STANFORD UNIVERSITY

THE STANFORD EMERGING TECHNOLOGY REVIEW 2023

A Report on Ten Key Technologies and Their Policy Implications

CHAIRED BY Condoleezza Rice, John B. Taylor, Jennifer Widom, and Amy Zegart

DIRECTED BY Herbert S. Lin

09

SPACE

KEY TAKEAWAYS

- Space technologies are increasingly critical to everyday life (e.g., GPS navigation, banking, missile defense, internet access, and remote sensing).
- Space is a finite planetary resource. Dramatic increases in satellites, debris, and competition are threatening access to this global commons.
- Private-sector actors play a critical and growing role in many aspects of space-based activities (e.g., launch, vehicles, and communications), because they offer better, cheaper, and rapidly deployable capabilities.

Overview

Sputnik 1 was the world's first artificial satellite, placed into orbit by the Soviet Union in 1957. A technology demonstration, Sputnik broadcast an easily monitored radio signal from space for a few weeks. This little 184-pound, 2-foot-diameter capsule launched the space age—and today many thousands of satellites provide Earth-bound nations and their citizens with communications, navigation, multispectral observation, and imagery of terrestrial phenomena that are useful in many walks of life. A substantial amount of scientific discovery is also made possible with space-borne instrumentation. Finally, space operations support military forces on Earth and thus space itself is a domain in which international conflict and competition play out.

The global space sector experienced growth in 2022, driven primarily by commercial and private activities.[1]

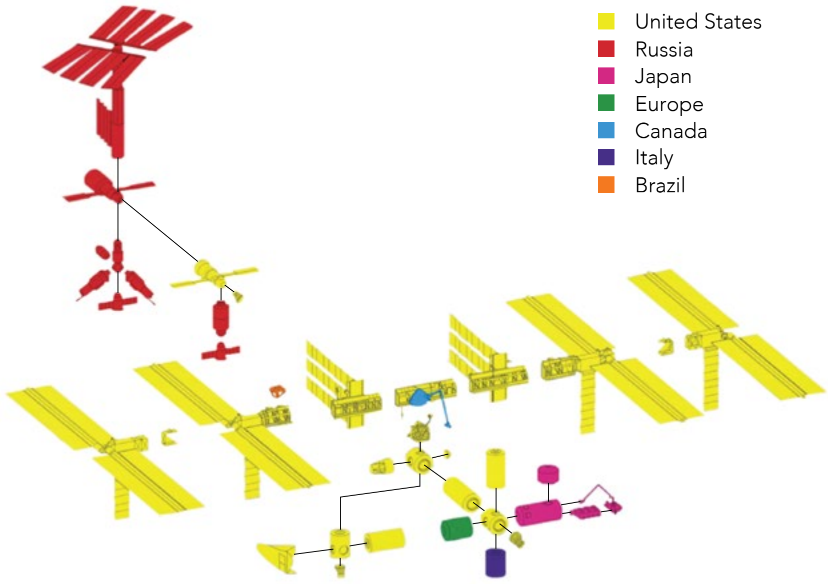
It was valued at $424 billion in 2022, showing an 8 percent growth from the previous year, with projections suggesting it might reach $737 billion within the next decade.[2] This growth coincided with a shift from government-operated launches to private providers. There were 180 global rocket launches in 2022, an increase from the previous year.[3] Private space investments in 2022 saw a 25 percent reduction, attributed to an economic downturn affecting start-ups, though the year maintained high investment figures.

By definition, space technology is any technology developed for the purpose of conducting or supporting activities beyond the Kármán line (i.e., 100 kilometers or 62 miles above Earth's surface). A space mission is a system of systems that is designed to optimally accomplish objectives, generally through the art and science of space systems engineering. A space mission includes several components:

- The mission objectives, which can be scientific, commercial, or military
- A space segment, which includes the spacecraft and the orbits that have been selected and designed to accomplish the objective of the space mission
- A ground segment, which includes the rocket launcher, ground stations, and mission control centers

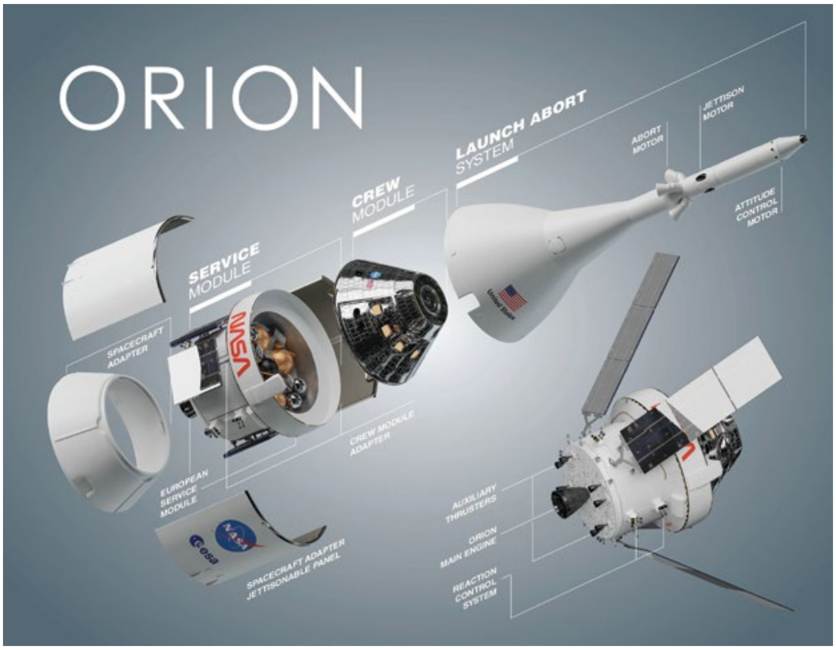
An example of an extremely complex space mission is the International Space Station (ISS) (see figure 9.1). The space segment includes the ISS itself, the structure that is the space station, several cargo and crew vehicles (e.g., SpaceX Dragon, Soyuz, Automated Transfer Vehicle), and data relay satellites (e.g., the Tracking and Data Relay Satellite system). The ground segment includes the rockets

FIGURE 9.1 The International Space Station



Source: National Air and Space Museum Archives via Smithsonian Institution

FIGURE 9.2 NASA's Orion spacecraft



Source: NASA

that are used to deploy those elements into space as well as a worldwide network of ground-based control centers.

A key part of a space mission is a spacecraft consisting of a payload and a bus (see figure 9.2). The payload is a collection of instruments that are used to achieve the mission objectives, while the bus is anything else that supports the payload in achieving those objectives. The bus consists of a variety of subsystems that are analogous to individual organs within a living being. These subsystems manage (1) translational (orbit) and rotational (attitude) motion of a spacecraft; (2) communications satellite-to-ground and satellite-to-satellite when available; (3) data storage and processing; (4) generation, distribution, and dissipation of electrical power to all other subsystems and to the payload as well; (5) thermal control to ensure that the components of the spacecraft are within their maximum and minimum temperature operational and survival limits; and (6) the structure to hold the various components and protect them from the physical stresses encountered during the mission lifetime.

One way to classify space systems is by whether they are crewed or uncrewed. The former includes systems used for crew transportation to and from space (Orion, Soyuz, Dragon), space stations (ISS, Lunar Gateway, Tiangong, Orbital Reef), and land-based surface systems to provide human habitat, in situ resource utilization, and scientific experimentation. The first crewed space flight from US soil since 2011 was a suborbital test flight operated by Virgin Galactic, a private company. Crewed US access to the International Space Station since 2011 has been aboard rockets operated by Russia and more recently by the private company SpaceX. The NASA-operated Artemis program plans to launch its first crewed mission, a moon flyby, in late 2024.

Uncrewed systems include systems for Earth and planetary remote sensing (the Gravity Recovery and Climate Experiment; Doves, SkySats, and RapidEye of the private company Planet; the Mars Reconnaissance Orbiter); communication and navigation (the Tracking and Data Relay Satellite system, the European Galileo, Starlink); astronomy and astrophysics (the Hubble, James Webb, and Nancy Grace Roman telescopes); space logistics/in-space assembly and manufacturing (Restore-L, the Mission Extension Vehicle); and planetary exploration (Perseverance, Ingenuity, Zhurong).

Alternatively, space systems can be characterized by size. At one end of the distribution are large structures such as the International Space Station with a mass of about 420 tons and a truss length of 94 meters. New commercial space stations include Orbital Reef, being built by Jeff Bezos's Blue Origin; Starlab by Airbus; and an as-yet unnamed space station by Northrop Grumman. These commercial space stations are set to eventually replace the outdated ISS, which is expected to be retired in 2030, and they will be of comparable size.

At the other end of the distribution are much smaller satellites, often called smallsats. A NASA Ames Research Center report classifies anything under 500 kilograms as a small spacecraft.[4] This includes Sprite chipsats, which weigh less than a gram and were developed by a former faculty member of the Stanford Aeronautics and Astronautics department. CubeSats are the most popular small satellites today. Introduced in 1999 by Bob Twiggs of the Stanford Aeronautics and Astronautics department, each CubeSat unit measures 10 x 10 x 10 cm, weighs a kilogram, and can be combined to build larger satellites. Originally intended for educational use, CubeSats now support a growing commercial market. Today, a large majority of functional satellites in space weigh between 100 and 1,000 kilograms.

Space systems can be characterized by the orbits where they move. One category refers to objects

FIGURE 9.3 Perth, Australia, as seen from SkySat-1

Source: Planet Labs PBC

in orbit around Earth: such space systems can be classified as being in low Earth orbit (LEO, less than 1,000 km in altitude), medium Earth orbit (MEO, between 2,000 and 35,000 km in altitude), high elliptical orbit (HEO), or geosynchronous orbit (GEO). The image in figure 9.3 was obtained by a commercial satellite in LEO, operated by a space start-up founded by Stanford students.

Another category where space systems move is defined by the Lagrange points in space, the most significant of which are hundreds of thousands or a million kilometers away. Lagrange points are defined with respect to two bodies, such as the Sun and Earth or the Earth and Moon, and denote points around which an orbiting spacecraft can remain in a fixed spatial relationship to the two considered bodies.

The most well-known Lagrange point orbits are referred to as halo orbits and were discovered at Stanford in 1966 by Professor John V. Breakwell and his PhD student Robert Farquhar. Lagrange point orbits provide many benefits; for example, in a Sun-Earth halo orbit, the fixed spatial relationship of a spacecraft relative to the Earth and Sun means that it is possible to view Earth with the same illumination conditions—that is, with sunlight shining on terrestrial objects with the same intensity, from the same angles, and casting the same shadows. Furthermore, Earth-Moon Lagrange points are particularly good places in space at which to stage missions entailing travel between the Earth and Moon.

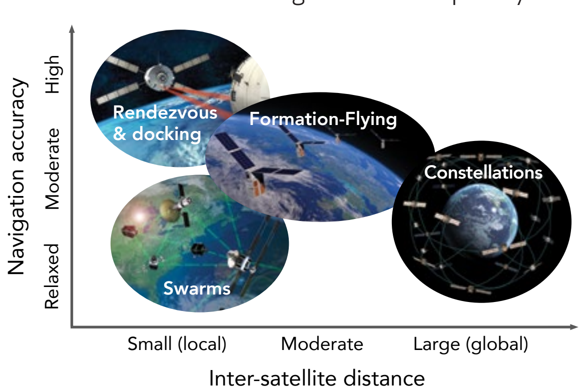
Finally, a number of interplanetary probes have been launched to every planet—and some asteroids—in our solar system. Some have gone beyond the solar system, including Voyager 1 and Voyager 2, which were both launched in 1977 and are now the human-made objects most distant from Earth today.

The space systems described above generally consist of a single spacecraft, which has limited capability because of its constraints in carrying capacity (size and volume) and maneuverability (propellant). Distributed space systems—made of two or more spacecraft that interact and sometimes work together—can accomplish objectives that would otherwise be very difficult or impossible with a single spacecraft.

A distributed system can be characterized along two axes—the distance between space segment components, which could be virtually nothing to tens of thousands of kilometers, and the positional accuracy needed of each component relative to other components (see figure 9.4). In this classification, several architectures emerge:

- **Rendezvous and docking** are characterized by small separations and high positional accuracy.

FIGURE 9.4 Characterizing a distributed space system



Source: Diagram by Simone D'Amico from NASA images

This architecture was necessary for the United States to land humans on the moon and today is a key technology needed for removal of space debris from orbit, for in-orbit servicing of satellites, and to assemble and manufacture larger structures in space.

- **Formation-flying** architectures are needed for observational missions that call for large effective apertures, such as space-based telescopes whose optical components are controlled very precisely with respect to one another at separations of tens to hundreds of meters. Gravimetric and interferometric missions require the same architecture.

- **Swarms** that sense the environment or share resources such as power or computation remotely also need to be kept in a relatively tight formation (i.e., close to each other), but the components do not necessarily need to be at fixed distances from one another.

- **Constellations** have components that are separated by tens of thousands of kilometers for global ground coverage, but their relative positioning need not be particularly precise. Examples of constellations include satellites of the Global Navigation Satellite System (GNSS) such as the US GPS, the Chinese BeiDou, the Russian Globalnaya Navigatsionnaya Sputnik Sistema (GLONASS), and the European Galileo systems; communications satellites providing worldwide coverage such as Starlink; and remote sensing and imaging satellites.

Key Developments

Space technology has proved its value to the national interest. Some of the most important applications today include:

Navigation This includes, more generally, position, navigation, and timing services around the world and in space. GPS satellites (and those of other nations as well) help people know where they are and how fast and in which direction they are going, whether they are 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.

Communications Although the vast bulk of international and long-haul communications traffic is still routed through landlines (mostly fiber optic), satellites provide voice and data communications as well as internet access in otherwise inaccessible places around the world and, of course, for mobile phone users in cars and planes and on ships. Recent innovations in space-based communications technology include the development of optical communication systems—which use light to carry data and offer higher bandwidth and security. These include laser communications both space-to-ground and space-to-space, which hold a particularly high value for government and military.

Remote sensing Satellites gather information about a geographical area, the environment, or an object by detecting and measuring energy that may be reflected or emitted by the entity being sensed. These satellite systems generate data to create a "digital twin of the Earth" for disaster prediction, prevention, monitoring, mitigation, and recovery, and will play a huge role in the future by enabling simulation and prediction of terrestrial phenomena and especially disasters. Space-based remote sensing is used to observe and surveil large forest fires, weather formation, the evolution of cloud cover, erupting volcanoes, dust storms, changes in the geography of a city or in farmland or forests (e.g., as the result of fires, earthquakes, or flooding), changes in terrain such as glacier movement or landslides, and surface topography. Space-based remote sensing can scan large areas of Earth rapidly, though at some cost in resolution. Remote sensing also varies by revisit rate—revisiting on the order of hours or days is needed for rapidly unfolding phenomena, such as the progression of a hurricane, while applications such as glacier monitoring require much less frequent measurements.

Scientific research Space-based telescopes, such as the James Webb space telescope, play an important role in various areas of astronomy and cosmology. They help in studying the earliest stars and understanding the creation of the first galaxies and offer in-depth insights into the atmospheres of planets that might support life.

Space transportation The space transportation industry is becoming increasingly privatized and provides launch services for parties wanting to orbit satellites and transport services to in-orbit space stations. The costs of placing payloads into LEO have fallen from a high of $65,000 per kilogram to $1,500 per kilogram in 2021,[5] largely driven by the advent of multiple launch capability of a single rocket—as many as 100 to 150 at a time—coupled with reusable rocket launch vehicles.

National security Space-based satellites scan Earth looking for launches of ballistic missiles that may be aimed at the United States or its allies, for nuclear weapons explosions on the surface anywhere in the world, and for radio traffic and radar signals from other countries. Of course, all these applications—navigation, communications, and remote sensing—are valuable in a military context.

There is an increasing trend toward privatization across most space technologies as the space sector moves away from legacy space technologies owned by the government or large contractors. These legacy systems are characterized by large, expensive spacecraft with long development timelines. Today, a "NewSpace" economy is turning to private companies, creating a global space environment in which systems and services are more accessible and

Satellite systems generate data to create a "digital twin of the Earth" . . . and will play a huge role in the future by enabling simulation and prediction of terrestrial phenomena and especially disasters.

less expensive—and available to all. Governments are also looking to commercial space for new capabilities, like awarding contracts to private companies to develop smallsat constellations or for in-space servicing, assembly, and manufacturing (ISAM).

Over the Horizon

Impact of Space Technologies

Future applications of space technology are likely to include:

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 the effects of gravity on fabrication can be minimized, enabling more perfect crystals and more perfect shapes to be fabricated, to give examples.

Mining The moon and asteroids may well have vast storehouses of useful minerals that are hard to find or extract on Earth (e.g., rare-earth elements). Future space mining operations may bring some of these to Earth or utilize them for further human expansion in the solar system.

Power generation It is well known that the sun's radiation on Earth can generate electricity through solar cells. But above Earth's atmosphere in certain orbits, the sun never stops shining; indeed, it shines more brightly because it is not attenuated by Earth's atmosphere or by weather. It may be economically feasible in the future to capture such energy and beam it to Earth for sustainable electrical generation.

National security Although the Outer Space Treaty prohibits the placement of nuclear weapons or other weapons of mass destruction in space, there are no restrictions on other military uses of space, including the placement of conventional weapons in space. Furthermore, space-based capabilities are integral to supporting modern warfighters; accordingly, they will be the targets of foreign counterspace threats. Rapid-launch capabilities to facilitate fast replacement of satellites rendered inoperative during times of war or conflict will increase the resiliency of critical national space assets.

In-space logistics, servicing assembly, and manufacturing (ISAM) Dominance, security, and sustainability in space require infrastructure that supports cheap, quick, reliable access and the ISAM capabilities to approach, inspect, assess damage to, repair, prolong the lifetime of, retire, or remove space assets without jeopardizing the space environment.[6] Spacecraft autonomy, in combination with Rendezvous, Proximity Operations, and Docking (RPOD), is a critical technology for ISAM. For example, orbital tugs, in-orbit fuel depots, or orbital transfer vehicles (OTVs) are needed for space logistics and to enable a circular space economy.

Challenges of Innovation and Implementation

Public entities, driven by the need for public accountability, have become more risk averse, often showing reluctance to embrace innovation unless traditional methods are unviable. In contrast, private companies pursue innovation when it provides economic viability and a competitive edge via intellectual property. Collaborative efforts between academia and industry are pivotal for technology commercialization and real-world demonstrations of advancements codeveloped by industry and academic partners.

The emergence of low-cost, high-quality information from space-based assets—increasingly launched and operated by private companies—is also an important driver of open-source intelligence (OSINT) that data analysts can buy on the open market. OSINT threatens to upend traditional intelligence gathering as closely held information and analysis becomes more readily available.

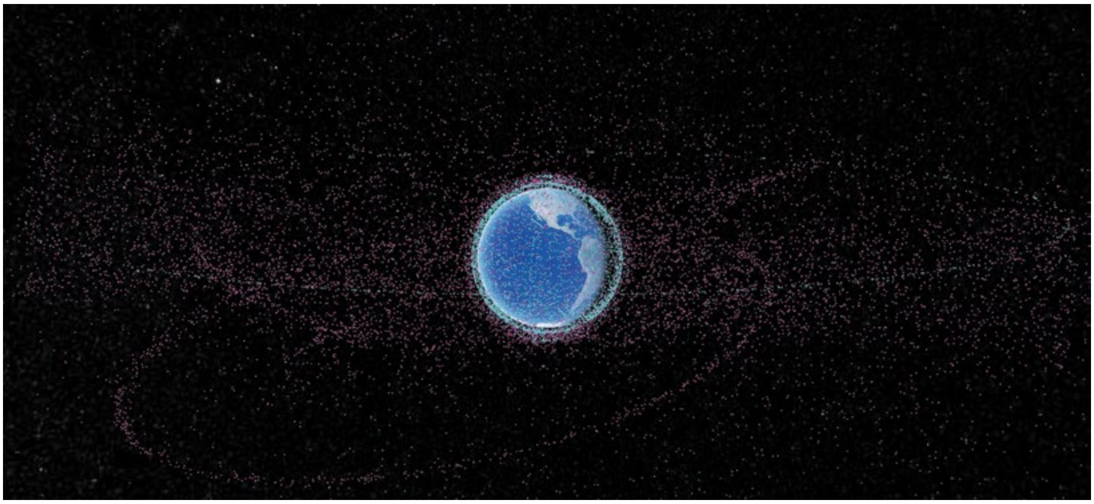
Policy, Legal, and Regulatory Issues

SPACE GOVERNANCE

Space governance has developed at the same rapid pace as the rest of the industry.[7] Within the United States, the growth of the satellite sector far outpaces the capabilities of the current licensing process. The system relies heavily on the Federal Aviation Administration (FAA) for licensing the operation of launch and reentry vehicles, and for the use of launch sites, and on the Federal Communications Commission (FCC) for communications. The demand for space-based communications is growing rapidly. In 2020 and 2021, the FCC reviewed license applications for over 64,000 new satellites, compared to a total of about 8,400 in-orbit satellites today.

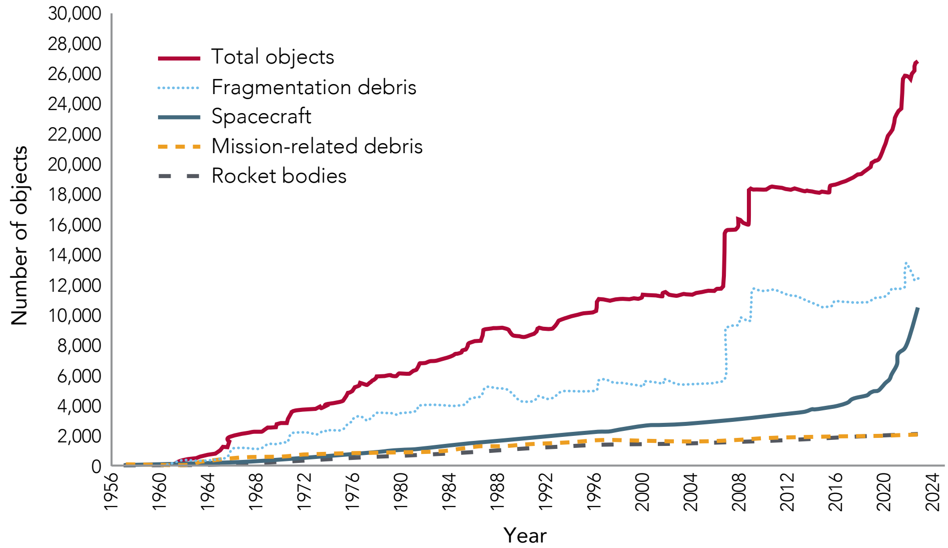
Despite their importance, space assets today are not designated by the United States as critical

FIGURE 9.5 A cloud of objects in space



Source: Privateer

FIGURE 9.6 Objects in space over time



Source: *Orbital Debris Quarterly News* 27, no. 1 (March 2023): 12.

infrastructure. Legislation has been proposed to make this designation, and as of this writing the prospects of passage are unknown.[8]

MAINTAINING SPACE ACCESS

An important grand challenge for the future of spaceflight is the preservation of space as a global resource. The near-Earth space environment is increasingly crowded, driven by lower launch costs and satellite miniaturization.

Figure 9.5 depicts objects resident in space, which include functioning satellites but also nonfunctioning satellites, or pieces of spacecraft after breakup, as well as launch vehicle components.[9] With so many objects in space, the risk of collision between two such objects is growing.

Collision has two consequences. First, if one of the two colliding objects is a useful spacecraft, it is likely to be destroyed or seriously damaged, and the likely impact velocities are so high that it is not feasible to armor satellites adequately. Second, a collision between two objects is highly likely to produce a cloud of thousands of smaller debris objects, each of which will remain in orbit to threaten still other useful spacecraft. Although a few such collisions have occurred and another few have been avoided, the possibility of a chain reaction today is relatively low. But at some point in the future, as the number of satellites being placed into orbit grows rapidly, the probability of a catastrophic chain reaction known as the Kessler syndrome will also grow. If this happens, the cloud of debris orbiting Earth resulting from such a reaction will essentially prevent space access as we know it today.

The number of objects in space has grown rapidly. Figure 9.6 shows the total number of tracked objects (each larger than 10 cm) in space since 1959. Today, there are around 35,000 such objects, of which 8,400 are working satellites—4,500 alone belonging to the Starlink satellite network. There are

2,000 nonfunctional satellites and 2,000 discarded rocket stages, and the remainder are unidentified objects.[10] There are an estimated one million fragments, between 1 and 10 cm in size.

In addition, increasing volumes of space traffic may lead to communications interference. Coordination of space activities such as orbit planning will be increasingly difficult to manage with the increase of space actors—more nations and private companies. Large satellite constellations may fill up useful orbits in ways that prevent others from using those orbits.

To reduce the impact of such factors, activities are underway that will focus on:

- **Removal of debris from orbit**, which will reduce the likelihood of collision. Requirements on actors that launch to de-orbit spacecraft shortly after they reach the end of their useful lives and active de-orbiting measures for objects such as existing discarded rocket stages will both be necessary. Some such regulatory requirements are in place, but because compliance incurs additional expenses, enforcement of these regulations is rare.

- **Automated collision avoidance systems** that will enable spacecraft to maneuver to avoid impact with space debris and other resident space objects.

- **Increased registration of launched objects** with the United Nations Register of Objects Launched into Outer Space—a registry that has existed since 1962—and bilateral or multilateral data sharing on objects to be placed in orbit would facilitate object tracking.

- **Management of space traffic**, which will require improving adherence to existing guidelines for space sustainability and strengthening international cooperation.

GEOPOLITICS, NATIONAL SECURITY CONCERNS AND CONFLICT IN SPACE

International disputes and tensions threaten the peaceful operation of satellites, space stations, and other space activities. The Outer Space Treaty was signed in 1967, at a time when the potential for the exploitation of space resources for both civilian and military purposes was not nearly as apparent as it is today. It can therefore be expected that the treaty will come under increasing pressure due to the national interests of the treaty's signatories.

The proliferation of antisatellite weapons is a major concern. To date, four nations have tested weapons capable of destroying or interfering with satellites in space—China, Russia, India, and the United States. Nations deploy antisatellite capabilities because the space capabilities of adversaries, left unchecked, provide those adversaries with military advantages. These nations can be expected to take measures to defend their own space assets while trying to degrade and deny the space assets of adversaries.

Additionally, the threat environment of the 1967 Outer Space Treaty did not anticipate cyberattacks on space missions, which can lead to data corruption, jamming, and hijacking of space intelligence providers and customers.[11] GNSS MEO-based services are especially vulnerable due to their weak signals and underline the importance of LEO-based services, as well as the exploitation of signals of opportunity—such as from mega-constellations—and passive means toward position, navigation, and timing. US Space Policy Directive-5 addresses some space cybersecurity concerns for private-sector space actors but is widely regarded as an unfunded mandate that simply adds to costs of space access. A continuing lack of governance and agreed-upon international policy thus raise the possibility of direct conflict in space.

NOTES

1. Morgan Stanley, "5 Key Themes in the New Space Economy," May 19, 2022, https://www.morganstanley.com/ideas/space-economy-investment-themes.

2. Euroconsult News, "Value of Space Economy Reaches $464 Billion in 2022 despite New Unforeseen Investment Concerns," January 9, 2023, https://www.euroconsult-ec.com/press-release/value-of-space-economy-reaches-424-billion-in-2022-despite-new-unforeseen-investment-concerns-2.

3. Alexandra Witze, "2022 Was a Record Year for Space Launches," *Nature* 613, no. 7944 (January 11, 2023): 426, https://doi.org/10.1038/d41586-023-00048-7.

4. Stevan M. Spremo, Alan R. Crocker, and Tina L. Panontin, *Small Spacecraft Overview*, NASA Technical Reports Server, May 15, 2017, https://ntrs.nasa.gov/citations/20190031730.

5. Ryan Brukardt, "How Will the Space Economy Change the World?," McKinsey & Company, November 28, 2022, https://www.mckinsey.com/industries/aerospace-and-defense/our-insights/how-will-the-space-economy-change-the-world.

6. White House, "White House Office of Science and Technology Policy Unveils National In-Space Servicing, Assembly, and Manufacturing (ISAM) Implementation Plan," Press Releases, December 16, 2022, https://www.whitehouse.gov/ostp/news-updates/2022/12/16/white-house-office-of-science-and-technology-policy-unveils-national-in-space-servicing-assembly-and-manufacturing-isam-implementation-plan.

7. Sophie Goguichvili et al., "The Global Legal Landscape of Space: Who Writes the Rules on the Final Frontier?," Wilson Center, October 1, 2021, https://www.wilsoncenter.org/article/global-legal-landscape-space-who-writes-rules-final-frontier.

8. Sarah Fortinsky, "Bipartisan Bill Designates Space as Critical Infrastructure Sector," *The Hill*, July 27, 2023, https://thehill.com/homenews/space/4123413-bipartisan-bill-designates-space-as-critical-infrastructure-sector.

9. *National Geographic*, "Orbital Objects," accessed August 30, 2023, https://www.nationalgeographic.com/science/article/orbital-objects.

10. Space Safety, "Space Debris by the Numbers," European Space Agency, last modified August 11, 2023, https://www.esa.int/Space_Safety/Space_Debris/Space_debris_by_the_numbers.

11. Northern Sky Research, *Global Space Economy*, 3rd ed., January 2023, https://www.nsr.com/?research=global-space-economy-3rd-edition.