MARCH 2017

Implications of Ultra-Low-Cost Access to Space

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A Report of the

CSIS AEROSPACE SECURITY PROJECT

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Contents

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Executive Summary

Since the advent of the space age, a primary constraint on military, commercial, and civil space missions has been the cost of launch. Launching objects into space requires substantial investments in launch systems and infrastructure, which has restricted the market to only a handful of national governments and several large private companies. This paper explores the possibility of a space industry significantly less constrained by the cost of access to space.

To understand a future where the cost of access to space is only a fraction of what it is today, CSIS turned to a curated group of space experts including launch providers, satellite manufacturers, government analysts, space law practitioners, and military strategists. This report details trends in low-cost access to space, identifies key opportunities for further cost reductions and policies needed to spur innovation, and explores new military missions that would be enabled if these trends lead to significant reductions in the cost of access to space.

Potential Disruptions in the Cost of Access to Space

This report first examines some of the potential disruptions in the space market that could significantly reduce the cost of access to space. Reductions in launch costs could occur in many ways, including economies of scale and learning efficiencies, novel propulsion systems, fully or partially reusable launch vehicles, and streamlined launch operations. Commercial companies are also developing on-orbit servicing and on-orbit mining and manufacturing capabilities that could reduce the cost of access to space by reducing the amount of mass that needs to be launched. Although these disruptions may seem promising, each of these disruptions on its own is not likely to reduce the cost of access by an order of magnitude or more. Rather, it is the combination of these disruptions that together could lead to ultra-low-cost access to space (ULCATS).

Policy Implications

Just as there are a variety of disruptions occurring in the space launch market that could lead to low-cost access to space, there are also a variety of ways in which the U.S. government can access, leverage, or respond to innovative and disruptive technologies. To achieve the full potential of ULCATS, the government will need to adopt policies that allow it to both enable and benefit from innovations from many different sources. This approach may entail modifications in how the government buys and manages launches for its purposes, how it encourages and supports innovation by traditional space providers, how it utilizes services from commercial players in the space market, and how it accesses innovation occurring entirely beyond the usual government sphere of influence.

If ULCATS is achieved, the commercial space market is likely to be a driving force behind it. To encourage these developments, the U.S. government should adopt policies that foster innovation in commercial space companies and support the commercial space marketplace by creating more-flexible approaches to intellectual property, building government expertise in the global space market, investing in key dual-use technologies and efficient launch infrastructure, and leveraging its approach with that of its allies.

Given the importance of the commercial space market to lowering the cost of access to space, the U.S. government's approach to shaping the continued development of the commercial space market is critical. The current U.S. regulatory structure for commercial space is made of a consortium of agencies that handle licenses related to their field. For example, the Federal Aviation Administration manages licenses for launch and reentry requests. However, this patchwork of agencies creates an inefficient and difficult system for commercial companies in the space market. To support, promote, and shape ULCATS developments, the U.S. government needs to develop a streamlined and minimally burdensome regulatory process with available licenses that address the full set of commercial space missions.

Impacts on Military Space Operations

The final section of this report examines how a significant reduction in the cost of access to space would affect military space operations. The way the military uses space today has been shaped in no small measure by the high cost of access to space. Many of the current constellations of military satellites were designed to use a small number of large, highly aggregated satellites to reduce launch costs. The cost of access to space, especially the cost of launch, has also meant that many potential space missions have been deemed infeasible, such as space-based kinetic ground attack weapons, space-based missile defense and antisatellite systems, and space-based directed-energy systems. However, if the cost of access to space were reduced significantly, some of these missions could become feasible. ULCATS could also enable space transportation and logistics for the military, which could create new military capabilities, such as the ability to deploy small numbers of special operations forces around the world in minutes. If ultra-low-cost access to space develops in large part due to advances in commercial space technologies, as this report suggests is likely, the technology could spread globally. Lower cost of access, specifically lower-cost launch vehicles, could allow other nations to proliferate missile technology, including intercontinental ballistic missiles, which would create significant secondary effects for the U.S. military.

1. Introduction

The United States is arguably at an inflection point for civil, commercial, and military space systems. Commercial space activity has been steadily accelerating over the past decade, and forecasts are projecting a surge in space activity over the coming decade.[1] Despite this growth, many skeptics recall the 1990s when innovations in space technology and plans for commercial space systems grew to the point where the promise of low-cost access to space seemed just around the corner—only to never materialize. However, with the increase in commercial space activity led by several billionaire investors and an expanding military space presence, this space revolution may have staying power. Many of the current developments and disruptions in the space industry have the potential to significantly alter the global space market. This study evaluates likely disruptions that would drive down the cost of access to space, U.S. government policy and regulations that will be affected by a subsequent increase in space activity, and the new military missions and operations that could be enabled by ultra-low-cost access to space. To study the disruptions that could impact the cost of access to space, the study team began with a few essential assumptions and definitions.

First, the phrase "cost of access to space" is used in a specific way in this report. It refers to the cost of placing and maintaining a capability in space. It is not only, or even primarily, launch costs. While today the cost of a space launch vehicle is a major factor in the cost of access to space, other costs such as the cost of launch infrastructure, launch operations, and the size and number of payloads required to operate a capability in space, contribute greatly to the cost of access to space. For this report, "ultra-low-cost access to space" (ULCATS) indicates a reduction by an order of magnitude or more, as measured by total effective cost per pound delivered to orbit. For example, this would mean the cost of launching a typical communications satellite to geosynchronous orbit (GEO) would be in the range of $10 million, rather than the $80 million to $120 million today.

This study also assumes that commercial companies will likely be the primary driver of any significant reduction in the cost of access to space. Moreover, it is assumed that commercial space will grow as a fully international market in which national governments play a limited but essential role. Like many emerging technologies developed in the commercial sphere, governments will not hold complete control over the technology's dissemination in the global market. Also, while smarter government approaches to purchasing launch may cause some cost reductions, major reductions are likely to be driven by significant growth in commercial space activity. Global entities will be able to buy these technologies or use them as services. However, governments will remain essential in supporting the research and development of space technologies and enabling them to emerge on the global market.

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[1] Space Foundation, "The Space Report 2015," https://www.spacefoundation.org/sites/default/files/downloads/The_Space_Report_2015_Overview_TOC_Exhibits.pdf.

In this report, "commercial space activity" refers to space activity carried out by private-sector firms and individuals in a market that exists primarily to serve private-sector needs. There can and often will be substantial government involvement in that market. Importantly, the sale of a commercial service to the government does not remove the "commercial" nature of the activity. In this sense, the meaning as used in this report is close to the concept of commercial item used in government contracting, but without the exacting market analysis often required to receive a commercial item determination from the government.[2] As part of this research, the CSIS study team conducted two private workshops with participants from industry, the U.S. Congress, law, academia, nonprofits, other think tanks, international partners, and U.S government agencies. These participants contributed a wide array of ideas and experiences to the discussion, which helped inform the study team's research and writing.

The report begins by identifying key areas of disruptions that could lead to ULCATS: launch vehicle costs, launch operations costs, on-orbit servicing, and on-orbit manufacturing and mining. While it is not intended to be an exhaustive accounting of all possible disruptions, it highlights some of the key ways in which ULCATS can be achieved. The discussion then moves to the policy implications of these disruptions and the potential policy and acquisition strategies the U.S. government could employ to enable and sustain ULCATS. This discussion includes a description of the current U.S. regulatory structure for commercial space, how ULCATS could stress that structure, and changes that may be needed to U.S. government regulations and licensing structures. The report concludes by evaluating the new military missions, space architectures, and operational concepts that ULCATS could enable, as well as potential secondary effects that could impact the space market and global security environment.

[2] Office of the Secretary of Defense, Acquisition, Technology and Logistics, *Commercial Item Handbook 2.0* (Washington, DC: U.S. Department of Defense, November 2012), www.acq.osd.mil/dpap/cpic/draftcihandbook08012011.docx.

2. Potential Disruptions in the Cost of Access to Space

Disruptive breakthroughs that could significantly reduce the cost of access to space may come in many forms. Technological advances could reduce the cost of launch vehicles, improve or simplify ground operations, and develop on-orbit servicing and manufacturing to reduce the amount of mass that needs to be launched. This chapter explores a range of potential disruptions and the combinations of factors that could reduce the total effective cost per pound delivered to orbit by an order of magnitude or more.

Launch Vehicle Costs

One of the most frequently touted and pursued methods for reducing the cost of access to space is making launch vehicles themselves less expensive. In particular, building launch vehicles in much greater quantities is often cited as a key method for reducing costs, the theory being that larger production quantities can enable economies of scale and learning efficiencies that reduce the costs of manufacturing.

Economies of Scale and Learning Efficiencies

Economies of scale are gained when the rate of production increases to a higher threshold level that allows for changes in the manufacturing process and the procurement of inputs that would otherwise not be economical at lower production rates. For example, a much higher production rate for a launch vehicle could allow the manufacturer to invest in more advanced automated processes and assembly systems that reduce touch labor and drive down unit costs. This creates a dilemma for industry because without a clear demand for large quantities of launch vehicles it cannot make the investments needed to achieve economies of scale in production. However, without reductions in the unit cost of launch vehicles, the demand for launch vehicles is unlikely to rise significantly. Because the space launch industry has so far existed in a relatively low-demand environment, with production typically limited to a handful of vehicles per year per type, the price elasticity of demand remains largely unknown. In other words, it is difficult to know with any certainty how much of a drop in price would be needed to significantly stimulate demand.

Learning efficiencies are distinctly different than economies of scale and can occur in parallel. Whereas economies of scale can come from shifting to a different manufacturing process, learning efficiencies are derived from repeating the same process over and over. Researchers at McCook Field (what is today known as Wright-Patterson Air Force Base) first quantified the learning curve effect in the 1920s. They found that the amount of direct labor required for airplane assembly declined by a constant percentage every time the quantity doubled.[3] For example, the second airplane requires only 80 percent of the labor as the first, and the fourth airplane requires 80 percent of the labor as the second, and so on.

The learning percent varies by different industries, but for aerospace systems it typically falls within the range of 80 to 90 percent.[4] Assuming a learning percent of 85, the number of items produced would need to increase by a factor of more than 18,000 for the unit cost to fall by a factor of ten. Therefore, assuming only learning efficiencies, the cost of the one-millionth launch vehicle of a particular type would be about one-tenth the cost of the 60th launch vehicle of that type. While learning efficiencies from large production runs can help reduce costs, they are unlikely to yield order-of-magnitude reductions on their own.

Novel Propulsion Systems

Another potential disruptor that could reduce launch vehicle costs is the development of novel propulsion systems. Rocket propulsion relies on expelling mass out of a rocket in the opposite direction of flight to accelerate the vehicle. Since the beginning of the space age, launch vehicles have used chemical propulsion systems of one kind or another. In a chemical propulsion system, the energy used to expel mass at a high velocity comes from breaking chemical bonds (e.g., combustion) and the mass being expelled is the byproduct of the chemicals' reactions that occur. In a liquid oxygen / liquid hydrogen propulsion system, for example, the energy comes from combusting hydrogen and oxygen and the mass expelled from the rocket is H20 (water vapor).

Currently, only chemical propulsion systems have been demonstrated at the high levels of thrust needed for launch. Ion propulsion, which uses electrical power to expel mass at a high velocity, is used on some satellites for station keeping. While ion thrusters are highly efficient—roughly an order of magnitude better in terms of specific impulse (I_{sp})—they only produce thrust at very low levels. For example, the NASA Evolutionary Xenon Thruster (NEXT)—arguably the most advanced ion thruster to date—has a maximum thrust of just over 0.05 pounds of force.[5] In comparison, the RD-180 rocket engine used on the Atlas V launch vehicle produces 860,000 pounds of force at liftoff.[6]

Novel forms of propulsion have been proposed that could one day dramatically disrupt the cost of launch vehicles. Escape Dynamics, a small start-up based in Colorado, began work on a propulsion system in 2010 that would use high-powered microwave beams transmitted from ground stations to power a thermal thruster on a launch vehicle. The concept, if successful, may have resulted in significant reductions in launch vehicle costs. However, the

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[3] Miguel A. Reguero, *An Economic Study of the Military Airframe Industry* (Ohio: Wright-Patterson Air Force Base, Department of the Air Force, October 1957), 213–14, https://babel.hathitrust.org/cgi/pt?id=uc1.b3289166;view=1up;seq=239.
[4] Defense Acquisition University, "Defense Manufacturing Management Guide for Program Managers," October 16, 2012, 292, https://acc.dau.mil/docs/plt/pqm/mfg-guidebook-10-16-12.pdf.
[5] George R. Schmidt, Michael J. Patterson, and Scott W. Benson, *The NASA Evolutionary Xenon Thruster (NEXT): The Next Stop for U.S. Deep Space Propulsion* (Cleveland, OH: NASA Glenn Research Center, 2008), 3, https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20080047732.pdf.
[6] United Launch Alliance (ULA), *Atlas V Launch Services User's Guide* (Centennial, CO: ULA, March 2010), 1–5, http://www.ulalaunch.com/uploads/docs/AtlasVUsersGuide2010.pdf.

company abandoned work on this project in 2015 citing the high costs of completing the research and development required to make the system economically feasible.[7]

The National Aeronautics and Space Administration (NASA) is in the process of testing a new impulsive thruster system known as an EM Drive. In theory, the thruster works by directing microwaves into a closed truncated cone, which pushes against the cone and propels the device forward. This would seem to violate Newton's conservation of momentum, but a recently published paper by NASA scientists suggests that the EM Drive works in practice. The scientists measured a thrust of 0.00027 pounds of force per kilowatt of power applied.[8] Thus, to achieve thrust of the scale of the RD-180 engine, the thruster would require some 3.2 terra watts of power—the approximate output of 400 of the largest power plants in the world combined. This technology—if it proves to be legitimate—would only be useful for in-space applications, such as station keeping for satellites, rather than launch. While novel propulsion systems may one day provide a technological breakthrough that lowers launch costs, there do not appear to be any technologies poised to do so in the foreseeable future.

Reusability

Perhaps the most promising means to reduce launch vehicle costs is to make the vehicles reusable. If an entire launch vehicle could be reused 10 times with minimal maintenance between flights, it could in theory reduce the effective vehicle cost by roughly an order of magnitude. Importantly, the savings from reusable vehicles is somewhat exclusive of the savings that can be achieved from economies of scale and learning efficiencies because making vehicles reusable means that fewer would need to be built. The now-retired Space Shuttle reused the solid rocket boosters and orbiter but not the external tank. More recently, SpaceX and Blue Origin have demonstrated a fly-back capability that allows for reuse of their first-stage boosters by landing them vertically on a pad. While neither of these companies has demonstrated reuse of an upper stage, United Launch Alliance has announced plans for a new upper stage, the Advanced Common Evolved Stage (ACES), which would have some limited reusability for maneuver and potentially on-orbit servicing.[9]

Reusability has the potential to make space launch more like commercial aviation, where payloads (satellites) are launched and the vehicle (or major components of the vehicle) is returned and quickly readied for another launch. This was the original vision for the Space Shuttle when it was designed in the 1970s. Launch costs for the shuttle were predicted to be as little as $10.5 million per flight in 1972 (roughly $49 million in today's dollars). But as John Logsdon, professor emeritus at George Washington University's Elliott School of International Affairs, has noted, "the cost of operating the shuttle turned out to be at least 20 times higher

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[7] Escape Dynamics closed its doors at the end of 2015 citing technical risks and uncertainty in cost and timeline and no longer has a working company website. However, an overview of their external propulsion launch system can be found here: https://csis-prod.s3.amazonaws.com/s3fs-public/170112_Dynamics_External_Propulsion.pdf.
[8] Harold White et al., "Measurement of Impulsive Thrust from a Closed Radio-Frequency Cavity in Vacuum," *Journal of Propulsion and Power* (November 2016), http://arc.aiaa.org/doi/10.2514/1.B36120.
[9] Jonathan Barr, *ACES Stage Concept: Higher Performance, New Capabilities, at a Lower Recurring Cost* (Centennial, CO: ULA, 2015), http://www.ulalaunch.com/uploads/docs/Published_Papers/Upper_Stages/ACES-Stage_Concept-AIAASpace_2015.pdf.

than was projected."[10] After each mission, the orbiter and solid rocket boosters required extensive inspection and repairs, and the frequency of flight originally envisioned was never achieved. The Space Shuttle experience demonstrates that simply being able to reuse major components of a launch system does not necessarily reduce total launch costs. Reusability should be combined with other changes, particularly reductions in launch operations costs, in order to achieve significant savings.

Launch Operations Costs

Launch operations costs include both fixed and variable costs. Costs that vary with the number of launches include the integration of payloads with launch vehicles and the operation of launch pads and ranges during launch. Fixed costs that do not vary with the number of launches include the regular upkeep and maintenance of launch infrastructure and ranges between launches. Overall, launch operations are a significant factor in total launch costs. In FY 2016, for example, the military budgeted roughly $760 million in fixed costs for United Launch Alliance (ULA) to maintain its launch infrastructure for the Delta IV and Atlas V families of launch vehicles, with the Air Force paying 75 percent of ULA's costs and the National Reconnaissance Office funding the remaining 25 percent.[11] The government pays separately for variable launch costs based on the number of launch vehicles it acquires from ULA. In FY 2016, the Air Force budgeted $680 million in variable costs for four launch vehicles from ULA.[12] Importantly, these fixed and variable costs only include the costs incurred by ULA and not launch-operation costs paid directly by the government, such as the costs of government-furnished facilities and personnel.

Increasing the number of launches is perhaps the most immediate way to reduce launch-operation costs. With increased launches from any given launch site, fixed costs could be spread more broadly and thus lower the effective cost per flight. Variable launch operation costs are largely driven by labor, such as the ground crew personnel needed for payload integration, testing, and launch vehicle operations. With more launches, these personnel would gain more experience and progress down the learning curve more quickly. However, even tripling or quadrupling launch frequency would not achieve an order-of- magnitude reduction in launch operation costs.

More substantial reductions in launch operation costs could be achieved by fundamentally altering the preflight testing regime and payload integration process to operate more like aviation. Currently, satellites are often delivered to the launch facility one or two months in advance of launch to undergo extensive preflight checks before being fueled and encapsulated in the payload faring. These preflight operations typically occur in a cleanroom environment, which adds to the complexity and cost. The payload faring with the satellite inside is mated with the launch vehicle in a final assembly building and then rolled out to the

[10] John M. Logsdon, "Was the Space Shuttle a Mistake?," *MIT Technology Review* (October 2012), https://www.technologyreview.com/s/424586/was-the-space-shuttle-a-mistake/.
[11] U.S. Department of Defense (DoD), *LI MSEELC - Evolved Expendable Launch Capability* (Washington, DC: DoD, February 2016), 2, http://www.dtic.mil/procurement/Y2017/AirForce/stamped/U_P40_MSEELC_BSA-1_BA-1_APP-3021F_PB_2017.pdf.
[12] Ibid.

launch pad. Additional tests are conducted on the launch pad to ensure the payload and launch vehicle are in good order. SpaceX, for example, conducts a full static test firing of its first stage just before launch with the payload mated.[13]

Shifting to a more aviation-like model for preflight operations could be possible with advanced reusable launch vehicles. Since the vehicles would be designed to fly repeatedly, testing between launches could be reduced to something more akin to the walk-around inspection conducted by pilots before a flight. More importantly, to achieve aviation-like efficiency in ground operations, payload integration with the launch vehicle would need to be accomplished within hours, rather than days or weeks, which would mean open-air payload integration at the launch pad and satellites that are designed to tolerate open-air conditions.

On-Orbit Servicing

Another potential disruption that could significantly reduce the cost of access to space is on-orbit servicing. On-orbit servicing vehicles can be used to reposition satellites so they do not expend their own propellant for routine station-keeping maneuvers and to upgrade satellites with new capabilities by swapping out sensors and communications modules with the latest technology as long as the core satellite bus remains functional.[14] Servicing can also be used to repair satellites on-orbit by replacing failed components or fixing mechanical issues, such as a solar array that fails to deploy. Reusing components and extending the life of satellites would ultimately have the same effect as reducing launch costs because less mass would need to be launched. For example, instead of launching an entire 5,000 kg satellite when new or upgraded capabilities are needed, a 500 kg payload could be launched and added to an existing satellite. Reducing the amount of mass that needs to be launched into orbit by an order of magnitude can decrease the effective cost of access to space by an order of magnitude.

On-orbit servicing is not new technology. NASA conducted five manned servicing missions to the Hubble Space Telescope in low-Earth orbit (LEO) from 1993 to 2009. The first servicing mission corrected a critical flaw in the telescope's primary mirror. Subsequent missions replaced and upgraded instruments, repaired failed instruments, and installed new batteries, new gyroscopes, new solar panels, and a new computer. Astronauts trained for years in advance of each mission to service Hubble . Many of the most expensive and massive commercial and military satellites, however, reside in geosynchronous orbit (GEO), an environment less hospitable for humans. For on-orbit servicing to be economically viable and disruptive to the cost of access to space, it will need to be conducted robotically in a variety of orbits from LEO to GEO.

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[13] Chris Bergin, "SpaceX test fires returned Falcon 9 booster at McGregor," NASASpaceFlight.com, July 2016, https://www.nasaspaceflight.com/2016/07/spacex-returned-falcon-9-booster-mcgregor/.
[14] A satellite bus is the core infrastructure of a satellite that includes power, control, navigation, communications, and other subsystems that support one or more payloads on the satellite. A single satellite bus can be used in many different satellite designs.

Several efforts are already underway to build and deploy on-orbit servicing vehicles. The Defense Advanced Research Project Agency's (DARPA) Robotic Servicing of Geosynchronous Satellites (RSGS) program is intended to be a public-private partnership to develop a GEO robotic servicing vehicle capable of conducting "dozens of missions over several years."[15] Separately, Orbital ATK's on-orbit satellite-servicing venture ViviSat has announced plans to develop its own servicing vehicle, known as the Mission Extension Vehicle (MEV), independent of government support.[16] In both cases, the business model envisioned for on-orbit servicing is that satellite operators, both government and private sector, would be able to purchase servicing as needed from a servicing vehicle operator. Thus, one servicing vehicle could potentially service dozens of satellites from multiple customers over the course of its life.

On-Orbit Mining and Manufacturing

Similar to on-orbit servicing, on-orbit mining and manufacturing could significantly decrease the cost of access to space by reducing the amount of mass that needs to be launched from Earth. This could be achieved by mining raw materials from asteroids and other celestial bodies or recycling manmade objects already in space, such as dead satellites. These materials could then be fashioned into usable components in space using three-dimensional printing or other manufacturing techniques, and assembled robotically with components from Earth to create fully functional satellites.

Companies such as Planetary Resources and Deep Space Industries are beginning work on asteroid mining capabilities. The first step planned for both companies is to survey prospective asteroids in orbits around the Sun that are similar to Earth's orbit. Once an asteroid is identified with materials of interest, such as water, carbon, and various metals, a probe can be dispatched to rendezvous with the asteroid and extract materials. Moving mass from an asteroid in a near-Earth orbit to LEO requires less energy than launching that same mass from the surface of the Earth to LEO.[17] Thus, using materials sourced in space could significantly reduce overall launch requirements, but not likely by an order of magnitude unless combined with on-orbit manufacturing and other innovations.

On-orbit manufacturing could be used to turn raw materials into satellite components. Manufacturing in the zero-g vacuum of space presents many challenges, but NASA is making some progress in this area. In March 2016, NASA installed the Additive Manufacturing Facility (AMF) on the International Space Station in partnership with the private firm Made In Space. The AMF is a three-dimensional printer designed to operate in microgravity. It can print polymer components up to 14 cm by 10 cm by 10 cm.[18] While the manufacture of more complex satellite components, such as reaction wheels and batteries, are still beyond reach,

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[15] Defense Advanced Research Projects Agency (DARPA), "Program Aims to Facilitate Robotic Servicing of Geosynchronous Satellites," March 2016, http://www.darpa.mil/news-events/2016-03-25.
[16] Peter B. de Selding, "Orbital ATK believes in satellite servicing, but not rocket reusability," *Space News*, March 2016, http://spacenews.com/orbital-atk-believes-in-satellite-servicing-but-not-in-rocket-reusability/.
[17] L.M. Shoemaker and L.E. Helin, *Earth-Approaching Asteroids as Targets for Exploration* (Pasadena, CA: Division of Geological and Planetary Sciences, California Institute of Technology, 1978), http://www.clowder.net/hop/railroad/Shoemaker_Helin_1978.pdf.
[18] Made In Space, "Additive Manufacturing Facility (AMF)," http://www.madeinspace.us/projects/amf/.

the on-orbit fabrication of basic structures from composite and metal alloy materials may be feasible within the near future.

Perhaps the single-most-beneficial material to mine and manufacture in space is propellant. It is possible to make high-energy propellants from water and carbon dioxide, given a sufficient source of electrical power. For example, electrolysis can be used to separate hydrogen and oxygen from water, and the resultant hydrogen can be combined with carbon dioxide to make methane (CH4) and additional water. Both SpaceX and Blue Origin are currently designing methane-powered rocket engines with the specific intent of using propellants manufactured in space for return missions from other celestial bodies.[19]

Implications of Disruptions for the Cost of Access to Space

As the foregoing discussion makes clear, there is no single source of disruption that is likely to deliver an order-of-magnitude reduction in the cost of access to space in the near to mid-term. However, there is potential that a combination of the disruptions discussed could together result in truly significant reductions in the cost of access to space. These disruptions would cause the global space market to change, and as governments around the world seek to leverage these changes to their advantage, the United States will need to adjust its policies to advance U.S. interests.

[19] Kim Newton, "NASA Tests Methane-Powered Engine Components for Next Generation Landers," National Aeronautics and Space Administration (NASA), October 28, 2015, https://www.nasa.gov/centers/marshall/news/releases/2015/nasa-tests-methane-powered-engine-components-for-next-generation-landers.html.

3. Policy Implications of Disruptions

Just as there are a variety of disruptions occurring in the space launch market that are driving the potential for low-cost access to space, there are also a variety of ways in which the U.S. government can access, leverage, or respond to disruptive technologies and innovative approaches to space. To achieve the full potential of ultra-low-cost access to space, the government will need to adopt policies that allow it to both enable and benefit from innovations from many different sources. This approach will entail potential modifications in how the government buys and manages launches for its purposes, how it encourages and supports innovation by traditional space providers, how it utilizes services from commercial players in the space market, and how it accesses innovation occurring entirely beyond the usual government sphere of influence.

The Center of Innovation Matrix

A September 2015 CSIS study titled "Keeping the Technological Edge: Leveraging Outside Innovation to Sustain the Department of Defense's Technological Advantage"[20] uses a framework, the Center of Innovation Matrix (see Figure 1), to describe the variety of innovation sources and how they relate (or don't, as the case may be) to the Department of Defense (DoD). This construct provides a useful framework for analyzing the different ways in which the DoD, or in this case, the U.S. government more broadly, can both facilitate and respond to innovation in space. The key insight captured by this matrix is that the U.S. government can support and benefit from innovation in different ways depending on the source of the innovation. Realizing the potential for ULCATS depends on the U.S. government actively pursuing innovation in all quadrants of the matrix.

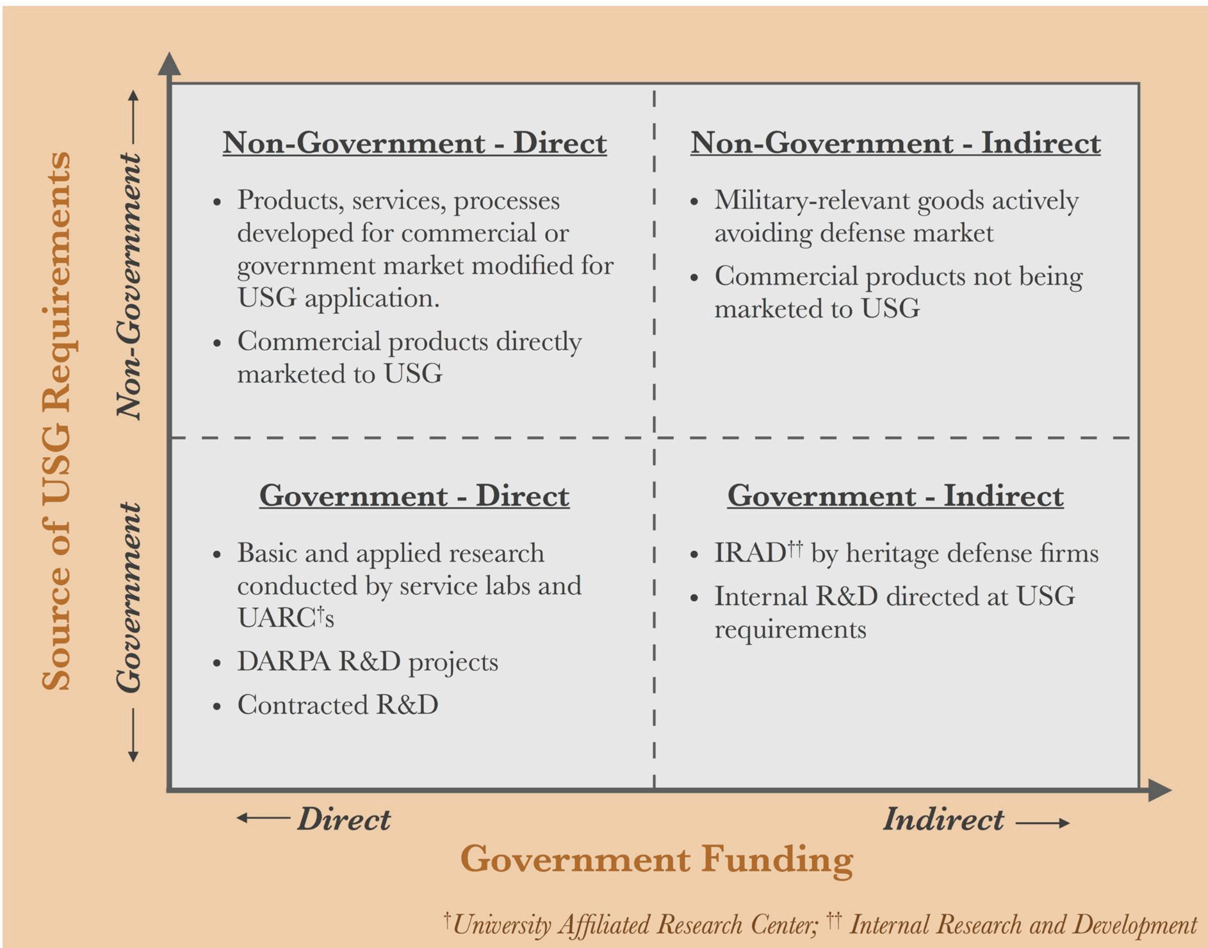
Government–Direct

In many high-technology sectors of the economy, governments remain the dominant players in the market. This has certainly been the case historically in space. U.S. government and Soviet/Russian investments in space dwarfed the space activity of all other participants until the mid-1990s, and early investments in programs like the Atlas and Saturn rockets provided the foundation for the U.S. space industry. In recent decades, Europe, China, Japan, and India have become players in the space market, but much of this activity remains government controlled and directed. Direct government activity in space, such as government launches by the United Launch Alliance, falls in the government-direct quadrant of the matrix, as this activity responds to government requirements and is financed by government resources. Government drives innovation in this quadrant when it chooses to invest in developing new capabilities to meet government needs. An example is NASA's

[20] Andrew P. Hunter and Ryan A. Crotty, *Keeping the Technological Edge: Leveraging Outside Innovation to Sustain the Department of Defense's Technological Advantage* (Washington, DC: CSIS, September 2015), https://www.csis.org/analysis/keeping-technological-edge-0.

investment in the Space Launch System, a new rocket designed to launch NASA payloads for deep-space missions.[21] Another example of a government-direct investment is the development of a new U.S.-origin rocket engine, the AR1, to replace the Russian RD-180 engine currently in use on the Atlas V.[22] This engine will be financed mostly with direct government funding, although the manufacturer, Aerojet Rocketdyne, has indicated it will invest its own resources in the project making this a hybrid-case with aspects of government-indirect.

Figure 1: Center of Innovation Matrix



Source: Adapted from Hunter and Crotty's "Keeping the Technological Edge," the Center of Innovation Matrix describes how sources of innovation relate to the U.S. government. Items that appear lower in the matrix have increasingly more government requirements than nongovernment requirements. Items that have more direct government funding than indirect government funding appear further towards the left in the matrix.

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[21] NASA, "Space Launch System," fact sheet, October 2015, https://www.nasa.gov/sites/default/files/atoms/files/sls_october_2015_fact_sheet.pdf.

[22] Brian Berger, "Aerojet Rocketdyne pitches AR1 as the only direct replacement for RD-180," *SpaceNews*, April 12, 2016, http://spacenews.com/aerojet-rocketdyne-pitches-ar1-as-the-only-direct-replacement-for-rd-180/.

Nongovernment–Direct

Almost from the beginning of the "Space Age," space has seen market activity by nongovernment actors. Launches of commercial telecommunications satellites began in the 1960s, including Telstar I (1962) and Intelsat's Early Bird (1965). This activity falls in the nongovernment part of the matrix because it is being carried out by commercial firms, and is aimed primarily at meeting the needs of telephone companies and television broadcasters for global communications. However, commercial space services are also commonly purchased by governments, and so receive direct financial support in the form of revenues.[23] In fact, early commercial space launches commonly used government-provided launch vehicles and launch infrastructure, a very concrete form of government support.[24] Even today when there is a robust commercial market for space-based communications and remote sensing, most commercial space launches utilize government-provided launch infrastructure, including non-U.S. launch facilities. So while this activity is not primarily aimed at military needs, governments still have direct influence in this quadrant. Telstar is an example of an activity in the nongovernment-direct quadrant because it was built by AT&T's Bell Laboratory to sell primarily to commercial customers. As is true more broadly of commercial satellite communications capabilities today, most are developed to meet the needs of nongovernment customers but the government plays a significant role in providing supporting services and capabilities as well as revenue.

Commercial remote sensing, such as that provided by the firms GeoEye and DigitalGlobe, was originally designed to serve private-sector needs for satellite imagery at a time when the U.S. government relied on its own imagery satellites to meet military and intelligence needs. Despite their principal commercial use, imagery services provided by commercial firms have served a variety of U.S. government needs from the beginning. These include purchases by the U.S. government of unclassified imagery that is shareable with partners, allies, and the U.S. public and imagery where collection by non-U.S. government assets better serves the national interest. Of particular note is that even from the earliest days the U.S. government recognized that commercially available remote sensing capabilities could potentially provide advanced capabilities to foreign powers, raising significant policy issues relating to export controls.[25] SpaceX also presents a significant example of the power of nongovernment-direct innovation. SpaceX has modeled itself from its inception as a provider of commercial launch capabilities. However, government usage of SpaceX by both NASA and the U.S. Air Force has translated into major government purchases of SpaceX's commercial launch services.

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[23] Defense Business Board (DBB), *Taking Advantage of Opportunities for Commercial Satellite Communications Services: Report to the Secretary of Defense* (Washington, DC: DBB, 2013), http://dbb.defense.gov/Portals/35/Documents/Reports/2013/FY13-02%20Taking%20Advantage%20of%20Opportunities%20for%20Commercial%20Satellite%20Communications%20Services.pdf.

[24] Federal Aviation Administration (FAA), "Origins of the Commercial Space Industry," n.d., https://www.faa.gov/about/history/milestones/media/Commercial_Space_Industry.pdf.

[25] Jeffrey T. Richardson, "Declassified Documents Trace U.S. Policy Shifts on Use of Commercial Satellite Imagery from 1970s to Today: Lack of Control over Foreign Developments, Desire to Promote American Firms, and Potential Benefits Vied with National Security Concerns," National Security Archive, Washington, DC, November 27, 2012, http://nsarchive.gwu.edu/NSAEBB/NSAEBB404/.

Government–Indirect

Companies that are traditional partners of the U.S. government also invest in new capabilities outside the scope of their direct activities in support of the government. The government indirectly supports these activities because their efforts are inherently supported by profits generated from their business with the U.S. government. Intelsat is a classic example for a government-indirect market player. The company spent the first 37 years of its existence as an intergovernmental consortium established to manage a constellation of communications satellites, so multiple national governments were directly involved in its founding and management even though they were not intended as its primary customers. However, in 2001 Intelsat became a private company evolving toward more of a nongovernment-direct matrix position. In the 1990s Orbital Sciences, a company that primarily supported U.S. government space activities, entered this quadrant with its Pegasus rocket, a privately financed air-launched rocket.

The potential development of a commercial market for on-orbit servicing is an example of how government-indirect innovation can greatly affect the space sector. The U.S. government is not currently asking industry to provide it with commercially available on-orbit servicing, but aspiring commercial on-orbit service providers, such as Vivisat (a venture of Orbital ATK), are long-time participants in the government space complex. Vivisat is working to ensure that its system is compatible with a wide variety of commercial satellites, explicitly targeting commercial satellite operators as users of their products.[26] Of course, given that governments own a large proportion of on-orbit assets, it is likely that many customers for on-orbit servicing will be governments, including the U.S. government. This example demonstrates the sometimes cyclical nature of innovation. An innovation that begins with direct government support can lead to government-indirect innovation when that product is commercialized. It may then create new markets that spur competition from outside the traditional government contractors, which in turn can feed nongovernment-direct innovation when the government purchases from these new suppliers.

Nongovernment–Indirect

In mature commercial industries operating in free-market conditions, governments are not significant market actors as either investors or purchasers. This does not mean that government has no participation in the market (it may in fact purchase products and services produced in the industry), but its participation as a market actor is so small that it effectively carries no significant influence. Even markets that begin with significant government support and involvement, such as commercial passenger aviation, can reach this status. While the U.S. government routinely purchases airline tickets, its involvement in the passenger airline market as a market participant is such a small share of the overall market that the vast majority of U.S. airlines now do not shape their services specifically to meet government needs. It is important to note, however, that governments remain significant actors in most markets as regulators, and this will remain true for space launch, where the U.S. government

[26] Vivisat, "Satellite Life Extension Services," http://www.vivisat.com/?page_id=10.

has responsibility for space activities originating from U.S. persons and U.S. territory as an international treaty obligation.[27]

In recent years, a growing number of nontraditional space companies are working to access the space launch market, particularly in the area of space tourism, where the government has shown no significant interest in investing or in purchasing this service. Virgin Galactic provides one example of this kind of market participant. In this quadrant, the government's interests are best served in shaping a constructive regulatory environment that ensures the health of the industry while also protecting public safety and national security.

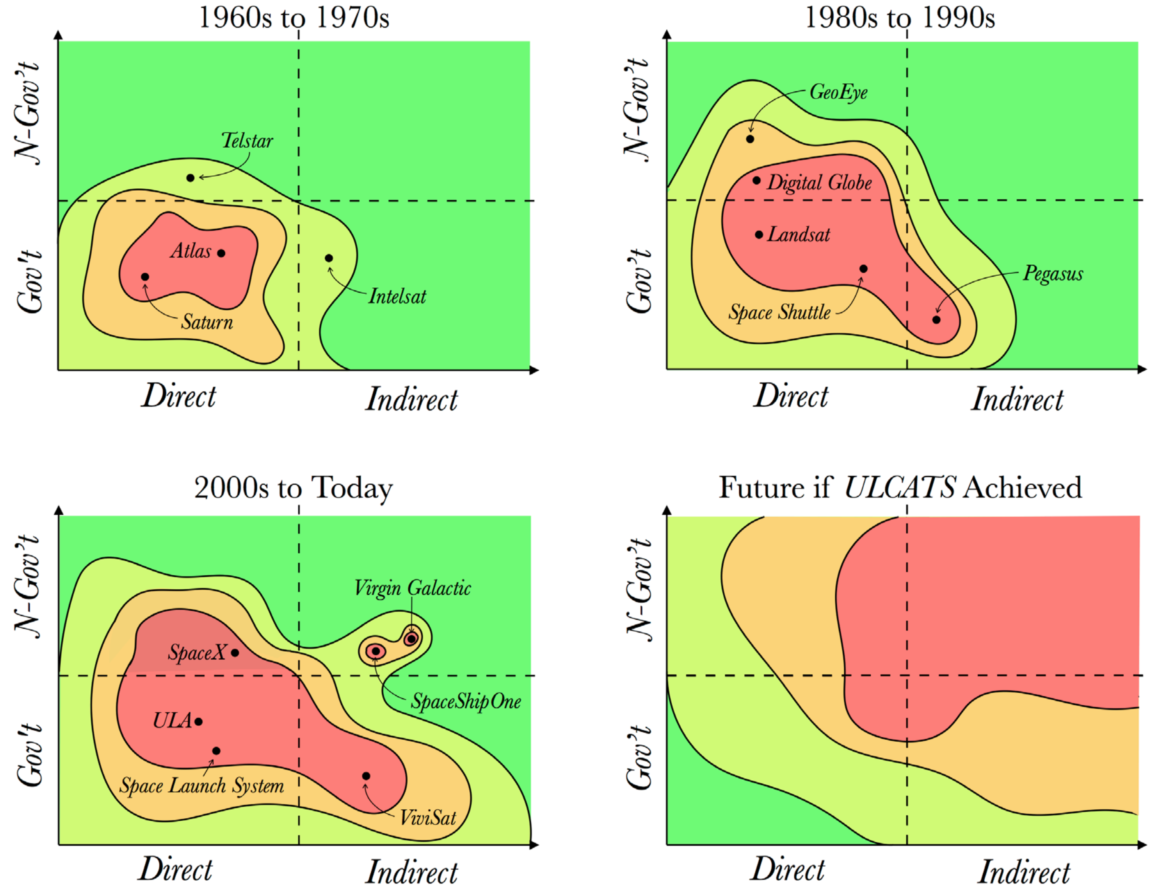
Evolution of the Space Industry on the Innovation Matrix

Starting with its inception as a government/military activity, the space industry has evolved over the years toward increasing levels of activity outside the government-direct quadrant of innovation where it began. As illustrated in Figure 2, innovation in space launch began in the government-direct quadrant with government programs such as the Atlas and Saturn rockets. In the 1960s, satellite communications developed in the nongovernment-direct (Telstar) and government-indirect (Intelsat) quadrants led by substantial commercial demand. Beginning in the 1980s and accelerating in the 1990s, other commercial space activities began to emerge with the development of robust commercial remote sensing satellites through outside players such as GeoEye and Digital Globe, and with increasing government purchases of commercial satellite communications and commercial imagery. Beginning in the 2000s and continuing in the current decade, the nongovernment-indirect quadrant has begun to develop with SpaceShipOne winning the Ansari XPRIZE in 2004 and effort to develop space tourism businesses, such as Virgin Galactic and Blue Origin.

This progression highlights an important point. Although there have been many predictions for the rapid development of commercial space over the years that have proven premature, the trend line for commercial space is nonetheless clear. It has trended upward over the last 50 years, often with significant government support and involvement. While it would be foolish to project that the development of the nongovernment-indirect quadrant of the space market will grow in a predictable linear fashion from today, it would also seem unwise to ignore the potential offered by developments in this quadrant. As the "Future" matrix above indicates, ultimately achieving order-of-magnitude reductions in the cost of access to space depends on the development of a robust commercial market. One effect of the growth of commercial space in the future is that the government's involvement as a direct market actor that sets requirements and provides direct funding may be significantly smaller, as is now the case in the aviation industry.

[27] UN Office of Outer Space Affairs, "Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, Including the Moon and Other Celestial Bodies," http://www.unoosa.org/oosa/en/ourwork/spacelaw/treaties/introouterspacetreaty.html.

Figure 2: Evolution of the Space Industry on the Innovation Matrix



Note: Each of the four subplots represents an era of the space industry. "Hotter" areas represent more activity within the global space market, and "cooler" areas represent fewer activities. The final subplot projects what a space market may look like should the cost of access to space fall by an order of magnitude or more.

Direct Government Actions to Lower the Cost of Access to Space

As the discussion of the innovation matrix illustrates, lower-cost access to space will draw upon innovative technologies and approaches coming from a range of actors both inside and outside the traditional government sphere of influence. It will utilize intellectual property (IP) and financing that is directly government supported, as well as IP and financing that is only indirectly related to government activity. Government approaches to support the development and maturation of a robust commercial space market—which is ultimately required to deliver ULCATS—should take into account the need to foster a diversity of innovation. This section focuses on how the government can use its purchasing power and policies to foster the innovations that will lower space access costs.

Build Government Expertise in Utilizing Commercial Space

Ensuring the government can leverage an increasingly robust commercial space services market means building the government's expertise in buying these services. An important transition in the U.S. government's approach to procuring access to space through commercial service agreements is already underway with NASA's commercial crew and cargo program. Under this program, NASA is using commercial services agreements with Orbital ATK and SpaceX to conduct resupply missions to the International Space Station. It is also working with industry to develop and certify U.S. commercial crew spacecraft.[28] The U.S. Air Force (USAF) is now procuring commercial space launch services from SpaceX; however, it continues to purchase launch services from ULA using traditional Federal Acquisition Regulation (FAR) Part 15 negotiated cost-plus contracts. Because there are unique cost and administrative burdens associated with each approach, this situation exacerbates an uneven playing field in USAF space launch and inhibits effective competition in this sector of the market. The USAF and other U.S. government agencies should work to use commercial space launch contracts for regularly scheduled launches to the maximum extent possible. A small percentage of these launches, such as those supporting especially large or highly valuable payloads, may need to be carried on launch vehicles using a noncommercial contract approach.

- Recommendation: The USAF and other U.S. government agencies should use commercial space launch contracts for regularly scheduled launches to the maximum extent possible.

The U.S. Air Force, National Reconnaissance Office (NRO), NASA, the National Geospatial-Intelligence Agency, the Defense Information Systems Agency, and General Services Administration should work together to build the government's expertise in the procurement of commercial space services. These agencies are currently purchasing commercial services, with varying levels of experience in this process. Better intragovernmental dialogue on the purchase of commercial space services—and what services are available—can help build expertise in each agency and provide a more consistent approach to the commercial space industry. In addition, it is essential that the government establish a robust, continuous, and two-way dialogue with the commercial space industry to share information on commercial space market developments, opportunities, and challenges.

- Recommendation: The U.S. government should establish a commercial space services community of interest to share best practices in purchasing commercial space services and to support dialogue with the commercial space industry.

Adjust and Extend Government Standards to Support Lower-Cost Access to Space

The standards that the U.S. government applies to launch providers are a major factor in the cost of government launches. Significant progress was made in this area in recent years

[28] NASA, "Commercial Resupply Services Overview," https://www.nasa.gov/mission_pages/station/structure/launch/overview.html.

when the U.S. Air Force developed a certification process for commercial space- launch providers such as SpaceX. Rather than resting on its laurels with this success, the Air Force should continue to review ways in which the launch provider certification process can be simplified so that it buys launch services in a fashion much closer to how a nongovernment commercial customer purchases these services. While some high-value national security launches will likely need to continue to meet exacting quality standards because the consequences of failure are too severe, many other types of military space services could likely accommodate a higher degree of risk, including launches of smaller payloads as part of large constellations and services for the refueling or repositioning of assets the U.S. Air Force had assumed would cease operations. By altering the risk equation for many aspects of commercial space services, the United States can lower the cost of access to space on less sensitive payloads.

A shift to a more commercial approach to purchasing launch services and higher-risk tolerance may be particularly important in the purchase of reusable launch capabilities as these develop. If commercially viable reusable launch vehicles become commonplace, the Air Force may even consider purchasing a small fleet of these vehicles to serve high-value government missions even as it continues to purchase launch as a service for many of its routine missions. Certification processes, with appropriate risk thresholds, should also be developed for emerging commercial space services, such as on-orbit servicing, to allow for competitive sourcing of these services by U.S. government customers.

- Recommendation: The U.S. government should consider taking a more commercial approach to risk in existing space certification processes and when developing certification processes for purchasing emerging space services when appropriate.

In addition, the U.S. government can help bring industry players together and participate in the development of commercial satellite interface standards that facilitate the development of robust on-orbit servicing and on-orbit modification options in future commercial satellite designs. This standards-setting approach would be intended to replicate the success that similar standards bodies have provided in advancing the development of wireless technologies and that have begun to bear fruit in the Air Force's open mission systems efforts for aircraft. The widespread adoption of such standards would not only facilitate the development of the commercial space services market, but would also likely serve to lower the cost of U.S. government satellites over the longer term by allowing the government to effectively compete satellite buses and payloads independently.

- Recommendation: The U.S. government should work with industry to develop common interface standards for satellite architectures, particularly with respect to emerging commercial space services.

Use Government Investment and Purchasing Power to Support Commercial Space

Given the significant benefits that will accrue if a robust commercial space market led by U.S. companies were to develop, there is a strong case for the government to lean forward in supporting this market. This action would be consistent with the U.S. government's past support for the development of commercial space services. The government can do so by taking a cooperative approach to the commercialization of government-supported designs, consistent with national security, to allow for the spinout of new services in the government-indirect quadrant on the innovation matrix (see Figure 1). The government can use its purchasing power to provide a base load of demand for emerging services, such as on-orbit servicing, as it has in the past through transporting air mail on commercial airlines and by purchasing large volumes of commercial satellite communications and commercial imagery in block buys. The government should also consider the development of a Civil Reserve Air Fleet (CRAF)-type approach to space launch. Under CRAF, the U.S. government pays airlines for the right of preemptive use of commercial airline capacity in cases of urgent government need. Such an approach could be useful to facilitate responsive space launch for the government particularly as capabilities develop for highly reusable launch, launchers optimized for small payloads, and regularly operating "space liners."

- Recommendation: The U.S. government should continue to support the commercialization of government-supported space technology, consistent with national security, and should consider providing a base level of demand for emerging commercial space services, potentially including the development of a CRAF-like approach to commercial space services.

The U.S. government is also the best-positioned entity to invest in cutting-edge space technologies in their early stages that are likely to have future applications to both military and commercial space approaches. The U.S. government should invest resources directly into the development of systems and software for the control and exploitation of large satellite constellations. In addition, the government should invest in developing ways to execute military space missions using significantly smaller, and in some cases distributed, payloads. Such investments can pave the way for the commercial development of large satellite constellations as well as prepare for their use in some of the new military missions identified later in this report.

- Recommendation: The U.S. government should invest in key dual-use technologies that can facilitate ULCATS such as systems for the control and exploitation of large satellite constellations, and in the development of small, distributed payloads.

Lastly, the government should invest in improving current government launch infrastructure for more efficient launch operations, and be willing to collaborate on future designs capable of significantly higher operational tempos than those possible today. There are opportunities here to partner with state and local governments that have also demonstrated interest and ability to invest in space launch infrastructure, such as the state-owned launch pad at Wallops Island, VA. In addition, the government can work with industry to develop or expand mechanisms for joint investment, such as public-private ventures, to improve launch infrastructure.

- Recommendation: The U.S. government should work with industry, and with state and local governments where appropriate, toward designing and implementing launch infrastructure capable of much higher operational launch tempos.

Leverage the Contributions of Partners and Allies in Space

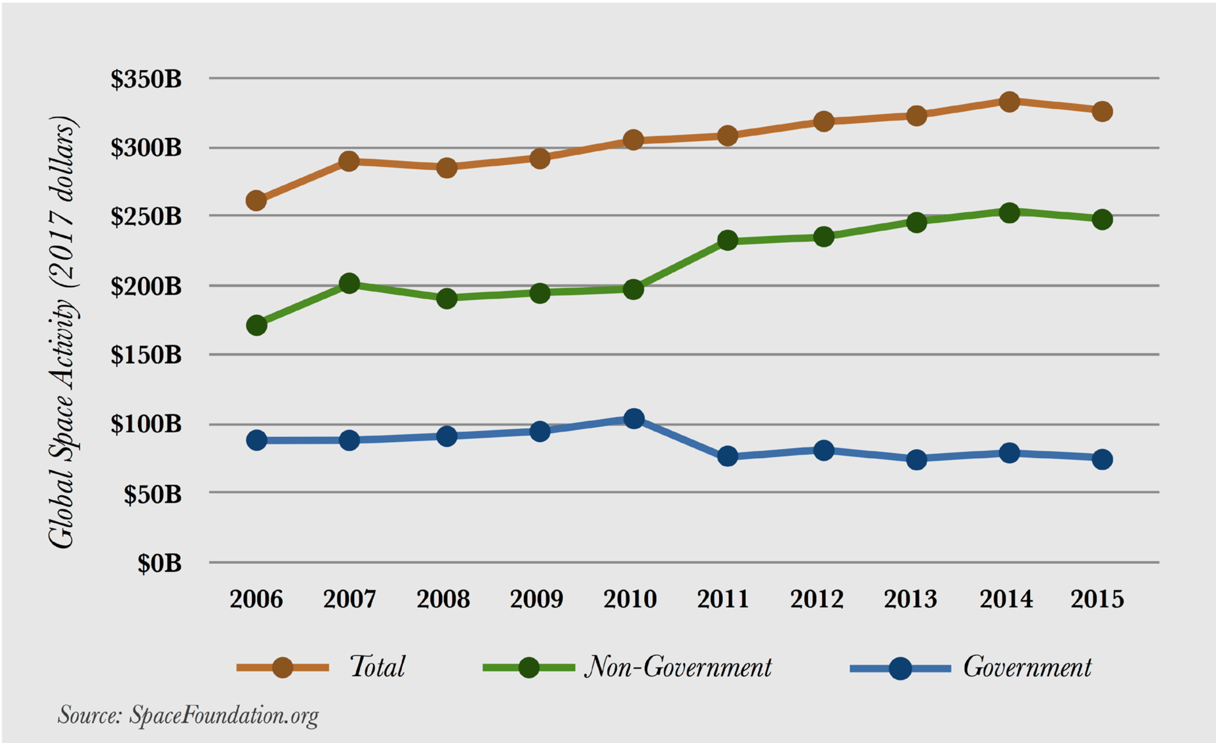
From launching foreign astronauts to sharing space-derived intelligence to the famous Canadian-developed robotic arm on the American space shuttle, the U.S has a long history of working with other nations in space. Each of the government actions discussed in this section could be strengthened or reinforced if carried out in concert with other nations. While it will not be possible or practical to engage in international cooperation for all of these efforts, there is potential application for cooperation with allies and partners in building and leveraging commercial space-buying expertise, setting appropriate standards for accepting risk, providing base load demand for space services, and investing in early-stage technologies and launch infrastructure.

- Recommendation: The United States should work with allies and partners among the leading spacefaring nations, where possible and consistent with national security, on measures to support the development of the commercial space market.

Shaping Development of the Commercial Space Market

Given the importance of the commercial space market to lowering the cost of access to space, the U.S. government's approach to shaping the continued development of the commercial space market is critical. As illustrated in Figure 3, the growth of the commercial space market has been steady in recent years. The government institutions that oversee and regulate the industry have developed in a slow manner as issues that require government involvement surface. Today's U.S. government approach to commercial space activity is essentially one of hand-crafted regulation that tailors its approach to individual launches and licenses and engages with new services as they come to fruition. This hand-crafted approach offers the government enormous flexibility to respond to new space activity as it determines appropriate, but it suffers from a lack of transparency, clarity, predictability for industry, and lacks the ability to operate at scale as commercial space activity expands. This section outlines what the U.S. government's responsibilities are in providing regulation and oversight of commercial space, how it is implementing them today, and what the government can do to shape the development of the commercial space market.

Figure 3: Global Space Market (2006–2015)



Note: This figure illustrates the change in space activity from 2006 to 2015. Activity is measured in 2017 dollars. "Nongovernment" refers to commercial infrastructure and support industries as well as commercial space products and services. "Government" refers to both U.S. and foreign government space budgets.

Government Responsibilities in Space

Space has been an international sphere from its earliest days. As with other industries that developed in the immediate post–World War II era, it was shaped greatly by the Cold War power struggle between the United States and the Soviet Union. As a result, there is an international framework for space governance, but one in which each country essentially polices its own space activities. The number of nations that have active space launch capabilities has grown well beyond the United States and Russia, but it remains relatively small. The commercial space marketplace, however, is truly global. There are customers of commercial space services in every corner of the globe. The demand signal coming from international customers greatly shapes the market, even as the main spacefaring nations make supply choices that bring new capabilities to the market. The fact that space is a highly international marketplace, but also one in which nation-states are responsible for policing their own activities, presents both challenges and opportunities to the United States for helping to shape the development of a robust commercial space market.

International Space Governance

The foundational international agreement governing space is the Outer Space Treaty, more formally known as the Treaty on Principles Governing the Activities of States in the

Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies.[29] Over 100 nations have ratified the treaty including all the major spacefaring nations. Under the treaty, nations agree to follow international law (including the Law of Armed Conflict) in outer space and each nation is “responsible for national space activities whether carried out by governmental or non-governmental entities.”[30] The treaty makes clear that nation states are liable for any objects in space as a result of their space activities. The Outer Space Treaty establishes a set of important, but fairly loose guideposts for nationally led space activity. By referencing international law generally, but not specifying how exactly this law applies to activities in space, a great deal of ambiguity is created and it is not clear exactly which entity might resolve international disputes that arise in the interpretation of the international legal framework for space. The treaty only establishes the requirement for participating nations to consult and agree to be consulted with on matters in dispute.[31]

Similar international legal dynamics exist in the maritime domain, and it is likely that even nations that might agree to a more explicit legal framework for space would only do so with potentially significant caveats and reservations, as is the case today with the United Nations Convention on the Law of the Sea.[32] Legal issues such as piracy and salvage, that are likely to be increasingly relevant in space, do not currently have clear application there. Absent U.S. leadership, these legal issues will continue to fester, possibly inhibiting the development of commercial space services. Standards may be shaped by other nations that may seek to gain advantage in the process. The United States is unique in that it has a competitive space industry and is not likely to shape international definitions and standards in a way that would favor individual firms or promote its narrow national interests.

Given these conditions, it is highly advantageous to the United States to establish sound national space governance procedures capturing best practices, including clear legal definitions, standards, and “norms” of behavior. For example, there are no widely accepted standards for how close one satellite can maneuver to another satellite and what a safe distance is for passage. The United States should lead the effort to establish these procedures as international standards that are eventually adopted by other nations.[33]

- Recommendation: The United States should lead by example and establish sound national space governance procedures, including clear legal definitions, standards, and “norms” of behavior for commercial space activity, and work to advance these approaches as the basis for the development of similar international standards.

[29] UN Office of Outer Space Affairs, “Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space.”
[30] Ibid.
[31] Ibid.
[32] UN Oceans and Law of the Sea, “Declarations and Statements: UNCLOS,” October 29, 2013, http://www.un.org/depts/los/convention_agreements/convention_declarations.htm.
[33] European Union, “EU proposal for an international Space Code of Conduct, Draft,” European Union External Action Service, Brussels, Belgium, 2014, https://eeas.europa.eu/topics/disarmament-non-proliferation-and-arms-export-control/14715_en.

The U.S. Government's Regulatory Approach to Commercial Space

Many innovative commercial space companies based in the United States are producing new technologies to bring onto the international market. These innovations, which are needed to drive down the cost of access to space, are bringing new challenges in regulation and licensing that the U.S. government needs to consider seriously if this commercial space revolution truly comes to pass.

U.S. regulations on space-related missions, such as operating imaging satellites, communications satellites, and permits for launch, are spread across several agencies making the licensing process complicated and sometimes unclear. It also creates gaps in U.S. government commercial space regulations, authorities, and licensing processes. For newly emerging technologies and ventures, regulations processes are either not comprehensive or do not exist at all. For example, companies that want to pursue innovative space technologies, such as on-orbit servicing, do not have clear regulatory or licensing authorities for all aspects of their mission. These gaps can limit innovative companies and without proper licensing it is increasingly difficult for companies to receive the investments or insurance needed to pursue these cutting-edge technologies.

National Oceanic and Atmospheric Administration

The National Oceanic and Atmospheric Administration (NOAA) provides regulations and licenses pertaining to all operations involving Earth imagery.[34] According to its statuary authority, NOAA has 120 days to issue a license.[35] However, this statutory deadline is not easily achieved, as another gap in the U.S. regulations system is the limited number of licensing personnel available. During one of the workshops CSIS conducted for this study, participants lamented that NOAA only has one licensing person on staff.[36] However efficient this licensing expert undoubtedly is, as commercial space expands the burden of licensing will grow significantly. This gap is not unique to NOAA, but to most regulatory bodies within the U.S. government that work on space-related issues. Small numbers of licensing personnel will inevitably serve as a bottleneck in the process and make it extremely difficult for fast-moving high-tech companies to pursue innovative solutions in space.

- Recommendation: Develop the mechanisms and personnel necessary at agencies reviewing space-related licenses to provide increased capacity for licensing new and existing commercial space activities.

Federal Communications Commission and the National Telecommunications Information Administration

Satellite communications companies obtain licenses at the Federal Communications Commission (FCC), which controls the frequency allocation process in order to prevent

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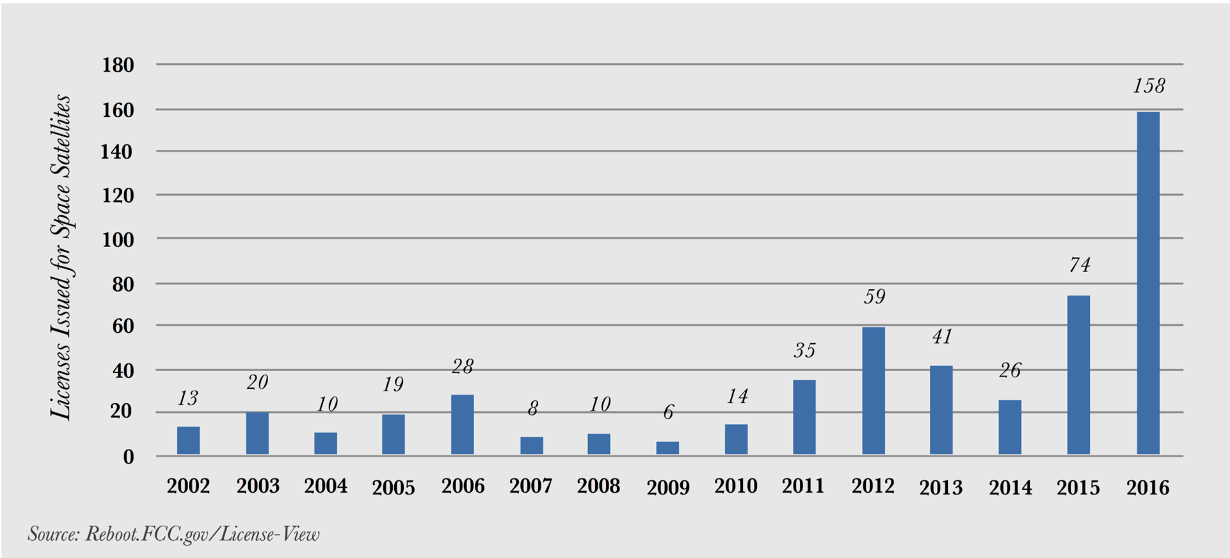
[34] National Oceanic and Atmospheric Administration (NOAA), "About the Licensing of Private Remote Sensing Space Systems," U.S. Department of Commerce, https://www.nesdis.noaa.gov/CRSRA/licenseHome.html.
[35] NOAA, "FAQ," https://www.nesdis.noaa.gov/CRSRA/generalFAQ.html.
[36] See Appendix F.

radio-frequency interference. "This includes public safety, commercial and non-commercial fixed and mobile wireless services, broadcast television and radio, satellite and other services."[37] Unsurprisingly, telecommunications companies hold the most active licenses for spectrum allocation. The FCC estimates it issued 179,154 licenses in 2016 alone.[38] Significantly, of these, 158 were space-related licenses. As shown in Figure 4, 158 licenses is more than a 200 percent increase from the number of space-related licenses issued in 2015.

Figure 4: FCC Licenses Issued for Space Satellites (2002–2016)



Note: "Space Satellite" licenses include geostationary space stations (SSGs) and non-geostationary space stations (SSNs).

Federal government spectrum allocations are allotted by the Department of Commerce through the National Telecommunications and Information Administration (NTIA). Among other responsibilities, NTIA assigns frequencies, maintains spectrum use databases, and establishes policies regarding allocation and regulation of federal spectrum use. "NTIA is also collaborating with the Federal Communications Commission to make available a total of 500 megahertz of Federal and nonfederal spectrum over the next 10 years for mobile and fixed wireless broadband use." These efforts will almost double the amount of spectrum available for commercial use.[39]

Currently the FCC holds the right to deny licenses to commercial companies in the interest of American national security. There is substantial opportunity for confusion, however, when such a license denial occurs. Since the cause of denial may relate to sensitive government activities, the government may be less than forthcoming about the reasons for the decision. The same issue often arises in the NOAA review process for Earth remote-sensing space applications. This is a serious issue in the regulatory structure as it limits the predictability and transparency of licensing for commercial space activities, concerns that will only grow as the

[37] Federal Communications Commission, "Licensing," https://www.fcc.gov/licensing-databases/licensing.
[38] Reboot.FCC.gov, "FCC License View," Federal Communications Commission, http://reboot.fcc.gov/license-view/. Data collected January 9, 2017.
[39] National Telecommunications and Information Administration, "Spectrum Management," U.S. Department of Commerce, https://www.ntia.doc.gov/category/spectrum-management.

commercial space market expands. The United States needs a policy that allows companies to understand, after being denied a license, how to amend their mission or capabilities in order to get approval for spectrum-use for their commercial space activities. This will likely require granting security clearances to a limited number of people in companies applying for licenses so that they can have a classified dialogue with the government over licenses that raise national security issues. Additionally, being clearer upfront about expectations for licensing will help alleviate the process greatly.

- Recommendation: Establish processes at the FCC, NOAA, and other agencies to communicate clearly with industry on issues likely to lead to license denial, including, where appropriate, by granting security clearances to a limited number of company personnel to facilitate classified discussions.

Federal Aviation Administration

The Federal Aviation Administration oversees the licensing of spaceports, scheduled launches, permits for reentry, and test permits across the country. A launch or reentry operator license authorizes launch or reentry from one site within a range of agreed-upon operational parameters of vehicles from the same family, with specific classes of payloads or performing specific activities. The operator licenses are effective for two to five years from the issue date.[40] Therefore, not only does the FAA regulate launch, reentry, and launch sites, it also regulates the payloads for each commercial mission.[41]

Significantly increased demand for licenses due to ULCATS calls into question whether or not the FAA is the correct organization to perform oversight on payloads. Licensing payloads is akin to licensing each person or piece of cargo that flies on a commercial airline. For commercial space launch to become more like aviation, the United States may need to transition to a system where payloads are regulated by exception—only specific items are not allowed to be launched or can be launched only if certain criteria are met. Currently the system operates successfully, but with increased demand caused by lower-cost access to space, and the potential for evaluating hundreds of launches per year instead of the 11 U.S. commercial space launches in 2016, the system will need significant support and clarity.[42] Understandably, this dramatic increase will put significant strain on FAA resources for approval of licenses, not counting the extensive process of regulating payloads. With ULCATS, the U.S. government needs to identify and resource a suitable organization to handle payload licensing.

[40] FAA, "Launch or Reentry Vehicles," https://www.faa.gov/about/office_org/headquarters_offices/ast/licenses_permits/launch_reentry/.
[41] George Nield, "Statement before the House Committee on Science Space, and Technology, Subcommittee on Space, on Necessary Updates to the Commercial Space Launch Act," February 4, 2014, http://testimony.ost.dot.gov/test/nield1.pdf.
[42] FAA, "Commercial Space Data," https://www.faa.gov/data_research/commercial_space_data/.

- Recommendation: Move toward an approach to licensing space payloads, similar to the airline model, that allows the transport of regular payloads except for specifically excluded items and consider an appropriate organization for this approach.

A launch-site license is more difficult to obtain, as the site has to go through multiple physical evaluations, as well as an evaluation with other U.S. departments, such as DoD, Department of State (DoS), and NASA, to see if the site would present any issues with "U.S. national security or foreign policy interests, or international obligations of the United States."[43]

Currently, there are 10 active approved launch sites within the United States and 12 active launch licenses that range from early December 2016 to June of 2021.[44] At today's launch rates, this small number of sites is satisfactory. However, with ULCATS, the demand for launch could increase dramatically and 10 sites may no longer be sufficient. If the U.S. government wishes to keep up with the pace of commercial launch with ULCATS, many more sites could be needed even if launch throughput rates are increased. Some states are taking it upon themselves to develop launch facilities.

- Recommendation: The FAA should monitor the development of U.S. launch site capacity to determine whether it is unduly constraining the development of the commercial space market.

In addition, progression toward ULCATS will create an increasingly complex set of issues related to space situational awareness and space traffic management that are not currently being addressed. As one of the world's most active operators in space, and as a key leader in the development of commercial space, the United States may be expected to bear much of this burden. The U.S. government should create a clear set of standards and processes, driven by industry, to check orbits for collision risks and ensure there are plans for safe reentry disposal and debris mitigation.[45] Within the U.S. Congress, the proposed American Space Renaissance Act addresses this by requiring the designation of a lead government agency for space traffic management activities and services. Such a lead agency would be tasked to implement effective, adaptable, and minimally burdensome space traffic management system. The successful management of such a system could be extended internationally, and it is likely in the United States' national interest, to help develop an international space traffic management system. The aviation industry can again serve as an important model of this dynamic, as U.S.-developed standards and procedures greatly influenced the development of the international system of air traffic management to the great mutual benefit of the industry.

- Recommendation: The U.S. government should take a leadership role in space situational awareness and space traffic management by creating a clear set of

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[43] FAA, "Launch Site Policy Review and Approval," https://www.faa.gov/about/office_org/headquarters_offices/ast/licenses_permits/launch_site/policy/.
[44] FAA, "Active Licenses," https://www.faa.gov/data_research/commercial_space_data/licenses/.
[45] Todd Harrison, "Commercial Space Needs Regulatory Clarity," *Breaking Defense*, July 25, 2016, http://breakingdefense.com/2016/07/commercial-space/.

standards and processes, driven by industry, and work to establish this approach at the model for an international approach to space traffic management.

Department of Justice and the Federal Trade Commission

The Federal Trade Commission (FTC) and the Department of Justice (DoJ) maintain antitrust laws, which promote competition to protect consumers from mergers or business practices that remove competition.[46] For commercial space, antitrust laws are crucial to promote competition within the commercial space sector. The level of commercial activity needed to deliver ULCATS will necessarily require a relatively open international commercial space market. DoJ and FTC antitrust policies should promote robust competition in commercial space to allow ULCATS to flourish within the United States and for the United States to maintain a lead in space operations, whether civil or military.

The FTC and DoJ also monitor mergers and acquisitions among commercial companies that have already greatly affected competition in the space-industrial base. Throughout the 1960s and 1970s, numerous companies were active in the space-launch commercial market. However, due to lowering demand for launch, the Boeing Company and Lockheed Martin felt that to decrease costs and remain in the space launch industry, their launch operations and manufacturing needed to merge.[47] This new 50-50 partnership between Boeing and Lockheed Martin was renamed the United Launch Alliance (ULA). However, the merger virtually eliminated domestic competition in the medium to heavy space-launch market until the emergence of SpaceX's Falcon 9 launch vehicle.[48]

A similar story can be said about two of the United States' main imagery companies, GeoEye and DigitalGlobe, which merged under the DigitalGlobe brand in 2013. As competitors in the remote sensing market, the two companies merged in order to increase market share and lower prices. After the merger, executives from the company announced that they expected about 50 percent of revenue to come from the federal government.[49] While both of these mergers may have been appropriate at the time they were approved, the expectations for competition in the space market will need to grow in step with the market itself.

Ultra-low-cost access to space will come to pass only if the U.S. government, through the FTC and DoJ, allows and encourages competition in all space-associated markets—including but not limited to space-launch, remote sensing, on-orbit servicing, mining, and hosted payloads. Therefore, to enable and sustain ULCATS, the FTC and DoJ should discourage large-scale mergers like the ones that created ULA and DigitalGlobe, wherever possible, to keep competition high.

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[46] Federal Trade Commission (FTC), "Guide to Antitrust Laws," https://www.ftc.gov/tips-advice/competition-guidance/guide-antitrust-laws.
[47] Joan Johnson-Freese, *Space as a Strategic Asset* (New York: Columbia University Press, 2007), 45–46.
[48] SpaceX, "About," http://www.spacex.com/about.
[49] Steven Overly, "GeoEye, DigitalGlobe agree to $900 million merger," *Washington Post*, July 23, 2012, https://www.washingtonpost.com/business/capitalbusiness/geoeye-digitalglobe-agree-to-900-million-merger/2012/07/23/gJQAgA2G5W_story.html.

- Recommendation: U.S. government agencies should prioritize maintaining competition in the commercial space market and do so increasingly as the market develops.

Department of State and the Department of Commerce

Space is currently seen as an integral part of the United States' national security enterprise. Therefore, export controls are extremely tight when it comes to space technology and services. In a 2014 study conducted by the Department of Commerce's Bureau of Industry and Security titled "U.S. Space Industry 'Deep Dive' Assessment: Impact of U.S. Export Controls on the Space Industrial Base,"[50] space-industry survey respondents reported several areas of business where the U.S. export control system negatively impacted their organization. According to the study, the most common impact of International Traffic in Arms Regulations (ITAR)-regulated products and services was that companies began avoiding the production and exportation of these ITAR-restricted space-related projects.[51] This indicates that ITAR and other stringent export controls are causing companies to actively avoid developing and selling these space-related products. Respondents also noted that they often avoid exporting space-related products because of the complexity of the regulations and fear of penalties. Respondents to the survey also reported that non-U.S. organizations are often incentivized to avoid buying or using American space products in their systems. Some non-U.S.-based organizations advertise "ITAR-free" space-related products and services, as it is widely known that ITAR can hamper the acquisition of a product or system from the United States. The complexities of U.S. export controls and ITAR are significantly impacting the U.S. space industry and U.S. space-based investments.[52]

ULCATS will result in a dramatically increased volume of commercial space activity with new technologies and services emerging into the space-industrial base. To cope with this increased volume, the U.S. government will need to reexamine policies on space launch and space-related products for export. Opportunities like the Export Control Reform (ECR) initiative established by President Obama in 2009 will hopefully clarify and ease export controls on space-related products. The space-related phase of the ECR was implemented in November 2016.[53]

- Recommendation: Approach export controls for commercial space technologies with the clear understanding that space is a global market in which the United States benefits greatly when the industry leaders are U.S. firms.

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[50] Brad Botwin, *U.S. Space Industry "Deep Dive" Assessment: Impact of U.S. Export Controls on the Space Industrial Base* (Washington, DC: U.S. Department of Commerce, February 2014), https://www.bis.doc.gov/index.php/forms-documents/technology-evaluation/898-space-export-control-report/file.
[51] Ibid., 53.
[52] Ibid., 53–55.
[53] Directorate of Defense Trade Controls, "Export Control Reform," U.S. Department of State, October 2016, http://pmddtc.state.gov/ECR/index.html.

National Aeronautics and Space Administration

NASA's founding statute specifically tasks promotion and regulation of commercial space activities as a core responsibility of the administration.[54] The National Aeronautics and Space Act, which founded NASA, states, "In the performance of its functions the Administration is authorized to make, promulgate, issue, rescind, and amend rules and regulations governing the manner of its operations and the exercise of the powers vested in it by law."[55] However, NASA is currently led as a civil research and development agency, not a regulatory agency, which is why many civil and commercial space regulations and policy decisions are made by the other U.S. government agencies and administrations discussed previously.

Currently, NASA is not focused on promoting commercial space beyond its commercial cargo and crew program to support the International Space Station. Given NASA's substantial involvement in international cooperation in space, it may be able to serve a valuable role in building support for the adoption of U.S.-developed standards and protocols as international norms. NASA's lead role in pursing the purchase of commercial launch services could also be an important resource to be leveraged by other U.S. government agencies in order to facilitate broader government adoption of these services. In the future, NASA may be able to open up its commercial launch services Space Act agreements for use by other government customers.

- Recommendation: Leverage NASA's expertise at acquiring commercial space capabilities and robust international partnerships to support the development of the commercial space market.

State and Local Governments

As mentioned previously, government involvement in the commercial space market extends beyond the federal government. State and local governments are involved in commercial space as well, usually as a result of their interest in spurring the development of space-related economic activity around a current or proposed launch site. Perhaps the most significant role for state governments today, however, is associated with legal liability for damages resulting from space activity. The underlying structure of the U.S. legal system often leaves liability issues to state law, but there are important exceptions in markets that are inherently national in scope. A reasonably consistent liability structure for space activity would assist greatly in the development of this market by reducing the uncertainty of legal liabilities.

- Recommendation: Work with state governments to develop increased expertise on liability issues for space activities. Consider developing a model liability regime for

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[54] National Aeronautics and Space Administration, *Public Law 11-314: Enactment of Title 51 – National and Commercial Space Programs*, December 2010, Section 20112.A.4-5, https://www.nasa.gov/sites/default/files/atoms/files/public_law_111-314-title_51_national_and_commercial_space_programs_dec._18_2010.pdf.
[55] *National Aeronautics and Space Act of 1958*, http://history.nasa.gov/spaceact.html.

state governments to use as a starting point and evaluate areas where a national approach may be needed.

Evolving the Regulatory Approach to Support ULCATS

To support, promote, and shape ULCATS developments, the U.S. government needs to develop a streamlined and minimally burdensome regulatory process with available licenses that address the full set of commercial space missions. Today's regulatory approach in many respects addresses each launch or space mission individually. It lacks the capacity to process the likely flood of daily requests for space activity approvals that would occur under ULCATS. It lacks transparency because there is a dearth of clear policy guidance and license applications are sometimes rejected without explanation. These unclear policies create a highly cumbersome process because the burden is on the commercial firm to seek and apply for licenses from each of the various government agencies previously described.

Commercial development and innovation will be fostered by increased regulatory capacity and by providing clear policy guidance and standards for commercial space activities. An additional measure to ease the regulatory path for commercial space firms would be to establish a single point of entry into the federal regulatory process for space. This approach is consistent with the "mission authorization" approach recently outlined by the White House Office of Science and Technology Policy in a report to Congress.[56] Providing industry with a single entry point would ease the burden of pursuing multiple licenses for each space mission on smaller firms and larger firms alike, encouraging the development of this market while still allowing the government to involve all of the relevant expertise needed to assess the mission. Strong U.S. leadership on these regulatory issues is crucial to the development of the robust global commercial space market that is the most likely path to deliver ULCATS.

- Recommendation: Consider a single point of entry for all approvals required in the U.S. government regulatory process for space.

[56] John P. Holdren, "John Holdren to John Thune and Lamar Smith," April 4, 2016, Executive Office of the President: Office of Science and Technology Policy, Washington, DC, 2016, https://www.whitehouse.gov/sites/default/files/microsites/ostp/csla_report_4-4-16_final.pdf.

Recent Congressional and Administration Actions

It is apparent that Congress is aware of regulatory gaps and is taking steps to establish regulatory processes, while allowing for continued innovation in the commercial sector. In November 2015, the "Spurring Private Aerospace Competitiveness and Entrepreneurship (SPACE) Law," also known as the "U.S. Space Launch Competitiveness Act," was signed into law. Among other stated goals, this act intends "to facilitate a pro-growth environment for the developing commercial space industry by encouraging private sector investment and creating more stable and predictable regulatory conditions."[57] In short, the SPACE Law will prevent, for the next eight years, the U.S. government from regulating commercial space companies developing private space travel assets. Many within the U.S. commercial space sector, such as SpaceX, Blue Origin, and Virgin Galactic, have applauded the SPACE Law, as it indicates that private space travel is a still developing industry that needs more time to experiment and grow before having full regulations leveraged on the industry.[58] Additionally the SPACE Law acknowledges the right of any U.S. citizen to own resources mined from asteroids and encourages commercial exploration and development of asteroid mining technologies.[59] Overall, the SPACE Law encourages further development of new commercial technologies that will be enabled by ULCATS.

> …Within the national space enterprise, there is a Department of Defense enterprise, a commercial space enterprise, a civil space enterprise, [but] there does not seem to be one national space enterprise.
>
> ***- Rep. Jim Bridenstine***

The SPACE Law also required the White House Office of Science and Technology Policy (OSTP) to submit a report on current and emerging space technologies developed by commercial activity to Congress. OSTP was asked to identify both the emerging technologies and the U.S. governmental organization that would be best suited for authorizing and supervising these developments.[60] This report was submitted in April 2016 and details several current and emerging technologies and U.S. commercial companies' goals for space development and space travel. The recommendation for regulatory-oversight on these technological developments was that it is too early in their development to warrant a decision on oversight and regulatory control. Therefore, OSTP recommended a temporary "mission authorization" system until a clearer and well-defined regulatory system emerged. Modeled after the FAA's Payload Review process, OSTP recommended to give out regulatory approvals, denials, and licenses on a case-by-case basis to companies pursuing innovative

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[57] U.S. Congress, *Public Law 114-90: U.S. Commercial Space Launch Competitiveness Act*, 2015, https://www.congress.gov/114/plaws/publ90/PLAW-114publ90.pdf.
[58] Loren Grush, "Private space companies avoid FAA oversight again, with Congress' blessing," *Verge*, November 16, 2016, http://www.theverge.com/2015/11/16/9744298/private-space-government-regulation-spacex-asteroid-mining.
[59] Planetary Resources, "President Obama Signs Bill Recognizing Asteroid Resource Property Rights Into Law," November 25, 2015, http://www.planetaryresources.com/2015/11/president-obama-signs-bill-recognizing-asteroid-resource-property-rights-into-law/.
[60] Marcia S. Smith, "White House Wants DOT in Charge of Commercial Space 'Mission Authorization,'" SpacePolicyOnline.com, May 2016, http://www.spacepolicyonline.com/news/white-house-wants-dot-in-charge-of-commercial-space-mission-authorization.

space activities. This temporary system outlines that the secretary of transportation can grant authorizations for space missions, if prior to authorization the secretary coordinates with the secretary of defense, secretary of state, secretary of commerce, the NASA administrator, the director of national intelligence, and other appropriate agencies. OSTP believes this to be a temporary solution and recommends further analysis before creating a more permanent and robust regulatory system.[61]

Also in April 2016, Rep. James Bridenstine (R-OK) introduced H.R. 4945, the American Space Renaissance Act. If passed as is, H.R. 4945 would move responsibility for commercial space situational awareness away from DoD to the FAA. In an interview with *SpaceNews*, Representative Bridenstine explained that his bill attempts to address the discontinuity among regulations within the space enterprise. Representative Bridenstine has also made statements of his intent to ensure the FAA's Office of Commercial Space Transportation and the NOAA receive full funding in the future. H.R. 4945 also addresses uncertainty in both funding and leadership within NASA by supporting a more stable funding mechanism and instituting a five-year term for the NASA administrator.[62]

[61] Holdren, "John Holdren to John Thune and Lamar Smith."
[62] Jeff Foust and Mike Gruss, "Bridenstine introduces American Space Renaissance Act," *SpaceNews*, April 13, 2016, http://spacenews.com/bridenstine-introduces-american-space-renaissance-act/.

4. Impacts on Military Space Operations

A significant reduction in the cost of access to space and the policy changes that would accompany these disruptions could affect the way the U.S. military operates in the space domain in many ways.[63] ULCATS could enable entirely new military space missions that are currently impractical or unaffordable due to the high cost of launch and could result in more robust commercial space capabilities the military could leverage. New space capabilities and missions may also enable or require new operational concepts for how the military uses space systems. While these changes would certainly affect the U.S. military, they could alter the capabilities and operations of other nations' militaries as well. Depending on how the cost of access to space is reduced, it could create secondary effects the military must also consider.

New Military Space Missions

Many technical factors affect whether military missions can be effectively and efficiently performed using space-based platforms, such as the distance over which actions need to be performed, how quickly actions must occur, and the availability of terrestrial alternatives. These factors already support using space-based platforms for many military missions even with launch costs at their current levels. The military relies on space-based systems for imagery, missile warning, communications, signals intelligence, precision navigation and timing, weather and environmental monitoring, and nuclear detonation detection, among many other missions.

As Ellen Pawlikowski, Doug Loverro, and Tom Cristler noted in a 2012 article, high launch costs have influenced the architectural choices for current military space systems, leading the U.S. military to concentrate its space assets in a small number of highly aggregated, and highly expensive, satellites.[64] High launch costs have also made some military space missions and alternative architectures prohibitively expensive. This section considers what new space missions or architectures could become feasible if the cost of access to space were significantly lower. It does not attempt to provide a comprehensive accounting of all possible missions; rather, it explores some of the new missions that could have the most significant impact on national security and the way the military uses space.

Space-based Kinetic Ground Attack

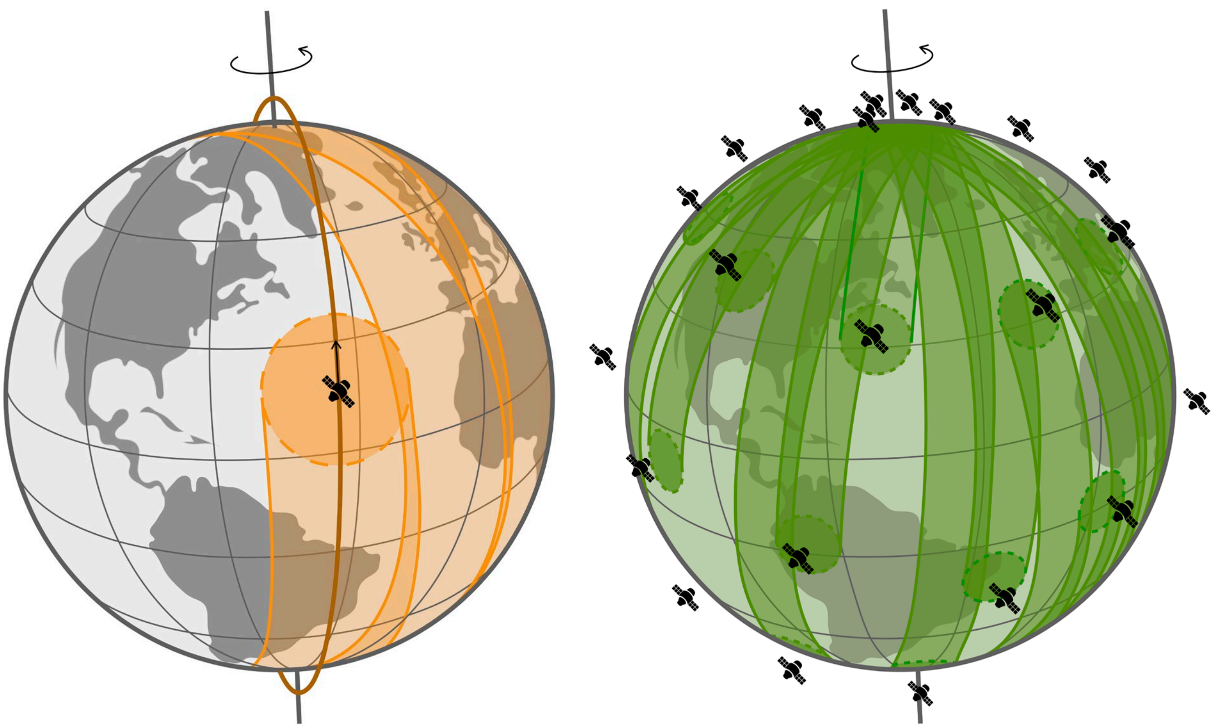
The idea of using space-based systems for kinetic attack against ground targets has been around since the dawn of the space age. Conventional weapons using either explosive

[63] Ellen Pawlikowski, Doug Loverro, and Tom Christler, "Space: Disruptive Challenges, New Opportunities, and New Strategies," *Strategic Studies Quarterly* (Spring 2012): 27–54, http://www.au.af.mil/au/ssq/2012/spring/pawlikowski.pdf.
[64] Ibid.

charges or the sheer kinetic energy of impact could be placed in orbit and deorbited upon command to strike fixed targets on Earth. Notwithstanding the important policy implications of this decision, which would be considered weaponization of space by nearly any definition, the technology to build and deploy such a system is feasible.[65] The challenge is that a space-based ground attack system would cost substantially more than the terrestrial equivalent—ground-based ballistic missiles.

A conventional ballistic missile can reach virtually any target on Earth within 30 to 45 minutes of launch. Building an equivalent space-based capability would require orbiting a constellation of many satellites in LEO because the deorbit time from higher orbits is longer than the requirement to strike a target within 45 minutes. For example, the time required to deorbit an object from GEO is approximately five hours compared to about 15 minutes from LEO.[66] Faster deorbit times can be achieved but require using more propellant, which significantly increases the total mass that needs to be orbited and therefore the launch costs.

Figure 5: Using Polar Orbits for Global Coverage.



Source: Adapted from *The Physics of Space Security*, the left subfigure illustrates a single satellite in polar orbit, which passes within range of every point on the Earth's surface every 12 hours. The subfigure on the right illustrates a constellation of 48 satellites in polar orbit so that a satellite is within range of every point on Earth every 45 minutes. David Wright, Laura Grego, and Lisbeth Gronlund, *The Physics of Space Security: A Reference Manual* (Cambridge, MA: American Academy of Arts and Sciences, 2005), 93.

[65] Johnson-Freese, *Space as a Strategic Asset*, 137.
[66] David Wright, Laura Grego, and Lisbeth Gronlund, *The Physics of Space Security: A Reference Manual* (Cambridge, MA: American Academy of Arts and Sciences, 2005), 66, https://www.amacad.org/publications/Physics_of_space_security.pdf.

Satellites in LEO move at a high speed relative to the Earth, orbiting roughly once every 90 minutes. To be capable of striking targets at any point on Earth's surface, a satellite would need to be in an orbit that passes over the poles (i.e., a polar orbit). As a satellite orbits around the poles the Earth rotates underneath it, causing it to pass over each part of the Earth in a pattern that repeats twice each day, as shown in Figure 5. Thus, multiple satellites would need to be in orbit so that one is always within 45 minutes of any given location.

Assume a constellation of strike weapons are placed in a 500 km orbit and each is capable of deorbiting and traveling up to 650 km laterally to strike a target. To provide a continuous ability to strike any target on Earth with 45 minutes, a total of 48 weapons would be need to be placed in orbit arranged in 16 orbital planes with three satellites per plane, as shown in Figure 5.[67] Importantly, this would provide the ability to strike one target at a time anywhere on Earth. To strike a second target, the operator would need to wait until another weapon moves within range. As weapons are used, it would create time gaps in the coverage of the constellation until replacements are launched.

With a 450 kg warhead, equal to that of a Tomahawk cruise missile, such a system could pose a serious threat to targets on the ground—especially considering the kinetic energy from its velocity that could help the warhead penetrate hardened or buried targets. Until it is used, the warhead would need to operate much like a satellite while waiting in orbit and would need a "garage" that provides: a guidance, navigation, and control system to direct its reentry; a communications system to enable monitoring and activation while on orbit; a propulsion system for station keeping and deorbiting; a heat shield to protect it during reentry; and batteries and solar arrays for power. All of this could add another 100 kg to its mass, plus about 200 kg of propellant that would be needed to deorbit.[68] Thus the total mass of each strike weapon would be roughly 750 kg.

One launch vehicle could orbit all of the weapons within a single orbital plane. Due to the significant energy required to change orbital planes, however, it would probably not be practical to have a single launch vehicle deliver weapons across more than one orbital plane.[69] This hypothetical constellation would therefore require 16 separate launch vehicles, each carrying three 750 kg weapons, for a total mass to LEO of 2,250 kg per launch. This is within the payload range of a low- to medium-lift launch vehicle like the Delta II. Thus, a space-based kinetic ground attack system capable of striking one target within 45 minutes would require 16 launch vehicles and 48 orbital weapons. Even if the weapons were not used, they would need to be replaced approximately every 10 years due to orbital decay and the degradation of components on the satellites. Over 30 years, this would require a total of 48 launches and 144 weapons, not including any losses due to launch or on-orbit failures.

Assuming an average unit cost of $10 million per weapon and $50 million per launch vehicle (the approximate cost of a Delta II), the total procurement cost of the system would be $3.8 billion over 30 years (in 2017 dollars). This does not include one-time development and

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[67] Ibid., 92.

[68] This assumes a deorbit delta V of 0.7 km/s and an I_{sp} of 230 s, which is typical for a hydrazine monopropellant thruster.

[69] Wright, Grego, and Gronlund, *The Physics of Space Security*, 56.

testing costs, which could be as much as the total procurement cost. For comparison, a 2006 Congressional Budget Office (CBO) report estimated the procurement cost of a space-based system of 40 weapons in a slightly different orbital configuration would be $9.3 billion over a 30-year period, $6.5 billion of which is for launch costs, with an additional $4.8 billion in one-time development costs (all figures converted to 2017 dollars).[70] A main difference in the CBO estimate is that it assumes higher launch costs, which was true in 2006. Since then, however, launch costs have started to decline.

In comparison, the terrestrial equivalent to strike one target within 45 minutes would be just one ballistic missile and one warhead. Using the cost assumptions above, the total procurement cost for the terrestrial equivalent would be $60 million—the approximate cost of a single intercontinental ballistic missile and warhead. For the procurement cost of the example space-based system, a terrestrial system could be fielded with more than 60 missiles capable of hitting 60 targets simultaneously. Moreover, a terrestrial system could last 30 years or longer without replacement. Both the space and terrestrial strike systems would require operations and sustainment funding for the personnel and control systems needed for 24-hour readiness, which would likely add to the total lifecycle costs of each by similar amounts.

As this example demonstrates, launch costs are a significant factor in making a space-based kinetic ground attack system cost much more than a terrestrial-based equivalent. However, if the cost of a medium-lift launch vehicle fell by an order of magnitude to $5 million, the procurement cost of the space-based system used in this example would be cut by more than half to $1.7 billion (in 2017 dollars). While it would still be more expensive, a space-based system could be attractive at this price level because, unlike a conventionally armed ICBM, it would not be confused for a nuclear ballistic missile attack.

Space-based Kinetic Missile Defense

Another concept that has been considered in the past, but never fielded, is a constellation of space-based kinetic missile interceptors. Unlike a ground attack system, a missile defense system must be able to respond more quickly to be effective. A system designed to intercept a missile during the boost phase would need to respond within 2 to 4 minutes of launch, while a system designed to intercept during mid-course could have as much as 15 to 20 minutes, depending on the trajectory. Because a space-based system could defend against launches from virtually any location on Earth, there is no terrestrial equivalent for comparison.[71]

The Brilliant Pebbles concept, proposed by the George H. W. Bush administration, called for a minimum of 1,000 space-based interceptors in LEO for global protection against a limited attack.[72] In a 2004 study, the American Physical Society (APS) provided a more detailed

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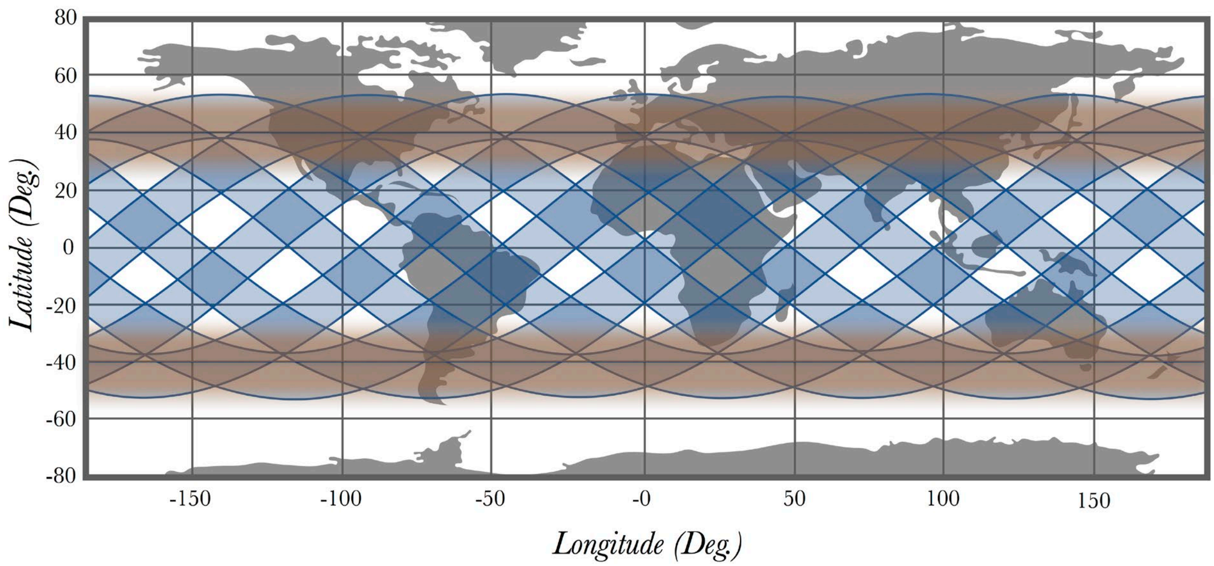
[70] Congressional Budget Office, *Alternatives for Long-Range Ground-Attack Systems,* Congress of the United States, March 2006, 50, https://www.cbo.gov/sites/default/files/109th-congress-2005-2006/reports/03-31-strikeforce.pdf.
[71] Wright, Grego, and Gronlund, *The Physics of Space Security*, 96.
[72] Henry Cooper and Stephen Hadley, "Briefing on the Refocused Strategic Defense Initiative" (presentation, Department of Defense, Washington, DC, February 12, 1991).

analysis of the requirements for a space-based system designed to intercept during the boost phase. The study found that more than 1,600 interceptors would be needed to ensure at least one (but on average two) interceptors would be in position to target a missile with a 120-second response time based on the burn time of solid propellant missiles. The APS study assumed that the system would be designed only for coverage between 45 degrees latitude North and South, which is sufficient to cover North Korea, Iran, and most of China, but provides little coverage of Russia, as shown in Figure 6.[73]

Figure 6: 45-Degree Inclination Constellation Coverage Map.



Source: This two-dimensional map illustrates the ground coverage of a constellation of satellites composed of orbits at a 45-degree inclination. The seven satellite paths depicted in this particular system can only observe regions of the Earth between about 50 degrees latitude North and South, with full coverage of latitudes between 30 and 50 degrees North and South, some coverage between these bands, and no coverage outside of these bands. The two bands of highly observed regions are depicted in orange. This figure was adapted from Wright, Grego, and Gronlund, *The Physics of Space Security*.

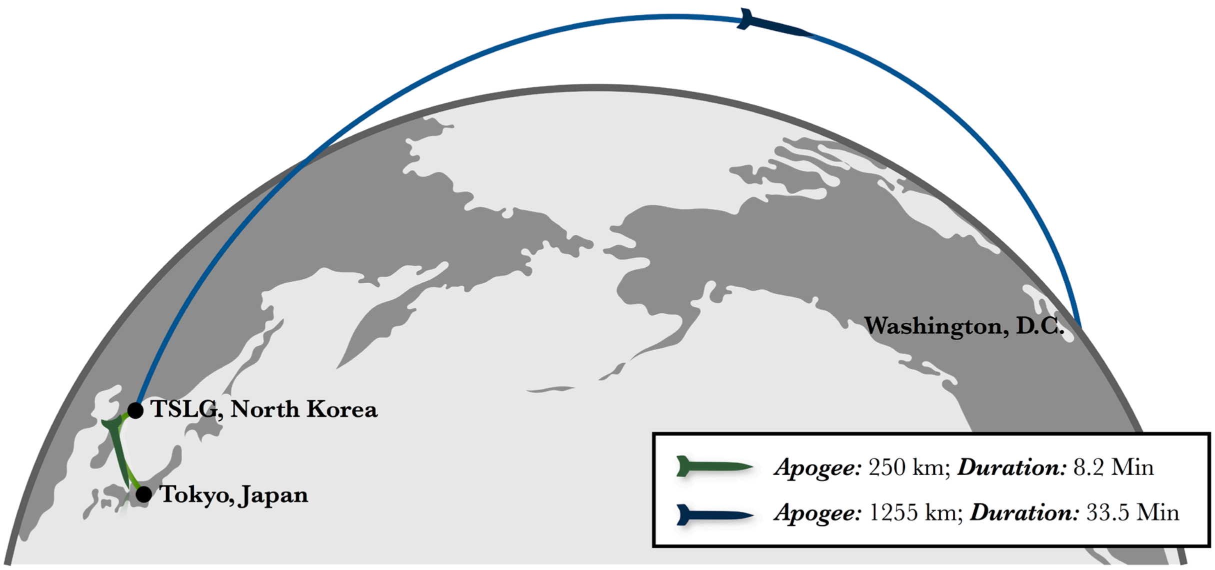
Intercepting missiles in mid-course is technically more challenging because once the booster burns out it can deploy decoys and becomes more difficult to track. Conversely, a mid-course intercept allows for a significantly longer response time and a higher intercept altitude, both of which reduce the number of satellites required. The incoming missile would also be less maneuverable after burnout, requiring less maneuver propellant on the interceptor.[74]

The number of interceptors required in a space-based mid-course system depends to a great extent on the range of missiles it is intended to intercept. Missiles with a longer range have a longer time of flight and thus allow for a longer response time. Longer-range missiles also have a higher apogee and thus can be intercepted at a higher altitude, although this increases the risk of orbital debris persisting after the engagement. For example, a missile

[73] David K. Barton et al., "Report of the American Physical Society Study Group on Boost-Phase Intercept Systems for National Missile Defense: Scientific and Technical Issues," *Reviews of Modern Physics* 76, suppl. 1 (October 2004): 108–110, http://journals.aps.org/rmp/pdf/10.1103/RevModPhys.76.S1.
[74] Missile Defense Project, "Missile Defense—Midcourse Discrimination Video," CSIS, http://missilethreat.csis.org/analysis/midcourse-discrimination/#video.

launched from North Korea to Tokyo on a minimum energy trajectory would have a flight time of just over 8 minutes and reach an apogee of 250 km, while a missile launched from North Korea to Washington, D.C., on a minimum energy trajectory would take more than 33 minutes and reach an apogee of 1,255 km, as shown in Figure 7. A mid-course system able to intercept long-range missiles must also be designed to cover higher latitudes because many long-range ballistic trajectories to the United States transit the arctic region.

Figure 7: Missile Trajectories from North Korea



Note: This figure depicts two missile trajectories from the Tonghae Satellite Launching Ground in North Korea. One missile, to Tokyo, demonstrates a suborbital ballistic trajectory that requires only 8.2 minutes of flight before impact. The second missile, to Washington, D.C., demonstrates the low-Earth orbit apogee required for a longer-range ballistic attack. This second missile reaches a maximum altitude of 1,255 km and takes 33.5 minutes from launch to impact.

For both a boost-phase and mid-course system, the kill vehicle could be relatively small, about 50 kg or roughly the size of the Exoatmospheric Kill Vehicle used in the existing Ground-based Midcourse Defense system (not including propellant). To deorbit and maneuver to intercept an incoming missile as quickly as required would use approximately 841 kg of propellant for a boost-phase system and 409 kg for a mid-course system.[75] The interceptors would also need a "garage" while on orbit for station keeping, communications, and power, which could add another 100 kg, bringing the total mass of each interceptor to about 991 kg for boost-phase and 559 kg for mid-course.

Table 1 shows three hypothetical options for a space-based interceptor system using the same methodology as the APS study. Each option assumes the cost of the interceptor is the same, only accounting for learning efficiencies as more copies of the interceptor are built in larger constellation systems. All three hypothetical constellations are designed to intercept a minimum of one missile at a time and assume the system must be replaced every ten years.

[75] This assumes a deorbit delta V of 4 km/s and an I_{sp} of 230 s. The difference in propellant mass is due to the maneuver delta V, which is assumed to be 2.5 km/s for a boost-phase intercept and 1.0 km/s for a mid-course intercept.

The procurement costs shown are in constant 2017 dollars for a thirty-year period and do not include development, test, operations, and sustainment costs.

Table 1: Hypothetical Options for a Space-based Interceptor System

	Boost-Phase Interceptors (APS 2004 Study)	Mid-Course Interceptors for Short-Range Trajectories	Mid-Course Interceptors for Long-Range Trajectories
Interceptor Orbit Altitude	300 km	300 km	1,100 km
Intercept Altitude	200 km	200 km	1,100 km
Response Time	120 s	240 s	900 s
Deorbit ΔV[76]	4 km/s	4 km/s	4 km/s
Maneuver ΔV	2.5 km/s	1.0 km/s	1.0 km/s
Max. Coverage Latitude	45°	50°	90°
# of Interceptors	**1,646**	**350**	**38**
Interceptor Avg. Proc. Unit Cost	$9–14 million	$13–20 million	$24–36 million
Propellant Mass	841 kg	409 kg	409 kg
Total Interceptor Mass	991 kg	559 kg	559 kg
Constellation Mass	1,631,921 kg	195,488 kg	21,224 kg
# Launches Required[77]	91	11	6[78]
Total Procurement Cost	**$67–109 billion**	**$17–26 billion**	**$4–7 billion**
Total Procurement Cost with 90% Reduction in Launch Costs	**$48–73 billion**	**$14–22 billion**	**$3–4 billion**

A main drawback to a space-based missile defense system is that once interceptors are used, a gap opens up in the constellation. An adversary can exploit this by launching a salvo of missiles at once, effectively saturating the system in one location with more missiles than there are interceptors within range.[79] Doubling the number of missiles that can be intercepted in a salvo requires doubling the size of the overall constellation (since you don't know in advance when or where the salvo will be launched)—a cost that scales in favor of the attacker. Depending on the altitude and approach velocity, a space-based interceptor system may also produce orbital debris. While the debris from low-altitude intercepts (less than 300 km) would decay within days or weeks, the debris from a higher-altitude intercept, such as 1,100 km in the long-range trajectory example system in Table 1, could linger for many years and pose a serious threat to other satellites in LEO.

[76] The ΔV (delta V) is the change in velocity required for an orbital maneuver.
[77] Launch vehicle unit costs are assumed to range between $80 million and $150 million under current conditions for a Falcon 9 or Atlas V-class launch.
[78] A minimum of six launches is assumed because the interceptors would need to be placed in different orbital planes.
[79] Wright, Grego, and Gronlund, *The Physics of Space Security*, 97.

Because the kill vehicle required for a missile intercept is more technologically complex (and therefore more costly) than the warhead used in a space-based ground attack system, launch costs are a smaller share of the cost for a space-based missile defense system. In this example, launch costs range from 10 to 40 percent of the total procurement cost of the hypothetical systems shown in Table 1. An order-of-magnitude reduction in launch costs reduces the total procurement cost by roughly one-third or less for each option analyzed. As a result, the decision to build a space-based kinetic missile defense system is not as sensitive to the cost of access to space as a space-based ground attack system.

Space-based Kinetic ASAT and Counter ASAT

Missile defense systems have an inherent antisatellite (ASAT) capability. Ground-based interceptors, such as the SM-3, are capable of striking satellites in LEO, as was demonstrated by the United States in 2008.[80] A space-based missile interceptor system could also be adapted to strike other satellites in space. The large amount of propellant each interceptor needs to deorbit and maneuver into an oncoming missile could also be used to change its orbital trajectory to intercept another satellite. A change in velocity (delta V) of 4 km/s, as assumed for the example interceptors in Table 1, would be sufficient to boost an interceptor from LEO to as high as geosynchronous orbit (35,786 km).[81] The interceptor would need sensors and algorithms capable of homing in on a satellite rather than a warhead or booster, but such a change would not be technologically prohibitive. A system designed for mid-course intercept would likely have the hardware it needs to identify and track a satellite in GEO, making an ASAT capability an inherent feature of the system. Like other kinetic ASAT systems, a space-based kinetic ASAT system would produce orbital debris that would threaten other satellites in similar orbits indiscriminately and at higher altitudes.

A space-based interceptor system could also be used to defend against ASAT weapons. A direct-ascent ASAT weapon launched from the ground toward a satellite in LEO would look much like a ballistic missile and therefore could be intercepted in the same way. The timeline for intercept, however, would be shorter than that of a mid-course ballistic missile intercept because the ASAT missile's trajectory would be designed to hit its target near the middle of its trajectory. The altitude at which the defensive system intercepts the attacking system would need to be below that of the satellite being attacked. Thus, a space-based counter-ASAT system designed to protect satellites in LEO from direct-ascent ASAT weapons would need to have more interceptors than the example constellation for short-range trajectory mid-course interceptors shown in the table. This would make the overall cost slightly higher but the benefit from reduced cost of access to space would be similar.

Space-based Directed Energy

A directed-energy weapon damages or destroys its target with energy transmitted in the electromagnetic spectrum, typically via high-powered microwaves in the radio wave portion

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[80] Missile Defense Agency, "AEGIS Ballistic Missile Defense: One-Time Mission: Operation Burnt Frost," U.S. Department of Defense, https://www.mda.mil/system/aegis_one_time_mission.html.
[81] Wright, Grego, and Gronlund, *The Physics of Space Security*, 101.

of the spectrum or high-powered lasers in the visible and infrared portions of the spectrum.[82] The main advantage of directed-energy weapons is that they travel at the speed of light, providing more time and decision space. Key disadvantages are that they require a high level of power to be effective, the power of the beam decreases in proportion to one over the square of the distance traveled, and the atmosphere and ionosphere can block or interfere with transmissions at certain wavelengths.

A space-based directed-energy system could be used to target ballistic missiles during boost phase, missile warheads once they are deployed, other satellites in space, and fixed or mobile targets on the ground. Basing a directed-energy weapon in space gives it greater access to places that ground and airborne systems cannot reach. Moreover, when targeting objects in space, the beam does not have to pass through the atmosphere and thus avoids the distortion that it causes. Because a directed-energy system can strike targets at the speed of light, a much smaller constellation of satellites would be needed to maintain continuous coverage over a wide range of latitudes than a kinetic system. Each satellite, however, would be much larger and more expensive in order to house the power source for the weapon and the large optics or antennas needed to direct the beam. As a 2004 RAND study noted, each satellite in the constellation would need to be on the order of the size and complexity of a next-generation space telescope.[83]

A critical factor in determining how many satellites are needed and how many targets can be prosecuted at once is knowing how long a directed-energy weapon must dwell on its target in order to destroy it. The dwell time is a function of the power a weapon can deliver to the target and the "hardness" of the target. A higher-power beam on a soft target does not need to dwell as long as a lower-power beam on a hardened target. A directed-energy weapon with larger optics (for a high-powered laser) or a larger antenna (for a high-powered microwave) can concentrate power more effectively on a smaller area and over greater distances. Thus, the effectiveness of a space-based directed-energy weapon depends in no small part on the ability to launch large, heavy structures.[84]

The RAND study cites an example of a 5-megawatt hydrogen fluoride chemical laser with a 10-meter-diameter mirror attempting to hit medium-range missiles while in the boost phase. In the 49 seconds the laser would have to engage missiles once they are above the atmosphere but before burnout (when the missile body is most susceptible to damage), RAND calculated that the system would be able to engage three missiles and would consume 500 to 750 kg of laser fuel.[85] Because a satellite such as this orbiting in LEO would pass in and out of range of a particular launch site as it orbits the Earth, a constellation of satellites would be needed to maintain continuous coverage. The study further calculated that a constellation of 24 satellites orbiting in six orbital planes at a 1,248 km altitude and a

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[82] For the purposes of this discussion, jamming or other forms of electromagnetic interference are not included as directed-energy weapons. Space-based jamming systems are similar to satellite communications payloads and thus are not fundamentally different than space systems already in use.
[83] Bob Preston et al., *Space Weapons Earth Wars* (Santa Monica, CA: RAND, 2002), 26, http://www.rand.org/content/dam/rand/pubs/monograph_reports/2011/RAND_MR1209.pdf.
[84] Ibid., 29–30.
[85] Ibid., 114.

60-degree inclination would be able to engage a minimum of one missile at all times and a maximum of six, depending on where the satellites are in their orbits at the time of launch.

However, as the RAND study cautiously notes, the actual performance of a system is highly dependent on the hardness of the target and how effectively the laser energy is able to interact with the skin of the booster missile to heat it to the point of failure. Thicker materials or a reflective coating applied to the skin would require a longer dwell time and thus reduce the number of missiles that can be intercepted. A midcourse intercept with a directed-energy weapon would be even more difficult because the warhead has a heat shield designed to protect it from the extreme heat of reentry, making it a much harder target to attack successfully.

Since the RAND study was conducted in 2004, many advances have been made in high-powered solid state and free electron lasers.[86] While they are not yet at the size and power levels required for space-based applications, it is possible they could be in the foreseeable future. The advantage of solid state and free electron lasers is that they use electricity rather than chemicals to power the laser. A space-based chemical laser needs to carry large tanks of fuel to power the laser, and the total number of shots it can fire is limited by the amount of fuel it carries. In contrast, a solid state laser would have a virtually unlimited shot capacity because it could recharge itself using its solar arrays. The limitation of a solid state laser is how much power it can store for rapid-fire engagements and how quickly it can recharge once its power is expended. Thermal management can also be an issue, which could require large cooling systems on the satellite to dissipate heat.

Given the inherent uncertainties and the relative immaturity of the technology that would be needed, it is difficult to provide even a rough estimate of the costs of a space-based directed-energy system. It would likely involve launching dozens of satellites with large structural components, such as a mirror 10 meters in diameter, and massive tanks of laser fuel or power storage components. Thus, the cost of such a system would likely benefit significantly from a reduction in the cost of access to space. In addition to reducing the cost of the overall system, lower launch costs could improve the performance of the system by enabling larger mirrors, more laser fuel (for chemical lasers), and larger batteries and solar arrays (for free electron and solid state lasers). On-orbit servicing could be a critical enabler for a chemical laser system in particular because it would allow satellites to be refueled after they are they are used, preventing the need to launch new satellites.

Space-enabled Transportation and Logistics

Another space mission that could potentially be enabled by lower-cost access to space is transportation and logistics. Personnel and supplies could be delivered using launch vehicles to virtually any location on Earth within 30 to 45 minutes. This could be used to deliver time-critical supplies, such as spare parts or ammunition, to forward operating bases. It could also be used to rapidly deploy small numbers of special operations forces for time-sensitive missions over great distances. For example, if a U.S. embassy or consulate in a remote area

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[86] Ronald O'Rourke, *Navy Shipboard Lasers for Surface, Air, and Missile Defense: Background and Issues for Congress* (Washington, DC: Congressional Research Service, June 2015).

came under attack, a rapid response force of special operations personnel could arrive from the United States within 30 to 45 minutes of launch.

Several companies are working on space tourism systems that could in theory be adapted by the military to provide space-enabled transportation and logistics. Blue Origin's New Shepard capsule is designed to carry six people on a suborbital flight. Under NASA's commercial crew program, SpaceX is developing the Dragon capsule and Boeing is developing the CST-100 Starliner capsule to ferry cargo and crew to LEO. These systems would need to be adapted to land precisely on the ground in an unprepared location, which could add to their costs.

Delivering cargo and personnel by space launch would only be cost feasible with a significant reduction in the cost of launch, and even then it would remain an exquisite capability for use in the most extreme situations. As a rough rule of thumb, a launch vehicle that can place a payload in LEO has sufficient thrust to propel the same payload on a ballistic trajectory halfway around the world. The capsule would essentially be expendable in this application because it would not be practical to retrieve it from a remote and potentially dangerous location. The booster rocket, however, could be reused.

New Architectures and Operations Enabled by ULCATS

Depending on the combination of market disruptions that lead to a significant reduction in the cost of access to space, the military could be induced to consider new space architectures and new ways of operating in space. For example, rather than satellites getting smaller and disaggregated, on-orbit servicing could incentivize the military and commercial firms to develop large, space station-sized modular satellite buses that aggregate many payloads together. These "mega" satellites could be built with enough space and power to host a wide variety of interchangeable payloads for a variety of commercial, civil, and military customers.

Mega satellites would perhaps make the most sense for commercial firms in geostationary orbit, where many users are already competing for a limited number of orbital slots, especially over key regions of the world. A mega satellite bus could provide a common structure, source of electrical power, station keeping, and pointing control for all of the payloads it hosts—costs that scale in favor of aggregation. The bus itself could be designed for periodic refueling, maintenance, and upgrade, such as the replacement of solar arrays, batteries, and gyros, over a life spanning multiple decades. Because the core components of the satellite bus (e.g., the structure) would only have to be launched once and the common services it provides (e.g., guidance, navigation, and control) could be shared by all of the payloads it hosts, the result would be less overall mass being launched.

A key risk the military would need to consider in such an architecture is that the aggregation of so many capabilities on one platform makes it an enticing target for potential adversaries. Even if a mega satellite does not host any military payloads, it could be targeted by an adversary to disrupt commercial and civil space capabilities in a particular region. The U.S. military is already heavily reliant on commercial satellites for communications, imagery, and other services, which gives it a more direct stake in the future resiliency of these systems.

On-orbit servicing could also make highly modular space architectures possible. In a completely modular architecture, satellite buses and payloads could be built and launched independently. On-orbit servicing vehicles could deliver and install payloads on satellite buses and swap payloads between satellites as needed. This would give the military greater flexibility to adjust its space capabilities to meet requirements on Earth. For example, the military could maintain a constellation of generic satellite buses in geostationary orbit distributed around the globe. In a crisis, it could launch or move a combination of communications, missile warning, and other payloads to satellites in a particular region to increase coverage and capacity. In this type of architecture, an adversary would not be able to easily determine which specific payloads are on which satellites at any given time. This strategy would increase the resiliency of military space systems by creating a degree of ambiguity on where key U.S. military space assets are located and therefore complicate an adversary's targeting of U.S. military space capabilities.

As previously mentioned, if launch vehicle reusability becomes commonplace and the range of military space missions expands, the U.S. military may need to consider owning and operating its own fleet of reusable launch vehicles. A military fleet of launch vehicles may be necessary to meet unique military requirements that cannot be adequately served by commercial launch operators, as is the case for many other types of military platforms such as trucks, ships, and aircraft. For example, a fleet of military-operated launch vehicles may be needed for missions that require the ability to launch payloads with little advance notice because commercial operators may not be willing or able to let DoD jump ahead of other customers. Moreover, some new military space missions, particularly the deployment of space-based weapons, may be deemed inherently military and should therefore be carried only by military-owned and -operated vehicles.

Secondary Effects

Another factor that should be considered is the secondary effects of ultra-low-cost access to space. These secondary effects depend in part on which disruptions occur and how the United States responds. A chief concern is that whatever causes a significant reduction in the cost of access to space is not likely to benefit the United States exclusively. Technological breakthroughs are at best a fleeting advantage. Technology can be lost in microseconds through cyber espionage, giving rogue nations the ability to catch up without the time or investment devoted by first movers. Moreover, disruptions in the cost of access to space that originate or are driven by private-sector firms may not be controllable by the U.S. government. The space launch market, while certainly segmented in some areas, is increasingly global. Government efforts to restrict low-cost launch technology from being accessed by others could backfire. U.S.-based commercial firms could relocate to other countries with less strict restrictions, and new firms could arise in other countries that attempt to copy the technology and business practices of U.S. firms but without U.S. government constraints. This is similar to what occurred in the 1990s in the commercial remote-sensing industry when U.S. government restrictions eroded the competitive advantage of U.S. remote sensing firms.[87]

Another concern is that a reduction in launch vehicle costs could have the secondary effect of increasing the proliferation of long-range missiles. A launch vehicle capable of placing payloads in LEO is effectively an intercontinental ballistic missile (ICBM) and if the cost of these systems declines significantly it would become more attractive for smaller nations to obtain such capabilities. Proliferation of medium- and long-range ballistic missiles has been limited to a certain extent by the Missile Technology Control Regime (MTCR), but this informal association of governments does not have a formal compliance mechanism. Nonstate actors, such as terrorist organizations operating in ungoverned spaces, may also be able to acquire missile technology if costs decline and proliferation controls break down. Additionally, countries that already possess ballistic missiles could greatly increase their missile forces and create a larger, more complex missile defense problem for the United States.

A decision by the United States to pursue some of the new space missions discussed in this chapter, such as space-based ground attack and missile defense systems, could induce other nations to follow suit. Moreover, if the cost of access to space falls significantly, other nations may be incentivized to pursue space-based weapons regardless of whether the United States does. For nations that do not have the global power-projection capabilities of the United States, these technologies could be part of a strategy to offset U.S. military advantages. A space-based ASAT system, for example, could hold a wide array of U.S. military satellites at risk and cause the United States to question whether these investments and the advantages they provide will be available during a conflict. Likewise, a space-based ground attack system could hold high-value targets at risk even in the U.S. homeland without the use or threat of nuclear attack. These capabilities could be used by an adversary to strengthen conventional deterrence against the United States and undermine American power-projection capabilities.

[87] Kevin M. O'Connell et al., *U.S. Commercial Remote Sensing Satellite Industry: An Analysis of Risk* (Santa Monica, CA: RAND, 2001), https://www.rand.org/content/dam/rand/pubs/monograph_reports/2009/MR1469.pdf.

5. Conclusions

Reductions in launch vehicle and launch operations costs, on-orbit servicing, and on-orbit manufacturing and mining collectively have the potential to drive down the cost of access to space by an order of magnitude or more. The innovative technologies needed for this change are becoming more possible than ever before with increasing commercial space activity within the United States and abroad. Whether or not ultra-low-cost access to space is achieved depends to a great extent on the development of the commercial space market and the U.S. government's approach to shaping and accessing this market. To achieve a robust space market, the U.S. government needs to support commercial space ventures, encourage competition in the market, and provide a transparent, well-structured, and minimally burdensome regulatory system. Currently, companies can be disincentivized from developing innovative space-related technologies because strict regulations like ITAR limit their growth and sales and the regulations and licensing statutes are overly complex. One potential solution to clarify regulations from the commercial end is to provide one common agency or department for space-related commercial activity that will then help coordinate and direct the company to the right regulatory and licensing authorities.

A significant reduction in the cost of access to space could enable new military space missions that rely on large, high-mass constellations of satellites. Lower launch costs could enable the fielding of constellations for space-based ground attack, missile defense, and rapid transportation and logistics. The U.S. military should consider new operational concepts for space, such as designing modular constellations of satellites with payloads that can be moved between satellites as needed to adjust to evolving security requirements on the ground. The United States will also need to consider the secondary effects of ULCATS, such as the potential for missile proliferation and the threat posed if other nations pursue some of the new space missions ULCATS could enable.

Though the global space economy is growing, only a few players have demonstrated their commitment to disrupting the industry and lowering the cost of access to space. If trends in the current space economy continue, where individual investors and newcomers are motivated to compete with federal and commercial giants, then ultra-low-cost access to space may be approaching more quickly than previously expected.

Appendix A. Looking to Space: The Evolution of U.S. Deterrence

Kristen R. Hajduk and Scott Aughenbaugh

> "Every age had its own kind of war, its own limiting conditions, and its own peculiar preconceptions."—Carl von Clausewitz, *On War*[88]

Deterrence is defined as the threat of action—usually military—to persuade a potential enemy to avoid certain courses of action by ensuring that an adversary's perceived benefits from taking the action are less than its perceived risks and costs.[89] Though the concept of deterrence predates the existence of nuclear weapons, the majority of scholarly discourse on the subject from the Cold War to the present has focused on the dynamics of nuclear deterrence. However effective nuclear weapons may or may not be at preventing mutually assured destruction, nuclear weapons have not prevented conventional conflicts, even among nuclear-armed states.[90]

The continuation of conflict and competition among nuclear states requires the United States to maintain its conventional superiority. In the 1970s, the United States accomplished this by pursuing an offset strategy that focused on improved guided munitions; intelligence, surveillance, and reconnaissance (ISR) platforms; stealthy aircraft; and the use of space-based systems for advanced communications, navigation, and ISR.[91] These technologies also led to new operational concepts focused on developing and leveraging battle networks that deployed precision-guided munitions. As a result of these innovations and new operational concepts, the U.S. military has enjoyed a qualitative conventional edge in the air, sea, and space domains.[92]

This dominance led U.S. adversaries to press their advantage in areas where the United States does not have as decisive of a military edge, particularly the land domain. Asymmetric tactics and hybrid warfare have challenged U.S. superiority in the land domain. The United States' inability to provide a legitimate deterrence against these threats undermines U.S. global security. As in the earlier offset strategy, the United States must find new capabilities, methods, and domains to project its power and provide a credible deterrence. Most notably,

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[88] Michael Howard and Peter Paret, eds., *On War* (Princeton, NJ: Princeton University Press, 1989).
[89] Thomas Schelling, *The Strategy of Conflict* (Cambridge, MA: Harvard University Press, 1960), 9.
[90] John Mearsheimer, *Conventional Deterrence* (Ithaca, NY: Cornell University Press, 1983), 14–17; Colin S. Gray, *National Security Dilemmas: Challenges and Opportunities* (Dulles, VA: Potomac Books, 2009).
[91] Barry D. Watts, *The Maturing Revolution in Military Affairs* (Washington, DC: Center for Strategic and Budgetary Assessments, 2011), http://csbaonline.org/uploads/documents/2011.06.02-Maturing-Revolution-In-Military-Affairs1.pdf; Arend G. Westra, "Radar versus Stealth: Passive Radar and the Future of U.S. Military Power," *Joint Force Quarterly* 4, no. 55 (2009): 136–43.
[92] Shawn Brimley, *While We Can: Arresting the Erosion of America's Military Edge* (Washington, DC: Center for a New American Security, December 2015), https://s3.amazonaws.com/files.cnas.org/documents/While-We-Can-151207.pdf.

the Department of Defense's third offset strategy is focused on achieving these innovations in the cyber and space domains.

Advanced nonnuclear space capabilities, however, provide a more stable solution to conventional deterrence. Each year, the U.S. military fields nonnuclear space capabilities that add to its deterrence capability. And although military innovations may change, the nature of deterrence does not. Deterrence will continue to depend on the number of munitions that can be directed at a potential adversary. Future deterrence potential is most notable in the areas of electronic and cyber warfare. For example, the Counter-electronics High-powered Advanced Missile Project (CHAMP) is a tested capability that uses high-powered microwaves to incapacitate electronic systems without razing buildings or causing collateral damage.[93]

Moreover, the world has already entered an age where cyber-attacks, such as the Stuxnet operation, can be directed precisely at sensitive national and military capabilities and infrastructures without massive destruction or loss of life.[94] Because these capabilities do not result in immediate massive destruction,[95] they are not shrouded in the same taboo as nuclear weapons.[96] This improves deterrence by increasing the credibility of the threat. If these and future advanced nonnuclear capabilities can effectively neutralize adversary abilities to threaten credibly or use nuclear weapons, there may be a future in which nuclear weapons are no longer the dominant feature in a state's deterrence calculus.[97]

Deterrence in Space

A world in which the cost of access to space is significantly lower presents new opportunities and challenges to conventional deterrence (notwithstanding the other goals of defeat and defend). Technologies that were once forgotten, or confined to the realm of science-fiction, could become possible.

Current space nations such as Russia and China have access to significant cyber resources and are interested in further exploiting this domain. However, other nations like Nigeria (which was the first country to receive a call from President Kennedy on the Syncom II satellite on August 23, 1963) are in earlier stages of their space programs but have fast-

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93 Fahmida Rashid, "Modern Warfare Game Changer: Boeing's CHAMP Missile Knocks Out Electronic Systems," *Security Week Online* October 24, 2012, http://www.securityweek.com/modern-warfare-game-changer-boeings-champ-missile-knocks-out-electronic-systems.

94 David Sanger, "Obama Order Sped Up Wave of Cyberattacks Against Iran," *New York Times*, June 1, 2012, http://www.nytimes.com/2012/06/01/world/middleeast/obama-ordered-wave-of-cyberattacks-against-iran.html?pagewanted=all&_r=0; "Times Topics: Cyberattacks on Iran—Stuxnet and Flame," *New York Times*, 2012,
http://topics.nytimes.com/top/reference/timestopics/subjects/c/computer_malware/stuxnet/index.html?8qa.

95 Although advanced nonnuclear capabilities have the potential for secondary or tertiary destruction or disruption (e.g., a recent Defense Science Board 2013 report *Resilient Military Systems and the Advanced Cyber Threat* posits that an offensive cyber-attack to an electric grid could hypothetically prove to be an existential threat), this paper is concerned with the damage *immediately* resulting from deployment of a capability.

96 John Mueller, "The Escalating Irrelevance of Nuclear Weapons," in *The Absolute Weapon Revisited: Nuclear Arms and the Emerging International Order*, ed. T.V. Paul, Richard J. Harknett, and James J. Wirtz (Ann Arbor: University of Michigan Press, 1998), 73–98.

97 Michael S. Gerson, "Conventional Deterrence in the Second Nuclear Age," *Parameters* (Autumn 2009): 34–35.

developing cyber infrastructure. In an ULCATS world, massively distributed electronic intelligence capabilities could be opened to a whole new group of developing nations—and increased ability to disrupt systems through intrusion.

Concern of that intrusion should extend to the effects of electromagnetic pulse (EMP), which has been discussed since the early days of nuclear testing. Before that first test in 1945, K.T. Bainbridge observed:

> [Enrico] Fermi has calculated that the ensuing removal of natural electrical potential gradient in the atmosphere will be the equivalent to a large bolt of lightning striking that vicinity. We were plagued by the thought that other such phenomena might occur in an unpredictable or unthoughtful manner. All signal lines were completely shielded, in many cases doubly shielded.[98]

This concern still exists today and will dwell into the future as many of our devices like cell phones, robotics, and drones rely on electronics and a combination of external systems, including GPS. Many of the newer commercial satellites that are being put into space today are unshielded, making them vulnerable to EMP or a "once-in-a-century geomagnetic storm."[99] If one benefit of an ULCATS-world is more of these new satellites, then an opportunity exists to disrupt and deter by electromagnetic attack.

A lowering of the barriers to space can make way for increased space activity—from state and nonstate actors—and may lead to conflicts. In this potential future operating environment, states may rely on nonnuclear space capabilities to compete and clash without triggering nuclear escalation, deterring conventional wars in new or innovative ways.[100] As Figure A-1 illustrates, advanced nonnuclear capabilities—including space-based capabilities—could take on a greater role in U.S. deterrence across a broader range of conflicts.

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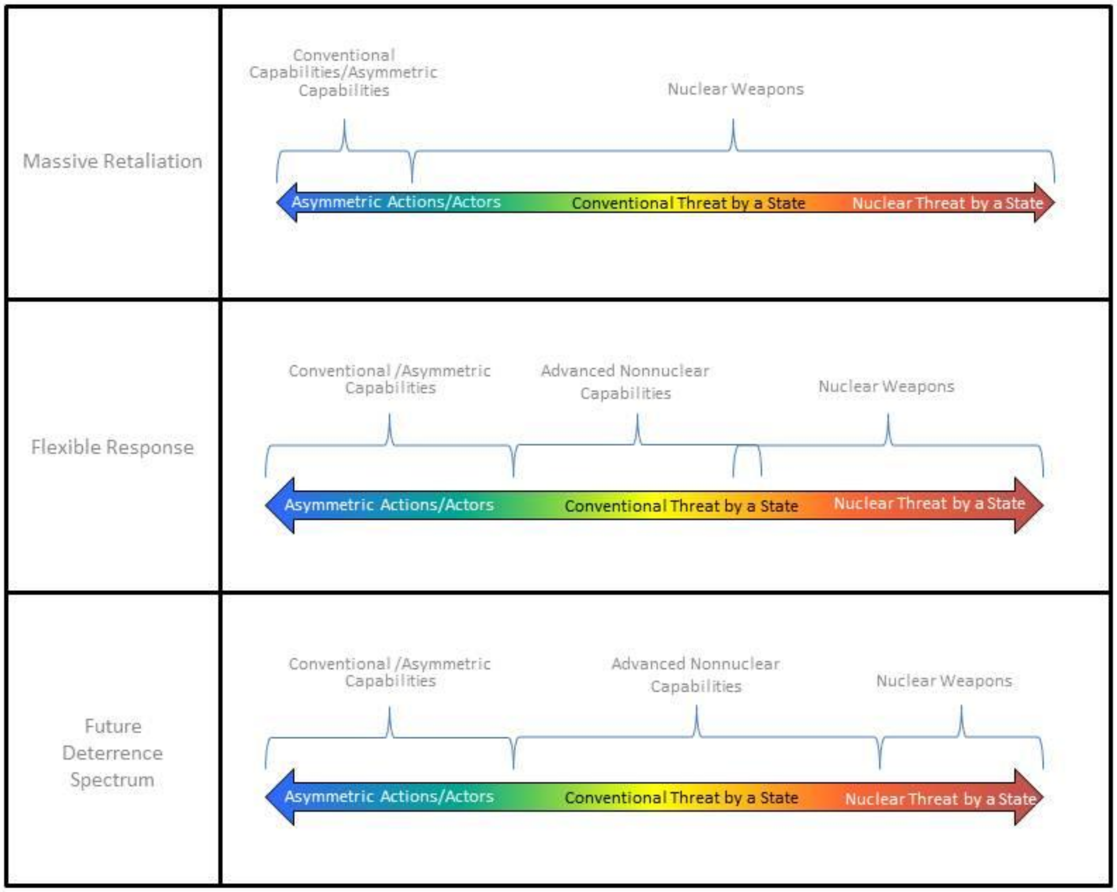
[98] K.T. Bainbridge, *Trinity* (Los Alamos, NM: Los Alamos Scientific Laboratory, May 1976), https://fas.org/sgp/othergov/doe/lanl/docs1/00317133.pdf.

[99] Yousaf Butt, "The EMP threat: fact, fiction, and response," *Space Review*, January 25, 2010, http://www.thespacereview.com/article/1549/1.

[100] Some U.S. military strategists have begun to realize the role of conventional weapons, but only as a part of a larger, vaguer package termed "strategic deterrence" that is meant to include nuclear and conventional weapons as well as diplomatic, economic, and informational tools. The *2001 Nuclear Posture Review Report* referred to this as the "New Triad." However, this paper is attempting to isolate the role of advanced nonnuclear capabilities to deter adversaries.

Figure A-1: Notional Deterrence Spectrum over Time[101]



Conclusion

Countries that do not have the capability or inclination to develop an internal nuclear deterrent logically look to security alliances with nuclear weapons states to obtain extended deterrence against mutual adversaries. Thus current U.S. deterrence is as much of a concern to U.S. allies as it is to the United States. The gradual nuclear arsenal drawdown, too, has particularly relevant security consequences. And while understanding the strategic consequences of drawing down is important, these advanced nonnuclear capabilities should play a greater role in U.S. discussion with key allies.

With each innovation in advanced nonnuclear capabilities, U.S. deterrence has evolved, bringing about changes in the U.S. deterrence spectrum as well as subsequent adjustments in the deterrence calculus of U.S. allies, partners, and potential adversaries. What the United States needs to communicate to its allies—and what allies should understand about future

[101] Francis Gavin, "The Myth of Flexible Response: American Strategy in Europe during the 1960s," *Nuclear Statecraft: History and Strategy in America's Atomic Age* (Ithaca, NY: Cornell University Press, 2012), 30–56; John Lewis Gaddis, *Strategies of Containment: A Critical Appraisal of American National Security Policy during the Cold War* (Oxford: Oxford University Press, 2005); Patrick M. Morgan, *Deterrence: A Conceptual Analysis* (Beverly Hills, CA: Sage Production, 1977).

U.S. security assurances—is that with the addition of each new advanced nonnuclear capability, the U.S. strategic deterrence *improves*. Despite continuing comparative fiscal austerity, the United States is making significant shifts in procurement and funding priorities to cyber, electronic, surveillance, intelligence, and space capabilities.

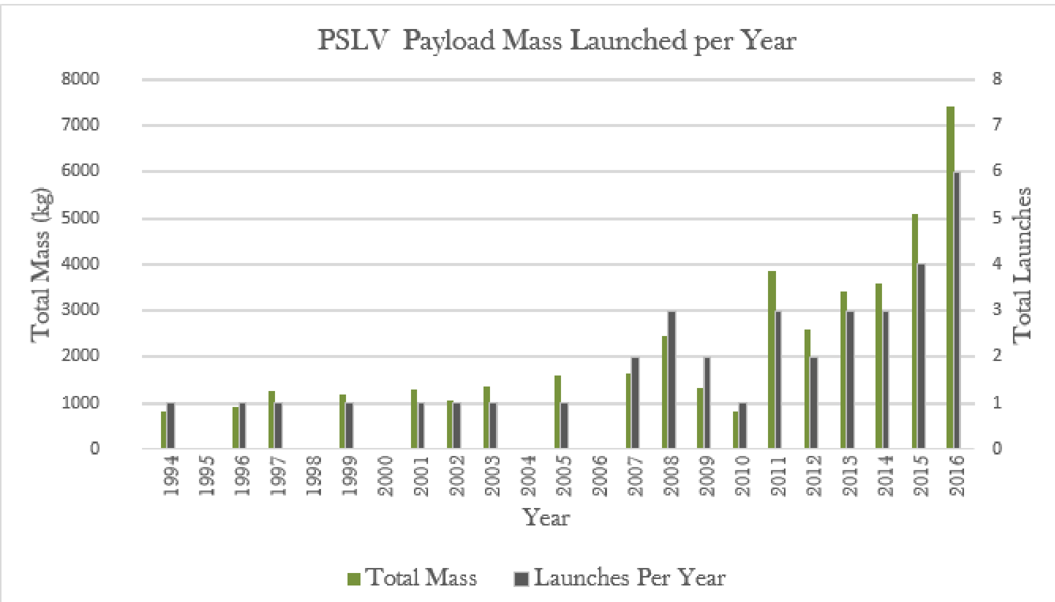
In the seven decades since the advent of the nuclear bomb, military capabilities for both nuclear and conventional forces have changed considerably. If deployed effectively, advanced nonnuclear capabilities augment the ability to deter adversaries by disrupting and disabling critical military infrastructure with minimal collateral damage. If these and future nonnuclear space capabilities can effectively neutralize adversarial threats, there may be a future in which nuclear weapons are no longer the dominant feature in a state's deterrence calculus and security alliances. U.S. strategic deterrence has the potential to shift again from Mutually Assured Destruction to Mutually Assured Disruption.

Appendix B. India's Low-Cost Space Program

John Schaus and Jake Stephens

In relatively short time, India's space program has made significant progress in space launch systems. Moving from one launch, or fewer, from 1993–2006, India has progressed to a steadily growing number of launches the past decade. In the same time period, India's launch payloads have grown from 846 kg per year to 7,432 kg.

Figure B-1: India's Polar Satellite Launch Vehicle (1994-2016)



Source: This figure depicts the increasing capability of the Polar Satellite Launch Vehicle (PSLV) as both launches per year and total mass of payloads (in kg) per year between 1993 and 2016. Indian Space Research Organization, "Polar Satellite Launch Vehicle," Department of Space, Government of India, http://www.isro.gov.in/launchers/pslv.

India's growing market share is attributed largely to its low price-point for many launches. The Polar Satellite Launch Vehicle (PSLV), India's most frequently used launch vehicle, is estimated to cost approximately $15 million per launch, roughly one-quarter the price of a private U.S.-based launch cost of $60 million.[102] The low cost brings limitations relative to other launch vehicles. Specifically, the maximum payload of the PSLV is roughly one-fourth that of a U.S.-based launch vehicle to the same orbit, as displayed in Table B-1.

[102] Peter B. de Selding, "SpaceX's reusable Falcon 9: What are the real cost savings for customers?," *SpaceNews*, April 25, 2016, http://spacenews.com/spacexs-reusable-falcon-9-what-are-the-real-cost-savings-for-customers/.

Table B-1: Indian Launch Vehicles

	ISRO				SPACE X	
			Future	Future		Future
	PSLV[103]	GSLV[104]	LVM3[105]	RLV-TD[106]	Falcon 9[107]	Falcon Heavy[108]
First Flight	1993	2001	2017	2030	2012	2017
Liftoff Mass	320 tons (XL)	414.75 tons	640 tons		549 tons	1421 tons
Height	44 m	49.13 m	43.43 m	39 m*	70 m	70 m
Diameter	2.8 m	2.8 m	5.0 m	21.6 m (Wingspan)*	3.7 m	12.2 m
No. of Stages	4	3	3	2	2	2
Variants	3 (G/CA/XL)	1	1	1	1	1
Maximum Thrust	4800 kN (Stage 1)	4700 kN (Stage 1)	9316 kN (Boosters)		7607 kN (Stage 1)	22,819 kN (Stage 1)
Fuels	HTPB, UDMH, N2O4, NMH, MON	UDMH, N2O4, HTPB, LOX, LH2	UDMH, N2O4, HTPB, LOX, LH2	Air-Breathing First Stage (from M3-M9)	LOX, RP-1	LOX, RP-1
To LEO	3800 kg	5000 kg	8000 kg	10,000 kg**	22,800 kg	54,500 kg
To GTO	1425 kg	2500 kg	4000 kg	10,000 kg**	8300 kg	22,200 kg
Cost (USD)	$15 million	$36 million	$35 million		$62 million	$90 million

Note: A single asterisk (*) refers to a data point based on a scale model. A double asterisk (**) refers to an unconfirmed estimate.

[103] Indian Space Research Organization, "Sounding Rockets," Department of Space, Government of India, http://www.isro.gov.in/launchers/sounding-rockets.
[104] Indian Space Research Organization, "Polar Satellite Launch Vehicle," Department of Space, Government of India, http://www.isro.gov.in/launchers/pslv.
[105] Indian Space Research Organization, "Geosynchronous Satellite Launch Vehicle (GSLV)," Department of Space, Government of India, http://www.isro.gov.in/launchers/gslv.
[106] Dennis S. Jesudasan, "ISRO plans to test air-breathing propulsion system," *The Hindu*, May 2016, http://www.thehindu.com/sci-tech/science/ISRO-plans-to-test-air-breathing-propulsion-system/article14340514.ece; Indian Space Research Organization, "LVM3," Department of Space, Government of India, http://www.isro.gov.in/launchers/lvm3; Yang Kai and Qu Jing, "India's Space Race," *Beijing Review*, February 2014, http://www.bjreview.com.cn/world/txt/2014-02/10/content_595651_2.htm.
[107] Indian Space Research Organization, "RLV-TD," Department of Space, Government of India, http://www.isro.gov.in/launchers/rev-dt; Rajesh Suseelan, "SpaceX Falcon 9 vs ISRO's Resuable Launch Vehicle," Medium.com, May 2016, https://medium.com/@rsn/spacex-falcon-9-vs-isros-reusable-launch-vehicle-c52d4d56f87d#.e42nfiqju; SpaceX, "Capabilities & Services," http://www.spacex.com/about/capabilities; SpaceX, "Falcon 9," http://www.spacex.com/falcon9.
[108] SpaceX, "Falcon Heavy," http://www.spacex.com/falcon-heavy; SpaceX, "Capabilities & Services."

Having established a solid position in the international space launch market, India is investing in additional launch vehicle systems to increase both its lift capacity and reduce its cost. Specifically, it is pursuing development of a Geosynchronous Launch Vehicle (GSLV) and a Reusable Launch Vehicle (RLV).

The GSLV has been launched 10 times, including two failures and three partial successes. The RLV is in the technology demonstration phase, and has seen scale-model real-world testing as recently as May 2016. The RLV will provide India with a fixed-wing, reusable vehicle that operates similarly to the former U.S. space shuttle.

The RLV program, if successful, could contribute to India's efforts to reduce costs for space access in two ways: reusability and mass reduction. ISRO estimates as much as a 10-times reduction in cost due to the reusability of the system. The second potential savings would be from a new engine design on the first stage of the RLV. The new design would draw oxygen from the atmosphere rather than from internal oxidation tanks. As a result, the liftoff mass of the RLV could be reduced. The vehicle would still require some form of oxidizing chemical for early stages of liftoff, and for operations above approximately 90km altitude, moderating the overall cost-savings.

The increasing adoption of small satellites, micro satellites, and nano satellites is driving much of the expansion in India's foreign-launch business. Approximately 50 percent of its total foreign payloads have been launched since 2013, with all but a handful of those payloads being less than 50 kg. Advances in miniaturization may enable India to continue to expand its offerings for space launch, as smaller launch vehicles may be more equipped to launch with a full load than their larger cousins.

Appendix C. China’s Efforts to Enhance Low-Cost Access to Space

John Schaus and Jake Stephens

The number of Chinese space launches per year has grown substantially over the past 30 years: from two in 1986 to 22 in 2016.[109] During that time, launch vehicles have increased in lift capacity, driven primarily by the requirements of its manned space program.

While the trajectory of China’s space program in general has been on the “bigger-is-better” track, it has also taken steps in recent years to establish and develop platforms to enhance low-cost access to space. Notably, a new organization, Expace, conducted its first commercial launch in January 2017. There are competing reports of the cost of Expace launches, as the chairman of Expace has indicated that its launch costs are close to $30,000 per kilogram, which he indicated are less than $40,000 per kilogram for other country’s solid-fuel rocket lift vehicles.[110] Other sources indicate China seeks to expand its share of the commercial space launch market—and particularly the market for small satellites—from its current position at 3 percent of the market to 15 percent of the market by 2020.[111]

According to a December 2016 white paper, China plans to further develop launch technologies that will enable lower-cost access to space.[112] China’s first reusable platforms, a reusable rocket booster landing system and reusable human spacecraft, are anticipated to move beyond the prototype stage by 2020 and will provide lift to LEO by 2020.[113] China’s new Long March 5 rocket with its Yuanzheng-2 upper stage will allow a single vehicle to place multiple satellites directly into their desired orbits, eliminating the need for individual propulsion systems for each payload.[114] China is also pursuing a single-stage, sub-orbital space plane, with a first model designed to carry 10 tons and a follow-on model to carry 100 tons, to LEO, with a goal of reusing the platform 50 times before refurbishment.[115]

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[109] “China Launch Log,” Global Security.org, http://www.globalsecurity.org/space/world/china/log.htm.
[110] Zhao Lei, “Rocket to Cut Cost of Missions,” *China Daily*, January 10, 2017, http://usa.chinadaily.com.cn/epaper/2017-01/10/content_27914554.htm.
[111] “Eyeing Commercial Space Launch,” *Beijing Review*, March 14, 2013, http://www.bjreview.com.cn/THIS_WEEK/2013-03/10/content_525288.htm.
[112] State Council Information Office of the People’s Republic of China, *China’s Space Activities in 2016*, White Paper (Beijing: Information Office of the State Council, 2016).
[113] “China Aiming for Reusable Manned Spacecraft: Chief Engineer,” Xinhua, April 24, 2016, http://news.xinhuanet.com/english/2016-04/24/c_135307643.htm; “China Testing Own Reusable Rocket Technologies,” Xinhua, April 21, 2016, http://news.xinhuanet.com/english/2016-04/21/c_135300443.htm.
[114] Thomasz Nowakowski, “China to Debut Powerful Next-Generation Long March 5 Launch Thursday,” *Spaceflight Insider*, November 1, 2016, http://www.spaceflightinsider.com/organizations/china-national-space-administration/china-debut-powerful-next-generation-long-march-5-launcher-thursday/; “China Sends Satellite, upper Stage Craft into Orbit,” *Global Times*, November 4, 2016, http://www.globaltimes.cn/content/1015859.shtml.
[115] Lin and Singer, “China’s private space industry prepares to compete with SpaceX and Blue Origin.”

Appendix D. Russian Antisatellite Program

Thomas Roberts

The United States and the Soviet Union both began pursuing robust antisatellite (ASAT) programs in the late 1950s and early 1960s. The United States developed and tested six different ASAT systems using direct-ascent trajectories. Soviet and Russian programs utilized co-orbital trajectories.[116] Co-orbital ASATs enter the target's orbit, spend several hours slowly approaching the target satellite within that orbit, and detonate once they are close enough for assured destruction. Direct-ascent ASATs collide with satellites less than an hour after their launch, often using only the kinetic force of the collision to destroy their targets.

In 2007, the Chinese government successfully tested a direct-ascent ASAT weapon, destroying a weather satellite, named FengYun-1C, and creating the largest-ever single-event debris cloud in low-Earth orbit, with over 3,000 traceable objects.[117] In 2008, the United States used a modified SM-3 missile defense interceptor to down a defunct U.S. government satellite. Because this intercept occurred at a much lower altitude, it created fewer than 200 pieces of traceable debris, much of which was burned up in the atmosphere within days or weeks.[118] In December 2016, Russia was suspected of testing its most recent ASAT weapon.[119] Unlike the tests carried out by China and the United States, the recent Russian test did not intercept or destroy a target and has not been verified. Thus, no debris was created. Nonetheless, experts believe it was a mission involving the PL-19 Nudol, a component of Russia's antimissile system.[120]

Currently, kinetic ASAT systems are expensive, and only nations with robust spacefaring infrastructures are testing these technologies. If the cost of access to space were to fall by a factor of 10 or more, the development of ASAT programs could become more viable and displays of capability much more frequent.

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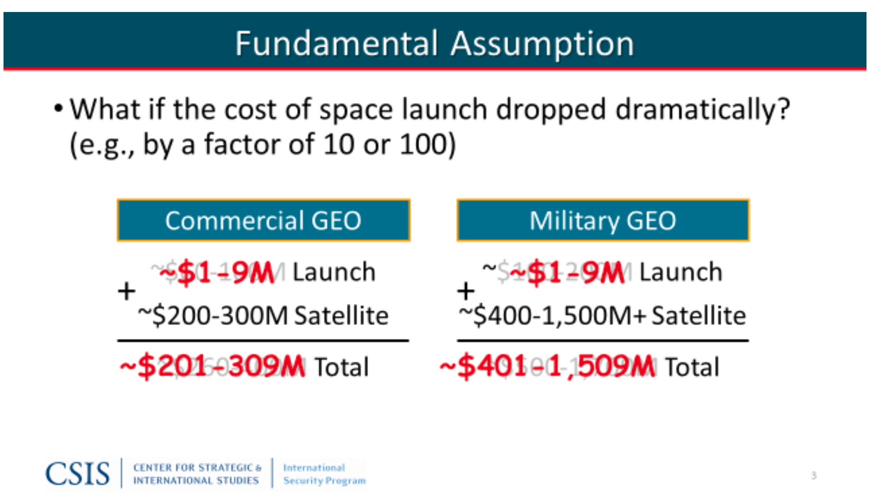
[116] Asif A. Siddiqi, "The Soviet Co-Orbital Anti-Satellite System: A Synopsis," *Journal of the British Interplanetary Society* 50, no. 6 (1997): 225–40, http://faculty.fordham.edu/siddiqi/writings/p7_siddiqi_jbis_is_history_1997.pdf.
[117] F.C, Conahan, *Status of the U.S. Anti-Satellite Program* (Washington, DC: General Accounting Office, 1985).
[118] Secure World Foundation, "Who We Are," 2015, http://swfound.org/about-us/who-we-are/.
[119] George Leopold, "Russian test reported, but was it ASAT?," DefenseSystems.com, https://defensesystems.com/articles/2016/12/22/russian.aspx.
[120] L. Todd Wood, "Russia tests anti-satellite weapon," *Washington Times*, December 21, 2016, http://www.washingtontimes.com/news/2016/dec/21/russia-tests-anti-satellite-weapon-pl-19-nudol/.

Appendix E. Workshop on New Space Missions and Operations Enabled by ULCATS

The Center for Strategic and International Studies held its first workshop on ultra-low-cost access to space (ULCATS) on September 19, 2016, which focused on new military and commercial space missions that could be enabled if the cost of space launch dropped by an order of magnitude or greater. This workshop was conducted on a not-for-attribution basis with participants from a variety of government, industry, and nonprofit organizations. The notes from this meeting reflect the general discussion that took place and do not necessarily represent the views of CSIS or the project team supporting this effort.

As a starting point for discussion, it was noted that ULCATS could mean that the cost of launching a typical commercial or military satellite to GEO would be in the range of $1–9 million. For less expensive satellites, this would represent a significant reduction in total mission cost, but for more expensive satellites—particularly military satellites that can cost over $1 billion each—such a reduction in launch costs would not significantly reduce the total mission cost. The participants in the workshop were asked to indicate potential new missions in space as a result of ultra-low-cost access, as well as expand upon the challenges that may be presented if these new missions were pursued by the U.S. military, commercial industry, or foreign governments.



Ultra-Low-Cost Access to Space and Its Military Implications

Several ideas were presented in the workshop regarding the implications of ULCATS for the U.S. military.

Introducing smaller payloads with shorter lifespans, which are able to be cheaply and quickly replaced, was one of the first ideas discussed. Developing and launching these smaller satellites could become increasingly important for the U.S. military. Replacing satellites already in orbit more frequently means that new technologies that have been developed since the initial launch of the satellite system could be included more quickly. Naturally, this could foster further technological innovation for both military and commercial missions.

However, because space is a finite domain, without a plan for removal of these smaller satellites from orbit, the amount of space debris accumulated in popular orbits could increase substantially. For example, small satellites, particularly cubesats, could crowd low-Earth orbit relatively quickly if the cost of launch were to dramatically decrease. Many of these satellites do not include onboard propulsion for maneuvering in order to reduce costs, which means that even if a conjunction is identified well in advance, there may be nothing that can done to avoid a debris-producing collision. Participants also noted that ultra-low cost to launch could also impact the process of removing damaged or incapacitated satellites, making it significantly more economical for countries to remove space debris that their space missions have created over time. This increased ability to behave responsibly in orbit could expose a gap in international laws and obligations for how space debris is removed and who pays for its removal in the future.

Ultra-low-cost access to space could also make the servicing of satellites less expensive and more viable for a larger range of satellite operators. Servicing satellites could include a number of options, including refueling, repairing, or updating satellites by adding new technologies in a “plug and play” approach. The option of servicing active in-orbit satellites could fundamentally alter the concept of satellites and space operations similar to how aerial refueling revolutionized air operations for the military. It was noted that several entities, such as NASA, DARPA, and Orbital ATK, are already moving forward with concepts for on orbit servicing.

However, ULCATS could also reduce the incentive for on-orbit satellite servicing. Instead of refueling or repositioning satellites or upgrading payloads and components on satellites, it may be more economical to launch a new satellite instead. The lifecycle cost of satellites could greatly impact the decision to service an existing system or launch a new satellite to replace an outdated or damaged satellite. If keeping the old satellite system alive by refueling, repairing, moving, or updating it is more expensive over the lifetime of the satellite, then with ULCATS it may be less expensive to launch a replacement instead. On the other hand, if the satellite is expensive with core capabilities that don't become dated over time (such as the core optics on the Hubble Space Telescope) then on-orbit servicing will continue to be more economical even if the cost of launch is dramatically reduced.

Ultra-low-cost access to space would also increase the potential for space to become a weaponized domain. Concepts like "Rods from God" for prompt global strike from space, "Brilliant Pebbles" for space-based missile defense interceptors, and "Brilliant Eyes" for space-based missile tracking from low Earth orbit, could become more economically feasible with ULCATS. These concepts rely on large constellations of small satellites, require many launches, and involve lofting a large amount of mass into orbit—attributes that allow them to benefit from lower launch costs.

If these concepts become more economically feasible for the United States, they would presumably become more feasible for other nations as well, which could pose serious security threats. An example of this might be strike capability from space, which could target virtually any place on Earth with impunity. A kinetic strike vehicle deorbited from low Earth orbit would be traveling at such a high velocity that it would be difficult if not impossible to intercept it. The opportunity capabilities like this present for an adversary to close the power-projection gap with the United States could prove irresistible and result in a more aggressive posture in space. With ULCATS, the U.S. military would need to fundamentally reevaluate space operations and overall force posture and protection in light of these new threats.

Nuclear policy and the missile technology control regime would also be impacted. With the price of launch significantly reduced, the potential of further proliferation of launch technologies and nuclear capabilities would be a serious consideration because it could mean that intercontinental ballistic missiles could be produced at much lower costs, making large arsenals of missiles more affordable for even minor military competitors. This reduction in costs could inspire nonnuclear countries, or third-party actors, to develop such ballistic missiles and potentially the warheads to top them.

Significantly lower launch costs would likely be in part a result of reusable launch vehicles and more frequent launch operations. More frequent launches would allow the U.S. military to more quickly respond to satellite malfunctions, attacks, threats on space systems, or other issues in space. It could mean an especially quick response time to LEO, as well as a game-changing response time for GEO-based systems.

ULCATS could also enable a rapid replenishment approach where a government, military, or commercial company keeps prebuilt satellites on-hand and ready for rapid integration and launch. For example, if the United States knew some of its satellites were high-priority targets in a conflict, it could build and store replacement satellites so that if one were attacked, a replacement could be launched within weeks, days, or even hours after the threat was neutralized, significantly reducing the long-term benefits a country could gain by attacking U.S. space systems.

With more satellites in space, traffic management, rules and regulations, and verification become important issues for consideration. If the number of launches and satellites increases exponentially due to ultra-low-cost access to space, responsibility for space traffic management becomes increasingly important. As a likely first mover in this area, the United States could use this opportunity to shape and influence the creation of international standards or norms of behavior in space on terms that favor continued open, responsible, and peaceful uses of outer space, similar to how the United States shaped global aviation at the advent of flight. To seize the initiative in this area, the U.S. government must quickly determine what approach it intends to take. Should there be an FAA-like organization for space? How will compliance with international standards and norms be verified? How will U.S. government agencies with space oversight responsibilities interface with their counterparts in other countries?

Ultra-low-cost access to space could also lead to nontraditional actors in space, such as pirates preying on relatively unprotected space systems. History has shown that where there is commerce, particularly new types of commerce that occurs in distant places with relatively weak governance, criminal activity is likely to follow.

Lastly, many commercial companies, including Blue Origin, SpaceX, and Virgin Galactic, view space tourism as a near-term possibility. Participants noted that this new industry poses risks and may lead to new demands on the U.S. government. If civilian and commercial sailors get lost or stuck at sea, the U.S. Coast Guard is called upon to rescue said sailors. With ULCATS and the almost-certainty that space travel will become open to civilians, the United States and other nations may need to consider a Coast Guard-like service to recover and rescue stranded or endangered civilians travelling through space.

Ultra-Low-Cost Access to Space and Its Civilian Implications

Ultra-low-cost access could also significantly impact the commercial sector and the space missions that are financially viable. Many missions that used to be government-led, such as space-based Earth imaging, have shifted to the commercial sector already, and it can be expected that this trend will continue in other mission areas. As mentioned earlier, several companies are already developing human spaceflight capabilities for space tourism. Current trends indicate that space tourism may grow and become a small but notable part of the global space economy.

Companies like Facebook, for example, are expanding their portfolio to include space-based capabilities. The Israeli-owned, Facebook-operated satellite that was recently lost due to an accident on SpaceX's Falcon 9 rocket was intended to be part of a larger effort to bring internet access from space to parts of sub-Saharan Africa through a collaboration between Facebook and a French satellite communications company. Despite the launch failure, this is a prime example of multinational commercial companies working together to further develop space-based capabilities.

Different types of private organizations may also look to enter the space domain if ULCATS is achieved. For example, nongovernmental organizations (NGOs) that might want to focus a satellite on a certain area of the world could do so. NGOs could use their satellites to monitor areas of violence or known human rights abusers. These initiatives would aid in many NGOs' missions to be a watchdog and obtain timely and independent information.

With ULCATS, weather and environmental monitoring could become more specific. With more satellites observing the globe, meteorologists could process more specific data to help them monitor the weather. At present, large space-based weather systems gather information and send it back to Earth. With lower launch costs, scientists and meteorologists could send up much smaller satellites to monitor areas of frequent disaster or violent weather more frequently.

Standardized shipping containers revolutionized trade and shipping worldwide. If ULCATS was achieved, the next area of transportation of goods may be through space. Standardized and regulated shipping missions could drastically reduce the time it takes to ship goods from one side of the world to the other. A network of space delivery routes could greatly increase the speed of economic interconnectivity around the globe and lead to a new era of globalization.

Increased commercial activity in space could also lead to an increase in space debris, particularly if international regulations do not keep pace with commercial activity. Other limiting factors for commercial companies, as demonstrated in the SpaceX Falcon 9 explosion in early September 2016, is the liability of launching goods, services, or people into space—especially if the mission or goal could be accomplished on the ground. If policymakers do not address these commercial risk and liability issues it could hinder activity in the space domain.

Deep-space ambitions could also be aided by ULCATS, including asteroid mining projects and establishing colonies of people living and working in space. Both Blue Origin and SpaceX have publicly announced their intentions of working toward having people live and work in space. The Lunar COTS (co-orbital transfer system) model, which is a "public-private funding approach for the development of an infrastructure based upon the use of lunar polar ice to facilitate transportation throughout cis-lunar space,"[121] was brought up as an example of how many experts are already looking to develop the moon in order to further space exploration and travel to Mars. Additionally, ULA's CisLunar 1000 plan depends on significantly lower cost to launch in order to develop space manufacturing, asteroid mining capabilities, and commercial habitats.[122] Again, these actions would bring in a new aspect to the world's economy, potentially fundamentally shifting the global marketplace.

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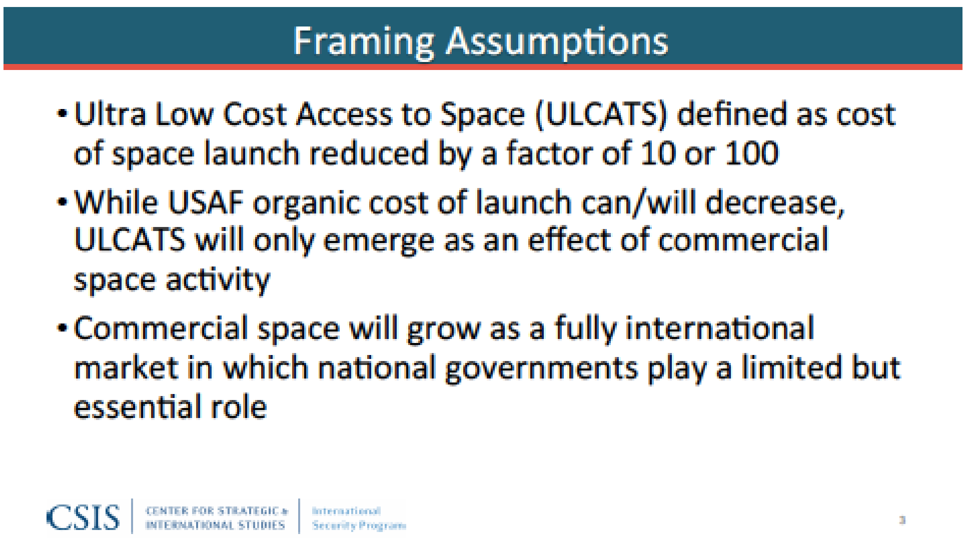
[121] LunarCots, http//:lunarcots.com.
[122] ULA, *Transportation Enabling a Robust Cislunar Space Economy* (Centennial, CO: ULA, April 2016), http://www.ulalaunch.com/uploads/docs/Published_Papers/Commercial_Space/2016_Cislunar.pdf.

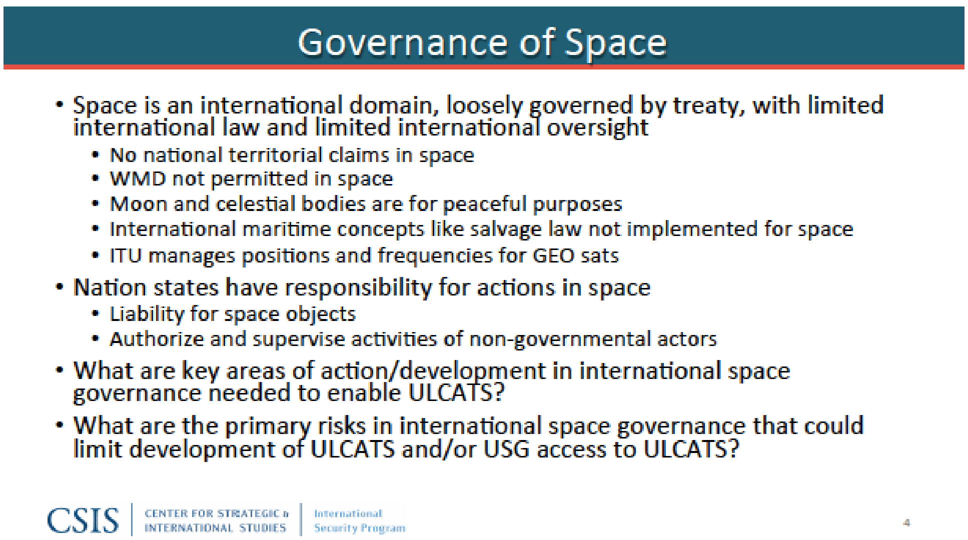
Appendix F. Workshop on Legal, Policy, and Acquisition Implications of ULCATS

The Center for Strategic and International Studies held its second workshop on ultra-low-cost access to space, which focused on both international and U.S. national legal, policy, and acquisition implications that would arise with a dramatic decrease in the cost of launching payloads to orbit. In addition to the insightful points and discussion that occurred on legal, policy, and acquisition changes that may be needed to both accelerate and respond to ultra-low-cost access to space, the participants identified areas where careful definition of terms is required to ensure clarity of options in the discussion.



The discussion of framing assumptions centered first on the likelihood of whether space launch cost reductions on the level of one or two orders of magnitude were possible or likely. Several participants expressed doubt about whether order-of-magnitude cost reductions are possible absent a major technological breakthrough. Similarly, they expressed doubt as to whether a significant uptick in commercial space activity was likely to materialize, noting that previous predictions of rapid growth in commercial space have not been born out. However, there was general agreement that while cost reductions are available in part from smarter government approaches to purchasing launch, major cost reductions are likely to become available to the extent that commercial space activity shows significant growth, driving substantial increases in the number of launches and providing impetus for the effective use of reusable launch vehicles and alternative payload approaches. On the final assumption, some participants questioned the significance of the international nature of the market, noting that a small number of nations currently have viable launch capabilities, and that leadership of emerging reusable commercial launch capabilities are located predominantly in the United States. However, most participants agreed that to the extent that commercial space activity does grow substantially, the demand for substantially greater volumes of launch would, of necessity, include a substantial number of international customers, as is already the case in space-based telecommunications.

A significant aspect of the discussion of framing assumptions was a critique of how commercial space activity is defined. Whether, for example, government purchases of commercial launch services counted as commercial space activity, and how the cost of launch is to be calculated; whether cost was being confused with price; and whether the relevant question was the cost of individual launches or the cost of launch at industry/sector level. The CSIS study team agreed to the necessity to carefully define these terms to ensure clarity of discussion and analysis.



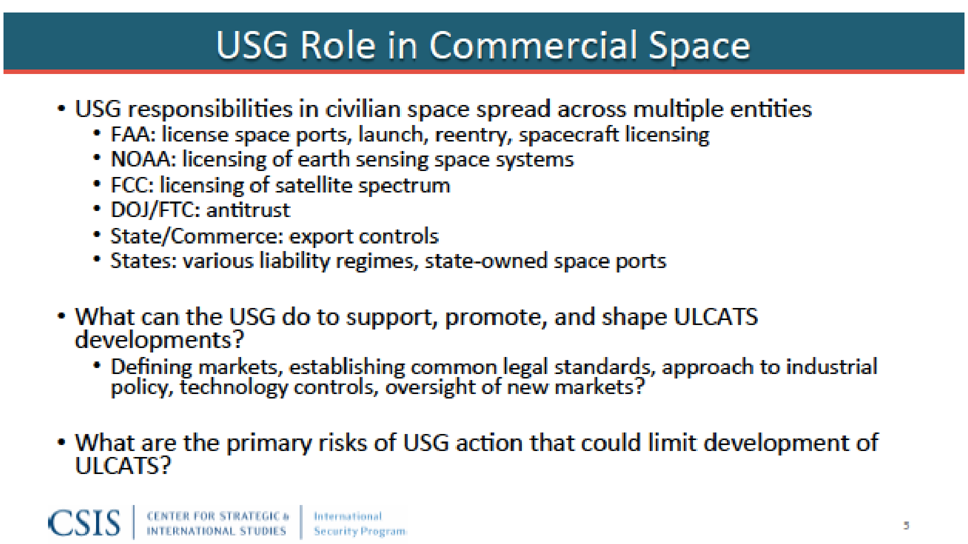
The current international role in space governance sets important, but loose, guideposts for nationally led space activity. This portion of the discussion explored whether ULCATS would drive a need to expand or develop new policy and laws on an international scale. Given that ULCATS would most likely come about as a result of significant increases in commercial space launch in all orbits, it could drive the need for an expansion of the UN's International Telecommunications Union (ITU) or a new ITU-like organization to allocate and monitor LEO activities.

However, more international involvement could make countries reluctant to agree to new measures because of loss of power and sovereignty. The current treaties that govern space do not have universal support and some countries could be unwilling to give up further control over their space capabilities. Due to this reason, further international policy in this area would most likely grow out of policies at the national level. This dynamic creates an incentive for the United States to develop its space policies early with an eye to setting standards for international commercial space activity in mind.

The discussion then referenced existing and historical models for how international law, regulation, and policy developed in other global commons. A maritime example that may be instructive is UNCLOS, or the United Nations Convention on the Law of the Sea. Notably, many countries that formally ratified UNCLOS did so with major caveats and reservations, a dynamic that may repeat in space. However, without clear norms, space remains a grey area of acceptable actions, with many potential consequences for countries like the United States that rely heavily on space systems. Also, the existing body of international law is likely to apply to activities in space such as the law of armed conflict and laws of international business. While increased commercial activity in space may require some extension of these bodies of law, they can likely be adapted to space activity in a fairly straightforward manner.

With new entrants into the space domain and space market comes significant traffic-management issues. *(This was a point also brought up in the first workshop CSIS held on the ULCATS issue.)* This means an entity responsible for traffic management needs to be established in order to manage the finite domain of lower-Earth orbit. The necessity of allocation harkens back to the beginnings of air traffic management when international air travel became possible. The United States led the way in air traffic management, which caused the American system and rules for traffic management to be adopted globally. Something similar to this could be possible in the space domain if the United States began to manage space traffic of the few space-operating countries and companies. However, some countries may not be so accepting of the United States' leadership role. Space has long been an area with strong government-led operations and many commercial and civil space operations have strong ties with federal agencies. The aviation transportation industry transitioned to a mostly commercial industry much earlier in its history.

To move forward with rules and regulations for space, a suggestion may be for the United States to start with nonenforcing international standards that lay out the best practices for operating in space. This could be modeled off the National Institute of Standards and Technology (NIST), which operates in a similar fashion. If these norms, standards, or rules are created with an international aspect in mind, they may be more easily adopted globally.



One issue raised about the slide itself was that NASA was not included in the first bullet section of U.S. government responsibilities in civilian space. While it was agreed that NASA is not currently very active in promoting or regulating commercial space activity, NASA's founding statute specifically tasks it with responsibility in this area.

What, if anything, can the U.S. government do to shape the commercial space market so that ULCATS can develop? One participant raised the importance of spectrum allocation between commercial and government uses, especially if commercial activity experiences a significant increase. The U.S. government approach here has tended to limit commercial activity by making overly broad reservations of spectrum, being slow to issue decisions, and by establishing opaque roadblocks to spectrum allocation. The lack of transparency can halt developing commercial space activities in their tracks.

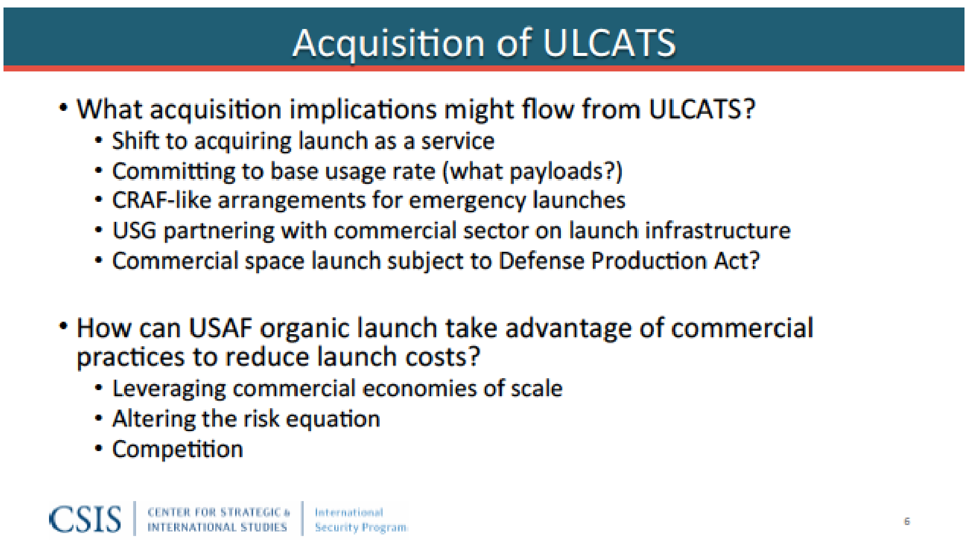
Many participants saw on-orbit satellite servicing as a clear, near-term way forward for both ULCATS and the growth of commercial space. The U.S. government can encourage this both by buying commercial on-orbit services and by developing policies that enable the growth of this part of the industry. On-orbit servicing could alter the industry in unpredictable ways that could run counter to the vision of high-volume launches of many small satellites that is sometimes depicted as the inevitable result of ULCATS. However, on-orbit servicing can still lower the cost of access to space by reducing the amount of payload that needs to be launched to establish capability even as it may undercut a move to high-volume launches of new satellites.

Participants also discussed issues with licensing and intellectual property rights. Currently, licensing offices are inherently size and personnel limited in dealing with this type of commerce. Training and hiring of new licensing personnel would be needed if commercial space activity increases. For example, the NOAA office currently only has one licensing person on staff. This is already causing the potential for delays with ongoing space operations.

Another major issue that was raised is the application-centric nature of our current system. Both the U.S. government and international actors deal with space systems and acquisition on an individual application-like basis. With ULCATS, satellite servicing, and the potential for future unexplored options in space, this application-centric approach might not be the most efficient way to acquire space systems. There is potential to establish a more comprehensive approach that may be better suited for the future of space activity. One solution may be an agency or process within the U.S. government that focuses solely on space, rather than having each aspect of space divvied up to different agencies, as it is in the current system. However, if the government becomes too comprehensive in its oversight role, it could inhibit innovation. The Department of Defense and the intelligence community are crucial to many space projects, but can also be inhibitors to commercial space approaches to innovation.

Additionally, some participants noted that there are other nonregulatory-focused areas where the government can promote and support ULCATS and other space-oriented innovations. Already the U.S. government supports many public and private labs across the countries that are working on innovative space technologies. This leading edge of technology development needs continual and increased support if major innovations in space launch are to be implemented. Some participants argued that industry, especially small commercial innovation centers, can not put in similar amounts of investment as that of the U.S. government because of a significant amount of risk. Since the government can take on more risk than other investors, it is paramount that the government continues to invest in research.

Participants also noted that another way the U.S. government can affect commercial space is through technology transfers. Our government has the resources to develop next-generation technology, but in order to keep moving forward and bring in more innovative solutions, technology transfers to private industry may be necessary. The U.S. government can also continue to influence the commercial side by promoting competition between the different commercial space companies. If the U.S. government fosters a strong commercial space market, there will ultimately be lower prices and more innovation.



As discussed earlier in the conversation, an important way of acquiring ULCATS and other space technology innovations is to buy launch capabilities as a service, instead of the traditional way in which the Air Force purchases launch hardware. Buying launch as a service fundamentally changes the way the U.S. government has historically operated in space. While the Air Force currently buys launch as a service in a technical sense, it has retained extensive control over exactly how that service is delivered. As ULCATS develops, the government would need to be willing to behave much more like, if not exactly like, commercial launch customers to enjoy the lowest-cost access to space. This change is likely even more imperative if there is increasing use of commercial reusable launch vehicles. Such approaches will require a change in the U.S. government approach to mission assurance and risk assessment and the acceptance of commercial approaches to achieving higher reliability in space operations.

This portion of the discussion further explored how the government could support the development of commercial space through purchasing of commercial space services and by providing an economic base of support for these activities much as airmail served as an initial economic base for aviation. Previous examples of this include government purchases of block buys of services such as commercial satellite imagery and the use of a Civil Reserve Air Fleet (CRAF)-type model to ensure preferential government access to commercial launch capacity during times of national emergency. A CRAF model could displace the need to exercise Defense Production Act priority ratings on space launch assets at such times.

Another aspect of commercial space launch discussed was the substantial state and local involvement in commercial space, both as financers and operators of launch infrastructure and as regulators through tort and liability law. Wallops Island and the Kennedy Center already provide examples of this phenomenon and several other locations are seeking or have begun to implement similar models.

Given the international nature of the space domain and the likely commercial character of ULCATS, the U.S. government will have to think carefully about how to apply technology controls to commercial space. If the government prohibits or substantially limits how American commercial companies market this capability internationally, it is likely to encourage the spread of the technology to potential international competitors. The level of commercial activity needed to deliver ULCATS will necessarily require a relatively open international commercial space market. This capability needs to be shared in order for it to flourish and for the United States to maintain a lead in space launch. Policies should promote robust competition in commercial space.

However, it must be noted that governmental efforts to encourage competition and international cooperation in space will confront some natural limits. U.S. companies will be competing in some places with sovereign-subsidized companies and national champions. Some nations will want to keep their launch services independent of the United States.

As ULCATS develops to fruition, the cycle could even turn back toward a place where the government could resume a more traditional role. The United States, and other nations, may want to purchase and operate a fleet of commercially developed reusable launch vehicles in order to launch quickly and without the complications of commercial involvement. This type of block buy would create a different model for launch than what was discussed previously. This strategy would also ensure secrecy for government operations, which is an asset with current and emerging space technologies.

Other unknowns are also bound to arise and the U.S. government must be prepared to deal with potential unintended consequences of ULCATS and other new space technologies. Lower costs could cause the proliferation of technology such as missiles and the increase of potentially hostile activity in space. However, the government should present clear requirements for acquisition, as well as a positive vision for the future of space launch.

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