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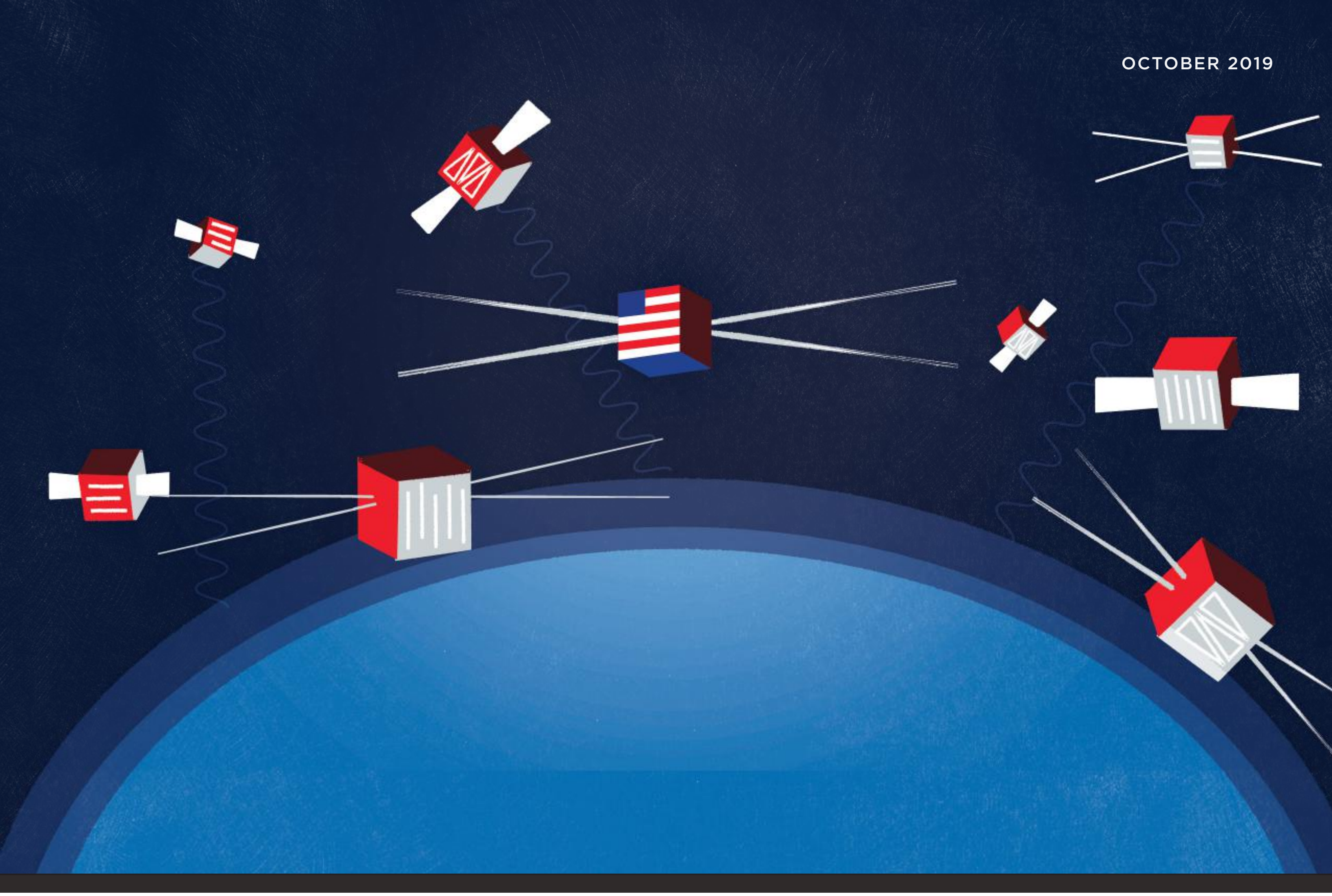

Small Satellites in the Emerging Space Environment

Implications for U.S. National Security–Related Space Plans and Programs

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About the Author

STEVEN KOSIAK is a nationally recognized expert on the U.S. defense and international affairs budgets, with extensive experience in national security planning and budgeting. Presently, he is a partner with ISM Strategies, a Washington, DC based consulting firm that provides high-value counsel, expert assessments and other strategic support to a range of clients working in the defense and international affairs fields. Areas of expertise include the federal budget process, especially within the Executive Branch, and the national security planning and budgeting processes within the Executive Office of the President, as well as the programs and budgets of the Department of Defense, and the Department of State and other international affairs Agencies. Mr. Kosiak is also an Adjunct Senior Fellow in the Defense Program of the Center for a New American Security (CNAS) and a faculty member at American University's School of International Service (SIS), where he teaches a graduate-level course on US Budgeting for Foreign Policy and National Security.

Prior to joining ISM Strategies in the fall of 2014, Mr. Kosiak served for five-and-a-half years as the Office of Management and Budget's (OMB's) Associate Director for Defense and International Affairs, the senior White House official for national security and foreign policy budgeting. In that position, he was responsible for overseeing the budgets of the Departments of Defense, State/USAID, Treasury (International), and Veterans Affairs, as well as the National Nuclear Security Administration, the Intelligence Community and a range of smaller agencies. Mr. Kosiak led OMB's oversight and direction of those agencies from the initial development of budgetary guidance, through the review of their budget submissions, OMB's issuance of "Passback" decisions, and the resolution of agency appeals, to the drafting of the final budget request and its submission to Congress. He also served as the OMB representative to the National Security Council (NSC) Deputies Committee, and coordinated efforts to ensure that Presidential priorities were protected and advanced through agency budgets.

From 1996 to 2009, Mr. Kosiak was Vice President for Budget Studies at the Center for Strategic and Budgetary Assessments (CSBA). While at the Center, he authored numerous reports and dozens of briefing papers, concerning everything from weapons modernization, space programs, force structure, readiness, and military compensation, to the cost of military operations, homeland security programs, and the implications for national security spending of overall federal budget trends and priorities. Mr. Kosiak also supervised, directed and edited all staff work concerning national security spending issues, including the work of senior analysts and outside consultants. In addition, from 2000 to 2008, he served as an adjunct faculty member at Georgetown University's Security Studies Program, where he taught a graduate-level course on US National Security Budgeting and Planning. Mr. Kosiak has been widely quoted in the national and defense media, frequently testified before Congress, and briefed many members of Congress, and senior government and industry leaders. He holds a JD from the Georgetown University Law Center (1998), an MPA from the Woodrow Wilson School of Public and International Affairs at Princeton University (1986) and a BA in History and Political Science from the University of Minnesota (1982).

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Cover Illustration
Melody Cook/CNAS

Executive Summary

In coming years, constellations composed of large numbers of small, less complex, and less costly satellites are likely to become progressively more cost-effective relative to constellations made up of small numbers of large, more complex, and more expensive satellites. Movement in this direction, which is already clearly visible in commercial space, is the result of a variety of factors, including continued improvements in the miniaturization of computers, sensors, and other technologies and, even more importantly, reductions in space launch costs.

While it would be hazardous to assume that launch costs for satellites will be cut dramatically in the near future, it seems likely that at least some significant further reductions will be achieved, given the success of efforts to reduce those costs in recent years and the number and maturity of ongoing efforts focused on this goal. Because launch costs presently account for a far higher share of overall lifecycle costs for small, less expensive satellites than for large, costly satellites, these reductions are likely to improve the overall cost-effectiveness of the former more than the latter.

The dispersion of space assets among large constellations of small satellites also offers an important means of complicating a potential adversary's task of attacking space-based assets. However, this advantage is by no means a panacea, given the variety of anti-satellite capabilities being developed and potential countermeasures available. More compelling is the opportunity small-satellite capabilities offer as a means of constituting a substantial wartime reserve.

Taken together, recent and projected trends in commercial constellation design, miniaturization, launch costs, and anti-satellite capabilities fall short of supporting a dramatic near-term reorientation of U.S. space capabilities. However, those trends do suggest that now is an appropriate time for the U.S. military and intelligence community to at least modestly increase their investment in small satellite capabilities—both as a hedge and to create options. Specifically, they should:

- Commit to the development and deployment of one or more constellations composed of large numbers of small and relatively low-cost satellites, including the use of hosted or specially modified payloads on dispersed constellations of small commercial satellites, in order to gain greater familiarity with the operation of such constellations.
- Acquire a modest reserve of small satellites, focusing on expanding the replenishment pool needed by large constellations of small satellites due to their frequent and routine replenishment requirements.
- Provide greater support for the development of more efficient and cost-effective space launch vehicles—particularly small launch vehicles—as well as a more agile and survivable space launch capability.

Altogether, implementing these recommendations would likely require half a billion dollars a year initially, growing to perhaps $1-2 billion annually within five years. In the context of a national defense budget exceeding $700 billion, finding funding of this magnitude, while not simple—given other budgetary pressures—should prove manageable. And such an expenditure would place the U.S. military and intelligence community in a far better position to effectively respond to and exploit changes in the space environment driven by improvements in small satellite capabilities—whether those changes, ultimately, turn out to be more evolutionary or revolutionary in nature.

Introduction

The U.S. military and national intelligence community have traditionally depended primarily on satellite constellations made up of small numbers of highly capable, large, complex, and costly satellites. These satellites generally take many years to develop and produce, and—largely because of their high cost—can be replaced only after many years in service. Increasingly, some critics have argued that the U.S. military should shift away from this architecture toward one that makes greater use of much larger constellations made up of smaller, less complex, and less capable satellites that are individually less costly but, at present, have proportionally higher launch costs.[1]

The potential for such a shift is driven by historical and projected trends in a number of areas, including the miniaturization of electronics, computing, and other technologies related to satellite design and reductions in launch costs (especially costs associated with small launch vehicles). According to some observers, because of these factors and the natural advantages of dispersed satellite constellations for some missions, the time is fast approaching when large constellations made up of small satellites will in many instances prove more cost-effective than the small constellations of large, costly, and complex satellites that currently dominate most national security missions.[2] Trends in the commercial satellite market also suggest a growing role for small satellites deployed in large constellations.

Moreover, some analysts argue that as potentially significant as the advantages of such constellations are in peacetime, their advantages grow much more pronounced when wartime considerations are taken into account.[3] Over the past several decades, measured by the number and types of anti-satellite (ASAT) capabilities possessed by potential U.S. adversaries, the threat to U.S. space-based assets has grown dramatically. Those who advocate moving toward greater use of small, less costly, and less complex satellites argue both that large constellations of such satellites would be inherently more survivable in wartime and that they could affordably and quickly be expanded or replenished, as needed, to meet wartime operational demands.[4]

Notwithstanding these trends and the potential advantages associated with small satellites, the implications of these factors for future satellite and constellation design can be discerned only roughly and imperfectly. No approach to satellite or constellation design is risk- or cost-free—all have strengths and weaknesses, and all entail tradeoffs and potential opportunity costs. Moreover, even where the direction of future trends may seem relatively clear, the pace is less certain.

The purpose of this report is to explore questions about the relative merits for the U.S. military and intelligence community of the traditional approach to satellite

The Air Force's Advanced Extremely High Frequency satellite pictured above is an example of a highly capable, large, complex, and costly satellite. It reflects the U.S. military's traditional approach to satellite development. (U.S. Air Force Flickr)

While not part of a Department of Defense mission, the Nanoracks Cubesats pictured above depicts the dramatic reduction in satellite size compared with more traditional, larger satellite designs. (Bill Ingalls/NASA Flickr) and constellation design and a space architecture that would involve greater reliance on large constellations of small satellites. The goal is not to provide definitive answers on the specific shape of future U.S. satellite investments and utilization. Instead, the purpose of this assessment is to raise the level of discussion and debate concerning how technological trends and other considerations are likely to impact the relative strength of these two approaches in coming years. To the degree these findings allow, the report also provides some tentative recommendations concerning the U.S. military's and intelligence community's plans for space.[5]

No approach to satellite or constellation design is risk- or cost-free—all have strengths and weaknesses.

The report begins with a brief description of the U.S. military's and intelligence community's current space architecture and plans for modernizing that architecture over the coming decade. The opening section also contains a brief discussion of the commercial space sector, including the growing use of small satellites. This is followed by a discussion of trends in two areas particularly relevant to a future space architecture: trends in the miniaturization of various satellite technologies and trends in space launch capabilities, especially small launch vehicles. The next part of the report considers the implications of these and other trends, including the growing threat posed by the ASAT capabilities of potential adversaries, for the future of satellite and constellation design. The report closes with a set of recommendations intended to improve the U.S. military's and intelligence community's position with respect to a possible shift toward such a new space paradigm.

U.S. Military and Intelligence Community Space Architecture and Plans

The U.S. military and intelligence community currently operate over 150 active satellites, according to the Union of Concerned Scientists (UCS) Satellite Database.[6] These satellites are used to carry out a broad range of missions, including reconnaissance, communication, navigation, electronic intelligence gathering, weather forecasting, ballistic missile early warning, and technology development. This satellite architecture is dominated by relatively small constellations composed of relatively large, complex, highly capable, and costly satellites, designed with long service lives in mind—typically in the range of 10-15 years. Moreover, this space architecture is projected to remain largely focused on satellites and constellations with these attributes for the foreseeable future.

Due to data limitations arising from the classified nature of some programs, the technical specifications of many military and intelligence community satellite programs are unavailable. However, based on the data that is available (and that encompasses the vast majority of U.S. military and intelligence community satellites), it is possible to generate a fairly clear picture of the U.S. national security satellite architecture. Satellites are commonly classified into a number of different classes based on their weight at launch (or "separated mass"). These categories range from 1,200 kilograms and under for small satellites to 1,201-2,500 kilograms for medium satellites, 2,501-4,200 kilograms for intermediate

A United Launch Alliance Delta IV-Heavy rocket launches a National Reconnaissance Office (NRO) payload. The use of the heavy-lift launcher demonstrates the large size of the NRO payload. (Airman Yvonne Morales/U.S. Air Force) satellites, 4,200-5,400 for large satellites, 5,401-7,000 kilograms for heavy satellites, and 7,001 kilograms and above for extra-heavy satellites (see Table 1).[7] In addition, the "small" class is further broken down into six subcategories ranging from Femto (under 0.1 kilogram) to small (601-1,200 kilograms).[8]

TABLE 1: SATELLITE MASS CLASSES

Class Name	Kilograms	Pounds
Femto	0.01-0.10	0.02-0.20
Pico	0.09-1.0	0.19-2
Nano	1.1-10	3-22
Micro	11-200	23-441
Mini	201-600	442-1,323
Small	601-1,200	1,324-2,646
Medium	1,201-2,500	2,647-5,512
Intermediate	2,501-4,200	5,513-9,259
Large	4,201-5,400	9,260-11,905
Heavy	5,401-7,000	11,906-15,432
Extra Heavy	7,001+	15,433+

"The Annual Compendium of Commercial Space Transportation: 2018," (Federal Aviation Administration, January 2018), 94.

The difference in size between the largest and smallest satellite classes reflects a revolution in satellite technology and a shift in satellite design.

Mass data is publicly available for 104 of the roughly 120 U.S. military and intelligence community satellites used for operational missions (i.e., excluding technology development) that are specifically identified in the UCS Satellite Database.[9] These 104 satellites have an average mass of about 4,300 kilograms, putting the average satellite into the large class. The dominance of large satellites in the existing national security satellite architecture can also be seen in a breakdown of those 104 satellites (see Table 2). A total of 45 of those satellites fall into the large, heavy, and extra-heavy classes. Combined, these three classes account for 72 percent of the total mass for all U.S. military satellites in orbit. Of the remainder, 47 satellites fall into the medium or intermediate classes, and only 12 are classified as small. Moreover, all 12 of these satellites have masses of over 1,000 kilograms, placing them just barely within the largest of the six small-satellite subclasses and outside the range of most discussions of small satellites—which tend to focus on satellites with masses under 600 kilograms.

As Table 2 shows, 44 percent of the military and intelligence community satellites are of the large or heavy to extra-heavy class. This segment of satellites makes up 72 percent of the share of total mass despite being less than half of all military and intelligence community satellites.

Generating a high-confidence estimate of the average cost of U.S. military and intelligence community satellites is more difficult, again in part due to classification issues. However, detailed cost data is publicly available for five different satellite systems (comprising a total of roughly three dozen satellites) that have been acquired in recent years or are still in production.[10] Based on that sample, it is clear that designing satellites to maximize capability and longevity comes at a cost: Most U.S. military and intelligence community satellites are not only relatively large but also expensive. The unit acquisition (development plus procurement) cost of satellites in this sample has a weighted average of some $1.5 billion. In addition, the satellites in this sample have a weighted average mass of about 4,000 kilograms, very similar to the average mass for the broader sample of satellites discussed above—at least suggesting that this cost estimate may have broader applicability for other current-generation U.S. military and intelligence community satellites. With the exception of the Navstar Global Positioning Satellite (GPS) constellation, which currently consists of about 30 operational satellites, most of the constellations used for various national security missions comprise a half-dozen or fewer satellites.

It is important to note that, in addition to its own constellations of satellites, the U.S. military also leases capacity from commercial satellite constellations for some missions. This is particularly important for communications. By one estimate, the private sector provides

TABLE 2: MILITARY AND INTELLIGENCE COMMUNITY SATELLITES BY MASS CLASS

Class Name	Active Satellites	Share of Satellites	Share of Total Mass
Small	12	17%	3%
Medium	36	35%	16%
Intermediate	11	11%	9%
Large	18	17%	19%
Heavy to Extra Heavy	27	27%	53%

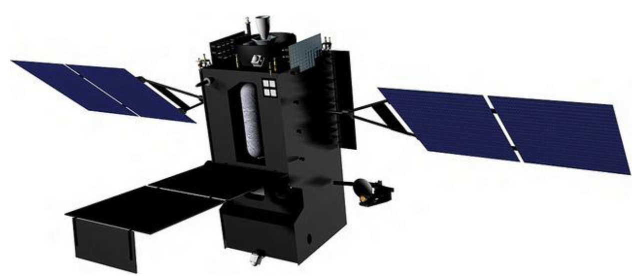
Author's estimates based on UCS Satellite Database, https://www.ucsusa.org/nuclear-weapons/space-weapons/satellite-database#.W60XF_IRfIU.

as much as 80 percent of the military's satellite communications requirement.[11] At over $1 billion a year, spending on commercially leased satellite communications is considerable.[12] Nevertheless, it represents only a fraction of the U.S. military's annual investment in its own space assets. The military and intelligence community have also made use of commercial satellites to "host" dedicated defense communications and sensor payload modules. The use of such hosted payloads, or modified payloads tailored to provide special capabilities to the U.S. military (e.g., greater imaging resolution or access to certain frequency bands) not provided to commercial customers, offers the potential of getting capabilities in orbit faster and more affordably, as well as spreading capabilities across a larger number of satellites.[13] However, so far the U.S. military and intelligence community have made only limited use of these approaches.[14]

In terms of unclassified programs, the U.S. military's and intelligence community's current acquisition plans project a continuation of the historical preference for relatively small constellations made up of large, complex, highly capable, and costly dedicated military satellites. Major U.S. military and intelligence community satellite acquisition programs include the Advanced Extremely High Frequency (AEHF), the GPS III, and the Space-Based Infrared System (SBIRS).[15]

- **AEHF:** This system is intended to provide secure, jam-resistant communication globally, replacing the legacy Milstar satellite system. So far, four AEHF satellites have been placed in orbit. Another three are scheduled for deployment over the next three years, resulting in a six-satellite constellation by 2020. The AEHF satellite has a mass of about 6,200 kilograms and a unit acquisition cost of about $2.6 billion.[16]
- **GPS III:** This satellite represents the latest iteration of the GPS navigation satellite program. The first GPS III satellites was launched at the end of 2018, with a total of 10 satellites to placed in orbit over the next several years. Plans currently call for the acquisition of a further 10 follow-on GPS III satellites to be procured over the 2020-23 period, and an additional 10 satellites to be procured in later years. The GPS III satellite has a mass of about 2,300 kilograms and a unit acquisition cost of about $600 million.
- **SBIRS:** This system is designed to provide early warning of a ballistic missile attack against the United States or its allies. The system replaces the legacy Defense Support Program. The first SBIRS satellite was deployed in 2011, with a total of four now in orbit. In addition to these four satellites in geosynchronous orbit, the constellation is supported by hosted payload modules carried aboard two other satellites operating in highly elliptical orbits. SBIRS satellites five and six are currently in production; they are intended to replace the first two satellites in 2021 and 2022. Originally, a total of eight SBIRS satellites were to be procured. But the Air Force recently canceled the last two. It now plans to begin development of a more survivable follow-on system. Like SBIRS, the planned follow-on system would consist of a small number of highly capable and costly satellites.[17] The SBIRS satellite has a mass of about 4,800 kilograms and a unit acquisition cost of about $3.2 billion.

The U.S. military and intelligence community have by no means entirely ignored small-satellite capabilities. The Defense Advanced Research Projects Agency (DARPA), for example, under its "Blackjack" project, is soliciting bids from companies for small-satellite concepts focused on the potential for less expensive commercial satellites to host military payloads, replacing much more expensive custom-built military satellites for missions such as surveillance and communications.[18] And the agency's director, Steven Walker, has expressed a desire to see the services move toward greater use of large constellations of small satellites operating in low earth orbit (LEO).[19] Similarly, the Air Force is involved in a number of efforts focused on small satellites. By orders of the deputy secretary of defense, the Air Force's Operationally Responsive Space office was created in 2007. The goal of the office is to rapidly respond to urgent, currently unmet needs for satellite capabilities identified by operational commanders. Over the past decade, it has produced and deployed about a half-dozen small and relatively inexpensive satellites of different types, typically holding costs to under $100 million and keeping development times under three years.[20] In addition, the Air Force



A artist's rendering of the Space-Based Infrared System satellite, which supports the warfighter in four distinct mission areas: missile warning, missile defense, technical intelligence, and battle space awareness. (U.S. Air Force Flickr)

Gen. Ellen Pawlikowski has been vocal about the need to utilize small satellites in U.S. military satellite architectures. (U.S. Air Force)

plans to purchase a number of small weather satellites[21] and has proposed to fund a nearly $200 million multi-year effort to purchase small-satellite launch services.[22] Moreover, in recent years, Air Force leadership has expressed support for a greater emphasis on small-satellite capabilities. For example, in early 2018, Gen. Ellen Pawlikowski, the former head of Air Force Material Command, argued that trends in launch costs, ASAT capabilities, and the commercial space market would require the United States to place greater emphasis on small satellites.[23] Nevertheless, in terms of unclassified programs and funding, U.S. military and intelligence community space programs remain focused primarily on the development and deployment of large, complex, and costly satellites.

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Commercial Space Architecture and Trends

As in the case of national security–related space systems, relatively small constellations of large, costly, and complex satellites continue to dominate commercial space architectures. This dominance can perhaps best be seen by comparing the total mass of various classes of active commercial satellites currently in orbit—since satellite mass is generally correlated with complexity and cost. The UCS Satellite Database provides mass information for about 700 of the 800 active commercial satellites currently in orbit. Of those 700 satellites, slightly more than half fall into the small-satellite class (see Table 3).[24] However, those satellites account for only about 5 percent of the total mass for all active commercial satellites in orbit.[25] By comparison, large, heavy, and extra-heavy satellites, while accounting for less than a quarter of the total number of active commercial satellites, account for about 61 percent of the total mass for commercial satellites.[26] The remaining roughly one-quarter of active commercial satellites fall into the medium and intermediate classes and absorb the remaining 35 percent total mass for commercial satellites.[27]

As Table 3 demonstrates, pico to small satellites are increasingly utilized by the commercial sector.

While relatively large, complex, and costly satellites continue to dominate the commercial satellite market in terms of the dollar value and capabilities, small satellites have made significant inroads into the commercial market. From 2012 to 2017, the number of small satellites placed in orbit each year increased from about 70 to 380.[28] The vast majority of these satellites were very small, and most were deployed to provide commercial

TABLE 3: COMMERCIAL SATELLITES BY MASS CLASS

Class Name	Active Satellites	Share of Satellites	Share of Total Mass
Pico to Small	383	54%	5%
Medium	43	6%	6%
Intermediate	124	17%	29%
Large	78	11%	26%
Heavy to Extra Heavy	83	12%	35%

Author's estimates based on UCS Satellite Database, https://www.ucsusa.org/nuclear-weapons/space-weapons/satellite-database#.W60XF_IRfIU services. In 2017, for example, about 300 (80 percent) of the small satellites placed in orbit were nano-class (3-22 kilograms) or smaller.[29] Likewise, more than two-thirds of the small satellites deployed in 2017 were operated by commercial entities, with the remainder operated primarily by academic, civil government, or nonprofit entities.[30]

The growth in the number of small commercial satellites deployed in recent years reflects not only the greater capability now possible with small satellites, but also, because of their much lower cost, the opportunities they offer for the deployment of much larger satellite constellations. Among the first companies to take advantage of this opportunity was Planet (formerly Planet Labs). In 2014, the company began deploying a constellation of Dove CubeSat optical imagery satellites, each with a mass of only some four kilograms. By the end of 2015, this constellation of CubeSats numbered roughly 100, growing to about 175 today.[31] Operating in LEO, the constellation provides global coverage and resolution in the 3-5 meter range.[32] More recently, BlackSky Global has developed an optical imagery satellite which it plans to deploy in a constellation consisting of 60 satellites, six of which were in orbit by the end of 2017.[33] These satellites—which weigh about 55 kilograms each and will also be deployed in LEO—are capable of providing one-meter (or better) resolution imagery.[34] When the full constellation is deployed, it will provide revisit rates under one hour for over 95 percent of the globe.[35]

Among the most ambitious small commercial satellite efforts is OneWeb's plan to deploy a massive

Two Planet Dove satellites are deployed from the International Space Station (ISS). The satellites' small size allows them to be deployed from the ISS. (NASA)

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constellation of small satellites to provide global Internet broadband service, in a joint venture with Airbus. Current plans call for a constellation of 720 OneWeb satellites, each with a mass of about 150 kilograms and a unit cost ranging from about $500,000 to $1 million.[36] Deployment of this constellation is expected to begin in early 2019, with service projected to start in 2020, after the first few hundred satellites are deployed. This constellation is projected to be fully operational by 2027.[37] Ultimately, OneWeb plans to add another 1,260 satellites to the constellation.[38] An even larger constellation of Internet satellites has been proposed by SpaceX. The company's plans envision a constellation consisting of 4,425 satellites, eventually expanding to as many as 12,000 satellites. SpaceX hopes to begin deployment of the Starlink constellation in the next few years and to start providing Internet broadband service after the first 800-900 satellites have been deployed.[39] Nor are these efforts limited to American companies. As noted above, the OneWeb constellation is being developed in a joint venture with Europe's Airbus. Companies from other countries with plans to launch large constellations made up of small satellites include the China Aerospace and Technology Corporation (300 communications satellites)[40] and Canada's Telestat (117 communications satellites).[41]

Driven by the plans of companies like these, the number of small satellites in orbit seems likely to continue to grow in coming years. According to one industry forecast, as many as 11,600 small satellites—defined in this case as satellites with masses under 500 kilograms—will be placed in orbit between 2018 and 2030, an average of nearly 1,000 small satellites annually.[42] Even with growth of this magnitude, it seems likely that for at least the next decade, large, complex, and costly satellites will remain dominant for many, if not most, commercial missions. Nevertheless, the move toward small satellites, and especially large constellations of small satellites, represents an important shift in the commercial space market.

Historically, the small-satellite market has been shaped by many factors. These include trends in the miniaturization of electronics and other technologies and trends in satellite launch vehicles and launch costs.

Trends in Miniaturization

The miniaturization of various technologies has played a key role in the world's economic development, as well as military capabilities, over the past several decades. Areas as diverse as consumer electronics, communications equipment, sensors, and computing have all benefited from advances in miniaturization. Commercial and military satellites have shared in these benefits.

Satellite capabilities are dependent on a wide range of technologies. Among the most important of these are electronics and computing. Both of these (closely related and overlapping) areas have experienced rapid and sustained progress toward increased miniaturization. Today's laptop computers, and in many cases even smartphones, commonly have far greater processing power than mainframe computers—filling entire rooms—did a few decades ago.[43] Although the increase in the amount of computational power that can be packed into ever-smaller computers, phones, and other devices represents perhaps the most dramatic example of the impact of miniaturization, it is by no means the only one. Other advances in miniaturization relevant to satellite design and construction have also been made in, for example, mechanical systems, batteries, and sensors.[44]

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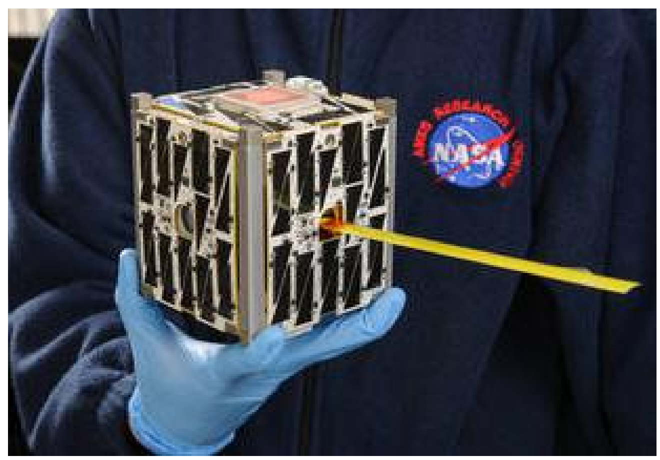
These trends not only have permitted great leaps in miniaturization but have been accompanied by reductions in cost. By one estimate, since the mid-1960s, the cost of manufacturing transistors, for example, has declined by an average rate of 20-30 percent annually.[45] As a result of this decline and similar trends in related areas, computers and other electronic devices have declined dramatically not only in terms of size over time but also in cost, even as capabilities have greatly increased. These trends have helped drive advances in the capabilities of small satellites and the expansion of the small-satellite market.

Although advances in miniaturization have significantly improved the effectiveness of small satellites and contributed to the growth of the small-satellite market, such advances have not solely benefited small satellites. In principle, satellite-related technological advances that allow more capability to be packed into a smaller space can be taken advantage of in one of two ways: holding capabilities relatively constant and deploying smaller satellites, or holding satellite size constant and packing those satellites with greater capability. Historically, the latter choice has often been made. And it is possible that this same judgment may be made in coming years in reaction to further advances in miniaturization. On the other hand, it is possible that when combined with reductions in launch costs and advances in ASAT capabilities (both of which are discussed below), a different judgment will be reached.



NASA's Ames Research Center developed PhoneSat 2.5 (pictured) using commercially available smartphone technology. PhoneSat 2.5 would not have been possible without the miniaturization of technology. (NASA)

Trends in Launch Costs

Current-generation small launch vehicles are much less efficient lifters than medium and heavy launch vehicles—helping to make launch costs a major challenge for small satellites. Medium launch vehicles are designed to carry payloads roughly in the 2,000-20,000 kilogram range to LEO, while heavy launch vehicles can lift payloads in the 20,000-50,000 kilogram range, and super heavy launch vehicles can lift payloads in excess of 50,000 kilograms. Assuming full utilization of payload capacity, U.S. medium and heavy space launch vehicles can typically lift payloads into LEO for roughly $5,000-$18,000 per kilogram.[46] By comparison, existing small U.S. space launch vehicles, which have payload capacities to LEO of up to 2,000 kilograms, have lift costs per kilogram in the $30,000-$100,000 range.[47]

This means that for large, complex, and costly satellites—which are lifted into orbit on medium or heavy launch vehicles—launch costs typically account for a relatively small share of overall lifecycle costs, while for small, relatively inexpensive satellites lifted into orbit on small launchers, launch costs can be prohibitive. Given this dynamic, holding all else constant, there is a considerable incentive to pack capability into a relatively small number of large and costly satellites, rather than distributing capability across a large constellation small satellites.

Due to the high cost of small launch vehicles, currently most small satellites are lifted into space not by those small vehicles but as secondary payloads aboard medium or heavy launch vehicles carrying large satellites as their primary payloads. Although less costly than using dedicated small launchers of current design, "rideshare" costs are still relatively high compared with the per-kilogram price charged to the primary payloads carried by these launchers.[48] Another significant downside of this approach is that the user has very little or no control over the timing of the launch or its precise orbital parameters.

Currently, the only way to hold launch costs for small satellites to the per-kilogram price achievable with medium and heavy launch vehicles is to deploy multiple small satellites in batches from a single medium or heavy launch vehicle. This is how OneWeb, for example, plans to place its 720-satellite constellation in orbit. Specifically, OneWeb has contracted for 21 Soyuz medium launchers, each of which will lift 34-36 OneWeb satellites into orbit. [49] This implies a total payload of around 5,000 kilograms per launcher, roughly comparable to the mass of a typical large military or commercial satellite. This, in turn, results in comparable payload costs per kilogram. This approach works for constellations, like OneWeb's, where a very large number of satellites are to be placed in orbit and the satellites have similar orbital characteristics.[50] For small-satellite constellations involving fewer satellites, however, this approach is unlikely to be viable.[51]

In addition, even systems that involve extremely large numbers of small satellites and can use medium or heavy launch vehicles as a relatively cost-effective means of initially deploying their constellations will need to make use of small launch vehicles to replace malfunctioning satellites. And these costs can be significant. To meet its replenishment requirements, OneWeb, for example, has contracted with Virgin Orbit for 39 of its soon-to-be-operational LauncherOne vehicles, with an option to purchase another 100 if needed.[52] Each of these vehicles, which are launched from modified Boeing 747 aircraft, is projected to cost $12-15 million, implying total costs of $500 million or more.


The SpaceX Falcon 9, pictured at left, is a medium rocket, while the United Launch Alliance's Delta IV-Heavy, right, is an example of a heavy-lift rocket. (U.S. Air Force Flickr/United Launch Alliance)

Future Space Launch Capabilities

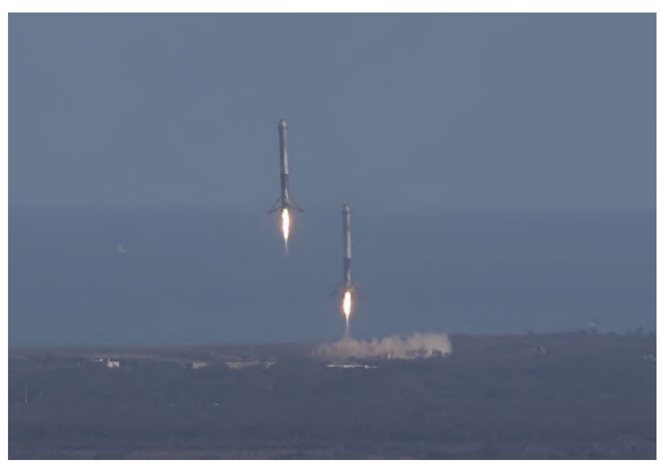
A key question is whether and to what extent launch costs, and especially costs associated with the use of small launch vehicles, are likely to decrease in coming years.[53] Many observers believe that space transportation capabilities stand on the cusp of a major breakthrough—one that could lead to a substantial, and possibly revolutionary, reduction in launch costs.[54] There are currently a wide range of efforts underway aimed at reducing space launch costs. Efforts focused on medium and heavy launch vehicles include, for example, SpaceX's Falcon 9 family of launchers. The Falcon 9 is among the least expensive U.S. medium launchers. Its payload capacity to LEO is in excess of 13,000 kilograms.[55] With each Falcon 9 costing about $62 million for commercial payloads, this works out to a price per kilogram of approximately $5,000.[56]

SpaceX has also developed the Falcon Heavy. This launch vehicle, first tested in 2018, is derived from the Falcon 9 (having two additional "side core" first-stage boosters attached) and will be capable of lifting payloads in the range of 60,000 kilograms or more to LEO. SpaceX claims that each Falcon Heavy will cost about $150 million, equating to costs per kilogram of only some $2,500, if filled to capacity.[57] In addition, Blue Origin is developing a new heavy launch vehicle, with two- and three-stage variants. The first flight test of the company's (two-stage) New Glenn heavy launcher, which will have a lift capacity to LEO of about 45,000 kilograms, is projected for around 2020.[58] Finally, United Launch Alliance (ULA), which currently operates the Atlas V and Delta IV medium and heavy launch vehicles, is developing the new Vulcan launch vehicle. Expected to be tested in 2019, the Vulcan is projected to have a payload capacity of about 9,000-18,500 kilograms to LEO.[59] Although both the New Glenn and Vulcan launchers are expected to achieve reductions in launch cost, reliable cost estimates are at present unavailable.

One way all space launch providers plan to further lower costs is by reusing the launch vehicles' first stage—a move that SpaceX, for example, projects could yield cost savings on the order of 30 percent per launch.[60] Another way to lower costs per launch would be to increase launch rates. Holding all else constant, increasing launch rates would result in learning curve improvements, greater economies of scale, and the ability to spread overhead costs over a larger number of missions. It might also reduce the need for relatively intrusive, extensive inspections and other quality control measures, with mission assurance requirements instead being met through the increased reliability likely to accrue from an increase in launch rates and the concomitant increase in experience.[61] Over the past few years, SpaceX has already increased its launch rate for the Falcon 9 from less than once a month in 2016 to an average of 1.7 per month in 2018.

Efforts to reduce launch costs focused on relatively small payloads include the XS-1 spaceplane being developed by DARPA, Virgin Orbit's and Stratolaunch's air-launched systems,[62] and Rocket Lab's Electron and Firefly Aerospace's Alpha 2.0 launch vehicles. These efforts vary dramatically in terms of their maturity, planned payload capacity, and projected costs—with planned payload capacities ranging from 150 to 1,350 kilograms, and projected launch costs ranging from as much as $50,000 to as little as $4,000 per kilogram.

SpaceX's Falcon 9 (pictured) is an example of innovative launch solutions to reduce launch costs. (Joe Raedle/Getty Images)



The SpaceX Falcon 9, pictured as it lands, was designed to have a reusable first-stage booster to lower launch costs. (Joe Raedle/Getty Images)

As with Space X's Falcon 9, both reusability and higher launch rates are central to the cost savings projected for the XS-1 spaceplane, among the most ambitious of the small launcher efforts. DARPA has stated, "A key program objective [for the XS-1] is to fly 10 times in 10 days to demonstrate 'aircraft-like' operability, cost efficiency and reliability." For this to happen, DARPA in large part is counting on the creation of a virtuous circle: It expects the XS-1 spaceplane to be able to achieve a rate of 10 flights in 10 days because it anticipates that the system will have aircraft-like operability, cost efficiency, and reliability. In turn, DARPA expects the system to have these aircraft-like operational characteristics in large part because it expects the system to be conducting frequent flights, on a short turnaround basis, like an aircraft. In 2017, Boeing was awarded a contract to complete the design of the XS-1, with the goal of building and testing a technology demonstration vehicle, dubbed the *Phantom Express*, by the end of 2019.[63]

> **A key question is whether and to what extent launch costs, and especially costs associated with the use of small launch vehicles, are likely to decrease in coming years.**

Implications of New Launch Capabilities for Small Satellites

Notwithstanding the broad and intense efforts being made to reduce launch costs, it is unclear to what degree these efforts will succeed, or on what timeline any success might be achieved. And given past predictions of a revolution in launch costs that proved premature at best, it would be hazardous to bank on *dramatic* reductions in launch costs being achieved in the *near future*. Nevertheless, given the significant reductions in launch costs that have already occurred in recent years and the relatively mature status of some ongoing efforts, it seems likely that coming years will be marked by at least some significant further reductions in launch costs. Moreover, to the extent that such reductions are achieved, they seem likely to benefit small and less costly satellites more than large and expensive satellites, and to improve the relative cost-effectiveness of the former compared to the latter.

Fundamentally, this is because the impact of lower launch costs is closely linked to their share of overall lifecycle costs, and that share varies greatly between different types of satellites. As discussed earlier, at present launch costs generally account for a far higher share of overall lifecycle costs for small, inexpensive satellites than they do for large, complex, and costly satellites—due to the much greater efficiency (measured in terms of payload cost per kilogram) of medium and heavy launch vehicles. For the latter, launch costs, while considerable in absolute terms, typically account for only a relatively modest and, in some cases, negligible share of overall lifecycle costs. In those cases, by definition, even a dramatic reduction in launch costs can only have a relatively modest impact on overall cost and cost-effectiveness. By contrast, for constellations made up of small, inexpensive satellites, where launch costs currently represent a major component of the system's lifecycle costs, even a relatively modest reduction in those costs could significantly impact overall lifecycle costs.

A more concrete sense of how the impact of lower launch costs is linked to their share of overall lifecycle costs can be seen through a simple example: Where launch costs account for 10 percent of total lifecycle costs, even a halving of those costs will reduce total lifecycle costs by only 5 percent. Conversely, where launch costs account for 50 percent of lifecycle costs, cutting those costs in half would result in a 25 percent cut in overall lifecycle costs—having a dramatically more significant impact on cost-effectiveness.

While only improvements in the cost of medium or heavy launchers would likely have a significant impact on the lifecycle costs of large, costly satellites, any improvements in launch costs would likely lead to some improvement in the cost-effectiveness of small satellites and small-satellite constellations. For example, reducing the cost of medium and heavy launch vehicles would lower not only the cost of deploying large, costly satellites, but also the cost of deploying batches of small satellites employed in very large constellations. Such advances would also help drive down rideshare fees for small satellites.

For their part, improvements in small launch vehicles would be especially important in lowering the costs associated with deploying constellations of small satellites that, because of their limited size, are not suitable candidates for batch launches from medium launch vehicles. In addition, they would help lower the cost of replacing individual malfunctioning satellites that are part of large constellations. More efficient small launch vehicles could also prove useful in situations where, because of uncommon orbital parameters or urgency, rideshare is not a practical alternative. Indeed, by some accounts, the greater flexibility and control over scheduling that small launch vehicles could provide to small satellite operators may be the most important potential impact of these vehicles.[64]

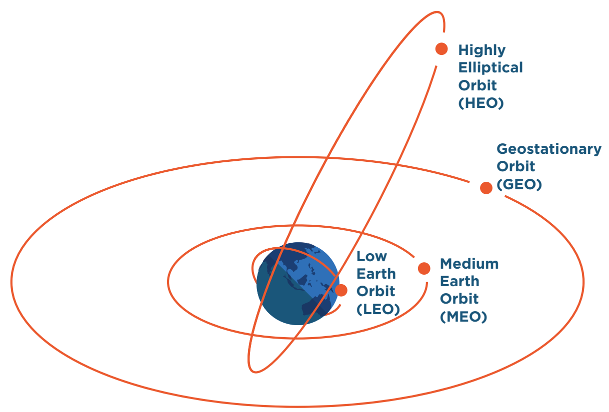
To the degree that the cost of small launch vehicles is driven down, it may also encourage the creation of a virtuous circle in which lower launch costs encourage greater use of small, relatively inexpensive satellites and the greater use of such satellites facilitates further reductions in launch costs. The basic argument is that as the demand for small satellite launches increases, launch rates grow, causing average launch costs to decline. This would then further increase the attractiveness of small satellites, and thus the demand for small satellite launch services. Similarly, as the cost of placing small satellites into orbit declines, satellites would increasingly be designed with the expectation that they would be frequently replaced, reducing their unit acquisition costs (reflecting the fact that, because of their more frequent replacement, each generation of the satellite would be less in need of a very costly technology refresh). Lower satellite cost would, in turn, lead to lower insurance costs and reduce the perceived need for costly and timely pre-launch "checkout" procedures, further facilitating increased launch rates, increasing the market for small launch vehicles, and lowering their costs.

Pace and Extent of Shift to Small Satellites

Over time, the trends in miniaturization and, perhaps especially, launch costs discussed above are likely to substantially improve the cost-effectiveness of large constellations of small, less costly satellites relative to small constellations of large and expensive satellites. However, just how quickly and dramatically the balance will shift in the direction of dispersed satellite constellations composed of small satellites is far less clear.

The difficulty of accurately predicting the likely impact of these trends can be seen by considering the relative merits of small constellations of satellites placed in geostationary orbit (GEO), some 35,800 kilometers above the surface of the Earth, versus much larger constellations of satellites placed in LEO, typically a few hundred kilometers to 1,000 kilometers above the Earth. Many, if not most, satellite missions can, in theory, be performed by either type of constellation. But the former approach requires small numbers of complex and costly satellites, while the latter approach requires large numbers of less complex and costly satellites. The GEO versus LEO competition is perhaps the most common manifestation of the cost versus quantity tradeoff made in the design of satellite constellations.

At present, the relative efficiency of medium and heavy launch vehicles, which are used to place large, costly satellites into GEO, helps make such constellations more cost-effective for many missions than large constellations made up of small satellites. Individually, the cost of lifting large satellites into GEO is very expensive. But compared with the cost of lifting large numbers of small satellites



Given their significantly different orbital characteristics, the value proposition among low earth orbit, medium earth orbit, and geostationary orbit will require careful consideration.

into LEO, the overall launch costs associated with GEO constellations are relatively low. This is due both to the much larger number of satellites that must be placed in orbit in the case of LEO constellations and the substantially less efficient capabilities of current-generation small launch vehicles.

Improving the efficiency with which small satellites can be placed in orbit will render large LEO constellations composed of such satellites relatively more cost-effective than small, costly GEO constellations. However, the relative cost of placing GEO versus LEO constellations in orbit—although certainly important—is only one of many tradeoffs that must be considered in judging the relative cost-effectiveness of the two types of constellations. Both approaches have many inherent advantages and disadvantages.

In addition to the high cost of placing individual satellites in GEO, because of the great distances involved, such satellites must be equipped with more powerful communications equipment, and larger and more costly optical and other sensors, than satellites in LEO—resulting in satellites that are generally relatively large, complex, and costly. On the other hand, because their position remains stationary relative to the surface of the Earth, they can focus continuously on particular portions of the globe. Their stationary position relative to the Earth also simplifies the task of ground stations used to monitor and maintain satellites in GEO. Moreover, because of their high altitude, GEO satellites have a wide field of view that allows a constellation consisting of as few as three satellites to maintain global coverage (excluding polar regions).

By comparison, because the distances involved are so much shorter, satellites operating in LEO can be equipped with less powerful communications equipment and smaller, less complex sensors—resulting in satellites that are generally smaller, less complex, and less costly than satellites operating in GEO. In some cases, they can also perform missions, such as very high resolution electro-optical and infrared imaging and synthetic aperture radar (SAR) imaging, that are impractical for GEO-based satellites. On the other hand, because satellites not in GEO move with respect to the surface of the Earth, maintaining continuous coverage of particular geographical areas of interest requires relatively large satellite constellations. In addition, since the satellites are frequently moving in and out of the field of view of ground stations, the task of monitoring and communicating with the LEO constellations is more complex.

A satellite in LEO sits relatively close to the Earth, as seen in the above photo from the International Space Station. (NASA)

This very brief (and by no means comprehensive) description of the strengths and weaknesses of GEO versus LEO constellations gives a sense of the complexities and tradeoffs involved in designing satellite constellations. In reality, constellation design is a far more complex process than even suggested here. Among other things, this is because satellites can also be operated in medium earth orbit (MEO), and because both the MEO and LEO categories actually encompass a wide range of different orbital altitudes—each with its own set of strengths and weaknesses. Moreover, altitude is only one of a number of key orbital parameters that drive constellation design. For the purposes of this report, the important point is simply that determining the most cost-effective constellation design depends on how a particular mission meshes with all of those advantages and disadvantages—not just with launch costs. And the kind of detailed tradeoff analysis required to make such a determination for various missions is well beyond the scope of this report.

That said, as noted earlier, given the far greater share of overall lifecycle costs that launch costs currently represent for small, less complex satellites than they do for large, complex satellites, it seems reasonable to conclude that if substantial reductions in launch costs can indeed be achieved, the implications for the design of satellite constellations could be significant. The case for moving toward large constellations of relatively small and inexpensive satellites also appears more compelling when wartime considerations are taken into account.

Wartime Considerations and Implications

The trends in miniaturization and launch costs discussed above are not the only trends of note that have affected the relative merits of different space architectures in recent years. Another key trend has been the growth in ASAT capabilities and the increased vulnerability of space-based assets.[65] Over the past several decades, the threats to satellite constellations have grown dramatically in at least three dimensions: the types of ASAT threats that exist or are being developed, the extent to which those capabilities represent serious threats to U.S. satellite capabilities, and the number of countries that possess at least some ASAT capability. Existing and potential ASAT capabilities can usefully be divided into four broad categories:[66]

- **Kinetic-Energy Physical:** This category includes terrestrial or space-based interceptors, or orbiting space mines, that use physical impact or the detonation of a warhead to disable or destroy satellites. It also includes aircraft, missiles, and other weapons used to make physical attacks on satellite ground stations.
- **Non-Kinetic Physical:** These systems include laser, high-powered microwave, and electromagnetic pulse (EMP) weapons that aim to cause physical damage to satellites or ground stations, but unlike kinetic-energy weapons do not actually make physical contact.
- **Electronic:** This includes a broad range of techniques for interfering with transmission and reception of radio frequency signals used by satellites and ground stations for purposes of tracking, surveillance, communications, and related tasks. It can range from brute jamming to more complex and sophisticated attempts to spoof the receiver.
- **Cyber:** Rather than attempting to physically damage, disable, or destroy satellites or satellite ground stations through kinetic or electronic means, cyber-attack systems aim to access the computer systems upon which satellites and ground stations are dependent and manipulate or block the flow of data.

Today, a significant number of countries, including a number of U.S. competitors and potential adversaries, possess substantial ASAT capabilities and are moving to improve those capabilities. Among these countries, the most advanced ASAT capabilities belong to China and Russia. Although substantially less advanced, Iran and North Korea also possess significant ASAT capabilities. Other countries with modest ASAT capabilities include a number of U.S. allies in Europe, as well as Japan, India, Pakistan, Libya, Egypt, and Ukraine. Increasingly, some non-state actors also may pose a threat.[67]

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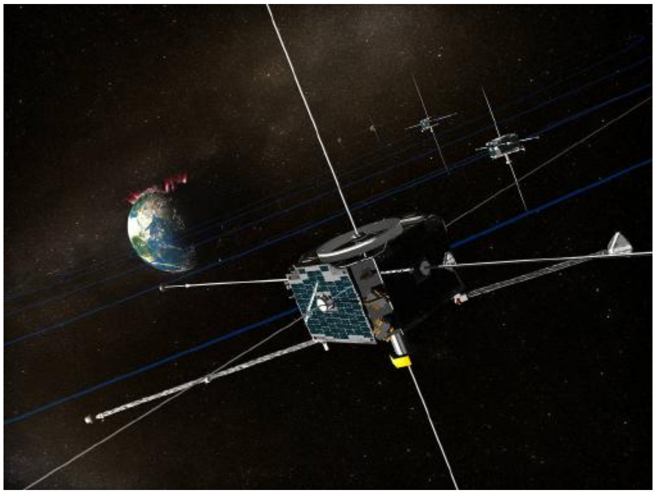
For the purposes of this report, the key question is: To what degree do these trends impact the case for moving away from small constellations composed of large and costly satellites toward smaller, less costly satellites, including constellations composed of large numbers of such satellites? There are at least two ways in which one could argue that these trends should, indeed, lead to a greater emphasis on constellations

In 2008 an SM-3 missile launched from USS Lake Erie *(pictured) was used to destroy a non-responsive U.S. satellite, U.S. 193. The SM-3 destroyed USA-193 through a kinetic-energy physical attack. (U.S. Navy via Getty Images)*



While the artist's rendering does not picture a military constellation, it does show a small satellite constellation. Constellations of small satellites are an option for a resilient satellite architecture. (NASA)

made up of small satellites. First, survivability can be significantly enhanced by dispersing satellite capabilities. Here the argument is that increasing the number of satellites that must be targeted expands and complicates an attacker's task.

A second argument is that the threat posed by ASAT capabilities can be effectively countered by acquiring large numbers of satellites to replenish constellations damaged in wartime and that only small satellites can, realistically, be procured in the quantities needed to represent an adequate replenishment reserve. In addition, an effective replenishment capability requires an agile and survivable launch infrastructure, and arguably it would be easier to maintain such a capability for small satellites than large satellites.

Satellite Dispersion

The argument that dispersed satellite systems are likely to be more survivable in wartime is intuitively appealing and clearly has merit. All else being equal, a target set composed of a large number of satellites will be harder to disable or disrupt than one composed of a small number of satellites. That said, it is unclear how effective increasing satellite constellation size would prove to be as a countermeasure to various ASAT threats. This is for a number of reasons. Not all ASAT capabilities are likely to be negatively affected by constellation size. Moreover, even for kinetic attacks it is unclear to what extent proliferation represents a cost-effective countermeasure. In addition, as with any ASAT countermeasure, there will be some opportunity costs associated with the use of satellite proliferation as a means of countering ASAT capabilities.

Holding all else constant, increasing the number of satellites in orbit would clearly complicate and expand the task of an attacker who sought to disable or destroy a satellite constellation through the use of kinetic-energy weapons. On the other hand, in the case of many other forms of attack, increasing the number of satellites in the targeted constellation might have little or no impact on the effectiveness of the ASAT capability. For example,

> **The argument that dispersed satellite systems are likely to be more survivable in wartime is intuitively appealing and clearly has merit.**

increasing the number of satellites in orbit would not improve the survivability of satellite ground stations and appears unlikely to provide a cost-effective protection against either EMP or cyber-attack.

Even in the case of kinetic-energy ASAT attacks, it is unclear how cost-effective increasing the number of satellites in orbit would be as a countermeasure. The cost-effectiveness of this approach would depend, among other things, on the cost of the individual satellites, the cost of the ASAT interceptors, the effectiveness of the interceptors, and the relative wealth—in terms of budgetary resources—of the two sides in the competition. Finally, there are opportunity costs associated with increasing the number of satellites in orbit. Funding used to expand the number of satellites in orbit could instead be used, for example, to improve a satellite's shielding, provide it with added maneuverability, or enhance its resistance to jamming or cyber-attack. Though beyond the scope of this report, an additional avenue for countering these threats might involve greater investment in terrestrial-based or air-breathing assets to carry out some missions currently performed by satellites.

None of this should be taken to mean that moving toward greater reliance on larger satellite constellations made up of smaller, less complex, and less expensive satellites, and away from small constellations of complex and costly satellites, cannot help to effectively counter existing or projected ASAT threats. The discussion above does, however, suggest that tradeoffs will need to be made over time among satellite dispersion, maneuverability, onboard defenses, and other potential countermeasures to kinetic and non-kinetic threats.

Satellite Replenishment

Another argument for developing a more robust small-satellite capability is that small satellites represent the most cost-effective approach to acquiring a wartime replenishment reserve. This path is attractive in the case of dispersed constellations of small satellites, not only because of the relatively low cost per satellite but also because—due to the shorter designed service lives of individual satellites—routine replenishment is inherent to the operation of such constellations. Rather than a reserve of dedicated satellites held in long-term storage, this warfighting "reserve" might involve increasing the number of satellites maintained in the replenishment pool, with the pool continually refreshed and upgraded with new technology. However, in the event of an attack, this pool would also constitute an effective reserve.

The existence of a significant wartime reserve could have a deterrent effect. And, if deterrence fails, such a reserve could provide for an effective reconstitution capability. In principle, large, complex satellites could also be built and held in reserve. But as a practical matter, the high cost associated with such satellites would likely make it prohibitively expensive to acquire a significant number of them to be used as a wartime reserve. Moreover, as larger satellites have long planned service lives, managing technological obsolescence for reserve satellites "in the barn" would be problematic. In addition, the launch infrastructure needed to support the deployment of large satellites might be less agile and survivable in wartime. Thus, a strong case can be made that a wartime reserve (i.e., expanded replenishment pool) made up of small, less complex satellites represents the more cost-effective approach, even if it might come at the price of less capability in some cases.

Future warfare will require an ability to constantly replenish disabled or destroyed satellites. Without new satellites, warfighters, like the ones shown here at the Global Strategic Warning and Space Surveillance System Center, will be handicapped. (Krystal Ardrey/ U.S. Air Force Flickr)

That said, as in the case of using small satellites to create a larger target set and thereby increasing survivability in wartime, expanding the use of small satellites to create a cost-effective reconstitution capability would involve some tradeoffs, opportunity costs, and other complexities. Perhaps most importantly, buying a substantial wartime replenishment reserve would absorb funding that could otherwise be used to increase the survivability of currently deployed satellite constellations.

Another important point is that the existence of a substantial reserve of satellites would not, of course, be sufficient by itself to constitute an effective deterrent in peacetime or countermeasure in wartime. To represent an effective replenishment capability, any such reserve would have to be combined with a highly survivable, rapid launch capability. Specifically, this means a space launch infrastructure and launcher capabilities that could provide for the rapid deployment of large numbers of satellites, including those with different orbital parameters and timing requirements. And there is no guarantee that such a capability will somehow naturally emerge, especially if the commercial and military market for small satellites remains more limited than the market for traditional large, costly satellites. But it could be the case even if there is substantial growth in the number and size of small-satellite constellations deployed in coming years.

As mentioned earlier, SpaceX, like other launch providers, is pursuing several approaches to lowering launch costs and increasing launch rates. The company has already substantially increased its launch rate for the Falcon 9. As noted earlier, in 2017 SpaceX launched a total of 18 Falcon 9 launchers. Under current plans, it expects to continue increasing its launch rate until it levels out at around 30-40 launches annually, including both the Falcon 9 and the new Falcon Heavy launchers.[68] This would mark a significant improvement in launch capacity for both traditional large satellites and batches of small satellites. But the ability to conduct launches even at this rate could fall well short of what a serious wartime reconstitution capability would require.

Another argument for developing a more robust small-satellite capability is that small satellites represent the most cost-effective approach to acquiring a wartime replenishment reserve.

Even if other medium and heavy launch vehicle providers like ULA or Blue Origin, which are likewise working to improve their capabilities, were to develop a capacity similar to that planned by SpaceX, the United States would be left with launch capabilities that could prove woefully inadequate in wartime—even if launch vehicle providers were capable of providing very robust and low-cost space launch services in peacetime. Another potential vulnerability would exist if these capabilities were to continue to rely, as they currently do, on a small number of launch sites.

Some new space launch vehicles under development could provide a much more responsive capability. These include, for example, DARPA's XS-1 reusable (first-stage) vehicle if it can achieve the ability to conduct 10 flights in 10 days, as called for under current plans. Even in this case, however, the capabilities that would suffice in peacetime might differ significantly from the capabilities needed in wartime.

For example, even assuming only one or two flights a week, in peacetime a single vehicle of this type might be able to deploy several hundred small satellites each year. On the other hand, providing an effective wartime replenishment capability might require a sizable fleet of

Launch infrastructure capable of supporting rapid, on-demand launch will be critical for replenishing satellites in quick order. (Bill Ingalls/NASA via Getty Images)

More traditional launch options, like current medium and heavy-lift vehicles, may not be sufficient to ensure the U.S. military's space architecture during a future war. New launch options need to be advanced to ensure satellites can be deployed effectively. (Joel Kowsky/NASA via Getty Images)

such vehicles—with the number of vehicles depending, among other things, on how sustainable the "10 flights in 10 days" goal would be during a conflict that might continue for months or even years, and the variety of orbital parameters that would need to be satisfied on a daily or weekly basis. Indeed, in wartime, even a fleet of five such vehicles (comparable to the number of space shuttles the United States used to operate) might prove inadequate. In addition, it is unclear just how survivable the XS-1 will be. The goal is to develop a relatively simple transporter-erector-launcher for the XS-1 and keep the size of the crew needed for maintenance small, allowing for autonomous operations and flexible basing.[69] But given the relatively large size and complexity of the XS-1, achieving these goals may be difficult.

Expanding the use of small satellites to create a cost-effective reconstitution capability would involve some tradeoffs.

Conclusions and Recommendations

The discussion above suggests that in coming years constellations composed of large numbers of small, less complex, and less costly satellites are likely to become progressively more cost-effective relative to constellations made up of small numbers of large, complex, and more expensive satellites. The pace and degree to which improvements in these areas will be made, as well as the likely impact of any such changes on particular missions and capabilities, is far less clear. The reasons for this uncertainty range from the unpredictability of advances in small launch vehicles to the complexity of ascertaining the impact on specific missions of any further improvements in launch costs, miniaturization, or other areas, as well as the added complexity of factoring in wartime considerations.

As such, the best available evidence does not support a dramatic, near-term reorientation of U.S. satellite capabilities toward large constellations of small satellites. The evidence, however, is strong enough to suggest a number of steps that represent "reasonable bets"—i.e., steps related to the *potential* for small satellites to transform space capabilities and improve wartime survivability and resilience. These steps could be taken at relatively modest cost. In other words, while it may be too early to commit to a major reorientation of space capabilities , now is an appropriate time for the U.S. military and intelligence community to modestly increase their investment in small satellite capabilities—both as a hedge and to create options. The recommendations below include a range of actions that could help on both counts.

Greater Experience with Small Satellites

The U.S. military and intelligence community should commit to the development and deployment of one or more satellite constellations that are made up of large numbers of small and relatively low-cost satellites. In addition to one or more dedicated constellations of national security satellites, this effort should also include the use of hosted or specially modified payloads on dispersed constellations of small commercial satellites. This might, for example, involve an expansion of DARPA's Blackjack project described earlier—which is currently a fairly limited effort focused on soliciting proposals from commercial operators for satellite concepts that could be tested for under $6 million.[70]

The Department of Defense and intelligence community will need to determine what mission or missions might be the best candidates for such a capability—a complex question that cannot be answered here. However, one strong contender might be a constellation of electro-optical/infrared and SAR-equipped satellites for use in locating and tracking mobile and relocatable targets. This is an important mission for which there is currently a major shortfall in capability. It is also a mission for which a large constellation of small satellites in LEO might prove especially effective because of the satellites' relatively low altitude and high revisit rates—assuming cross-link and constellation management challenges can be overcome.

Leaders in the Department of Defense and the White House must decide on the appropriate ways to employ smaller satellites. (Win McNamee/Getty Images)

Critically, the goal of the effort would be to gain experience with the development, deployment, and operation of satellite constellations that—compared with existing satellite constellations used for the same missions—are *significantly* larger and lower-cost, not simply *incrementally* larger constellations composed of *incrementally* smaller, less complex, and less costly satellites. To meet this objective, some substantial programmatic and budgetary discipline would need to be imposed to ensure that the effort does not devolve into the acquisition of a system more akin to a traditional U.S. military or intelligence community satellite constellation in terms of size and cost.

Ensuring that the new systems acquired under this effort mark a significant departure from current constellation and satellite designs is critical if the U.S. military and intelligence community are to use the effort to gain experience in the acquisition and operation of satellite systems that truly and meaningfully test the strengths and weaknesses of a very different satellite paradigm. That paradigm would be one in which the U.S. military and intelligence community would need to learn how to effectively use systems made up of satellites that are individually less capable—perhaps substantially so—and may require greater effort to coordinate, monitor, and control. It would also be important for them to gain experience in how the operation of such systems could be most effectively meshed with existing, smaller traditional satellite constellations to achieve synergies where possible and better understand how different constellation designs might best provide complementary or supplementary capabilities.

Just how much funding would be needed to adequately support this effort would depend on the number of systems to be acquired; the size and complexity of those systems; whether they are envisioned as primarily experimental prototypes or, instead, operational systems; and the timeline on which they are developed, procured, and placed into orbit. In addition, it would depend on how the effort was balanced between the acquisition of dedicated national security satellites and the use of hosted or specially modified payloads on commercial small satellites. More widespread use of public-private partnerships has been proposed as a means of retaining significant control over the development of space systems, including capability requirements, while both leveraging the private sector's strength in innovative technology and shifting onto the private sector some of the cost and risk associated with development programs.[71] And the use of hosted or modified payloads may offer a particularly cost-effective type of public-private

It is also important that new satellite architectures are meshed with existing satellite systems, like the ground segment seen here. (Joe McFadden/U.S. Air Force Flickr)

partnership. The Government Accountability Office found that on those few occasions when the Defense Department (DoD) has, in recent years, made use of hosted payloads on commercial satellites, it allowed for the faster deployment of military technologies.[72] Likewise, DoD estimates that its use of hosted payloads on commercial satellites—although, again, so far extremely limited—has achieved savings of several hundred million dollars since 2009.[73]

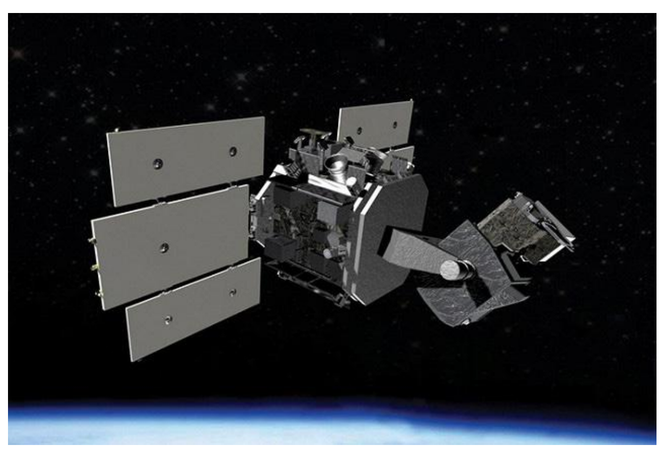
Until these and other details are worked out, it is impossible to formulate anything like a high-confidence estimate of funding requirements for these efforts. However, as a first approximation, an annual budget on the order of several hundred million dollars initially to perhaps half a billion within the next five years might represent a reasonable estimate, at least initially—with funding growth in later years dependent on the results achieved. This level of funding should suffice to develop and deploy one or possibly several systems, depending on their size and capabilities, over the next decade. To be sure, given the greater costs generally associated with military and intelligence community space systems, managing this effort within budgets of this level would take a degree of discipline not typically found in DoD acquisition programs. On the other hand, the pressure could provide a useful incentive to rely on commercial technology (including through the expanded use of hosted or modified payloads)—which now represents the leading edge in many areas of satellite technology. Perhaps more importantly, imposing discipline, including budgetary discipline, is also likely to be critical to ensuring that the U.S. military and intelligence community keep efforts focused on the development and deployment of the new kinds of satellite systems discussed here, and avoid the tendency to revert to systems that represent little more than incremental modifications of existing satellite systems.

Improving Replenishment Capabilities

In parallel with efforts to begin experimenting with the development and limited deployment of larger, dispersed satellite constellations composed of small satellites, the U.S. military and intelligence community should start acquiring a modest replenishment reserve of satellites. As noted earlier, cost considerations would likely make the acquisition of a replenishment reserve consisting of more traditional—large, complex, and costly—satellites impractical.

Rather than a dedicated wartime reserve of small satellites to be held in long-term storage, the best approach would likely involve expanding the replenishment pool that large constellations of small satellites need due to their frequent and routine replenishment requirements. As with the first recommendation, the effort would also need to involve the extensive use of public-private partnerships. The U.S. military and intelligence community depend on commercial space assets to help perform a number of missions, especially for global communication. Moreover, under the first recommendation, the U.S. military and intelligence community would move toward the expanded use of hosted or specially modified payloads on dispersed commercial satellite constellations. As such, encouraging these commercial satellite operators upon which the U.S. military and intelligence community are dependent to expand their satellite replenishment pools would be key to establishing an effective wartime replenishment capability.

Developing a high-confidence estimate of the funding requirements for creating a substantial replenishment reserve of satellites would necessitate a detailed analysis well beyond the scope of this report. However, given other important space-related priorities, including the



Like the Space Based Space Surveillance System depicted here, the U.S. military should have modest replenishment reserve satellites capable of providing similar services. (U.S. Air Force Flickr) other two major recommendations discussed in this report, an upward bound for the level of resources that might be committed to this effort is probably in the range of several hundred million to half a billion dollars annually—similar to the estimate for the development, deployment, and operation of one or more dispersed small-satellite constellations included in the first recommendation above.

Greater Support for Improved Space Launch Capabilities

The U.S. government should do more to encourage and support the development of more efficient and cost-effective space launch vehicles, and particularly small launch vehicles, as well as a more agile and survivable space launch capability. Reducing launch costs would improve the cost-effectiveness of all types of satellite systems. However, as discussed earlier, because medium and heavy launchers tend to be much more efficient lifters than small launch vehicles, launch costs currently account for a far higher share of overall lifecycle costs for small satellites than for large, complex satellites. As a result, constellations made up of large numbers of small, low-cost satellites generally have more to gain in terms of cost-effectiveness from a reduction in launch costs than do those composed of large, complex, and costly satellites.

The decision to start a major effort to acquire and deploy one or several large satellite constellations made up of small satellites, as proposed above, would in itself help encourage the space transportation industry to develop more cost-effective small launch vehicles and more efficient launch services—both by expanding the market for such launchers (and, in the case of reusable vehicles, launches) and by signaling greater interest in such capabilities on the part of the U.S. military and intelligence community.

Small launch vehicles, like the one from Rocket Lab, seen here with CEO Peter Beck, could be effective solutions to emerging launch needs. (Phil Walter/Getty Images)

In terms of improving launch capabilities, perhaps the greatest need is for the U.S. government to support capabilities that, while perhaps not important or even needed in peacetime, could prove critical during a crisis or in wartime. In particular, this likely means the development of launch capabilities that are both highly responsive and survivable. The commercial space market may on its own create a powerful incentive to lower the cost of lifting small satellites, and especially large constellations of small satellites, into orbit in peacetime. However, as discussed earlier, there is no guarantee that such a capability—even if highly efficient in peacetime—would prove adequate in wartime.

To create such a survivable and responsive capability, the U.S. military and intelligence community should more aggressively encourage the development of not only less costly launch vehicles but also launch vehicles that rely on survivable basing modes and can be purchased and deployed in sufficient numbers to support an effective and resilient reconstitution capability. Holding all else constant, it is easier to make small launch vehicles survivable than medium or heavy launch vehicles. Among other things, this is because, by definition, it is easier to develop mobile or transportable launchers for small launch vehicles, and a greater number of locations are likely to prove adequate for use as launch sites in the case of small launch vehicles. However, the fact that it is easier to make small launch vehicles more survivable does not mean that such launchers are likely to be deployed and operated in a survivable manner. Driven by peacetime market forces alone, space launch vehicle providers generally have little incentive to pay the added costs needed to create these more survivable launch capabilities, or even to create options that might allow for the rapid development of such capabilities. Similarly, peacetime market forces—which reward just-in-time delivery—create an incentive for providers to keep launch vehicle inventories to a minimum.[74]

In short, the U.S. government needs to encourage the creation and sustainment of launch capabilities that, while perhaps excessive and inefficient in peacetime, could prove critical in wartime or times of crisis. How to most effectively, and cost-effectively, carry out this task is unclear. But, once again, the use of public-private partnerships offers perhaps the best approach.

Public-private partnerships are already being used in a number of launch vehicle–related projects. These include development of the XS-1, the contract for which

Leaders in the Pentagon, White House, and other government agencies need to encourage the development of launch options that ensure U.S. access to, and use of, space.
(Chip Somodevilla/Getty Images)

is structured as a public-private partnership to which both DARPA and the Boeing Company contribute funding.[75] The Air Force has also used public-private partnerships, involving four companies, to facilitate the development of a new rocket propulsion system.[76] Similarly, NASA used public-private partnerships to support the competitive development, among three companies, of a commercial transportation and supply system for its activities on the International Space Station.[77] NASA is also supporting the development of small space launch vehicles through public-private partnerships with eight different companies.[78] Greater use of public-private partnerships could mean both expanding the number of programs supported through such efforts and, if necessary, increasing the share of financing provided by the Defense Department or other U.S. government agencies.

Providing a high-confidence estimate of the level of additional funding that might be required to help incentivize companies to focus greater attention on mobility or at least transportability—or other features likely to improve survivability—in the development of launch vehicles would necessitate a detailed analysis well beyond the scope of this report. Much would depend on the funding split needed to attract private-sector partners. In the examples, noted above, the private sector's contribution ranged from as much as 60 percent to as little as 25 percent. It might also be possible to hold down government costs by encouraging participation, partly by giving partners some advantage when competing for contracts to provide various space-related goods and services to U.S. government agencies, rather than through direct funding.[79] While a high-confidence estimate of funding requirements is beyond the scope of this report, given the relatively modest costs associated with the development of many new small launch vehicles, it seems likely that funding of several hundred million to half a billion dollars—comparable to the amounts suggested for each of the first two recommendations above—could go far toward leveraging significant capability improvements.

Even taken together, the three recommendations described here have relatively modest funding requirements—initially totaling on the order of half a billion dollars a year, growing to perhaps $1-2 billion annually within five years. In the context of a national defense budget exceeding $700 billion, finding funding of this magnitude should not prove too difficult. If instead, as a result of political and bureaucratic constraints, it becomes necessary to find this budgetary headroom within the national security–related space budget in particular, the task would require making more difficult tradeoffs. The demands confronting U.S. space assets have grown significantly, and as in other areas the Defense Department faces programmatic and budgetary pressures built up over much of the past decade. But even in this case, it should be possible to identify offsets sufficient to support funding in this range.

For 2018, the overall space budget for the U.S. military and intelligence community amounted to some $12.5 billion for unclassified programs, likely growing to over $20 billion annually when funding for classified programs is included.[80] Thus, the funding levels recommended here equate to only a small percentage of the Defense Department's total annual space budget initially, increasing to still only about 5-10 percent of overall space funding over the next five years. While far from painless, a funding shift of this magnitude would be both appropriate—given the stakes involved—and manageable, given the level of offsets that would need to be made.

Endnotes

1. For a discussion of the potential advantages of small satellites, including distributed constellations comprised of small satellites, for a variety of missions, see, for example, Martin N. Sweeting, "Modern Small Satellites: Changing the Economics of Space," *Proceedings of the IEEE*, 106 no. 3 (March 2018), 343-61, https://ieeexplore.ieee.org/stamp/stamp.jsp?arnumber=8303876; Charles D. Norton and Sergio Pellegrino (co-leads), "Small Satellites: A Revolution in Space Science" (Keck Institute for Space Studies, California Institute of Technology, July 2014), http://kiss.caltech.edu/final_reports/SmallSat_final_report.pdf; and Bob Preston, Mel Eisman, and Michael Brown, "Distributed Satellite Constellations Offer Advantages over Monolithic Systems," Project Air Force Research Brief (RAND, 2004), https://www.rand.org/pubs/research_briefs/RB92/index1.html.

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8. Ibid.

9. Figures for the number and mass of U.S. military satellites and commercial satellites cited in this report are the author's estimates based on the UCS Satellite Database.

10. This data was taken from the Defense Department's Selected Acquisition Reports (SARS) for the AEHF, GPS III, MUOS, WGS, and SBIRS satellite systems. For consistency, all cost figures in these documents have been converted into 2018 dollars.

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12. Government Accountability Office (GAO), "Defense Satellite Communications: DoD Needs Additional Information to Improve Procurement," Report No. GAO-15-459 (GAO, July 2015), https://www.gao.gov/assets/680/671484.pdf.

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14. Since 2009, DOD has used three commercially hosted payloads, with three more missions planned or underway through 2022. To date, these payloads have been primarily experimental—designed to demonstrate and test on-orbit capabilities—rather than operational missions. Government Accountability Office (GAO), "Military Space Systems: DoD's Use of Commercial Satellites to Host Defense Payloads Would Benefit from Centralized Data," Report No. GAO-18-493 (GAO, July 2018), 10, https://www.gao.gov/assets/700/693481.pdf.

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