Issue Brief

Advanced Space Technologies

Challenges and Opportunities for U.S. National Security

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June 2025

Executive Summary

The U.S.-government-designed uncrewed Surveyor moon lander program first flew in 1966 and cost $658 million per lander in 2024 dollars.[1] The government-designed Apollo missions cost $23 billion per launch when adjusted to 2020 dollars. Since then, NASA has taken a different approach: in February 2024, the company Intuitive Machines successfully delivered a lander to the surface of the moon, fulfilling an agency contract costing just $118 million.[2]

Today, U.S. companies find themselves fulfilling roles that were historically the domain of the government—and taking on missions that even the government has yet to embrace. From exploration systems to in-space manufacturing to satellite refueling, companies are deploying new systems for novel applications at a rapid pace and lower price. We call these companies part of the "advanced space technology" market and include in this category businesses that provide positioning, navigation, and timing; space situational awareness (SSA); exploration; in-space satellite services; and in-space manufacturing.[*]

Our analysis of 91 U.S. advanced space technology companies shows that—unlike established commercial markets such as satellite communications, remote sensing, and space launch, where company formation peaked around 2015—the number of newly founded advanced space technology companies grew fastest in 2021 after years of steady expansion. More than half of these companies work in areas where the government has limited services: 40 percent work on in-space servicing and related technologies, and 16 percent work on in-space manufacturing. A further 40 percent are focused on space exploration and science, embracing government funding but also leveraging other capital and business models to make exploration more affordable to government customers. Less than 10 percent of these companies exist to surveil space from the ground or to provide navigation and timing services, areas where the U.S. government currently invests billions.

Corporate growth in this market appears to follow two interrelated factors. The first is the march of technology, harnessing the increasing performance and reliability of

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[*] While advanced space technology could include multiple additional areas—such as space nuclear power and propulsion or deep space communications—this paper limits itself based on available data and the near-term realizability of these technologies. Furthermore, while in-space assembly and manufacturing are often grouped together, data shows more near-term commercial ventures pursuing manufacturing without assembly.

smaller electronics and embracing cheaper experimentation to field capabilities at scale.

The second factor is the shift from the government as a developer and provider of technology to the government as a consumer of space products and services. This includes NASA's purchases of commercial resupply, crew, and lunar payload services, as well as the U.S. Department of Defense's purchases of SSA data. Technology transfers from government to industry have also helped lower barriers to entry for innovative companies, using tools such as technology transfer agreements to support in-space manufacturers or new technology feasibility demonstrations.

The United States has long relied on advanced technologies for security in space and terrestrially. From navigation-enabled warfare to precision strike capabilities, there has often been overlap between Earth and space. The next generation of advanced space technologies will be no different. Given the national security importance of advanced space technologies and the breadth of what falls under this banner, this paper identifies several challenges and opportunities facing companies as they deliver capabilities to the U.S. government.

- **Challenges**: Even for established markets such as launch and remote sensing, profitability can be a struggle for new space companies. In emerging mission areas with unproven technology, the profitability challenge is even greater. This—coupled with loosened but still restrictive limits on exporting U.S. technology abroad and the government provision of free-to-the-public services such as GPS and SSA—means that new firms may face an uphill struggle for survival even with valuable products.

- **Opportunities**: The advanced space technology market in the United States is small enough to enable policymakers and government agencies to have an outsize impact with relatively modest investments. Government money and attention could support American space companies in seizing a first-mover advantage for the nation compared to unfriendly states. Encouraging technology and knowledge transfer across multiple advanced technology areas may also accelerate commercial technological and economic developments. Whether that leads to a new era of cheaper science missions, provides strategic advantages against unfriendly nations in space, or both is a matter of planning and policy—and an opportunity to be seized.

For the U.S. government to advance its national security interests in conjunction with partners and allies, this paper makes the following recommendations:

1. **Federal agencies—especially the DOD, the Intelligence Community, and NASA—should invest in hedge portfolios for advanced technology missions with national security applications and outsize risks if the United States cedes leadership.**

2. **The U.S. government should act as an anchor tenant by purchasing and investing in research for commercial services in selected advanced technologies, especially in-space satellite servicing, for which the U.S. government does not currently field a solution at scale.**

3. **The U.S. government should continue to purchase services and make targeted investments (including infrastructure upgrades) in advanced technology areas where it is the dominant service provider to build resilience in government systems.**

4. **The State Department, in consultation with the DOD and Department of Commerce, should harmonize export controls with allied nations actively building similar technology.**

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Authors' Note

Much of the research, analysis, and writing for this paper was accomplished by Summer 2024. Since then, many of the trends have continued, with new vehicles being approved for reentry. While there is still work to be done, some of the recommendations that this paper makes are already being implemented, even before publication (such as easing of export controls). Prediction of the pace of advanced technology development and implementation remains difficult. Nevertheless, we are heartened by the work done by government and market participants in this advanced technology arena.

Introduction

The United States has long viewed itself as a technology leader, taking pride in inventing sustained powered flight, creating the transistor, landing a man on the moon, and building the internet. While much of space technology is taken for granted today, there are still new emerging and advanced technologies that push the boundaries of the possible and stand to open up new economic opportunities.

These types of technology are important not just for their own sake but for that of U.S. national security. From navigation and timing for the financial industry to telecommunications and weather monitoring, the United States relies on space for safety, security, and the economy. Similarly, just as the United States bets on terrestrial technological superiority for security on Earth, technological progress is mandatory for security in space.[3]

Previous CSET papers evaluated space technologies within established markets: remote sensing and launch. This paper's analysis turns to advanced technologies, the companies trying to commercialize them, and the national security consequences of those developments.

Our study examines five commercial "advanced space technologies" in particular:

1. Positioning, navigation, and timing (PNT)
2. Ground-based space situational awareness (SSA)
3. Exploration
4. In-space satellite services

5. In-space manufacturing

Each area includes companies vying to augment or replace costly government services or deliver technologies that even governments cannot yet field at scale or speed.

The analysis leverages the authors' annotation of information about companies from PitchBook Data, Inc. (PitchBook). PitchBook provides a commercially available dataset to identify companies and trends in business formation and operating status.[*] This paper reviews the national security importance, history, and current trends within each of these five areas and identifies macro trends across the entire advanced technology area and some related factors driving those trends. The paper also identifies challenges and opportunities to market and national security success. Finally, it concludes with recommendations for policymakers to build, grow, and extend U.S. national security interests alongside allies and partners.

[*] See Appendix 1 for more details and caveats.

Five Advanced Space Technologies

This paper focuses on five advanced technology subsectors, described in Table 1. In many cases, these technologies have only recently begun in-orbit tests and evaluation. Importantly, this paper focuses only on *commercial* technologies and does not address any capabilities that may be in development for strictly military purposes or that are funded completely by the U.S. government. In-space manufacturing is a prototypical example: companies are testing today but have not yet fielded or commercialized operational systems.[4]

The companies analyzed were identified using the PitchBook dataset. PitchBook provides industry assignments, which were used to select companies relevant to the space economy. The authors then assigned each of the 543 companies in the "space technology" vertical to appropriate subsectors.[5] The company assignments were based on the authors' professional knowledge and a detailed review of the company description, website, and news reports from PitchBook.[*]

This paper defines advanced space technologies as those just starting to be tested in orbit, as well as one more group: services that have long been the sole domain of governments. This is especially relevant in the areas of PNT and SSA.[†] In these areas of "high government involvement," the government used to be the sole provider of services; likewise, parts of the market with "low government involvement" may have benefited from research funding, but there is no existing federal service to compete with (though of course, treaties and regulations still apply).

[*] Additional criteria were used to assign companies to other subsectors. For further detail, please contact the authors.

[†] The differences between space domain awareness and SSA are nuanced and not highly relevant to this analysis, so we simplify by labeling SDA a government activity supported by commercial and government SSA sensors and capabilities.

Table 1. Advanced Space Technology Subsectors

	Subsector	Description
High Government Involvement	PNT	PNT provides positioning, navigation, and timing services to users. The U.S. Space Force–operated Global Positioning System (GPS) is the most well-known example of such a system and service.
High Government Involvement	Ground-Based SSA	SSA, or space situational awareness, detects and tracks objects in space. The U.S. Space Force operates a large network of sensors called the Space Surveillance Network (SSN) to support this mission. This category is limited to commercial operators using ground-based sensors that are most similar to the Space Force's SSN sensors.
High Government Involvement	Exploration	Exploration includes technologies destined to orbit, measure, or land on other celestial bodies, or to support other spacecraft that will.
Low Government Involvement	In-Space Satellite Services	This broad category includes the following technologies: • Space-based technologies to perform and support SSA • Debris remediation, or those technologies that can manipulate space debris to remove it from orbit • In-space servicing, repair, and refueling of satellites • In-space transport, which helps satellites make large maneuvers after an initial rocket launch
Low Government Involvement	In-Space Manufacturing	In-space manufacturing allows chemicals, pharmaceuticals, and other sensitive items to be fabricated in space, where disturbances from gravity can be minimized to enable new products. It includes manufacture of products for use in space or on Earth.

Having defined the five subsectors, we will examine each in turn for their potential impact on national security and the U.S. economy.

Positioning, Navigation, and Timing

The most visible space service to the general public is GPS. Today, the positioning signal generates billions to trillions of dollars in total economic value, depending on the assessment, benefiting both individuals and companies as varied as Google and John Deere.[6] GPS's timing signal benefits everything from network communications to financial transfers worldwide. Despite its overwhelming economic value, GPS was originally developed to address military PNT needs, such as navigation at sea and precision military strikes.[7]

GPS transmits precise timing signals that let receivers determine their location. Free worldwide for peaceful civil uses, GPS relies on signal-broadcasting satellites with precise clocks and a complex ground network to tightly coordinate timing.

Despite the military and civil economic benefits, however, the enterprise is not cheap: the U.S.-government-provided service costs taxpayers more than $1.5 billion per year.[8] Nor was its creation quick. Development began following the Soviet Union's launch of Sputnik in 1957, and GPS as it exists today was not fully fielded until the early 1990s.[9]

Importantly, GPS originally included a "selective availability" that degraded the public GPS signal by a factor of 10 so that adversaries could not use it against U.S. forces.[10] In 2000, along with congressional direction, the president ordered that selective availability be turned off, and since 2007, it is no longer included in any new satellites.[11]

Threats to military use of GPS have grown alongside its expanding civilian use.[12] With satellites orbiting 20,000 kilometers away (about 12,500 miles), their signals are weak and easily disrupted once they reach the ground.[13] Equally important, other countries have recognized the importance of GPS to weapons, targeting, and military movements. Knowing this, the U.S. military, with congressional support, has sought alternative PNT solutions that could be relied upon when GPS is unavailable.[14]

In response to the need for alternative PNT, some companies have proposed the use of cheaper clocks and the creation of low earth orbit (LEO) constellations with hundreds of satellites.[*] Such a solution may offer higher-power, militarily relevant jam resistance and improved precision for new commercial applications.[15] At least a small number of investors agree, as one company, Xona Space Systems, raised more than $25 million

[*] Commonly known as "proliferated" constellations.

and successfully flew an on-orbit test vehicle.[16] Still, fewer than 1 percent of all space companies in our dataset are pursuing PNT missions.[17]

Ground-Based Space Situational Awareness

While most people have heard of GPS, SSA occurs mostly in the background of American life. The military uses a network of mostly ground-based sensors and computers called the SSN to detect and track space objects. In a service called "space traffic management," the DOD regularly notifies military and commercial users alike about potential collision risks.[18]

Beyond civil uses, SSA also forms the foundation of military space domain awareness.[19] By combining the finding, tracking, and identifying functions of SSA with intelligence and other data sources, SDA gives military commanders a fuller picture of the space environment and can quickly detect, alert, and identify threats to systems and infrastructure in space—and the consequences for forces below.[20]

Like PNT, SSA was spurred by Sputnik and the recognition of a military need to track satellites.[21] In particular, tracking would warn of satellite overflight for sensitive operations, support missile warning systems by disambiguating overflying satellites from incoming missiles, and monitor potential space-based weapons delivery systems.[22]

Throughout the late 1960s, requirements drove enhancements: improved computation, data calibration, and the fielding of the first dedicated surveillance radar. In the 1970s, new types of radars improved throughput, and new missile warning satellites identified new space launches.[23] From the 1980s until today, changes have been progressive: new optical sensors, some mathematical advances, and space-based sensors have been fielded.[24] Many of these are operationally important but not revolutionary.[*]

Despite incremental upgrades, the challenges to the current SSN architecture have outpaced the improvements. Senior leaders have identified the need for systems to "operate [on] timelines that are shrinking" and be prepared against "new challenges."[25] One of those challenges is the sheer congestion of space: there are physically more satellites, rocket parts, and pieces of debris to track. For instance, 2023 saw over 200 orbital launch attempts globally, more than double that seen in 1979 when the tracking process was computerized.[26] Collisions, explosions, and weapons tests have

[*] Space-based sensors have intelligence and tracking benefits, but they are few in number.

generated debris, while the average launch today carries far more payloads, and many of those payloads are far smaller and harder to track.[27] All of this space “stuff” has to be monitored. Adding the burden of contested space, where space assets may be targeted by adversaries, only raises the importance of the tracking mission.

There are benefits to using commercial data to meet the challenges posed by contested and congested space. Companies can access locations where political or security sensitivities prevent or slow DOD access, their data is natively shareable, and, finally, some commercial sensors (like those shown in Figure 1) may outperform the DOD’s systems, tracking objects one-fifth the size of the SSN’s typical stated limits.[28] A Government Accountability Office study found that since at least 2014 there have been companies providing SSA services, with a current market of over 50 companies.[29] While the PitchBook dataset finds fewer companies, this is clearly an area of active commercial work, despite the existing government architecture.

Business challenges do exist, however. Because the DOD provides basic SSA services free of charge, companies must provide additional or differentiated value, such as faster data updates or support for automation.[30] Further, many companies expect (and currently need) the government to be an “anchor” customer, making the marketplace particularly sensitive to ebbs and flows in government funding and unable to persist without government contracts.

Figure 1. Commercial Space Surveillance Radar (LeoLabs Azores Phased Array)

Source: LeoLabs, “Phased Array Radars,” 2024, https://leolabs.space/radars/.

Exploration

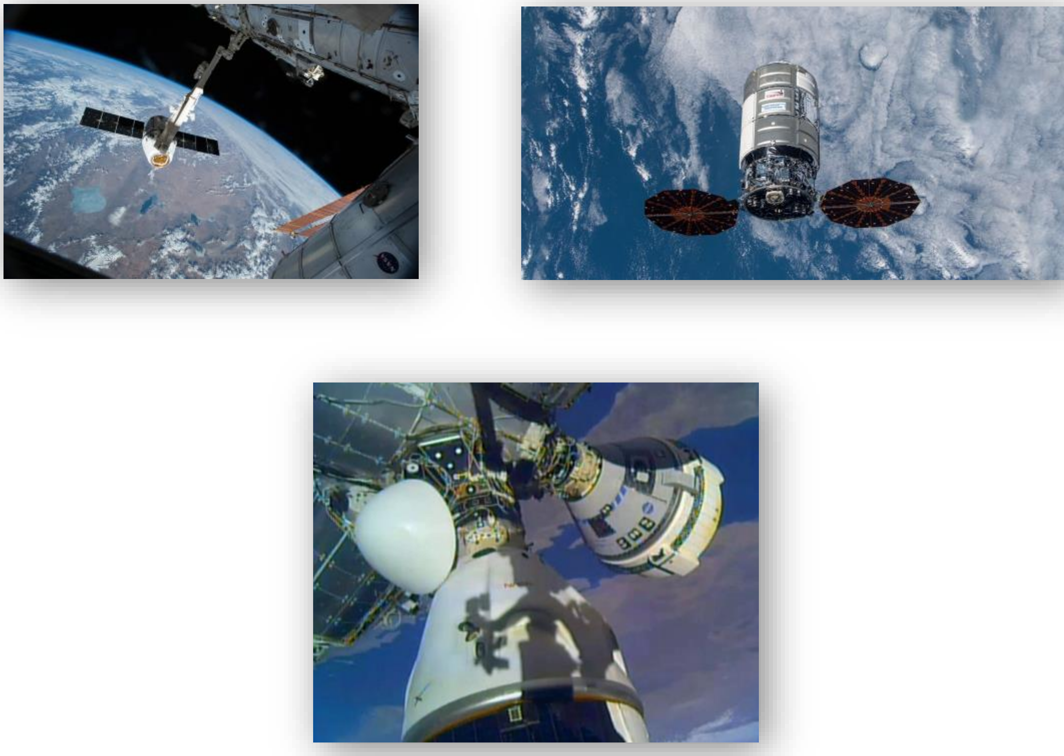
Compared to PNT and SSA, exploration may seem less important, but a failure to maintain leadership in it has strategic risks. Exploration inspires the domestic workforce and encourages high-skilled immigration to the United States.[31] Technology spin-offs also provide second-order benefits. Early U.S. dominance in semiconductor manufacturing was driven by the space program, and many of the earliest uses were directly related to exploration programs.[32]

Generally defined as the use of technologies destined to orbit, measure, or land on other celestial bodies or support other spacecraft that will, exploration has historically been backed almost entirely by government funding and technical direction. From the Mercury, Gemini, and Apollo missions of the 1960s and 1970s to the Space Shuttle of the 1980s through its retirement in 2011, crewed missions were government missions. Robotic exploration was the same: the U.S. federal budget and international government partners paid for telescopes like Hubble and planetary missions like the Mars Exploration Rovers.[33]

Federal funding has continued to dominate the exploration mission area, but there are two primary differences from the previous era. First, agency engineers now mostly set top-level requirements for companies and oversee implementation of those requirements rather than the older approach of retaining full ownership and full decision authority over the design. Second, today’s operations are mostly handled by the company under a (mostly) fixed-price or service construct rather than a cost-plus arrangement.[34] Cargo and crew missions to the International Space Station (ISS) are good examples of this change.

Following the loss of two Space Shuttles and their crews in 1986 and 2003, NASA saw a need for new, safer, and more cost-effective vehicles to support human spaceflight in LEO. Beginning with the Commercial Resupply Services program (Figure 2, top), commercial vehicles began ferrying cargo to the ISS in 2012.[35] The agency would entrust its astronauts to commercial vehicles next, starting crewed launches in 2020 (Figure 2, bottom).[36]

Figure 2. Commercial Resupply (Top) and Commercial Crew Vehicles (Bottom)



Sources: (top left) Cargo Dragon, NASA, www.nasa.gov/wp-content/uploads/2015/06/iss043e122264.jpg;

(top right) Cygnus, Northrop Grumman, www.northropgrumman.com/space/nasa-commercial-resupply-mission-update;

(bottom) SpaceX Dragon Freedom and Boeing CST-100 Spacecraft 2 docked at the ISS, "Commercial Crew Program Vehicles," May 24, 2022, Wikimedia Commons, https://upload.wikimedia.org/wikipedia/commons/0/0b/Commercial_Crew_Program_vehicles.jpg.

NASA continues to purchase services, including the commercially flown 2022 Cislunar Autonomous Positioning System Technology Operations and Navigation Experiment (CAPSTONE) pathfinder mission to test the orbit for a planned lunar-orbiting space station.[37] Even more audacious are the Commercial Lunar Payload Services (CLPS) contracts, with at least eight lunar landings planned. CLPS notched the first success in February 2024 with the landing of Intuitive Machines' IM-1 lander.[38] Since then, there have been hints of commercial missions to Mars and Venus, though no launches yet.[39] NASA's interest in commercial Mars missions is growing, especially with fiscal challenges to the top-priority Mars sample-return mission.[40]

As NASA has become increasingly willing to engage with commercial entities outside of legacy prime contractors, the industry has responded. Well over half of exploration companies were founded since 2013 (and 24 percent since the start of 2020 alone), compared to 11 percent before 2000. Three-quarters of these companies are major defense contractors.[41] While our dataset may not capture all such companies, the trends are clear: most exploration companies were only recently founded (see Table 2).[*]

Table 2. Most Exploration Companies Were Founded Recently

Commercial Exploration Companies		
Companies in dataset		37
Companies founded..................before 2000	11%	4
....2000 to 2012	30%	11
....2013 to 2019	35%	13
....2020 or later	24%	9

Source: PitchBook Data, Inc.; author analysis.

In-Space Satellite Services

In-space satellite services encompass space-based SSA; debris remediation; satellite life extension; servicing, repair, and refueling; and in-space (postlaunch) transport of satellites.[42] Each is different, but they all have two common factors:

1. Detecting and tracking other satellites and often maneuvering around them
2. Technical progress in one in-space service area helps advance other areas

These factors make the technology fundamentally dual use: in-space services enable novel, sustainable uses of space as well as militarization. For example, a system that removes defunct satellites can be used to remove foreign satellites, so observers took note when China demonstrated an orbital debris remediation capability in 2022.[43] The dual-use nature of the technology is also not a new one: the technology basis of in-

[*] The trend is more pronounced when compared to other space businesses, like those in the space subcomponent business. See Appendix 1 for additional context.

space services—rendezvous and proximity operations (RPO)—grew out of the Cold War.[44]

More dual-use cases exist too. Refueling extends satellite lifetimes and enables maneuvers to evade tracking. Even planning provides a strategic advantage: a country that helps set international refueling standards advantages its domestic industry and may benefit military planners.[45] In each area, the United States and its allies should lead rather than cede advantage to others.

Beyond technology, challenges remain in delivering military or economic value. Despite numerous experiments and attempts, companies are still testing new servicing techniques and new business models for in-space services.[46] Consider debris remediation. The 2020 U.S. Space Policy directs the government to "evaluate and pursue… active debris removal," while the 2022 National Orbital Debris Implementation Plan directs studies and research and development on debris "remediation."[47] Studies have provided plausible technical paths forward, and there are early hints of cost-efficient, effective technical solutions.[48] NASA has even recently funded a consortium to make in-space servicing, assembly, and manufacturing capabilities a routine part of space architectures and mission life cycles.[49] Funding large enough to jump-start a market, however, has not yet materialized. Since debris regulation remains relatively permissive, there are few current financial incentives for commercial remediation.[50]

Instead, debris remediation is being used as a stepping stone to other markets. The UK, Japan, and the United States have contracted with Tokyo-headquartered Astroscale for technology demonstrations, and the company has had early success with its ELSA-d mission.[51] Astroscale had continued with its *ADRAS-J* mission, which approached and safely navigated around actual debris, delivering the first commercial image of space debris using RPO from just a few hundred meters away (Figure 3).[52] The company's demonstrations of rendezvous, docking, and eventual debris removal are directly linked to corporate goals as "an orbital servicing company, not a debris removal company."[53] Other missions are also serving as stepping stones. SpaceX, for example, has tested in-space propellant transfer during a developmental test of its Starship rocket ahead of crewed Artemis moon landings.[54]

Figure 3. Space Debris Seen by Astroscale's *ADRAS-J* Spacecraft in 2024 (Top) and the U.S. Air Force's *XSS-11* in 2005 (Bottom)

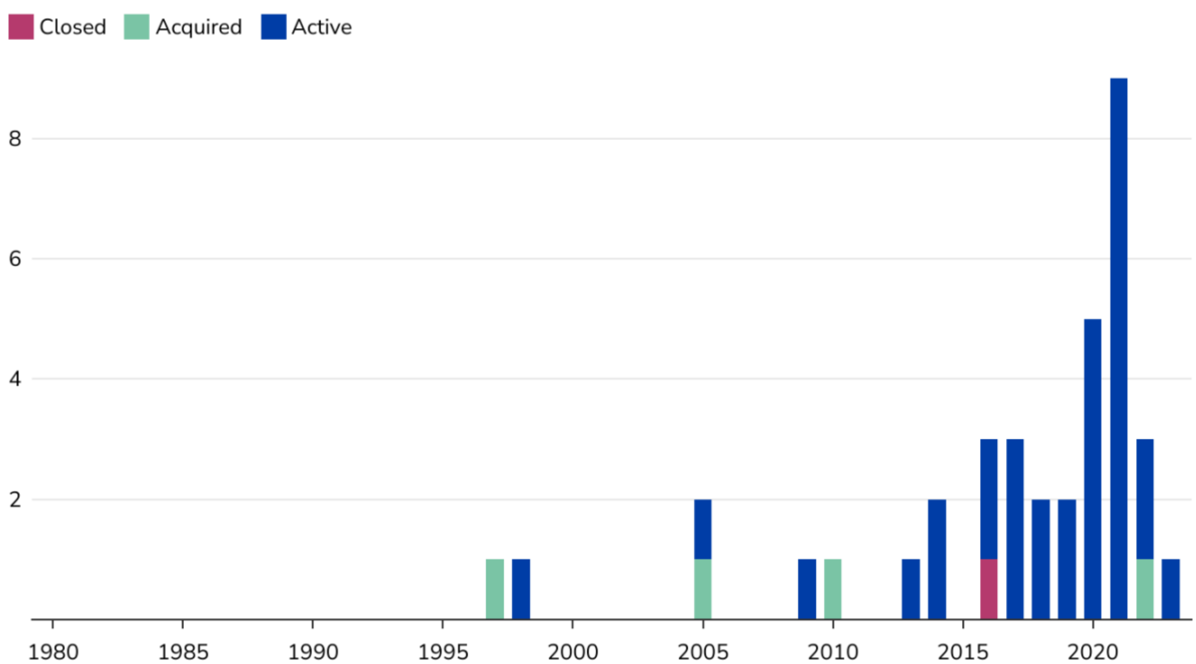
Sources: (top) Astroscale, 2023; (bottom) U.S. Air Force, 2005.

Note: U.S. Air Force–led XSS-11 imaged its own rocket. ADRAS-J imaged separate debris.

Despite the many challenges, companies are forming to address in-space servicing. Founding data shows progress, with about half of all identified servicing companies forming in the last five years, and five out of every six in the past 12 years (Figure 4).[55]

Figure 4 also shows the accelerated trend. Interestingly, compared to other markets like remote sensing and launch, where corporate founding activity peaked around 2015, in-space services peaked in 2021.[56] Causation is difficult to determine with certainty, but launch cost reductions, successful technology demonstrations,* initial hints of market viability from those early demonstrations, greater government attention and funding, and continued progress in electronics—especially the sensing and computation required for RPO—are likely contributors.[57]

Figure 4. In-Space Satellite Services Companies: Founding Years and Operating Status



Source: PitchBook Data, Inc.; author analysis.

Note: Closed refers to companies no longer in business; acquired refers to companies still active but have been purchased by another company and may or may not be operating under another name; active refers to companies still operating as of publication.

* Including the successful deployment of commercial life-extension services.

In-Space Manufacturing

In-space manufacturing is the fabrication of items in space for use in orbit or on Earth.[58] Much of the technology derives from in-space servicing and, to a lesser extent, exploration. Indeed, manufacturing for use in orbit can enable exploration. While not dismissing this use case, we focus here on manufacturing goods for use on Earth.

NASA has led much of this work, and the ISS has been a long-term test bed for the research.[59] Orbit is difficult to reach but offers unique manufacturing benefits: the vacuum of space is far cleaner than the best clean rooms on Earth, and microgravity allows for more uniform mixing and crystal growth.[60] Since over 60 percent of pharmaceuticals are crystalline, research or production of medically relevant compounds in orbit can benefit people on Earth.[61] Other applications such as semiconductor and materials fabrication and fiber optics production present opportunities—nascent, to be sure, but promising ones.[62]

While the economic benefits of in-orbit manufacturing are direct, the national security benefits are less obvious. There are at least two primary challenges to in-space manufacturing: creating automated processes that can work unattended in the space environment and safely returning the products to Earth. The second requires guidance and control to enable precise landings as well as sufficient thermal protection material to survive reentry.[63] These same technologies are needed for long-range missiles, and so are understandably carefully managed under export control rules.[*] Technologies meeting these challenges, however, have become more widely available as electronics and materials science have developed. In 2024, the first commercial capsule landing occurred with Varda Space Industries' W-1 capsule (Figure 5),[†] which processed medical compounds and returned them safely to Earth.[64]

[*] Capsule and missile speed and entry angle vary, needing different thermal shielding.

[†] Not counting human-rated vehicles that return people and experiments from the ISS.

Figure 5. Varda Reentry Capsule Safely Lands after In-Space Manufacturing Test

Source: Varda Space Industries (@VardaSpace), “Some Photos from Our Team’s Recovery of W-1…,” Twitter, February 22, 2024, https://twitter.com/VardaSpace/status/1760726397889466792.

Despite the small number of competitors in this business area (see Table A3 in Appendix 2), this successful proof-of-concept return is likely to encourage continued development.

Industry and Technology Trends

The five advanced technology areas are at different points along their development timelines but have significant similarities that can be broken down into two categories: trends and factors. Trends describe what is happening in the industry, while factors note the activities, technology, and organizational elements that may contribute to the trends.

Trends

In 2010, the New Space movement was still nascent, while large aerospace and defense contractors focused on meeting government-directed requirements and building government-directed designs rather than commercialization.[65] Since then, the growth in these advanced technology areas has been small in total company numbers but notable nonetheless.

Consider the set of “space technology” companies within the publicly available PitchBook database: while not an exhaustive list of all space companies, trends within this dataset generally match those of the larger industry.[66] We identified 91 companies in PitchBook that are working on advanced space technologies, which is just shy of 17 percent of all companies within the “space technology” vertical (Table 3). More than a third of the advanced-technology-identified companies are pursuing in-space services, with one-sixth planning for in-space manufacturing.[67]

Table 3. Share of Advanced Technology Companies by Subsector

Government Involvement	Subsector	Within Advanced Technology Sector	Within Space Vertical
High	PNT	4 (4.4%)	0.7%
	Ground-Based SSA	4 (4.4%)	0.7%
	Exploration	37 (40.7%)	6.8%
Limited	In-Space Satellite Services[68]	37 (40.7%)	6.8%
	In-Space Manufacturing	15 (16.5%)	2.8%
	All Advanced Technology	**91[*]**	**16.8%**

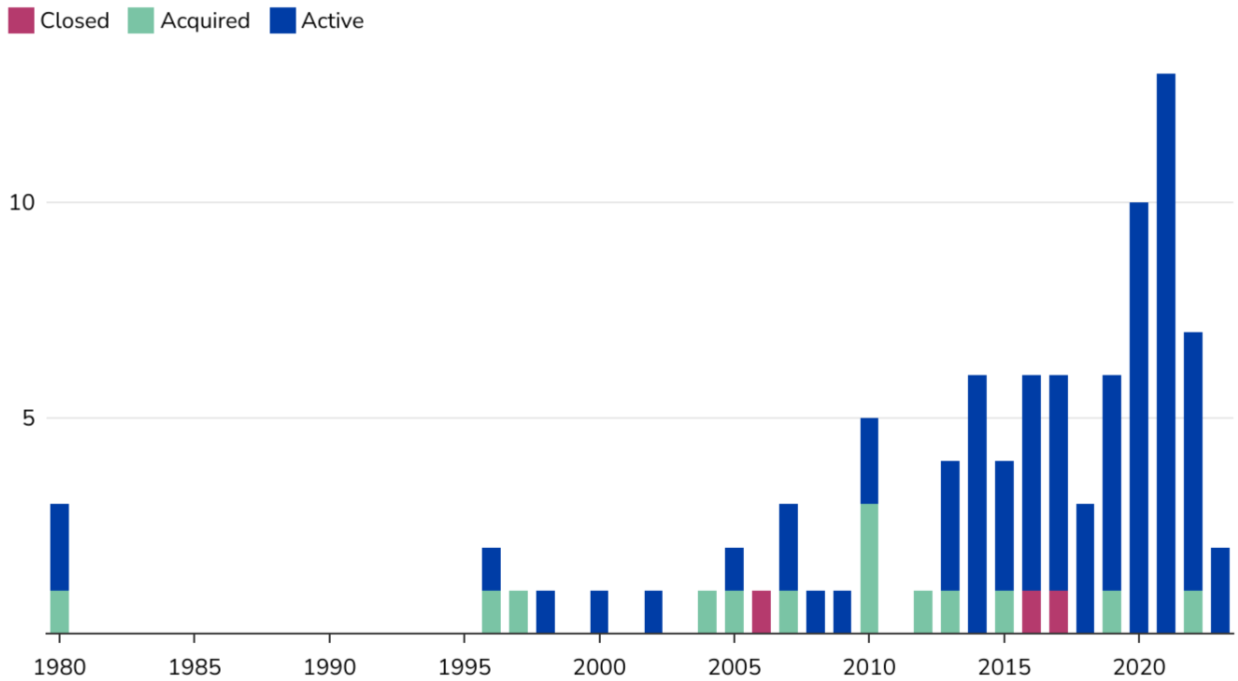
Source: PitchBook Data, Inc.; subsectors determined through author analysis. See methodology for more details.

Ground-based commercial SSA providers are also a relatively small group. While this is likely an undercount based on similar datasets, the small number of companies in markets already served by government services is notable when compared to the other subgroups.[69]

As noted earlier, the majority of companies within the advanced technology category were founded after 2010 (Figure 6). Trends in two other periods are notable: 2013 began a spike in company founding activity that persisted for nearly a decade, while the 2020–2021 timeline marked a brief burst of further accelerated growth.

[*] Actual sum is 97, however companies can be tagged in more than one subsector. Ninety-one reflects the number of *unique* advanced technology companies we identified. The PitchBook dataset is extensive, but even so may not capture all companies in the advanced space technology sector.

Figure 6. Advanced Space Technology Companies: Recent Spike in Founding Activity



Source: PitchBook Data, Inc.; author analysis.

(Note): Companies formed before 1980 are included in the 1980 column. Closed refers to companies no longer in business; acquired refers to companies still active but have been purchased by another company and may or may not be operating under another name; active refers to companies still operating.

Related Market Factors

There should be few companies selling and developing advanced technologies that were founded before 2010. Indeed, technologies are not usually considered advanced if they have been on the market for decades. Before 2010, each of the technologies in this category was either the domain of government with government-sized budgets (SSA, PNT) or considered so difficult that the Defense Advanced Research Projects Agency (DARPA)—known for tackling "transformational change rather than incremental advances"—was working on demonstrations.[70] Nevertheless, the trends in this area provide insights into the market.

As noted earlier, 2013 marks the start of a run of company formation activity. While causation is hard to attribute, this was the start of dropping launch costs and the rise of small, cheap satellite viability. The following year, in 2014, SpaceX began to gain significant market share from then leader United Launch Alliance.[71] Similar growth trends were seen in the remote sensing market.[72] Notably, another New Space company, Planet Labs, launched its first 65 operational satellites in 2014, making the first start toward a proliferated satellite constellation in decades.[73]

The 2021 announcement of NASA's Commercial LEO Destinations project added fuel to the advanced space tech marketplace.[74] This ISS divestment strategy did two things: it offered a new market to companies in LEO and refocused NASA resources toward exploration beyond LEO.[75] In doing so, NASA could save operational costs by reducing spending on the ISS, which amounted to about $1.3 billion annually, plus $1.8 billion for cargo and crew replenishment in the 2021 fiscal year.[76]

Also notable is the difference between the PNT and SSA subgroups and exploration. All three fall into mission areas with high government involvement, but exploration has nearly ten times the number of companies as the other two categories (see Appendix 1 for a list of companies). While acknowledging that human curiosity might disproportionately draw founders to exploration-focused missions, NASA's early embrace of commercial involvement in exploration, compared with the DOD's slower strides, may be a contributor.

Engineering Factors

Cheaper launches, smaller satellites, and government contract opportunities are helpful, but it's hard to make a profit if the technology is not technically ready. That's why two additional factors may also come into play: improved engineering, especially in electronics and materials science, and government technology transfer. Both of these factors decrease the cost of progress. The tight interplay between the two appears to drive much of the recent development in advanced space technology.

Some of these engineering advancements are the result of government support. The Varda Space Industries reentry capsule seen in Figure 5 is a great testament to commercial creativity, but the capsule uses heat shield material manufactured by NASA's Ames Research Center. A planned technology transfer will allow Varda to produce the material, but early government partnership has been fundamental to project success.

Similar government support and technology transfers may factor into commercial PNT alternatives. In 2004, the National Institute of Standards and Technology and DARPA developed atomic clocks the size of a computer chip (appropriately called chip-scale atomic clocks) and flew them to the ISS in 2011.[77] The new clocks are cheap, light, and low power, while GPS satellites fly multiple heavy clocks, costing millions of dollars each. While chip-scale clocks' timing drifts approximately 100 times faster than their high-performance cousins, researchers estimate that LEO satellites with positioning updates approximately once per orbit rather than once per day can deliver performance close to that of GPS.[78] Some of the same researchers now work for one of the PNT companies in the PitchBook dataset.[79]

Continued progress in electronics and the downward cost trends provide openings in other areas. Commercial SSA providers are a great example.[80] Widely dispersed networks are a major advantage in the mission area, and geographically diffuse networks are now easier to develop and manage. Costs for high-performance cameras and optics have also fallen. Here, commercial vendors offer advantages that government providers cannot match: a company can quickly build capability worldwide, while the U.S. government must work through long negotiations to build facilities abroad, making commercial options technically competitive against taxpayer-funded services.

The same advancing technology applies to space-based SSA as well. Today, relatively few systems do this mission: for example, the U.S. Geosynchronous Space Situational Awareness Program, U.S. Space Based Space Surveillance, and Canada's Sapphire satellite.[81] This leaves room for other companies to conduct non-Earth imaging as satellites get cheaper and cameras and pointing equipment improve.[82]

Challenges and Opportunities

Advanced space technology companies hold promise for national security missions and economic gains. Their success or failure is still uncertain, however, and policymakers interested in supporting an American advantage in these emerging technology areas should consider the challenges and opportunities unique to the marketplace.

Challenge 1: Profitability

Advanced space technology is by definition less established than remote sensing, launch services, and communications technologies, with fewer proven profitable niches. This poses risks to three groups: First, investors have fewer examples of companies that have successfully navigated the challenges of the mission area, though with added risk comes greater potential upside. Second, the companies themselves do not have proven templates to follow for profitability or legacy business models ripe for disruption, but likewise benefit from the ability to shape their market. Third, the national security organizations that work with advanced technology companies must also plan for uncertain profitability. Regardless of the national security benefits, if a company is not profitable, its services will not persist for long.[83] Agencies must plan for the potential struggle or disappearance of important service providers.

Challenge 2: Export Controls

There are areas of advanced technology where the United States either does not possess a clear lead or where the country benefits from working with others. U.S. export controls can be a barrier to leveraging the resources of allies and partners.

For instance, while early missions relevant to active debris removal were flown by the United States, today Japan and the UK are leading with commercial missions.[84] One of the primary contenders, Astroscale, is headquartered in Japan with U.S.-based and other foreign subsidiaries.[85] Though export control reforms in 2013 and 2018 helped reduce the burden, there are still areas where participation by Americans is limited. For instance, under current International Traffic in Arms Regulations limitations, satellites that “autonomously perform collision avoidance” are restricted, even though that capability is inherently important to servicing and debris-mitigation satellites.[86] Participation by American nationals in these endeavors is therefore limited, reducing the ability of American companies to learn from some of our closest allies.

To leverage the talents of allies and partners or even adopt so-called friend-shoring strategies, the U.S. government will need to address export control regulations—akin to its joint synchronization efforts under AUKUS and existing close ties with Canada's defense industrial base.[87] Similarly powerful would be the ability for international partners to jointly fund technology development efforts rather than paying for separate missions.

Challenge 3: Space-Based PNT

Given congressional interest in resilient PNT and multiple concurrent DOD programs to find GPS alternatives, it is surprising that our data only identified a single company providing a space-based solution. This is especially so considering the expanding commercial use of navigation services, such as self-driving vehicles and precision agriculture, that would benefit from new PNT sources.[88]

Alternative explanations—such as poor coverage within our data, or satellite communications companies intending to meet the needs of both the satellite communications and PNT markets—could clarify the dearth of companies, as could a focus on Earth-bound solutions or the current provision of good-enough GPS by the U.S. government. Nevertheless, to meet military needs for high-precision, high-accuracy positioning and timing signals across vast regions of land and ocean, actively broadcasting satellite services would seem effective and relatively survivable. The path to profitability may require leveraging government interest in alternative PNT solutions, alongside commercial needs for improved precision.

Opportunity 1: Commercial Interplanetary and Science Missions

NASA is charged with advancing many objectives: aeronautics; Earth, atmospheric, and planetary science; heliophysics; astronomy; and human exploration. Depending on inflation accounting, the agency's budget is the same as it was 30 to 50 years ago, but with a far wider purview.[89] NASA has smartly turned to commercial vendors for greater portions of its activities to mitigate these budget challenges: first cargo transport to the ISS, then crew transport to the ISS, and now an ISS replacement itself. With the CLPS program, multiple lunar landers are now being cheaply built by multiple American companies, while other countries' space agencies build one-off devices. The return of humans to the moon is using a commercial-government hybrid, with SpaceX and Blue Origin winning contracts for lunar landers.[90] In the face of massive costs, NASA is even considering commercial approaches to returning samples from the surface of Mars.[91] This all frees talent and funding within the agency to focus on new, harder problems and responsibilities expected of the organization.

With hints of commercial involvement in the interplanetary exploration of Mars and Venus to come, NASA has the opportunity to commit to a commercial "hedge" portfolio for many of its science missions, accepting more technical risk to save cost. Some requirements, such as planetary protection measures, are less flexible. Nevertheless, a commercial hedge—where the agency dedicates a moderate portion of its budget to a set of technically risky, high-payoff approaches—could encourage competition throughout project life cycles and inspire creative solutions to scientific problems, all while allowing government budgets to go farther and unleashing existing agency talent to focus on novel problems.

Such an opportunity is not risk free, of course. The flight times for deep space missions are years to decades long, meaning mission failure may also mean decades of lost science. Furthermore, there will be a fine balancing act in allocating funding between the notionally low-risk "primary" path and the higher-risk hedge portfolio. Commercial profitability for these missions is far off, and in the near term, government funding is necessary. The spin-off technologies that may result and the ability to stretch research dollars to more programs will be the major payoff from industry involvement. While government-funded science must take the lead for years to come, there is a place for experimentation with commercial platforms. NASA has taken great strides in this area and can continue to accept more risks.[*]

Opportunity 2: Combining Multiple Advanced Technologies

To meet the profitability challenge, the combination of multiple advanced technologies may be a solution. Refueling and debris remediation is one such promising match. If a vehicle for debris removal can itself be refueled, and the equation for removal no longer becomes one spacecraft per piece of debris, then the activity may be more financially viable. In this way, a business challenge is transformed into a technical one. Any company that can solve the (admittedly large) technical challenge of refueling has a major advantage in both the satellite servicing and debris remediation markets. At least one company, Astroscale, sees value in this combination and is pursuing both technologies.[92]

Other combined-technology approaches are also promising: commercial space stations can help scale in-space manufacturing, in-space servicing technology can increase the payload capacity of exploration missions, and ground-based SSA can maintain safety

[*] Technical and programmatic risk, not risk to human participants and the public.

when in-space servicing capabilities approach other spacecraft. Progress in one area will support progress in others.

Opportunity 3: First-Mover Advantage

Being the first company (or country) to field an advanced technology will provide major advantages. We have seen such advantages elsewhere in the space industry, as SpaceX's development of reusable rockets has brought cost, reliability, and scaling benefits, along with major market share. Within satellite servicing and refueling, this advantage may be even more important than usual. Whoever shows a viable technical solution and business case may define the standard refueling interface for all future satellites.

Such a standard will take an investment of time and resources. However, the ability to define that standard will provide three primary benefits. First, having a national standard to work toward can eliminate duplication of effort across industries, avoiding each company defining a design that changes for each mission.[*] Second, by establishing servicing and refueling standards that match existing U.S. and allied engineering standards and design principles, there are fewer changes required for the design of the rest of a satellite equipped with a servicing and refueling system. Third, if a standard is set among domestic, allied, and partner industries, satellites are more likely to be interoperable. From a market perspective, this is desirable; from a national security perspective, this may be invaluable.

Opportunity 4: Commercial SSA Shareability

There have long been laments that military space activities are overclassified. Though progress has been made, more work remains.[93] Just as steadily improving commercial satellite imagery has challenged defense planners to think differently about security, so, too, will commercial SSA drive similar changes in the national security space community. Commercial capabilities will probably make it easier to track U.S. national assets alongside foreign systems. Doing so may motivate finding new solutions to the security overclassification problem often associated with space programs. Commercial SSA also provides additional opportunities to enhance sharing with allies and partners, since data is generated on unclassified systems, uses unclassified algorithms, and transits unclassified networks.

[*] Or, at worst, a small number of acceptable standards across satellite providers.

Commercial SSA can prove advantageous as a policy tool because the information generated by commercial sensors is publicly releasable. Just as commercial space imagery was used to great effect in Ukraine, so, too, can SSA data highlight unfriendly activities without revealing American military capabilities.[94]

American and allied leadership in the commercial SSA market is also militarily beneficial. In the exceptional cases where there is no good solution but to mask, delay, or limit dissemination of militarily relevant SSA data, negotiations with companies from friendly nations are far easier than those with poorer relations.

Recommendations

In the advanced technology arena, the U.S. government has a history of conducting bold demonstrations. Today, commercial vendors are pursuing some of those same capabilities with an eye toward solving major security, sustainability, or exploration problems. Each company must eye profitability too. Based on the challenges and especially the opportunities above, the following are recommendations for how the United States can press its advantage in commercial space and provide a foundation for national security advantages well into the future.

1. **Federal agencies—especially the DOD, the Intelligence Community, and NASA—should invest in hedge portfolios for advanced technology missions with national security applications and outsize risks if the United States cedes leadership.**

   Many military acquisition programs, space or otherwise, enter their engineering and manufacturing development phase with a single large defense contractor. This is risky technically and financially because failures require government acquirers either to invest more time or budget to meet requirements or to start their development process over again. Even in a fixed-price contracting arrangement, schedules can regularly slip.

   Establishing a small hedge portfolio within a program may mitigate these risks. A hedge portfolio is a small investment that hedges or compensates against the risk that the single large contractor fails to deliver. This can be funding for either a high-risk, high-reward alternative solution from a different vendor or another contractor able to continue a program should the prime falter and do so without starting over from scratch.

   There are multiple benefits to setting aside a reasonable (small but non-negligible) amount of funding for a commercial competitor to attempt the same task: competition continues into the later stages of an acquisition, and commercial innovation can develop alongside government needs.[95] Nontraditional suppliers as a hedge to traditional contractors and cost-plus contracts may also improve the time-to-capability for a given mission.

   Turning to nontraditional suppliers does come with risks to programs. Beyond the technical risk inherent in novel solutions, there are other disincentives for program management: failure may be public, with heavy congressional interest, while success may be private, with little benefit to project members.[96] Because of this, a diversified approach, combining traditional contractors with a nontraditional hedge, should be used to manage both technical and programmatic risk.

NASA's multiple experiences with commercial resupply, commercial crew, CLPS, and similar programs show that the commercial space industry can deliver solutions to challenging problems. The federal government should provide opportunities and support so industry can do so.

2. **The U.S. government should act as an anchor tenant by purchasing and investing in research for commercial services in selected advanced technologies, especially in-space satellite servicing, for which the U.S. government does not currently field a solution at scale.**

The outsize impact of advanced technologies, like in-space satellite services, means that the United States should prioritize viable solutions. To encourage companies to field such solutions, the government can reduce the risk by acting as an anchor tenant when a company deploys a new security-relevant technology.

Service purchases can take the form of grants, contracts, technology transfer agreements, advanced purchase agreements, and the like. Such support can inform future government architecture while providing a broad vision to industry. Further, by acting as an advanced purchaser of services, the U.S. government encourages a rapid scaling of capability once it is reliably demonstrated. While the public noticed this approach in pandemic-era vaccine purchases, intelligence agencies have leveraged similar approaches for remote sensing.[97]

A similar advanced purchase approach to emerging space technology, where the government commits to buying a certain quantity of a service once fielded, is reasonable. Rather than the U.S. government managing and designing a government-purpose system, this approach encourages industry to deliver broadly useful products and services. Then, the government serves as an anchor customer once a capability is fielded. This balances risk between the government and investors: investors gain confidence that an early market will exist, while the government commitment is relatively low if products fail.

Early government commitment to act as an anchor, however, is crucial. Without commitment and attendant funding, the companies that are ready and willing to provide services may run out of start-up capital and fail, leaving the United States reliant on legacy solutions and paying legacy costs. Such a commitment is necessary soon after a need is identified. Recent examples include the Commercial LEO Destinations program once the ISS deorbit date was set and in-space servicing agreements once lunar exploration plans demanded the technology.

Balancing the use of service agreements with more formal development contracts will need to be done on a case-by-case basis. For those areas, such as in-space servicing and refueling, where there is a major national security interest in a first-mover advantage, development contracts in addition to service agreements are most appropriate.

3. **The U.S. government should continue to purchase services and make targeted investments (including infrastructure upgrades) in advanced technology areas where it is the dominant service provider to build resilience in government systems.**

   These purchases will generally look like commercial services contracts, research and development contracts, or, in some cases, an advanced purchase agreement—should a technology show operational suitability for military applications. In areas such as global PNT services, a wholesale withdrawal of GPS from the market in favor of commercial alternatives would be chaotic and undesirable. Instead, focusing on alternative services—such as those resilient to GPS jamming or able to provide better positioning—and ensuring a viable market for them is critical. GPS alternatives are needed for national security, but they must work alongside GPS. Likewise, SSA services are largely provided by major government installations. Smaller, distributed systems not yoked to aging infrastructure and computing architecture can provide a viable path to an improved government system or to a more heavily commercial future. In the latter case, government systems could be used primarily for military purposes rather than all space traffic management services.

4. **The State Department, in consultation with the DOD and Department of Commerce (DOC), should harmonize export controls with allied nations actively building similar technology.**

   While export control revisions have eased the burden on space system development, minor tweaks are still appropriate. However, rather than having the regulations constantly chasing changes in technology, generalizing the strategic approach taken in the AUKUS partnership—where export controls are harmonized across countries, enabling freer trade in dual-use and military-purpose goods between member states—is a better way forward.[98]

Many of the countries embracing advanced space technologies are also U.S. treaty allies. They possess talented technical workforces. Whereas the United States has expertise across multiple areas by virtue of its large population and advanced economy, these allied nations often have deep capabilities in fewer areas: Japan in debris remediation, New Zealand in rocketry, and Australia in ground networks and space surveillance, to name a few.[99] A common space and defense market within existing bilateral (e.g., U.S.-Japan) and multilateral arrangements (e.g., AUKUS, Five Eyes) would enable knowledge sharing and more efficient use of government and commercial funding.

At the same time that export controls are being harmonized, government agencies, led by DOC, can update and streamline the regulatory framework for commercial space activities to continue balancing innovation promotion with ensuring safety and security. This includes setting clear timelines for approvals, simplifying the certification process, and providing support for treaty compliance. DOC has demonstrated clear leadership in this area and, given sufficient resources, can continue to do so.

Alongside domestic regulatory streamlining, reducing export barriers and harmonizing controls on advanced space technologies among close allies can help the United States better compete with national security threats, especially those posed by China.

Conclusion

The forward march of advanced space technologies tends to be unpredictable by its very nature. The United States, however, has long relied on such technology for the security of its deployed forces and the homeland. Increasingly, technology is developed and fielded by the private sector, versus solely through government development contracts.[100] This reliance requires a strong industrial base with an innovative and talented workforce. But the private sector also benefits greatly from focused investment and government support.

Just as the advent of GPS could only have been brought about through government support, so, too, will its supplements need to be shepherded. Just as the moon landings drove the development of computing, so, too, is the next generation of moon exploration driving innovation in lunar landers and orbital servicing and refueling. The U.S. government and the policymakers who lead it should take heed of the examples from the past: early investment and contracts such as advanced purchase agreements smoothed the scaling up of vaccine production in a pandemic. In space, they offer steady opportunities once uncertain technologies are proven.[101] Taking these actions to enhance the commercial advanced space technology market will put the United States and its allies and partners in a better position to compete against adversaries, leaving the nation and world safer.

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Acknowledgments

For their careful review, thoughtful comments, and constructive feedback, we would like to thank Emelia Probasco, Kyle Miller, Sam Bresnick, Igor Mikolic-Torreira, and our external reviewers Dr. Bhavya Lal, Dr. Mike Ryschkewitsch, and Mr. Ryan Conroy. Thanks also to Shelton Fitch for his editorial support, Christian Schoeberl for his data support, Catherine Aiken for data oversight, Rai Hasen Masoud for formatting support, and Jason Ly for his graphic design talents.

Disclaimer

The conclusions and opinions expressed in this research paper are those of the authors and do not necessarily reflect the official policy or position of the U.S. government, the U.S. Department of Defense, the U.S. Space Force, or the Air University. Any and all errors are those of the authors alone.

Document Identifier: doi: 10.51593/20240018

Appendix 1: Methodology Details

The goal of this publication is to capture the history and current status of advanced (or "emerging") technology subsectors of the broader space economy, given its relevance to policymakers and the national security community.

This analysis leverages a dataset from PitchBook Data, Inc. (PitchBook), which provides rich information about corporate financial information and investment fund activity for public and private companies. This insight into corporate finance allows fine-grained analysis of various industries and companies, along with how those industries change through investments and mergers and acquisitions. PitchBook provides industry assignments for companies within their dataset, which we use to select companies relevant to the space economy. We then assign each of the 543 companies in the "space technology" vertical to appropriate subsectors.[102] The company assignments were based on our professional knowledge and a detailed review of the company description, websites, and news reports from PitchBook.[*] For example, the following criteria (Table A1) were used to assign companies to one of the five subsectors.

[*] Additional criteria were used to assign companies to other subsectors. For further detail, please contact the authors.

Table A1. Criteria for Assigning Company Subsectors

Primary Question	Secondary Question / Note	Subsector "Tag"
Does the company produce satellites or leverage data produced by satellites?	Does the company provide space-based positioning, navigation, and timing services (like GPS)?	PNT
	Is the company planning to conduct SSA from space, conduct space debris remediation, or offer refueling and related services (like movement of spacecraft in orbit postlaunch)?	In-Space Satellite Services
Does the company provide awareness of satellite location and behavior (SSA) using ground-based sensors?		SSA
Does the company provide exploration technologies (especially lunar exploration)?		Exploration
Does the company provide technologies for in-space manufacturing?		In-Space Manufacturing

Company subsector assignments were determined by the authors' expertise and analysis using the criteria noted in Table A1. These companies were individually identified through manual analysis by the authors of all companies in Pitchbook's space vertical. Companies can belong to multiple subsectors or none at all. Once companies are assigned, data related to each company's founding date, operating status, and merger activity are acquired from PitchBook. In this publication, there are four companies assigned to PNT and four to ground-based SSA, along with 37 assigned to in-space satellite services and 37 to exploration, with 15 assigned to in-space manufacturing.

Due to a few companies that belonged to multiple subsectors, the total number of advanced space technology companies is 91.

There are limits to the data. While a data aggregator like PitchBook is unlikely to identify every space company, our ultimate goal is to provide analysis and trends for key corporate metadata, including foundation year, business status, acquisition status, and investment health (though this paper does not address investment health). Using manual annotation of companies provides a human check on the relevance of a company to the analysis. Further boosting confidence in the data and analysis, we found that other research, commercial datasets, and internal sampling showed similar trends.[103]

Additionally, given the developing nature of the space economy, companies may grow or shrink their product portfolios. The data represents a current snapshot of the space economy to maximize usefulness to policymakers and the national security community today. Future work should continue or expand the annotation process to ensure continued accuracy.

Appendix 2: Additional Data Tables

Table A2. Most In-Space Satellite Servicing Companies Founded Recently

Commercial In-Space Satellite Servicing Company Founding Trends		
Companies in dataset		37
Companies founded...........................before 2000	5%	2
....2000 to 2012	11%	4
....2013 to 2019	35%	13
....2020 or later	49%	18

Source: PitchBook Data, Inc.; author analysis.

Table A3. Most In-Space Manufacturing Companies Founded Recently

Commercial In-Space Manufacturing Company Founding Trends		
Companies in dataset		15
Companies founded...........................before 2000	0%	0
....2000 to 2012	7%	1
....2013 to 2019	40%	6
....2020 or later	53%	8

Source: PitchBook Data, Inc.; author analysis.

Table A4. Companies from PitchBook

PNT	SSA	In-Space Satellite Services	In-Space Manufacturing	Exploration
KOfinder	L3 Applied Defense Solutions	Ad Astra Rocket	Above Space	Aquarian Space
Satelles	LeoLabs	Altius Space Machines	Axiom Space	Argo Space
Xairos (Information Services (B2C))	Numerica (Space Domain Awareness Division)	Apex (Culver City)	CisLunar Industries	Astrobotic
Xona Space Systems	Privateer	Argo Space	In Orbit	AstroForge
		Arkisys	LatticeX (Acquirer)	Blue Origin
		Atomos (Aerospace and Defense)	Made in Space	Boeing
		CisLunar Industries	MaxSpace	Cislune
		Exclosure	Odyssey SpaceWorks	Constanellis Aerospace
		Free Space	Outpost	Deep Space Industries
		Galactiv	Redwire (Jacksonville)	Dynetics
		GeoJump	reOrbital	Firefly Aerospace
		Guardian Space Technology Solutions	Sierra Space	Gravitics
		iMetalx	Space Tango	Interlune
		Impulse Space	Uplift Aerospace	Interorbital Systems

		Intelligent Space	Varda Space Industries	Interplanetary Space Sciences
		Kall Morris		Intuitive Machines
		Katalyst Space Technologies		Lunar Outpost
		L3 Applied Defense Solutions		Masten Space Systems
		Launchspace Technologies		Moon Express
		Modularity Space		Motiv Space Systems
		Momentus		Next Giant Leap
		New Frontier Aerospace		Northrop Grumman
		Orbit Fab		Off Planet Research
		Outpost		OffWorld
		plasmOS		Orbital Outfitters
		Quantum Space		Orion Span
		SCOUT Space		Planetary Resources
		Sierra Space		PowerLight Technologies
		Skycorp		Ragnarok Industries
		Space Cowboy		Rhea Space Activity
		SpaceBilt		Rocket City Space Pioneers
		Spacedev		Sierra Space
		Starfish Space		SpaceX

		ThinkOrbital		Starpath
		True Anomaly		Golden Spike Company
		Turion Space		TransAstra
		Vissidus Technologies		Vaya Space

Source: PitchBook Data, Inc.; subsectors for each company determined by author analysis.

Endnotes

[1] "Surveyor 1," NASA Space Science Data Coordinated Archive, NASA, accessed February 27, 2025, https://nssdc.gsfc.nasa.gov/nmc/spacecraft/display.action?id=1966-045A; "CPI Inflation Calculator," U.S. Bureau of Labor Statistics, accessed February 27, 2025, https://data.bls.gov/cgi-bin/cpicalc.pl?cost1=67&year1=196601&year2=202403.

[2] Jeff Foust, "Final Preparations Underway for Launch of First Intuitive Machines Lunar Lander," *SpaceNews*, February 15, 2024, https://spacenews.com/final-preparations-underway-for-launch-of-first-intuitive-machines-lunar-lander/.

[3] David Vergun, "Official Details Space-Based Threats and U.S. Countermeasures," DOD, April 26, 2023, www.defense.gov/News/News-Stories/Article/Article/3375577/official-details-space-based-threats-and-us-countermeasures/; Rebecca Grant, "The Second Offset," *Air & Space Forces Magazine*, June 24, 2016, www.airandspaceforces.com/article/the-second-offset/.

[4] The paper explicitly excludes those technologies that are, and may remain, decades away, such as asteroid mining.

[5] The "space technology" vertical was used by our team to generate candidate companies prior to manual review. The use of labeled verticals improves comparisons between industries over other methods. See: "What Are Industry Verticals," PitchBook, accessed February 27, 2025, https://pitchbook.com/what-are-industry-verticals.

[6] Loura Hall, "How NASA and John Deere Helped Tractors Drive Themselves," NASA, August 15, 2023, www.nasa.gov/technology/tech-transfer-spinoffs/how-nasa-and-john-deere-helped-tractors-drive-themselves/; Office of Space Commerce, "DOC Study on Economic Benefits of GPS," Department of Commerce, June 10, 2019, www.space.commerce.gov/doc-study-on-economic-benefits-of-gps/.

[7] Paul Lushenko, "Trust but Verify: U.S. Troops, Artificial Intelligence, and an Uneasy Partnership," Brookings Institution, January 22, 2024, www.brookings.edu/articles/trust-but-verify-u-s-troops-artificial-intelligence-and-an-uneasy-partnership/.

[8] Undersecretary of Defense (Comptroller), *Program Acquisition Cost by Weapon System*, Fiscal Year 2025 Budget Request, March 2024, https://comptroller.defense.gov/Portals/45/Documents/defbudget/FY2025/FY2025_Weapons.pdf; "Program Funding," GPS.gov, accessed February 27, 2025, www.gps.gov/policy/funding/.

[9] The pre-GPS history is an important element in the transition from strategic system to tactical, and ultimately commercially relevant, government service. Following Sputnik, the DOD recognized that space-based navigation would aid the U.S. Navy's undersea second-strike nuclear mission. In 1960, the Advanced Research Projects Agency (then ARPA, now DARPA) launched the first Transit navigation satellite, and the U.S. Navy filled an operational constellation by 1968. Transit satellites, however, orbited low, carried lower-precision clocks, and required heavy ground equipment to use: fine for nuclear-armed submarines, but less so for ground forces. Positioning only worked once an hour. GPS

uses higher-precision clocks and flies in much higher orbits, enabling constant coverage for much of the world's population. See: "Transit Satellite: Space-Based Navigation," Innovation Timeline, DARPA, accessed February 27, 2025, www.darpa.mil/about-us/timeline/transit-satellite; "A Brief History of GPS," Aerospace Corporation, accessed February 27, 2025, https://aerospace.org/article/brief-history-gps; Catherine Alexandrow, "The Story of GPS," DARPA, 2008, archived at the Wayback Machine, June 29, 2011, https://web.archive.org/web/20110629003311/http://www.darpa.mil/WorkArea/DownloadAsset.aspx?id=2565; "Transit (NNSS)," eoPortal, last modified June 18, 2012, https://www.eoportal.org/satellite-missions/transit.

[10] The American military would use an encrypted signal without the degradation. See: "Selective Availability," GPS.gov, accessed February 27, 2025, www.gps.gov/systems/gps/modernization/sa/.

[11] Global Positioning System, 10 U.S.C. § 2281 (2000), www.govinfo.gov/app/details/USCODE-2000-title10/USCODE-2000-title10-subtitleA-partIV-chap136-sec2281.

[12] GPS is actually a spread spectrum signal, which means it is usable even at low received power levels and in the presence of some interference. However, with enough jamming strength, even the GPS signal becomes difficult to use, requiring different devices or techniques to mitigate. Peter Grier, "GPS in Peace and War," *Air & Space Forces Magazine*, April 1, 1996, www.airandspaceforces.com/article/0496gps/; Larry Greenemeier, "GPS and the World's First 'Space War,'" *Scientific American*, February 20, 2024, www.scientificamerican.com/article/gps-and-the-world-s-first-space-war/.

[13] This is known as medium Earth orbit, or MEO. Dianne M. Zorri and Gary C. Kessler, "Position, Navigation, and Timing Weaponization in the Maritime Domain: Orientation in the Era of Great Systems Conflict," *Joint Forces Quarterly* 112 (January 2024), https://ndupress.ndu.edu/Joint-Force-Quarterly/Joint-Force-Quarterly-112/Article/Article/3678180/position-navigation-and-timing-weaponization-in-the-maritime-domain-orientation/; "Space Segment," GPS.gov, accessed February 27, 2025, www.gps.gov/systems/gps/space/.

[14] Exec. Order No. 13905, 85 FR (2020); Government Accountability Office, *GPS Alternatives: DOD is Developing Navigation Systems but is Not Measuring Overall Progress*, GAO-22-106010 (Washington, D.C.: GAO, August 5, 2022), www.gao.gov/products/gao-22-106010; National Defense Authorization Act for Fiscal Year 2021, S. 4049, 116th Cong, (2020), see § 1601.

[15] For instance, while the approximately three-meter accuracy in GPS specifications or the 0.6 meter accuracy observed (95% CI) is good for navigating from one point to another, higher accuracy is highly desirable for autonomous vehicles. See: DOD, *Global Positioning System (GPS) Standard Positioning Service Performance Standard* (Washington, D.C.: DOD, April 2020), www.gps.gov/technical/ps/2020-SPS-performance-standard.pdf; "GPS Accuracy," GPS.gov, accessed February 27, 2025, www.gps.gov/systems/gps/performance/accuracy/.

[16] Crunchbase ($30M), PitchBook ($25.9M); "Xona Space Systems Develops a Private GNSS (Global Navigation Satellite System)," eoPortal, May 10, 2022, www.eoportal.org/satellite-missions/xona#xona-space-systems-develops-a-private-gnss-global-navigation-satellite-system.

[17] PitchBook Data, Inc.; author analysis.

[18] The collision-avoidance function is currently transitioning to DOC from DOD, so the latter can focus more on military threats to satellites. Jeff Foust, "From Space Traffic Awareness to Space Traffic Management," *SpaceNews*, October 20, 2021, https://spacenews.com/from-space-traffic-awareness-to-space-traffic-management/; James E. David and Charles Byvik, eds., *What's up There, Where Is It, and What's It Doing? The U.S. Space Surveillance Network* (Washington, D.C.: National Security Archive, March 13, 2023), https://nsarchive.gwu.edu/briefing-book/intelligence/2023-03-13/whats-there-where-it-and-whats-it-doing-us-space-surveillance; Nicholas Johnson, "The Collision of Iridium 33 and Cosmos 2251: The Shape of Things to Come," 60th International Astronautical Congress, October 16, 2009, https://ntrs.nasa.gov/citations/20100002023.

[19] Space Training and Readiness Command, "STARCOM Releases Space Domain Awareness Doctrine Publication," press release, November 16, 2023, www.starcom.spaceforce.mil/News/Article-Display/Article/3589828/starcom-releases-space-domain-awareness-doctrine-publication/.

[20] "Space Domain Awareness and Combat Power," Space Systems Command, Space Force, accessed February 27, 2025, www.ssc.spaceforce.mil/Program-Offices/Space-Domain-Awareness-Combat-Power.

[21] Felix R. Hoots, Paul W. Schumacher, and Robert A. Glover, "History of Analytical Orbit Modeling in the U. S. Space Surveillance System," *Journal of Guidance, Control, and Dynamics* 27, no. 2 (March 2004): 174–185, https://doi.org/10.2514/1.9161.

[22] The Outer Space Treaty disallowing orbital weapons of mass destruction would not come until 1967. Rick W. Sturdevant, "From Satellite Tracking to Space Situational Awareness: The USAF and Space Surveillance, 1957-2007," *Air Power History* 55, no. 4 (2008): 4–23, www.jstor.org/stable/26275054.

[23] Early tracking methods included visual observers and radios. By 1961, NASA and DOD agreed to centralize the computing required to manage the hodgepodge of sensors. Thus began NORAD's long role in the satellite tracking mission. Radar upgrades included the addition of phased array radars. The Defense Support Program missile warning satellites helped tell missile launches and orbital launches apart. A unified catalog under the Space Defense Operations Center (SPADOC) also came online. See: Sturdevant, "From Satellite Tracking to Space Situational Awareness."

[24] The optical sensors are called Ground-Based Electro-Optical Deep Space Surveillance System. Sturdevant, "From Satellite Tracking to Space Situational Awareness."

[25] Maj. Gen. John E. Shaw, "2019 Amos Conference Keynote 2," YouTube, December 2, 2019, https://youtu.be/JWOVAbbvIIs?feature=shared&t=169.

[26] Michael O'Connor and Kathleen Curlee, "Shaping the U.S. Space Launch Market," (Washington, D.C.: CSET, February 2025), https://doi.org/10.51593/20240017; The computer system, called SPADOC, is still in use today with modifications, despite many years of trying to replace it. See: Theresa Hitchens, “Space Force Effort to Replace Aging Space Tracking Software Lagging: DOT&E,” *Breaking Defense*, February 02, 2024, https://breakingdefense.com/2024/02/space-force-effort-to-replace-aging-space-tracking-software-lagging-dote/.

[27] Including China’s destruction of its FY-1C satellite in an anti-satellite weapon test and Russia’s similar test in 2021, along with satellite and upper-stage collisions and explosions. Policy efforts by the United States have had modest effects, but certainly not reversed the growth. See: “Presidential Directive on National Space Policy,” February 11, 1988, in FAS Space Policy Project, last modified January 3, 1998, https://spp.fas.org/military/docops/national/policy88.htm#:~:text=The%20directive%20states%20that%20the%20national%20security%20space%20sector%20will,Space%20Control.

[28] Whether this is truly accurate is beyond the scope of this paper. Some elements of the SSN may have equal levels of performance. See GAO, *Space Situational Awareness: DOD Should Evaluate How It Can Use Commercial Data*, GAO-23-105565, (Washington, D.C.: GAO, April 2023), 15, 19, www.gao.gov/assets/gao-23-105565.pdf; Debra Werner, “LeoLabs Scans Skies with West Australian Space Radar,” *SpaceNews*, January 30, 2023, https://spacenews.com/leolabs-commissions-australia-radar/.

[29] Because PitchBook lists few as space technology companies, trending is difficult. “One company… has been providing SSA to other companies for 9 years”: GAO, *Space Situational Awareness*, 19.

[30] GAO, *Space Situational Awareness*.

[31] “Why Space Exploration Is Always Worthwhile,” Planetary Society, August 30, 2021, www.planetary.org/articles/space-exploration-is-always-worthwhile; Zachary Arnold et al., “Immigration Policy and the U.S. AI Sector: A Preliminary Assessment” (CSET, September 2019), https://doi.org/10.51593/20190009; Manjari Chatterjee Miller, “To Compete with China, the United States Needs to Fix Immigration,” Council on Foreign Relations, February 27, 2023, www.cfr.org/blog/compete-china-united-states-needs-fix-immigration; Andrew Roush, “How the Space Race Changed American Education,” *TechNotes*, April 3, 2023, https://blog.tcea.org/space-race/.

[32] Charles Fishman, “How NASA Gave Birth to Modern Computing—and Gets No Credit for It,” *Fast Company*, June 13, 2019, www.fastcompany.com/90362753/how-nasa-gave-birth-to-modern-computing-and-gets-no-credit-for-it; “Technology Benefits,” Hubble Space Telescope, NASA, accessed February 27, 2025, https://science.nasa.gov/mission/hubble/impacts-and-benefits/technology-benefits/.

[33] “History: How Hubble Came About,” European Space Agency, accessed February 27, 2025, https://esahubble.org/about/history/; Office of Inspector General, *NASA’s Mars 2020 Project*, IG-17-009, NASA, January 30, 2017, https://oig.nasa.gov/wp-content/uploads/2024/02/IG-17-009.pdf.

[34] “Commercial Crew Program Essentials,” NASA, July 26, 2023, www.nasa.gov/humans-in-space/commercial-space/commercial-crew-program/commercial-crew-program-essentials/.

[35] "Commercial Orbital Transportation Services" (Washington, D.C.: NASA, February 2014), www.nasa.gov/wp-content/uploads/2016/08/sp-2014-617.pdf.

[36] "What Is Commercial Crew?," NASA, accessed February 27, 2025, https://www.nasa.gov/humans-in-space/commercial-space/commercial-crew-program/commercial-crew-program-overview/; NASA, "Commercial Crew Program Essentials."

[37] "What Is CAPSTONE?," NASA, last modified February 7, 2025, www.nasa.gov/smallspacecraft/capstone/.

[38] "Commercial Lunar Payload Services," NASA, last modified June 15, 2023, www.nasa.gov/reference/commercial-lunar-payload-services/; "Commercial Lunar Payload Services (CLPS) Deliveries," NASA, accessed February 27, 2025, https://science.nasa.gov/lunar-science/clps-deliveries/.

[39] "Mission to Mars," Impulse Space, accessed February 27, 2025, www.impulsespace.com/mars; Jonathan O'Callaghan, "The First Private Mission to Venus Will Have Just Five Minutes to Hunt for Life," *MIT Technology Review*, August 29, 2022, www.technologyreview.com/2022/08/29/1058724/the-first-private-mission-to-venus-will-have-just-five-minutes-to-hunt-for-life/. A privately funded mission to Venus, in cooperation with MIT and Rocket Lab, estimated for launch in 2024 is now looking at a 2026 launch date. See: Jeff Foust, "Rocket Lab Plans Launch of Venus Mission as Soon as Late 2024,"*SpaceNews*, October 30, 2023, https://spacenews.com/rocket-lab-plans-late-2024-launch-of-venus-mission/.

[40] Eric Berger, "For the First Time NASA Has Asked Industry About Private Missions to Mars," *Ars Technica*, February 1, 2024, https://arstechnica.com/space/2024/02/for-the-first-time-nasa-has-asked-industry-about-private-missions-to-mars/; Abbey A. Donaldson, "NASA Sets Path to Return Mars Samples, Seeks Innovative Designs," NASA, April 15, 2024, www.nasa.gov/news-release/nasa-sets-path-to-return-mars-samples-seeks-innovative-designs/.

[41] Or divisions of those prime contractors.

[42] In-space refueling, in-space servicing, and in-space assembly and manufacturing are together referred to as ISAM. See: "In-Space Servicing, Assembly, and Manufacturing (ISAM)," NASA, accessed February 27, 2025, www.nasa.gov/nexis/isam/.

[43] "China Debuts New Space Capabilities," TRADOC G2, December 15, 2022, https://oe.tradoc.army.mil/2022/12/15/china-debuts-new-space-capabilities/;
Andrew Jones, "China's Shijian-21 Towed Dead Satellite to a High Graveyard Orbit," *SpaceNews*, February 22, 2023, https://spacenews.com/chinas-shijian-21-spacecraft-docked-with-and-towed-a-dead-satellite/; State Council of the People's Republic of China, "China Launches Shijian-21 Satellite," October 24, 2021, archived at the Wayback Machine, October 24, 2021, https://web.archive.org/web/20211024145321/http://english.www.gov.cn/news/topnews/202110/24/content_WS6174f654c6d0df57f98e3bd0.html.

[44] Simplified, RPO is the ability to approach and navigate around objects in space. The Gemini missions of the 1960s tested the ability to approach and maneuver around other spacecraft, while the Apollo missions depended on it. The mid-to-late 1990s saw crewed RPO and docking hit their stride with regular Space Shuttle station dockings. Because humans can compensate for hardware and software limitations, uncrewed missions had to wait for technology to catch up, and so have a shorter heritage (there are some exceptions where uncrewed vehicles docked with uncrewed but human-rated vehicles). The *XSS-11*, DART, and Orbital Express missions in the mid-2000s demonstrated autonomous RPO. Orbital Express also accomplished the easy sounding but difficult to do transfer of fuel between spacecraft.
See: “Gemini 4,” NASA, accessed February 27, 2025, https://nssdc.gsfc.nasa.gov/nmc/spacecraft/display.action?id=1965-043A; “Shuttle Mir,” NASA, accessed February 27, 2025, www.nasa.gov/space-shuttle/shuttle-mir/; NASA, “This Week in NASA History: Discovery Becomes First Space Shuttle to Dock with International Space Station — May 29, 1999,” NASA, June 1, 2016, www.nasa.gov/image-article/this-week-nasa-history-discovery-becomes-first-space-shuttle-dock-with-international-space-station-may-29-1999/. Also note that this DART mission is not the one from 2022 that impacted an asteroid. Space Vehicles Directorate, “XSS-11 Micro Satellite” (fact sheet), Air Force Research Laboratory, September 2011, https://www.kirtland.af.mil/Portals/52/documents/AFD-111103-035.pdf?ver=2016-06-28-110256-797; “DART: Rendezvous,” eoPortal, last modified May 26, 2012, www.eoportal.org/satellite-missions/dart-rendezvous#eop-quick-facts-section; Boeing, “Boeing Orbital Express Conducts First Autonomous Spacecraft-to-Spacecraft Fluid and Component Transfer,” news release, April 17, 2007, https://boeing.mediaroom.com/2007-04-17-Boeing-Orbital-Express-Conducts-First-Autonomous-Spacecraft-to-Spacecraft-Fluid-and-Component-Transfer.

[45] Matt Sheehan, Marjory Blumenthal, and Michael R. Nelson, “Three Takeaways from China’s New Standards Strategy,” Carnegie Endowment for International Peace, October 28, 2021, https://carnegieendowment.org/2021/10/28/three-takeaways-from-china-s-new-standards-strategy-pub-85678.

[46] For example: A DARPA project, the Robotic Servicing of Geosynchronous Satellites program, is set to demonstrate servicing capabilities at high orbits. Other programs have had mixed results. Congress provided $227 million annually from 2021 to 2023 for a now-canceled NASA refueling and servicing mission. More successfully, defense prime Northrop Grumman sold Mission Extension Vehicle services in geosynchronous earth orbit. These vehicles extend the life of satellites low on fuel, attaching like a “jetpack” to extend operations. The approach isn’t as complex or intrusive to the host as a fuel transfer, but it represents an entry into a nascent servicing market. See: Stephen Forbes, “RSGS: Robotic Servicing of Geosynchronous Satellites,” DARPA, accessed February 27, 2025, www.darpa.mil/program/robotic-servicing-of-geosynchronous-satellites; Sandra Erwin, “DARPA’s Robot Could Start Servicing Satellites in 2025,” *SpaceNews*, February 2, 2023, https://spacenews.com/darpas-robot-could-start-servicing-satellites-in-2025/; Consolidated Appropriations Act, Pub. L. No. 116-260 (2021), https://www.congress.gov/117/plaws/publ328/PLAW-117publ328.pdf; Consolidated Appropriations Act, Pub. L. No. 117-103 (2022), www.govinfo.gov/app/details/PLAW-117publ103; Consolidated Appropriations Act, Pub. L. No. 117-328 (2023), www.govinfo.gov/app/details/PLAW-117publ328; Jeff Foust, “NASA Cancels OSAM-1 Satellite Servicing Technology Mission,” *SpaceNews*, March 1, 2024, https://spacenews.com/nasa-

cancels-osam-1-satellite-servicing-technology-mission/; Intelsat, "Northrop Grumman and Intelsat Make History with Docking of Second Mission Extension Vehicle to Extend Life of Satellite," news release, April 12, 2021, https://www.intelsat.com/newsroom/northrop-grumman-and-intelsat-make-history-with-docking-of-second-mission-extension-vehicle-to-extend-life-of-satellite/; Mark Holmes, "Satellite Servicing Becomes an Actual Market," *Via Satellite*, February 14, 2019, https://interactive.satellitetoday.com/satellite-servicing-becomes-an-actual-market/.

[47] National Space Policy, 85 Fed. Reg. 81769, December 16, 2020, www.govinfo.gov/content/pkg/FR-2020-12-16/pdf/2020-27892.pdf; Orbital Debris Interagency Working Group and National Science and Technology Council, *National Orbital Debris Implementation Plan* (Washington, D.C.: Executive Office of the President, July 2022), https://bidenwhitehouse.archives.gov/wp-content/uploads/2022/07/07-2022-NATIONAL-ORBITAL-DEBRIS-IMPLEMENTATION-PLAN.pdf.

[48] Thomas J. Colvin, John Karcz, and Grace Wusk, *Cost and Benefit Analysis of Orbital Debris Remediation* (Washington, D.C.: NASA, March 10, 2023), www.nasa.gov/wp-content/uploads/2023/03/otps_-_cost_and_benefit_analysis_of_orbital_debris_remediation_-_final.pdf.

[49] Roxana Bardan, "NASA Creates In-Space Servicing, Assembly, Manufacturing Consortium," NASA, April 19, 2023, https://www.nasa.gov/news-release/nasa-creates-in-space-servicing-assembly-manufacturing-consortium/.

[50] U.S. Senate Committee on Commerce, Science, & Transportation, "Cantwell, Hickenlooper Bill to Clean Up Space Junk Passes Senate Unanimously," news release, November 1, 2023, www.commerce.senate.gov/2023/11/cantwell-hickenlooper-bill-to-clean-up-space-junk-passes-senate-unanimously; ORBITS Act of 2023, S. 447, 118th Cong. (2023), www.congress.gov/bill/118th-congress/senate-bill/447. Fundamentally, the technology exists to remove debris, but unless and until a government demonstrates a willingness to fund this service, or a company identifies a way to profitably "mine" the material, it can be expected to remain a niche capability.

[51] Astroscale, "Astroscale on Course for First UK National Mission to Remove Space Debris," news release, March 7, 2023, https://astroscale.com/astroscale-on-course-for-first-uk-national-mission-to-remove-space-debris/; "CRD2: Commercial Removal of Debris Demonstration," Research and Development Directorate, JAXA Japan, accessed February 27, 2025, www.kenkai.jaxa.jp/eng/crd2/index.html; Astroscale, "Astroscale's Elsa-D Successfully Demonstrates Repeated Magnetic Capture," news release, February 26, 2023, https://astroscale.com/astroscales-elsa-d-successfully-demonstrates-repeated-magnetic-capture/.

[52] Stephen Clark, "Before Snagging a Chunk of Space Junk, Astroscale Must First Catch Up to One," *Ars Technica*, February 20, 2024, https://arstechnica.com/space/2024/02/before-snagging-a-chunk-of-space-junk-astroscale-must-first-catch-up-to-one/; Mike Wall, "Wow! Private Space-Junk Probe Snaps Historic Photo of Discarded Rocket in Orbit," Space.com, April 26, 2024, www.space.com/astroscale-adras-j-space-junk-rendezvous-mission-photo; Astroscale, "Astroscale Unveils World's First Image of Space Debris Captured through Rendezvous and Proximity Operations," news release, April 26, 2024,

https://astroscale.com/astroscale-unveils-worlds-first-image-of-space-debris-captured-through-rendezvous-and-proximity-operations/.

[53] Clark, "Before Snagging a Chunk of Space Junk."

[54] Matthew Sparkes, "Starship Launch: Third Flight Reaches Space but Is Lost on Re-Entry," *New Scientist*, March 20, 2024, www.newscientist.com/article/2422279-starship-launch-third-flight-reaches-space-but-is-lost-on-re-entry/.

[55] See also: Table A2 in Appendix 2.

[56] Michael O'Connor and Kathleen Curlee, "Eyes Wide Open" (Washington, D.C.: CSET, June 2024), https://cset.georgetown.edu/publication/eyes-wide-open-harnessing-the-remote-sensing-and-data-analysis-industries-to-enhance-national-security/; O'Connor Curlee, "Shaping the U.S. Space Launch Market,"

[57] Early successful demonstrations include Northrop Grumman's Mission Extension Vehicles described in endnote 46**.**

[58] When manufacture is for use in orbit or on the surface of other celestial bodies, it's often grouped with in-space servicing and assembly into ISAM. See: NASA, "In-Space Servicing, Assembly, and Manufacturing (ISAM)."

[59] "In Space Production Applications (InSPA)," NASA, accessed February 27, 2025, www.nasa.gov/international-space-station/space-station-research-and-technology/in-space-production-applications/.

[60] "In-Space Production Applications: Crystal Growth," ISS National Laboratory, accessed February 27, 2025, www.issnationallab.org/ispa-crystal-growth/; Debbie Senesky, "What It Takes to Grow Crystals in Space," *Scientific American*, November 1, 2023, www.scientificamerican.com/article/what-it-takes-to-grow-crystals-in-space/.

[61] ISS National Laboratory, "In-Space Production Applications: Crystal Growth."

[62] Semiconductors are also crystalline, though the massive scale of Earth-bound factories make it difficult for space-based fabrication to compete in the market. Nevertheless, semiconductor supply chains or specific chip types may benefit from orbital fabrication. See: Jessica Frick et al., "Semiconductor Manufacturing in Low-Earth Orbit for Terrestrial Use," OSFPreprints, November 8, 2023, https://doi.org/10.31219/osf.io/d6ar4; Jonathan O'Callaghan, "What Goes Up…" *Aerospace America*, July/August 2022, https://aerospaceamerica.aiaa.org/features/what-goes-up/.

[63] For example, a commercial reentry capsule from Varda had a landing ellipse of 22 x 28 miles. See: Federal Aviation Administration, *Final Environmental Assessment for Reentry, Landing, and Recovery Operations of a Varda Space Industries Capsule within Utah Test and Training Range (UTTR) South or Northern Dugway Proving Ground (DPG), Utah* (Washington, D.C.: Federal Aviation Administration, February 2024), 2-5, www.faa.gov/sites/faa.gov/files/20240214-Varda-at-UTTR-Reentry-Final-EA.pdf.

[64] Stefanie Waldek, "'Them Space Drugs Cooked Real Good:' Varda Space Just Made an HIV Medicine in Earth Orbit," Space.com, March 29, 2024, www.space.com/varda-space-microgravity-pharmaceutical-production-success; Haley C. Bauser, et al., "Return of the Ritonavir: A Study on the Stability of Pharmaceuticals Processed in Orbit and Returned to Earth," ChemRXiv, March 21, 2024, https://chemrxiv.org/engage/chemrxiv/article-details/65faecbee9ebbb4db91b4ac1.

[65] "New Space" refers broadly to companies with low-cost, space-related products and services to meet commercial needs, not just traditional government requirements. Gary Martin, *NewSpace: The Emerging Commercial Space Industry*, ISU MSS 2017 (Moffett Field, CA: NASA Ames Research Center, 2017), https://ntrs.nasa.gov/api/citations/20170001766/downloads/20170001766.pdf; Erik Kulu, *NewSpace Index*, accessed February 27, 2025, www.newspace.im/.

[66] The trends in PitchBook were similar to those found using a keyword search of a different commercial database, Crunchbase. Furthermore, other researchers have found similar trends in other parts of the commercial space economy.

[67] Three companies hold both tags.

[68] This category combines companies the authors identified as developing capabilities for or performing in-space SSA, debris remediation, in-space servicing/ISAM, and in-space transport.

[69] Crunchbase; other companies in the space (e.g., ExoAnalytic, https://exoanalytic.com/) are not listed in PitchBook's space technology vertical.

[70] "Research Opportunities," DARA, accessed February 27, 2025, www.darpa.mil/work-with-us/opportunities.

[71] O'Connor and Curlee, "Shaping the U.S. Space Launch Market."

[72] O'Connor and Curlee, "Eyes Wide Open."

[73] Another 26 were lost when an Antares rocket failed during an ISS resupply mission. Gunter D. Krebs, "Orbital Launches of 2014," *Gunter's Space Page*, accessed April 23, 2024, https://space.skyrocket.de/doc_chr/lau2014.htm.

[74] Michael Sheetz, "NASA Wants Companies to Develop and Build New Space Stations, with up to $400 Million up for Grabs," CNBC, March 27, 2021, www.cnbc.com/2021/03/27/nasa-commercial-leo-destinations-project-for-private-space-stations.html.

[75] "Commercial Destinations in Low Earth Orbit," NASA, accessed February 27, 2025, www.nasa.gov/humans-in-space/commercial-space/low-earth-orbit-economy/commercial-destinations-in-low-earth-orbit/.

[76] *FY 2021 Budget Estimates* (Washington, D.C.: NASA, 2020), www.nasa.gov/wp-content/uploads/2021/04/fy_2021_budget_book_508.pdf?emrc=664dff36cb2be; *FY 2022 Budget*

Estimates (Washington, D.C.: NASA, 2021), www.nasa.gov/wp-content/uploads/2015/01/fy2022_congressional_justification_nasa_budget_request.pdf?emrc=664e01f8b865b. The ISS science budget is only about $400 million (FY21) out of the more than $3 billion for ISS-related operations. That budget, of course, should remain and expand should cost efficiencies be gained via the Commercial LEO Destinations effort.

[77] Alternatively, it's about the size of a nine-volt battery, but lighter. Laura Ost, "Success Story: Chip-Scale Atomic Clock," National Institute of Standards and Technology, December 2, 2020, www.nist.gov/noac/success-story-chip-scale-atomic-clock; Eric Long, "Experimental Chip-Size Atomic Clock: Time and Navigation," Smithsonian Time and Navigation, 2012, https://timeandnavigation.si.edu/multimedia-asset/experimental-chip-size-atomic-clock; DARPA, "DARPA Chip-Scale Atomic Clocks Aboard International Space Station," Phys.org, March 28, 2012, https://phys.org/news/2012-03-darpa-chip-scale-atomic-clocks-aboard.html.

[78] Within a factor of 2–2.5. Tyler Gerald René Reid, "Orbital Diversity for Global Navigation Satellite Systems" (PhD diss., Stanford University, June 2017), https://web.stanford.edu/group/scpnt/gpslab/pubs/theses/TylerReidThesis2017.pdf; Tyler Reid et al., "Navigation from Low Earth Orbit" (Stanford University GPS Lab, April 26, 2016), http://web.stanford.edu/group/scpnt/gpslab/website_files/LEO_sat_nav/aiaa_affiliates_meeting_2016_tyler_reid.pdf.

[79] Here, the coverage of the PitchBook data does pose challenges. Since it doesn't provide 100 percent coverage of space companies, and the PNT market is likely small given the existence of a free government-provided GPS signal, it is hard to draw trends. Additionally, while GPS is clearly space based, many GPS alternatives may not be. See: Sandra Erwin, "No GPS? No Problem, There Are Increasingly More Options," *SpaceNews*, January 23, 2023, https://spacenews.com/no-gps-no-problem-there-are-increasingly-more-options/; Michelle Hampson, "Building an Alternative to GPS," *IEEE Spectrum*, October 5, 2021, https://spectrum.ieee.org/an-alternative-to-gps; Xona Space Systems, "Xona Passes Critical Testing Milestone," news release, May 10, 2022, www.xonaspace.com/xonapassescriticaltestingmilestone; Xona Space Systems, "International Committee on GNSS, Workshop on Low Earth Orbit (LEO) PNT Systems" (Burlingame, CA: Xona Space Systems, June 2023), www.unoosa.org/documents/pdf/icg/2023/ICG_WG-S_LEO-PNT_Workshop_June_2023/ICG_LEO-PNT_Workshop_2023_04.pdf.

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

[81] "Space Domain Awareness: Sapphire Mission," MDA Space, accessed February 27, 2025, https://mda.space/earth-and-space-observation; "Geosynchronous Space Situational Awareness Program," Space Force, accessed February 27, 2025, www.spaceforce.mil/About-Us/Fact-Sheets/Article/2197772/geosynchronous-space-situational-awareness-program/; "Space Based Space Surveillance," Space Operations Command, Space Force, accessed February 27, 2025,

www.spoc.spaceforce.mil/About-Us/Fact-Sheets/Display/Article/2381700/space-based-space-surveillance.

[82] "Non-Earth Imaging," Maxar, accessed February 27, 2025, www.maxar.com/maxar-intelligence/products/non-earth-imaging; Maxar, "Maxar Secures NOAA Approval to Provide Non-Earth Imaging Services to Government and Commercial Customers," news release, December 5, 2022, www.maxar.com/press-releases/maxar-secures-noaa-approval-to-provide-non-earth-imaging-services-to-government-and-commercial-customers.

[83] For example, the Bigelow Expandable Activity Module: NASA, "Engineering Services for the Bigelow Expandable Activity Module (BEAM)," SAM.gov, December 10, 2021, https://sam.gov/opp/220ac7db7bef4b4085636f3cd65dc5c2/view. Bigelow is effectively defunct but provided the only inflatable module on the ISS. See: Jeff Foust, "Bigelow Aerospace Lays Off Entire Workforce," *SpaceNews*, March 23, 2020, https://spacenews.com/bigelow-aerospace-lays-off-entire-workforce/.

[84] Jeff Foust, "Astroscale's Adras-J Mission Enters Next Phase," *SpaceNews*, April 12, 2024, https://spacenews.com/astroscales-adras-j-mission-enters-next-phase/; UK Space Agency, "UK Builds Leadership in Space Debris Removal and In-Orbit Manufacturing with National Mission and Funding Boost," news release, September 26, 2022, www.gov.uk/government/news/uk-builds-leadership-in-space-debris-removal-and-in-orbit-manufacturing-with-national-mission-and-funding-boost.

[85] "About Astroscale," Astroscale, accessed February 27, 2025, https://astroscale.com/about-astroscale/about/.

[86] Office of Space Commerce and Office of Commercial Space Transportation, U.S. *Export Controls for the Commercial Space Industry* (Washington, D.C.: Department of Commerce and Federal Aviation Administration, November 2017), www.faa.gov/about/office_org/headquarters_offices/ast/media/export_controls_guidebook_for_commercial_space_industry_doc_faa_nov_508.pdf; The United States Munitions List, Code of Federal Regulations, 22 C.F.R. 121.1 (2012), www.govinfo.gov/app/details/CFR-2012-title22-vol1/CFR-2012-title22-vol1-sec121-1.

[87] Bureau of Industry and Security, "Commerce Significantly Streamlines Export Controls for Australia and the United Kingdom Advances Goals of the AUKUS Enhanced Trilateral Security Partnership: Bureau of Industry and Security," news release, April 18, 2024, www.bis.gov/press-release/commerce-significantly-streamlines-export-controls-australia-and-united-kingdom.

[88] In some very dense cities, space-based solutions might not be ideal for self-driving vehicles, given multipath challenges, and different approaches might be more reliable. However, those same solutions may not work in more rural areas where farming can also benefit from better navigation. Again, however, there *may* be simpler solutions than new satellite constellations. Nevertheless, this is likely partially a data problem, as our research has shown a small number of companies pursuing space-based PNT that are not included in the PitchBook dataset.

[89] Thomas G. Roberts and Todd Harrison, "History of the NASA Budget," Aerospace Security Project, CSIS, September 1, 2022, https://aerospace.csis.org/data/history-nasa-budget-csis/; "Your Guide to NASA's Budget," Planetary Society, accessed February 27, 2025, www.planetary.org/space-policy/nasa-budget;
[90] Lee Mohon, "Work Underway on Large Cargo Landers for NASA's Artemis Moon Missions," NASA, April 19, 2024, www.nasa.gov/directorates/esdmd/artemis-campaign-development-division/human-landing-system-program/work-underway-on-large-cargo-landers-for-nasas-artemis-moon-missions/.
[91] Abbey A. Donaldson, "NASA Exploring Alternative Mars Sample Return Methods," NASA, October 8, 2024, www.nasa.gov/news-release/nasa-exploring-alternative-mars-sample-return-methods/.

[92] Astroscale, "About."

[93] U.S. Space Command, *USSPACECOM: From the Ultimate High Ground to the Last Tactical Mile* (Peterson Space Force Base, CO: U.S. Space Command, 2023), 14–17, https://media.defense.gov/2023/Apr/14/2003199875/-1/-1/1/2023%20USSPACECOM%20MAGAZINE.PDF.

[94] Marisa Torrieri, "How Satellite Imagery Magnified Ukraine to the World," *Via Satellite*, October 24, 2022, https://interactive.satellitetoday.com/via/november-2022/how-satellite-imagery-magnified-ukraine-to-the-world/.

[95] Care does need to be taken to avoid macroeconomic mistakes of the past, like the government-driven structural unprofitability of early aircraft acquisitions: Madeline Zimmerman, "America's First Dual-Use Technology," *Kinetic Reviews*, February 21, 2024, https://kinetic.reviews/p/americas-first-dual-use-technology?utm_source=profile&utm_medium=reader2.

[96] Few program managers and senior leaders want to be saddled with public failures like those associated with some early clean energy loans (e.g., Solyndra). See: Mark Paul and Nina Eichacker, "Why We Should Be Funding More Solyndras," *MIT Technology Review*, November 19, 2020, https://www.technologyreview.com/2020/11/19/1012302/solyndra-climate-change-industrial-policy-opinion/; Katie Fehrenbacher, "Why the Solyndra Mistake Is Still Important to Remember," *Fortune*, August 27, 2015, https://fortune.com/2015/08/27/remember-solyndra-mistake/.

[97] Ian Thornton, Paul Wilson, and Gian Gandhi, "'No Regrets' Purchasing in a Pandemic: Making the Most of Advance Purchase Agreements," *Globalization and Health* 18 (2022), https://globalizationandhealth.biomedcentral.com/articles/10.1186/s12992-022-00851-3; Rachel Jewett, "NRO Awards 5 Contracts for Commercial Electro-Optical Imagery," *Via Satellite*, December 6, 2023, www.satellitetoday.com/government-military/2023/12/06/nro-awards-5-contracts-for-commercial-electro-optical-imagery/.

[98] DOD, "AUKUS Defense Ministers' Joint Statement," news release, April 8, 2024, www.defense.gov/News/Releases/Release/Article/3733790/aukus-defense-ministers-joint-statement/.

[99] Partly related to expertise in carbon composite manufacturing. See: Ashlee Vance, *When the Heavens Went on Sale: The Misfits and Geniuses Racing to Put Space within Reach* (New York: Ecco, 2023);

"Position Statement- Australian Space Industry," Australian Academy of Science, accessed April 22, 2024, www.science.org.au/supporting-science/science-policy/position-statements/statement-space-industry.

[100] Barry Blechman and Jonas Vaicikonis, "Unblocking the Road to Zero: US-Russian Cooperation on Missile Defenses," *Bulletin of the Atomic Scientists* 66, no. 6 (November 2010): 25–35, https://doi.org/10.1177/0096340210387041.

[101] Rutger Daems and Edith Maes, "The Race for Covid-19 Vaccines: Accelerating Innovation, Fair Allocation and Distribution," *Vaccines* 10, no. 9 (September 2, 2022): 1450, https://doi.org/10.3390/vaccines10091450.

[102] The "space technology" vertical was used by our team to generate candidate companies prior to manual review. The use of labeled verticals improves comparisons between industries over other methods. See: PitchBook, "What Are Industry Verticals."

[103] E.g., Erik Kulu, "Satellite Constellations," *NewSpace Index*, accessed February 27, 2025, www.newspace.im/; Erik Kulu, "Nanosats," Nanosats Database, accessed February 27, 2025, www.nanosats.eu/.