from the Earth-moon system on a trajectory that rarely, if ever, returns to that neighborhood. As in the case of storage orbits, this option also requires detailed analysis of the long-term orbit behavior and the necessary accuracy for the insertion maneuver.

These spacecraft disposal options, except for crashing the object into the moon, directly parallel methods in the current U.S. ODMSP for Earth-orbiting missions. Additional study is needed to inform their effective use and relative merits for cislunar missions, but these disposal methods are broadly considered viable options in the space community.

Future iterations of the ODMSP and similar guidance documents will need to address protection of orbital regions in the space beyond GEO. Increasing cislunar activity will result in the placement of space systems in unusual orbits (by today's standards). Disposal practices for cislunar orbits would need to account for lunar planetary protection policies and specify acceptable disposal options. Space system developers will need incentives and flexibility to incorporate reliable means to achieve successful disposal.

Future operations will need to strike a balance between mitigation of debris (preventing its accumulation) and remediation (removal of nonfunctional and potentially dangerous objects from useful orbits). For the foreseeable future, mitigation will be more economical than remediation. However, perfect mitigation is not possible, and the technical and economic feasibility of remediation may improve, so both options should be explored in long-term planning.

For the foreseeable future, mitigation will be more economical than remediation. However, perfect mitigation is not possible, so both options should be explored.

Enabling Remediation

In cases where debris mitigation is not sufficient, active remediation may be warranted. However, in addition to technical and economic challenges, other significant barriers to debris remediation must be addressed. These challenges include international law granting perpetual ownership of space objects to their launching states and concerns about potentially hostile actions.

Eventually, as space operations become more sophisticated and active removal becomes a practical way to remediate debris, space salvage restrictions will likely need to be revised in some manner to allow actions akin to salvage at sea.[11] Diplomats in the 1960s were not thinking about establishing a business-friendly environment for space salvage, as the primary focus was on national security concerns. That emphasis persists to a large extent today, and diplomats are not likely to emphasize space commerce unless the required technologies, plausible business cases, and political feasibility are within sight.

In the international space treaty regime, the Outer Space Treaty (OST) of 1967[12] established the Cold War's only rules governing the treatment of orbital debris. The issue was less pressing at the time, and the link to debris is indirect. Article IX, which is primarily concerned with contamination from extraterrestrial matter, is generally interpreted to be applicable to orbital debris as well, due to language that directs "appropriate international consultations" prior to engaging in activities that could cause "potentially harmful interference with activities of other States Parties." To address the sensitivities of the United States and the Soviet Union—each worried that the other would try to abscond with its satellites—the OST granted perpetual ownership of space objects to their launching state, even after the objects are deactivated and become uncontrolled junk. Although this is an obstacle to effective cleanup efforts, most active spacefaring nations (including the United States) are reluctant to suggest changes to the OST, even though Article XV permits any signatory to offer amendments.

In addition to the OST, there are three multilateral space treaties to which the United States is party: the Assistance Agreement (1968),[13] the Liability Convention (1972),[14] and the Registration Convention (1975).[15] They were designed to expand on provisions of the OST and do not directly address orbital debris or space traffic management. However, they do play a role in debris discussions and incident resolution because they deal with space object ownership, liability for damages, and public recordkeeping by parties responsible for space objects.

In a new era of greater numbers of government and private operators in space, some means to permit routine transfer of ownership and the development of an accompanying liability framework are necessary. Operators should have legal and efficient options to allow cleanup of valuable orbits through removal, with permission, of space objects left there by another party.

Advances in robotics, satellite bus design, automated rendezvous and docking, and orbital maneuvering systems, coupled with a variety of efforts to reduce launch costs, may make debris remediation practical in the next 10 to 15 years. Using the same technologies, commercial space operators have demonstrated substantial progress toward satellite servicing capabilities.[16,17] Northrop Grumman achieved a major milestone in February 2020, as its Mission Extension Vehicle-1 completed the first docking of two commercial satellites by successfully capturing the client Intelsat-901. The MEV-1 is planned to take over maneuvering for Intelsat-901 to extend the useful life of the client by five years. Adding to the complexity of the mission, the Intelsat satellite was not originally designed for docking.[18] Meanwhile, NASA conducted risk-reduction demonstrations for satellite refueling aboard the International Space Station starting in 2011[19] and in December 2016 awarded a contract for a satellite servicing demonstration spacecraft, Restore-L, to be flown in 2023.[20,21] Building on these satellite servicing developments, if satellite retrieval becomes an accepted norm, it could usher in a market for used satellites as debris remediation is accompanied by repair and refueling services.

With proximity operations and satellite servicing becoming mainstream space activities, a space traffic management system will need to adopt safety of flight rules analogous to those in the air and maritime domains. Future rules and guidelines should enable and promote sharing of flight plans among operators and mechanisms for cooperative conjunction analysis and collision avoidance.

Operators should have legal and efficient options to allow cleanup of valuable orbits through removal of space objects left there by another party.

In addition to the limitations on salvage in international law, another concern that must be overcome is that rendezvous and proximity operations look like (and could double as) anti-satellite (ASAT) missions. Potential objectors to widespread use of proximity operations will need to be convinced that the benefits outweigh the risks.

Differentiating between benign and potentially nefarious rendezvous and proximity operations becomes even more difficult for many cislunar orbits due to diminished space domain awareness capabilities and longer distances. Therefore, guidelines for proximity operations should aim not only to improve safety and interoperability, but also to provide a framework for identifying bad actors who pose a potential threat to other operators. Guidelines could be developed through collaboration of government and industry stakeholders and then be reflected in licenses issued by government regulators to organizations involved in cislunar operations. In the United States, this has begun with the Consortium for Execution of Rendezvous and Servicing Operations (CONFERS), an industry-led initiative that currently has 35-member companies and initial seed funding from the Defense Advanced Research Projects Agency (DARPA). CONFERS aims to research, develop, and publish nonbinding, consensus-driven standards for a wide variety of orbital operations.[22]

The resulting U.S. guidelines could be offered up as a model in international forums such as COPUOS or as an addendum to a future space code of conduct. This would be a multi-year process, as was the case with the debris mitigation guidelines, but, if successful, the effort could prove its value in promoting growth in cislunar space activities, reducing the debris threat, and easing tensions regarding potentially threatening behavior in space.

To ease concerns about nascent ASAT capabilities, prospective U.S. proximity operations guidelines, at a minimum, could include a prohibition against interference with nonhostile satellites that have not been offered up for salvage. Other key provisions could include:

- Prior public notification of launch or orbital maneuvers to initiate satellite servicing and retrieval missions.
- Prior notification to satellite owners of operations near their space assets (e.g., within 10 km).
- Immediate alert of any servicing or retrieval mission that does not go as planned and may create a hazard for others (e.g., by generating debris).

Conclusion

As more nations become spacefarers and cislunar traffic increases, established and emerging players should employ lessons learned from operations in LEO and GEO to be better caretakers of the expanded orbital neighborhood. The space lanes throughout the cislunar region would benefit from the conscientious care of the global community in a coordinated effort to ensure safe operations in the best interests of all parties. Responsibility for coordination of the effort may reside with existing international organizations but could also be assisted by an international business collective similar to the Space Data Association, which has proven that critical operational issues affecting both government and nongovernment sectors can be addressed through cooperation among competitor-colleagues.

The following steps will be necessary to establish a cislunar sustainability paradigm:

- Extend space domain awareness capabilities to cover future operating orbits in the Earth-moon system.
- Continue analyses of the complex cislunar orbit dynamics to determine effective methods of spacecraft disposal and define the valuable regions that merit careful protection.
- Formulate space traffic management protocols, along with debris mitigation and disposal practices.
- Address the present ownership and transparency obstacles to space salvage in current international law with the intent of enabling active removal of discarded objects.

For the foreseeable future, debris mitigation will be more economical than debris remediation, but the balance between the two approaches will continue to evolve. With this in mind, it is noteworthy that Space Policy Directive-3 states "standard practices should be updated to address current and future space operating environments."[23] Although intended as a reference to the original ODMSP, this statement should remain an axiom of space operations from this point onward.

Now is the time to develop practical and broadly applicable debris mitigation and remediation practices for cislunar orbits. Today, these orbits are in near-pristine condition, and their future usability must be ensured.

Acknowledgment

The authors thank Jonathan Aziz for generating the cislunar orbit graphics.

References

[1] U.S. Government Orbital Debris Mitigation Standard Practices, December 2000 (http://www.iadc-online.org/References/Docu/USG_OD_Standard_Practices.pdf).

[2] IADC Space Debris Mitigation Guidelines (IADC-02-01), October 15, 2002, revised in September 2007 (http://www.iadc-online.org/Documents/IADC-2002-01,%20IADC%20Space%20Debris%20Guidelines,%20Revision%201.pdf).

[3] U.N. General Assembly Official Records, 62nd Session, "Report of the Committee on the Peaceful Uses of Outer Space," Supplement No. 20 (A/62/20) Annex, 2007 (http://www.oosa.unvienna.org/pdf/gadocs/A_62_20E.pdf).

[4] U.N. General Assembly Resolution 62/217, "International cooperation in the peaceful uses of outer space," February 1, 2008, paragraphs 26-28 (http://www.un.org/en/ga/search/view_doc.asp?symbol=A/RES/62/217&Lang=E).

[5] U.N. Committee on the Peaceful Uses of Outer Space, "Report of the Scientific and Technical Subcommittee on its forty-eighth session, held in Vienna from 7 to 18 February 2011," U.N. General Assembly Report A/AC.105/987, March 7, 2011, para. 178-201 (http://www.oosa.unvienna.org/pdf/reports/ac105/AC105_987E.pdf).

[6] U.N. Committee on the Peaceful Uses of Outer Space, "Guidelines for the Long-Term Sustainability of Outer Space Activities," U.N. General Assembly Report A/AC.105/2018/CRP.20, June 27, 2018 (http://www.unoosa.org/res/oosadoc/data/documents/2018/aac_1052018crp/aac_1052018crp_20_0_html/AC105_2018_CRP20E.pdf).

[7] U.S. Government Orbital Debris Mitigation Standard Practices, November 2019 Update (https://orbitaldebris.jsc.nasa.gov/library/usg_orbital_debris_mitigation_standard_practices_november_2019.pdf).

[8] Donald J. Trump, Space Policy Directive-3, "National Space Traffic Management Policy," June 18, 2018 (https://www.whitehouse.gov/presidential-actions/space-policy-directive-3-national-space-traffic-management-policy/).

[9] Diane C. Davis, Kenza K. Boudad, Sean M. Phillips, and Kathleen C. Howell, "Disposal, Deployment, and Debris in Near Rectilinear Halo Orbits," 29th AAS/AIAA Space Flight Mechanics Meeting, Ka'anapali, Maui, Hawaii, January 13–17, 2019.

[10] Diane C. Davis, Kenza K. Boudad, Rolfe J. Power, and Kathleen C. Howell, "Heliocentric Escape and Lunar Impact from Near Rectilinear Halo Orbits," AAS/AIAA Astrodynamics Specialist Conference, Portland, Maine, August 11–15, 2019.

[11] For a discussion on how international space salvage rules may be modified to accommodate debris cleanup and recycling, see James A. Vedda, "Orbital Debris Remediation Through International Engagement," Aerospace Corp., Center for Space Policy & Strategy, March 2017 (https://aerospace.org/sites/default/files/2018-05/DebrisRemediation.pdf).

[12] Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies, January 27, 1967 (http://www.oosa.unvienna.org/oosa/en/SpaceLaw/outerspt.html). Ratified by 109 countries and signed by 23, including all major spacefaring nations, as of January 2019.

[13] Agreement on the Rescue and Return of Astronauts, and the Return of Objects Launched into Outer Space, April 22, 1968 (http://www.unoosa.org/oosa/en/ourwork/spacelaw/treaties/introrescueagreement.html). Also referred to as the Rescue and Return Agreement. Ratified by 98 parties, signed by 26 as of January 2019.

[14] Convention on International Liability for Damage Caused by Space Objects, March 29, 1972 (http://www.unoosa.org/oosa/en/ourwork/spacelaw/treaties/introliability-convention.html). Ratified by 96 parties, signed by 23 as of January 2019.

[15] Convention on Registration of Objects Launched into Outer Space (http://www.oosa.unvienna.org/oosa/en/SORegister/regist.html). Entered into force in 1975. Ratified by 69 parties, signed by 7 as of January 2019.

[16] In 2011, Canada's MacDonald Dettwiler & Associates (MDA) proposed a satellite refueling demonstration as early as 2015 with Intelsat as its anchor customer (Peter B. deSelding, "Intelsat Signs Up for Satellite Refueling Service," *SpaceNews*, March 14, 2011). However, the project did not move forward, illustrating the challenge of initiating this service (Jeff Foust, "Satellite Servicing Efforts Grapple with the Business Case," *SpaceNews*, April 15, 2013, p. 17, http://www.spacenews.com/article/satellite-telecom/34747satellite-servicing-efforts-grapple-with-the-business-case).

[17] Orbital ATK planned to develop a robotic system to dock with commercial GEO satellites to provide life-extending propulsion starting in 2018. Jeff Foust, "Orbital ATK signs Intelsat as first satellite servicing customer," *SpaceNews*, April 12, 2016 (http://spacenews.com/orbital-atk-signs-intelsat-as-first-satellite-servicing-customer/). Northrop Grumman continued development of the Mission Extension Vehicle when it acquired Orbital ATK.

[18] Caleb Henry, "Northrop Grumman's MEV-1 servicer docks with Intelsat satellite," *SpaceNews*, February 26, 2020 (https://spacenews.com/northrop-grummans-mev-1-servicer-docks-with-intelsat-satellite/).

[19] Debra Werner, "NASA Defends On-orbit Satellite Refueling Demonstration," *SpaceNews*, June 27, 2011, p. 10; Frank Morring, "Robotic-Servicing Testbed Is Being Upgraded: New technology-demonstration tasks are en route to the space station for Dextre," *Aviation Week & Space Technology*, Jul 29, 2013, p. 38.

[20] NASA Headquarters Contract Release C16-032, "NASA Awards Contract for Refueling Mission Spacecraft," December 5, 2016 (https://www.nasa.gov/press-release/nasa-awards-contract-for-refueling-mission-spacecraft).

[21] NASA Satellite Servicing Projects Division (SSPD) Restore-L webpage (https://sspd.gsfc.nasa.gov/restore-L.html). For fiscal year 2020, Congress appropriated $227.2 million for Restore-L and the Space Infrastructure Dexterous Robot (SPIDER), with no less than $180 million of that amount reserved for Restore-L.

[22] CONFERS website (https://www.satelliteconfers.org/).

[23] SPD-3 (ref 6), Sec. 5, a. iii.

CENTER FOR SPACE POLICY AND STRATEGY

JANUARY 2020

DEVELOPING A SUSTAINABLE SPECTRUM APPROACH TO DELIVER 5G SERVICES AND CRITICAL WEATHER FORECASTS

DAVID G. LUBAR, DAVID B. KUNKEE, AND LINA M. CASHIN
THE AEROSPACE CORPORATION

SUSAN K. AVERY
WOODS HOLE OCEANOGRAPHIC INSTITUTION

AEROSPACE

Summary

Fifth-generation (5G) wireless networks bring expectations of very fast, data intensive connectivity, with new capabilities that exceed today's 4G cellular networks. These 5G systems are the future of data connectivity, providing faster download speeds and more capacity to facilitate realtime general consumer and industrial applications. Implementation of 5G wireless networks will require the use of additional swaths of the radio spectrum.[a] Although 5G will utilize multiple frequency bands, the United States is working to permit new communications system uses of the spectrum in millimeter wave bands above 24 gigahertz (GHz) that are adjacent to key satellite remote sensing bands, making measurements of signals in that part of the electromagnetic spectrum critical for weather forecasts difficult to detect without comprehensive regulatory protection.

Introduction

Timely and accurate weather forecasts are essential for many sectors of the economy and help protect life and property. Meteorologists and hydrologists generate weather forecasts after reviewing observations and consulting outputs from numerical weather prediction (NWP) models running on supercomputers. Satellites provide over 90 percent of the input data for these NWP models.[1]

Weather monitoring and communication applications (i.e., measurements from weather satellites and [high band] 5G signals) are about to become neighbors in the radio spectrum. Some new 5G frequencies are adjacent to the bands where weather data for temperature, water vapor, and humidity are measured. It is important to avoid having extraneous signals generated by 5G infrastructure because these extraneous signals can contaminate neighboring remote sensing bands used to detect natural emissions of the atmosphere that contribute to the computer model outputs for the forecast. The current U.S. domestic limit[2] at 24 GHz of –13 dBm/MHz presents a significant potential risk as this value was designed to protect other terrestrial systems and not the sensitive measurements needed for passive sensing. This interference impact has yet to manifest as a problem because 5G infrastructure in this millimeter wave band has yet to deploy to a significant extent within the Americas to produce an upwelling component.

Regulators are not proposing to reallocate the same spectrum frequency the passive sensors use to make measurement of temperature and water vapor. Rather, the frequency being reallocated is so close that unwanted interference signals could result in

[a] See FCC's FAST plan and the discussion of high-, mid-, and low-band spectrum: https://docs.fcc.gov/public/attachments/DOC-354326A1.pdf

contamination of the weather information from the 5G signal. This 5G out-of-band signal that can result in contamination does not contribute to the transmission of information for 5G users. It is a by-product of generating the main signal that is working to allow mobile and fixed users to communicate. World experts disagree on the threshold limits for out-of-band signals beyond which measurements taken by the passive weather bands would be degraded and no longer able to serve their purpose to inform weather forecasts. Frequency regulators will include limits in their rules to constrain the level of the interference. How to arrive at the right limit is the issue in question.

To foster understanding of this complex issue, this paper describes 5G, weather passive remote sensing, and usage of adjacent electromagnetic spectrum. A companion technical paper from The Aerospace Corporation will discuss many of these topics in more depth to facilitate further understanding.

A Few Questions and Answers Are Necessary to Describe the Issue

What are weather satellites measuring and why can't they simply move elsewhere in the radio spectrum?

Microwave-based measurements from instruments on orbiting weather satellites measure natural properties of Earth and the atmosphere. Instruments may measure the amount of water vapor at different heights or may detect weak signals emitted by the atmosphere that can be used to determine the temperature or the humidity at different altitudes. The signals originate from the natural physical properties of the atmosphere and do not exist at different frequencies.

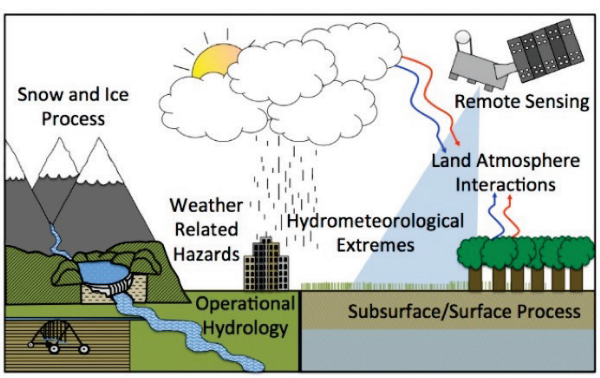


Figure 1: Natural phenomena sensed by weather satellite. (Source: American Meteorological Society, courtesy of Joshua K. Roundy.[3])

Do satellite instruments work like the receivers in our smartphones? Aren't they performing a similar function?

Actually, the type of signal being received with 5G to convey information to and from a user is quite different from the weak natural signal being detected with the weather satellite. Any detection system encounters a level of noise (primarily thermal in nature) that establishes a lower level for a receiving system. A communications signal rides above that "noise floor," where it may be captured by a communications receiver (e.g., a smartphone or outdoor fixed receiver for 5G), which then separates and processes the voice, video, or email (information content) for the user. Any unwanted by-products from generating the communications signal, if they fall below the noise floor, are ignored by the receiver and do not impact the information transfer to a user.

A passive microwave instrument on a weather satellite is actually a radiometer, which is not a communications signal receiver. It detects weak power levels emitted from Earth or the atmosphere. These signals manifest themselves as variations of noise floor. *Unwanted by-products from a 5G signal that falls within the frequency range detected by the weather satellite could raise the noise floor, masking the values of interest to the satellite or confusing the sensor.* There is no current method to separate the unwanted interfering signals from the desired natural signal. The microwave sensor, which measures the total power received, would not know the data had been contaminated by the operations of the 5G communications infrastructure.

Can't the satellite simply filter out the undesired signal or predict what the measured value should be?

The atmosphere is always changing, and the satellite sensor has no idea what specific level it may measure in any particular passive band of the spectrum at a given time. If a value is dramatically out of range, it will likely be discarded during data processing, providing a gap in the data. Otherwise, the sensor cannot determine that the measured value has been altered from the natural state by the neighboring 5G signal. Filtering out unwanted signals within the contaminated bandwidth is not feasible to the precision required by the passive sensor data applications. Unwanted signals increase the noise measured by the weather sensor.

Why would 5G transmitters cause contamination if other existing services using the radio spectrum do not? Don't 5G towers point downward as they communicate with users? How can they impact a satellite?

The proposed 5G infrastructure, which communicates data reliably and quickly for end users, will require closely spaced small cell transmitters. Since millimeter wave signals cannot directly penetrate building walls, glass, leaves, or human bodies, and the signal attenuates over a short distance on the ground, the communications equipment and transmitters are spaced closely, perhaps every 100 meters apart,[b] and installed to avoid blockages. 5G towers are likely to use antenna arrays with multiple beams steered electronically. Although the tower antennas are tilted below the horizon, the 5G signals will bounce off the ground, buildings, or terrain such that some of the energy of the unwanted out-of-band signal will move in an upward direction. An impact of the component of the 5G communications signals that propagate in an upward direction can change signals measured by the satellite instrument.

Figure 2 illustrates the upwelling effect of unwanted 5G out-of-band emissions. A hyperlink in the electronic version of this paper will play a video of this scenario.

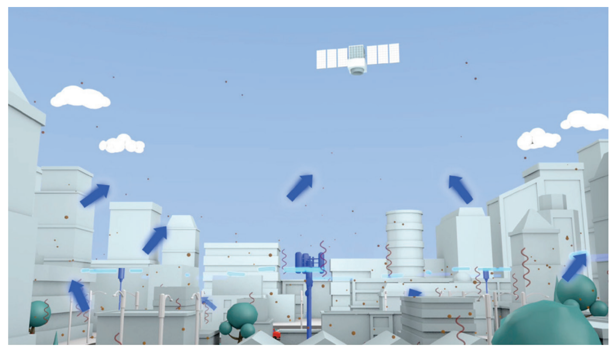


Figure 2: Upwelling adjacent band emissions and the natural upwelling signals from Earth and the atmosphere.

What impact would interference have on the products created from the satellite data?

Estimates of temperature and water vapor derived from passive microwave measurements are used in conjunction with numerical weather prediction (NWP), either as input to the models or as a quality control or data correction value. Per the European Centre for Medium-Range Weather Forecasts (ECMWF)[c] and the National Aeronautics and Space Administration's (NASA's) Global Modeling and

---

[b] The uncertainty in the actual density of the 5G infrastructure, contributes to the challenges in determining the necessary protection value for the passive bands. Significant increases in 5G tower density could increase the economic investment by the industry in order to achieve levels of service.

[c] ECMWF is the European Centre for Medium-Range Weather Forecasts, the home of the Integrated Forecasting System, the "so-called" Euro model cited by U.S. broadcast meteorologists. See https://www.ecmwf.int/sites/default/files/elibrary/2019/19026-radio-frequency-interference-rfi-workshop-final-report.pdf.

Assimilation Office (GMAO)[d], the largest contributor to the reduction in forecast error is microwave-based passive remote sensing measurements from weather satellites.

Forecasters use the outputs of NWP models for situational awareness and guidance as they create nearly all meteorological or hydrological forecasts, warning, or advisory products. This includes products that warn of severe weather phenomena such as (but not limited to) hurricanes, flooding, severe thunderstorms, snow, ice, and fog. Forecast products are used by industry segments (e.g., air, land, and sea transportation; energy exploration and production; and others).

ECMWF, the organization that creates the 10-day medium range model (commonly referred to as the "Euro" model on U.S. television) said:

> "The degradation in the forecasts without microwave observations means a loss of average forecast skill of around 3–6 hours for most centres, for a 72-hour (i.e. 3 day) forecast. In other words, without microwave observations, the same level of forecast guidance could only be given 3–6 hours later than it is today. This means a significant loss of time to issue warnings, for instance, in the case of severe weather events."[4]

Impacts of 5G operations from contamination of out-of-band signals into the nearby passive microwave band will not cause the total elimination of using microwave data in weather models. However, disruption of one or more microwave bands over diverse geographic areas would adversely impact the starting conditions of the NWP models. It is not practical to implement a meteorological experiment that would precisely emulate the impacts to NWP from 5G infrastructures that do not currently exist and whose properties are not well known.

Another product that could be impacted within the United States is a blended Total Precipitable Water (bTPW) operational product that provides imagery information overlaid on a global map to help forecasters analyze and forecast heavy rain and flooding and understand the transfer of moisture from ocean to land.[5] This product uses both microwave-sensed and other satellite information in its creation.

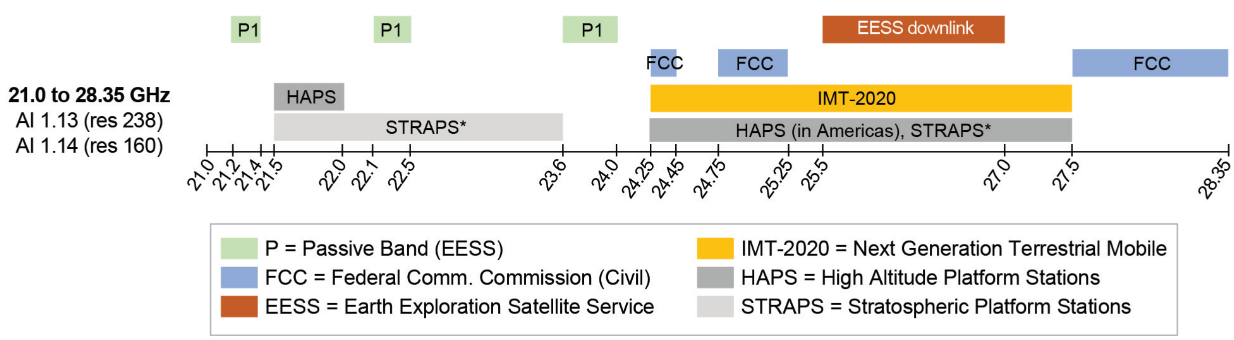


Figure 3: Spectrum frequency ranges proposed for 5G and other services shown with passive spectrum (21–24 GHz) used for weather forecasting.

[d] NASA's Global Modeling and Assimilation Office (GMAO) supports NASA's Earth Science mission and aims to maximize the impact of satellite observations on analyses and predictions of the atmosphere, ocean, land, and cryosphere. Observation Impact Monitoring is shown at https://gmao.gsfc.nasa.gov/forecasts/systems/fp/obs_impact/

Spectrum Regulatory Considerations

The Federal Communications Commission (FCC) determines what frequencies to auction for domestic 5G operations and the relevant protection values for adjacent Earth Exploration Satellite Service (EESS) passive services. The FCC may be advised by changes to the international radio regulations. The International Telecommunication Union's (ITU's) World Radiocommunication Conference 2019 (WRC-19)[e] updates the international radio regulations, which are a treaty obligation of the United States. WRC-19, which just concluded in late November 2019, considered a number of services in proximity to the passive bands used, with the 26 GHz 5G band and the adjacent passive band shown in Figure 3. Note the bands that were considered for 5G applications are denoted in ITU terminology as International Mobile Telephony-2020 (IMT-2020). Current domestic U.S. bands are shown in blue and labeled "FCC" (Federal Communications Commission).

Table 1 shows the band results from WRC-19 for 5G use internationally and the out-of-band protection limits for bands where specified. The values in the yellow rows signify those bands that WRC-19 selected[f] for 5G and are adjacent to passive weather bands.

Spectrum Policy Considerations, Challenges and Mitigations

Considerable discussion ensued before the protection levels were selected for the 24 GHz passive band. Despite years of study and technical assessment, little is certain about the 5G equipment out-of-band signal characteristics and the number and density of such transmitters. This information is necessary for a more accurate determination of the impacts of 5G transmissions at a given protection level on measurements used by the weather community.

Subsequently, the specific impact of contamination to a given band in a geographic region and what that contamination will do to weather forecasting models is difficult to precisely quantify. It is clear that inadequate levels of protection will have a negative

Table 1: Selected 5G Band Results from ITU
(Source: ITU WRC-19 Provisional Final Acts[6])

5G Frequency Proposal[g]	Selected at WRC-19 for 5G (Yes/No)	Adjacent Passive Weather Band	Base Station Protection Level (in 200 MHz Bandwidth)	User Equipment Protection Level (in 200 MHz Bandwidth)
24.24–27.5 GHz	Yes	23.6–24.0 GHz	–33 dBWatts[h]	-29 dBWatts[i]
31.3–31.8 GHz	No	31.3–31.5 GHz	Not selected for 5G use at this WRC	
36.0–40.5 GHz	Yes 37–43.5 GHz	36–37 GHz	–43 dBWatts/MHz and –23 dBWatts/GHz within the 36–37 GHz band [COM4/9][7]	
45.5–47 GHz	Yes	None		
47.2–48.2 GHz	Yes	None		
50.4–52.6 GHz	No	50.2–50.4 GHz	Not selected for 5G use at this WRC	
66–71 GHz	Yes	None		
81–92 GHz	No	86–92 GHz	Not selected for 5G use at this WRC	

impact on the use of this data. In respect to the results from WRC-19, ECMWF stated, "regarding the important 24 GHz observations is a big disappointment."[8] The WMO Secretary-General Petteri Taalas stated, "This WRC-19 decision has the potential to significantly degrade the accuracy of data collected in this frequency band which would jeopardize the operation of existing Earth observation satellite systems essential for all weather forecasting and warning activities of the national weather services."[9] More analysis is needed to determine the impact that ITU WRC-19 values of –33/–39 dBWatts for this band may have on forecasting. However, determining the correct protection value would require understanding some of the unknown issues mentioned above. More testing and transparency across the two science fields, radio communication and passive remote sensing for weather, would promote more solutions.

The ramifications of a stricter limit applied to the 5G infrastructure, could drive additional transmitter sites operating with lower power or a different beamforming scheme to install more sites, driving up 5G costs or reducing performance. The promulgation of an inadequate limit would impact the passive data sensed by weather satellites, with ramifications on how well products derived from that data provide accurate and advance guidance to forecast professionals.

Other mitigation approaches should be studied, including time sharing, where the 5G infrastructure changes frequency or switches back to 4G for a few seconds while 5G transmitters are within the footprint of orbiting passive sensing weather satellites. Carriers already have discussed sharing schemes between 5G and 4G systems.

As another option, changes to modulation schemes or optimization of beamforming methods could also be examined to determine if that would reduce the unwanted adjacent band emissions.

Past and Future Domestic Spectrum Actions

The FCC already auctioned the 24.25 to 24.45 and 24.75 to 25.25 GHz bands in May 2019. The stated emission limit for the adjacent passive band of –20 dBWatts/200 MHz was apparently identical to the existing terrestrial out-of-band limit stated in different units.[j] However, the terms associated with the auction indicate that the FCC can revise provisions for license holders if changed in an FCC rulemaking. This provision could be used to revise the emission limits in accordance with the new ITU Radio Regulations resulting from WRC-19.

There is nothing constraining the FCC from offering additional millimeter wave bands for use by 5G, even if those bands are not in compliance with the ITU Radio Regulations, as long as such use would not adversely impact an adjoining administration whose systems are operating in compliance with the Radio Regulations. Since this WRC did not recommend any usage change to other bands near other passive spectrums,[k] the FCC would not be prevented from a domestic regulatory change to add further 5G bands. Finding 5G Radio Access Nodes and handsets that would operate in different frequency bands from the remainder of the world could complicate any potential action.

One significant passive frequency range that is critical to weather forecasting is from approximately 50 GHz to 58 GHz, where atmospheric vertical

[j] Emission limits for the Upper Microwave Flexible Use Service are stated in 47 CFR §30.203.

[k] There were eleven frequency ranges evaluated internationally for 5G, and as a result the ITU announced five new frequency ranges for 5G. Of those new bands, only two were directly adjacent to passive bands (24.25-27.5 GHz, and 37–43.5 GHz). See https://news.itu.int/wrc-19-agrees-to-identify-new-frequency-bands-for-5g/.

temperature profiles are derived. Throughout the entire globe, satellite measurements are used to derive the temperature of the atmosphere at different heights. These temperatures are essential initial conditions used as input to the NWP models. The different colors shown in Figure 4 represent the various temperature values for this actual measurement example.

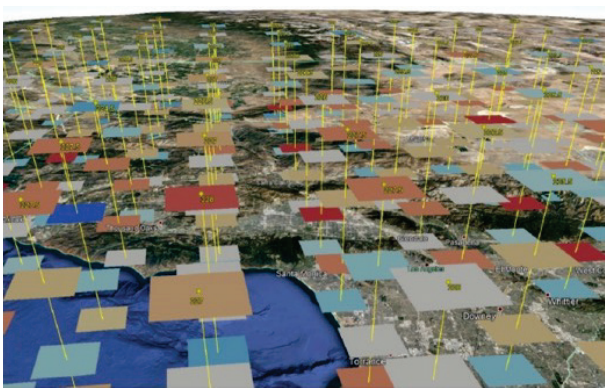


Figure 4: Vertical temperature radiances derived from satellite passive measurements. Colors represent temperature. *(Source: N. Powell, Raytheon Company)*

Future allocations near these bands would require stringent protection levels for out-of-band emissions or a suitable alternative mitigation, as discussed below. Interference in the 50 GHz to 58 GHz region would alter these crucial vertical temperature values and cause the input values for the computer models to be incorrect. Wrong input values would yield an inaccurate output for the computer models.

The ramifications of any such future domestic regulatory actions should be studied before they are proposed and implemented. Due diligence would be needed to understand the potential impacts and the effectiveness of any proposed mitigation.

A workshop report (Radio-frequency Interference Workshop–Sept 2018 [ECMWF])[10] summarizes the impact of the various input data types (to weather forecasting models) and concludes that satellite passive microwave observations contribute more than any other factor to accurate initial states and forecasts.

The importance of passive remote microwave sensing should not be underestimated. Microwave measurements made from space allow a view down into a hurricane when it is obscured by clouds from above. Figure 5 combines the inside view from a microwave passive sensor with that of an infrared or visible image. That additional microwave data leads to better characterization of the hurricane properties or exact location of the eye, all of which contribute to the ability to forecast the future evolution and movement of the hurricane.

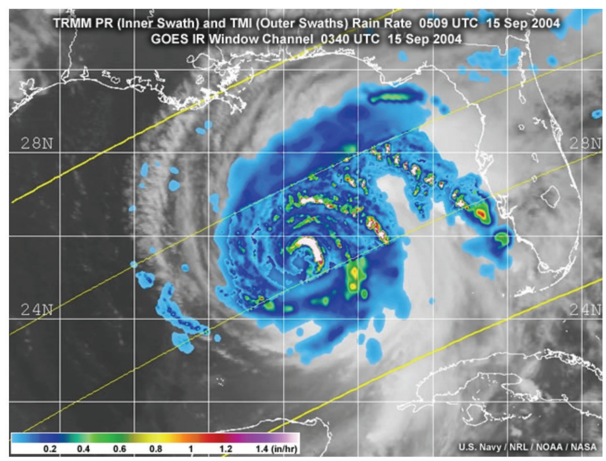


Figure 5: Microwave sensed image of a hurricane overlaid onto an infrared image. *(Source: USN, NOAA, NASA via MetEd)*

Microwave imagery also assists the forecaster by providing situational awareness and the ability to see below clouds, which other types of imaging sensors typically cannot do.

The NWP models support the creation of all types of forecasts, not just hurricane warnings. The prediction of flooding, the temperature ranges for the next week, rainfall, and the occurrences of extreme snow all originate with the availability of timely and accurate NWP model outputs to assist forecaster decisions. Forecasts are used for emergency response, industry operations, insurance valuation, city management, military operations, and by the public for decisionmaking. No area of our planet is immune from the impacts of severe weather.

Therefore, the necessary due diligence and evaluation of potential impacts to weather forecasts, from adjacent band interference caused by future 5G infrastructure should be undertaken. The risk of interference to forecast accuracy has significant consequences, both to safety of life and property and economic impact to segments of the economy.

In 2018 and as of October 2019, large-event weather-related disaster costs in the U.S. totaled \$100.8 billion.[l,11] These were just the events that met the National Centers for Environmental Information (NCEI) reporting criteria for Consumer Price Index (CPI)-adjusted \$1 billion or greater disasters.[m] These numbers do not account for every severe weather event in the country. An assessment of projected economic impacts from all categories of severe weather is warranted. Subsequently, a determination of further impacts to the safety of life and property and for recovery from such events should be made if significant diminished forecast accuracy manifests from the spectrum contamination. The results from both efforts could be compared to the cost of applying mitigations to the 5G infrastructure. The focus on the economic impacts should not ignore the potential impact to safety of life.

Conclusion

Implementing a 5G communications infrastructure in select millimeter wave bands (above 24 GHz) could result in significant unintended consequences for critical measurements of temperature and water vapor used in weather forecasting. Prior to any spectrum allocation decision, policymakers should carefully consider the protection of incumbent use of the spectrum for passive remote sensing. Applying the existing U.S. domestic value at 24 GHz of –13 dBm/MHz presents a significant risk because this value was designed to protect other terrestrial systems and not the extremely sensitive measurements needed for passive microwave sensing of temperature and water vapor measurements. More analysis is needed to determine whether the ITU WRC-19 values of –33/–39 dBWatts (for the 24 GHz band) are adequate to protect environmental forecasting.

Selecting the appropriate threshold values for noninterference operations requires understanding of how passive microwave sensing measurements are made. The operations of satellite microwave remote sensing instruments are considerably different than communications receivers, and protections suited for one are not appropriate for both services. Moreover, consideration of alternative mitigation processes, such as time sharing, is warranted if more stringent protection criteria is not applied to the appropriate millimeter wave bands.

Other bands, such as the lower portion of the 37 GHz and the lower and mid portions of the 50 GHz band, are the source of concerns similar to the 24 GHz band. Policy decisions should also adequately protect these passive bands from unwanted interference as well.

International and domestic regulators must issue regulations that provide adequate protection between weather forecasting data frequencies and other spectrum users in order to ensure forecasters’

[l] All amounts stated are in U.S. dollars.

[m] CPI-adjusted costs of billion-dollar events from 1980 to 2019 (to date) are \$1.714 trillion as of October 8, 2019.

access to the data. This data is essential to delivery of trusted forecasts required for day-to-day use and protection of life and property from severe weather. It is important to take into account the contribution of environmental satellites to weather forecasting. Making decisions for protecting life, safety, and economy should balance the benefits of improved communications from 5G infrastructure with impacts of weather forecast diminished by reduced timeliness and accuracy.

References

[1] Bormann, N., et.al., “Global observing system experiments in the ECMWF assimilation system,” Technical Memorandum 839, ECMWF January 2019, page 3.

[2] 47 CFR § 30.203

[3] http://hydrology.faculty.ku.edu/index.html

[4] Ibid, ECMWF final report cited in Footnote a.

[5] https://www.star.nesdis.noaa.gov/portfolio/detail_bTPW.php

[6] https://www.itu.int/en/ITU-R/conferences/wrc/2019/Documents/PFA-WRC19-E.pdf

[7] WRC-19 Provisional Final Acts, CMR 19/2000-E, pages 394–396.

[8] https://www.ecmwf.int/en/about/media-centre/news/2019/ecmwf-statement-outcomes-itu-wrc-2019-conference

[9] https://public.wmo.int/en/media/news/wmo-expresses-concern-about-radio-frequency-decision

[10] ECMWF Sep 2018 Newsletter. Retrieved November 2019. https://www.ecmwf.int/en/newsletter/159/news/forecast-performance-2018.

[11] https://www.ncdc.noaa.gov/billions/summary-stats

Section 4
Leading in a Time of Change

- Space Leadership in Transition
- Strategic Foresight: Addressing Uncertainty in Long-Term Strategic Planning
- Space Game Changers: Driving Forces and Implications for Innovation Investments
- Defense Space Partnerships: A Strategic Priority
- Space-Based Solar Power: A Near-Term Investment Decision

CENTER FOR SPACE POLICY AND STRATEGY

NOVEMBER 2019

SPACE LEADERSHIP IN TRANSITION

JAMES A. VEDDA
THE AEROSPACE CORPORATION

AEROSPACE

Summary

For generations, Americans have heard government officials, academics, technology pundits, and others talk about leadership in space. From this we can infer that space leadership has enduring importance. However, it seems to mean different things to different people. It also changes over time—space leadership today does not have the same characteristics and share the same priorities as in the days of Sputnik and Apollo. This paper discusses how we should characterize space leadership in the post-Cold War, twenty-first century context, and examines the hypothesis that the primary showcase for national space leadership for the foreseeable future will be cislunar space development.

The Changing Landscape

In recent years, U.S. space operators and decisionmakers have become increasingly concerned about threats to U.S. space leadership. In the civil sector, this has been driven largely by U.S. dependence on Russia for crew access to the International Space Station (ISS) since the termination of the space shuttle program in 2011. In national security, foreign development of counterspace systems has become a regular feature of public statements by U.S. defense and intelligence officials.[1] This is reminiscent of similar concerns about the Soviet Union's space program between the launch of Sputnik 1 in 1957 and the success of the Apollo lunar missions. The threat of Soviet dominance in space turned out to be less formidable than expected, but it continued to drive policy and programmatic decisions for decades, until the Soviet Union ceased to exist.

Generally, the global proliferation of space-related technologies and know-how has made the twenty-first century space environment a very different

"There is rather more to space exploration than shooting men into orbit, or taking photos of the far side of the Moon. These are merely the trivial preliminaries to the age of discovery that is now about to dawn. Though that age will provide the necessary ingredients for a renaissance, we cannot be sure that one will follow. The present situation has no exact parallel in the history of mankind; the past can provide hints, but no firm guidance."

—Arthur C. Clarke
Profiles of the Future (1963)

playing field from what it was in the Cold War. In today's world, particularly with the rise of space activities in China, India, and many other countries, and the resurgence of Russia as a strategic competitor, U.S. leadership faces a fundamentally different challenge: how to productively interact with a global array of collaborators and competitors, not simply outperform a single peer rival.

Another critical development of the current era, at least as important as the growth in the number of spacefarers worldwide, is humanity's inflection point in space operations. For the past three generations, we have learned to use space applications that have made us safer, richer, and more connected. These impressive benefits have been achieved almost entirely using disposable space systems that receive and transmit electromagnetic information. The next plateau, for which we seem poised to reach, will be more difficult to achieve but potentially much more rewarding: the routine physical manipulation of objects in space (e.g., building, servicing, mining, manufacturing, and debris cleanup) accompanied by human habitation in space on a scale significantly beyond anything experienced to date. This could result in profound changes, not only in how we operate in space, but also to the extent that space becomes integrated with our economy and our culture.

Growth in the number of spacefaring nations and continuous improvement of technical and operational capabilities ensure that national leadership will remain a fluid concept. This makes space leadership hard to identify and categorize, and yet it has been invoked so often that it risks becoming little more than a rhetorical tool.

Calls for U.S. Space Leadership: A Brief History

In anticipation of the 2016 U.S. presidential election, a group of space-related professional associations issued a statement titled "Ensuring U.S. Leadership in Space." The group offered a list of 10 objectives to shore up U.S. leadership, such as stable budgets, a strong industrial base, innovative partnerships, and reduced trade barriers. However, the group did not try to define space leadership, leaving open the question of how to recognize when it has been achieved (aside from the size of the nation's space-related market share).[2] This is just one recent example in the long history of concern over U.S. space leadership.

Space leadership has been a staple of U.S. policy and rhetoric since the administration of President Dwight Eisenhower. In a document that can be considered the first U.S. directive on overall space policy,[3] the Eisenhower administration noted "a tendency to equate achievement in outer space with leadership in science, military capability, industrial technology, and with leadership in general." In the wake of Sputnik, "further demonstrations by the USSR of continuing leadership in outer space capabilities might, in the absence of comparable U.S. achievements in this field, dangerously impair the confidence of these peoples [non-aligned nations] in U.S. over-all leadership." At a time when the benefits of space applications had yet to be realized, the administration believed that the nation's performance in this area would be a reflection of U.S. leadership across many important national interests, especially military, economic, and scientific. Eisenhower supported research "to achieve and maintain leadership in such applications" and listed the following as the first of four objectives in the directive [emphasis added]:

> Development and exploitation of U.S. outer space capabilities as needed to achieve U.S. scientific, military, and political purposes, and **to establish the U.S. as a recognized leader in this field**.

For the next two decades, presidential administrations addressed space policy in short, targeted directives rather than comprehensive national policies, but calls for U.S. leadership did not disappear from the dialogue. In a prominent example, at the birth of the Apollo program, President John F. Kennedy sent a query to Vice President Lyndon Johnson asking if there was a "space program which promises dramatic results in which we could win?"[4] In his response 18 days later, after consulting with NASA and other stakeholders, Johnson made it clear that he interpreted this as a "request for positive recommendations for placing this country on the way toward leadership in space."[5]

Articulation of overarching national space policy made its reappearance in the Jimmy Carter administration, including a statement that "We will maintain U.S. leadership in space science and planetary exploration and progress."[6] Early in his presidency, Ronald Reagan asserted that "The United States is fully committed to maintaining world leadership in space transportation" and will preserve its "leadership in critical aspects of space science, applications, and technology."[7] Shortly before leaving office, he noted that "a fundamental objective guiding United States space activities has been, and continues to be, space leadership.… The United States civil space sector activities shall contribute significantly to enhancing the Nation's science, technology, economy, pride, sense of well-being and direction, as well as United States world prestige and leadership."[8]

More recently, Barack Obama's National Space Policy, which remains in effect, repeatedly articulated the intent to strengthen, reinvigorate, and demonstrate U.S. leadership in a broad range of space activities.[9] Leadership also has been a theme of Donald Trump's series of Space Policy Directives.[10] In general, statements from U.S. officials insist that the United States will maintain (or regain) leadership. As a result, space projects of significant size (e.g., launch vehicle development as well as human and robotic exploration) have come to symbolize leadership, not just in the United States but also in emerging spacefaring countries.

The Old Metrics

Leadership is difficult to measure, having both quantitative and qualitative aspects. In the early days of the space age, the most widely reported and recognized measures of a nation's space activities favored the quantitative:

- The size of the space budget.
- The capacity of the largest launch vehicles.
- The frequency of launches.
- The number of operational satellites.
- The number of significant space "firsts" achieved. (This covered an array of activities; e.g., first satellite, first pictures of the lunar far side, first man in orbit, first woman in space, first multi-person space capsule, first spacewalk, first robotic probe to another planet, and first crew to land on the moon.)

The perception of who was "winning" was a key element of the geopolitical rivalry. Initially, the Soviet Union was winning on the numbers: larger-capacity launch vehicles, more launches, more satellites, and more "firsts" in both robotic and human spaceflight. The relative amount of funding was hard to determine accurately mostly due to lack of transparency on the Soviet side, but it seemed reasonable to assume that all those firsts were backed by a lot of rubles. On the American side, funding ramped up quickly in the 1960s, but the decline of NASA budgets as the Apollo program wound down in the early 1970s was seen by some observers as neglect, or even abdication, of U.S. leadership. Another assumption at the time, less quantifiable but clearly important, was that the Soviets had matched or surpassed the United States in all or most space-related technologies. This was a subjective assessment that was measured indirectly through quantitative evidence such as number of successful missions or firsts.

These measurements of Soviet leadership turned out to be a mischaracterization. Launch vehicles were bigger because Soviet missiles had been designed for bulky nuclear warheads that were heavier than their U.S. counterparts. Launches were more frequent and satellites more numerous because Soviet satellites were not reliable and did not last very long. The Soviet space firsts were driven by often reckless political pressure from leaders seeking propaganda victories, which prompted an overestimation of the state of Soviet space technology.

Today, it is appropriate to question which of these old measures are still valid. More than a half century of experience in space has shown the world that leadership is not determined solely by how much you spend, but also by how you spend it. Investment aimed at maintaining and extending leadership ideally should yield innovation and sustained progress, even if there are failures along the way. Investment dominated by playing it safe, which can unreasonably extend legacy projects at the expense of innovation, may not earn points toward recognition as a leader. Political and business decisionmakers have not always taken the big-picture view and balanced their portfolios to ensure leadership, choosing instead to appease entrenched (often short-term) interests. [13,14]

Numbers in Perspective – 2018[11,12]

- China led the world with 39 orbital launches.
- The United States had 31 launches, all of which were conducted by commercial entities. Only one Chinese launch was commercial.
- SpaceX, a company with 6,000 employees, completed 21 of the U.S. orbital launches.

Achieving space firsts, which carried great significance in the East-West geopolitical competition to win hearts and minds around the world, counts for less in today’s world, where capabilities are more dispersed and international collaboration is the norm for ambitious projects. (However, space firsts may still hold significance for the domestic and regional audiences of emerging spacefarers.) Similarly, numbers of rockets launched or satellites deployed do not indicate leadership unless they contribute to increasing humanity’s knowledge and capabilities or build infrastructure that paves the way to accomplish these things in the future. Nationalistic statements and actions that appear designed to flex muscles are likely to clash with foreign policy, trade, and technical collaboration imperatives and be seen as undesirable and anachronistic.

Investing in space leadership-by-the-numbers has opportunity costs: Could the resources be more productively applied elsewhere? For example, is having the largest launch vehicle more or less important, for operational and prestigious reasons, than having the ability to assemble, repair, and refuel on-orbit assets? Similarly, are the historic accolades and scientific and technical advances to be obtained from putting the first humans on Mars worth more or less than the economic, scientific, and technical advances gleaned from investing the

> ***"The long-term health of a nation is probably shown most clearly by the time scale of the programs it undertakes. The willingness to commit to ventures of many years' duration, with potential very large returns, is the hallmark of a nation confident of its own future. The fear of any commitment beyond one or two years is the symptom of disease, signaling a fundamentally hopeless view of the future and the intention to cut the losses and get out of the game."***
>
> —Gerard K. O'Neill
> *2081* (1981)

same resources in the development of cislunar space? The late physicist John Marburger succinctly summarized this concern shortly after he completed his tenure as science advisor to President George W. Bush:

> If the architecture of the exploration phase is not crafted with sustainability in mind, we will look back on a century or more of huge expenditures with nothing more to show for them than a litter of ritual monuments scattered across the planets and their moons.[15]

For examples of how old metrics still hold some influence in today's space community, we need to look no further than reactions to the Chinese achievement of becoming the first country to land on the moon's far side in January 2019. This event did not provoke the same level of panic as did Sputnik in 1957, but some analysts sought to portray it as a demonstration that the United States is losing a new space race. A commentary in the *Washington Post* at the time correctly identified the harvesting and use of space resources as a critical element in the next generation of space development but lapsed into Cold War rhetoric in statements such as this one:

> China is best placed to win a space race, given its well-coordinated, disciplined, technocratic system, able to set and maintain long-term goals, with a vast population and talent base. The United States is disorganized regarding space and cannot offer a serious challenge to the long-term plans China is setting in this domain.[16]

Substituting "the Soviet Union" for each occurrence of "China" in the previous statement will yield the same argument that was heard through much of the Cold War. The difference today is that China has the second-largest economy in the world and is well integrated with global commerce. This gives it a distinct advantage over the old U.S.S.R., but it does not mean that all space ambitions will be realized on schedule and with no mishaps. Nor does it mean that Chinese space leadership can be defined simply by numbers of launches or space firsts.

The successful landing of Chang'e-4 on the lunar far side was a great achievement, but it was not the only remarkable space activity going on at the time. Between late November 2018 and early January 2019, NASA landed the InSight mission on Mars, put OSIRIS-REx into orbit around an asteroid, did a flyby encounter with a Kuiper Belt object with the New Horizons spacecraft, and awarded nine contracts for Commercial Lunar Payload Services (CLPS) to support lunar surface activities.

Similarly, the hiatus in the launch of crews to orbit from the United States after the 2011 retirement of the space shuttle must be put into perspective. It was fortunate that the Russian Soyuz option was available, allowing ISS operations to continue even though the hiatus has lasted longer than expected. But does temporary dependency on a spacefaring partner constitute loss of leadership? In this case, that could be true in a micro sense because the reasons for the delay include inadequate federal funding in the early years of NASA's Commercial Crew program, followed by development delays experienced by the contractors. In the macro sense, this was a big step forward in human spaceflight: the United States has become the first country to turn to its commercial sector for human access to orbit. This provides the U.S. government—and other customers—with two commercial sources for sending humans into space, with more expected to follow. This puts the U.S. squarely into a leadership position, driving what is expected to be a trend in access to orbit. Commercial services aimed at the lunar surface and other locations in cislunar space are expected to follow in the near future.

Space leadership is a source of power in the world. It enables sophisticated collection and distribution of information that can yield real economic and national security strength. Pride in space accomplishments promotes national prestige. This implies that failures of space leadership can diminish the strength of major powers. In a world that includes ongoing geopolitical rivalry, space competition in its various forms will continue and grow.

Updating the Metrics for Space Leadership

If leadership measures of the early space age are no longer valid—or at least, have lost some of their significance—then development of new measures for the twenty-first century is required. Some generic national leadership characteristics applicable to politics, economics, and science can be applied specifically to spacefaring efforts:

- Reputation as a respected partner with whom others are eager to team—the partner of choice, not just necessity
- A proactive, not reactive, approach to programs and investments aimed at innovation and development
- Substantial global market presence in key hardware and services industries
- Prime mover in establishment of procedural norms and technical standards

Based on these generic indicators, a country's concerns about loss of leadership should be focused on factors such as declining partnerships, inadequate forward-looking investment, shrinking global market share, and reduced influence in standard-setting bodies. These factors are far more important than which country had the most launches last year. Global space players, as they evolve, inevitably seek independent capabilities and ways to maximize their own economic benefits. That is part of a healthy competitive environment, so shifting markets should be no surprise. The difficulty arises when a country finds itself sidelined or excluded from international activities in which it formerly exercised influence.[17]

Leadership measures for the twenty-first century can draw from scholarship of the last century. Dr. Sally Ride's 1987 report to the NASA administrator gives excellent guidance for reevaluation of leadership indicators. Although the report was written more than three decades ago and speaks from a U.S. perspective, it contains several insights that have lasting value for a broader community. The essential points are summarized here [emphasis added]:[18]

- **Leadership cannot simply be proclaimed—it must be earned.**

- **Leadership does not require preeminence in all areas and disciplines of the space enterprise.** In fact, the broad spectrum of space activities and the increasing number of spacefaring nations make it virtually impossible for any nation to dominate in this way.

- Being an effective leader requires that a country **have capabilities which enable it to act independently and impressively** when and where it chooses, and that **its goals be capable of inspiring others**—at home and abroad—to support them.

- Leadership results from both **the capabilities a country has acquired** and **the active demonstration of those capabilities**; accordingly, a leading country must have, and also be perceived as having, the ability to meet its goals and achieve its objectives.

- A space leadership program must have **two distinct attributes**.

  - First, it must contain **a sound program of scientific research and technology development**—a program that builds the nation's understanding of space and the space environment, and that builds its capabilities to explore and operate in that environment. A country will not be a leader in the 21st century if it is dependent on other countries for access to space or for the technologies required to explore the space frontier.

  - Second, the program must **incorporate visible and significant accomplishments**; a country will not be perceived as a leader unless it accomplishes feats which demonstrate prowess, inspire national pride, and engender international respect and a worldwide desire to associate with the nation's space activities.

- Perhaps most significant, **leadership is also a process. That process involves selecting and enunciating priorities for the civilian space program and then building and maintaining the resources required** to accomplish the objectives defined within those priorities.

Dr. Ride recognized long ago that the space operating environment would become simultaneously more collaborative and more competitive. She emphasized the continuing need for scientific research and technology development. She repeatedly identified capabilities (not destinations) as a strategic driver and acknowledged their importance in demonstrating to other nations why they should be eager to partner with the United States.

Dr. Ride's vision of space leadership overlaps and is compatible with the generic leadership characteristics listed at the beginning of this section. Merging the two yields a robust framework for an updated paradigm of space leadership for any nation that aspires to it:

- The continuing quest for scientific knowledge

- Development of advanced technology and the ability to use it

- An ongoing record of achievement based on proactive government and industry investments

- A cooperative posture that prompts other nations' willingness and eagerness to collaborate on programs as well as the establishment of standards, norms, and rules

Although counting missions and tallying budgets will always play a role in measuring achievement, the new paradigm should not be "leadership by the numbers." Technologically, it should be capabilities-driven and business-savvy. Politically and strategically, it should embrace both collaboration and competition but shun space races and other short-term, resource-depleting endeavors that do not contribute to long-term collective goals and objectives. By embracing this approach, leading spacefarers can become far better at answering the question: Why spaceflight?

Reconsidering Rationales, Rebranding Spaceflight

Two respected polling organizations each conducted national polls on the U.S. space program in 2018. Their results were very similar. Both found that a strong majority of respondents believe NASA continues to play a vital role in space exploration, even as private sector organizations demonstrate greater capabilities and ambitions. In a Pew Research poll, 72 percent agreed that "it is essential for the U.S. to be a leader in space exploration."[19] A poll by Bloomberg asked about the level of investment rather than leadership, and 76.6 percent said that U.S. government spending on space exploration was either "just the right amount" or "too little."[20] These two polls appear to document resounding public support for the United States as a space leader and for NASA as a key element of that leadership.

However, the poll results regarding priorities tell a different story than the message typically heard from U.S. leaders and the space community, who often portray human exploration as NASA's core mission. In both polls, respondents' top two mission priorities by far were climate change research and monitoring of asteroids that pose impact threats to Earth. Both polls placed human missions to the moon and Mars at the bottom of the list. A more recent poll (May 2019) placed asteroid monitoring at the top of the priority list and scientific research (all types, including climate research) in second place, with human missions to the moon and Mars at the bottom once again.[21] Altogether, these polls seem to suggest a substantial disconnect between the preferences of U.S. citizens and the projects and rhetoric promoted by their elected leaders.

Spaceflight enthusiasts, and even seasoned professionals, too often do a poor job of justifying space investments in a way that resonates with uninvolved citizens. Writing and rhetoric on the subject tend to lean heavily on national prestige, scientific discovery, technological spinoffs, inspiration of youth, and our "destiny" or "nature" to explore. While each of these rationales has merit, some have weakened considerably in our post-Cold War, high-tech world. Collectively, they may no longer be sufficient to justify the associated cost and risk in the minds of the general public.[22] It is debatable whether we can unambiguously achieve all of these aspirations as effectively as we did in the 1960s with the Apollo program.

> ***"We could fill books with problems of fundamental importance to the human race which can be solved only by spaceflight, more easily by spaceflight, or more probably by spaceflight."***
>
> —Dandridge Cole
> *Beyond Tomorrow* (1965)

Nationally and globally, there is insufficient agreement on prioritization of the *primary* drivers of current and future spaceflight efforts. Space offers an array of worthwhile *secondary* rationales (e.g., spinoffs and inspiration), but investments and risk assessments should be made based on primary rationales. A brief assessment of the traditional justifications demonstrates the altered circumstances that have developed in the twenty-first century.

- **National Prestige.** Emerging spacefaring nations undoubtedly are hoping for a boost in prestige from their growing space activities. However, it seems unlikely that exploration and development efforts by a country acting alone, no matter how successful, would win hearts and minds in the international arena to the extent experienced in the Apollo era. In the absence of large-scale benefits shared generally, resentment or suspicion of the lone actor may result. This could dramatically alter the calculus for a nation seeking leadership status.

- **Scientific Discovery.** Science is obviously the primary goal on dedicated missions, but it has always been secondary in human spaceflight. In either case, the science community's investment decisions will tend to favor robotic systems for anything beyond cislunar space and perhaps for many lunar investigations. As the sophistication and productivity of robots improve, there will be no scientific motive for a rush to send humans to distant destinations given the added risk and expense. This perpetuates the tension and resource competition that has existed between science and human spaceflight efforts for decades.

- **Technology Spinoffs.** Spinoffs are not a sufficient justification for a space exploration program. They are secondary applications, and an investment of this magnitude must be justified on its primary applications. Any attempt to argue that spinoffs provide the rationale for spaceflight is easily countered: direct investment in technology development in the absence of a space program would bring similar results at less cost.

- **Inspiration to Youth.** Inspiration is a very positive *side-effect* of the space program, but it is not a primary rationale for going into space or a justification for expending substantial resources and taking on exceptionally high risk. Post-baby boom generations, who did not grow up watching Project Apollo unfold, tend to take spaceflight for granted. Space-related news and information struggles to rise above the noise level amid the multitude of distractions that draw attention in twenty-first century society.

- **Human destiny.** Not all individuals and cultures embrace exploration, so if it is human destiny to explore, this is only true for some humans. At the national level, a society that seeks to grow, enrich itself, advance its technology, and stimulate its creativity must explore in some manner.[23] However, that does not necessarily mean space exploration will be the first choice, even if the technological capability to do so exists. Analysis of opportunity costs is inevitable: If a society invests substantial resources in space, what other investments are sacrificed?

A healthy appreciation for history is clearly important. However, critical analysis of that history should reveal the importance of inflection points that re-vector human efforts toward a new plateau. As noted earlier, humanity is now facing such an inflection point in space development, if it chooses to engage and to persevere.

To reach the new plateau, decisionmakers must resist pressure to be hidebound by historical experience that lacks applicability to the future. Nations that aspire to space leadership in the twenty-first century must revisit their fundamental goals as they plan the transition to the next plateau: What do we want to accomplish *that space can contribute to*? Presumably, the answer will include some combination of the following: expand human knowledge and resources, improve the economy and the quality of life, and increase chances for survival.

To achieve these goals—indeed, to determine the extent to which space activity can contribute to these goals—leading spacefaring nations must take on these five challenges:

1. **Conduct cislunar development** that advances science, commerce, and security.
   a. Fund and perform early-stage, high-risk research and development.
   b. Build or sponsor key infrastructure elements.
   c. Become an anchor tenant for promising new space industries and/or facilities.
2. **Address the two greatest physiological challenges** to long-duration spaceflight: microgravity and radiation exposure.
   a. Pursue development of rotating variable gravity habitats and determine the minimum gravity level needed to maintain health.
   b. Experiment with shielding and medical countermeasures to mitigate radiation exposure; plan for solar flare scenarios.
3. **Demonstrate that humans can "live off the land"** in space.
   a. Optimize reuse of space systems.
   b. Learn how to routinely use extraterrestrial material and energy resources.
   c. Develop the means for extraterrestrial production of routine supply needs.
4. **Increase efforts on planetary defense and human survival**, encompassing both the outsider threat and the insider threat.
   a. Outsider threat: Detect, categorize, and track solar system bodies that may pose a collision threat for Earth. Develop countermeasures and response plans.
   b. Insider threat: Expand the spatial, spectral, and temporal observation of Earth and its atmosphere to detect and report anomalies and identify trends. Beyond the scientific benefits of such activities, the systems should be designed to rapidly deliver results that are useful to national and international decisionmakers, space operators, and other relevant responders.
5. **Transition to a new generation of science missions** that include humans and robots working together on planetary surfaces and deep-space robotic probes that are assembled in orbit, which may allow for much more ambitious missions.

These five challenges address major aspects of the learning curve for reaching the next plateau, and cislunar space is the proving ground (for the human components in particular). However, it may also be a disproving ground. Along the way, we may discover that certain key capabilities will take far longer to become viable than we had anticipated (e.g., mining water ice on the moon or minerals on asteroids). Even negative findings are important, however, as they will compel us to adjust the pace or priorities of space development.

Conclusion

The challenges awaiting us on the next plateau of space development require *transforming* leadership (in pursuit of higher collective goals) not simply *transactional* leadership (incremental actions that satisfy specific individuals or groups).[24] For generations to come, national leadership in space may be defined and judged chiefly by how nations and their subnational entities advance the development of cislunar space and reap (and share) its benefits. In such a scenario, cislunar development will be justified on its own merits, not simply as a stepping-stone to points beyond. International and industrial collaborators will be true partners and investors, not simply contractors providing hardware or services.

Future space "firsts" will be cheered, and traditional by-the-numbers measurements will continue to be promoted, but topping the list of metrics for space leadership will be steady technological advancement, contributions to enduring space infrastructure, willingness to partner and share, and concerted efforts to address highest-salience global challenges.

References

1 For example, see James R. Clapper, "Worldwide Threat Assessment of the U.S. Intelligence Community: Statement for the Record, Senate Select Committee on Intelligence," January 29, 2014 (http://www.intelligence.senate.gov/140129/clapper.pdf); Cecil D. Haney, "Statement before the Senate Committee on Armed Services," February 27, 2014 (http://www.armed-services.senate.gov/imo/media/doc/Haney_02-27-14.pdf); Marcia Smith, "Dragons, Snakes, and the Dark Side: Space Council Hears About Satellite Vulnerabilities," *Space Policy Online*, October 9, 2017 (https://spacepolicyonline.com/news/dragons-snakes-and-the-dark-side-space-council-hears-about-satellite-vulnerabilities/).

2 "Ensuring U.S. Leadership in Space," March 2016. Signatories to the statement include Aerospace Industries Association (AIA), Aerospace States Association (ASA), American Institute of Aeronautics & Astronautics (AIAA), American Astronautical Society (AAS), Commercial Spaceflight Federation, Space Foundation, Coalition for Deep Space Exploration, Colorado Space Coalition, Satellite Industries Association (SIA), Silicon Valley Space Business Roundtable, Space Angels Network, Space Florida, and Students for the Exploration & Development of Space (SEDS). (https://www.aiaa.org/uploadedFiles/Whats_New/EnsuringUSLeadershipInSpace_FINAL.pdf)

3 Dwight D. Eisenhower, "Preliminary U.S. Policy on Outer Space," NSC 5814/1, August 18, 1958 (https://aerospace.org/sites/default/files/policy_archives/NSC-5814-1%20Space%20Policy%20Aug58.pdf).

4 John F. Kennedy, Memorandum for Vice President, April 20, 1961 (https://aerospace.org/sites/default/files/policy_archives/JFK%20to%20LBJ%2020Apr61.pdf).

5 Lyndon B. Johnson, Memorandum for the President, May 8, 1961 (https://aerospace.org/sites/default/files/policy_archives/LBJ%20memo%20to%20JFK%208May61.pdf).

6 Zbigniew Brzezinski, "Civil and Further National Space Policy," PD/NSC-42, October 10, 1978 (https://aerospace.org/sites/default/files/policy_archives/PD-42%20Civil%20%26%20Natl%20Space%20Policy%20Oct78.pdf).

7 Ronald Reagan, "National Space Policy," NSPD-42, July 4, 1982 (https://aerospace.org/sites/default/files/policy_archives/National%20Space%20Policy%20Jul82.pdf).

8 Ronald Reagan, "National Space Policy," February 11, 1988 (https://aerospace.org/sites/default/files/policy_archives/National%20Space%20Policy%20Feb88.pdf).

9 Barack Obama, "National Space Policy of the United States of America," PPD-4, June 28 2010 (https://aerospace.org/sites/default/files/policy_archives/National%20Space%20Policy%2028Jun10.pdf).

10 Donald J. Trump, "Reinvigorating America's Human Space Exploration Program," SPD-1, December 11, 2017 (https://aerospace.org/sites/default/files/policy_archives/Space%20Policy%20Directive%201%20-%2011Dec17.pdf); "Streamlining Regulations on Commercial Use of Space," SPD-2, May 24, 2018 (https://aerospace.org/sites/default/files/policy_archives/Space%20Policy%20Directive%202%20-%2024May18.pdf); "National Space Traffic Management Policy," SPD-3, June 18, 2018 (https://aerospace.org/sites/default/files/policy_archives/Space%20Policy%20Directive%203%20-%20STM%2018Jun18.pdf); "Establishment of the United States Space Force," SPD-4, February 19, 2019 (https://aerospace.org/sites/default/files/2019-02/Space%20Policy%20Directive%204%20-%20Space%20Force%2019Feb19.pdf).

11 Gunter's Space Page – Orbital Launches of 2018 (https://space.skyrocket.de/doc_chr/lau2018.htm)

12 Space Launch Report (http://www.spacelaunchreport.com/log2018.html); SpaceX (https://www.spacex.com/missions)

13 Roger D. Launius & Howard D. McCurdy (eds.), *Spaceflight and the Myth of Presidential Leadership*, University of Illinois Press, 1997.

14 James A. Vedda, *Becoming Spacefarers*, Xlibris Corp., June 2012.

15 John Marburger, "Remarks on the background for the Vision for Space Exploration presented to the Review of U.S. Human Space Flight Plans Committee," August 5, 2009 (http://www.nasa.gov/pdf/376646main_11%20-%20jhm%20Augustine%20Committee%2009-05-09B.pdf).

16 Namrata Goswami, "Losing the space race against China," *Washington Post*, January 11, 2019, A21 (https://www.washingtonpost.com/opinions/the-new-

space-race-pits-the-us-against-china-the-us-is-losing-badly/2019/01/10/bcdcad10-14f9-11e9-b6ad-9cfd62dbb0a8_story.html?utm_term=.ef918c8305ff).

17 For a discussion of how this could play out in one space-related area, see Bhavya Lal, et al., "Global Trends in Space Situational Awareness (SSA) and Space Traffic Management (STM)," IDA Science & Technology Policy Institute, April 2018 (https://idalink.org/D9074).

18 Sally K. Ride, "Leadership and America's Future in Space," report to the NASA Administrator, August 1987 (https://history.nasa.gov/riderep/leadspac.htm).

19 Cary Funk & Mark Strauss, "Majority of Americans Believe It Is Essential That the U.S. Remain a Global Leader in Space," Pew Research Center, June 6, 2018 (http://assets.pewresearch.org/wp-content/uploads/sites/14/2018/06/05153653/PS_2018.06.06_science-and-space_FINAL.pdf).

20 Riley Griffin & Justin Bachman, "Americans Think NASA Should Focus on Climate Change – Trump Doesn't," *Bloomberg News*, August 1, 2018 (https://www.bloomberg.com/news/articles/2018-08-01/americans-think-nasa-should-focus-on-climate-change-trump-doesn-t).

21 Associated Press/NORC Center for Public Affairs Research (University of Chicago), "Space Exploration: Attitudes toward the U.S. Space Program," May 2019 (http://www.apnorc.org/projects/Pages/Space-Exploration-Attitudes-toward-the-U-S--Space-Program.aspx).

22 For an extensive discussion of this point, see James A. Vedda, *Choice, Not Fate: Shaping a Sustainable Future in the Space Age*, Xlibris Corp., December 2009, Chapter 7.

23 Steven J. Dick, "Why We Explore" (first in a series), NASA History Division, October 2004 (https://www.nasa.gov/missions/solarsystem/Why_We_01pt1.html).

24 James MacGregor Burns, *Leadership*, New York: Harper & Row, 1978.

STRATEGIC FORESIGHT: ADDRESSING UNCERTAINTY IN LONG-TERM STRATEGIC PLANNING

Kara C. Cunzeman and Robin Dickey

The space domain and the policy issues surrounding it provide a key opportunity for the application of strategic foresight. Space is an increasingly complex physical, political, economic, and threat environment, with significant and rising uncertainty. Many space systems involve capabilities that are on the bleeding edge of technological development in a field rife with surprise from both forward leaps and setbacks. Future uncertainty in space is not just about technology, however. The geopolitics of great power competition in space, rising questions about the civil and commercial regulatory environment, and the state of the space workforce all pose challenges for future planning due to complex interactions, long lead times, and high costs of miscalculation. Strategic foresight can help because it takes a holistic approach to considering and preparing for what is possible instead of relying on existing conditions and trends to predict the future. Long-term vision is needed to navigate the toughest issues in space policy and help the United States proactively shape the path toward its preferred futures.

Introduction

If there is anything the COVID-19 pandemic has proven, it is that the future is ruled by uncertainty. Few could have predicted at the beginning of 2020 that the year would be shaped by a global pandemic causing disruptions to politics, economics, and the very foundations of human activity. The certainty that uncertainty will play a central role in the future indicates that policymakers looking forward must ask themselves not only what issues must be addressed but how they will approach planning and decisionmaking as a process. In order to navigate and even influence the paths created by disruption, we must examine our toolbox of methodologies for planning for the future.

The goal of foresight is not to predict the future, but to ensure we have adequately challenged our assumptions and are prepared for a variety of possible outcomes.

Strategic foresight is one such methodology. Strategic foresight is a varied set of tools and techniques that help to envision possible future outcomes so that we can make better decisions today.[1] Instead of bracing for disaster or change, strategic foresight helps us to envision preferred futures, identify key events and decision points along the path to those futures, and integrate uncertainty into the planning process from the beginning. The goal of foresight is not to predict the future, but to ensure we have adequately challenged our assumptions and are prepared for a variety of possible outcomes.[2] In this framing, policymakers can accept and proactively shape to preferred futures through the uncertainties of life instead of simply responding to them after the fact.

Applying Strategic Foresight to the Key Issues of Space Agenda 2021

The *Space Agenda 2021* report has raised numerous key issues and decision points for policymakers to consider. The four major topics covered in the report—managing the growth of space traffic, national security space, space exploration and economic development, and shaping the future—are all complex and dynamic challenges that decisionmakers will face in the coming years.

Table 1 demonstrates the timeliness and complexity of the issues raised in *Space Agenda 2021*. Each chapter is summarized in terms of key technologies with the potential to affect the issue in coming years, cross-cutting factors shared with other chapters, and major opportunities and recommendations provided by the chapters' authors. The cross-cutting factors are particularly important because they demonstrate the integration of different challenges and opportunities across all facets of space activities. Although each chapter in *Space Agenda 2021* stands on its own, the topics discussed in each chapter often cannot be addressed without thinking about how the cross-cutting factors apply to other areas. The integration and complexity of space policy issues also bring to light several tensions that will need to be navigated as policymakers make decisions. These include balancing a number of dichotomies: regulatory oversight for security versus open paths for commercial growth; classification of sensitive information versus sharing for commercial and international partnerships; growth in activity versus space traffic management; moving as quickly as possible versus driving with purpose; the Space Force's role in international cooperation with partners versus use of force to defend national security; and actors who may be cooperative in some aspects and competitive in others.

One methodology within strategic foresight is the identification of key uncertainties and investigation into how they can affect the future. Two such uncertainties were uncovered through a special internal futures study led by Aerospace's Strategic Foresight Initiative. They are both deemed critical for the development of all four policy areas discussed in the report. Exploring potential implications against each issue is a helpful first step toward making actionable decisions for the next several years. The first critical uncertainty identified by our team is the degree to which space will be commercialized, and the second is the evolution and transformation of global power states. These two uncertainties focus on the form and function of actors involved in space and cut across a wide variety of space policy challenges (demonstrated in Table 1) as they relate to the two cross-cutting factors that appear in the most chapters ("expanding commercial capability and investment" and "global proliferation of space actors and space systems").

The first critical uncertainty identified by our team is the degree to which space will be commercialized, and the second is the evolution and transformation of global power states.

Although this brief review cannot provide the answers or solutions to the challenges faced in space, it can help to provide questions that will start decisionmakers on the line of inquiry needed to develop strategies and policies that are adaptable, flexible, and inclusive of uncertainty instead of resistant to it.

Managing the Growth of Space Traffic | National Security Space | Exploration and Economic Development | Shaping the Future

Table 1: A Strategic Foresight Summary of *Space Agenda 2021* Chapters

Chapter Title	Key Technologies	Crosscutting Factors	Opportunities/Recommendations
Airspace Integration in an Era of Growing Launch Operations	• Faster space launch/“responsive” launch • Reusable launch systems, launch system reliability	• Expanding commercial capability and investment • Managing regulatory frameworks • Environmental conservation and management • Global proliferation of space actors and space systems	• Better data sharing between launch providers and National Airspace • Air and Space stakeholder dialogue • “Designed for demise” hardware
Space Traffic Management	• Space situational awareness • On-orbit servicing • Small satellites • Cheaper launch • Mission life extension • Active disposal at end of life/active debris removal • Large constellations • Data fusion	• Expanding commercial capability and investment • Managing regulatory frameworks • Environmental conservation and management • Global proliferation of space actors and space systems • Collaborating with international partners • Norms and behavior leadership	• Clearly establish organizational authorities and required resources for a national approach to space safety • Establish mechanisms for international coordination and cooperation with government and commercial entities • Develop clear definitions of nationally “acceptable” levels of safety and risk to enable development of norms of behavior and performance-based rules
Light Pollution from Satellites	• Cheaper launch • Satellite materials • Automation and miniaturization	• Managing regulatory frameworks • Environmental conservation and management • Expanding commercial capability and investment • Global proliferation of space actors and space systems	• Establish an organized avenue for coordinated discussion on guidelines and mitigation strategies for satellite light pollution • Regulators, astronomers, and industry should be in communication about their respective operational needs to explore options for building optical interference mitigation into existing constellation licensing application processes

Managing the Growth of Space Traffic | National Security Space | Exploration and Economic Development | Shaping the Future

Table 1: A Strategic Foresight Summary of *Space Agenda 2021* Chapters

Chapter Title	Key Technologies	Crosscutting Factors	Opportunities/Recommendations
Organizing for Defense Space	Flexible systems that can accomplish multiple missions and continue to provide capability when contested	• Great power competition • Global proliferation of space actors and space systems	Balance the missions that are supporting the joint force with missions focused on providing independent space capabilities.
Continuous Production Agility (CPA)	• Modularity, scalability, and interoperability in space systems • Faster/responsive launch	• Expanding commercial capability and investment • Great power competition • Global proliferation of space actors and space systems	• Recognize a whole of government approach • Break down monolithic, requirements-driven system into phases for an innovative development ecosystem, steady procurement, and deployment with smooth technology insertion • Align USSF acquisition authorities for modular open standards architecture (MOSA) and CPA
Leveraging Commercial Developments for National Security Space	• Faster/cheaper/responsive launch • Space situational awareness • Large constellations • Vulnerability of space-based systems	• Expanding commercial capability and investment • Global proliferation of space actors and space systems • Future markets and new space systems	• Consider which acquisition model (traditional, off-the-shelf, or purchased services) can best balance different challenges • Continue efforts to explore commercial partnerships • Revisit whether DOD organizational models need to adjust to better leverage commercial developments
Developing Foundational Spacepower Doctrine	Flexible systems that can accomplish multiple missions and continue to provide capability when contested	• Great power competition • Norms and behavior leadership • Global proliferation of space actors and space systems	• Future versions of Space Capstone Publication should build more explicitly from, and include, more dialogue with existing doctrine • Consider interdependencies and holistic strategic contributions of space capabilities • Flow Space Force organizational culture up from fundamental principles

Managing the Growth of Space Traffic | National Security Space | Exploration and Economic Development | Shaping the Future

Table 1: A Strategic Foresight Summary of *Space Agenda 2021* Chapters

Chapter Title	Key Technologies	Crosscutting Factors	Opportunities/Recommendations
Space Deterrence	◆ Space domain awareness ◆ Resilient space ◆ Satellite defense ◆ ASAT weapons (reversible, nonreversible, kinetic, non-kinetic)	◆ Great power competition ◆ Global proliferation of space actors and space systems	◆ Develop a comprehensive attribution strategy to strengthen adversary perception of U.S. ability to attribute attacks ◆ Consider how to communicate directly or indirectly to potential adversaries the resilience of U.S. space capabilities
A Roadmap for Assessing Space Weapons	◆ Smallsats, lasers, and high-power microwaves ◆ Faster/cheaper launch ◆ Proliferated LEO constellations ◆ Vulnerability of space-based systems ◆ Space domain awareness	◆ Great power competition ◆ Norms and behavior leadership ◆ Managing regulatory frameworks	Further research in: ◆ Effects of Chinese and Russian ASAT capabilities on the merits of U.S. space weapons ◆ Whether space-based weapons are protected by right of unrestricted overflight ◆ Strategy if Russia or China deploy space-to-Earth weapons first ◆ Effects of gray zone activities on space weaponization
The Arctic: Space-based Solutions	◆ Space-enabled Arctic communication, navigation, and observation ◆ Hybrid networks, enterprise cloud solutions ◆ Seamless data and connectivity	◆ Great power competition ◆ Expanding commercial capabilities and investment ◆ Collaborating with international partners ◆ Environmental conservation and management.	◆ Open, available, and shared systems for multi-partner operation ◆ Integrate evolving Arctic Strategy with U.S. allies ◆ Engage and incentivize commercial sector

Managing the Growth of Space Traffic	National Security Space	Exploration and Economic Development	Shaping the Future

Table 1: A Strategic Foresight Summary of *Space Agenda 2021* Chapters

Chapter Title	Key Technologies	Crosscutting Factors	Opportunities/Recommendations
Challenges and Opportunities for NASA's Artemis Program	• Improved propulsion systems • Inflatable entry, descent, and landing system • Next generation spacesuit • Lunar landers / lunar surface transport systems • Reliable power • Laser communications • In-situ resource utilization • Lunar Gateway	• Expanding commercial capability and investment • Managing regulatory frameworks • Collaborating with international partners • Environmental conservation and management • Norms and behavior leadership	• Rethink acquisition strategy for Mars missions • Consider policies to improve transitions between programs and missions • Apply lessons learned from Apollo to Artemis • Explore opportunities for international and private sector involvement, particularly in LEO
Emerging Issues in New Space Services	• On-orbit inspection and maintenance • Active debris removal • Non-Earth imaging • Planetary protection • Spaceflight safety • Commercial RF collection	• Expanding commercial capability and investment • Managing regulatory frameworks • Environmental conservation and management • Global proliferation of space actors and space systems	• Seek technically informed and enabling regulation • Develop guidelines and best practices • Encourage the use of commercial capabilities as a service to government missions; • Fund critical R&D
Human Spaceflight Safety	• Launch/spaceflight reliability • Fast-paced suborbital flights • Long-distance transportation (point to point) • Moon and Mars travel	• Expanding commercial capability and investment • Global proliferation of space actors and space systems • Managing regulatory frameworks	• Update mishap investigation requirements • Implement performance-based regulations when appropriate • Establish a space safety institute

Managing the Growth of Space Traffic | National Security Space | Exploration and Economic Development | Shaping the Future

Table 1: A Strategic Foresight Summary of *Space Agenda 2021* Chapters

Chapter Title	Key Technologies	Crosscutting Factors	Opportunities/Recommendations
Defense Space Partnerships	• Networked SSA • Hosted payloads • Systems integration/interoperability • Combined space operations with international allies and partners • Combined space systems acquisition	• Collaborating with international partners • Great power competition • Norms and behavior leadership • Global proliferation of space actors and space systems	• Prioritize defense space international partnerships • Lower space system classification levels and international ally and partner information releasability • Involve international allies and partners in exercises and wargames • Increase foreign liaison and exchange officer opportunities • Develop common norms of behavior
Space-Based Solar Power	• Wireless power transmission • Solar cell efficiency • Cheaper launch (large satellites needed) • Modular spacecraft components • Space robotics for very large projects/ constellations	• Future markets and new space services • Environmental conservation and management • Expanding commercial capability and investment	• Decide whether to independently pursue, internationally collaborate, or pass on this technology • Opportunity to establish U.S. leadership through R&D investment • Could develop sustained and coordinated program leading to large-scale demonstration • Adopt a portfolio management approach to encourage complete vision, efficient resource management and collaboration with partners
Space Game-Changers	• Breakthrough • Disruptive • Incremental • Game changers	• Future markets and new space services • Expanding commercial capability and investment • Global proliferation of space actors and space systems	The national security space enterprise should institutionalize an innovation portfolio management framework to achieve enterprise goals and better resource and risk management—coverage across disruptive, breakthrough, and incremental technologies, applications, and business models

Managing the Growth of Space Traffic

The first section of this report covered issues related to managing the growth of space traffic and orbital debris as well as the related issues of airspace integration and light pollution. Many of these challenges lend themselves to a strategic foresight approach due to the complexity and interaction of different actors and technologies. The problem of space debris is particularly relevant to the strategic foresight framework. Because behavior by any one actor in space can affect everyone and because hazards such as orbital debris accumulate over time, many decisions will need to be made in the near-term horizon to navigate toward the preferred outcomes in the long run. Although there may not be significant immediate incentives to mitigate or remove space debris, the actions taken (or not taken) now could have serious consequences for the space environment in the future. Questions raised by the two key uncertainties that will affect the path toward the future include "What actors and organizations will have the most interest and capability in shaping norms, laws, and best practices in debris management?" and "In what ways will commercial actors exacerbate or mitigate space traffic and orbital debris?"

Uncertainty in what kinds of actors will be pursuing what kinds of behaviors in space means uncertainty in how best to approach developing norms, regulations, and best practices that will be most effective at managing space traffic. There are many possibilities in the degree to which commercial actors will affect space traffic in the future and whether those effects will be positive (such as through innovative technologies or mechanisms of debris mitigation or removal) or negative (such as through increased risk of collisions through the exponential expansion of constellations). As always, there is a spectrum of possible futures with any combination of these factors.

When looking to manage uncertainty and mitigate potential disruptors in the field of space traffic management, decisionmakers will need to ask themselves several key questions in order to determine a path forward:

- What incentives and disincentives can be provided to shape international behavior toward our preferred future?
- How do we develop patterns of cooperation between actors involved in activities related to space traffic management?
- How can decisions made by the U.S. government now affect which actors play the most important role in space traffic management in the future?

Applying the methodology of strategic foresight to these questions while scanning the horizon for indicators of what is to come can help form strategies for how to proceed.

National Security Space

The next category, national security space, features such issues as military organizations and doctrines, space weaponization, space deterrence, and synergies with other domains and the Arctic. As with the challenge of managing the growth of space traffic, applying strategic foresight to national security space will require consideration of timeliness and unity of approach. When scanning the horizon on this issue, the two key uncertainties raise questions such as "How will increased commercial activities and capabilities affect the relationship between military space and civilian contractors?" and "How will changes in the shape and form of alliances and adversaries affect how the military approaches collaboration, competition, and communication on national security issues?"

> ***…the long lead times on programs and systems development and inertia involved in some national security trends indicate that actions will need to be taken very soon, during the next presidential term, in order to influence these trends before the window of opportunity closes.***

The web of interconnected relationships and authorities between military, intelligence, civil, commercial, and policymaking organizations with a stake in national security space means that the preferred future for national security space and the actions taken to pursue it will need to be considered and coordinated across government and beyond. Furthermore, the long lead times on programs and systems development and inertia involved in some national security trends indicate that actions will need to be taken very soon, during the next presidential term, in order to influence these trends before the window of opportunity closes. For example, with the creation of the Space Force as the first new military service in over 70 years, it stands to reason that organizational and doctrinal decisions guiding the force could now shape its culture and capabilities for decades to come. That means that the fundamental decisions guiding the Space Force will not only have to keep in mind the current operational environment, but also the possible uncertainties and changes that will shape the space domain 20, 50, or 100 years into the future.

Therefore, several questions should be asked of national security space policymakers now in order to anticipate inflection points and calculate what actions can help navigate the uncertainties:

- How can we gain experience and insight into international space security actors now to prepare for future conflicts and disruptions?
- What kinds of flexibility, adaptability, and assurance can be built into formal processes like contracting and acquisitions or organizational structures themselves?
- How might the culture around innovation and risk-taking need to change to ensure we stay ahead?
- How can U.S. national security organizations posture themselves to effectively influence the security environment and anticipate how other actors might respond?

National security decisionmakers have always had to contend with uncertainty, but applying the methodologies and asking the questions raised by strategic foresight can make uncertainty an enabler for security instead of an obstacle.

Exploration and Economic Development

Apart from national security, exploration and economic development are two of the biggest topics that come to mind when thinking of the future of space. Just like space traffic management and national security space, activities in exploration and economic development such as NASA programs, new space services, human spaceflight, and workforce development will be dramatically affected by the progression of the two critical uncertainties. How will the balance between innovation and regulation shift over time, and how will that challenge affect which countries and industries become competitive and which fall behind? How will the changing actors and degree of influence of the commercial sector determine which aspects of space exploration and development are valued and pursued?

The public perception of the value of space, through taxpayers, investors, workers, and innovators will play a major role in which projects are pursued and, on a more fundamental level, how much attention and funding space activities will get as a whole. In times of economic, social, and political disruption and uncertainty, it is difficult to predict how space will be compared to other pressing issues. It is important to recognize, however, that activities in space are not a one-way street, and exploration and development in space can also have significant impact on capabilities and activities on Earth even though these effects can sometimes take many years to develop.

Policymakers will therefore find insight by examining responses to several questions:

- How can we anticipate and influence the perception of value in space activities?
- How can we work with stakeholders now to see what kinds of regulations will incentivize sustainable behaviors without disincentivizing operating in the United States?
- What pursuits in exploration and development have the greatest potential to affect life on Earth, whether tangibly or intangibly?
- How do we create a sustainable, thriving ecosystem that enables freedom and prosperous presence of humans in space?

Shaping the Future

The final category of chapters in *Space Agenda 2021* captures a diverse range of topics, all of which take approaches similar to the strategic foresight framework discussed in this chapter by emphasizing strategies to navigate potential disruptors. These disruptors could be technological (like space-based solar power) or political (like the diverse array of international space actors). Disruptors could even come in the form of new business processes or markets, as described in the "Space Game Changers" chapter. While no one set of trends could unify or encapsulate the themes discussed in these chapters, they serve as representations of how tools from the strategic foresight collection can be used to scan the horizon and plan to navigate disruption before it happens.

Again, the answers will not come easily and some may be impossible to fully grasp while dealing with uncertainty. The future is not set or predetermined for any of these issues, but many actions taken in the near future will have irrevocable effects on the direction in which we move. Therefore, asking the right questions and looking for these potential inflection points become the first steps in a process of scanning the horizon, developing insight, and taking action to move incrementally toward the preferred future.

Conclusion

The space enterprise has witnessed significant evolution and upheaval in recent years with the authorization of the U.S. Space Force and other organizational changes, proliferation of ever-larger and more capable constellations in low Earth orbit (LEO), and the progress of the Artemis Program toward a manned return to the moon. The COVID-19 pandemic has served as a sobering reminder of how surprise and uncertainty can disrupt the space enterprise from all angles. The pandemic has placed limitations on how the space workforce builds systems, shares information, and conducts business. It has revealed vulnerabilities in government agencies, large contractors, and small startups alike as crucial meetings have been canceled, supply chains have been interrupted, and businesses of all sizes have faced financial disaster. In many cases, the people and programs of the space enterprise have demonstrated incredible resiliency in the face of such disruption, but resiliency alone will not ensure the health of the enterprise against future crises. Applying tools such as strategic foresight can help policymakers holistically manage complexity or catastrophe; foresight can improve future preparedness and shape our nation's vision for achieving our preferred future for the space enterprise *today*.

At this crucial turning point, we should consider how incorporating anticipatory thinking might look at a national level, thinking through our vision across multiple futures and laying out a roadmap for how we will get there. Several futures for the space enterprise could develop following the COVID-19 pandemic, including a return to business as usual, the slashing of budgets and programs amid economic crises, or the strategic adaptation of programs and process allowing the United States to outpace its adversaries in space.[3] Once we identify, clarify, and align around preferred futures, we can also identify the push and pull factors that will help or hinder pursuit of that set of goals and the potential strategic levers that the United States can employ. This could include factors such as the recovery or failure of small businesses or the relative intensity with which adversaries pursue their own space programs despite the economic effects of the pandemic. The key is to be strong on vision and flexible on approach. The United States needs to know where it wants to go, but it must be ready to adapt and respond to obstacles on the road to get there.

Whichever future we arrive at, it is fast approaching. Decisions made in 2021 will determine where we go next, and the stakes are high. With the clarity of vision and flexibility of approach enabled by strategic foresight practices, today's decisionmakers can determine tomorrow's success for the nation's leadership in space, even in the face of uncertainty.

> ***The key is to be strong on vision and flexible on approach. The United States needs to know where it wants to go, but it must be ready to adapt and respond to obstacles on the road to get there.***

References

[1] Kara C. Cunzeman and Paul C. Frakes, "Surfing Disruption: A Primer in Strategic Foresight," The Aerospace Corporation, May 2020. [Limited Release to USG]

[2] Ibid.

[3] Air Force Warfighting Integration Center, "Global Futures Report: Alternative Futures of Geopolitical Implications in a Post-COVID World," June 2020 (https://www.afwic.af.mil/Portals/72/Documents/AFWIC%20Global%20Futures%20Report_FINAL.pdf?ver=2020-06-18-124149-070).

CENTER FOR SPACE
POLICY AND STRATEGY

SPACE GAME CHANGERS: DRIVING FORCES AND IMPLICATIONS FOR INNOVATION INVESTMENTS

Karen L. Jones

The advancement of new space technologies, architectures, applications, and emerging business models will continue with many breakthroughs as well as some disappointments. A rapid and relentless pace of change requires timely analysis. This report offers a framework for government decisionmakers as they consider complex space sector innovation strategies and how best to prioritize investment decisions. The framework calls for recognizing innovations that offer market disruption for new users or applications, breakthrough capabilities, or incremental improvements and suggests a strategy for investment and risk management to advance these innovations to game changers that benefit civil, military, and national security interests. Ultimately, a portfolio management approach is needed across the whole-of-government to rationalize U.S. government investments in space innovation.

Background

Frequent technology disruption is the new normal in all aspects of our lives, and the space industry is no exception. The advancement of new space technologies, architectures, applications, and emerging business models will continue with many breakthroughs as well as some disappointments. A rapid and relentless pace of change requires timely analysis. This report offers a framework for considering complex innovation strategy and prioritizing investment decisions, and capsule descriptions of several emerging space gamechangers.

As government space stakeholders make critical innovation investment decisions, they should be mindful that much of the innovation is occurring outside government laboratories and research and development (R&D) centers. Establishing an innovation portfolio management strategy can start by broadly exploring technologies, applications, or business trends that could potentially disrupt the status quo by:

- propelling a product or service ahead of its competitors;
- introducing new products, services or capabilities; or
- rearranging the space value chain.

Government and business leaders need sound analyses to separate the hype from reality so they can make informed decisions regarding those space sector game changers that:

- Require seed funding and other types of financial levers to evolve and adapt.
- Are critical to national security space (NSS) needs.
- Are vulnerable to supply chain or industrial base security risks.
- Provide the U.S. with an asymmetric advantage.
- Require trade and intellectual property (IP) protection to prevent adversaries from gaining asymmetric advantage.

While most organizations who follow the satellite industry, including banks, agree that the space sector has grown significantly over the past 20 years, estimates vary widely.[1] According to Bryce Space and Technology, from 2000 to 2005, the industry received more than $1.1 billion in investment from private equity, venture capital, acquisitions, prizes and grants, and public offerings. During a later time period, between 2012 and 2017, the industry had received more than $10.2 billion.[2] Although private investment has fueled unprecedented growth in the space industry, recent global satellite industry revenues[*] have decreased by 1.5 percent to $271 billion during 2019, according to Satellite Industry Association's "State of the Satellite Industry Report."[3] The space sector has reached an inflection point where reduced satellite manufacturing revenues reflect a more modest sized GEO industrial base, a competitive shakeout of the low Earth orbit (LEO) industrial base, and a SATCOM capacity surplus. Adding to this market challenge, rising government deficits due to the COVID-19 pandemic has set the stage for a more constrained government budget environment. These market challenges underscore the importance of a broad, agile, and strategic approach to space innovation investing.

Five Forces Driving Space Evolution

Industry game changers are those technologies, applications, business models, or architectures that significantly change the status quo, often by defining a new product technology or service and by meeting a previously unmet customer need. The following five driving forces are worth noting, along with how these trends may converge, to further accelerate game changers across key space elements or technologies, applications, business models, and architectures.

1. From Spin-off to Spin-in. In the past, the space industry was a key starting point for technology creation. NASA, for instance, has developed technologies for space exploration that have made their way into everyday life. A few eclectic examples include memory foam; aerogel insulation; ultraviolet-resistant sunglasses; improved cloud computing; advanced digital imaging; and translucent polycrystalline alumina, which is now used in invisible dental braces.[4] Klaus Schwab notes in "Shaping the Fourth Industrial Revolution" that "today, the space sector is experiencing a huge degree of innovation, but it is largely being driven by 'spin-in' benefits from other sectors."[5] This implies that space stakeholders and decisionmakers must be prepared to determine the potential application of emerging game changers *outside* the space sector and take action to encourage awareness, investment, and adoption.

2. Billionaire Investors. Fifty years ago, the space race involved a fierce rivalry between Russia and the United States. Today's space race is now partially fueled by private billionaires, driven by a mix of motivations, including idealism, vision, and a conviction that investments in space travel and applications will pay off in the long run. Capital infusion from serial entrepreneur billionaires has supported the space sector's growth over the past several years. These billionaires include:

- Jeff Bezos – Blue Origin (space launch for cargo and tourism) and Project Kuiper (Internet satellite constellation)
- Elon Musk – SpaceX (reusable rockets) and Starlink (Internet satellite constellation)
- Richard Branson – Virgin Galactic (space tourism) and Virgin Orbit (air-launched rocket)

[*] This satellite industry growth statistic does not include government space budgets and commercial human space flight. The total global space economy grew by 1.7 percent to $366 billion during 2019.

3. Democratized Space Disrupters. Clayton Christensen, a business consultant who popularized the theory of disruptive innovation, wrote a seminal book called *The Innovator's Dilemma*.[6] A central theme of the book is that it is *not* ineptitude that prevents leading companies from predicting disruption. Instead, it is the companies' rational approach to building better products and their focus on their most attractive customers and markets. This rational approach can blind them from seeing an undercapitalized upstart erode their market share. The disruptor starts at the bottom of the market and moves up by improving a technology or product.

Disruption in the space sector appears to have accelerated after SpaceX, founded in 2002, challenged the established launch firms by offering rocket launches at half the price of its more traditional competitors.[†] SpaceX, now valued at $36 billion, further disrupted the launch business by introducing reusable rockets.[7] Within the satellite sector, for example, we have seen the emergence of inexpensive CubeSats and nanosats, including do-it-yourself satellite kits that started primarily to serve academic users for research projects. In classic disruptor style, CubeSats are working their way up the value chain and are now serving larger-scale civil missions for weather, remote sensing, and communications. The space sector is also being disrupted by tools that were not available just a few years ago, such as enterprise class mission control and spacecraft flight software using open source software and standards. For instance, the 2019-2020 NASA Software Catalog offers free and downloadable software programs for a wide variety of technical applications such as propulsion, vehicle management system testing, operations, data and image processing, electronics, and electric power.[8]

4. Fourth Industrial Revolution or Industry 4.0. Professor Klaus Schwab, founder and executive chairman of the World Economic Forum, describes the fourth industrial revolution's enormous potential along with the possible risks.[‡] There is no precedent for the speed of current breakthroughs. Industry 4.0 is characterized by a fusion of technologies that blur the lines between physical, digital, and biological spheres.[9] This digital revolution is characterized by exponential change through smart devices, cloud computing, Internet of things, advanced robotics, big data analytics, smart manufacturing, and augmented reality.

Riding on the coattails of fourth industrial revolution, open data and the proliferation of data-sharing continues to break down information silos. This allows for the data network effect to gain traction. *Data network effects occur when an application or product, powered by artificial intelligence (AI) and machine learning (ML), becomes smarter and potentially more valuable as it accumulates more data from users.* For the space enterprise, this means that greater value will accrue over time, as space-based remote sensing data becomes more useful through increased data source, fusion, and AI, and ML.

5. The Sharing and Virtualized Space Economy. Similar to Uber, and its ability to revolutionize the on-demand ground transportation market, the space industry has started to find efficiencies for transportation to orbit. Smallsat rideshare companies have discovered that small satellites can now be packed into a rocket faring to share the same ride into space. This is now a common practice. Spaceflight Industries (Seattle, Washington), for example, provides launch services, on rockets such as SpaceX's Falcon 9, for those launch companies seeking small or secondary payloads.

Infrastructure as a Service (IaaS) models are attractive to new space entrants who may desire flexibility, scalability, speed to market, and lower capital expenditure models, while harnessing the "know-how" of experienced infrastructure operators. Various IaaS models are growing rapidly in many industries, including space. These IaaS models allow for the "virtualization" of the space enterprise, which can result in lower barriers to entry. IaaS models also dynamically apply assets as needed, while avoiding excess capacity. Examples include:

[†] SpaceX advertises Falcon 9 rocket launches for $62 million compared to Arianespace's Ariane 5 or United Launch Alliance's Atlas V for $165 million each. Michael Sheetz, "Elon Musk touts low cost to insure SpaceX rockets as edge over competitors," CNBC, April 16, 2020.

[‡] The *first* industrial revolution refers to water and steam power to mechanize production; the *second* involves electric power for mass production; the *third* involves electronics and information technology.

- **Ground Station as a Service (GaaS)** is a fully managed service that allows satellite operators to control satellite communications, process data, and scale their operations as they grow without the need to invest in expensive ground-based infrastructure. Examples include Amazon's AWS Ground Station (United States), Kongsberg Satellite Services' KSAT Lite (Norway), and Atlas Space Operations' Freedom Platform (United States).

- **Cloud Services**, which underpin the transformation and growth in digital enterprises, offer virtualized network functions for GaaS and for an enormous variety of value-added analytic services using space data. Satellite operators are rapidly embracing a range of commercial cloud services. According to the Gartner Group, the global market for cloud system IaaS hit $44.5 billion in 2019, up 37.3 percent over 2018. The top five IaaS cloud providers, listed in order of 2019 revenue, are Amazon, Microsoft, Alibaba, Google, and Tencent, which collectively represent 80 percent of the market.[10]

- **Software-as-a-Service (SaaS)** allows users access to cloud-hosted software and data analytics remotely from any web browser. Potential applications could include data analytics from remote sensing data, and tools to navigate and manage space missions.

Taking the sharing concept even further, space capabilities such as Internet broadband connectivity and mobile communications can offer augmented infrastructure services to terrestrial broadband operators and mobile carriers, including 5G networks. Leveraging IaaS arrangements, satellite-terrestrial network convergence can create cooperative networks to address seamless coverage, broadcasting and multicasting capabilities, and Internet backhaul services.

Innovation Portfolio Strategy

While game changers can emerge from a range of trends, the forces driving space evolution can provide a spotlight for identifying key innovations. Once specific technologies, applications, or business models are identified, the next step is to analyze the lifecycle maturity, potential market impact, and degree of progress or improvement that the innovation could offer. Emerging innovations can then be categorized into breakthrough, disruptive, and incremental innovations. These innovation categories follow general strategies to advance to game changers in order to appeal to certain types of investors, project management styles, and goals, discussed below.

Lifecycle Maturity. Figure 1 illustrates various influential space elements (technologies, applications, business models, and architectures) in various lifecycle phases. Triggers are inflection points that may cause the space element to advance due to changes in market demand or adoption, performance or efficiency, regulation or policies, or societal expectations and norms.

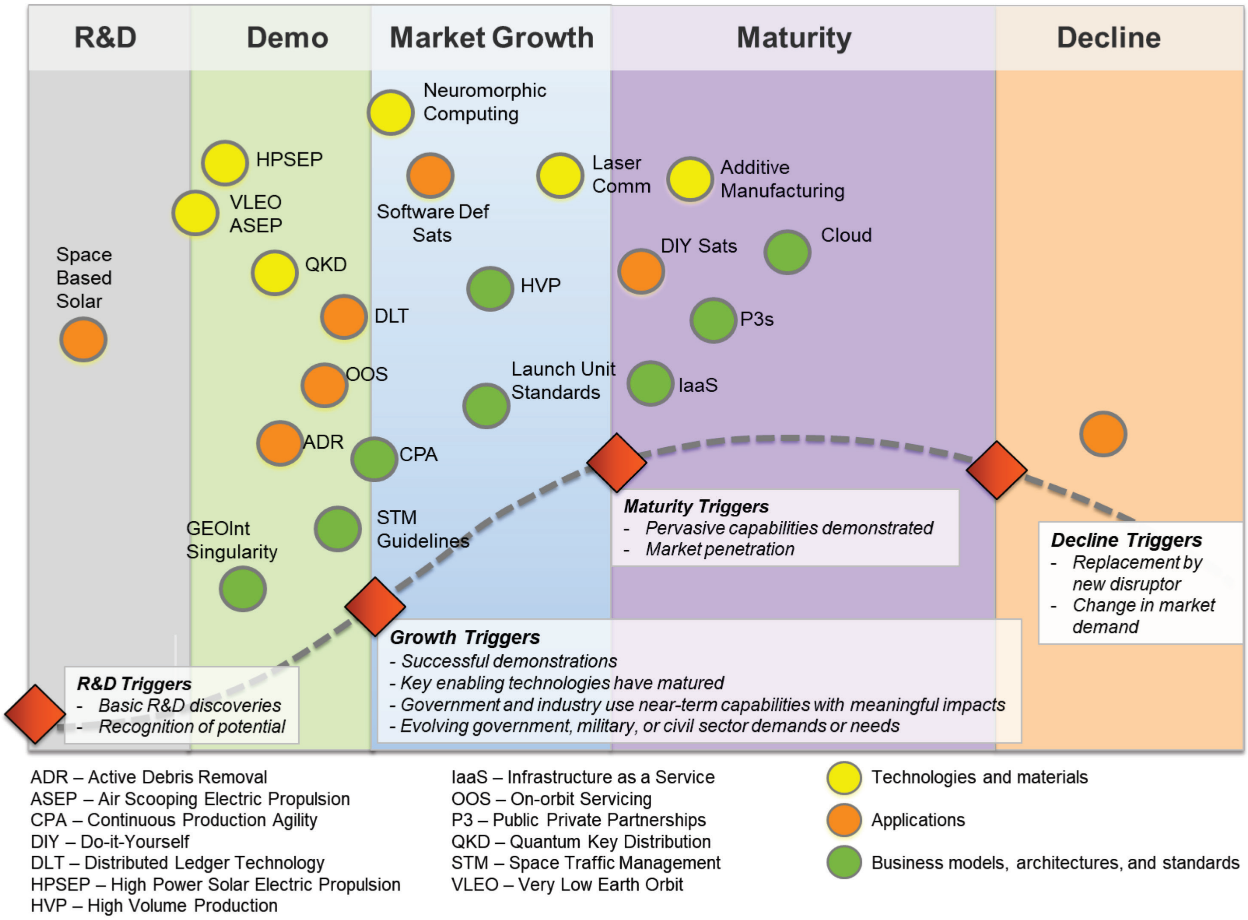


Figure 1: Lifecycle Maturity Curve. *Emerging space technologies, applications, business models, architectures, and standards span a range of lifecycles. Triggers are inflection points that can cause the technology, application, or business model to evolve based on innovation advances, increased market adoption or demand, regulatory or legal changes, and emerging social or cultural norms. Lifecycle phases include:*

- ***R&D.*** *Technology is new, most resources are spent on research and development.*
- ***Demo.*** *Some promising demonstrations emerge; there is a narrowing of potential designs, concepts and prototypes.*
- ***Market Growth.*** *After a successful demonstration, early adopters notice and rapid growth follows.*
- ***Mature Market.*** *Now widely adopted. Improvements and innovations are incremental, such as improved production processes and increased standards.*
- ***Declining Market.*** *This typically occurs after the market is disrupted by emerging innovation(s).*

Advancing to a Game Changer. The first step toward developing an optimal investment strategy is to identify key space elements that could support a range of space missions (e.g., national defense, weather, emergency response, environmental, etc.). These critical space elements can be mapped along two axes to categorize innovations as incremental, disruptive, breakthroughs, or game changers (see Figure 2):

- Market Impact (x-axis)
- Progress/Improvements (y-axis)

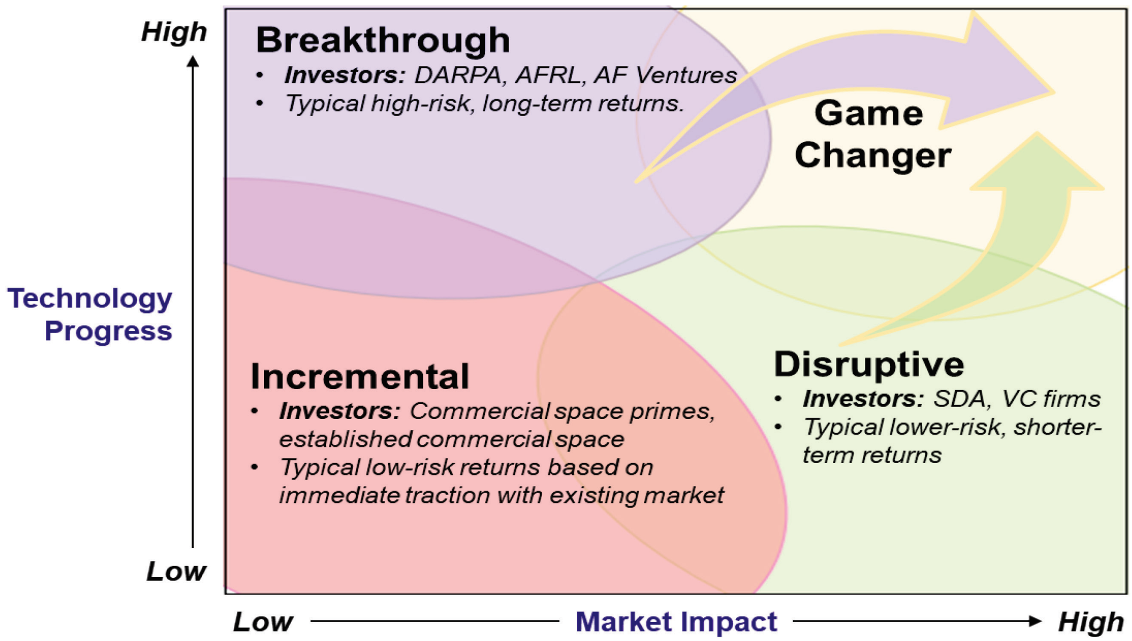


Figure 2: Advancing to a Game Changer. *For various technologies, applications, architectures, or business models:*

- ***Breakthrough.*** *Offers significant improvements and capabilities but may not change the market landscape.*
- ***Disruptive.*** *"[T]akes root initially in simple applications at the bottom of a market and then relentlessly moves up market, eventually displacing established competitors."*[11]
- ***Incremental.*** *Grows and improves gradually within an existing market or customer base.*
- ***Game Changer***. *Offers both significant technological and/or service progress and can result in high market impact.*

Source: Adapted from "Four Zones of Innovation" by Jim Kalbach.[12]

Space innovation decisionmakers who manage innovation funding (e.g., seed funding, grants, research agendas, etc.) should review their entire investment portfolio across incremental, breakthrough, and disruptive space elements. *Over time, and depending on the context or use case, innovations are fluid and can shift between breakthrough, incremental, disruptive or game changing.*

Breakthrough to Game Changer. Breakthroughs can transform into game changers with increased market traction and adoption (Figure 2, purple swoosh arrow).[13] A former Defense Advanced Research Programs Agency (DARPA) program manager, Jeremy Palmer, noted that "aiming for *Incremental* technology improvements is not part of DARPA's charter. Instead, the agency must focus on funding *Breakthrough* technologies—not so much the disruptive" because the focus is to look for novel technologies in the longer-term investment horizon.[14]

Investors. Typical investors for breakthrough technologies include DARPA, Air Force Research Labs (AFRL), AF Ventures, and In-Q-Tel. These organizations are emphasizing dual-use approaches for national space capabilities with the intent to adopt commercially viable innovations to gain a technological edge against our adversaries while encouraging the national competitiveness of the U.S. industrial base.

Also, a considerable amount of internal research and development (IR&D) by federally funded research and development centers such as The Aerospace Corporation or the Jet Propulsion Laboratory (JPL) can introduce breakthroughs in new technical capabilities.

Goals. Typical outlook is 20 years; high-risk and long-term returns, seeking market traction and adoption of novel technologies and applications.

Examples. A breakthrough technology can increase market adoption to become a game changer through a series of successful technology demonstrations, trials, and flight tests. These tests and demos must be carefully vetted and tailored to specific market applications. Moreover, the results must be shared widely with interested market participants who might be willing to fund the next stage of development. A few breakthrough examples in the space sector include:

- **Direct satellite to cellular phone link.** Research, tests, and demonstrations are currently underway to explore how existing cell phones (with minimal changes) can connect directly to satellites. This could be a significant breakthrough for both satellite and terrestrial mobile connectivity. The following three companies are pursuing direct satellite to cell phone links to exploit the Narrowband Internet of Things (NB-IOT) applications:
    - Apple Inc. (Cupertino, California) – internally funded "secret project" to beam internet services directly to devices, according to Bloomberg.[15]
    - Lynk (Falls Church, Virginia) – $20 million total funding; Lynk reported a successful text message demonstration from the Cygnus cargo spacecraft in February 2020.
    - AST & Science (Midland, Texas) – $110 million Series B, $128 million total.
- **High power solar electric propulsion (HPSEP).** Combines advancements in solar array and electric propulsion technologies. HPSEP enables spacecraft injection into LEO and can be used for orbit raising. HPSEP reduces the launch capacity needs and allows multi-manifesting of spacecraft, increased spacecraft mass for more mission hardware, or the use of smaller launch vehicles for lower launch cost. The tradeoff is longer transfer time to the mission orbit. Once on-orbit, HPSEP also provides greater electrical power to support advanced spacecraft mission needs.[16]
- **Additive manufacturing.** 3D printing for single piece-parts is already mature. However, printing complex components and systems for on-demand manufacturing capability is still emerging and being funded by NASA small business innovative research (SBIR) funding.
- **Solar power satellites (SPS)**. Space-based solar power transmission systems have been studied for the past 50 years and could have dramatic implications for all sectors of space activity. Key technical challenges include whether the system can be scaled up sufficiently and whether transmission across the long distances of cislunar space and through Earth's atmosphere is safe and practical. This technology is still relatively nascent, and funding has largely been fueled by U.S. and foreign-led space and research programs.[17]
- **The GeoInt singularity**. Data feeds from a plurality of sensors, combined with analytics and AI can create global intelligence for geospatial information. The convergence of existing technologies establishes new possibilities and opportunities that did not exist before.[18]
- **Very low Earth orbit (VLEO) airbreathing solar electric propulsion (ASEP) satellite.** Flying at VLEO utilizes ambient air as propellant. A constellation of VLEO satellites may offer significant advantages for connectivity and communication by reducing latency. An ASEP satellite can extend reach for excursions to higher elevation, such as

LEO, medium Earth orbit (MEO), and even geosynchronous Earth orbit (GEO), to provide tugging, deorbiting, and other servicing capabilities.

- **Neuromorphic computing (NC). NC** mimics the brain's efficiencies for neuro-biological architectures. NC could emerge as a game changer where mission success relies on fast and autonomous analysis of a vast array of incoming information from multiple sources.[19]

Disruptive to Game Changer. Some game changers emerge as disruptive technologies, applications, or architectures. A disruptive technology, in classic "innovator's dilemma" form, may start as a modest application or technology and over time, increase its functional capabilities or performance to become a game changer (see the green swoosh arrow in Figure 2). Derek Tournear, director of the Space Development Agency (SDA), has noted that the agency's Latin motto of *semper citius*, meaning always faster, is intended to emphasize that good-enough capabilities are preferable to delivering the perfect solution too late.[20] SDA intends to focus on disruptive technologies, where it can start with some immediate market traction (see the x-axis on the right in Figure 2) and realize performance or efficiency improvements with time. These disruptive products can dramatically lower the barriers to entry and encourage new players to enter the market.

Investors. Typical investors for disruptive technologies seek shorter-term rewards. For instance, SDA seeks to change the culture of national security space investments by leveraging smaller satellites and proliferated constellations. SDA is planning a "disruptive-to-game-changing" path by achieving persistent global coverage through proliferation of medium and wide field of view, hypersonic and ballistic tracking sensors. SDA intends to move quickly to provide a high capability return. Venture capitalists also look to disruptive technologies for long-term high returns. According to a report from Space Angels, during 2019, venture capitalists invested $5.8 billion in 178 commercial space startups worldwide, an increase of 38 percent from 2018.[21]

Goals. The outlook is five years or less, short-term returns; large return on investment; medium risk; seeking "good enough capabilities" that meet existing customer needs.

Examples. Strategically partnering with existing startup companies. Focus on AI, autonomy and robotics, cybersecurity, materials and manufacturing, next generation electronics and sensors, quantum technology, signals and communications, and new business models that can change the status quo. Examples include:

- **Do-it-yourself satellite applications for citizen space**. Citizen participation in space is now enabled by commercial picosatellite do-it-yourself (DIY) kits, and associated services and expertise to customize their missions and place payloads into orbit. With increased participation and new demographics of space actors, the possibility for technological advancement and unforeseen uses of picosatellites increases exponentially.[22]

- **Software-defined satellites (SDS)**. The need for flexible business cases combined with advances in digital technology are creating opportunities for satellite manufacturers to provide software-defined solutions that can respond to a dynamically changing business environment. Operators can upload applications on an as-needed basis to in-orbit SDS.

- **Distributed ledger technology (DLT) or blockchain.** As DLT gains traction in various space applications, many centralized third-party trust organizations focused on financial, legal, security, and logistical oversight functions will likely consider adapting their operating models to gain incremental efficiencies. DLT can also provide disruptive advantages by introducing new products and services and decentralizing traditional business models. DLT could be a critical enabling technology for sensor webs, the internet of things in space, deep space networking, and a token-based system for requesting and controlling satellite services on demand.[23]

- **Continuous production agility (CPA)**. An acquisition strategy and cultural shift from point solutions to agile solutions based on modular architecture principles. CPA's high-tempo, launch-on-schedule strategy will deliver an entire operational constellation over a short period (targeting five years for most constellations) and will replenish the constellation on a schedule-certain basis with frequent technology insertions to adapt and innovate at the speed of relevance.[24]

Incremental Improvements. The commercial satellite sector serves existing customers while concurrently introducing incremental improvements to expand products and revenues. According to Jeremy Palmer, "big aerospace [defense and national security] primes build mission and customer specific products, and their goal is to boost the margins." Palmer adds that venture capitalists and startups are "more willing to make the big bets."[25] Instead, following the classic *Innovator's Dilemma* archetype, a traditional space prime incumbent embraces a rational approach to introduce incremental innovation to existing products for its customers.

Investors. Typical investors include commercial space operators, primes, and payload providers.

Goals. The outlook is five years or less; low-risk returns.

Examples. Projects include proprietary technologies and solutions to grow customer base or expand mission, incremental improvements and demonstrations, customer outreach, and training. Incremental improvements could also result from investing in the development of best practices, guidelines, or standards (e.g., high-volume production best practices, launch unit standards, or space traffic management guidelines).

- **On orbit servicing (OOS).** On-orbit activities conducted by a space vehicle that performs up-close inspection of, or results in intentional and beneficial changes to, another resident space object.[26]

- **Quantum key distribution (QKD).** QKD could significantly advance the secure transmission of government and business information.[27] Seraphim Capital and other investors funded ArQit (London, United Kingdom), a satellite constellation that will use QKD for cyber-related applications using a blockchain ecosystem for tokens.

- **Laser Communication.** The European Data Relay System (EDRS) is one of the most sophisticated laser communication networks operating today. It was built to accelerate the flow of information from Earth-observation satellites. Laser communication is viewed as an incremental improvement because it could replace radio frequency communication links with faster data rates. After the initial laser development in the 1960s, there was a protracted period of research before the first bidirectional ground-to-orbit laser communication test in 1995.[28] Today R&D continues as the satellite communication industry seeks the advantages of laser communications, including low-error and high-throughput data communications.

- **Public private partnerships (P3s).** The public sector leverages commercial efficiencies and innovation while sharing risk with the private sector in exchange for profits linked to performance. Traditional infrastructure (e.g., roads, airports, and bridges) have leveraged P3s for decades. The space sector is now maturing its knowledge to optimize these risk and cost-sharing arrangements.[29]

- **Infrastructure as a service (IaaS).** A space enterprise rents or leases services such as ground station services, network operation centers, or storage in the cloud.

- **Cloud architectures and software as a service** These cloud computing architectures are characterized by fast growth and rapid maturation. The U.S. government's FedRAMP program, which verifies that cloud technologies meet rigorous security standards. The cloud hosts Amazon, Google, and Microsoft.

- **High-volume production (HVP).** New methods for mass production, adapted from other industries, could be applied to complex space systems. Design-for-production (DFP) principles can improve, simplify, and standardize to optimize the manufacturing process. Over time these methods could gradually transform the space sector particularly as large constellations of the future will need large-scale, efficient, and economical production.[30]

- **Launch unit standards.** A smallsat launch standard could facilitate the finding and utilization of excess space by standardizing the physical properties of the smallsat (size, volume, and vibrational modes) as well as the mechanical and electrical connections to the launch vehicle.[31]

- **Space traffic management guidelines and standards.** As space becomes more crowded, increased rules of the road for a variety of space activities is inevitable, including space object trackability and management, information sharing, orbit selection, post-mission disposal reliability, remote proximity operations, and dozens more technical and operational requirements.[32]

Conclusion: A Portfolio-Driven Strategy to Balance Risks and Rewards

Recognizing and understanding potential space game changers will inform stakeholders about possible large-impact advancements in the space sector and prepare national security, and civil and commercial space stakeholders for innovations that could significantly drive future policy or strategy decisions.

The private sector manages innovation investments in sophisticated ways using a variety of frameworks. These frameworks typically categorize innovations across a range of independent factors including:

- Lifecycle maturity.
- Type of transformation – e.g., breakthroughs, disruptive, incremental, or some other classification scheme.
- Risks – including market uncertainty and technical uncertainty.
- Rewards – benefits for bringing a successful innovation to market.
- Scale – size of investment.
- Time frame for development and implementation.

There is no one right or wrong innovation portfolio framework; instead, the mistake would be to *not* select one and *not* apply it consistently across the space enterprise. Without a portfolio management approach, the enterprise is often left to rely on simplistic decision gates for funding requests. A portfolio management approach allows a view where innovation investments can be compared to each other on a relative basis according to specific criteria such as return on investment, risk, long-term gains, etc. This yields a more strategic view and allows government managers the ability to see how various investment strategies could yield different results.

> ***There is no one right or wrong innovation portfolio framework; instead, the mistake would be to* not *select one and* not *apply it consistently across the space enterprise.***

The National Security Space enterprise should institutionalize a research and development portfolio management framework to advance commercial, civil, and national security capabilities in space to serve the interests of the nation. A portfolio-driven innovation strategy across the space enterprise could achieve completeness of vision surrounding current government programs and better resource management and risk management. Unfortunately, the public sector is decentralized and not typically organized to allow this type of enterprise approach. However, as national security space moves forward with a new organization, this is an appropriate time to adopt a portfolio-driven strategy to optimize investments and ensure appropriate coverage across disruptive technologies (short-term returns), breakthrough technologies (long-term returns), and incremental (lower-risk, incremental improvements).

References

[1] Keith W. Crane, Even Linck, Bhavya Lai, Rachel Y. Wei, "Measuring the Space Economy: Estimating the Value of Economic Activities in and for Space," Science & Technology Policy Institute (STPI), March 2020.

[2] Brian Higginbotham, "The Space Economy: An Industry Takes Off," U.S. Chamber of Commerce, October 11, 2018 (https://www.uschamber.com/series/above-the-fold/the-space-economy-industry-takes).

[3] Bryce Space & Technology, "State of the Satellite Industry Report," Satellite Industry Association, July 2020.

[4] NASA spin-off technologies (https://nasa.fandom.com/wiki/NASA_spin-off_technologies).

[5] Klaus Schwab, "Shaping the Fourth Industrial Revolution," World Economic Forum, 2018.

[6] Clayton M. Christensen, "The Innovator's Dilemma: When New Technologies Cause Great Firms to Fail," 1997.

[7] Michael Sheetz, "SpaceX is Looking to Raise about $250 million, valuing Elon Musk's Space Company at $36 Billion," CNBC, February 21, 2020.

[8] NASA Software (https://software.nasa.gov/).

[9] Klaus Schwab, "The Fourth Industrial Revolution: What it Means and How to Respond," *Foreign Affairs*, December 12, 2015.

[10] The Gartner Group, "Gartner Says Worldwide IaaS Public Cloud Services Market Grew 37.3% in 2019," August 10, 2020.

[11] Christensen, 1997.

[12] Jim Kalbach, "Clarifying Innovation: Four Zones of Innovation," June 3, 2012 (https://experiencinginformation.com/).

[13] Adapted from "4 Zones of Innovation" by Jim Kalbach, jim.kalbach@gmail.com (https://experiencinginformation.com/2012/06/03/clarifying-innovation-four-zones-of-innovation/).

[14] Jeremy Palmer, phone interview by Karen Jones, August 31, 2020.

[15] Mark Gurman, "Apple has Secret Team Working on Satellites to Beam Data to Devices," Bloomberg – Technology, December 20, 2019. (https://www.bloomberg.com/news/articles/2019-12-20/apple-has-top-secret-team-working-on-internet-satellites).

[16] Josh Davis, John P. Mayberry, Jay Penn, "Cost Reductions and Fuel Efficiency: High-Power Solar Electric Propulsion in Space," The Aerospace Corporation, November 2018 (https://aerospace.org/sites/default/files/2018-11/Davis-Mayberry_HPSEP_11212018.pdf).

[17] James Vedda, Karen Jones, "Space-based Solar Power: A Near Term Investment Decision," The Aerospace Corporation, October 2020 (https://aerospace.org/sites/default/files/2020-10/Vedda-Jones_SolarPower_20201006_0.pdf).

[18] Josef Koller, "The Future of Ubiquitous, Realtime Intelligence: A Geoint Singularity," The Aerospace Corporation, August 2019 (https://aerospace.org/paper/future-ubiquitous-realtime-intelligence-geoint-singularity).

[19] Gennadi Bersuker, Maribeth Mason, Karen L. Jones, "Neuromorphic Computing: The Potential for High-Performance Processing in Space," The Aerospace Corporation, November 2018. (https://aerospace.org/paper/game-changer-neuromorphic-computing).

[20] Sandra Erwin, "DoD space agency's programs don't have to be perfect but have to be fast," *SpaceNews*, August 4, 2020.

[21] Alex Knapp, "Space Industry Investments Hit Record High as Venture Capital Seeks the Next SpaceX," *Forbes*, January 16, 2020.

[22] Jake Singh, "Game Changer: Do-It-Yourself Satellites and Applications for Citizen Space," The Aerospace Corporation, March 2019 (https://aerospace.org/paper/game-changer-diy-sats-citizen-space).

[23] Karen L. Jones, "Game Changer: Blockchain in the Space Sector," The Aerospace Corporation, March 2020 (https://aerospace.org/paper/game-changer-blockchain-space-sector).

[24] Karen L. Jones, "Continuous Production Agility: Adapting at the Speed of Relevance," The Aerospace Corporation, (https://aerospace.org/paper/continuous-production-agility-adapting-speed-relevance).

[25] Jeremy Palmer, phone interview by Karen Jones, August 31, 2020.

[26] Joshua P. Davis, John P. Mayberry, Jay P. Penn, "On-Orbit Servicing: Inspection, Repair, Refuel, Upgrade, and Assembly of Satellites in Space," The Aerospace Corporation, April 2019 (https://aerospace.org/paper/game-changer-orbit-servicing).

[27] Joseph D. Touch, Lori W. Gordon, "Quantum Key Distribution in Space," The Aerospace Corporation, July 2020 (https://aerospace.org/paper/quantum-key-distribution-space).

[28] Mark Dmytryszyn, Matthew Crook, Timothy Sands, "Preparing for Satellite Laser Uplinks and Downlinks," Sci 2020, 2, 16, March 2020.

[29] Karen L. Jones, "Public-Private Partnerships: Stimulating Innovation in the Space Sector," April 2018 (https://aerospace.org/paper/public-private-partnerships-space).

[30] David S. Eccles, Susan E. Hastings, and Jeff B. Juranek, "Effects of High-Volume Production (HVP) on Space Systems," June 2020 (https://aerospace.org/paper/effects-high-volume-production-hvp-space-systems).

[31] Carrie O'Quinn, Danielle Piskorz, "Setting the Standard: Launch Units for the SmallSat Era," May 2018 (https://aerospace.org/paper/setting-standard-launch-units-smallsat-era).

[32] Michael P. Gleason, "U.S. Space Traffic Management: Best Practices, Guidelines, and Standards," April 2018 (https://aerospace.org/paper/us-space-traffic-management-best-practices-guidelines-and-standards).

CENTER FOR SPACE
POLICY AND STRATEGY

DEFENSE SPACE PARTNERSHIPS: A STRATEGIC PRIORITY

Robert S. Wilson, Colleen Stover, and Steven R. Jordan Tomaszewski

The United States has not fully leveraged its allies and defense partners in the space domain. This is partly due to significant obstacles, like classification and releasability, that have impeded more and deeper defense space partnerships. It also reflects the legacy of the Cold War, a period when space was dominated by a few major powers. A new space era is upon us. Allies and partners are developing significant space systems that can enhance U.S. capabilities. Concurrently, potential adversaries are developing weapons that could threaten U.S. and allied assets. The seriousness of the threat demands a more concerted and international approach. In this new space era, U.S. leadership should treat defense space partnerships as a strategic priority.

Introduction

The United States has defense agreements with countries that represent nearly a quarter of humanity, many of which are spacefaring nations.[1] Yet, the United States has only had limited success in converting some of its defense relationships into space security relationships. In 2019, the United States and Norway agreed to include U.S.-protected communications payloads on Norwegian satellites that will be launched in late 2022, which will mark the first time the United States has put operational national security payloads on a foreign satellite.[2] Although NATO's nuclear deterrent posture comprises a mix of U.S. and allied capabilities, and British submarines deploy U.S.-made submarine-launched ballistic missiles, we are just beginning to leverage the capabilities of our international partners for military space assets and operations.[*3]

Unlike during the Cold War, when space was dominated by a few major powers, space has become increasingly democratized. As of 2019, over 60 countries have a national space budget, over 70 countries own or operate satellites in orbit, and nine countries—plus the European Space Agency—can independently launch into orbit.[4] This growing international engagement in space presents enormous opportunities for defense space partnerships.

This new era also presents serious risks. Space is becoming increasingly contested. In April 2020, Russia tested a direct ascent anti-satellite missile.[5] A few months earlier, U.S. officials called out Russian satellites for trailing a U.S. national

[*] NATO's nuclear deterrent posture includes U.S. nuclear weapons forward deployed in Europe as well as capabilities and infrastructure from Allies, including dual capable aircraft, which NATO says are "central to NATO's nuclear deterrence mission." The Trident II submarine-launched missile is deployed on U.S. Ohio-class submarines as well as the United Kingdom's Vanguard-class submarines.

security satellite.[6] Also in April 2020, Chris Ford, a senior official in the State Department, said that China was exploring capabilities to attack U.S. satellites, including in high orbits such as those of U.S. nuclear command, control, and communications satellites.[7] The seriousness of the threat underlines the importance of defense space partnerships—the United States should not try to manage these threats purely on its own.

To enable more international defense space partnerships, U.S. leadership will need to treat such partnerships as a strategic priority, not as an afterthought or add on. This chapter looks at advantages, challenges, and mitigations for broadening and deepening security space partnerships that could prompt key decision points during the next presidential term.

Advantages of Partnerships

Defense space partnerships offer considerable advantages. These include allowing the United States to expand and improve its network and capabilities with fewer resources, deter adversaries from attacking its systems, and coalesce allied and partner thinking on space security concepts.[8] A look at some common space maturity metrics suggests that many of the most mature space nations in the world are partners of the United States. Specifically:

- The United States and its close partners make up 11 out of the top 15 countries with the biggest national space budgets.[9]
- Of the roughly 2,700 active satellites in orbit, over 500 are operated by international partners and over 1,300 are operated by the United States.[10]
- Among the world's 22 active space launch centers, six are operated by partners and five by the United States.[11]

Many allies are also taking steps to emphasize the seriousness of space security. In the past year, France and Japan have established their own military units dedicated to space.[12] The United Kingdom officially recognized space as an operational domain in 2018.[13] And NATO, which historically has said little on space, came out with a space policy in 2019.[14] Given the space maturity of many of its allies and partners, and the shared recognition of the importance of the domain, the time is advantageous for the United States to place more priority on establishing and deepening space partnerships for defense.

Expand and Improve Networks and Capabilities. Partners have capabilities that can improve U.S. systems and networks in geographically dispersed and strategic locations. This is particularly true in space situational awareness, an area in which a diverse set of geographically-distributed sensors can more accurately and completely capture the operational environment.[15] Partners can help us collectively attain more persistent surveillance and continuous global coverage of satellites and debris, which is only possible if we have more and better sensors in a variety of locations. Radars and optical telescopes spread around the world can also more comprehensively identify space threats. For example, Japan is developing a deep-space radar that will observe objects in geosynchronous orbit. Given the counterspace threats from potential adversaries, the radar could also be invaluable to the United States because of its capability and location.[16]

Additionally, space capabilities and operations are expensive. A clear advantage of military space partnerships is that they generate opportunities for sharing the financial burden of operating in space. As an example, the United States putting its security payloads on the Norwegian satellite will reportedly generate up to $900 million in savings.[17] Hosting U.S. payloads on foreign systems, like this example, represents an area in which the United States could leverage allied and partner capabilities more so than it does currently. Hosted payloads offer affordable means to expand protected communications satellites; position, navigation, and timing satellites; and space situational awareness capabilities, among other systems. Rather than host payloads, partners can also simply contribute to the cost of a satellite system. For example, through multilateral agreements, Canada, Denmark, Luxembourg, the Netherlands, and New Zealand provided funding for the U.S. Wideband Global SATCOM-9 satellite that launched in March 2017.[18] Or the United States can use partners' satellites. For example, the United States partners with Japan and Europe to obtain weather information from space-based sensors, providing accurate weather information to warfighters around the world and avoiding the need to field additional U.S. systems.[19] And it is not just satellites and payloads. Partners have terrestrial infrastructure and user equipment, including for position, navigation, and timing and satellite communications, that can be used collectively to achieve needed capabilities more efficiently. Leveraging allied systems can offer technological insights, system improvements, and capability expansions at lower costs.

Deter Aggression. Partnerships can create opportunities for integrating allied and partner capabilities, such as incorporating combined systems in satellite networks and ground infrastructure. Such integration can strengthen the cohesiveness of a defense partnership, which could also help deter an attack. A potential adversary may consider an attack on a purely U.S. system differently than an attack on a system that incorporates several allied and partner capabilities. Deployment of NATO's multinational battlegroups in the eastern part of the Alliance (Estonia, Latvia, Lithuania, and Poland) is an example of this concept in the ground domain. If Russia's military were to invade Estonia and attack the multinational forces there, the invasion could be seen as not just an attack on Estonia but on all of the countries represented in those forces and perhaps all of NATO.[20] A May 2017 NATO fact sheet on its multinational forces reaffirms this: "[The multinational] presence makes clear that an attack on one Ally will be considered an attack on the whole Alliance."[21] Similarly, in the space domain, an attack on a U.S. constellation of satellites with U.S. payloads might prompt a response from the United States; an attack on a satellite constellation with a mix of U.S. and partner capabilities might prompt a response from several countries acting collectively, which may help deter a potential adversary from attacking in the first place.

With integrated allied and partner systems, U.S. satellite networks and ground infrastructure, as well as other equipment and capabilities, can become more resilient. The more systems you have, the larger an attack would need to be to take out a given percentage of capability: all else equal, two satellites would be more resilient than one, three satellites more resilient than two, and so on. The resilience offered by integrating allied and partner capabilities into a network, therefore, may also contribute to deterring a potential adversary from attacking the network.

Coalesce Allied and Partner Thinking on Space Security Concepts. As part of defense space partnerships, allies can more thoroughly discuss the threats to space systems and potential space conflict scenarios. If the United States wants to fully leverage its allies and partners in any future conflict in space, the United States would benefit from having more discussions with its allies about the possibility and nature of such a conflict: how it might emerge, how the respective allies can contribute, the capabilities the allies should pursue in advance, and the actions that might constitute "red lines" or cross thresholds that are more severe than others.

In recent years, the United States has taken important steps to collaborate with allies and partners on space threats and space conflict. International partners participate in military space exercises such as Space Flag, Global Sentinel, and the Schriever Wargame.[22] The Five Eyes (the United States plus Australia, Canada, New Zealand, and the United Kingdom) along with France and Germany all are members of the Combined Space Operations initiative.[23] Experts we spoke to told us that the United States should continue and expand these efforts. Partner preparation for space conflicts could be valuable from an operational and geopolitical perspective. Todd Harrison, Director of the Aerospace Security Project at the Center for Strategic & International Studies, stated the following:

> Rotating allies in the [Combined Space Operations Center as part of the Combined Space Operations initiative] is important because it gives those countries experts on space security issues. Let's say Russia or China start interfering with our nuclear command and control and early warning satellites. Any allied country needs to have their own experts so they understand our response—they need folks who can say, "Yes, I understand why the Americans are escalating over this."[24]

In a conflict in space, even if an allied country does not have significant defense space capabilities, it should have an understanding why the United States or other allied countries are taking the actions that they are. That understanding might help that country support the United States and allies politically and militarily in other domains.

The United States and its allies having a shared understanding of space threats and space conflict will help in peacetime too. General John Raymond, the Chief of Space Operations, has prioritized developing norms for operating in space.[25] These could include something like taking steps to not create debris and announcing planned maneuvers into other orbits.[26] With a similar understanding of the issues, the United States and its allies will be better equipped to develop common ideas for responsible behavior in space. This will also help with multilateral discussions, such as United Nations (UN) proposals on space security. Our partners have not always supported U.S. positions on UN space security proposals, including our negation of proposals made by Russia and China. For example, in the 2014 UN vote on Russia's proposed draft resolution on No First Placement of Weapons in Outer Space, only three countries voted with the United States against the resolution and 125 voted for it with Russia.[27] New and deeper partnerships will create more commonality in assumptions and objectives for fostering a safe and secure space environment.

Challenges

Of course, there are legitimate reasons why the United States has not actualized more defense space partnerships. Part of this stems from the legacy of the Cold War in which the United States and the Soviet Union were the two major powers in space. A RAND report from 2000 says, "Historically, the predominance of U.S. investment in and experience with space systems has minimized the consideration of space as an area with potential interoperability problems," noting that "the United States has provided the bulk of products and services derived from space assets."[28] Because the United States had overwhelming capabilities in space relative to allies, little could be gained by defense space partnerships. Nowadays, it is rare to hear arguments against collaborating in the defense space domain. But there are deceptively simple yet significant obstacles in the way of realizing more defense space collaboration. Among these are classification and releasability of information; technology and logistics; and organizational issues. Although the mindset has changed around defense space partnerships, these mundane challenges will need to be addressed for the United States to establish more and deeper space partnerships.

Classification Levels and Releasability. No issue presents a greater impediment to defense space partnerships than an inability to share information. In conversations with allied attachés and exchange officers, classification and releasability routinely came up as the biggest obstacle they perceived to more effective security space collaboration. We need to protect information that helps the United States maintain its advantage, but it is possible to overdo secrecy, and we should continuously evaluate the classification and releasability of information in the space domain to better balance secrecy with collaboration.[29] Defense space information is frequently classified and often with a NOFORN (not releasable to foreign nationals) caveat. Such classification or dissemination control limits defense space collaboration. For example, a foreign partner could share sensing data with the United States, which is then processed through NOFORN software and made unavailable to the very country that captured it.

This issue has received attention at senior levels. General John Hyten has stated the need to remove NOFORN designations where possible.[30] In 2019, then Air Force Chief of Staff, General David Goldfein said with respect to space collaboration: "One of the challenges we have is that we over-classify things and that gets in the way of information sharing."[31] The Air Force is currently implementing a security classification review looking to improve information sharing for space operations. The experts we spoke with noted that although the United States has been making progress in this area, classification remains a major obstacle for defense space partnerships.

Compatibility in Standards and Technology. Defense space partnerships present logistical hurdles for sharing information too, including not having compatible systems and standards. Even in cases where U.S. officials are permitted to share sensitive information with partners, experts we spoke with pointed out that the United States and the partner country often cannot collaborate because they do not have the same or compatible classified conferencing capabilities or networks. The DOD's classified SIPRnet Secret-level computer network, for instance, was not designed to be a combined or allied system.[32] In some cases, defense space partnerships also require allies to align their standards, such as for data. In space situational awareness data sharing, for instance, government, industry, and international organizations have been adopting various standards for sharing orbital information, which is requiring complex data translation services or preventing sharing altogether.

Organizational. Another challenge is that with the myriad of organizations in the U.S. government that work on defense space partnerships and sharing, it is not easy for allies to know whom to talk to. Roles and responsibilities are spread out across the Department of Defense, the Intelligence Community, the Department of State, and others, and there is no single clear entry point for partners or potential partners to engage. The U.S. Space Force headquarters could be the entry point for training and exercises, U.S. Space Command for space operations collaboration, Office of the Director of National Intelligence for intelligence sharing, the National Geospatial-Intelligence Agency for imagery sharing and training, Space and Missile Command for combined space system acquisition, the Office of the Secretary of Defense for broader discussions. This issue surfaced in our discussions with allied attachés and foreign exchange officers. One official from a partner nation offered an anecdote in which an official from a separate nation called for help because he was unable to connect with the right people on the U.S. side. Many said that navigating the "U.S. space behemoth," as one official put it, and knowing whom to contact is extremely challenging.[33] Figure 1 captures the organizations that have a role in international security space collaboration.

The establishment of U.S. Space Command and the U.S. Space Force could spur changes in roles for defense space partnerships. It could create more opportunities for synchronizing departmental and U.S. government responsibilities for international security cooperation in space, but it could also bring more organizations into an already complicated landscape. Streamlining could benefit current and potential partners.

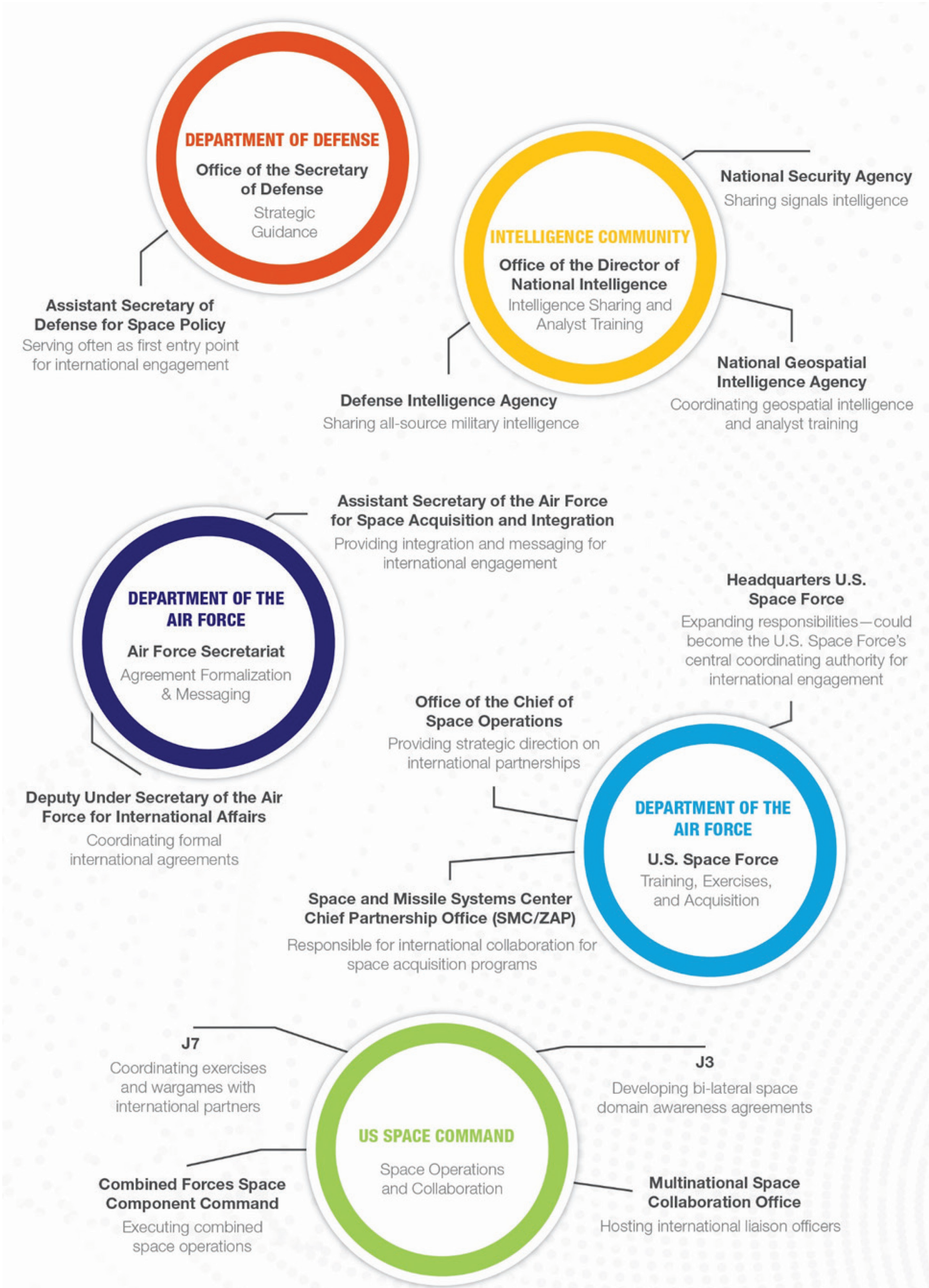


Figure 1: U.S. defense organizations responsible for international security space collaboration.

A Way Forward

Despite the impediments, the United States has made progress in broadening and deepening defense space partnerships. The Air Force has allowed allied and partner participation in military space courses on space fundamentals, operations, space domain awareness, and orbital mechanics. The United States has managed to share intelligence information on space with some allies, including the Five Eyes. In addition to the hosted payload agreement with Norway, Japan is scheduled to launch satellites with U.S. national security payloads in 2023, which will be the first time the United States has done this with a foreign satellite aboard a foreign launch vehicle.[34] U.S. Space Command has agreed to space domain awareness bilateral sharing agreements with 25 other countries.[35] Canada, the Netherlands, and the United Kingdom use the U.S. nuclear-hardened Advanced Extremely-High Frequency communications system.[36] Global Sentinel, a space situational awareness exercise, expanded its international participation in 2017 and now includes Australia, Canada, the United Kingdom, France, Spain, Germany, Italy, Japan, and the Republic of Korea.[37] These are just some examples of international space security collaboration.

Options for Enhancing Collaboration

- Lower classification levels and distribution restrictions to allow more sharing with allies and partners
- Involve more foreign programs in exercises and wargames
- Imbed foreign experts into USG programs across the space domain
- Increase experts in USG to liaise with foreign counterparts
- Streamline DOD organization for current and potential partners
- Prioritize ease of data sharing and interoperability with allies and partners through standardization
- Take more time and effort, and corresponding funding, to foster trusted space partnerships
- Develop common norms of behavior in partnership with other nations to strengthen cohesion and deterrence

But more can be done. We could invite more countries to engage in exercises and training, could seek out more opportunities for hosted payloads and combined systems, and design satellite networks and ground infrastructure with international partners in mind. U.S. leadership should consider lowering classification levels, reducing distribution restrictions like NOFORN, and involving more countries in space exercises. Information systems, like classified conferencing and messaging networks, could be required to be compatible with allies. Leadership could increase the number of trained experts who understand foreign information dissemination policy—people who can help organizations share information appropriately with allies—and imbed them in operational space commands, task forces, and operational centers. Our defense organizations need appropriate experts fluent in the minutiae of defense space partnerships—alignment of standards, technologies, and processes.

Our leadership should also tackle cultural issues that impede greater defense space partnerships. The security community is risk-averse and compliance-oriented; it is hard for the operational and political-military communities to work around the security officials knowing that one mistake can be career-ending. Good intentions run into implementation realities. New and deeper defense space partnerships will require higher tolerance for risk and deviations from traditional practice.

These partnerships will also require flexibility. Officials from allied and partner nations told us they want to meaningfully contribute to our common space defense—to include integrating forces and capabilities to deter and respond to aggression—rather than just supply data and intelligence. The United States spends more money on space than all other countries combined; therefore, any partnership or collaboration—particularly one in which allies are empowered to be equal partners—will require more time and effort.[38] These partnerships should not be viewed simply as a transactional benefit but as a strategic objective itself.

There are encouraging signs. As of May 2020, a number of allies were invited to engage with U.S. Space Command in the U.S. military's baseline operational plan—Operation Olympic Defender—to provide space-based capabilities to warfighters around the world. General Raymond, in his role as the Commander of U.S. Space Command, signed the order, which noted that the United Kingdom was the first country to sign up.[39] In June 2020, the Department of Defense released its Defense Space Strategy, which emphasizes international space partnerships. One of the objectives of the strategy is to "[i]ntegrate allies and partners into plans, operations, exercises, engagements, and intelligence activities."[40] The commitment to international defense partnerships reflects continuity with other relevant strategic documents, including the 2018 National Defense Strategy and 2011 National Security Space Strategy.[41]

The challenges should be understood too. Classification, shareability, and technological limitations are not the flashiest of issues. They may not seem as if they warrant senior-level attention. But if U.S. decisionmakers seek to broaden and deepen U.S. defense space partnerships, these challenges must be addressed. Decisionmakers will need to impress upon their organizations the importance of defense space partnerships and charge them with managing these obstacles.

In 2018, when the U.S. Air Force transitioned the Joint Space Operations Center to the Combined Space Operations Center, General Raymond said: "No one nation can do this alone… the partnerships we are forming today will no doubt lead to a more stable and sustainable space domain for years to come."[42] Partnerships hold the promise of leading to better resilience, stronger deterrence to attack, unified messaging to potential adversaries, lower costs, shared information, shared capabilities, and diplomatic progress for the United States to remain the world leader in space. Alliances and defense partnerships have been critical throughout our nation's history, dating even as far back as the French involvement in our Revolutionary War. During World War II, Winston Churchill reportedly said, "There is only one thing worse than fighting with allies, and that is fighting without them." Defense space partnerships may be difficult but are crucial—as such, U.S. space leadership should give them the priority they deserve.

References

[1] Adam Taylor, "Map: The U.S. is bound by treaties to defend a quarter of humanity." *The Washington Post.* May 30, 2015 (https://www.washingtonpost.com/news/worldviews/wp/2015/05/30/map-the-u-s-is-bound-by-treaties-to-defend-a-quarter-of-humanity/).

[2] Nathan Strout, "How 2 Space Norway satellites will help the Air Force in the Arctic." *C4ISRNET.* July 5, 2019 (https://www.c4isrnet.com/battlefield-tech/2019/07/05/how-2-space-norway-satellites-will-help-the-air-force-in-the-arctic/).

[3] North Atlantic Treaty Organization, "NATO's nuclear deterrence policy and forces." April 16, 2020 (https://www.nato.int/cps/en/natohq/topics_50068.htm) United States Navy, "Fact File: Trident II (D5) Missile." May 15, 2019 (https://www.navy.mil/navydata/fact_display.asp?cid=2200&tid=1400&ct=2).

[4] Union of Concerned Scientists Satellite Database. Union of Concerned Scientists. http://ucsusa.org/org. Data updated as of April 1, 2020; "Competing in Space," National Air & Space Intelligence Center, December 2018 (https://media.defense.gov/2019/Jan/16/2002080386/); United Nations Office for Outer Space Affairs, "Worldwide Space Agencies" (http://www.unoosa.org/oosa/en/ourwork/space-agencies.html); Space Foundation, "The Space Report 2020 Q2: The Authoritative Guide to Global Space Activity," 2020, (https://www.thespacereport.org/wp-content/uploads/2020/07/The-Space-Report-2020-Q2-Book.pdf).

[5] U.S. Space Command Public Affairs, "Russia tests direct-ascent anti-satellite missile." April 15, 2020 (https://www.spacecom.mil/MEDIA/NEWS-ARTICLES/Article/2151611/russia-tests-direct-ascent-anti-satellite-missile/).

[6] Michael Sheetz, "Russian spacecraft following US spy satellite in 'disturbing' manner, Space Force general says." February 10, 2020 (https://www.cnbc.com/2020/02/10/space-force-russians-tracking-us-spy-satellite-unusual-and-disturbing.html).

[7] U.S. State Department. "Whither Arms Control in Outer Space? Space Threats, Space Hypocrisy, and the Hope of Space Norms." Remarks by Christopher Ashley Ford, Assistant Secretary for Bureau of International Security Nonproliferation at the Center for Strategic & International studies. April 6, 2020 (https://www.state.gov/whither-arms-control-in-outer-space-space-threats-space-hypocrisy-and-the-hope-of-space-norms/).

[8] For other advantages and challenges associated with space partnerships, see Aerospace's 2018 report on *Alliance Rationales & Roadblocks: A U.S.-Canada Space Study*. (https://aerospace.org/paper/alliance-rationales-roadblocks).

[9] Simon Seminari, "Global government space budgets continues multiyear rebound." *SpaceNews.* November 24, 2019 (https://spacenews.com/op-ed-global-government-space-budgets-continues-multiyear-rebound/).

[10] Union of Concerned Scientists Satellite Database. Union of Concerned Scientists. (http://ucsusa.org/org) Data updated as of April 1, 2020.

[11] Thomas G. Roberts, "Spaceports of the World." Center for Strategic & International Studies. March 2019 (https://aerospace.csis.org/wp-content/uploads/2019/03/190313__SpaceportsOfTheWorld.pdf).

[12] "France to create space command within air force: Macron," *Reuters.* July 13, 2019 (https://www.reuters.com/article/us-france-nationalday-defence/france-to-create-space-command-within-air-force-macron-idUSKCN1U80LE).

[13] Sam Wilson and Gina Galasso, "What Brexit Means for UK Space Leadership." The Aerospace Corporation, April 2019 (https://aerospace.org/paper/what-brexit-means-uk-space-leadership).

[14] North Atlantic Treaty Organization, "NATO's approach to space," April 27, 2020 (https://www.nato.int/cps/en/natohq/topics_175419.htm).

[15] Aaron Bateman, "America Needs a Coalition to Win a Space War." *War on the Rocks.* April 29, 2020 (https://warontherocks.com/2020/04/america-needs-a-coalition-to-win-a-space-war/).

[16] Sam Wilson, "Japan's Gradual Shift Toward Space Security." The Aerospace Corporation. May 2020 (https://aerospace.org/paper/japans-gradual-shift-toward-space-security).

[17] Space and Missile Command Public Affairs. "EPS Follow-on Payload Program Completes Successful Delta Critical Design Review." December 3, 2019 (https://www.losangeles.af.mil/News/Article-Display/Article/2030921/eps-follow-on-payload-program-completes-successful-delta-critical-design-review/).

[18] Sandra Erwin, "Gen. Hyten wants more allies to fight alongside U.S. in space." *SpaceNews.* March 8, 2018 (https://spacenews.com/gen-hyten-wants-more-allies-to-fight-alongside-u-s-in-space/).

[19] National Oceanic and Atmospheric Administration. "International Partners in the Sky: Satellite Partnerships." February 12, 2018 (https://www.nesdis.noaa.gov/content/international-partners-sky-satellite-partnerships).

[20] Article V of NATO's charter says that collective defense means an attack against one ally is considered as an attack against all allies.

[21] North Atlantic Treaty Organization. "NATO's Enhanced Forward Presence." May 2017 (https://www.nato.int/nato_static_fl2014/assets/pdf/pdf_2017_05/1705-factsheet-efp.pdf).

[22] Captain Lauren Hill, "SpaceFlag holds first exercise with coalition partners," Air Force Space Command Public Affairs. August 25, 2019 (https://www.afspc.af.mil/News/Article-Display/Article/1943013/space-flag-holds-first-exercise-with-coalition-partners/); U.S. Strategic Command, "USSTRATCOM Hosts Fourth SSA Experiment with International Partners." October 5, 2017 (https://www.stratcom.mil/Media/News/News-Article-View/Article/1340856/usstratcom-hosts-fourth-ssa-experiment-with-international-partners/); Jack Detsch, "Pentagon Not Ready for Space Fight, Experts Say," Foreign Policy. June 18, 2020 (https://foreignpolicy.com/2020/06/18/pentagon-not-ready-space-flight-militarization-satellites/).

[23] Air Force Space Command, "Multinational Statement for Combined Space Operations." April 10, 2019 (https://www.afspc.af.mil/News/Article-Display/Article/1810793/multinational-statement-for-combined-space-operations/).

[24] Interview with Todd Harrison, May 2020.

[25] Sandra Erwin, "Raymond calls out Russia for 'threatening behavior' in outer space." *SpaceNews.* February 10, 2020 (https://spacenews.com/raymond-calls-out-russia-for-threatening-behavior-in-outer-space/).

[26] "Future Space Controls and the Invisible Hand." Workshop Report. *American Bar Association Standing Committee on Law and National Security* and *Nonproliferation Policy Education Center*. June 2019 (https://www.americanbar.org/content/dam/aba/administrative/law_national_security/june-2019-space-report.pdf); "Working Smarter with America's Spacefaring Allies," Workshop Report. *American Bar Association Standing Committee on Law and National Security* and *Nonproliferation Policy Education Center*. March 2020 (https://www.americanbar.org/content/dam/aba/administrative/law_national_security/march-2020-space-report.pdf).

[27] Nuclear Threat Initiative. "Proposed Prevention of an Arms Race in Space (PAROS) Treaty." April 23, 2020 (https://www.nti.org/learn/treaties-and-regimes/proposed-prevention-arms-race-space-paros-treaty/).

[28] Myron Hua, et al. "Interoperability: A Continuing Challenge in Coalition Air Operations." RAND. 2000. Chapter 6 (https://www.rand.org/content/dam/rand/pubs/monograph_reports/MR1235/MR1235.chap6.pdf).

[29] Jamie Morin, "Moving toward a need-to-collaborate culture for national security space." May 6, 2020. C4ISRNet (https://www.c4isrnet.com/opinion/2020/05/06/moving-toward-a-need-to-collaborate-culture-for-national-security-space/).

[30] General John E. Hyten, U.S. Strategic Command. Speech at Space and Missile Defense. August 8, 2017 (https://www.stratcom.mil/Media/Speeches/Article/1274339/space-and-missile-defense-symposium/).

[31] Sandra Erwin, "Air Force Chief Goldfein: To win in space, U.S. must work closer with allies." *SpaceNews.* April 13, 2019 (https://spacenews.com/air-force-chief-goldfein-to-win-in-space-u-s-must-work-closer-with-allies/).

[32] Michael Gleason and Charity Weedon, "Alliance Rationales & Roadblocks: A U.S.-Canada Space Study," The Aerospace Corporation. April 16, 2018 (https://aerospace.org/paper/alliance-rationales-roadblocks).

[33] Interviews with select allied officials and foreign exchange officers, July 2020.

[34] Paul McLeary and Theresa Hitchens, "US, Japan to Ink Hosted Payload Pact to Monitor Sats." *Breaking Defense.* August 5, 2019 (https://breakingdefense.com/2019/08/us-japan-to-ink-hosted-payload-pact-to-monitor-sats/).

[35] U.S. Space Command, "US, Peru expand space data sharing partnership." May 20, 2020 (https://www.spacecom.mil/MEDIA/NEWS-ARTICLES/Article/2193473/us-peru-expand-space-data-sharing-partnership/).

[36] Sandra Erwin, "USAF prepares to launch billion-dollar communications satellite while it studies future alternatives." *SpaceNews.* August 30, 2018 (https://spacenews.com/usaf-prepares-to-launch-billion-dollar-communications-satellite-while-it-studies-future-alternatives/).

[37] Captain Lauren Hill, "Schriever Wargames Concludes." Air Force Space Command Public Affairs. September 13, 2019 (https://www.afspc.af.mil/News/Article-Display/Article/1960610/schriever-wargame-concludes/).

[38] Simon Seminari, "Global government space budgets continues multiyear rebound." *SpaceNews.* November 24, 2019 https://spacenews.com/op-ed-global-government-space-budgets-continues-multiyear-rebound/).

[39] Theresa Hitchens, "'Major Milestone' as Allies Join SPACECOM's War Plan." *Breaking Defense.* May 21, 2020 (https://breakingdefense.com/2020/05/major-milestone-as-allies-join-spacecoms-war-plan/?utm_campaign=Breaking%20Defense%20Sea&utm_source=hs_email&utm_medium=email&utm_content=88627728&_hsenc=p2ANqtz-9qAlNTduO4RH5I3tZYyAmRI-tEgPlLy8llTqxintZ52Eu8qTggT-ezdF8pXlTTQBkpXi1AdfCsmHESAfpBuOaEtIY7Bw&_hsmi=88627728).

[40] Department of Defense. "Department of Defense Releases Defense Space Strategy." June 17, 2020 (https://www.defense.gov/Newsroom/Releases/Release/Article/2223539/department-of-defense-releases-defense-space-strategy/).

[41] Department of Defense, "National Security Space Strategy." 2011 (https://archive.defense.gov/home/features/2011/0111_nsss/); Department of Defense, "Summary of 2018 National Defense Strategy" (https://dod.defense.gov/Portals/1/Documents/pubs/2018-National-Defense-Strategy-Summary.pdf).

[42] U.S. Strategic Command. "Combined Space Operations Center established at Vandenberg AFB." July 19, 2018 (https://www.stratcom.mil/Media/News/News-Article-View/Article/1579497/combined-space-operations-center-established-at-vandenberg-afb/).

SPACE-BASED SOLAR POWER: A NEAR-TERM INVESTMENT DECISION

James A. Vedda and Karen L. Jones

The concept of space-based solar power, also referred to as solar power satellites (SPS), has been evolving for decades. In 1968, Dr. Peter Glaser of Arthur D. Little, Inc. introduced the concept using microwaves for power transmission from geosynchronous orbit (GEO) to an Earth-based rectifying antenna (rectenna). Since then, technology has advanced on several fronts to remove some of the technological and economic barriers to practical full-scale implementation. U.S. decisionmakers are now facing a pivotal moment as several countries continue to invest in this promising, game-changing technology. This paper discusses the history of SPS, a few leading innovators, key functional components, and market applications. Ultimately, the United States must decide whether and how to invest in SPS to optimize the various operational, competitive, and societal benefits that this type of application offers to commercial, defense, and civilian markets.

Background

The sixth mission of the U.S. Air Force's X-37B experimental space plane was launched in May 2020. Among its payloads, it carried an experimental solar power module from the Naval Research Laboratory (NRL) intended to demonstrate power generation and conversion to radio frequency energy that could be transmitted across long distances.[1] This is the latest development in a long history of efforts to realize the potential of large-scale collection of solar power in space and the delivery of that power to distant users.

The study of SPS has been conducted at government agencies, universities, and other research organizations in the United States for more than half a century. But the concept has yet to reach fruition because the technology is challenging and efforts to develop it have been inconsistent and minimally funded. Despite the current NRL test and other pockets of activity, little is being done in the United States to initiate a series of flight experiments that would lead to demonstration of a complete system including on-orbit and ground components, eventually scaling up to operational size.

Overview of SPS Research

Although the United States was a pioneer in this technology, its small and sporadic projects could become overshadowed by increasing international efforts. Japan has been keenly interested in SPS for a long time, and China, Russia, India, South Korea, and other countries have become active in pursuing SPS technologies.[2] If proven, SPS systems could have dramatic implications for all sectors of space activity and yield technology dividends to a variety of terrestrial markets, especially energy and transportation.[3,4] Ultimately, the race to become a leader in space-based solar power could serve long-term geopolitical interests as various countries compete to dominate cislunar space. Alternatively, leading space-based solar energy innovators could work *together* to address global energy security and greenhouse gas emissions challenges.

United States SPS Research. The ***Naval Research Laboratory (NRL)*** designed the world's first satellite powered by solar cells—Vanguard 1, which was launched in 1958. Since then, NRL has been involved in a variety of solar power research, including the following SPS-related projects:

- *Photovoltaic Radio-frequency Antenna Module* (*PRAM).* The first orbital SPS experiment was launched on the X-37B space plane in May 2020. It featured a 12-inch square photovoltaic module to test the viability of space-based solar power systems by converting sunlight to microwaves outside the atmosphere and analyzing the energy conversion process and resulting thermal performance.

- *Lectenna*. A light-emitting rectifying antenna converted a wireless network signal into electric power. This International Space Station experiment was conducted during February 2020.

- *Power Transmitted Over Laser (PTROL).* NRL conducted a successful demonstration of a land-based power beaming system using an infrared laser during 2019.

The ***Air Force Research Laboratory (AFRL)*** is focused on ensuring mission success by finding power solutions for forward-operating bases. To support this goal, AFRL is developing an SPS transmission capability using high-efficiency solar cells. The *Space Solar Power Incremental Demonstrations and Research (SSPIDR*) intends to capture solar energy in space and precisely beam it. Northrop Grumman is partnering with AFRL and was awarded a $100 million contract.

The ***Department of Defense (DOD) National Security Space Office (NSSO)*** conducted a 2007 study titled *Space-based Solar Power as an Opportunity for Strategic Security.* It concluded that the United States should begin a coordinated national SPS program.

NASA has a long history of SPS research dating back to 1975, when NASA and Raytheon used satellite components to send a wireless microwave electric signal across a mile-wide valley in Goldstone, California. Other examples over the past 50 years include:

- Mid- to late-1970s "Energy Crisis" era. Collaboration with the *Energy Research & Development Administration (ERDA)* (later reorganized to the Department of Energy) included SPS as part of alternative energy studies.

- 1995-1996. *A Fresh Look at Space Solar Power* updated the findings of previous NASA work on this topic. The study examined whether SPS could be a viable alternative to terrestrial electrical power, including economic, environmental, and safety perspectives.

- 2012. *NASA Innovative Advanced Concepts (NIAC)* study examined various concepts and supported Solar Power Satellite Arbitrarily Large Phased Array (SPS-ALPHA), including detailed studies of technology readiness and economic viability. The concept included individually aimed thin-film mirrors, typically in geosynchronous Earth orbit (GEO), which would capture and convert sunlight into a coherent microwave beam and transmit power to Earth or other destinations in space.

Leading International SPS Innovators. Both Japan and China appear to be international leaders in SPS.

The ***Japan Aerospace Exploration Agency (JAXA)*** has consistently included SPS in its space planning[5] and has made steady research investments in SPS since the late 1990s, including two conceptual designs:

- *SPS2000* - a low Earth orbit (LEO)-based constellation providing constant power to ground stations
- *SPS2004* - a GEO-based satellite with rotating solar collection mirrors

In 2014, JAXA announced a technology roadmap to build orbital solar power stations with a combined capacity of 1 GW by 2030. The objectives are to enhance the accuracy of the microwave beam-pointing control, increase the conversion efficiency from direct current (DC) power to microwaves (in space); increase the conversion efficiency from microwave to DC power (on the ground); and reduce the size and weight of the electronic modules.

China intends to become a global SPS leader and views SPS as a strategic imperative to shift from fossil-based energy and foreign oil dependence. China's SPS strategy is dual use—military and civil. SPS milestones include:

- 1990: Interest in SPS initiated
- 2010: Publication of an SPS roadmap
- 2019: Establishment of the first state-funded prototype SPS program
- *by 2025:* Demonstration of a 100 KW system in LEO
- *by 2030:* Plans for a 300-ton MW-level space-based solar power station[6,7]

Other International SPS Innovators. Russia, Europe, and India are also working to advance their space-based solar projects.

Russia announced during the late 1980s that it plans to use satellites to collect solar energy and beam it back to Earth.[8] Rather than microwaves, Russia's plans evolved to use infrared lasers spread across the area of the panels, with the intention of combining their radiation to create a powerful-enough laser beam to transfer the electricity to Earth.[9]

The ***European Union*** is funding long-term research with potential delivery of an operational system many years away. ***Solspace*** (scheduled to run from December 2020 to November 2025) involves large, lightweight reflectors redirecting sunlight onto terrestrial utility-scale solar power farms.[10]

India has been investigating SPS concepts for many years, seeing the technology as critical for "large-scale societal missions" as part of a "World Space Vision 2050."[11]

Market Applications: Power Beaming in and from Space

Users of rechargeable consumer electronics such as cell phones are already familiar with wireless power transmission using a near-field method such as resonant coupling. SPS involves far-field microwave energy transfer and can be achieved at long distances using precisely aimed microwaves or laser beams. The potential user community for space-based wireless power transmission can be described in three general categories:

- Terrestrial electric power providers

- Terrestrial electric power users with high demand or in remote locations (e.g., institutional users such as military bases, isolated towns, large mining and manufacturing operations, electric rail transportation systems)
- In-space infrastructure (e.g., satellites, space stations, lunar bases)

Terrestrial Electrical Utility Markets. Early studies, including one by NASA and the Department of Energy (DOE) in the late 1970s,[12] focused overwhelmingly on serving the terrestrial power grid. This remains an important objective as demand for electricity continues to grow worldwide,[13] although serving the other two categories of users may become technically and economically feasible much sooner. In the terrestrial power grid, SPS would compete with a variety of entrenched and relatively inexpensive energy sources, including fossil fuels and renewables. In populated areas, traditional sources can deliver power to consumers at a price of a fraction of a dollar per kilowatt. Some experts we spoke with believe SPS eventually can achieve a competitive price point, but the timeframe may be measured in decades. When that time comes, SPS may be capable of supplying the power grid with renewable energy that is not limited by day/night cycles or weather.

Specialized and High-Demand Terrestrial Applications. Some types of terrestrial users have special needs that incur much higher costs. Nowhere is the cost of electricity higher than in forward-deployed military bases, because it is measured in human lives and combat effectiveness as well as dollars. These bases are powered by generators that require liquid fuels to be trucked through potentially hostile territory, and fuel convoys have been frequent targets of attack.[14] For example, estimates for the cost of fuel deliveries in Operation Iraqi Freedom in the mid-2000s ranged from $15 to hundreds of dollars per gallon.[15,16] What's more, those estimates didn't include the cost of casualties. As of November 2007, "Approximately 80 convoys traveled continuously between Kuwait and Iraq destinations, all protected by uniformed forces. This degrades combat capability, resulting in real costs, even if not attributed to the supplies themselves."[17] A 2009 study documented increasing dependence on fossil fuels in wartime, and its contribution to ever-higher casualty rates. The study highlighted the link between improvised explosive devices (IEDs) from insurgent groups, which caused nearly two-thirds of coalition deaths in Iraq and Afghanistan, and fuel transportation activities.[18]

Apart from the military, there are many current and prospective electricity users that could benefit from beamed power from space. Isolated communities could end dependence on fuel-consuming generators. On-demand power beaming from orbit could replace or augment intermittent ground-based renewables. Heavy power users of the future could reduce or eliminate their dependence on the grid or dedicated power generation capabilities by leasing satellite beams. Such users may include large industrial facilities, electric rail systems serving regional or national routes, and power-hungry desalination plants that have been increasing in number and capacity worldwide.[19,20]

Space-to-Space Power Beaming Applications. Satellites and facilities in cislunar space may be the first customers of beamed power as it becomes available. On-board solar arrays have powered spacecraft ranging in size from a couple of kilograms to the approximately 400,000-kilogram International Space Station, which produces over 100 kilowatts of power. The cost of that power is high, and the systems to produce it are a substantial portion of the mass of the spacecraft. Projections for the growth of cislunar activity point to commensurate growth in demand for power, and some installations could require power levels in the multi-megawatt range, far higher than any power system deployed in space thus far. SPS systems could become one possible solution to address that demand.

Wireless power transmission could serve the needs of NASA, other national space agencies, and companies that are currently investigating lunar mining, especially the harvesting of ice deposits at the lunar south pole. The energy-intensive work of extraction and processing could be powered by SPS systems in lunar polar orbit. Alternatively, the sun-drenched peaks above near-polar craters could host solar collectors that beam power into the permanent darkness below, allowing easy redirection of the power to where it is needed.

Meeting the Technical and Operational Challenges

According to a 2011 study by the International Academy of Aeronautics, "There are no fundamental technical barriers that would prevent the realization of large-scale SPS platforms during the coming decades."[21] SPS technology maturation and adoption will depend upon investments in research and development, prototyping, and flight demonstrations. Concurrently, supportive development policies and favorable economics for durable applications will be needed to bring the concept to fruition.

Collection of solar power in space and transmission of power across distances are both demonstrated technologies. The technical questions that need to be answered have to do with whether the system can be scaled up sufficiently and whether transmission across the long distances of cislunar space and through Earth's atmosphere is safe and practical.

Skeptics of SPS systems have pointed to a litany of challenges that cast doubt on technical and economic feasibility. At the top of that list is the cost of access to orbit because the mass of an SPS system is likely to be very large, requiring many launches. Other challenges include the cost of space-rated components, the amount of extra-vehicular activity required for assembly, the ongoing operations and maintenance costs, and mitigation of environmental effects.

Over the years, researchers in the United States and abroad have proposed many architectural designs that attempt to address these challenges.[22] Early research in the 1970s focused on power beaming concepts involving large, monolithic transmitter and receiver structures. The 1990s saw a move toward structures that were at least partially modular, still using a common backbone. More recently, the focus has been on completely modular structures that reduce costs and increase flexibility.[23] Along the way, technical advances inside and outside the space industry have worked in favor of the feasibility of these design concepts:

- Launch opportunities are becoming more available and less costly
- Solar cell efficiency has improved dramatically since SPS studies began
- Mass production of modular spacecraft components, accompanied by interface and interoperability standards, is becoming a reality
- Very large commercial space projects (e.g., constellations of thousands of satellites), requiring multibillion-dollar investments from multiple sources, are now considered achievable
- The use of robotics for assembly and operations has become a credible substitute for space-walking astronauts
- Harvesting of lunar materials is being considered seriously, opening the possibility that not all of the mass of SPS components needs to be lifted from Earth

A commitment to SPS development should not be judged in isolation from other space efforts. If spacefaring nations and businesses plan to fulfill other missions by pursuing technologies applicable to SPS (e.g., large launch vehicles, advanced space robotics, assembly of large space structures, and exploitation of lunar and asteroidal materials), this investment in new capabilities will advance SPS development.

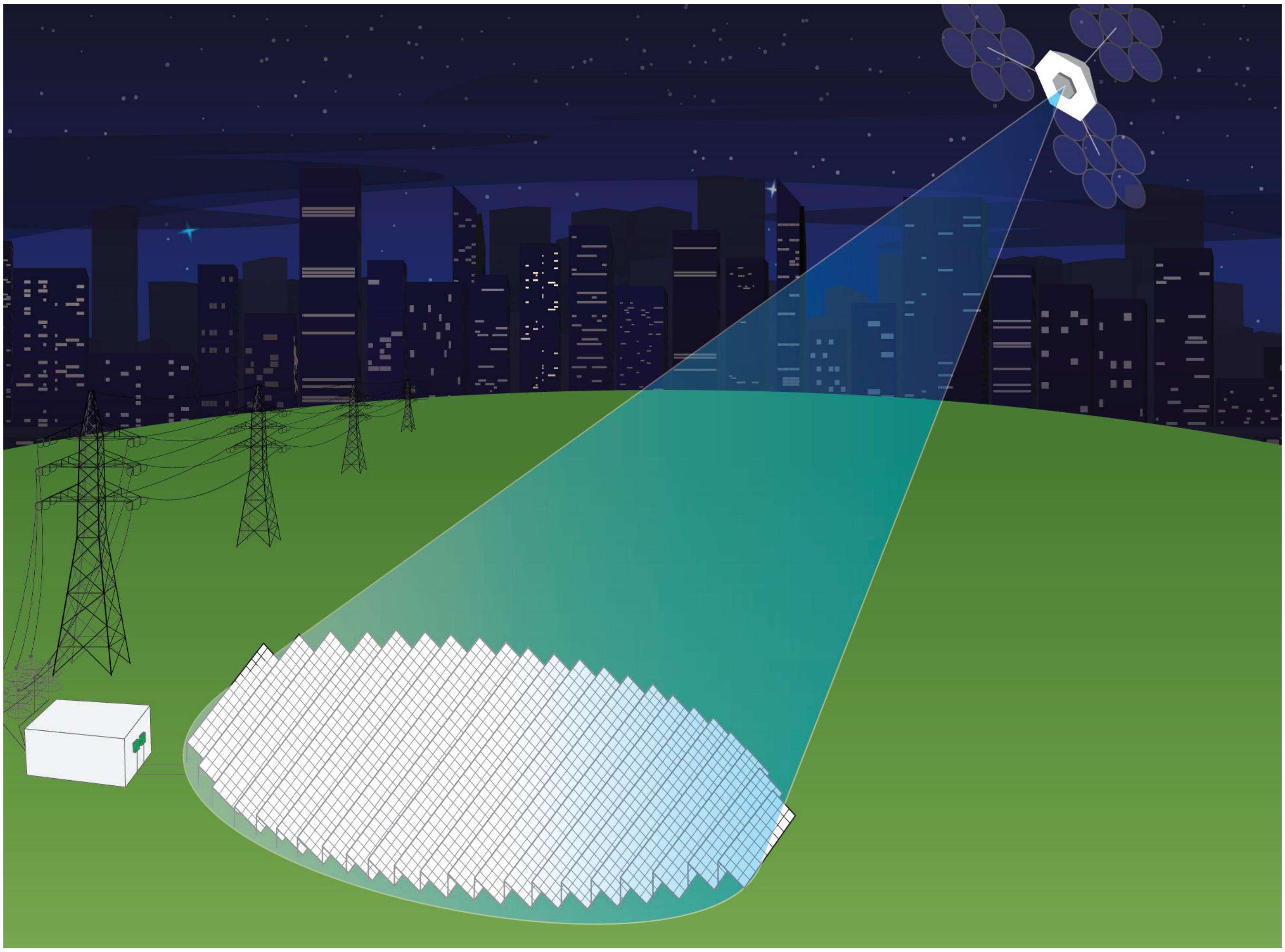


Figure 1: Artist's concept of a rectenna, a ground site that receives the microwave power transmission from a solar power satellite and converts it for a utility grid or other users.

Safety and Environmental Concerns. Power beaming systems will need to address safety and environmental concerns, both real and perceived. Although low-level microwaves are ever-present in modern society due to telecommunications infrastructure, high-power density microwave beams can cause serious harm to the environment, animals, people, and aviation operations. SPS operators will be responsible for complying with all safety, environmental, health, and interference protection practices, laws, and regulations. The standards organizations Institute of Electrical and Electronics Engineers (IEEE) and American National Standards Institute (ANSI) have established and approved exposure criteria and limits to protect against adverse health effects across various frequencies.[24] Ensuring that the power density is low enough (the maximum-allowable microwave power level has been set to 10 W/m^2 in most countries) to avoid any harm typically involves consideration of tradeoffs between the rectenna area size and power output. Perhaps someday, higher power density systems could be supported with appropriate safety regulations and protocols in place. However, for now, the IEEE and ANSI peak power density criteria provide a limiting factor on SPS and this is one reason why terrestrial rectenna sizes are rather large – often one or more kilometers in diameter.

Key Functional Components

Figure 2 provides an overview of the key functional components for SPS. Many SPS architectures have been proposed over the years. Most involve some combination of concentrators, solar cells, and either laser or microwave transmission.

Solar collection (Figure 2, left side) can be optimized with concentrators such as mirror assemblies. There is also considerable research in solar capture technologies:

- ***Flexible thin PV film.*** Optimized for low mass, low cost, and high production. Flexibility promotes deposition on lightweight inflatable structures needed for packaging large arrays in launch vehicles.
- ***High-efficiency, multi-junction PV.*** Significant improvements have been achieved over the years. Recently demonstrated efficiency of 39.2% under natural sunlight conditions.[25]
- ***Quantum dots.*** Although this new technology's power conversion efficiency is around 16.6% today, it could someday, theoretically, yield conversion efficiencies up to 66%, compared to 31% for today's high-efficiency solar cells.[26,27]
- ***Perovskite solar cells.*** These cells emerged in 2012 and have attracted considerable global R&D attention. Power conversion efficiencies have rapidly reached over 20%. Fabrication cost could be less than silicon PV cells. For the longer term, challenges remain regarding the material vulnerability to environmental stresses.[28]

Wireless power transmission (Figure 2, middle) involves either microwave or laser technologies. Laser power beaming has proven to be challenging because laser light can be blocked by cloud cover. Lasers are more suitable for space-to-space transmission where there are no concerns for atmospheric interference. By comparison, microwave transmission appears to be more practical for space-to-Earth applications because this type of directed energy is unimpeded by cloud cover in a wide frequency range. Microwave transmission involves:

- ***Convert and transmit.*** A microwave power generator using a transmit antenna beams microwave energy.
- ***Rectenna or rectifying antenna.*** (Figure 2, right side). The receiver station includes an antenna to capture the microwave beam and coverts RF energy to usable DC electrical energy.

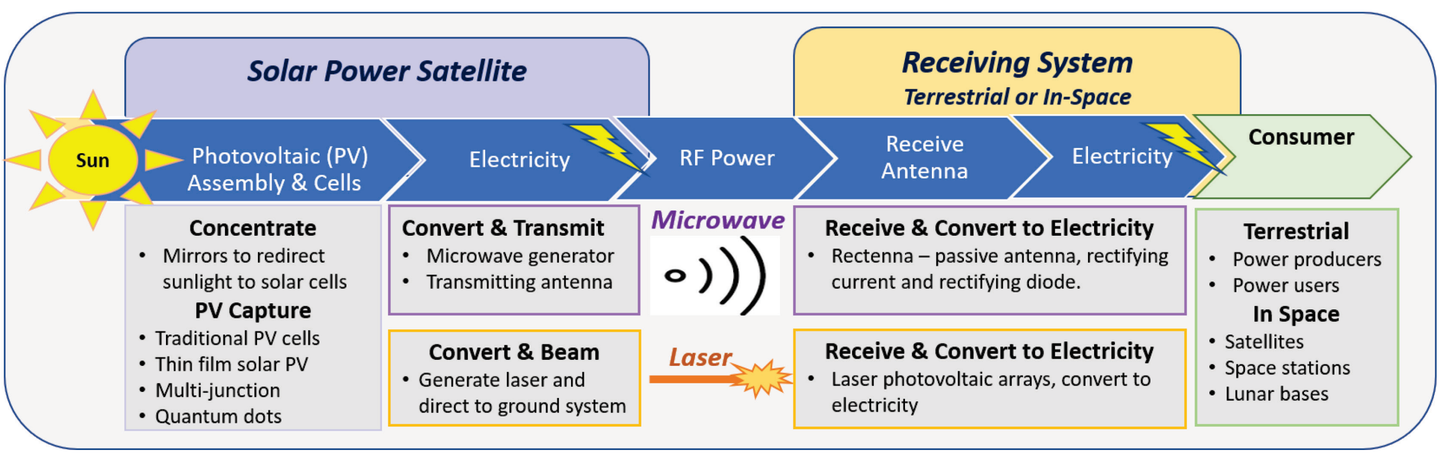


Figure 2: SPS functional components for microwave or laser transmission from GEO.

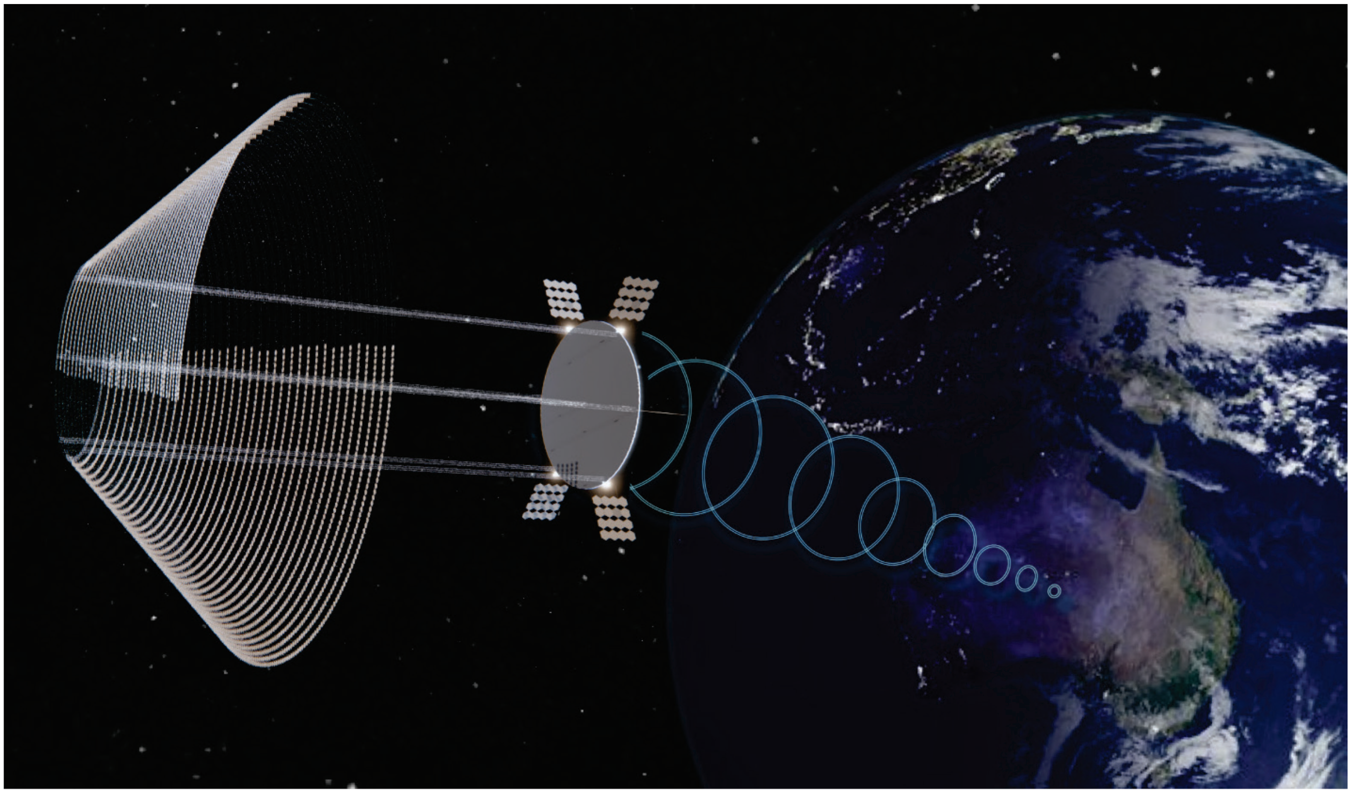


Figure 3: Highly modular SPS-ALPHA Mk-III space solar power system concept with light-weight structure and heliostat reflector array, transmitting power to Australia. *(Image courtesy of John C. Mankins)*

Various SPS architectures involve combinations of key functional components. All possible SPS designs must deal with the unique physical and economic challenges of the space environment. Within this unique trade space, new architectures are leveraging advances to address, for example: damaging high- and low-energy particle radiation on the PV cells; material mass efficiency requirements to ensure adequate mechanical support and launch mass restrictions; optimal PV cell efficiencies; and new materials such as carbon fiber composites. Additionally, thermal pathways to dissipate waste heat remain a challenge for PV cell design. However, there is ongoing research at the Department of Energy's (DOE) National Renewable Energy Laboratory and elsewhere to improve the efficiency of crystalline silicon solar cells which can reduce their temperature.

Spin-off Benefits. Advances in key functional components address a range of sectors— including terrestrial energy, defense, and mobile applications. Power beaming offers flexibility, allowing for a range of applications where the operator may want to "untether" a device from the power source. For instance, beaming microwaves or laser energy to unmanned aerial vehicles (UAVs) and other autonomous systems could increase operating time. Power beaming could also recharge Internet-of-Things devices, electric vehicle charging stations, auxiliary power for vehicles, and mobile communication terminals. Research related to power beaming could also be applied to the advancement of directed energy weapons for military applications.

Opportunity for Decisionmakers

The debate over SPS at times has included extreme positions. Proponents have portrayed it as the smartest, most comprehensive energy solution available, while detractors have seen it as an insanely expensive scheme that will never work. As is typically the case in such arguments, the reality lies somewhere in between – but no one knows exactly where because we have yet to invest sufficient resources to find out.

SPS will not be a quick, easy, or comprehensive solution. However, many other countries are moving in this direction, so the U.S. government must decide whether the nation should attempt to lead the pursuit of this potential game-changer, collaborate with others, or pass up this opportunity to focus instead on other energy solutions.

U.S. government forays into SPS investigations peaked in the late 1970s (the aforementioned NASA-Department of Energy study) and late 1990s (the NASA Fresh Look study).[29] In recent years, there has been growing interest in parts of the U.S. national security community.[30] Meanwhile, traditional barriers to SPS development— launch costs, the feasibility of robotic assembly and maintenance, and the need for high-volume production of modular components—have been overcome, or will be in the next few years if they continue on their current path.[31]

U.S. decisionmakers will have an opportunity during the next presidential term to establish the role of the United States in this potentially disruptive technology. If SPS can develop into a major component of orbital infrastructure, and someday contribute an additional source of renewable energy to users on Earth, the United States will want to be at the forefront of high-capacity power beaming in all its applications rather than become dependent on others for the technology and services they provide.

In addition to small-scale tests such as NRL's on-orbit power module experiment, many other space- and ground-based elements must be tested in realistic operational environments, including high-volume component manufacturing, affordable payload processing and launch options, on-orbit robotic assembly and maintenance, microwave beaming at high power levels across very long distances, and design and operation of ground receivers. A coordinated and sustained program leading to large-scale demonstration of a complete system is a logical follow-on to current experiments. In the meantime, the U.S. government could adopt a portfolio management approach to encourage:

- Completeness of vision surrounding current government programs
- Efficient resource management to avoid redundancies and to encourage judicious prioritization of critical projects
- Collaboration with international partners to leverage existing SPS competencies

An interagency working group with key interests represented could provide a well-defined strategy and rigorous assessment approach for the various projects.

Government and private sector investments in developing and deploying SPS likely would be spread over the next two to four decades, during which time cislunar activity is expected to grow dramatically while on Earth, trillions of dollars in new electricity-generating capacity will be required.[32] So far, in a half-century of study of the SPS concept, the U.S. government's on-again, off-again research funding has averaged only a couple of million dollars a year. A more coordinated and consistent investment may attract partners in the private sector, including some large enterprises not traditionally associated with space development (e.g., in the energy, transportation, and robotics industries). Decisionmakers must determine if there is a reasonable expectation of long-term societal benefits through government involvement beyond the current level of effort.

Acknowledgments

The authors would like to thank two leading space solar power researchers who provided helpful information and guidance: John Mankins, president of Mankins Space Technology Inc., and Dr. Paul Jaffe, researcher at the U.S. Naval Research Laboratory. We are also grateful for insight from Dr. Namrata Goswami, independent senior analyst, who shared her understanding of China's space solar research progress.

References

1 Conversation with Dr. Paul Jaffe, Naval Research Laboratory, July 17, 2020; Leonard David, "Military spaceplane experiment sheds light on space solar satellites," *Space News*, July 4, 2020 (https://spacenews.com/x-37b-experiment-sheds-light-on-space-solar-satellites/).

2 John C. Mankins, "New Developments in Space Solar Power," NSS Space Settlement Journal, December 2017 (https://space.nss.org/wp-content/uploads/NSS-JOURNAL-New-Developments-in-Space-Solar-Power.pdf); Ray Kwong, "China is Winning the Solar Space Race," ForeignPolicy.com, June 16, 2019 (https://foreignpolicy.com/2019/06/16/china-is-winning-the-solar-space-race/).

3 Keith Henson, "Space Based Solar Power – A Solution to the Carbon Crisis," Mafic Studios, Inc., April 2016 (https://www.youtube.com/watch?v=zrcoD_vHzxU).

4 United Launch Alliance, "ULA Innovation: CisLunar-1000," January 11, 2016, (https://www.youtube.com/watch?v=uxftPmpt7aA).

5 Government of Japan, Strategic Headquarters for Space Policy, "Basic Plan on Space Policy," various iterations, including June 2009, January 2013, January 2015, and June 2020 (https://www8.cao.go.jp/space/english/basicplan/2020/abstract_0701.pdf).

6 Conversation with Dr. Namrata Goswami, Independent Senior Analyst, July 23, 2020.

7 Dr. Namrata Goswami, testimony before the U.S.-China Economic and Security Review Commission, April 25, 2019 (https://www.uscc.gov/sites/default/files/Namrata%20Goswami%20USCC%2025%20April.pdf).

8 William J. Broad, "Soviet Studies Satellites to Convert Solar Energy for Relay to Earth," *New York Times*, Section 1, page 1, June 14, 1987.

9 James Burgess, "Russian Space Agency Looks to Build a Solar Power Plant in Space," *Oil Price*; March 7, 2013.

10 European Research Council, "Enhancing Global Clean Energy Services Using Orbiting Solar Reflectors," Fact Sheet (https://cordis.europa.eu/project/id/883730).

11 National Space Society, "Dr. Abdul Kalam – Space Solar Power, Key to a Livable Planet Earth," presentation at International Space Development Conference 2013 (http://space.nss.org/2013-isdc-video-dr-abdul-kalam-space-solar-power-key-to-a-livable-planet-earth/).

12 For an extensive collection of NASA and DOE reports on the "Satellite Power System Concept Development and Evaluation Program" of 1977-1981, see the National Space Society's online library (https://space.nss.org/satellite-power-system-concept-development-and-evaluation-program/). Also see: NASA, "Initial Technical, Environmental, and Economic Evaluation of Space Solar Power Concepts," Report No. JSC-11568, Vols. I and II, Aug. 31, 1976; and Office of Technology Assessment, "Solar Power Satellites," August 1981 (https://digital.library.unt.edu/ark:/67531/metadc39859/m2/1/high_res_d/8124.pdf).

13 U.S. Department of Energy, Energy Information Administration, "International Energy Outlook 2019," September 2019 (https://www.eia.gov/ieo).

14 Center for Naval Analysis, Military Advisory Board, "Powering America's Defense: Energy and the Risks to National Security," May 2009, p. 9 (https://www.cna.org/cna_files/pdf/MAB_2-FINAL.pdf).

15 Defense Science Board, Task Force on DOD Energy Strategy, "More Fight, Less Fuel," U.S. Department of Defense, February 2008, p. 30 (https://apps.dtic.mil/dtic/tr/fulltext/u2/a477619.pdf).

16 National Security Space Office (NSSO), "Space-Based Solar Power as an Opportunity for Strategic Security," U.S. Department of Defense, October 10, 2007 (https://space.nss.org/wp-content/uploads/Space-Based-Solar-Power-Opportunity-for-Strategic-Security-assessment.pdf).

17 Defense Science Board, 2008, p. 15.

18 Deloitte Development LLC, "Energy Security: America's Best Defense," 2009 (https://www.offiziere.ch/wp-content/uploads/us_ad_EnergySecurity052010.pdf).

19 James A. Vedda, *Choice, Not Fate: Shaping a Sustainable Future in the Space Age*, Xlibris Corp., 2009, Chapter 8 (https://www.amazon.com/Choice-Not-Fate-James-Vedda/dp/1450013481/).

20 For more on the challenge of powering desalination plants, see Selim Can Sazak & Lauren R. Sukin, "The Other Liquid Gold: Nuclear Power and Desalination in Saudi Arabia," *Foreign Affairs* Snapshot, November 10, 2015 (https://www.foreignaffairs.com/articles/saudi-arabia/2015-11-10/other-liquid-gold).

[21] John Mankins (ed.), *The First International Assessment of Space Solar Power: Opportunities, Issues, and Potential Pathways Forward*, International Academy of Astronautics (IAA), August 2011; (https://space.nss.org/wp-content/uploads/NSS-SSP-Space-Solar-Power-Background-Material-11-14-2011.pdf).

[22] Paul Jaffe, et al., "Opportunities and Challenges for Space Solar for Remote Installations," Naval Research Laboratory, NRL/MR/8243-19-9813, October 2019, Appendix D (https://www.researchgate.net/publication/337782857).

[23] Defense Advanced Research Projects Agency (DARPA) & Office of the Assistant Secretary of Defense for Research & Engineering (OASD(R&E)), "Department of Defense Power Beaming Roundtable," Executive Summary, August 2015.

[24] IEEE C95.1-1991, "IEEE Standard for Safety Levels with Respect to Human Exposure to Radio Frequency Electromagnetic Fields, 3 kHz to 300 GHz," approved November 18, 1992 by ANSI.

[25] Michael Irving, "Two New Solar Cells Break Records, including Highest Efficiency Ever," *New Atlas,* April 14, 2020.

[26] Robert F. Service, "Solar Energy – Can the Upstarts Top Silicon?" *Science*, February 8, 2008, pp. 718-20.

[27] Mark Hutchins, "A Quantum Solar Cell with 16.6% Efficiency," *PV Magazine*, February 2020.

[28] National Renewable Energy Laboratory, "NREL Research Boosts Stability of Perovskites, Helps Silicon Solar Cells," Department of Energy news release, March 5, 2020 (https://www.nrel.gov/news/press/2020/nrel-research-boosts-stability-of-perovskites-helps-silicon-solar-cells.html).

[29] John Mankins, "A Fresh Look at Space Solar Power: New Architectures, Concepts, and Technologies," IAF-97-R,2.03. October 1997 (https://space.nss.org/wp-content/uploads/1997-Mankins-Fresh1Look1At1Space1Solar1Power.pdf).

[30] NSSO, 2007; W. Neil Johnson, et al., "Space-based Solar Power: Possible Defense Applications and Opportunities for NRL Contributions," Naval Research Laboratory, NRL/FR/7650--09-10,179, October 23, 2009 (https://space.nss.org/wp-content/uploads/2008-NRL-SBSP-Possible-Defense-Applications-And-Opportunities.pdf); Air Force Research Laboratory "U.S. Air Force Research Laboratory Developing Space Solar Power Beaming," October 24, 2019 (https://afresearchlab.com/news/u-s-air-force-research-laboratory-developing-space-solar-power-beaming/).

[31] Conversation with John Mankins, Mankins Space Technology Inc., July 13, 2020.

[32] U.S. Department of Energy, 2019.

About the Authors

Dr. William H. Ailor is a Technical Fellow with the Center for Orbital and Reentry Debris Studies at The Aerospace Corporation in El Segundo, California. He has chaired 12 international conferences, including 8 on protecting Earth from asteroids, and served on the United Nations subcommittee that developed protocols for international cooperation in the event a threatening asteroid or comet is discovered. He testified to Congress and was featured on *NBC Nightly News*, *CBS Evening News, ABC News,* and CNN as an expert on the Leonid meteor storm's possible effects on satellites during the period of the storm. Ailor is also known for his expertise in space debris and reentry breakup and has appeared on CNN, the Discovery Channel, and the Learning Channel discussing these topics. He testified to the Columbia Accident Investigation Board on what might be learned from debris recovered after that event. He provided expert commentary during the reentry of the Upper Atmosphere Research Satellite (UARS) in 2011. He holds bachelor's and master's degrees from North Carolina State University and a Ph.D. in aerospace engineering from Purdue University.

Dr. Susan K. Avery is an atmospheric physicist and president emerita of the Woods Hole Oceanographic Institute, and a professor emeritus at the University of Colorado in Boulder. Avery's research interests include studies of atmospheric circulation and precipitation, climate variability and water resources, and the development of new radar techniques and instruments for remote sensing.

Layla Bryant is a Presidential Management Fellow at the Space and Missile Systems Center working on strategic communications for the Launch Enterprise Corp in support of the National Security Space Launch Program and Rocket Systems Launch Program. She was recently an intern at The Aerospace Corporation, where she supported the work of the Center for Space Policy and Strategy. Bryant has a bachelor's degree in astronomy and a master's degree in public policy, both from the University of Virginia.

Dr. Angie P. Bukley is an assistant principal director in the Human Exploration and Space Flight Division, Civil Systems Group, at The Aerospace Corporation. She has over 35 years of experience working in the space enterprise supporting both military and civil space programs. She has over 100 technical publications to her credit and nearly 30 awards for technical merit and service. She holds a Ph.D. in electrical engineering with a specialty in control theory from the University of Alabama in Huntsville.

Lina M. Cashin is a senior project engineer in The Aerospace Corporation's Defense Systems Group where she analyzes requirements for spaced-based capabilities and serves as a policy analyst for the Center for Space Policy and Strategy. She has more than 30 years of experience in national security, including 24 years in the Air Force as an expert in space operations and policy where she led a team to establish the U.S. space situational awareness data sharing program to ensure safety of spaceflight and pioneer international transparency for improved spaceflight operations.

Kara C. Cunzeman is the lead for strategic foresight for the Center for Space Policy and Strategy at The Aerospace Corporation. In her role, Cunzeman is focused on cultivating a formalized approach to futures thinking at Aerospace, helping the enterprise adequately prepare its organizations and capabilities to proactively shape the future through innovative approaches across strategy, acquisition, science, and technology portfolio management, policy, and operations. Prior to working at Aerospace, Cunzeman held roles in space systems engineering, vehicle operations, and space sensor development at Raytheon and General Atomics. Before that, she was at Packer Engineering, where her contributions were key to winning Phase II funding via a NASA Small Business Innovation Research (SBIR) award for extracting oxygen from lunar soil. Cunzeman received her bachelor's degree in multidisciplinary engineering and a master's degree in aeronautics and astronautics engineering from Purdue University. She is also a certified foresight practitioner and guest instructor at the Institute for the Future and the Center for Intelligence Studies.

Robin Dickey is a space policy and strategy analyst at The Aerospace Corporation's Center for Space Policy and Strategy, focusing on national security space. Her prior experience includes risk analysis, legislative affairs, and international development. She earned her bachelor's and master's degrees in international studies at Johns Hopkins University.

Dr. Michael P. Gleason is a national security senior project engineer at The Aerospace Corporation's Center for Space Policy and Strategy. Prior to joining Aerospace, he supported the Office of the Secretary of Defense Office of Net Assessment as a senior strategic space analyst. He served 29 years in the Air Force and is an accomplished national security space expert with experience in space policy, strategy, satellite operations, and international affairs. While in the Air Force, he served for five years at the Pentagon and two years at the Department of State. A graduate of the U.S. Air Force Academy, he holds a Ph.D. in international relations from George Washington University.

Peter L. Hays is a retired Air Force Lt Col who works as a defense contractor in the Pentagon supporting the assistant secretary of the Air Force for Space Acquisition and Integration. He has been directly involved in developing and implementing all major national security space policy and strategy initiatives since 2004. Professor Hays currently teaches graduate seminars on "Space and National Security" and "Science, Technology, and National Security Policy" at George Washington University, serves as the space chair at Marine Corps University (MCU), and teaches air- and spacepower seminars at the MCU School of Advanced Warfighting. He previously taught at the Air Force Academy, Air Force School of Advanced Airpower Studies, and National Defense University. Hays holds a Ph.D. from the Fletcher School and was an honor graduate of the Air Force Academy. Major publications include: *Handbook of Space Security*, *Space and Security*, and *Toward a Theory of Spacepower*.

Karen L. Jones is a senior project leader at The Aerospace Corporation's Center for Space Policy and Strategy. She has more than 30 years of experience as a management and technology strategy consultant across diverse industries, including federal government, information technology; telecommunications; wireless technologies; remote sensing; satellite industry, environmental technology and services, oil and gas, mining, and renewable energy. Prior to joining Aerospace, Jones was a management consultant with IBM Global Services and Arthur D. Little. She received a bachelor's degree in geology from Louisiana State University and a master's degree from the Yale School of Management.

Dr. Josef S. Koller is a senior systems director for The Aerospace Corporation's Center for Space Policy and Strategy, serving as an analyst and team leader on topics that cut across policy, technology, and economics. Prior to joining Aerospace, Koller served as a Senior Advisor to the Office of the Secretary of Defense for Space Policy, where he directly supported key national and international strategy efforts and provided technical advice and analysis on space-related U.S. government and DOD policy matters, including commercial remote sensing and space traffic management policy matters. Prior to that assignment, Koller managed and co-led over 40 scientists in the "Space Science and Applications Group" at Los Alamos National Laboratory. Koller also established and led the Los Alamos Space Weather Summer School to promote graduate student research. Koller has over 17 years of experience with global security and space physics programs. He has authored over 50 peer-reviewed scientific publications with 700+ citations. Koller has a Ph.D. in astrophysics from Rice University as well as master's degrees in physics and astronomy from the University of Innsbruck, Austria.

Dr. David B. Kunkee is currently a senior project leader in The Aerospace Corporation's Sensor Systems Subdivision within the Electronics and Sensors Division in the Engineering and Technology Group. He has provided his expertise on many microwave-based sensor payloads including the Defense Weather Satellite System, the Joint Polar Satellite System, and its predecessors. Dr. Kunkee is an officer in the IEEE Geoscience and Remote Sensing Society and has served on the National Academies' Committee on Radio Frequencies.

David G. Lubar is a spectrum management specialist and serves as senior project leader in The Aerospace Corporation's Civil Systems Technology Department within the Civil Systems Group. He has more than 34 years of experience with spectrum topics, with particular focus on meteorological satellites and space systems.

Jamie Morin is the executive director of the Center for Space Policy and Strategy at The Aerospace Corporation.

Ted J. Muelhaupt is the principal director of Aerospace's Center for Orbital and Reentry Debris Studies (CORDS). Applying more than 40 years of experience in analysis and operation of space systems, Muelhaupt provides corporate oversight for space debris analysis for Aerospace. In CORDS, Aerospace has one of the largest concentrations of space debris and collision avoidance experts in the world. Muelhaupt is also the principal director of the Southwest Regional Office at Aerospace, and is the deputy operations lead for National ETG. His technical specialties include orbit analysis, modeling and simulation, performance analysis, and software development. Muelhaupt has been a leading proponent of system visualization techniques and a leader or sponsor of major software tool developments. Throughout his career, he has also been a corporate leader in information technology issues, especially as they are applied to users. Muelhaupt holds a bachelor's degree in aerospace engineering and a master's degree in mechanics from the University of Minnesota. He is an Associate Fellow of the American Institute of Aeronautics and Astronautics.

Dr. George C. Nield is the president of Commercial Space Technologies, LLC. He served as the FAA associate administrator for Commercial Space Transportation from 2008 to 2018.

Dr. George E. Pollock IV is the associate director of the Astrodynamics Department at The Aerospace Corporation. He leads a team of analysts providing space domain awareness and advanced space mission analyses for the U.S. Space Force, Intelligence Community, and NASA customers. Pollock holds a bachelor's degree in aeronautical and astronautical engineering, a master's degree in aeronautics and astronautics, and a doctoral degree in aeronautical and astronautical engineering, all from Purdue University.

Geoffrey S. Reber is a senior project leader in The Aerospace Corporation's Space Development Division. He has spent 15 years working predominantly on rocket propulsion systems with a specialty in robust design methods and fluid flow analysis. He has also provided direct support to commercial, civil, intelligence, and defense space systems spanning from CubeSats to high value assets, mobile launch systems to human-rated vehicles, laboratory experiments to flight operations. Prior to joining Aerospace, Reber worked at The Boeing Company on proprietary projects and helped win a DARPA contract for the Orbital Express (an on-orbit servicing and logistics demonstrator). Reber holds bachelor's and master's degrees in aeronautics and astronautics from the Massachusetts Institute of Technology.

Dr. Rebecca Reesman is a project engineer in The Aerospace Corporation's Defense Systems Group, where she supports the headquarters' Air Force Studies, Analyses, and Assessment directorate, which provides analyses to major budgetary and policy decisionmaking. Before joining Aerospace in 2017, she was an American Institute of Physics Congressional Fellow, handling space, cybersecurity, and other technical issues for a member of Congress. Prior to the fellowship, she was a research scientist at the Center for Naval Analysis, providing technical and analytical support to the Department of Defense, with a focus on developing and executing wargames. Reesman received her Ph.D. in physics from The Ohio State University and a bachelor's degree from Carnegie Mellon University.

Luc H. Riesbeck is a recent graduate of the Space Policy Institute at George Washington University, researching space sustainability, orbital debris mitigation, and ethics in science and technology. A graduate of New York University Shanghai in 2018 with a bachelor's degree in social science with a minor in global China studies, Riesbeck recently served as a graduate intern at The Aerospace Corporation's Center for Space Policy and Strategy. They currently serve as a Space Policy Research Analyst at Astroscale U.S. In 2018, they were selected as a fellow in the Brooke Owens Fellowship's second annual class.

Russell Rumbaugh is a subject matter expert in The Aerospace Corporation's Center for Space Policy and Strategy. He has worked on defense policy, budgets, and acquisition for the Pentagon, Capitol Hill, and think tanks.

Marlon E. Sorge is a principal engineer for the Space Innovation Directorate of The Aerospace Corporation. He supports a wide variety of space debris and space situational awareness-related projects as well as strategic planning, conceptual design, technology development programs, and astrodynamics analysis. For more than 30 years, Sorge has conducted space debris research and analysis in a broad range of fields including debris risk assessment, fragmentation analysis, operations support, debris mitigation technique implementation, debris event reconstruction, satellite design for debris survivability, orbital and suborbital range and space safety, ballistic debris management, debris environment projection, collision avoidance, orbital reentry prediction, and national and international mitigation guideline and standards development. He developed the Aerospace fragmentation model and conducted some of the first work in realtime fragmentation event risk assessment. He organizes Aerospace's debris research program, is a DOD representative on the NASA delegation to the IADC, and is the U.S. lead for the ISO Orbital Debris Working Group. Sorge holds a bachelor's degree in physics and a master's degree in aeronautical and astronautical engineering from Purdue University.

Colleen Stover is a project manager in The Aerospace Corporation's Center for Space Policy and Strategy. Before joining the Center, she supported Aerospace efforts at The Missile Defense Agency for 10 years. Prior to joining Aerospace, she worked for The British Council in the international development field at various overseas posts. She has a bachelor's degree in interdisciplinary social science from San Francisco State University and a master's degree in comparative politics from The London School of Economics and Politics.

Dr. Roger C. Thompson a senior engineering specialist for The Aerospace Corporation's Mission Analysis and Operations Department. Thompson provides support for space situational awareness, collision avoidance, on-orbit breakup analysis and risk assessment, space debris issues, deorbit/reentry prediction, and orbital operations for many programs and space missions. He is one of the corporation's leading analysts in space traffic management and has represented Aerospace at high-level government and industry meetings where future space policy will be determined. Thompson has experience in uncertainty modeling, probability analysis, pointing and tracking systems, orbit and attitude dynamics, coverage analyses, optimal control systems, structural dynamics, and control of nonlinear systems. He also continues to support realtime launch and on-orbit collision risk assessment, orbit transfer and maneuver planning, orbital and trajectory modeling, and orbit determination. Thompson has a Ph.D. and a master's degree in engineering mechanics from Virginia Polytechnic Institute and State University as well as a bachelor's degree in engineering science and mechanics from North Carolina State University.

Steven R. Jordan Tomaszewski is a senior project leader at The Aerospace Corporation, performing oversight and policy guidance for the national security space enterprise. He also serves as an intelligence officer in the U.S. Air Force Reserve, supporting the 310th Operations Support Squadron. Jordan Tomaszewski holds a bachelor's degree in political science from the U.S. Air Force Academy and a master's degree in policy analysis from Indiana University

Robert M. Unverzagt is a principal director of The Aerospace Corporation with more than 30 years of experience in space launch, responsible for all corporate civil and commercial launch activity. He has developed and managed work for customers including NASA, the Federal Aviation Administration (FAA), commercial spaceports, and other commercial and international customers. He received a bachelor's degree in aerospace engineering from the University of Notre Dame and a master's degree in aerospace engineering from UCLA.

Dr. James A. Vedda is a senior policy analyst performing policy research and evaluation for various government agencies. He is the author of *Becoming Spacefarers: Rescuing America's Space Program and Choice*, *Not Fate: Shaping a Sustainable Future in the Space Age*. He holds a master's degree in science, technology, and public policy from George Washington University and a Ph.D. in political science from the University of Florida.

Tyler A. Way is a graduate research intern with The Aerospace Corporation's Center for Space Policy and Strategy. His research interests include policy and regulatory issues, the proliferation of space weapons, and space programs in developing countries. Prior to his time at Aerospace, Way interned with the Center for Strategic and International Studies' Aerospace Security Project, where he researched space threats as well as conducted research on the Nigerian space program. Way holds a bachelor's degree in international studies from Bowling Green State University and is pursuing a master's degree in international science and technology policy at The George Washington University.

Robert Samuel Wilson is a policy analyst at The Aerospace Corporation's Center for Space Policy and Strategy, where he is responsible for leading work on international space; nuclear command, control, and communications; and missile issues. Prior to joining Aerospace, he served as a senior analyst in the Defense Capabilities and Management division at the U.S. Government Accountability Office. There, he led reports on nuclear command, control, and communications; strategic force structure; arms control; and U.S. nuclear forces in Europe. Wilson received his bachelor's degree from the University of Virginia in political theory and his master's degree from the University of Virginia's Batten School in public policy.

About the Center for Space Policy and Strategy

The Center for Space Policy and Strategy is dedicated to shaping the future by providing nonpartisan research and strategic analysis to decisionmakers. The Center is part of The Aerospace Corporation, a nonprofit organization that advises the government on complex space enterprise and systems engineering problems.

The views expressed in this publication are solely those of the author(s), and do not necessarily reflect those of The Aerospace Corporation, its management, or its customers.

For more information, go to www.aerospace.org/policy or email policy@aero.org.

The Aerospace Corporation | 2310 East El Segundo Boulevard, El Segundo, California 90245-4609 USA | www.aerospace.org