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A Report on Ten Key Technologies and Their Policy Implications

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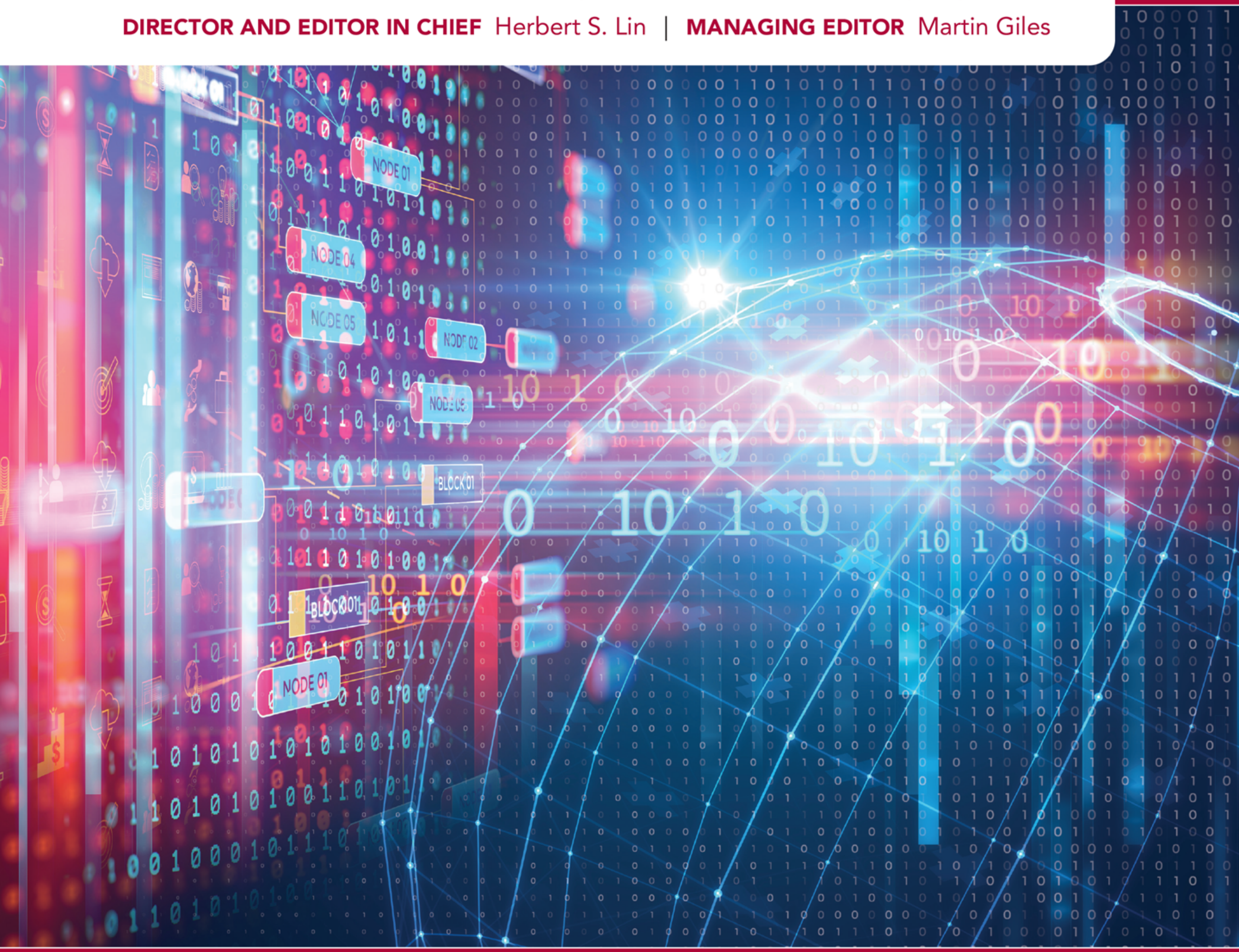


09

SPACE

KEY TAKEAWAYS

- A burgeoning "NewSpace" economy driven by private innovation and investment is transforming space launch, vehicles, communications, and key space actors in a domain that has until now 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 prevent and manage international conflict in space and ensure responsible stewardship of this global commons.

- A race to establish a permanent human presence on the Moon is underway, with serious concerns that, despite Outer Space Treaty prohibitions against it, the first nation to reach the Moon may be in a strong position to prevent others from establishing their own lunar presences.

Overview

Sputnik 1 was the world's first artificial satellite, a technology demonstration placed into orbit by the Soviet Union in 1957. Sixty-eight years later, humankind operates many thousands of satellites to provide communications, navigation, and Earth observation imagery that are 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 an average of 9 percent per annum.[1] Valued at $630 billion in 2023, it is forecast to potentially reach $1.8 trillion by 2035. This growth is driven by space-based technologies and their impacts on various industries, including defense, transportation, and consumer goods. It is supported by a shift in ownership of space assets from government to private providers.

Private-sector investment in space reached an all-time high of $70 billion in 2021–22, and commercial innovation continues to enhance the accessibility and diversity of space. The number of satellites launched per year has grown at a cumulative annual rate of over 50 percent from 2019 to 2023, supported by an increase in global rocket launches (223 in 2023).[2]

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 is by 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 late 2025, followed by a Moon landing in 2026–27.

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 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 be characterized by size. Very large structures include the ISS, whose mass is

FIGURE 9.1 Fires and damage at Antonov Airport in Ukraine, as seen from a commercial satellite constellation

Source: © 2022 Maxar Technologies

420 tons, and proposed future space stations such as Blue Origin's Orbital Reef. Vastly smaller satellites, called smallsats, weigh under 500 kilograms.[3] CubeSats are the most popular smallsat format, with each CubeSat unit measuring 10 by 10 by 10 centimeters and weighing 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 kilograms.

Space systems can be characterized by their trajectories in space. 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 (HEO); and geosynchronous orbit (GEO), with an orbit period equivalent to one Earth day. The image in figure 9.1 was obtained by a Maxar commercial satellite in LEO.

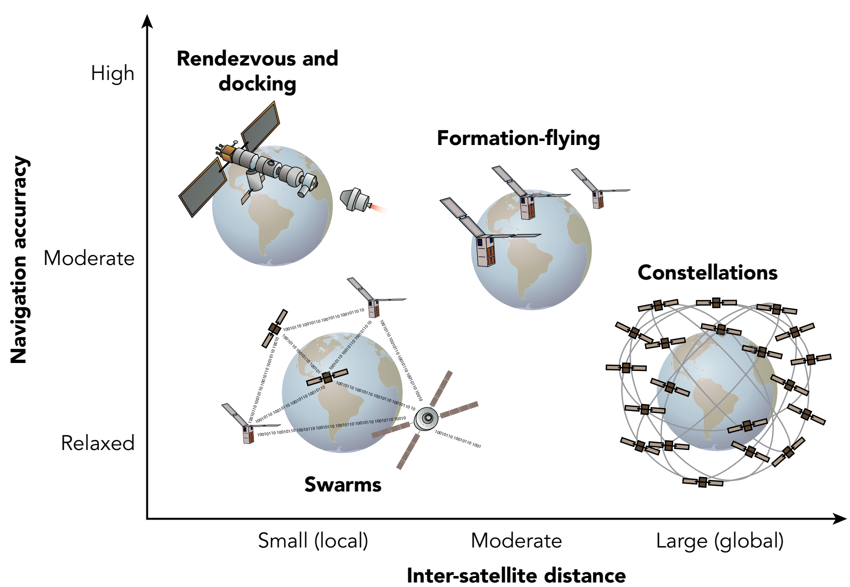
Another categorization of space systems focuses on their composition. Distributed space systems, comprising multiple interacting spacecraft, can achieve objectives that are difficult or impossible for single spacecraft. These systems take various architectural forms (see figure 9.2), defined by parameters 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.

- 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

FIGURE 9.2 Characterizing distributed space systems



Source: Adapted from a diagram by Simone D'Amico

FIGURE 9.3 An artist's conception of a satellite swarm in space

Source: NASA / Blue Canyon Technologies

not necessarily need to be at fixed distances from one another (see figure 9.3)

- Constellations separated by tens of thousands of kilometers so that they may provide global ground coverage for navigation, communications, and remote sensing services

Key Developments

Impacts of Space Technologies

Space technology has proven its 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 where they are and how fast and in which direction they are going, 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 is 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.

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. Kepler Communications is developing space-to-space and space-to-ground optical data relays, working toward an in-space internet for high-bandwidth satellite communications.

Remote sensing Remote sensing satellites, with their unique vantage point and sophisticated sensors, rapidly gather extensive data about areas and objects of interest. These data are integrated to create a "digital twin" of Earth, enhancing prediction, simulation, and response to terrestrial phenomena. 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, and Capella Space. Recent efforts have focused on increasing data resolution, reducing response times, and exploring other valuable information modes such as hyperspectral imaging,[4] synthetic aperture radar,[5] and radio-frequency sounding (i.e., exploration of the environment through the use and exploitation of radio waves).[6]

Scientific research Space-based astronomy and exploration provide in-depth insights into the origins of planets, stars, galaxies, and life on Earth. The past year has seen significant strides in solar system exploration, particularly involving asteroids. NASA's OSIRIS-REx mission successfully returned asteroid samples to Earth and will soon be followed by the launch of the Psyche mission, which intends 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.[7] Companies like SpaceX, Rocket Lab, Blue Origin, and Virgin Galactic have made progress in providing reliable launches and developing new vehicles. SpaceX's Starship—the most powerful rocket ever built—could dramatically reduce the cost of achieving LEO orbits, aspirationally between 10 and 100 times cheaper than today (see figure 9.4).[8] By the time this report is published, Blue Origin may have already launched the reusable high-volume heavy-lift New Glenn rocket.

Meanwhile, Blue Origin, Voyager Space, and Axiom Space 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 missile launches (both ballistic missiles and hypersonic missiles) aimed at the United States or its allies, nuclear weapons explosions anywhere in the world, radio traffic and radar signals from other countries, and the movements of allies and enemies in military contexts. 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 research and development to maintain space superiority and safety as space becomes increasingly congested and contested because of an influx of nation-state and private-sector actors.

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 nongovernment 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 architectures offers advantages in reduced costs, faster development timelines,

FIGURE 9.4 SpaceX's Starship could dramatically reduce the cost of achieving LEO orbits

Source: SpaceX. Used under CC BY-NC 2.0

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; 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. For example, technology for removing space debris could also be harnessed for antisatellite purposes.

The new 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. 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. India became the first nation to touch down near the lunar south pole—a prime target for settlement—and China became the first nation to land on the Moon's far side. Japan became the fifth nation to successfully touch down on the Moon, and Intuitive Machines became the first private company to land on the Moon.[9] The NASA-led Artemis program is developing a new launch system, lunar base camp, and lunar terrain vehicles, among other things, as steps needed for establishing a permanent human presence on the Moon.[10]

Over the Horizon

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, the microgravity environment of space 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 that are 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 may 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 Above Earth's atmosphere, in certain orbits, the sun shines for twenty-four hours a day and even more brightly than it does on Earth's surface. To meet clean energy needs, this permanent sunlight could eventually be harnessed for space-based power generation. Solar panels could generate electricity in orbit, later beamed to the surface via microwaves, or orbital mirrors could be used to reflect sunlight onto Earth's nightside, to be collected by solar farms. If realized, dramatically lower launch costs (which may be possible thanks to new launch vehicles) make such concepts more technically and financially feasible today than they have been in the past.

Space situational awareness (SSA) The number of active satellites has increased from roughly 1,000 in 2014 to about 10,000 in 2024—a figure that will likely rise to several tens of thousands in the next decade. In addition, the European Space Agency estimates that about 170 million pieces of debris larger than 1 millimeter in size are in orbit, many of which are dangerous to satellites and space stations.[11] Ground-based stations are currently used to track space objects, but there is a push toward leveraging space-based sensors for more timely and accurate results. For example, a piece of space debris carrying an electrical charge and moving through plasma may create plasma signatures called solitons that signal its presence.[12]

Companies such as NorthStar are making initial strides toward creating satellite constellations for SSA. The emergence of low-cost, high-quality imagery and other information from space-based assets—increasingly launched and operated by private companies—will also be an important driver of open-source intelligence that data analysts can buy.

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.[13] 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.

For example, orbital tugs and in-orbit fuel depots that can autonomously support in-orbit refueling are necessary components of a circular space economy that emphasizes the reuse and regeneration of products and materials in a sustainable manner. Hundreds of companies are developing new ISAM technology, but only a handful 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).

Energy harvesting in the space environment A piece of space debris moving in space carries significant kinetic energy. If it collides with another space structure, it generates energy that, in principle, can be harvested and put to constructive use. Rather than just asking, "Can we shield ourselves from the space environment?" we can also ask, "How can we harness it?"

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.[14] 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.

Challenges of Innovation and Implementation

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 are among other facets that 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.

GAPS IN SMALL SATELLITE TECHNOLOGY

NASA has identified a list of issues that are restraining growth in usage of small spacecraft.[15] 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 demonstration of several critical autonomous swarming technologies.[16] Among Starling's payloads is an optical PNT system newly developed by Stanford's Space Rendezvous Laboratory. This applies onboard cameras and advanced space robotics algorithms to navigate multiple satellites 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.

TRIPLE-HELIX INNOVATION

Public entities have become risk averse in space, prioritizing accountability over innovation unless traditional methods fail. In contrast, private companies pursue innovation for profit and competitive advantage. 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 Autonomy Research (CAESAR), which focuses on autonomy with Blue Origin and Redwire.

Policy, Legal, and Regulatory Issues

SPACE GOVERNANCE

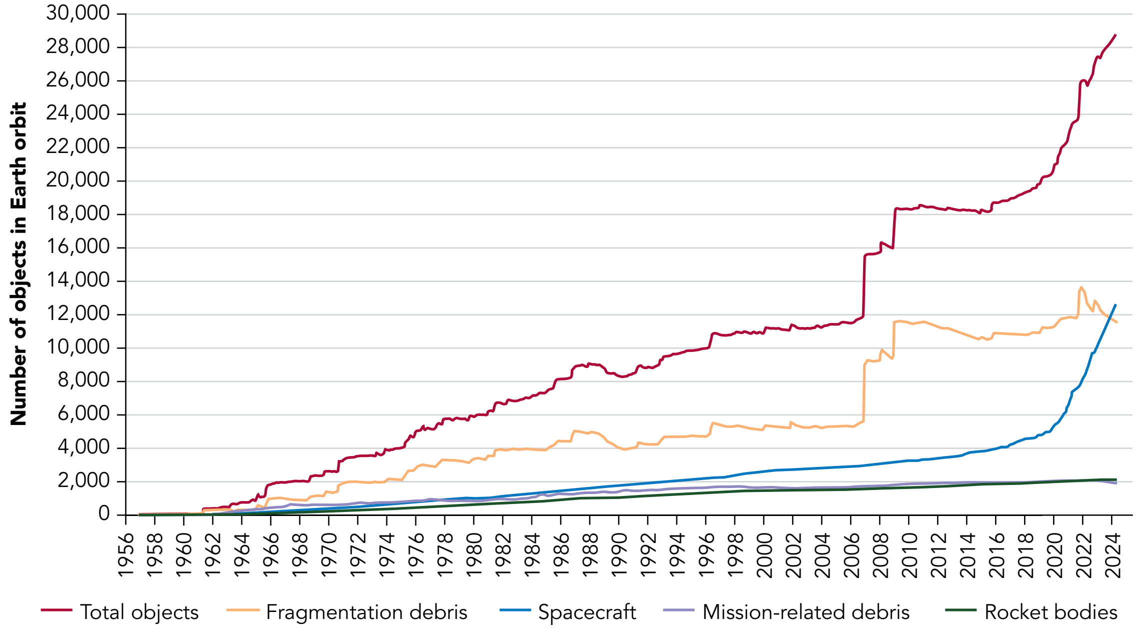
International and national space governance has not developed at the same rapid pace as space technology. Existing legal frameworks—many of which were products of the Cold War—do not address wide swaths of current activities and are often contested in scope and interpretation.[17] Attempts at improvement 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.[18] It also promised to release similar strategies in the future for activities on Earth; the orbital area near and around the Moon known as cislunar space; and 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.[19] 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 9.5 shows the total number of tracked space objects larger than 10 centimeters since 1959. Today, there are nearly 30,000 such objects, of which about 10,000 are working satellites.[20] There are also an estimated 1.1 million fragments between 1 and 10 centimeters in size. 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

FIGURE 9.5 The number of objects in space larger than 10 centimeters has grown rapidly



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

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, 115 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, and 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.[21]

In addition, there is no treaty, OST or otherwise, that limits other military uses of space, including the placement of conventional weapons in orbit. And because space-based capabilities are integral to supporting modern warfighters, they may become targets of foreign counterspace threats. Rapid-launch

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

capabilities to facilitate fast replacement of satellites rendered inoperative during conflict will increase the resiliency of critical national space assets.

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.[22]

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."[23] 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.

However, 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 successfully establish a lunar presence 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.[24] 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 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.[25] 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 that are controlled by a single individual—and raises important policy questions of how to ensure that US space efforts can continue in accordance with US national interests.

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24. China has chosen to disregard the findings of a tribunal convened pursuant to the United Nations Convention on the Law of the Sea that ruled against Chinese claims regarding its land reclamation activities in the South China Sea, despite the fact that China is a formal signatory to UNCLOS. See In the Matter of the South China Sea Arbitration (Phil. v. China), Case No. 2013-19, Award of July 12, 2016, ITLOS Rep., https://pcacases.com/web/sendAttach/2086.

25. Wes J. Bryant, "When a CEO Plays President: Musk, Starlink, and the War in Ukraine," *Irregular Warfare Initiative*, October 17, 2023, https://irregularwarfare.org/articles/when-a-ceo-plays-president-musk-starlink-and-the-war-in-ukraine/.

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