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A Report on Ten Key Technologies and Their Policy Implications

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SPACE

KEY TAKEAWAYS

- A burgeoning "NewSpace" economy driven by private innovation and investment is transforming space launch, in-space logistics, communications, and key space actors in a domain that until now has been dominated by superpower governments.
- Space is a finite planetary resource. Because of dramatic increases in satellites, debris, and geopolitical space competition, new technologies and new international policy frameworks will be needed to manage the traffic of vehicles, prevent international conflict in space, and ensure responsible stewardship of this global commons.
- The Trump administration has shifted priorities heavily toward human exploration of the Moon and Mars. This is at the expense of robotic exploration, space science, and aeronautics missions, leading to significant planned budget and personnel cuts to NASA. This trend may risk the long-term superiority of the United States in the global race for talent and technology.

Overview

Sputnik 1 was the world's first artificial satellite, a technology demonstration placed into orbit by the Soviet Union in 1957. Sixty-nine years later, humankind operates many thousands of satellites to provide communications, navigation, and Earth observation imagery relied upon in many walks of life. A substantial amount of scientific discovery is also made possible with space-borne instrumentation. Additionally, space operations support military forces on Earth, and thus space itself is a domain in which international conflict and competition play out.

Today, the global space economy is growing at about 7 percent per annum.[1] Valued at $600 billion in 2024, it is forecast to potentially reach $1.8 trillion by 2035.[2] This growth is driven by space-based technologies and their impacts on various industries, including defense, transportation, and consumer goods. One distinctive feature of the space industry is the predominance of government investment, which totaled $135 billion globally in 2024, more than $75 billion of which came from the United States.[3] While ownership of space assets is gradually shifting from governments to private providers, private-sector investment has declined for three consecutive years—from its all-time high of $18 billion in 2021 to $5.9 billion in 2024—reflecting ongoing challenges in commercialization and intensifying global competition.[4] The number of satellites launched per year has grown at a cumulative annual rate of over 50 percent from 2019 to 2024, supported by an increase in global rocket launches (271 in 2024[5]).

At its core, a space mission includes four components:

- The mission objectives, which can be scientific, commercial, military, or a combination thereof
- A space segment, which includes the spacecraft and the orbits that have been selected to accomplish the mission objectives
- A ground segment, which includes the rocket launcher, ground stations, and mission control centers
- A user segment, which includes all the users and stakeholders of the space mission

Space systems can be categorized in various ways. One such sorting factor is whether they are crewed or uncrewed. The International Space Station (ISS) is currently the nexus for spaceflight; since 2011, US-crewed access to the ISS has been via rockets operated by Russia—and more recently through vehicles provided by SpaceX and Boeing. In the future, the NASA-operated Artemis program plans to launch its first crewed mission, a Moon flyby, in early 2026, followed by a Moon landing in 2027 or 2028. Uncrewed systems include those for Earth and planetary remote sensing (such as Planet Labs' Dove satellites); communication and navigation (such as the United States' Global Positioning System, or GPS, satellites); astronomy and astrophysics (such as the James Webb Space

FIGURE 10.1 Fires and damage at Antonov Airport in Ukraine, as seen from a commercial satellite constellation

Source: © 2022 Maxar Technologies

Telescope); space logistics and in-space assembly and manufacturing (such as Northrop Grumman's Mission Extension Vehicles, or MEVs); and planetary exploration (such as the Mars Perseverance rover).

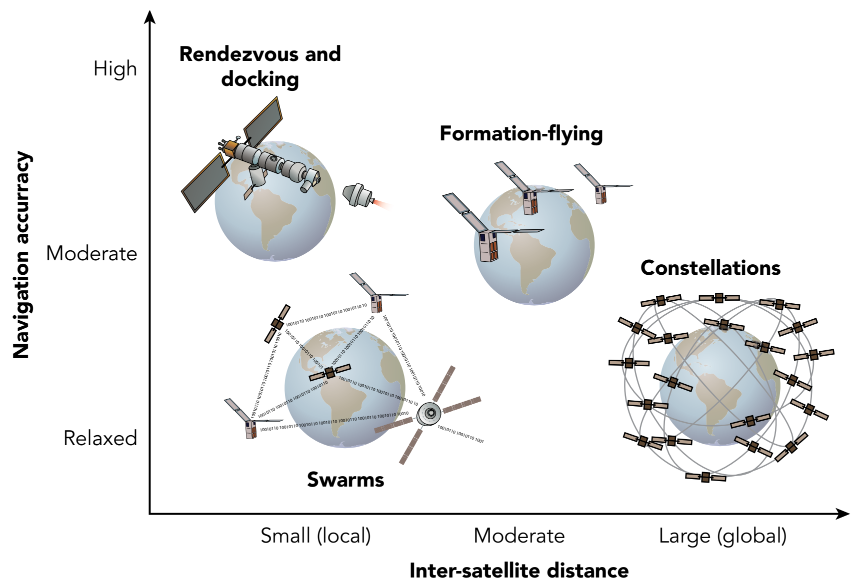
Space systems can also be characterized by size. Very large structures include the ISS, whose mass is 420 tons, and proposed future space stations that are part of the NASA-funded Commercial LEO Destinations (CLD) program, such as Orbital Reef (Blue Origin), and Starlab (Starlab Space, a joint venture of Voyager Space and Airbus). Vastly smaller satellites, called smallsats, weigh under 500 kilograms (kg).[6] CubeSats are the most popular smallsat format, with each CubeSat unit measuring 10 by 10 by 10 centimeters (cm) and with a mass of 1.33 kg (a couple of pounds). They can also be combined to build larger satellites. CubeSats support a growing commercial market, providing communications, Earth imagery, and other capabilities. Today, a large majority of functional satellites weigh between 100 and 1,000 kg.

Another classification of space systems reflects their trajectories. For example, objects in orbit around Earth can be in low Earth orbit (LEO), which is less than 1,000 kilometers (km) in altitude; medium Earth orbit (MEO), which is between 1,000 and 35,000 km in altitude; high elliptical orbit; and geosynchronous orbit (GEO), with an orbit period equivalent to one Earth day. The image in figure 10.1 was obtained by a Maxar Technologies commercial satellite in LEO.

A further categorization of space systems focuses on their composition. Distributed space systems, comprising multiple interacting spacecraft, can achieve objectives that are difficult or impossible for a single spacecraft. These systems take various architectural forms (see figure 10.2), defined by parameters like inter-spacecraft distances, required navigational accuracy, and number of satellites. They contrast with traditional single-spacecraft systems and offer expanded capabilities in space operations. Different compositions of space systems include the following:

- Constellations separated by tens of thousands of kilometers so that they may provide global

FIGURE 10.2 Characterizing distributed space systems



Source: Adapted from a diagram by Simone D'Amico

FIGURE 10.3 An artist's conception of the NASA Starling satellite swarm in space

Source: NASA / Blue Canyon Technologies

coverage for navigation, communications, and remote sensing services.

- Rendezvous and docking to support crew transportation, removal of space debris from orbit, in-orbit servicing of satellites, and assembly of larger structures in space. This involves small separations and high positional accuracy.

- Formation-flying architectures for observational missions that call for large effective apertures, such as space-based telescopes whose optical components are controlled very precisely at separations of tens to hundreds of meters.

- Swarms that cooperatively sense the environment or share resources such as power, computation, and communications but whose components do not necessarily need to be at fixed distances from one another (see figure 10.3).

Key Developments

Impacts of Space Technologies

Space technologies have proven their value to the national interest. Some of the most important applications today include the following:

Navigation This includes positioning, navigation, and timing (PNT) services around the world and in space. GPS and similar services operated by other nations help people know their position and velocity, whether on land, on the ocean surface, in the air, or in space. Less well known is the timing information that GPS provides—timing that is accurate to the nanosecond available anywhere in the world. This is a key tool for the financial sector, electric power grid, and transportation. Companies such as Xona Space

Systems, a start-up founded by Stanford alumni, have begun developing GPS alternatives that aim to deliver even greater precision and robustness. More recently, driven by the explosion in the number of satellites and other spacecraft in orbit, interest has been growing quickly in characterizing and managing in-space objects.

Communications Satellites provide vital communications in remote areas and for mobile users, complementing the terrestrial networks that carry most long-haul communications. Companies like SpaceX's Starlink, Amazon's Project Kuiper, Eutelsat OneWeb, and Astranis aim to offer low-latency, wide-coverage satellite internet. Recent innovations include optical communication systems, which use light for higher bandwidth and security. Vertical integration across orbital, aerial, marine, and ground segments will be a key asset for future communication infrastructure. Several start-ups, such as Aalyria and SpiderOak, are also developing technologies for the orchestration of different networks to ensure robust and secure communications.

Remote sensing Remote sensing satellites, with their unique vantage point and sophisticated sensors, can rapidly gather extensive data about areas and objects of interest. These data are then integrated and used to train artificial intelligence (AI) models to create a "digital twin" of Earth, enhancing prediction and simulation of terrestrial phenomena and responses to them. Applications include disaster response, environmental monitoring, topographical mapping, and geospatial intelligence tracking human, animal, and marine activity. Governments are expanding remote sensing programs, complemented by commercial companies like BlackSky, Maxar, Planet Labs, Spire Global, and ICEYE. Recent efforts have focused on increasing data resolution, reducing response times, and exploring other valuable information modes such as hyperspectral imaging,[7] synthetic aperture radar,[8] and radio-frequency sounding (exploration of the environment through the use and exploitation of radio waves).[9]

Scientific research Space-based astronomy and exploration provide in-depth insights into the origins of planets, stars, galaxies, and life on Earth. The past few years have seen significant strides in solar system exploration, particularly involving asteroids. NASA's OSIRIS-REx mission successfully returned asteroid samples to Earth in September 2023, while the NASA Psyche mission was launched in October 2023 and is en route to examine at close range a metal-rich asteroid worth potentially quadrillions of dollars.

Space transportation The space transportation industry has seen launch costs drop by more than an order of magnitude over a couple of decades to $1,500 per kilogram in 2021.[10] Companies like SpaceX, Rocket Lab, Blue Origin, Stoke Space, and Virgin Galactic have made progress in providing reliable launches and developing new vehicles. SpaceX's Starship—the most powerful rocket ever built (see figure 10.4)—could dramatically reduce the cost of achieving LEO, aspirationally making this between 10 and 100 times cheaper than today.[11] Also, in January 2025, Blue Origin launched its reusable high-volume, heavy-lift New Glenn rocket, which successfully deployed a prototype of its Blue Ring platform in MEO.[12] (Blue Ring can serve as a satellite support platform and a space tug that transfers cargo between different orbits.) While SpaceX currently dominates the space launch sector, overreliance on a single company could prove risky for the US government, especially given the multiple failed test launches of Starship in 2025.

Meanwhile, Blue Origin, Voyager Space, Axiom Space, and Vast are developing commercial space stations to replace the ISS, which NASA plans to decommission in 2030. These new stations aim to ensure continued orbital research and expand human presence in space.

National security Spacecraft constantly scan Earth for launches of ballistic and hypersonic missiles aimed at the United States or its allies, nuclear weapons tests anywhere in the world, radio traffic and radar

FIGURE 10.4 SpaceX's Starship could dramatically reduce the cost of achieving LEO

Source: SpaceX, CC BY-NC 2.0

signals from other countries, and the movements of allies and enemies in military contexts. A major focus of the Trump administration is the "Golden Dome," a proposed multilayer system partly based in space used for threat monitoring and missile defense.[13] US government investment in space for national security purposes continues to grow, including new commercial partnerships focused on data sharing for tracking objects in space and on Earth, satellite internet for battlefield communications, and in-space logistics (inspection and servicing) to maintain space superiority and safety.

Trends in Space Technology

Privatization, miniaturization, and reusability The space sector is shifting from government-owned legacy systems and their long development timelines and mission lifetimes to a "NewSpace" economy driven by private companies. This privatization makes space technologies more accessible and less expensive. CubeSats and reusable rockets like SpaceX's Falcon 9 exemplify private-sector innovations enabling new opportunities. Governments are also embracing small spacecraft and on-demand launches to expand space capabilities cost-effectively. The combination of smallsats and distributed architecture (e.g., constellations) offers advantages in reduced costs, faster development timelines, frequent technology updates, and improved resilience, flexibility, and performance.

However, the private sector's rapidly increasing role in space also presents new challenges. These include dealing with risks inherent in dual-use space technologies (for example, adversaries could use technology that was designed for removing space debris to attack other satellites); managing crises in a realm where lines separating individual private actors, the space sector as a whole, and government actors are increasingly blurred; differentiating between accidents and malevolent actions; and relying on companies whose interests may not be fully aligned with those of the US government.

The Moon rush Recent years have seen a renewed desire to maintain a permanent human presence in lunar orbit and on the lunar surface. The abundance of certain materials on the Moon provides opportunities for mining and manufacturing, known as in-situ resource utilization. Such activities would reduce the amounts of material that would otherwise have to be transported from Earth. Combined with the significantly lower amount of fuel needed to launch from the Moon rather than from Earth, moon mining and manufacturing facilitates the construction of moon bases, the conduct of space exploration missions, and even launches into LEO that could be undertaken with hardware manufactured with materials from the Moon.

There have been a number of successful lunar landings recently from both the commercial and the civil sectors, including the United States, China, India, and Japan.[14] The NASA-led Artemis program is developing a new launch system, lunar-orbiting space station, lunar base camp, and lunar terrain vehicles, among other things, as steps needed for establishing a permanent human presence on the Moon.[15]

Over the Horizon

Advances in Small Satellite Technology

NASA has identified a list of issues that are restraining growth in usage of small spacecraft.[16] They include limitations in launch capacity, autonomous capabilities, PNT capabilities, and propulsion systems. The past year has seen several mission failures due to these and other shortfalls.

NASA is responding to these challenges via technology demonstration missions such as Starling, which, in 2024, became the first successful in-orbit example of several critical autonomous swarming technologies.[17] Among Starling's payloads is an optical PNT system newly developed by Stanford's Space Rendezvous Laboratory. This applies onboard cameras and advanced algorithms to not only navigate multiple satellites cooperatively, but also to characterize resident space objects (RSO)—any human-made or natural object orbiting Earth—using only visual data. In doing so, it addresses a key technological gap for small spacecraft, which must typically rely on jammable GPS or expensive ground-based resources for navigation. However, more work is needed to take full advantage of smallsat architectures—and, by extension, distributed architectures featuring many smallsats working together.

New Applications of Space Technologies

Manufacturing For certain types of manufacturing, such as specialized pharmaceuticals, optics, and semiconductors, space offers two major advantages over terrestrial manufacturing. Because the vacuum of space is very clean, minimizing contamination is much easier. Further, space's microgravity environment means that phenomena resulting from the effects of gravity—such as sedimentation, buoyancy, thermal convection, and hydrostatic pressure—can be minimized. This enables, for example, the fabrication of more perfect crystals and more perfect shapes. Production processes for biological materials, medicines, metallizations, polymers, semiconductors, and electronics may benefit.

Mining The Moon and asteroids may well have vast storehouses of useful minerals that are hard to find or extract on Earth, such as rare-earth elements used in batteries and catalytic converters as well as in guidance systems and other defense applications. Helium-3 found on the Moon may be an important source of fuel for nuclear fusion reactors. Future space-mining operations could bring these resources back to Earth to meet growing demand in a sustainable way. Mining of regolith (loose rock that sits atop bedrock) and ice on the Moon is also critical for enabling a permanent human presence there and supporting subsequent expansion into the solar system.

Power generation Most orbits are exposed to a constant and intense sunlight, which can be a potential source of clean energy generation. Initial technology demonstrations have been performed in the past two years,[18] and several companies are trying to unlock the potential in this area through two main approaches:

- Solar panels in space that can capture solar energy, convert it to microwaves or laser light, and beam it down to Earth, where dedicated ground stations receive the transmitted energy
- Large mirrors in space that can directly reflect sunlight to existing solar farms on the ground

Both approaches can be advantageous for areas on Earth that cannot easily receive power or fuel supplies or access these around the clock. While this technology is still at a very early stage, interest in it has been growing steadily.

Space situational awareness (SSA) The number of active satellites has increased from roughly 1,000 in 2014 to about 11,000 in 2025—a figure that will likely rise to several tens of thousands in the next decade. In addition, the European Space Agency estimates that about 1.2 million pieces of debris larger than 1 cm in size are in orbit, many of which are dangerous to satellites and space stations.[19] Some potential methods of tracking this ultrasmall debris by leveraging its electrical charge and the plasma environment of space have been proposed.[20]

Traditionally, military organizations such as the North American Aerospace Defense Command and the US Space Force (USSF) were responsible for tracking space objects. However, beginning in fall 2024,[21] the US Department of Commerce's Traffic Coordination System for Space (TraCSS) program began taking over civil and commercial SSA responsibilities from the Department of Defense. TraCSS provides basic SSA data and services to support the safety of civil and private spaceflight operations.[22]

This transition was motivated by the fact that SSA is important to both the civil and commercial sectors and to both national and international actors, not only to the US defense sector. Furthermore, this transition will alleviate the burden on the USSF, allowing it to focus on national security priorities in space. Commercial players will be heavily involved in providing a more accurate and responsive space-traffic management system by improving ground tracking capabilities using radars and telescopes, and deploying satellites and payloads for more timely and responsive on-orbit surveillance.

In-space servicing, assembly, and manufacturing (ISAM) Leadership, security, and sustainability in space require ISAM capabilities to approach, inspect, repair, refuel, or remove space assets without jeopardizing the space environment.[23] Spacecraft autonomy, in combination with rendezvous, proximity operations, and docking (RPOD), is a critical technology for ISAM. RPOD refers to the ability of spacecraft to operate autonomously in combination with the ability to approach one another precisely and conduct close-up operations. Despite significant interest, only a handful of missions have demonstrated early RPOD capabilities in orbit; these include recent successes achieved by Astroscale (using its ADRAS-J smallsat in LEO) and Northrop Grumman (via its larger MEV satellites in GEO).

Exploration A critical limitation for space exploration missions is travel time: Getting to the outer solar system can take ten years or more. As spacecraft fly ever farther from the Sun, they will need novel forms of power, such as sources driven by nuclear reactions, for the propulsive energy needed to make their missions possible.[24] Better propulsion systems that can be quickly deployed will also be needed to intercept interstellar objects so that samples can be collected from them.

On-demand space exploration missions Today, it takes a very long time to prepare for exploration missions, which means that targets of opportunity that suddenly appear cannot be visited by such missions. An on-demand capability would enable the close-up investigation of suddenly appearing targets such as the Oumuamua interstellar object, which passed through the solar system in 2017. Undertaking such a mission requires that a spacecraft can be made ready for launch shortly after the target is identified. Because such targets are likely to originate outside our solar system, the scientific return from bringing back a sample would be enormous.

Policy Issues

Shift in US Executive Branch Priorities

The Trump administration has been reformulating national space priorities. While the current and proposed budgets for the domain aim to bolster human exploration to the Moon and Mars, they have also imposed significant cuts to numerous ongoing and planned scientific missions related to interplanetary exploration, aviation, and space science. These cuts have led to an outflow of talent from NASA, with the loss of four thousand employees (a fifth of the workforce) already.[25] Similar budget cuts have been made to the National Science Foundation, Department of Energy, and other space-adjacent federal agencies. These cuts have a large impact not only on academic research and development, but also on private companies, which receive a large amount of federal funding to serve as contractors for government space programs. These policies may put the United States at a competitive disadvantage relative to China and other global powers.

The Grand Challenge of Sustainability

Sustainability encompasses both terrestrial sustainability enabled by space and the sustainability of humankind's use of space.

- **Sustainability enabled by space** incorporates several of the technologies described above: for example, creating Earth's digital twin for disaster prevention and management, which requires integrating data from industry, government, and academia with advanced machine learning techniques. Space-based solar power and resource extraction from the Moon and other celestial bodies, among other facets, illustrate the potential here.

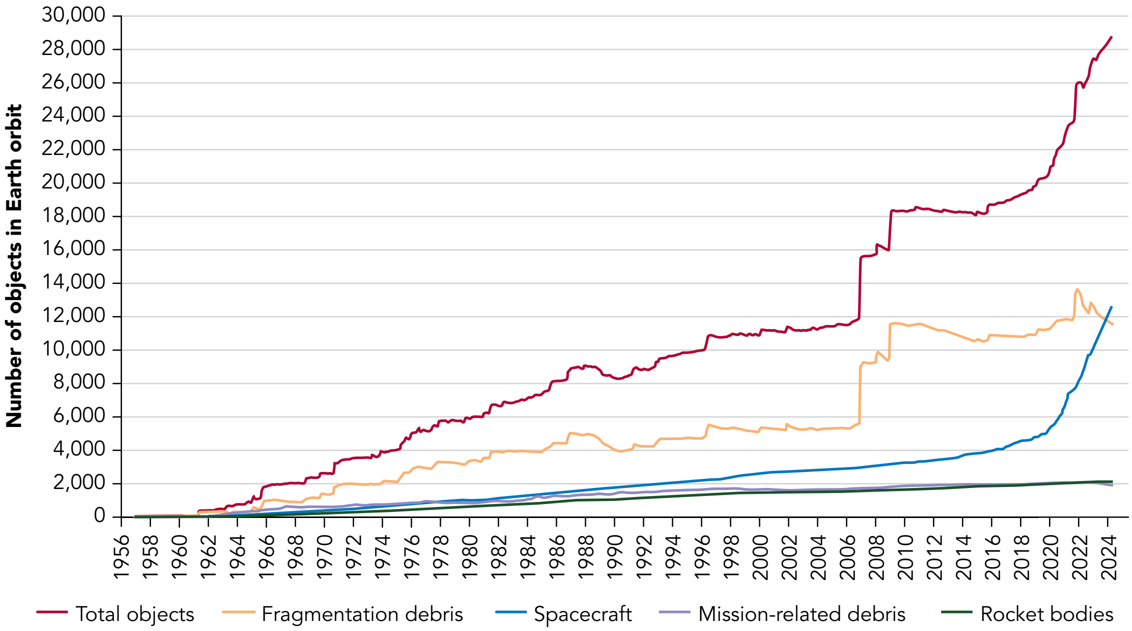
- **Sustainability of space** aims to create a circular, equitable space economy. Unlike Earth's organized transportation systems (which include traffic laws and gas stations), space lacks similar infrastructure. Addressing this requires making space assets reusable, establishing orbital services, managing debris, and quantifying orbital capacity. Space traffic management is essential to handle the increasing number of assets around the Earth and Moon. Developing guidelines for fair and safe orbital behavior—which don't currently exist—is essential.

The world ultimately faces a spaceflight sustainability paradox: The growing use of space to support sustainability and security on Earth will lead to more adverse impacts on the space environment itself. For example, multiple constellations of remote sensing satellites will contribute to greater space traffic challenges. Managing this complex issue will require advances in both policy and technology.

Triple-Helix Innovation

Collaborative efforts between academia and industry often focus on technology commercialization and real-world demonstrations, frequently supported by governments. This cooperative model, known as triple-helix innovation, combines academia, industry, and government. Notable examples include the proposed $2 billion Berkeley Space Center collaboration with NASA's Ames Research Center and Stanford University's Center for AEroSpace

FIGURE 10.5 The number of tracked space objects larger than 10 centimeters has grown rapidly



Source: Adapted from *Orbital Debris Quarterly News* 28, no. 3 (July 2024): 10

Autonomy Research (CAESAR), which focuses on AI-driven autonomy with Blue Origin, Redwire, and government agencies.

Space Governance

International and national space governance has not developed at the same rapid pace as space technology. Existing legal frameworks—many of which are products of the Cold War—do not address wide swaths of current activities and are often contested in scope and interpretation.[26] Attempts at improvement have often stagnated due to differing geopolitical aims. Even within the United States, space assets are not designated as critical infrastructure by the government despite their importance, and growth in space activity far outpaces the capabilities of current licensing processes run by the Federal Aviation Administration and the Federal Communications Commission (FCC).

Nonetheless, a number of developments in the past couple of years are notable. NASA released its strategy, including actionable objectives, for sustainability in space activities in Earth orbit.[27] It also promised to release similar strategies in the future for activities on Earth; for the orbital area near and around the Moon known as cislunar space; and for deep space, including other celestial bodies. In addition, the FCC issued its first-ever fine for a satellite not properly disposed of from geostationary orbit.[28] These short-term policy advances must be unified with a longer-term vision encompassing the next fifty to one hundred years to effectively address national security needs, support the space industry's continued development, and realize the responsible use of space as a global commons.

Maintaining Space Access

The number of objects in space has grown rapidly. Figure 10.5 shows the total number of tracked space

> **While prestige remains a factor, the current [Moon] race focuses on establishing a lunar presence for strategic and economic advantages.**

objects larger than 10 cm since 1959. Today, there are nearly 30,000 such objects, about 10,000 of which are working satellites. There are also an estimated 1.1 million fragments between 1 and 10 cm in size.[29] With so many objects in space, the risks of collision between them are growing. Each collision has the capacity to create even more debris, leading to a catastrophic chain reaction known as the Kessler syndrome, which would effectively block access to space. In addition, increasing volumes of space traffic (future mega-constellations will consist of tens of thousands of satellites) may lead to communications interference, and coordination of space activities such as orbit planning will be increasingly difficult to manage.

To tackle this issue, new domestic safety legislation and international cooperation will be needed for accurate tracking of space objects, facilitating the use of automated collision-avoidance systems, and removing debris from orbit. Similarly, more consistent guidelines will be needed to govern behavior in space, how space operations are conducted, and the sharing of data for situational awareness. Transparency and coordination among all players will be key, and the United States is in a good position to take a leading role among like-minded nations in advocating for these kinds of changes in space access.

Geopolitics, Security, and Conflict in Space

Many issues arise with respect to space and geopolitics. A key example is the Outer Space Treaty (OST), which entered into force in 1967; today, 117 countries are parties to the treaty, and 22 more have signed but not ratified it. Among other things, the treaty prohibits the placement of nuclear weapons or other weapons of mass destruction in space.

Recent evidence suggests the OST's norms are eroding. In 2024 Russia vetoed a United Nations resolution prohibiting the deployment of nuclear weapons in space, despite being a party to the OST; senior US officials revealed that they believe Russia is developing a satellite to carry nuclear weapons into LEO, where a detonation could destroy all satellite activity there for up to a year.[30] In addition, there is no treaty, OST or otherwise, that limits other military uses of space, including the placement of conventional weapons in orbit.

A second issue relates to nonnuclear anti-satellite weaponry and capabilities. To date, four nations—China, Russia, India, and the United States—have successfully tested kinetic anti-satellite weapons capable of physically destroying satellites in space. (Every such test has produced a significant amount of space debris.) More broadly, countries are developing a range of capabilities, from the ground and in space, to degrade, deny, and even destroy satellites of other nations. Cyberattacks are an important element of the non-kinetic threat spectrum against space missions, which can lead to data corruption, jamming, and hijacking of space intelligence providers and customers.[31]

A third issue involves various national efforts to reach the Moon. To facilitate an orderly and peaceful exploitation of the Moon's resources that is consistent with the OST, NASA and its partners have also proposed the Artemis Accords, which define "principles for cooperation in the civil exploration and use of the Moon, Mars, comets and asteroids for peaceful purposes."[32] So far, forty-three nations have signed the accords—but notably not Russia or China, which are among the parties seeking to establish a permanent Moon presence.

Nations today are engaged in a new "race to the Moon," though with different motivations than in the 1960s. While prestige remains a factor, the current race focuses on establishing a lunar presence for strategic and economic advantages. The first nation to establish a lunar presence successfully may well gain a first-mover advantage that enables it to be in a stronger position to set the terms for others to come. Although the OST prohibits claiming lunar sovereignty, there are concerns that nations might disregard this for national interests.[33] The possibility of a nation taking military action to prevent others from establishing their own lunar presence highlights the potential for conflict in this new space race.

Finally, in the past couple of years, the rise of the private sector's importance in providing capabilities for rapid space launch and space-based communications has been dominated by SpaceX and Starlink, which are owned by the same person. In 2022, the CEO of Starlink, which Ukrainian military forces relied on for communications, denied its use to conduct military operations around Sevastopol, in Crimea—thus directly interfering with the execution of Ukrainian battle plans.[34] In September 2024, NASA turned to SpaceX to return to Earth two US astronauts left on the ISS when their Boeing-built Starliner spacecraft experienced operational failures and was brought to Earth without them.

Such incidents demonstrate the extreme dependence of the US government on capabilities provided by a very limited number of companies and raise important policy questions of how to ensure that US space efforts can continue in accordance with US national interests.

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