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Key Points

The U.S. Space Force should proliferate, distribute, disaggregate, and diversify its SATCOM options by deploying non-GEO satellite constellations, particularly in LEO, as well as explore new delivery models for acquiring commercial SATCOM services.

The linchpin to realizing the full potential of these SATCOM constellations is to leverage space-based optical communications. The Space Force should therefore aggressively develop and deploy optical inter-satellite links as well as conduct rapid experimentation and demonstrate optical terminals on airborne and terrestrial systems.

To realize advancements in the space domain requires corresponding investment in the terrestrial infrastructure necessary to support it, including flexible terminals and enterprise management and control capabilities.

Building these capabilities in sufficient quantities will require the Space Force to incentivize cost reduction and manufacturability more in its contracting.

The Space Warfighting Analysis Center and other relevant acquisition organizations must be sufficiently funded to perform their detailed force structure analysis.

The Backbone of JADC2: Satellite Communications for Information Age Warfare

By General Kevin P. Chilton, USAF (Ret.)
Explorer Chair for Space Warfighting Studies, The Mitchell Institute Spacepower Advantage Center of Excellence

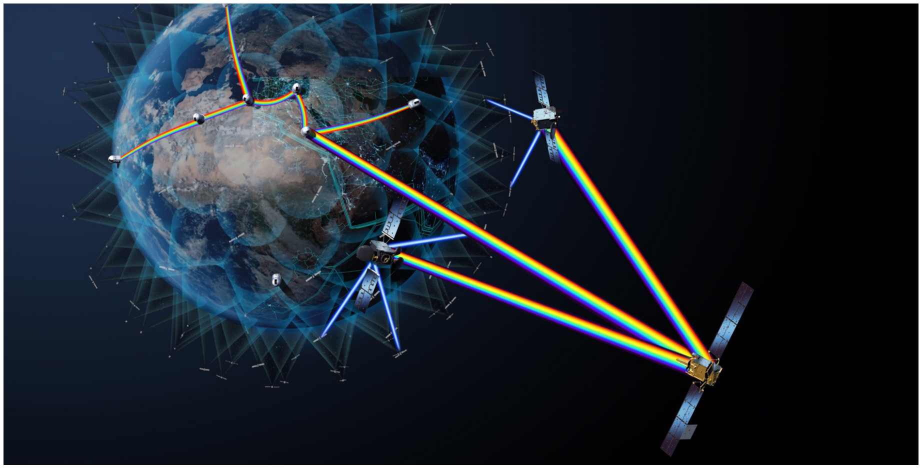
and Lukas Autenried
Senior Analyst, The Mitchell Institute Spacepower Advantage Center of Excellence

Abstract

Today, the Department of Defense's SATCOM enterprise is at a crossroads. Current systems and architectures are simply not designed for the speed, scale, and complexity that information age, all-domain operations demand, nor are they sufficiently resilient against modern counterspace threats. At the same time, consolidation of responsibility for SATCOM under the new Space Force presents a once-in-a-generation opportunity to chart a new path that ensures U.S. forces have the assured connectivity needed to defeat great power aggression.

Defending America's national security interests depends on the ability of its warfighters to collect, process, and share information to make better decisions faster than its adversaries. Achieving such decision superiority requires secure communications networks that can reliably facilitate the exchange of information to enable shared situational awareness, faster and better-informed command decisions, and the integration of forces distributed across the vast expanse of the Indo-Pacific and other theaters. By leveraging maturing technologies including laser communications and new space architecture designs, the Space Force could ensure the SATCOM enterprise serves as the backbone of DOD's networks and JADC2 initiatives to enable decisive all-domain operations.

Credit: ESA



Introduction

Defending America's national security interests depends on the ability of its warfighters to collect, process, and share information to make better decisions faster than their adversaries. Achieving such decision superiority in turn requires secure and reliable communications networks that can facilitate the exchange of information needed to enable shared situational awareness, faster and better-informed command decisions, and the integration of dispersed forces to meet mission objectives. For the U.S. military that must be ready to project power globally to remote, austere, and unpredictable locations, satellite communications (SATCOM) have provided the United States an asymmetric capability to extend its lines of communication to forces deployed in the field, enabling them to share information beyond their line-of-sight and synchronize their efforts on a global scale across all warfighting domains.

The standup of the U.S. Space Force and the consolidation of authority and responsibility for the SATCOM enterprise presents a once-in-a-generation opportunity to chart a new path forward to ensure U.S. forces can attain a decision advantage and retain operationally sufficient levels of assured connectivity.

Despite its past success and continued vital role, the Department of Defense's (DOD) SATCOM enterprise today finds itself at a crossroads. The current architecture is the product of choices and analyses predicated on now-outdated assumptions and operational concepts. Simply put, it has not remained apace of the growing threat posed by China and Russia to contest and degrade the United States' use of the space domain, nor is it designed for the speed, scale, and complexity that information age, all-domain operations demand. The causes of the current situation include onerous and costly acquisition processes, fragmented organizational authority and responsibility for SATCOM acquisitions and operations, and the tendency of services centered around other domains to shortchange space capabilities when balancing alternate priorities.

However, the standup of the U.S. Space Force and the consolidation of authority and responsibility for the SATCOM enterprise presents a once-in-a-generation opportunity to chart a new path forward to ensure U.S. forces can attain a decision advantage and retain operationally sufficient levels of assured connectivity. If U.S. forces are to achieve this, the Space Force cannot continue to simply procure incrementally better versions of the same kinds of exquisite space systems the U.S. military has relied on in the past. They are too few in number, unresponsive to new missions, and lag both the evolving threat environment and cutting-edge technologies. Assuming such legacy systems and outdated approaches will perform as effectively as they have in the past courts disaster at the very time these capabilities are needed most.[1]

Developing a more effective and resilient SATCOM enterprise demands that the Space Force take advantage of mature and emerging space technologies and novel system architectures that, to date, have largely been driven by the commercial sector. The U.S. space force could capitalize on these technologies to evolve each of the three segments that comprise the basic building blocks of the SATCOM system architecture: the orbital segment, consisting of the satellites in orbit equipped with communications payloads and other mission systems; the link segment, connecting the various nodes in the network together and transmitting data among them; and the terrestrial segment, encompassing all the equipment within the terrestrial domains necessary to launch, operate, and exploit the spacecraft—including the control stations, antennas, and user equipment such as satellite phones.

For the space segment, DOD should proliferate, distribute, disaggregate, diversify, and expand its SATCOM options by leveraging constellations of satellites in Low Earth Orbit (LEO) and Medium Earth Orbit (MEO) to augment its existing systems that primarily reside in Geosynchronous Earth Orbit (GEO). Proliferated satellites in multiple orbits would offer greater capacity and coverage, routing options with reduced latency, more optionality to meet mission-specific requirements, and improved resilience against counterspace attacks. In addition to developing and deploying its own satellites, DOD should improve its engagement with commercial providers to better exploit their capabilities and innovation, including exploring new delivery models for acquiring commercial SATCOM services.

While the pivot to proliferated constellations in lower orbits for SATCOM tends to garner more attention, the most critical technology for realizing their full potential resides in the link segment. Space-based optical communications—also known as laser communications—are key to forming the space mesh network. This will be critical to provide multiple, diversified connectivity paths to route information to, from, and through space at the speed, scale, and level of security needed to conduct all-domain operations. Laser communications will also be an important tool to negate the growing ability of adversaries to threaten U.S. communications networks. DOD should therefore aggressively develop and deploy optical inter-satellite links to connect its satellites together. It should also selectively integrate optical communications terminals for terrestrial and airborne systems that can send and receive data where it makes technical and operational sense.

Assured SATCOM is the connective tissue that empowers forces to share information and to command and control global, distributed operations in real-time. Without it, dispersed force elements can become isolated and dependent on limited range and resource-intensive line-of-sight communications with the overall effect of undermining the ability to converge integrated effects across multiple domains at speed and scale.

Fully realizing these advancements in the orbital and link segments requires a terrestrial segment capable of supporting it. This infrastructure requires the wider adoption of phased array antennas capable of handling the rapid and continuous satellite beam handovers inherent to the operation of LEO and MEO constellations. It also needs more flexible terminals that can seamlessly roam across different government, commercial, and international satellite networks that span multiple orbital regimes and operate over different frequency bands, waveforms, and security levels. Finally, for human operators to manage the speed and complexity of such operations, they will need cognitive enterprise management and control capabilities that can autonomously but transparently determine and select the best available network.

Together, these initiatives would enable the SATCOM enterprise to serve as the backbone that ties together all of DOD's various networks and service-led JADC2 initiatives to enable all-domain operations. Moreover, this modernized SATCOM enterprise would support mission success with higher probability, shorter periods of reduced capability, and across a wider range of scenarios and threats. Assured SATCOM is the connective tissue that empowers forces to share information and to command and control global, distributed operations in real-time. Without it, dispersed force elements can become isolated and dependent on limited range and resource-intensive line-of-sight communications with the overall effect of undermining the ability to converge integrated effects across multiple domains at speed and scale.

The Evolution of DOD's SATCOM Enterprise Since the Cold War

The term kill chain is a military concept that generally defines the process of attacking a target.[2] Overarching this kill chain is a decision loop that broadly consists of gaining an understanding of what is happening through available information, deciding what to do in alignment with commander's intent, and then taking action to achieve the desired effect. Historically, kill chains were contained within a single military unit, system, or even person because extended communication and coordination was not feasible. Over time, militaries have been able to leverage advances in information technology (IT) and associated changes to C2 processes to disaggregate the functional elements of the kill chain across a range of different systems spread over vast distances and domains into what are called battle networks to achieve significant military advantages.[3] The proper function of these battle networks and their ability to form and close kill chains depends first and foremost on assured communications. Otherwise, military forces must act in isolation without coordination or positive collaboration. As defense expert Christian Brose put it, "communications are the links in any military's kill chain."[4]

The value of integrating information from space assets across multiple weapon systems in an operational context was first demonstrated on a broad scale during Operation Desert Storm in 1991. Since then, the roles for DOD's communications satellites and other space assets within its battle networks has grown dramatically. Although the optimal communication links vary from mission to mission, the United States is a global military power whose forces operate at long ranges, over widely distributed areas, and in remote locations. These conditions tend to favor SATCOM, which "allows for the rapid dissemination of information on a global scale…to austere environments without terrestrial infrastructure."[5] In fact, SATCOM has been so effective and efficient in enabling the U.S. military to communicate, share data, and command and control forces that it has contributed to a concomitant reduction in alternate forms of relays for beyond-line-of-sight (BLOS) communications.

The effectiveness of SATCOM has also contributed to a sense of complacency wherein its continued availability could be taken for granted. Despite the crucial role space-enabled connectivity plays in the U.S. ability to project military power, most current SATCOM systems were driven by requirements and have designs that date back to the Cold War. At that time, space was generally viewed as a benign environment, efficiency and increased capability was prioritized ahead of resilience, and systems were designed to fulfill specific requirements with little consideration for the enterprise-wide architecture. However, this once benign and uncontested environment has changed. Given the growing importance of space-based connectivity to all commercial and government entities and rising threats posed to space capabilities, many U.S. legacy systems are not suited to the current strategic environment. General John Hyten captured this sentiment during his time as head of U.S. Strategic Command when he said, "I won't support the development any further of large, big, fat, juicy targets."[6] Although his is a poignant assessment of legacy U.S. satellite systems, reviewing the context within which these design decisions were made helps shed light on why they were reasonable at the time. This provides an important baseline to understand what has changed that both drives the need and offers the potential to develop a much more effective and resilient SATCOM enterprise for the future.

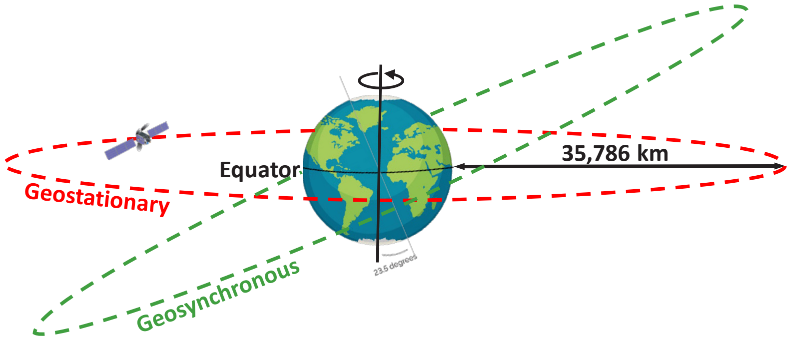


Figure 1: Geostationary orbits are a unique form of geosynchronous orbit around the equator looking at a fixed view of the planet.

Credit: Mitchell Institute

MILSATCOM satellites primarily reside in GEO

Most military comms satellites today reside in geostationary orbits, which are a unique form of geosynchronous orbit around the Earth's equator looking at a fixed view of the planet. In an uncontested space environment, placing communications satellites in geostationary orbit is extremely efficient and offers a high degree of flexibility, providing persistent access to information for military forces operating in widely dispersed and unpredictable locations.

The advantages of placing comms satellites in GEO were recognized since the initial conception of using an artificial satellite in space to broadcast and relay communications.[7] Satellites in higher orbits move slower than those in lower orbits, and they need to travel a greater distance to complete a full revolution around the Earth. Consequently, the time required for a satellite to orbit the Earth increases with altitude. At roughly 36,000 km above the Earth's surface, satellites can enter a geosynchronous orbit where they orbit at the same rate that the Earth rotates. This means that the satellite can be observed continuously from a single point on Earth, although it may appear to drift north and south depending on its inclination. A geostationary orbit is a special form of geosynchronous orbit that is circular in shape and is located directly above the Earth's equator, meaning it has an inclination of zero degrees. Because its orbital rate is synchronized with the rotation of the Earth and it moves along the same orbital plane, a satellite in geostationary orbit maintains the same fixed position relative to the Earth's surface. This enables a single satellite to provide continuous coverage of an area and precludes the need for users to have complex and oftentimes expensive satellite tracking equipment to send or receive signals. Placing satellites in GEO also simplifies the task of ground stations used to monitor and maintain them, which was a particularly important consideration prior to the advent of satellite crosslinks that enable a signal to hop from one satellite to another.

The other primary advantage of placing a communications satellite in GEO is the amount of coverage it can provide. Essentially, the higher a satellite's orbit, the larger the geographic area with which it can potentially communicate. This is because a satellite's line of sight to the Earth is limited by the horizon, which extends further out with increasing altitude. For example, the maximum observable area of a satellite in GEO is about 42 percent of the Earth's surface, whereas a satellite in a notional Low Earth Orbit (LEO) at an altitude of 1,000 km covers less than 7 percent of the Earth.[8] As a result, assuming sufficient transmit power and receiver sensitivity, three evenly distributed satellites in geostationary orbit can provide continuous worldwide communications coverage, excluding the polar regions and areas obscured by terrain features.

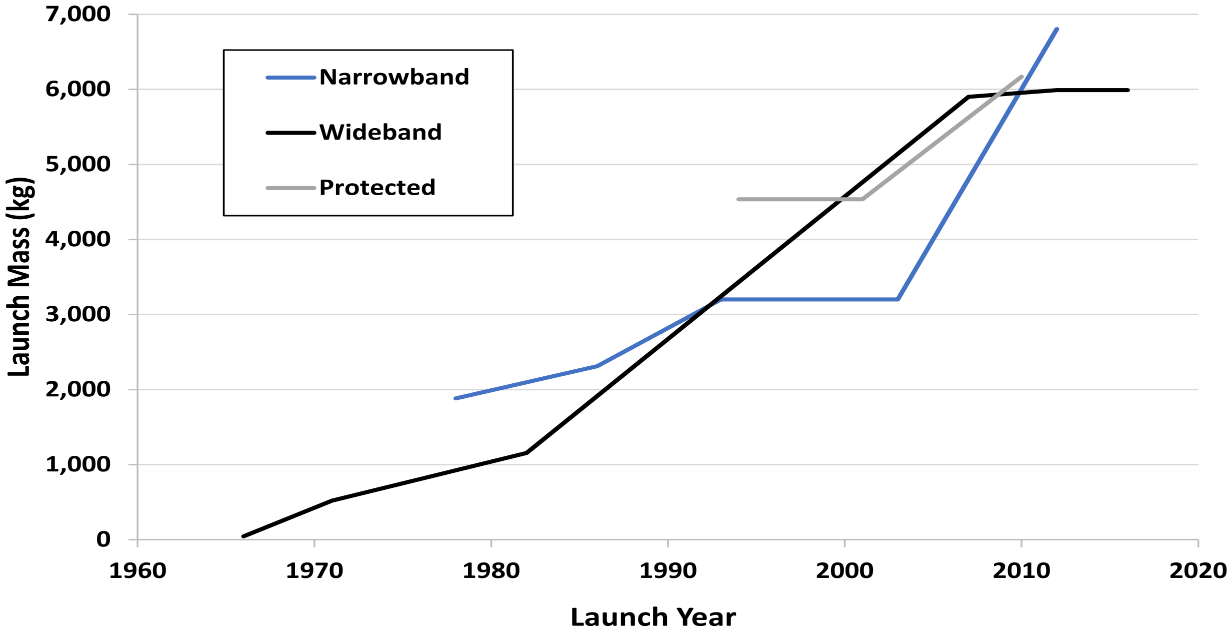


Figure 2: The size of MILSATCOM satellites has steadily grown over time.

Credit: Mitchell Institute

Satellite designs became increasingly large, complex, and expensive

Based on the assumption that the space environment would remain relatively benign and factoring the high cost of launch, DOD's communications satellites tended to increase in size, capability, and complexity over time. This, in turn also made them more costly and time-consuming to develop and build. As a result, core military satellite communications (MILSATCOM) today span just 36 satellites.[9] Reliance on such a small number of nodes creates a network where the loss of just a few platforms could result in critical failure of the system. This creates a vulnerability that adversaries with deep magazines of counterspace weapons could readily exploit in a conflict.

The approach of building large, multi-functional satellites is the product of requirements that prioritized maximizing satellite performance and longevity while achieving greater efficiency through aggregation of mission capabilities. For example, the Mobile User Objective System (MUOS) constellation of four satellites provides ten times the system capacity as the constellation of eight narrowband Ultra High Frequency Follow-On (UFO) satellites it was designed to replace.[10] However, the design and manufacturing of such exquisite systems is also complex and expensive, with the current generation of satellites consisting of the MUOS, Advanced Extremely High Frequency (AEHF), and Wideband Global SATCOM (WGS) constellations having an average acquisition cost that exceeds $1 billion per satellite.

That sort of expense constrains the quantity of systems DOD can afford to procure, which drives requirements to bundle as many capabilities as possible onto a single mission. For example, whereas the legacy Milstar constellation was designed exclusively to support nuclear command and control of strategic forces, its AEHF successor sought to additionally meet the growing demand of tactical users for highly reliable, secure communications. Such aggregation of capabilities layers on additional complexity, leading to even higher costs and longer production schedules. These dynamics tend to reinforce one another, resulting in a "vicious cycle of space acquisition" that yields large, highly integrated, and expensive space systems with ever longer production times and lower risk tolerance.[11] For SATCOM, the culmination of these dynamics was the Transformation Satellite Communications System program, which, prior to its termination, would have consolidated the wideband WGS and protected AEHF systems into a single architecture.

The other major driver for why communications satellites have grown larger and more aggregated is that launch options have traditionally been limited and the associated costs exorbitant. As General William Shelton, head of Air Force Space Command explained in 2012, "We cram everything we can on a single satellite. That's…driven largely by the cost of launch."[12] Launch cost constitutes a significant proportion of the total space segment cost and, critically, is not directly proportional to lift capability. On a cost-per-kilogram basis, medium and heavy launch vehicles are much more efficient than small launch vehicles, meaning that it is less expensive to launch a large satellite into orbit on a large launch vehicle than an equivalent amount of mass spread across several smaller satellites aboard multiple smaller launchers.[13] Furthermore, once a launch vehicle was selected, it made economic sense to maximize the system weight within the constraints of what the launch vehicle could support in order to optimize the return on investment.[14]

Military planners would typically avoid concentrating so much critical capability into such a limited number of platforms because it creates forces and networks that are overly brittle and reduces wartime effectiveness against a capable adversary. However, throughout the Cold War the risk of attack in space was thought to be minimal. Most national security space assets were focused on strategic conflict rather than conventional warfighting, so military actions in space might be interpreted as a prelude to nuclear war.[15] This view of satellites as primarily strategic assets largely held until the First Gulf War, in which space systems helped provide coalition forces with decisive operational and tactical advantages during combat operations.[16] In the succeeding years, the U.S. military has been engaged against adversaries that lacked the capability to attack its space systems, which perpetuated the perception of space as an operational sanctuary. As former Commander of the Space and Missile Systems Center General Ellen Pawlikowski pointed out, in those days "survivability wasn't even on the sheet."[17] Absent an imminent threat, ever greater technical capability was prioritized ahead of resilience short of nuclear war, resulting in increasingly large and complex systems.[18]

Military SATCOM comprise mainly closed, purpose-built, and often proprietary systems

Historically, numerous authorities spread across different combatant commands, services, DOD agencies, and acquisition organizations have been responsible for procuring and operating various SATCOM systems and services. These organizations have tended to focus on addressing their own specific needs with relatively little consideration for enterprise-level requirements. As a result, the current SATCOM enterprise consists of highly customized capabilities with limited interoperability and operational flexibility. Their integration is further hampered by vendor proprietary equities and the over-classification of both program information and mission data within the space realm.

MILSATCOM capabilities are broadly categorized into three types: wideband, narrowband, and protected. Rather than being developed according to a unified enterprise strategy, these systems evolved over time as a byproduct of advances in technology and to

Types of MILSATCOM

Wideband: Provides tactical and enterprise users high data rate communications for data and video. Generally operating in the super high frequency (SHF) bands, wideband communications are designed to provide connectivity to large, fixed terminals. Smaller terminals have been produced, but they are more expensive and not practical for highly mobile communications needs.

Narrowband: Designed for mobile, tactical end users, narrowband systems generally operate in the ultra high frequency (UHF) band. Compared to wideband SATCOM, the relatively lower frequency UHF bands have better penetration into buildings and through foliage, and they suffer less signal attenuation in adverse weather conditions such as rain, clouds, or fog. The relatively broad beamwidths of UHF terminal antennas are more practical for SATCOM on the move because they do not require precise pointing. UHF terminals are also relatively inexpensive, small, and lightweight, which is preferable for ground forces that account for most of its users. Due to its limited bandwidth, primary applications are voice and low-rate data transfer.

Protected: Provides assured, survivable communications to support nuclear command and control (C2) of strategic forces. Operating in the extremely high frequency (EHF) bands—the frequency range above SHF—protected SATCOM uses a variety of techniques to provide robust communications that can get at least limited messages through virtually any form of interference. These systems have also been designed to provide a low probability of detection/low probability of intercept (LPD/LPI) capability. Although protected SATCOM is increasingly available to tactical users requiring secure and reliable communications, a considerable portion of bandwidth access is withheld for strategic missions.

meet unique user requirements. For example, whereas the Air Force was the lead service for providing wideband and protected SATCOM, the Navy traditionally had oversight of narrowband space systems, and the Defense Information Systems Agency (DISA) managed the procurement of commercial satellite services to meet growing requirements for additional SATCOM capacity.

In terms of ground control terminals, DOD tends to deploy proprietary, standalone systems that are designed to operate a single satellite system instead of being able to operate multiple types. As a result, they generally only receive and process data from their own associated satellites, do not share their data with other ground systems, and are not capable of fusing data from multiple space systems to create a common operating picture.[19] Although this approach lowers acquisition risks and offers greater customization within a particular program, it results in a more disjointed and duplicative enterprise requiring more overall infrastructure and personnel to operate.[20]

The situation with user terminals is even more fragmented. For starters, each service is responsible for procuring its own terminals. Additionally, combatant commands have often bypassed the centralized DISA acquisition process to procure their own commercial SATCOM services to support ongoing military operations—leading to a lack of oversight and coordination. As a result, many terminals tend to be purpose-built to address the requirements of a specific satellite system, mission, or capability, which can drive widely different design solutions. For example, even within a given type of SATCOM there are tradeoffs among different waveforms, frequencies, and signal protection requirements. For wideband communications, the lower C-band frequencies are more robust in adverse weather, Ku-band frequencies are better optimized for mobiles users and can communicate with smaller antennas, and the Ka-band offers better data rates. Additionally, developing terminals for the military's broad range of platforms poses unique and varied integration challenges that levy stringent and often radically different host platform requirements in terms of size, weight, and power (SWaP), antenna profile, environmental operating conditions, and so on. As a result, across DOD there are 17,000 wideband terminals using approximately 135 unique designs.[21] Furthermore, current SATCOM infrastructure and processes were not designed to allow terminals to automatically roam between different services or networks when encountering threats or disruptions. Instead, the ability to access and use different networks requires multiple sets of equipment and involves bureaucratic and manual processes that can take days or weeks to complete. As the Space Force's Vision for Satellite Communications paper points out, "The practice of multiple authorities buying multiple SATCOM products and services led to stove-piped SATCOM systems, vertically integrated within each system, but with virtually no ability for users to receive simultaneous operational benefits from multiple systems."[22]

The fragmented SATCOM budgeting authority and acquisition process also creates enterprise management issues wherein funding, delivery, and deployment of satellites and their associated ground control systems and user terminals are not well synchronized. Whereas the satellite program office is responsible for delivering the satellites and the ground control segments, the user equipment is the responsibility of the individual military services and combatant commands. Launch adds a layer of complexity since the acquisition of launch services is handled by yet another separate program office. When delivery of these various segments is not properly aligned due to a myriad of potential reasons, the result is underutilized satellites and limited capability provided to the warfighter.[23] In these circumstances, the system bureaucracy becomes the focal point, not optimized end effects.

The over-classification of both program and intelligence space information further exacerbates the siloed nature of space. Multilayered security compartmentation in the space domain not only results in unnecessary duplication of space acquisition programs, but also impedes the integration of space capabilities into the plans and exercises of combatant commanders.[24] Furthermore, because SATCOM networks are built as closed systems—in part to help keep them more secure—joint force users are unable to exchange data with one another and are slowed in gaining approved system access, severely hampering tactical decision-making.[25] As the Commander of NORAD and USNORTHCOM General Glen VanHerck recently pointed out, "The biggest challenge with [using] space layer data right now is over-classification and sharing of information…we can't live with that data and information in stovepipes, it must be shared to take action on, in real time or near real time, for decision making or actual execution of deterrence or defense options."[26]

To help break down these stovepipes and provide a more coherent vision and approach, most of the SATCOM enterprise has now been consolidated within the U.S. Space Force (USSF). In 2018, DOD first handed commercial satellite procurement from DISA to the former Air Force Space Command, which was then reorganized into the USSF. The Navy handed oversight of narrowband satellite communications, for which it had been the executive agent, to the Air Force in May of 2019, and the Air Force subsequently transferred it to the USSF. In 2021, the Navy announced its plans to hand over operations of its remaining 13 satellites to the Space Force. Putting a single, coordinated entity in charge is a common-sense approach that must guide the future of this mission area. Integration cannot occur when unnecessary stovepipes exist.

The Imperative for a New Approach to

Satellite Communications

The military strategies and doctrine of the United States, China, and Russia all emphasize the growing importance of the information environment. All share the common theme that the side that can collect, process, share, and protect its information to make better decisions faster than their adversary will enjoy potentially decisive warfighting advantages.[27] Indeed, the ability to communicate and exchange information is fundamental to military success, enabling shared situational awareness, faster and more informed command decisions, and the integration of dispersed forces to meet mission objectives.

The U.S. military relies on satellite communications to support the bulk of its over-the-horizon communications, but its current systems are poorly aligned to meet the requirements of its emerging operational concepts and are increasingly vulnerable to adversary counterspace capabilities. Modern military operations are increasingly data intensive and dispersed, requiring secure networks to reliably share large amounts of data with minimal latency over vast distances, across different domains, to large numbers of users. DOD's communications systems must also be able to continue to operate and support missions despite adversary efforts to degrade or deny them. U.S. adversaries have taken note of the degree to which U.S. military operations depend on its space-based capabilities to achieve an information advantage. In response, they have been evolving their doctrine, organizations, and capabilities to deny the United States use of the space domain. The United States has been slow to adapt to these evolving threats. Post-Cold War complacency, paired with a myopic focus on low intensity operations in Iraq and Afghanistan, have exacerbated these trends. Changes that should have occurred in a concreted fashion over the past three decades must now happen on an accelerated timeframe.

New Operational Concepts

There is growing acknowledgement that the comparative U.S. military advantage has eroded significantly since the end of the Cold War. China and Russia have undertaken a massive buildup of their respective militaries and are developing new capabilities and approaches to negate America's traditional warfighting strengths. The U.S. military is highly unlikely to regain its competitive advantage through like-for-like replacements of its legacy platforms with incremental improvements while remaining beholden to industrial age notions of warfare focused on individual weapons systems and inflicting attrition.

Instead, DOD is in the process of developing warfighting concepts that require new capabilities and different force designs. These will depend foremost on the ability to rapidly obtain, process, and communicate information across forces conducting highly dispersed, all-domain operations in the Indo-Pacific and other theaters. By rapidly and seamlessly exchanging information, commanders can make faster decisions and better integrate the actions of available forces. The aim is to achieve both physical and psychological advantages by enabling friendly forces to operate inside an adversary's decision-making cycle and impose multiple, simultaneous dilemmas that confound and potentially paralyze the enemy's ability to effectively respond.[28]

Realizing this future vision requires changes to legacy command, control, and communications (C3) systems and processes that were not designed for the speed and complexity that information age all-domain operations demand. Overcoming these constraints will require not just material changes involving technology, but also

Figure 3: Next-generation secure satellite communications will be the linchpin of JADC2.

Credit: Image courtesy of Raytheon

a shift in how the role of networks and information systems are perceived relative to weapons and platforms. Recognizing this, DOD's Joint All Domain Command and Control (JADC2) strategy is intended to guide these changes.

JADC2 is a new approach to military decision-making that leverages emerging technologies such as artificial intelligence, cloud computing, and edge processing to automate and otherwise facilitate access to, analysis of, and sharing of data among commanders and forces in the field in near real-time and across domains.[29] The goal is to achieve and maintain an operational and informational advantage through greater adaptability and speed of decision-making. By enabling the sharing of data across domains, services, and coalition partners, commanders will have a better understanding of the battlespace and more options to deliver synchronized combat effects at speed and scale to accomplish their objectives.

Space-based communications are central to DOD's plans for JADC2; they are intended to serve as the backbone that ties all of DOD's networks together and integrate the various service-led JADC2 initiatives.[30] A core tenet of JADC2 is that any sensor can be dynamically connected to the best available shooter in service-, domain-, and path-agnostic ways to rapidly close kill chains at scale. As an example of teaming disaggregated mission assets to achieve an effect, a satellite in space could provide imagery to an aircraft over a target of interest, who in turn cues a missile launched by a ship at sea, all of which is made possible by space-based connectivity. Although there are a multitude of shorter-range terrestrial communications links that can pass targeting data, U.S. forces must operate at increased ranges and in a more distributed manner, as envisioned by DOD's emerging warfighting concepts. This inevitably makes passing information through space necessary. As General David Thompson, Vice Chief of Space Operations of the Space Force

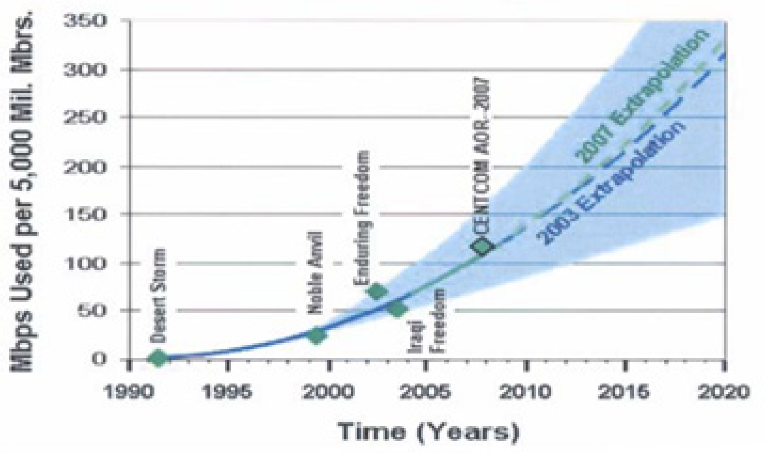


Figure 4: Trends in SATCOM usage (actual and projected).

Credit: Patrick Rayermann

explained, "Data relay, comms through space is what will enable JADC2."[31] While concepts such as JADC2 could provide significant warfighting advantages, they also impose novel communications demands that the current SATCOM enterprise is not optimized to support. Specifically, increasing bandwidth, providing options with reduced latency, and improving interoperability across networks will be critical to meeting DOD's future requirements.

Bandwidth. Available bandwidth poses a persistent challenge for military planners as growing demand for satellite communications consistently exceeds the capacity of available military systems both in terms of aggregate data rate and number of end users. As former Director of DISA Lt Gen Alan Lynn explained, "The requirement just keeps growing. Every day we have more throughput requirements."[32] This reflects a broader trend of increasingly data-intensive military operations since the First Gulf War. To bridge the growing gap in SATCOM capacity between what military systems can provide and the needs of its forces, DOD has increasingly relied on leasing commercial SATCOM services from companies such as Inmarsat, Viasat, Iridium, and Intelsat.

Several factors are driving this increasing demand for bandwidth. Improvements in sensor quality; the use of more data-intensive forms of intelligence, surveillance, and reconnaissance (ISR); and the proliferation of cheap and ubiquitous sensors among both government and commercial entities has led to an exponential growth in the amount of data being collected and available to be pushed to decision-makers and other consumers of data. As DOD's 2020 Data Strategy points out, "Weapons platforms, connected devices, sensors, training facilities, test ranges, and business systems generate enormous volumes of data."[33] The increasing emphasis the services and DOD's emerging warfighting concepts place on unmanned systems capable of persistent wide-area surveillance has been a particularly strong contributor to this trend.

In terms of the demand from forces looking to pull data, as the USSF's Spacepower capstone document highlights, "One key distinction of warfare in the Information Age is that many weapon systems rely on external sources of information to function."[34] A key tenet of DOD's Joint Warfighting Concept and other service operational concepts is the need to distribute and disaggregate forces to make them less vulnerable to attack. As a related goal, emerging DOD all-domain warfighting concepts seek to empower more responsive, creative force compositions that can achieve the virtue of mass through virtual aggregation. To integrate and coordinate their operations across domains and over great distances requires forces to remain connected, at least intermittently, to their tactical edge networks and the broader DOD Information Network, largely using SATCOM. Consequently, user terminals are being deployed not just to command centers, but increasingly at lower echelons to provide forces access to critical information. In addition to growing numbers of users, forces are increasingly using applications and techniques requiring higher data rates, such as high-definition imagery and video, remote piloting of unmanned systems, cloud storage, and artificial intelligence.[35]

Beyond the cumulative volume of SATCOM capacity required, another important consideration is how demand is distributed. During previous operations, large numbers of U.S. forces tended to be concentrated within relatively small geographic areas. For these sorts of contingencies of the past, communications satellites in GEO were well suited for massing frequency to where it was needed within their broad coverage footprints, providing a large amount of capacity and channels. Furthermore, when additional capacity was needed, multiple satellites in GEO could be maneuvered to access the same area, as occurred during the First Gulf War when a third Defense Satellite Communications System (DSCS) satellite was repositioned from its orbit over the Pacific to augment the two other DSCS satellites already supporting U.S. forces in Iraq.[36] Satellites in a LEO constellation cannot mass a comparable amount of capacity within a given area because, on a per-satellite basis, they tend to be smaller with fewer channels and can handle less throughput. Furthermore, their constant motion relative to the Earth means they can only remain overhead at any given location for a few minutes.

Although similar situations where capacity needs to be massed over certain areas in the future are plausible, including for contingencies such as humanitarian assistance and disaster response (HA/DR), DOD operational concepts increasingly emphasize distribution and mobility for its forces to be survivable against modern threats. Against more capable adversaries, massing frequency creates a larger electromagnetic spectrum (EMS) footprint that can make forces more susceptible to detection and targeting.[37] This has resulted in a growing demand for better signature management and SATCOM on-the-move to provide mobile communications in adverse conditions and with low-power terminals. With the distances involved for satellites in GEO, it is relatively difficult to provide high bandwidth to the smaller antennas and form factors required for these types of platforms.

Latency. A common issue with current SATCOM systems is the latency introduced by having to transmit the signal up to GEO and then back down to its intended recipient. For a satellite in GEO, the round-trip transmission time is, at best, roughly a quarter of a second. Other forms of delay can further exacerbate these latency issues, such as routing data via SATCOM out of theater for processing before sending it back to a tactical user. The latency for routing a signal halfway across the world is typically between one and two seconds. Although this may not appear significant, a delay of even split seconds can be prohibitive for an increasing number of military applications and processes that operate at machine speeds, including some forms of time-sensitive targeting, advanced heads-up displays, and autonomous or remotely piloted systems.[38]

Some steps can be taken to either reduce latency, such as forward-positioning data within a region, or else mitigate its impact, using techniques such as buffering and data compression to create the perception of real-time transmission for applications such as video conferencing. However, it is not possible to overcome the physics limitation of the speed at which light travels. Therefore, for applications and decisions that need to be based on data that reflects the real-time reality, the only way to reduce the latency associated with SATCOM is to shrink the physical distance that the transmission needs to travel, which requires leveraging orbits other than GEO. Although not all communications require such low latency, for many applications—such as intercepting an incoming missile or coordinating dynamic, disaggregated elements of a mission package—split seconds can be the difference between mission success or failure.

Interoperability. Equally important to JADC2 as increased bandwidth and lower latency is the need for greater information and network interoperability to enable disparate systems to interact with one another effectively. Improving joint, interagency, and coalition interoperability has been a longstanding issue for DOD, which operates many different communications systems and over 60 different waveforms that often support incompatible data communications protocols.[39] This broader challenge is reflected in DOD's SATCOM enterprise. Unlike modern cell phones, which can seamlessly jump between different cell towers and wireless networks to connect users regardless of their location, device, or service provider, SATCOM systems today lack a similar level of flexibility. Instead, they consist of proprietary, stove-piped systems developed for specific use cases that don't allow users to roam freely from one network to another and are unable to share or fuse data across multiple different systems.

The good news is that the commercial SATCOM industry is expanding and maturing to the point where the lack of interoperable, open standards is an acknowledged problem that multiple professional organizations are now attempting to address.[40] Although increased employment of such open standards will promote greater interoperability, inherent differences in mission requirements, the risks associated with upgrading vast quantities of legacy systems in situ while the military is still operating, and the number of organizations involved suggests that efforts within DOD to drive commonality across standards, networks, and waveforms are unlikely to ever fully succeed.[41] Therefore, a more promising approach for the U.S. military would be to supplement efforts to develop open standards with its own ad-hoc interoperability efforts.

Growing Threats to Space Systems

In addition to the growing demands placed on its SATCOM enterprise to support its own evolving operational concepts, DOD now faces the threat of attacks on its SATCOM networks and other space assets, with China and Russia posing the most immediate and serious threats. Cognizant of the enormous warfighting advantages that use of the space domain has provided the United States over the past 30 years, both China and Russia have assessed that the U.S. military's dependence on its mostly undefended space capabilities presents vulnerabilities that they can exploit. Furthermore, if irreversibly damaged, satellites currently cannot be replaced within a tactically relevant timeframe, thereby creating windows of opportunity that adversaries can capitalize on to achieve their objectives. Consequently, China and Russia have developed their doctrine, organizations, and capabilities to contest or deny U.S. access to and operations in space while simultaneously defending their own expanding use of the space domain to achieve their military goals.

The growing emphasis on space in both Chinese and Russian military doctrine dovetails with their views on the central role of information in modern warfare. Both militaries prioritize achieving information superiority as their main line of effort in future conflicts, believing it provides potentially decisive warfighting advantages.[42] Fundamentally, information superiority involves preserving one's own access to and use of battlespace information and denying it to the adversary. An essential means of attaining information superiority is through military space operations since space-based capabilities are both a major source and conduit of information. Consequently, both the People's Liberation Army (PLA) and the Russian Armed Forces regard U.S. information flows to, from, and within space as high priority targets against which they are developing and deploying multiple attack options. As a main line of effort of their information-centric strategies, both China and Russia seek to degrade, deny, and corrupt the flow of information by targeting every aspect of the U.S. space architecture, to include the orbital, link, and terrestrial segments, as well as the data it generates and transports.

People's Republic of China. PLA doctrine characterizes the current form of war as "informationized warfare."[43] According to their thinking, the information age has evolved the character of war to where information power—the ability to achieve and sustain information superiority—is now the dominant element of military power.[44] The PLA views contemporary warfare as a contest between competing systems-of-systems in a non-linear manner across the land, sea, air, space, cyber, electromagnetic, and psychological domains. This contest is driven by the incorporation of information technology across virtually all military forces and the subsequent networking of those forces.[45] According to the PLA, prevailing in this systems confrontation requires waging system destruction warfare, which seeks to paralyze or destroy the critical functions of the adversary's operational system.[46] In practice, this is achieved through offensive operations that emphasize seizing and maintaining the initiative in "system-vs-system operations featuring information dominance, precision strikes, and joint operations."[47]

The PLA also believes that seizing the initiative in outer space and gaining space superiority are essential to achieving information superiority and a prerequisite for

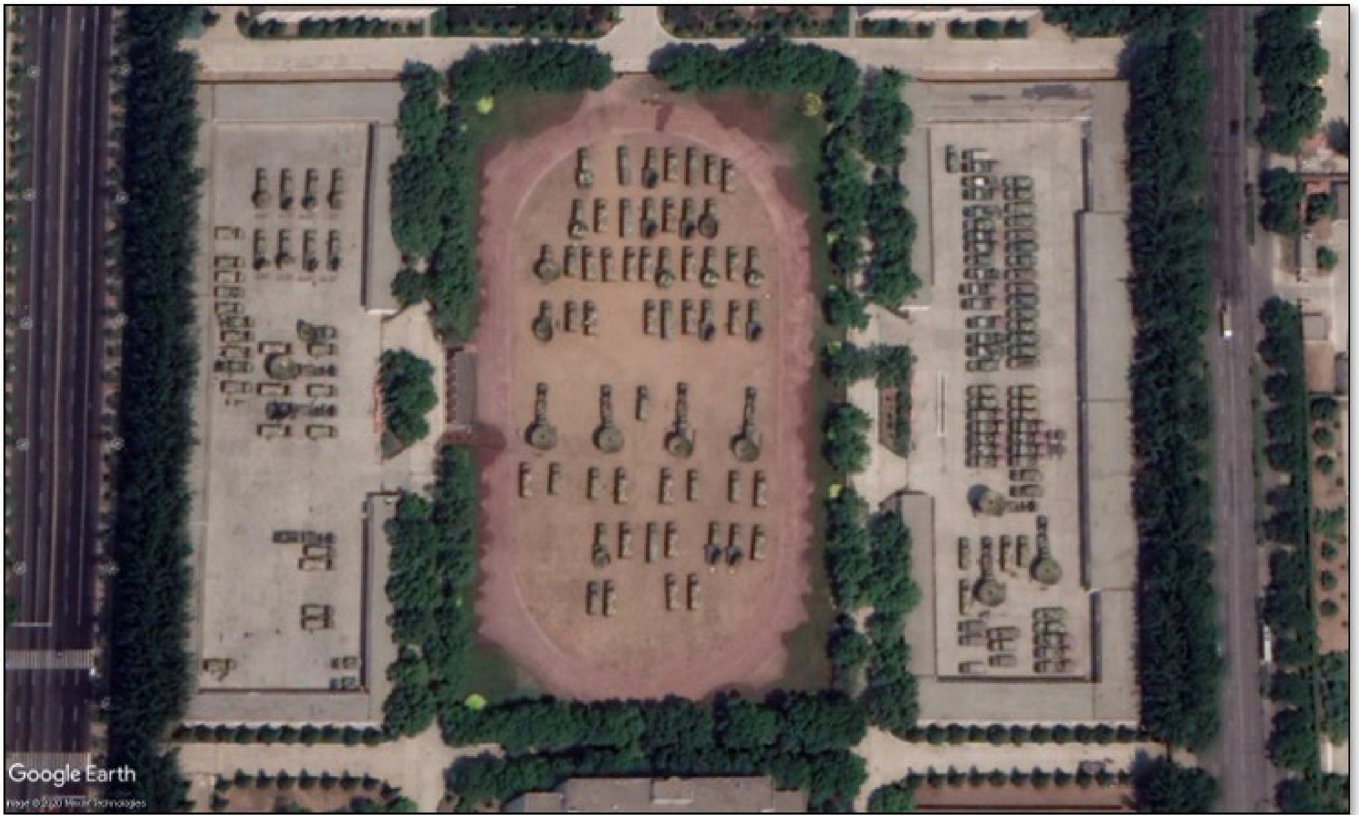


Figure 5: PLA electronic countermeasures (ECM) garrison in Langfang, China, likely including mobile SATCOM jammers (May 2017).

Credit: Source: Google Earth Pro 7.3.4.8248, May 16, 2017, Langfang, China, 39.570N 116.755E, Maxar Technologies 2020 success in other domains.[48] Space superiority—the ability to use one's own space-based systems while denying it to one's adversary—is critical because the PLA views space-based assets as one of the primary sources and conduits of battlespace information. Not only is the PLA itself increasingly reliant on space-based remote sensing; precise positioning, navigation, and timing (PNT) data; and BLOS communications as it seeks to operate further afield from its own territory, but it also views the United States as critically dependent on space information. For example, one Chinese military analysis assessed that the United States relies on space for 100 percent of its navigation needs, 80–90 percent of its communication needs, and 70–90 percent of its intelligence needs.[49] Recognition of the imperative to preserve their own access to and use of space information while denying it to their adversaries is why PLA strategists anticipate that future wars will likely begin in space and cyberspace, arguing that "seizing command of space and network dominance will become crucial for obtaining comprehensive superiority on the battlefield and conquering an enemy."[50]

Improving its ability to conduct space operations was a key objective of the PLA's military reforms initiated in 2015. Acknowledging space as having "become a commanding height in international strategic competition," China's 2015 Defense White Paper officially designated space as a warfighting domain for the first time.[51] This was followed by the formation of the PLA Strategic Support Force (SSF), which is intended to centralize and better integrate the space, cyber, and electronic warfare missions into joint operations as part of the PLA's information-centric approach to warfare. As one of two co-equal branches of the SSF, the Space Systems Department is responsible for nearly all PLA space operations. These developments reflect a growing emphasis on space and portend an increased role for space capabilities in Chinese military operations.[52] However, the SSF is only one part of China's much broader space enterprise that encompasses other military, government, and civilian organizations, including state-owned enterprises, academic institutions, and commercial entities.

In support of their information-centric strategy, the PLA is developing and fielding a range of counterspace systems. These capabilities provide multiple attack options that can hold the entire U.S. SATCOM enterprise at risk. In addition to more conventional means of attacking the terrestrial infrastructure that supports the operation of SATCOM and other space assets, China's arsenal of counterspace weapons includes direct-ascent missiles, co-orbital weapons, ground-based lasers, high power microwaves, offensive cyber tools to compromise information networks, and electronic warfare capabilities to jam or otherwise interfere with common satellite communication bands.[53] These weapons are supported by a robust network of space surveillance capabilities that can locate, characterize, track, and facilitate counterspace targeting of space assets in all orbits.[54]

Russian Federation. Like the PLA's adoption of an informationized warfighting strategy, Russian military strategy has evolved to prioritize influencing the information environment and their adversaries' decision-making. Russian military authors often emphasize the imperative to seize the initiative and control the information space, stating, for example, that "no goal will be achieved in future wars unless one belligerent gains information superiority over the other."[55] Within their concept of New Generation Warfare, Russian military strategists perceive the existence of an ongoing information confrontation with Russia's adversaries. Actions taken within this information confrontation broadly fall into two categories: information-psychological and information-technological.[56]

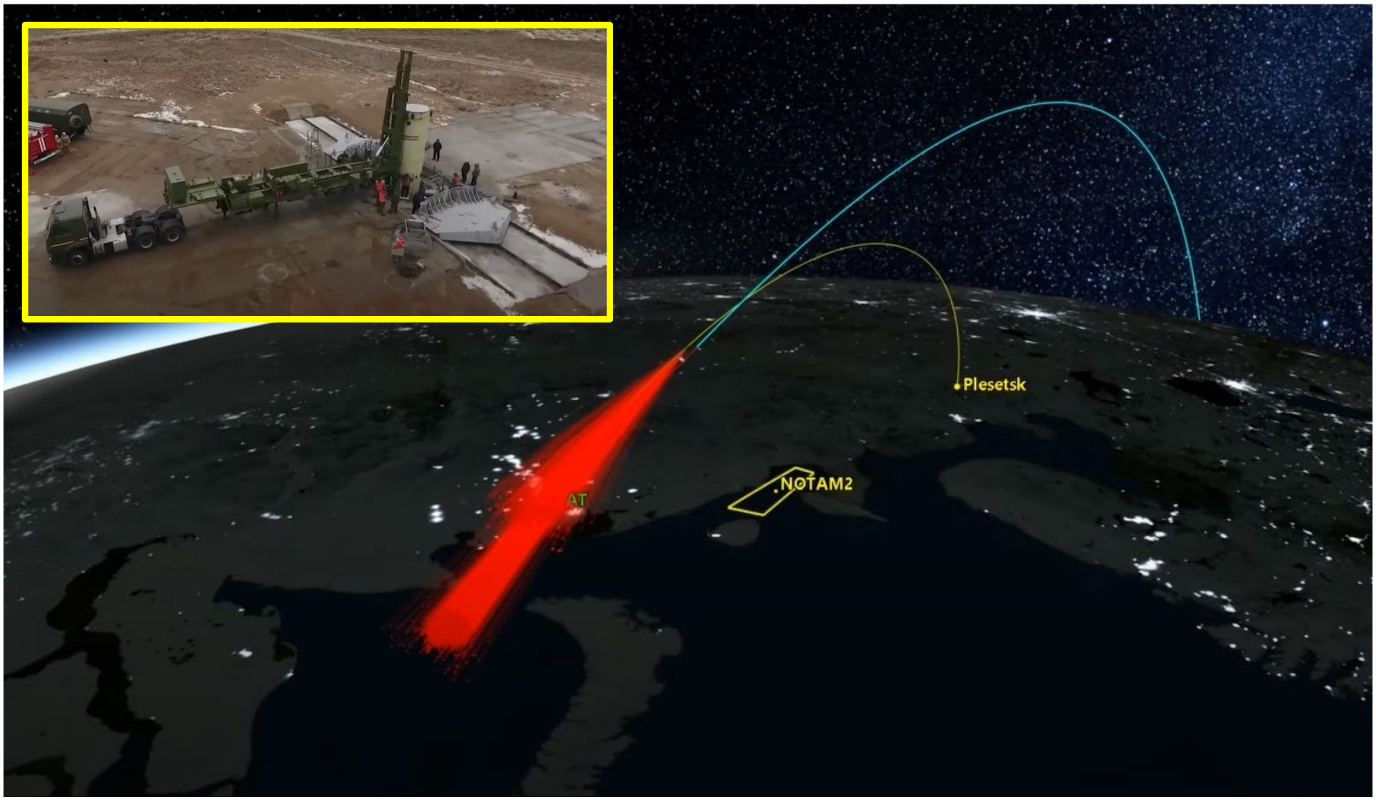


Figure 6: Physics-based recreation of November 15, 2021 Russian ASAT test that shot down the Russian satellite Cosmos 1408 (orbit shown in blue) using a direct-ascent kinetic weapon (trajectory shown in yellow), creating the resulting debris field (hypothetical depiction in red). Overlay is of the A-235 Russian ASAT system believed to have been used in the test.

Image source: AGI

Information-psychological measures seek to influence the target's perception, beliefs, and behavior either in favor of Russian strategic objectives or to sow dissent and confusion for the purposes of disrupting the adversary's decision-making.[57] Information-technological measures comprise any platform or capability involved in the collection and exploitation of information or in denying that ability to Russia's adversaries.[58] Psychological and technological measures often overlap and are coordinated more broadly with other military and non-military actions with the overall intent to attain information superiority and disorganize an opponent's military effort by targeting their C2 and information flows.[59]

Russian military leadership believes that within this information confrontation, the space domain plays an increasingly important role because of the expansion of the geographic scope of military action and the information needs of precision weapons that rely on satellite-supported information networks.[60] As several Russian military thinkers point out, "The present-day leading states accomplish communications, navigation, reconnaissance, and all command and control of strategic nuclear, missile defense, and precision-guided munitions through space."[61] Consequently, Russian military doctrine asserts space as a warfighting domain and that achieving supremacy in space will be a decisive factor in winning future conflicts.[62] At the same time, Russia views U.S. dependence on space as an exploitable vulnerability of its military power, and argues that disrupting C2 and information support, particularly from space, is critical to achieving Russian military objectives.

To better coordinate and streamline policy formulation, acquisition, and operation of its aerospace forces, in 2015 Russia created the Russian Aerospace Forces (VKS) by merging the former Air Forces and Aerospace

Defense Forces. Defense Minister Shoigu stated that the change was "prompted by a shift in the center of gravity…towards the aerospace sphere."[63] The standup of the VKS also involved reestablishment of the Russian Space Forces, which was initially created in 1992 but had most recently been dissolved in 2011. As one of three sub-branches within the VKS, the Russian Space Forces are responsible for most of Russia's activities in space, including conducting space launches, monitoring space objects, controlling spacecraft operations, and providing information support to the rest of the Russian military.

Russia's current counterspace capabilities benefit from a robust Soviet-era space program that developed a variety of operational weapons during the Cold War. Today, Russia continues to develop, field, and train its forces on an array of counterspace weapons to target U.S. and allied space operations, including SATCOM. These include jammers, directed energy weapons, on-orbit assets capable of rendezvous and proximity operations, and ground-based kinetic ASAT missiles.[64] These options to attack spacecraft in orbit and their communications links are complemented by capabilities directed against the terrestrial segment that support their operation, including cyberattacks against the computer systems that operate the spacecraft and strikes against ground infrastructure targets. Like China, Russia also has robust space surveillance and satellite control networks to support their counterspace operations.

Key Initiatives for a War-winning SATCOM Enterprise

Both the standup of the U.S. Space Force and the potential consolidation of authority and responsibility for the space domain present a unique opportunity to chart a new path forward for DOD's SATCOM enterprise. A major objective for future SATCOM should be to expand capacity, provide options with reduced latency, and improve interoperability. If accomplished, the resulting architecture could facilitate the secure transport of applications and information around the globe, enabling it to serve as the backbone that ties together all of DOD's networks and integrates the various service-led JADC2 initiatives. Another major objective should be to improve the architecture's resilience and agility in response to emerging threats, which would help enable mission success with higher probability, result in shorter periods of reduced capability, and make it a viable capability across a wider range of scenarios.

Achieving this will require the Space Force to leverage mature and emerging space technologies and novel system architectures that, to date, have largely been driven by the commercial sector. This entails changes across each of the three segments that comprise the basic building blocks of the SATCOM system architecture as well as the manufacturing, assembly, and testing methods used to produce and deploy these capabilities.

Proliferated smallsats in LEO and MEO offer reduced latency, improved capacity, and greater resilience against some forms of counterspace attack

LEO constellations were, until recently, dismissed as infeasible or at least impractical. However, satellite technology miniaturization and the reduction of launch costs driven by the commercial sector have significantly improved the cost-effectiveness of LEO constellations for meeting SATCOM demands. Within DOD, current efforts to leverage LEO for SATCOM are being led by the Defense Advanced Research Projects Agency (DARPA) and the Space Development Agency (SDA). Blackjack, a DARPA-led joint program in partnership with the Air Force Research Laboratory (AFRL) and Space Systems Command,

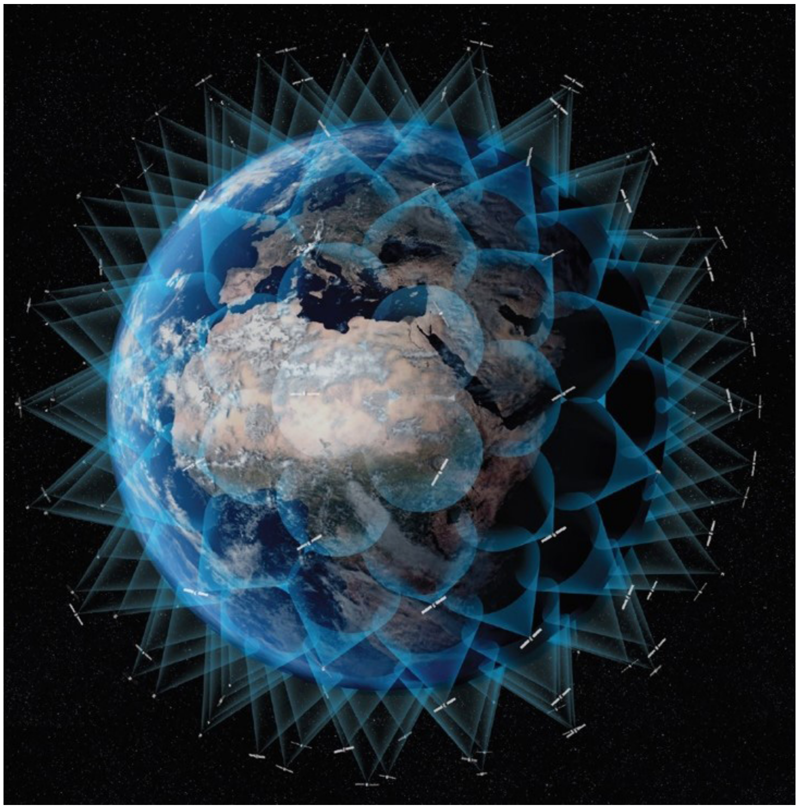


Figure 7: Artist's depiction of a proliferated LEO satellite network. Image source: ESA

seeks to "demonstrate the critical elements for a global high-speed network in low Earth orbit,"[65] and the SDA is developing its Transport Layer of at least 300 satellites to serve as the communications backbone for its larger National Defense Space Architecture.[66] To date SDA has collaborated with industry partners including General Atomics, SA Photonics, SEAKR Engineering, and SSCI to demonstrate on orbit some of the core underlying technologies for its Transport Layer as well as awarded contracts for its initial Tranche 0 satellites. Simultaneously, a range of companies led by SpaceX, Amazon, OneWeb, and Telesat are in the process of planning and deploying large constellations of small satellites in LEO to offer commercial broadband satellite internet services.

One of the most promising aspects of using satellites in LEO is the potential to reduce latency, since the much shorter distances signals need to travel relative to GEO significantly reduce the time needed to send and receive data. Based just on the physics limitation of the speed of light, the round-trip transmission time for a signal to a satellite in GEO and back to Earth is about 250 milliseconds, whereas for a satellite in LEO, it is on the order of 10 milliseconds. However, beyond the time it takes to propagate the signal, other forms of network delay impose additional time penalties. This means that, in practice, the return path latency for systems in GEO tends to be around 600 milliseconds. In contrast, DOD is seeking LEO SATCOM services that have latencies of 50 milliseconds or less.[67] For functions such as checking email, the impact of these split seconds is negligible, but for a hypersonic missile traveling at Mach 5 that can cover more than a kilometer in 600 milliseconds, it can be the difference between a successful intercept or mission failure. Such improvements in latency offered by lower orbit constellations therefore open the possibility to deliver remotely collected sensor data to shooters in real-time. This is critical to enable time-sensitive targeting and other missions central to DOD's Joint Warfighting Concept. In fact, because light travels faster through the vacuum of space than it does through the glass inside fiberoptic cables, a LEO satellite constellation could potentially offer lower latency over longer distances than even the fastest terrestrial networks currently available.

A traditional drawback of LEO satellites is that, due to their relatively small coverage footprints and constant motion relative to the Earth's surface, large constellations consisting of tens or even hundreds of satellites are required to provide continuous coverage. However, as the costs of building and launching them into orbit have declined, sufficient satellites can be economically deployed using a combination of orbital inclinations to simultaneously provide global coverage while concentrating the bulk of the constellation's capacity over areas with the greatest amount of user demand. From a commercial perspective, the fact that satellites in a LEO constellation can spend a significant portion of their orbit over unpopulated areas makes the business case more challenging. The U.S. military, however, operates globally, including in remote areas such as the Arctic that are poorly served by industry due to the lack of commercial customers, as well as areas outside the coverage of DOD's communications satellites in geostationary orbit. For this reason, proliferated LEO constellations can offer better coverage.[68]

Currently, for forces operating within the coverage footprint of a satellite in geostationary orbit, the further away they are from the equator, the greater the potential for terrain to impact their satellite communications. This is particularly true for ground forces that don't have the same line-of-sight advantages as aircraft operating at higher altitudes. To avoid interference from terrain or man-made structures, ground forces could be channelized into disadvantageous positions to maintain satellite connectivity.[69] For any given satellite in LEO, the potential for providing uninterrupted service is even lower, since its elevation and look angle relative to a given user will constantly be changing. However, within a large constellation of LEO satellites in multiple orbital planes, the probability of at least one satellite being within the ground user's field of view is much greater. This approach, while promising, would also require control gateways with sophisticated algorithms to recognize when a signal has been interrupted and then reroute traffic to an alternate satellite.

In terms of bandwidth, satellites in GEO can generally achieve greater capacity density than a given LEO constellation, particularly with newer high-throughput

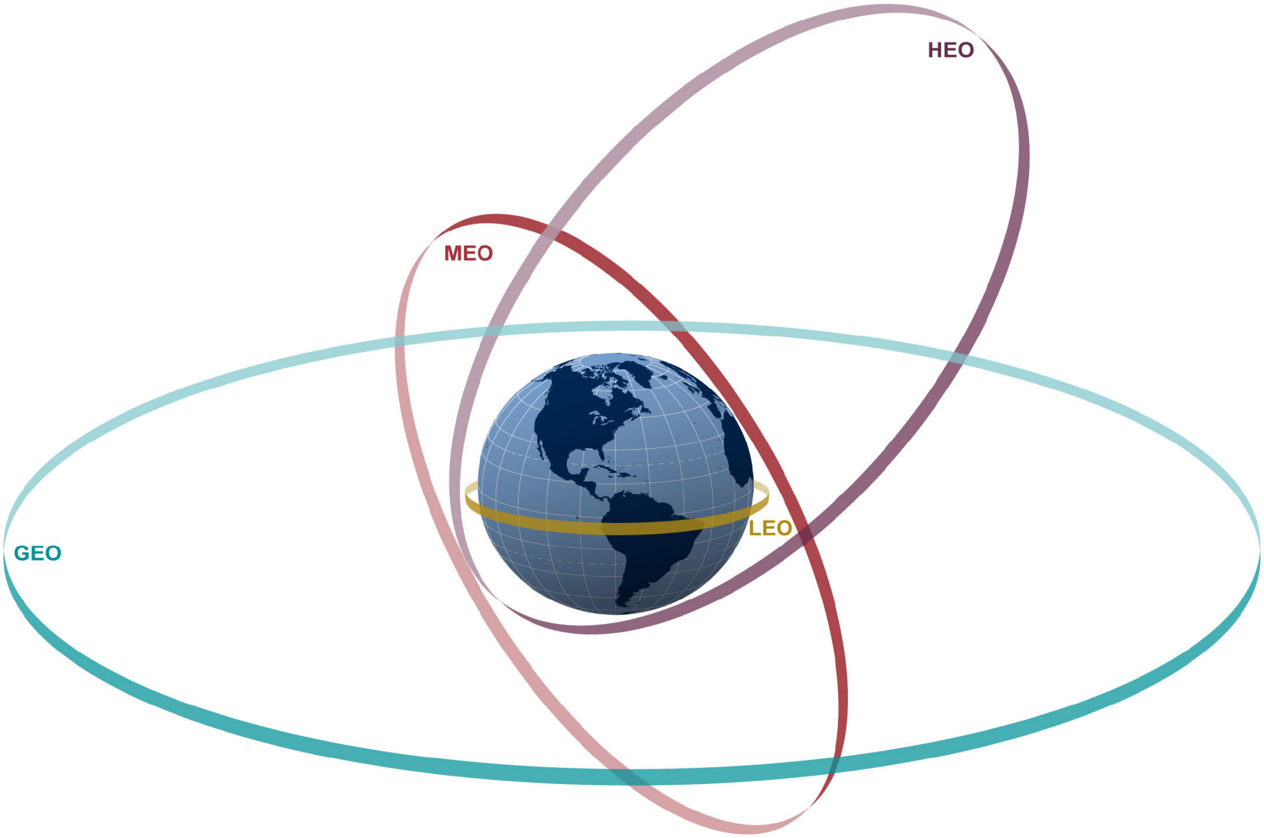


Figure 8: Comparison of orbits: Low Earth Orbit (LEO), Medium Earth Orbit (MEO), Highly Elliptical Orbit (HEO), and Geosynchronous Earth Orbit (GEO).

Image source: GAO

satellites that can reuse frequency using multiple narrowly focused spot beams. However, because of the number of satellites within a LEO constellation, the overall network capacity tends to be much greater. Furthermore, the closer proximity of LEO satellites to Earth means the signal strength to and from them is much greater and therefore requires less power. As a result, the antennas and power amplifiers can be much smaller. For DOD's emerging operational concepts that emphasize distribution, mobility, and maintaining a smaller footprint to reduce vulnerability to attack, SATCOM from LEO offers significant advantages that complement the capabilities that traditional GEO satellites already offer.

The much greater number of satellites in a LEO constellation also significantly improves the resilience of DOD's long-haul communications, particularly against kinetic attacks. The challenge for satellites is that, due to their predictable orbits along the same tracks and limited ability to maneuver, they are easy to locate and attack. Although there are some promising efforts in development, options for attack in space generally remain cheaper and less technologically challenging than those to improve the defenses of a given satellite.[70] Satellites in LEO do not fundamentally alter this calculus and are susceptible to a greater range of threats than satellites in GEO, including some longer-range surface-to-air missiles. LEO constellations increase resilience instead through dispersion and proliferation. Compared to a GEO constellation, the loss of the same number of nodes in a LEO constellation would result in a much smaller decline in overall capacity. As the former Program Manager of DARPA's Blackjack program explained, "If one satellite has fallen, its replacement is coming over the horizon 10 to 15 minutes later. You have a different approach to resiliency."[71] Whereas the loss of a few monolithic satellites in GEO would result in a catastrophic failure of the system, a proliferated LEO constellation would degrade much more gracefully and could withstand the loss of a relatively large number of satellites before losing significant capability. An adversary would have to launch a much larger and more concerted attack, requiring large numbers of costly weapons to destroy relatively inexpensive satellites, which could potentially shift the cost exchange dynamics into the defender's favor.[72]

In addition to greater built-in resilience, satellites in LEO can also be reconstituted more cheaply and rapidly than larger satellites in GEO—with spares available either on orbit or kept in ground storage. Satellites in LEO are by design cheaper, easier to build, and have shorter service lives, meaning that routine replenishment is inherent to the operation of such constellations. In the event of conflict, satellites in the production pipeline offer a ready-made wartime reserve that could provide a reconstitution capability to meet operational demands.[73] Production lines normally used to replenish commercial LEO constellations could also be repurposed to further bolster this industrial capacity during conflict, akin to how Ford production lines shifted from cars to tank and aircraft manufacturing during World War II. The regular operation of these commercial production lines should also help to drive down the cost and increase the cadence of space launches, providing DOD sufficient launch capacity. In crisis or conflict, commercial launch would offer even more options to augment or replace national security space systems.[74] A comparable reconstitution capability for satellites in GEO is not feasible: they have high cost and complex designs; managing the technological obsolescence of GEO satellites kept in reserve over their long planned service lives would prove difficult; and the United States is currently unable to launch replacements to

GEO on a tactically relevant timescale.[75]

DOD could further disperse and expand its sovereign SATCOM capacity beyond its own constellations—while retaining comparable advanced capabilities to protect against cyber and electronic attacks—by partnering with allied nations or commercial providers. Partners could host government communications payloads on their satellite buses that have sufficient margins to accommodate secondary mission payloads. Such hosted payload agreements would enable more rapid deployment of capabilities into orbit while reducing the cost to DOD by sharing the expense of integration, launch, and operations with the host satellite owner. Incorporating hosted payloads into DOD's SATCOM architecture would also enhance deterrence. For one, it would increase the scale and intensity of counterspace operations an adversary would need to consider before taking an aggressive action. It would also introduce the risk of horizontal escalation into the adversary's decision-making calculus since they would need to directly target the assets of countries that, depending on the scenario, may otherwise chose to not get involved.

There is some precedent for hosted payloads, such as Norway hosting the U.S. Space Force's Enhanced Polar System Recapitalization communications payloads on its Space Norway Arctic Satellite Broadband Mission systems. Overall, though, hosted payload arrangements remain limited. Impediments include compatibility issues in matching payloads to satellites, development and acquisition timing problems in which government payloads are not ready for integration and testing on commercial operators' timelines, and risk aversion stemming from the mission-critical nature of each satellite being launched.[76] The more recent increase in satellite construction and launch associated with the growing investment in non-GEO constellations, coupled with DOD's emphasis on commoditized buses and commercial-off-the-shelf (COTS) parts, should provide more opportunities to leverage hosted payloads. As an example of this trend, the Army recently awarded a contract to Iridium Communications to develop a payload to broadcast PNT data that will be hosted on another LEO commercial satellite constellation.[77]

Finally, DOD should better leverage new commercial LEO, MEO, and GEO constellations as they are deployed. The Air Force Research Laboratory has already experimented with integrating commercial space-based Internet networks with aircraft and ground stations to provide high-bandwidth communications and data sharing capabilities through its Global Lightning program.[78] Integrating military and commercial SATCOM networks into a hybrid architecture would provide warfighters with significantly greater capacity, flexibility, and resilience. Under a hybrid architecture approach, warfighters could roam across different satellite networks spanning multiple orbital regimes and operating over various frequency bands, waveforms, and security levels based on emerging threats and evolving mission requirements. Users could also leverage multiple networks simultaneously, with data transmissions hopping across multiple networks until they reach their intended receiver. This complicates adversary targeting as they attempt to identify which satellite to target and expands the options for commanders to enhance their communications plans.[79] Rather than having two or maybe three different communications options in space available, as is currently the case, a future military user on the ground could have hundreds of potential network nodes overhead at any given time and location. Such a hybrid architecture could also help prevent systemic failures since the various

Figure 9: Rendering of space-based optical communications demonstration.

Image source: General Atomics

independent layers of terrestrial infrastructure and different network management and cyber defense implementations would mean a latent defect in any given payload or piece of equipment could be isolated to a small portion of the overall architecture.[80]

Optical communications support networking of satellites and provide assured, high bandwidth space-based communications

The linchpin to realizing the full potential of SATCOM constellations is to leverage space-based optical communications. An optical terminal modulates data onto a low power laser beam that is then wirelessly transmitted through free space to an optical receiver. Lasers operate in much shorter wavelengths relative to traditional radiofrequency (RF) communications, which improves data transfer rates by at least an order of magnitude. This increase in performance is analogous to upgrading from a dial-up modem to broadband Internet. Shorter wavelengths also mean they can use lower power levels and smaller, lighter apertures to transmit narrower transmission beams that create more concentrated signals at receivers.[81] These improvements in size, weight, and power—sought after for virtually all military applications—are a particularly important consideration for systems that are launched and maintained on orbit. They are likely to only grow in importance as satellites trend toward smaller form factors.

The highly directional, narrow transmission beams of lasers also minimize the potential for interference from adjacent satellites and enhance the security of transmissions by reducing the area in which the signal can potentially be detected and intercepted by an adversary.[82] In DOD's parlance, lasers provide a low probability of detection, low probability of intercept capability. Even if detected and located, optical communications are incredibly difficult to disrupt. It would require shining another laser at exactly the right wavelength and with sufficient power within the very narrow field of view of the targeted optical communications receiver. This is even more challenging when the both transmitter and receiver are moving, as is the case with space-based platforms. Furthermore, the highly directed nature and minimum spillage of optical communications means that intercepting the signal would require an adversary to place their own receivers in ways that make them highly susceptible to counter-detection and countermeasures.

Optical communications can also be used to establish quantum key distribution (QKD) networks, providing a highly secure method of communication based on the laws of physics rather than just computational complexity. Although there are various QKD protocols, the basic principle is that it uses quantum states of light to enable the production and sharing of cryptographic keys without direct physical contact. Instead, QKD involves the transmission of polarized photons across an optical link. Critically, any attempt by a third party to intercept or tamper with the key changes the state of the photons, introducing detectable errors that prompt the system to discard the key. If tampering is not detected during the QKD exchange, then the keys it generates can be trusted to send secure messages using conventional encryption algorithms. QKD systems are already in use, most notably by financial services firms, but these applications use fiberoptic cables to distribute the keys, which are limited in range due to attenuation loss as photons propagate through the optical fiber. Although efforts are underway to extend the range, an already-demonstrated alternative is to distribute keys using satellites equipped with optical communications systems, since there is significantly less photon loss and decoherence within space and through the clear atmosphere.[83] Using this approach, secure QKD networks could be extended globally.

Satellites currently rely on RF communications that have little room for dramatic improvements in performance and are increasingly vulnerable to disruption and denial. In addition to deliberate adversary actions against RF communications, many inadvertent sources of disruption are becoming unavoidable, as these satellites now operate in an increasingly congested electromagnetic environment. In contrast, optical communications provide, at a minimum, an order of magnitude improvement in data rate performance. They also come in more compact form factors that consume less power and are highly secure. Whereas proliferated satellites provide greater resilience against physical forms of counterspace attack, connecting them using optical communications protects against much more prevalent electronic counterspace weapons such as jammers and hardens communications against cyberattacks. Optical communications not only enable better communications, but also new concepts and tactics.

A good initial application for optical communications is for satellite crosslinks to connect satellites on the same or adjacent orbital planes, across orbital regimes, and eventually to support communications in cislunar space. A satellite crosslink, also referred to as an inter-satellite link, enables satellites to pass data directly between each other rather than having to route their communications through a ground station. Exploiting the vacuum of space, these optical crosslinks could achieve data rates on the order of tens of gigabits per second (Gbps). For context, a 10 Gbps optical link could transmit an entire high-definition movie in about three seconds. This significantly improved performance of optical inter-satellite links (OISL) is critical to overcoming the limitations of traditional RF crosslinks, which, due to technological and regulatory constraints, are becoming a bottleneck for moving data in space.

OISLs are particularly important for LEO constellations because they are the basis for overcoming two of the fundamental limitations of satellites in LEO, which are

Figure 10: Artist depiction of a segment of a LEO constellation supported by laser communications. Equipping each satellite with multiple optical communications terminals forms a "mesh" network that provides numerous diversified connectivity paths through which to route data and information through space.

Image source: Mynaric

their limited coverage footprints and constant motion relative to the Earth's surface. Absent crosslinks, a LEO constellation would require an extensive terrestrial infrastructure to ensure each satellite can constantly maintain at least one ground control station within its coverage footprint. Otherwise, each satellite would only have limited windows in which to transmit and receive telemetry, tracking and control (TT&C) data. By instead using crosslinks to pass data directly between satellites, the amount of ground infrastructure necessary to monitor and control the constellation can be significantly reduced, and the terrestrial element tends to be one of the more expensive segments of the LEO value chain.

By enabling space-to-space data transport, crosslinks also eliminate the need for the signal transmitter to be within the same satellite footprint as the receiver. Absent crosslinks, for a satellite to communicate with a receiver beyond its coverage footprint would require using store and forward techniques that add significant time delays or else the signal would need to be routed down to a ground station within its footprint and then up to another satellite, a process that would then need to be repeated until the signal ultimately reaches a satellite within line-of-sight of the intended end user. This kind of single hop data transport adds significant network delay and unnecessary computational complexity; it is an extremely inefficient utilization of limited satellite resources. Instead, using OISLs, the signal can be relayed through a series of satellites until it reaches one within line-of-sight of the intended recipient, significantly reducing latency and helping to make it possible to deliver collected sensor data to warfighters in near-real time. This approach has the added benefit of enabling satellite constellations to bypass terrestrial networks in unsecure locations. This reduces the risk of interference or detection and minimizes the number of potential entry points for cyberattacks.[84]

By equipping each satellite with

several optical communications terminals (OCT)—generally three to five—they can communicate with multiple adjacent satellites to form “mesh” networks that provide numerous diversified connectivity paths through which to route data and information. Combining this mesh with an autonomous mission management system onboard each satellite to direct data transmission is the basis for creating a self-healing network in space. Leveraging advanced routing algorithms, this network could optimize its operations to ensure data is relayed through the fastest possible routes, preventing local data traffic congestion. Self-healing networks in space will also be able to reconfigure and repair themselves and adaptively route data around threatened or disabled satellites to ensure continuous connectivity.[85] Autonomous mission management systems such as DARPA’s Pit Boss program could also facilitate the shift toward on-orbit processing of data. Rather than sending unrefined data collected on orbit down to a ground station for processing, which can add significant delays and potentially overwhelm the system, a system such as Pit Boss would be able to task, process, and distribute tactically relevant information to fulfill users’ mission service requests without human input.[86] Collectively this translates to faster, more resilient connectivity—even in the face of attempted enemy disruption.

Compatible optical inter-satellite links could also be used to connect disparate satellite constellations on orbit that otherwise would not be able communicate with one another directly. Such optical cross-linking between commercial and government constellations would significantly increase the density, redundancy, and capacity of the space mesh network critical to empowering JADC2. The potential for other military and commercial intelligence and SATCOM providers to plug directly into its Transport Layer was part of the motivation for why SDA worked with its industry partners to develop an open standard interface. This includes a standard for the pointing, acquisition, and tracking (PAT) systems to ensure OCTs can establish and maintain a robust communications link.[87] Having drafted the standard in early 2021, the U.S. Naval Research Laboratory and Mynaric successfully connected their independently developed, standard-compliant modems via optical fiber for the first time at an SDA/NRL optical testbed later that same year.[88] More recently, SDA selected the first commercial synthetic-aperture radar company to demonstrate the ability to integrate its satellites with SDA’s architecture using optical communications based on SDA’s standards.[89]

Publishing such an approved open standard will help to promote greater interoperability, but complete standards convergence is highly unlikely and may not even be optimal because it can stymie future innovation and reduce the resiliency afforded by the existence of diverse systems throughout the force. Notably, commercial companies are already in the process of acquiring OCTs with specifications that meet the requirements to interconnect their own satellites but, to keep costs down, may not be compatible with other LEO constellations and are not reconfigurable.[90] To connect these fragmented, heterogenous constellations, DARPA’s Space-Based Adaptive Communications Node (Space-BACN) program is seeking to develop a reconfigurable, multi-protocol optical communications terminal consisting of a modular optical aperture and a reconfigurable modem that can support multiple optical waveforms.[91] The terminal itself could either be installed on dedicated satellites that serve as communications gateways or integrated on future satellites to give them this capability directly.

Beyond transporting data through space,

Image source: General Atomics

Figure 11: Airborne Laser Communications System payload. High-altitude C2ISR platforms that operate above usual weather phenomena offer good initial candidates for integration of such airborne optical terminals.

the ability to bring actionable information back down to the terrestrial warfighter is equally important. Satellites equipped with optical communication systems can not only communicate amongst each other in space, but also with terrestrial users, including submerged undersea vessels. For example, having successfully ground tested connecting its Airborne Laser Communication System (ALCoS) with an OCT onboard a satellite in GEO, General Atomics is now partnering with SDA to test both space-to-ground and space-to-air OCTs between a satellite in LEO and an MQ-9 Reaper remotely piloted aircraft (RPA). Although such downlinks are likely not capable of achieving the same data rates as satellite crosslinks due to atmospheric disturbances, they would provide forces with high bandwidth, LPD/LPI communications across domains—that furthermore are incredibly difficult to jam and requires significantly less power than traditional RF communications. In practical terms, this means forces will have assured connectivity even in contested environments, enabling them to share far more information faster than is possible with current systems.

Optical communications with or between terrestrial users presents additional technical challenges. For example, the link must account for distortions to the optical beam when propagating through the atmosphere. In addition to wave-front distortions caused by general atmospheric turbulence, particulates and water vapor in the air can absorb and scatter laser energy, causing atmospheric path attenuation. The impacts of atmospheric turbulence can be compensated for with a variety of techniques, including signal processing algorithms and adaptive optics systems that measure and dynamically correct the distortions that degrade performance using deformable mirrors. In addition to advanced techniques under development, weather effects can also be mitigated using proper operational planning based on increasingly robust predictive weather modeling and leveraging geographically dispersed optical terminals so that signals experiencing unacceptable performance degradation can be rerouted to a different downlink site.[92] However, the challenges in maintaining long-range optical communications downlinks in all weather conditions points to the benefits of a hybrid approach that leverages optical uplinks and downlinks to augment existing RF-based systems.[93] To that end, as well as to provide backward compatibility with platforms that will be slower to adopt OCTs, SDA's initial tranches of satellites include communications payloads that can integrate with Link-16 and the Integrated Broadcast System.

The severity of these atmospheric effects tends to decrease at higher altitudes and drops off dramatically above a few thousand feet. Given this consideration, high-altitude C2ISR platforms that operate above usual weather phenomena offer good initial candidates for integration of compact and conformal OCTs. To fully exploit the multiple, sophisticated sensor payloads that such aircraft carry in real-time requires data transfer rates that only optical communications can provide. RPAs such as the MQ-9 Reaper and RQ-4 Global Hawk would particularly benefit from optical communications, as it would also enable the aircraft to operate in increasingly prevalent

RF-contested environments.[94] RPAs are incorporating increasing levels of automation, but many functions still require a human-in-the-loop, and traditional C2 capabilities are susceptible to jamming and other forms of disruption. Furthermore, optical communications can operate in full-duplex mode. This means ISR assets using a single beam for transmission and reception of signals at both ends of the beam can be dynamically re-tasked via the uplink based on information obtained from the downlink.

Airborne communications gateways would also be good candidates as early adopters of OCTs. Operating at high altitudes, these platforms serve to relay communications beyond the line-of-sight of users at lower altitudes and to translate between various, incompatible waveforms. By plugging these aircraft into the space layer using optical communications, they could simultaneously provide robust, high-throughput backhaul while enabling users within the local network to access and share far more information than would otherwise be available. While this would be beneficial for all airborne gateways, the jam-resistant and LPD/LPI characteristics of optical communications would be particularly useful for aircraft operating in contested environments. The Air Force has previously referenced the need for a "penetrating ISR capability" that will likely take the form of a stealthy unmanned system.[95] Equipping such a platform with a conformal OCT that is fully receded within the frame of the aircraft would enable it to be clandestinely networked with other assets operating in contested airspace. It could also share collected information across the broader battlespace without needing to retrofit tactical aircraft with advanced SATCOM terminals or use resource-intensive daisy-chains of line-of-sight datalinks.[96]

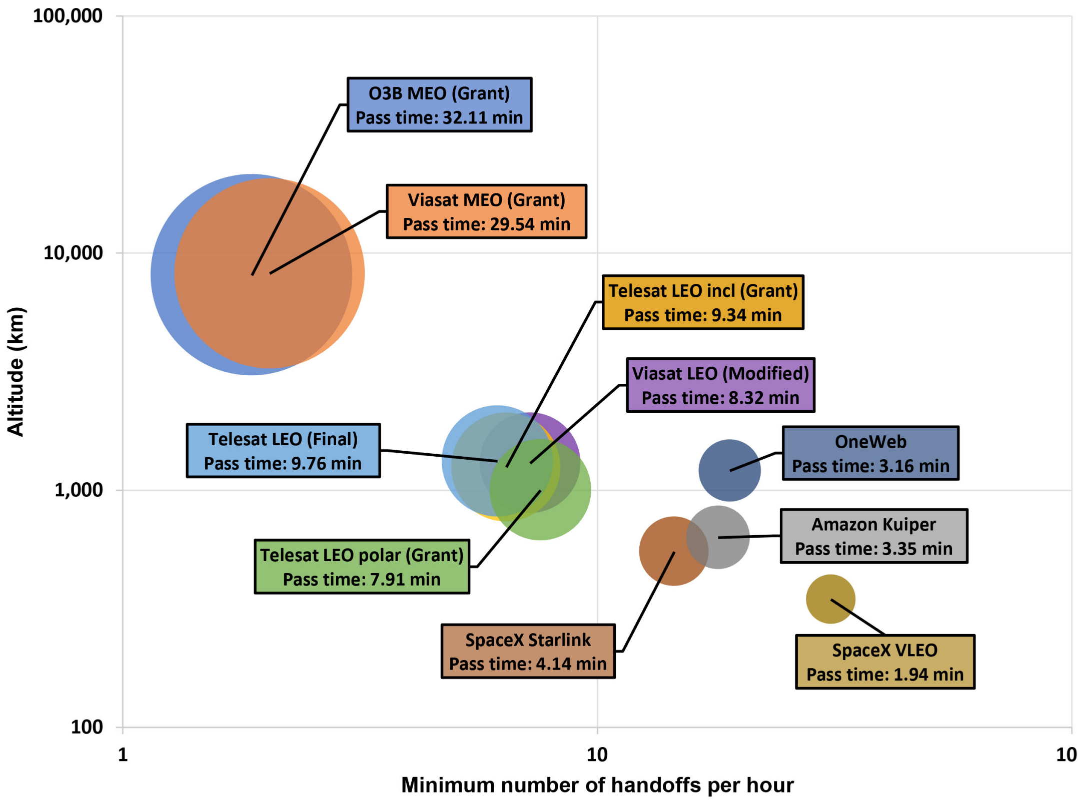


Figure 12: Illustrative maximum satellite pass times (represented by the size of the circles) and minimum number of handoffs per hour for various non-GEO constellations.

Credit: NSR Non-GEO Constellations Analysis Toolkit and Mitchell Institute

Improved terrestrial infrastructure, including flexible terminals and enterprise management and control capabilities, are necessary to support new architecture

To realize advancements in the space domain requires corresponding investment in the terrestrial infrastructure necessary to support it. This starts with the need for more agile and capable antennas as legacy systems are rapidly approaching their limits, both in terms of scalability and their ability to manage the speed and complexity of modern space architectures. For example, because LEO constellations have numerous satellites rapidly moving across a given ground receiver's field of view, these systems require sophisticated tracking and up to dozens of satellite beam handovers each hour at every user terminal. Traditional parabolic-dish antennas are poorly suited for such operations because they require mechanical steering and can only communicate with a single satellite at a time. This hinders their ability to maintain a continuous connection as satellites move in and out of their field of view. Likewise for ground control stations, single contact parabolic antennas have limited capacity to transmit and receive TT&C data and perform other functions.[97]

Replacing existing parabolic antennas with phased array antennas would represent a significant leap forward for both ground control stations and user terminals. Using a computer-controlled array of antennas that can be electronically steered without physical movement, phased array antennas can track and contact multiple satellites across different orbits and frequencies at the same time. For ground control stations, this would enable a single terminal to simultaneously support multiple satellites across different orbits and potentially perform several concurrent missions, including C2, launch operations, and mission data transmission. Recent tests of phased array antennas have demonstrated their ability to integrate with the U.S. Space Force's Satellite Control Network and establish contacts across different orbital regimes at the same time.[98] For user terminals, the capability of phased array antennas to simultaneously connect with multiple satellites is critical because it enables seamless handovers between satellites without losing connectivity in what are known as "make-before-break" handovers.[99] Although the U.S. military has used phased arrays for decades on high-end platforms, historic high cost and customized production limited their broader use. However, the emergence of large commercial markets for new satellite capabilities and constellations could provide high-volume production runs that drive down the costs for military users and allow for potentially broader adoption across the force.

Beyond simply switching among different transponders or satellites within a given constellation, DOD should field flexible terminals that can roam between service providers comprising government, commercial, and international satellite networks. The flexibility to operate across different networks in multiple orbits and frequency bands and utilize diverse DOD, industry standard, and proprietary commercial waveforms is critical to leverage the diverse and expanding set of SATCOM options currently being deployed. The ability for tactical users to dynamically access diverse networks without dropouts in operationally relevant timeframes not only helps ensure the requisite SATCOM capacity is delivered, but also provides resilience against adversary actions: it provides options to route traffic based on security level and trust in the link, as well as offers redundant links for mission-critical data thereby eliminating single points of failure. DOD has already undertaken a number of pathfinder projects to develop and demonstrate the building blocks for such a capability, including the flexible modem interface (FMI), which addressed the design, integration, operation, and management of a DOD terminal with multiple modems.[100]

Flexibility at the terminal should be combined with enterprise management and control capabilities that can autonomously determine why, when, and how the system should roam and transition from one network to another. The system could monitor the EMS environment and impacts on its performance, then use pre-positioned policies or a logical channel to select the best available network based on mission needs, threat considerations, and its situational awareness of all providers, satellites, and bandwidth available at any given time. Furthermore, by conducting this automated planning in a manner transparent to human operators, the switching could be done at either a central management point, such as a Government Network Operations Center, or by the end user. Such agile path diversity would provide more efficient bandwidth allocation as well as greater resilience to interference, jamming, or other outages.

Transitioning to SATCOM architectures that consist of significantly more satellites than are in use today will require an evolution in satellite development, manufacturing, assembly, integration, and testing methods and approaches.

Creating such a dynamic ground architecture must start with replacing analog Intermediate Frequency (IF) interfaces with an open, interoperable Digital IF industry standard.[101] Digital IF essentially turns the flow of data into an Internet Protocol (IP)-based network. Adoption of digital IF standards paves the way for the implementation of best practices for network design and usage that already underlie modern telecommunications and cloud service providers, including network function virtualization and software defined networking.[102] Virtualization, for example, replaces traditional hardware components with Virtual Network Functions (VNF), which enables digitized data to be processed in software. This allows the same commercially available hardware hosting these VNFs on general computing power to access multiple different satellite networks without having to acquire new dedicated hardware. Instead, it's just a matter of switching VNFs depending on what the user needs for any given link on any given network. This would allow DOD SATCOM to work much like how cell phones can now automatically roam across multiple cellular networks. Adopting these best practices could help DOD move away from closed, proprietary hardware to a virtualized, standards-based software ground infrastructure with the requisite flexibility, agility, and resiliency to support DOD's evolving operational concepts. Furthermore, it would help fully realize the potential of the suggested modernizations to the orbital and link segments outlined in this study.

Industrial base considerations

Transitioning to SATCOM architectures that consist of significantly more satellites than are in use today will require an evolution in satellite development, manufacturing, assembly, integration, and testing methods and approaches. Launching constellations consisting of hundreds or even thousands of satellites within a few years requires satellites to be manufactured at an unprecedented rate for the space industry. For example, SpaceX is reportedly building 120 satellites per month for its Starlink constellation, whereas Iridium—which previously held the record for largest commercial satellite constellation—produced six satellites per month at its peak.[103] Furthermore, the need for such high-volume production will be ongoing. Constellations in LEO require continual replenishment missions to maintain them, as the orbital drag experienced by satellites in LEO limits their operational lives. For example, SpaceX plans

Figure 13: 60 SpaceX Starlink satellites stacked into Falcon 9 launch vehicle fairing prior to launch. Establishing and maintaining proliferated constellations will require satellites to be manufactured at an unprecedented rate for the space industry.

Image via Elon Musk on Twitter

to deorbit its Starlink satellites after a mission life of about five years whereas satellites in GEO typically launch with a design life of 15 to 20 years.

The challenge facing industry is that traditional satellite manufacturing is often highly tailored, labor intensive, and involves prolonged quality assurance methods that do not lend themselves to such high-volume production. For large LEO constellations to be viable, satellites—including their various components and payloads—will need to leverage advances in low-cost manufacturing and assembly techniques such as additive manufacturing, the increased use of automation and robotics, and the incorporation of more commercial-off-the-shelf components. This, in turn, requires satellite bus and payload design to not solely prioritize performance, but also cost reduction and manufacturability.[104]

Currently, manufacturability at a scale that accesses the breadth of innovation in commercial industry poses some unique challenges for the Department of Defense. A common barrier to entry into the defense space market is the over-classification of national security space contracting opportunities. To even read a classified request for proposal (RFP), a company must obtain a government sponsor for a facility clearance and be vetted to both handle classified material and gain security clearances for its employees. New entrants to defense space attempting to compete for contracts often find themselves in a Catch-22 situation where they need the clearance to compete but cannot get a clearance until they win a competition. The overall impact of this is to dissuade a larger ecosystem of innovative commercial companies entering the defense market. It can also incentivize companies to pursue problematic workarounds. For example, a larger company seeking to enter the defense space market with sufficient capital to afford the upfront investment may choose to purchase another company that already holds classified contracts simply to gain a facility clearance. This shortcut into classified defense contracts can dissipate substantive initiative, workforce talent, and entrepreneurial independence of the smaller enterprise being bought out.

Manufacturability of space components also requires a substantial upfront investment in infrastructure such as cleanrooms and secure facilities. This critical requirement for clean manufacturing and assembly comes from costly lessons learned through error analysis after failures and accidents, yet cleanroom infrastructure is expensive and limited.[105] Likewise secure facilities to protect highly classified material and activities consumes limited resources. Such overhead needs to be accounted for to enable smaller, highly innovative companies to enter and compete successfully for defense contracting opportunities. A fresh partnership is needed between space acquisition and industry that deals with impediments to leveraging all sources of innovation while dealing with the limitations to scaling manufacturability in support of new operating concepts designed to improve space-based capabilities, capacity, and resilience.

A key initiative in this regard is for the U.S. government to partner with industry to develop and implement a modular open systems approach (MOSA) that encourages modular satellite bus designs with standard, nonproprietary payload interfaces. Using such an approach, the U.S. government could contract with multiple vendors for satellite buses and payloads, allowing for easy integration of compatible components while supporting rapid technology insertion as new innovations are developed.[106] The effectiveness of MOSA could be further enhanced through pairing with digital engineering practices to more efficiently and securely execute new design and integration efforts. By building "digital twins" of systems and components based on common standards that can be inserted into a shared virtual environment, DOD and its ecosystems of partners can validate and test systems early in the design stage as well as provide greater flexibility to modify designs as requirements change.

Increased, more rapid production coupled with greater and more stable demand from DOD to replenish its satellite constellations could yield significant benefits. For one, greater production may be distributed across a larger number of vendors, including companies beyond the traditional space defense primes, to foster more competition and innovation. The shorter design life of LEO satellites—coupled with the lower stress components experience stemming from orbits with milder radiation environments—also enables simpler, more flexible designs with less redundancy. Rather than constantly developing clean-sheet exquisite designs, companies can make greater use of commercially available parts while focusing more of their efforts on their particular areas of expertise or competitive advantage.

The need to continually replenish satellite constellations naturally offers more frequent opportunities to insert new technologies. This makes the constellation more responsive to emerging threats and improves requirements discipline, since program managers would have more flexibility to delay new requirements to the next production cycle rather than incorporating them midstream into ongoing timelines.[107] For example, SDA operates under a spiral development model that offers technology refresh opportunities every two years. This creates regular, planned technology insertion points, reducing the time to deploy enhanced capabilities and offering companies frequent opportunities to compete for new contracts.

Lastly, government and commercial companies planning large LEO satellite constellations still need to reduce launch costs to ensure long-term viability. Small satellites have traditionally been launched as rideshare or secondary payloads, but the demand for these opportunities exceeds the rate of large payload launches.[108] Improvements to launch capabilities in terms of cost, capacity, reusability, and availability are therefore critical. For both routine and wartime replenishment of satellite constellations, the space launch infrastructure must be able to provide for the rapid deployment of large numbers of satellites, including those with different orbital parameters and timing requirements.

Conclusion and Recommendations

The U.S. Space Force was established out of a recognition that unfettered access and freedom to operate in space is foundational to the nation's military, economic, and diplomatic power. At the same time, out of a concern for rising costs and bureaucracy, the Space Force was designed to be a lean and agile service, resulting in a budget that accounts for a mere 2.5 percent of total DOD spending in the fiscal year 2022 defense budget proposal. Today, America's advantage in—and reliance on—space is being aggressively challenged by China and Russia, who have both been evolving their doctrine, organizations, and capabilities to deny the United States use of the space domain. Thus, while the Space Force's efforts to establish a reputation for itself as a good steward of the nation's resources are admirable, the reality is the service requires additional resources to develop and field the capabilities necessary to accomplish the missions with which it has been tasked.

Updated SATCOM architectures enabled and boosted by laser communication will form the connective tissue that empowers U.S. global distributed operations in real-time.

The consolidation of authority and responsibility for the SATCOM enterprise within a single service presents a once-in-a-generation opportunity to chart a new path forward to ensure U.S. forces can attain a decision advantage and retain operationally sufficient levels of assured connectivity. However, without new SATCOM concepts and capabilities, the enterprise will be unable to provide the requisite support for promising new concepts such as JADC2; moreover, it will be vulnerable to adversaries' efforts to degrade or deny the asymmetric advantages that access to SATCOM provides. The following recommendations should inform development of the Space Force's future SATCOM force design plans and investments:

- The Space Force should distribute, disaggregate, diversify, and expand its SATCOM options by deploying non-geostationary satellite constellations to augment existing systems that primarily reside in GEO orbits. Proliferating satellites in multiple orbits will increase communications capacity and coverage, provide options with reduced latency, improve resilience against attacks, and create more options to meet mission-specific requirements.
- To further expand capacity beyond DOD-owned constellations, the Space Force should explore options to expand its partnerships with allied nations or commercial providers to host government communications payloads on their satellite buses that have sufficient margins to accommodate secondary mission payloads. The Space Force Commercial Satellite Communications Office should also leverage innovative cost models and material solutions offered by industry to acquire commercial SATCOM services.
- The Space Force should aggressively develop and deploy optical inter-satellite links to connect its satellites. Space-based optical communications are key to forming space mesh networks that provide diversified connectivity paths to route information to, from, and through space at the speed, scale, and level of security

needed for all-domain operations. To the extent possible, the Space Force should incentivize commercial partners and other government programs to adopt the Space Development Agency's open standard for their optical communications terminals. However, they should simultaneously fund ad-hoc interoperability efforts such as DARPA's Space-BACN program as well.

- The Space Force should conduct rapid experimentation and demonstrations of optical communications terminals on a range of airborne and terrestrial systems. High-altitude C2ISR platforms that operate above usual weather phenomena offer good initial candidates for integration of compact and conformal optical terminals. Rapid fielding of prototypes would allow operators to experiment and develop concepts that integrate the advanced capabilities that optical communications provide into exercises such as the Advanced Battle Management System onramps or Project Convergence.
- DOD should develop a terrestrial segment that allows it to fully realize the advantages of these new satellite networks and laser communications. On the front end, this will require phased array antennas capable of handling the rapid and continuous satellite beam handovers inherent to the operation of LEO and MEO constellations, as well as flexible terminals that can roam across different networks spanning multiple orbital regimes and operating over different frequency bands, waveforms, and security levels. On the back end, an effective infrastructure will also require cognitive enterprise management and control capabilities that can autonomously determine and select the best available network in a manner that is transparent to human operators.
- To build satellite busses and their various payloads in the quantities necessary to establish and sustain LEO constellations, the Space Force must prioritize and incentivize not just performance, but also cost reduction and manufacturability in its contracting.
- Additional analysis is necessary to identify detailed investment and divestment opportunities and steps for implementation of the future SATCOM enterprise. This will require the Space Warfighting Analysis Center and other relevant acquisition organizations to receive sufficient resources and manning.

Collectively, these initiatives would enable the U.S. SATCOM enterprise to serve as the backbone that ties together all of DOD's various networks and service-led JADC2 initiatives to enable all-domain operations—and do so in a way that supports higher probability of mission success and shorter periods of reduced capability across a wider range of scenarios and threats. Updated SATCOM architectures enabled and boosted by laser communication will form the connective tissue that empowers U.S. global distributed operations in real-time.✪

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About the Authors

Gen (Ret.) Kevin Chilton holds the Explorer Chair for Space Warfighting Studies at the Mitchell Institute for Aerospace Studies Spacepower Advantage Center of Excellence (MI-SPACE). Retiring in 2011, General Chilton completed a 34 1/2 year Air Force career as Commander of U.S. Strategic Command from 2007 to 2011. Prior to this assignment, General Chilton commanded at the wing, numbered air force, major command and unified combatant command levels, including serving as Commander of Air Force Space Command. He flew operational assignments in the R-4C and F-15 and, as an Air Force test pilot, he conducted weapons testing in various models of the F-4 and F-15. He also served 11 years as a NASA astronaut, where he flew as the Commander of STS-76, his third Space Shuttle mission, and served as the Deputy Program Manager for Operations for the International Space Station Program. General Chilton is a distinguished graduate of the U.S. Air Force Academy, with a Bachelor of Sciences degree in engineering sciences, a Columbia University Guggenheim Fellow with a Master of Sciences degree in mechanical engineering, and a distinguished graduate of the U.S. Air Force pilot training and test pilot schools. He also was awarded an honorary Doctor of Laws degree from Creighton University.

Lukas Autenried is a Senior Analyst at the Mitchell Institute for Aerospace Studies Spacepower Advantage Center of Excellence (MI-SPACE). Prior to joining the Mitchell Institute, Lukas Autenried was an Analyst at the Center for Strategic and Budgetary Assessments (CSBA), where his work focused on the development of new operational concepts, force planning, operations research, and defense budgeting and resourcing. He was also previously a Research Assistant for the Finance and Private Sector Development team at the World Bank and worked for the U.S. Department of State's Bureau of Political-Military Affairs and the Woodrow Wilson Center. He's an expert in force development, aerospace concepts and capabilities, defense budgets, and wargaming. He holds a Bachelor of Arts in Government and History from Georgetown University and a Master of Arts in Strategic Studies and International Economics from the Johns Hopkins University School of Advanced International Studies.

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