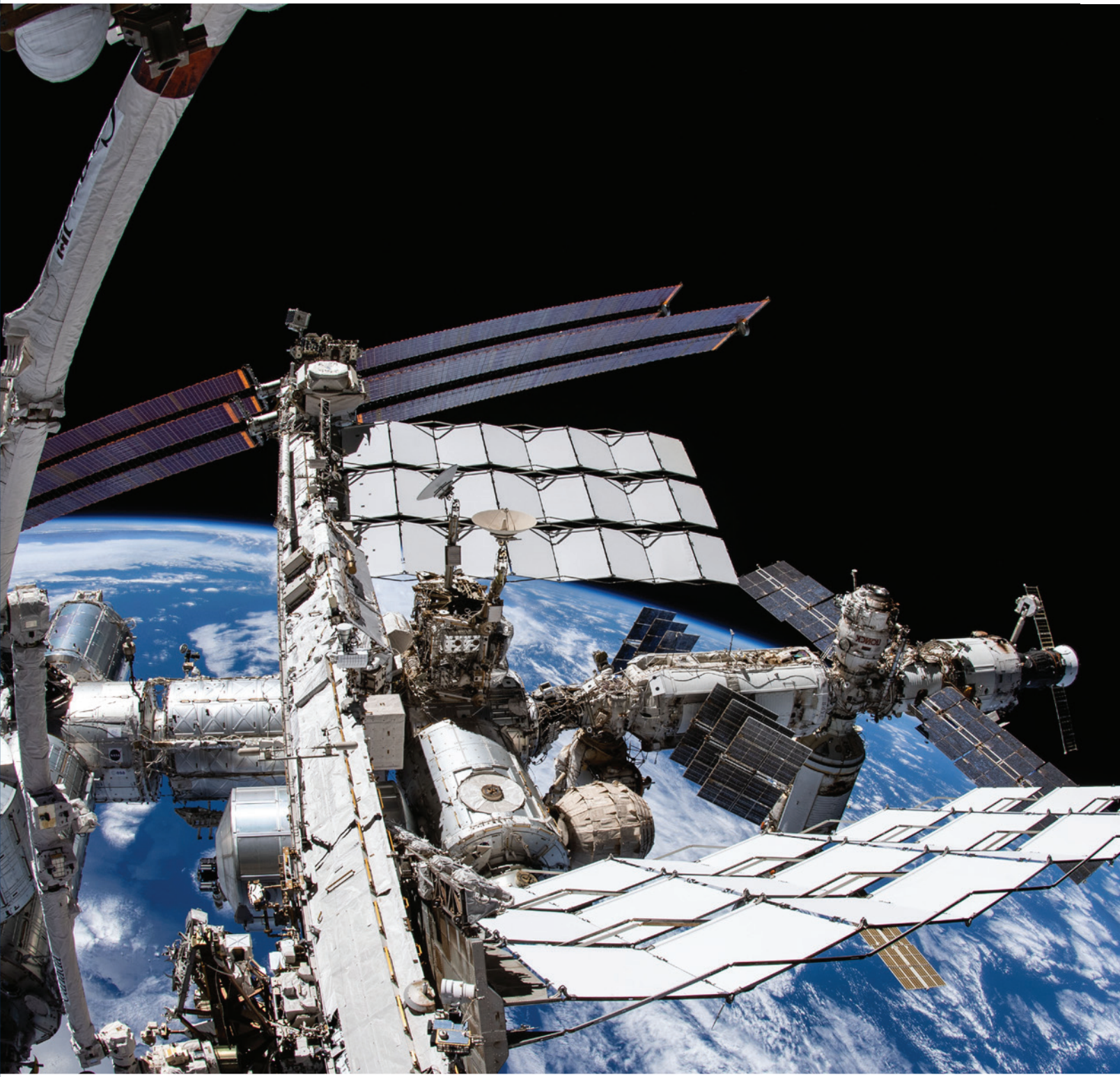
SPACE FOUNDATION

THE SPACE REPORT

THE AUTHORITATIVE GUIDE TO GLOBAL SPACE ACTIVITY

2021 Q4



2021 LAUNCH ANALYSIS | SPACE STATION BUILDING BOOM | ASTEROID MINING AND FAIR USE

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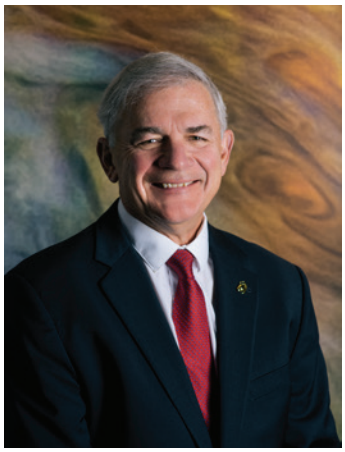

A Message from Our CEO

By every measure, 2021 was a remarkable year for the global space community.

Last year, eight nations conducted the highest number of orbital space launch attempts in history, narrowly surpassing 1967. The United States flew the first helicopter on another world as part of the Mars Perseverance mission, and by December, NASA and ESA enthralled the world with the successful launch and unfurling of the James Webb Space Telescope. A little closer to Earth, 14 civilians experienced space travel in 2021, double the number from all prior years combined. And in the last two years, the volume of transactions in the space and satellite sector has grown 61% since 2019, fueled by dozens of investors injecting billions of dollars.

Space has never been more important. It unites and inspires people around the globe. As we move forward in 2022, know this: Space Foundation will be your trusted source for information, education, and collaboration. It's more than a mission for us — as a nonprofit, it's a stewardship role we uphold for an increasingly diverse and global community that delivers more and still has more to do.

Through our 37th Annual Space Symposium, our signature live and online programming from Symposium 365, and our quarterly and digital content from *The Space Report*, Space Foundation provides access to the people, data, and research propelling the space industry forward.

Our Center for Innovation and Education offers a lifelong learning platform that delivers workforce development and economic opportunity for students, teachers, entrepreneurs, and professionals via programs offered digitally worldwide.

With our Global Alliance efforts we will facilitate collaboration across the global space ecosystem, connecting commercial, education, and government stakeholders for networking, open dialogues, and joint programs.

Through every platform, Space Foundation is committed to helping people find their place in the global space ecosystem. I invite you to visit www.spacefoundation.org to learn more about our programs for students, teachers, entrepreneurs, and professionals around the world.

Tom Zelibor
Rear Admiral, USN (Retired)
Chief Executive Officer, Space Foundation

Small Satellite Mass Categories

Femtosatellite:	0.001 – 0.01 kilograms
Picosatellite:	0.01 – 1 kilograms
Nanosatellite:	1 – 10 kilograms
Microsatellite:	10 – 100 kilograms
Minisatellite:	100 – 180 kilograms

Note: 1 kilogram equals 2.21 pounds

Source: "What are Smallsats and Cubesats." NASA. February 26, 2015. https://www.nasa.gov/content/what-are-smallsats-and-cubesats (Accessed March 10, 2019).

Common Cubesat Useful Volume Dimensions and Masses

1U:	10x10x10 centimeters/1.33 kilograms
1.5U:	10x10x15 centimeters/2 kilograms
2U:	10x10x20 centimeters/2.66 kilograms
3U:	10x10x30 centimeters/4 kilograms
6U:	10x20x30 centimeters/8 kilograms
12U:	20x20x30 centimeters/16 kilograms

Note: 1 centimeter equals .39 inches. 1 kilogram equals 2.21 pounds.

Source: "Cubesat Design Specification," Revision 13. California Polytechnic State University, San Luis Obispo. April 6, 2015. https://www.cubesat.org/s/cds_rev13_final2.pdf (Accessed March 10, 2019).

Primary Mission Segment Descriptions

Civil Government: Government-sponsored space products and services provided to the public, usually for little or no profit.

Commercial: Products and/or services sold to the public, using little or no public investment for running the business and mission.

Military: Government-sponsored missions and products serving a nation's defense and/or power projection.

Common Orbit Descriptions

- **Low Earth Orbit (LEO)** is commonly accepted as being between 200 and 2,000 kilometers above the Earth's surface. Spacecraft in LEO make one complete revolution of the Earth in about a 90-minute window.
- **Medium Earth Orbit (MEO)** is the region of space around the Earth above LEO (2,000 kilometers) and below geosynchronous orbit (35,790 km). The orbital period (time for one orbit) of MEO satellites ranges from about two to 12 hours. The most common use for satellites in this region is for navigation, such as the United States' Global Positioning System (GPS).
- **Geosynchronous Equatorial Orbit (GEO)** is a region in which a satellite orbits at approximately 35,790 kilometers above the Earth's surface. At this altitude, the orbital period is equal to the period of one rotation of the Earth. By orbiting at the same rate in the same direction as Earth, the satellite appears stationary relative to the surface of the Earth. This is effective for communications satellites. In addition, geostationary satellites provide a "big picture" view, enabling coverage of weather events. This is especially useful for monitoring large, severe storms and tropical cyclones.
- **Polar Orbit** refers to spacecraft at near polar inclination (80 to 90 degrees) and an altitude of 700 to 800 kilometers. Many polar-orbiting spacecraft are in a **Sun-Synchronous Orbit (SSO)**, in which a satellite passes over the equator and each latitude on the Earth's surface at the same local time every day, meaning that the satellite is overhead at essentially the same time throughout all seasons of the year. This feature enables collection of data at regular intervals and consistent times, conditions that are particularly useful for making long-term comparisons.
- **Highly Elliptical Orbits (HEO)** are characterized by a relatively low-altitude perigee (the orbital point closest to Earth) and an extremely high-altitude apogee (the orbital point farthest from Earth). These extremely elongated orbits have the advantage of long periods of visibility on the planet's surface, which can exceed 12 hours near apogee. These elliptical orbits are useful for communications satellites.
- **GEO Transfer Orbit (GTO)** is an elliptical orbit of the Earth, with the perigee in the LEO region and apogee in the GEO region. This orbit is generally a transfer path after launch to LEO by launch vehicles carrying a payload for GEO.

This methodology and algorithm is used to classify orbits based on their most recent orbital elements. It is not meant to classify other special orbits (heliocentric, planetocentric, selenocentric, barycentric, solar system escape, etc.).

Q4

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SPACE FOUNDATION

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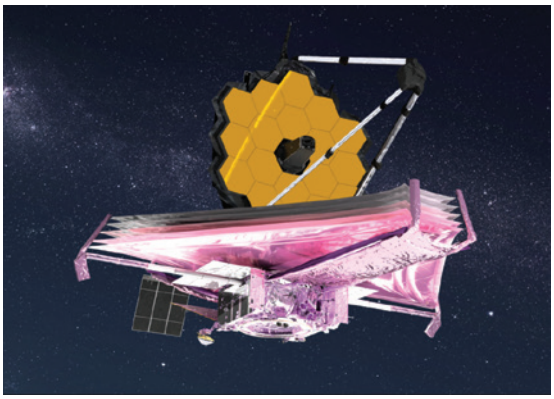
ABOUT THE COVER IMAGE:
NASA spacewalker Thomas Marshburn's camera points downward toward the International Space Station with the Earth 265 miles below him in this December 2021 photo. The Biden administration seeks to extend the life of the ISS to 2030, another six years beyond its scheduled decommissioning date.

Credit: NASA/MSFC/David Higginbotham

Introduction to *The Space Report* | Quarter 4

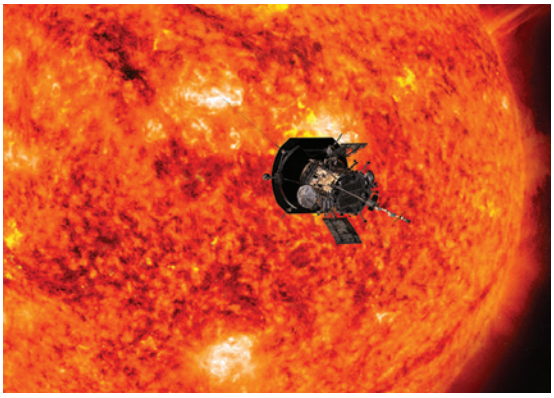
As 2021 ended, much of the world watched in awe as the James Webb Space Telescope, launched Dec. 25, began to unfurl it solar shield and bend its mirrors into a precise geometry with the promise to answer one of mankind's oldest questions: How did it all start?



This artist's conception of the James Webb Space Telescope in space shows all its major elements fully deployed.
Credit: NASA

Webb is a partnership between NASA, the European Space Agency and the Canadian Space Agency. Leaders say Webb, heading for a planned orbit 1 million miles from Earth, is the most powerful telescope ever launched. Using infrared imagery, it will peer back 13.5 billion years into the history of the universe.

Webb wasn't the only highlight for space scientists in the closing weeks of the year. Topping speeds of 364,000 mph, NASA's Parker Solar Probe whizzed closer to the sun than any earlier spacecraft, coming within 5.3 million miles of the sun's surface on Nov. 21. The Parker mission gathered data that will help scientists on Earth better understand how the sun works and the solar winds it radiates.



Artist's concept of Parker Solar Probe approaching the Sun.
Credit: NASA

The Webb launch, though, was the bookend for a frenetic final quarter for the busiest year in orbit Earth has seen since the Apollo era, as 2021 shattered records for launches, payloads, and tourism. *The Space Report* seeks to provide information and insight on all aspects of the global space industry by examining developing issues and offering long-term data analysis.

This edition of *The Space Report* looks back on 2021's accomplishments and peers ahead at what 2022 could offer.

1 | Space Infrastructure

The International Space Station (ISS) has been the cornerstone of microgravity research over the past 20 years but is nearing the end of its life. The Biden administration has committed to extending the life of the ISS to 2030, but between government and private interests, there are eight new stations already in development. NASA invested $415.6 million in commercial space station development as companies look to expand the low Earth orbit (LEO) economy and tap into three expanding markets: research, manufacturing, and tourism.

Orbital launch attempts and successful launches set new records in 2021, beating out 1967 with 145 and 134, respectively. While launch attempts broke records, the failure rate was still much higher than the past decade's average. China and the U.S. accounted for 73% of launch attempts last year, but China topped the list with 55 attempts compared to America's 51. The proportion of commercial launch missions continued a three-year growth trend, mostly due to the 31 commercial launches from the U.S.

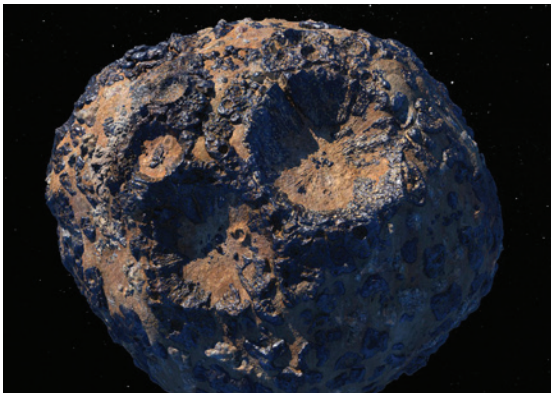


Illustration of the asteroid Psyche.
Credit: NASA

The rapid growth of commercial space enterprises has refueled debate on how mankind could exploit asteroid resources there, including one

metallic space rock that's thought to be worth tens of thousands of times more than Earth's annual gross domestic product. Industry leaders from around the world discuss the potential of asteroid mining and the international issues that have yet to be resolved.

2 | The Space Economy

While some space-sector stocks trailed other market indicators for the quarter, that didn't scare off investors. Equity financing activity in the space sector posted another near-record high in Q4 21, with 61 private investment equity transactions announced. Private investment activity was broad-based, and Enablement and EO/Geospatial led by transaction volumes with 23 and 16 transactions, respectively.

Space tourism took off in 2021, with 14 space tourists taking flight last year. From the dawn of the space age to the start of 2021, just seven space tourists had flown. Experts expect continued tourism growth in the foreseeable future.

3 | Space Products & Innovation

A commercial satellite venture set to orbit in 2022 promises the most comprehensive data from space to better predict weather and give scientists a clearer picture of global warming. The commercial satellites would join a new fleet of planned Earth-observing sensors set for launch by space agencies around the globe.

4 | Space Policy

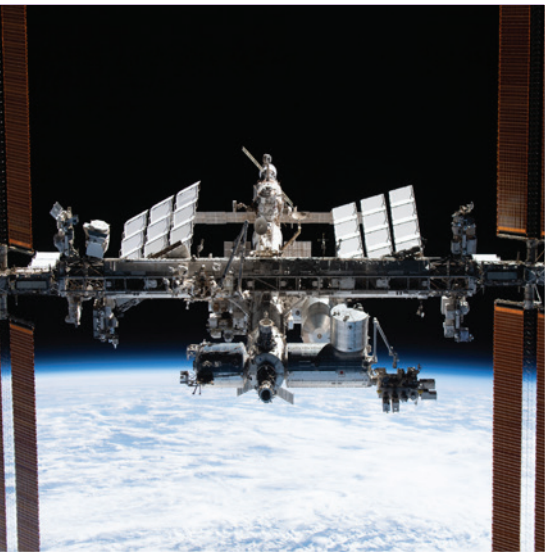
A Russian anti-satellite test in Q4 reignited calls for international rules to rein in spacefaring nations and limit orbiting debris. Space Foundation space law and political affairs intern Tuana Yazici takes a closer look at what it might take to reach a new international accord, examining debates surrounding the top three space law barriers to the future of international space — the Artemis Accords, the legality of anti-satellite (ASAT) weapons, and space debris mitigation — and other recommendations for the United States and other international actors.

Space Foundation asked a mix of policymakers, industry leaders, and leading experts to give their best estimates of what 2022 could bring. What are the challenges, the opportunities and what will take our collective breath away?

As you read this report

The data presented is a quarterly snapshot of global space activity.
To learn more, updates from *The Space Report* are available on a subscription basis, as are data sets that are not included in this document. To find the data you need, sign up today at:

TheSpaceReport.org



Introduction | *The low Earth orbit (LEO) economy is developing rapidly, and new infrastructure will help LEO activity continue to grow. While the International Space Station (ISS) is nearing the end of its life, there are eight confirmed LEO space stations in development, including China's space station, Tiangong. For the United States, private industry is getting involved in building and managing space stations.*

This photo shows the International Space Station and was captured during the first "fly-around" conducted by a Crew Dragon spacecraft.
Credit: NASA

The Next Space Stations: Building Blocks of an Orbital Economy

On the last day of 2021, the Biden administration announced it would extend operations of the ISS until 2030, working with the space agencies of Europe, Japan, Canada, and Russia, to provide use of the station for another six years.[1] The expressed commitment will require funding approval from Congress, and renewed agreements from each cooperating agency.[2] In announcing the decision, NASA Administrator Bill Nelson emphasized what the 20-year operation of the station has meant and will continue to mean.

"The International Space Station is a beacon of peaceful international scientific collaboration and for more than 20 years has returned enormous scientific, educational, and technological developments to benefit humanity," he said in a statement. "The United States' continued participation on the ISS will enhance innovation and competitiveness, as well as advance the research and technology necessary to send the first woman and first person of color to the Moon under NASA's Artemis program."

Over the last two decades, the ISS has hosted more than 3,000 scientific research and technology development projects from researchers in 108 countries, according to NASA. Some of those tests led to products that now earn billions of dollars for companies that developed them. But the station's contribution extends well beyond use as a research platform. ISS helped spur the growth of the CubeSat market by launching hundreds of payloads, offered some of the earliest space tourism opportunities, and accelerated scientific understanding of what long-term habitation in space requires — knowledge that will provide a foundation for building off-world communities on the Moon and Mars.

That track record underpins why the United States, China, Russia, India, and private interests are pursuing new space station development. Not maintaining a station in low Earth orbit risks losing traction on scientific advancement and future revenue streams, but worse, creates potential that other nations will gain ground in the evolving LEO economy.

Timeline of Upcoming Space Stations

All the announced space stations plan to have at least their first modules up by 2030, the new target date for decommissioning the ISS, but China is well ahead of that timeline. The first module of its Tiangong station, which is expected to operate 15 years, is operating in orbit. Its second and third modules, which will complete the station, are

expected to be completed this year. Earlier this month, the China Manned Space Agency announced testing of the station's robotic arm had been successful.[3]

China has released that it has more than 1,000 tentative experiments lined up to perform on the station.[4] Most of these experiments are from Chinese researchers who have been unable to collaborate on the ISS because of the Wolf Amendment, which prohibits NASA from collaborating with China on scientific research.

Russia has its own space station in development to use after the ISS is retired, the Russian Orbital Service Station (ROSS). This is in part related to political tensions, as Russia had threatened to leave the ISS in 2024 due to sanctions imposed by the United States.[5] Although Russia eventually retracted this statement, the first module of ROSS is still supposed to be launched within five to six years, and the design will be adapted from a research and power module that Roscosmos was originally planning to send to the ISS in 2024.[6]

India plans to launch its station by 2030.[7]

While the United States evaluates the longevity of ISS, NASA has also turned to U.S. companies to design and operate the next space stations.

In 2020, NASA awarded Axiom Space a $140 million contract for a habitable commercial module that would attach to the ISS.[8] Axiom is aiming for the first module to be attached by 2024.

NASA founded the Commercial LEO Destinations (CLD) project in 2021 to develop space stations and other commercial destinations in space. It had initial interest from 52 groups and received about a dozen proposals at the end of August.[9] NASA announced the three awards in December 2021, which were granted to Nanoracks, Blue Origin, and Northrop Grumman.[10]

Nanoracks' Starlab will be deployed in a single launch in 2027. Orbital Reef, managed by Blue Origin and Sierra Space, is targeting between 2025 and 2030 to launch. The Orbital Assembly Corporation is designing multiple classes of stations, but the company states that the first, Gravity Ring, will be operational by 2023. The newly announced Northrop Grumman station does not have a target date yet.

NASA Commercial LEO Destinations Awards

Company	Awarded Amount
Nanoracks (Starlab)	$160 million
Blue Origin (Orbital Reef)	$130 million
Northrop Grumman	$125.6 million
Total Awarded	$415.6 million

While costs to develop a commercial space station will likely be drastically lower than the $150 billion NASA alone spent on the development of the ISS, estimates have varied widely and will not be reliable until space station designs are more concrete.

The earlier a space station is operational, the more time its owners will have to grow a customer base before facing potential competition. Nanoracks' Starlab station is designed to be placed into orbit in a single launch, which drastically reduces costs and allows the station to be tested and cleared for human activity much sooner. Axiom Space's station, by attaching to the ISS, can build its user base early and eventually transfer continuing research to its own station when the ISS is retired.

Credit: Nanoracks

At a Glance: Starlab

Partners: Nanoracks, Voyager Space, Lockheed Martin

Starlab will be continuously occupied by four astronauts focusing on scientific research. The station will have a volume of 340 m^3, about a third the size of the ISS.

Starlab will host the George Washington Carver Science Park, which is currently operating on the ISS. The leadership team will be: The Universities Space Research Association, SIN Technologies, The Ohio State University, and the International Association of Science Parks and Areas of Innovation.

A Developing Platform

Since it became operational, the ISS has slowly shifted to allow more commercial activities on board. The three main business cases on space stations thus far are microgravity research, in-space manufacturing, and tourism.

The ISS U.S. National Laboratory, in charge of non-NASA U.S. activities on board, has partnered with 10 companies to bring 18 permanent commercial facilities that fit into the broader category of on-orbit servicing, assembly, and manufacturing (OSAM). This includes three deployers managed by Nanoracks that have deployed 262 CubeSats as of June 14, 2021.[11]

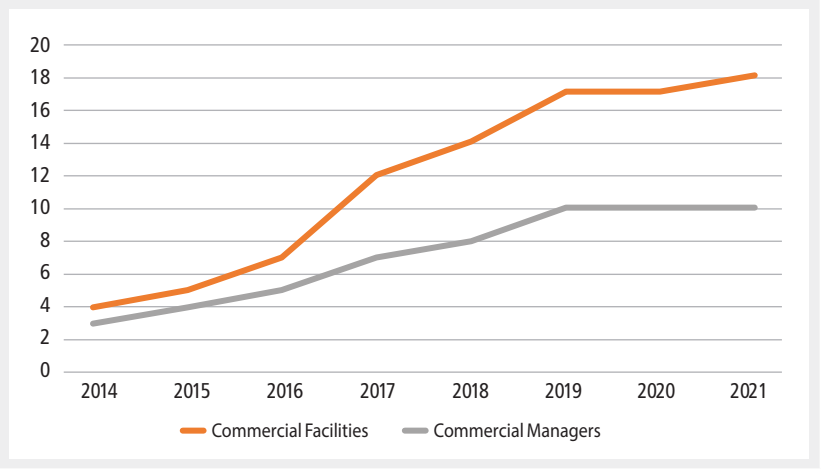
In the area of microgravity research, some of the advancements developed in space have fueled business development on Earth:

- The U.S. pharmaceutical company Amgen in the early 2000s used the microgravity environment on space shuttle missions to the ISS to test three drugs. These included Denosumab, which it sold as Prolia, for the treatment of osteoporosis, and later, Xgeva, to treat bone metastases from several forms of cancer.[12] In 2020, the two drugs generated $4.6 billion in sales for Amgen.[13]
- From 2013 to 2016, Planet Labs used the ISS to launch 110 Earth-imaging satellites, subsequently proving the feasibility and utility of providing daily photographs of the planet's surface.[14] In fiscal year 2021, Planet's reported revenue was $110 million, and projections for consolidated revenue in FY2026 are $693 million.[15]
- A device initially used to measure how much nitric oxide astronauts exhaled was developed by the Swedish company Aerocrine to diagnose and control airway breathing issues for asthma and allergy patients.[16] In 2015, U.K.-based Circassia Pharma acquired Aerocrine for nearly US$219 million.[17] By June 2021, Circassia had provided testing to 40 million patients worldwide.[18]

Some commercial facilities on the ISS, such as the Additive Manufacturing Facility (AMF), are serving as technical demonstrations for in-space manufacturing. Manufacturing in microgravity has benefits for Earth use, such as the optical ZBLAN fibers produced by Made in Space, now owned by Redwire, which have a much lower chance for defects than those produced through traditional manufacturing processes.

Current transportation costs and capacity restraints make full-scale manufacturing of products on the ISS largely experimental. Christian Maender, director of In-Space Manufacturing and Research at Axiom Space, anticipates that "lower-mass, high dollar items" will be most feasible initially because they will be easier and cheaper to return to Earth, and their price could offset the high costs of manufacturing on orbit.

ISS National Laboratory Commercial Facilities



Source: ISS National Laboratory Annual Reports

Space tourism also evolved on the ISS. Russia partnered with Space Adventures in the early 2000s to bring tourists to the station before it reached full crew capacity. In the past couple of years, it has become feasible for private astronauts to return to the ISS, such as the Japanese billionaire Yusaku Maezawa. NASA has also included private astronaut missions in its commercial and marketing pricing policy, and Axiom Space plans to send the first fully private astronaut crew to the ISS in 2022.

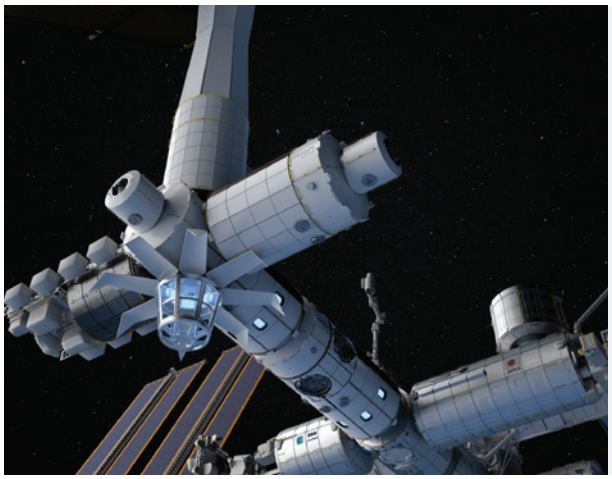
Supply and Demand

The capacity for in-space research, manufacturing, and tourism in LEO likely will increase dramatically over the next decade as more space stations are launched, but this underdeveloped market could lead to an initial mismatch between supply and demand.

There are indicators of growing commercial interest in microgravity activities, such as the number of experiments China has accepted; however, the NASA Office of Inspector General cautions that the commercial market in LEO is not robust yet and will likely need to be heavily supported by the government for at least the near future. NASA will serve as an anchor customer on one or more commercial space stations projects and estimates that its demand will be two dedicated astronauts performing about 200 investigations every year.[19]

For the short term, the main demand for LEO research will continue to come from governments rather than the commercial sector. Beyond NASA, other space agencies such as the Japan Aerospace Exploration Agency (JAXA) will likely be customers on commercial space stations. Axiom announced that Mitsui & Co, a Japanese trading house, is investing in the company with plans to potentially add a Japanese module to its space station. While the module may not be affiliated with JAXA, this partnership will give Axiom "a global network to help [it] generate commercial demand".[20]

NASA's investment in commercial space stations through the CLD project provides companies seed money, but it also serves as an unofficial endorsement for other investors. Adrian Mangiuca, vice president of infrastructure at Voyager Space, a partner in the Starlab station, said that this "stamp of approval" from NASA is incredibly important for the technical legitimacy of a space station design. Even with that, he said, "patient capital" is a big need for space stations because payback periods will most likely be a lot longer than other investments.



Credit: Axiom Space

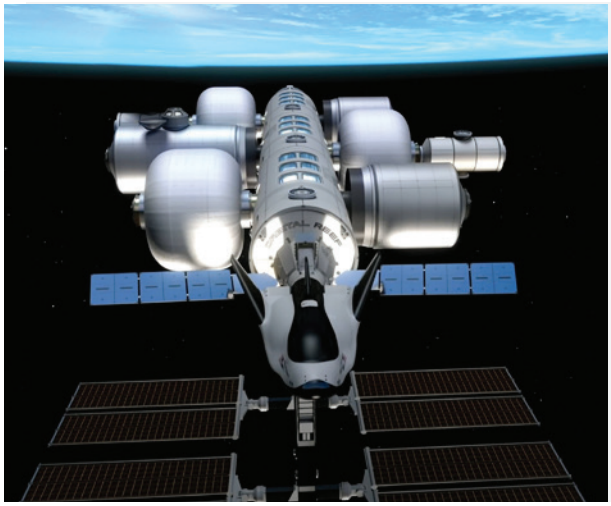
At a Glance: Axiom Station

Partners: Axiom Space and NASA

In 2020, NASA awarded Axiom Space $140 million to develop "at least one habitable commercial module" for the ISS. Axiom aims to connect a total of four modules to the ISS, which will expand the ISS' usable space to almost twice what it is now.

Two of the modules are "hubs" for living and research, while there will also be a research lab and a power and storage module. Axiom plans to launch the first module, manufactured by Thales Alenia Space, in 2024.

Other recent investment activity suggests industry confidence in the future of commercial space stations. Axiom Space raised $130 million in a Series B funding round in February 2021.[21] Sierra Space also announced a Series A funding round in November 2021 that raised $1.4 billion.[22] This funding is going to be split between the Large Integrated Flexible Environment (LIFE) module and the Dream Chaser spaceplane, both of which are contributing to Orbital Reef.



Credit: Sierra Space

At a Glance: Orbital Reef

Partners: Blue Origin, Sierra Space, Boeing, Redwire Space, Genesis Engineering Solutions, Arizona State University

Orbital Reef is going to be slightly smaller than the ISS in volume but will be able to host 10 people at a time. Many of the companies involved have been developing technology that can be applied to Orbital Reef since before the announcement of the station, such as Blue Origin's New Glenn reusable rocket that has enough power to lift heavy loads to LEO.

Blue Origin will be responsible for the core module(s) of the space station, while Sierra Space's Large Integrated Flexible Environment (LIFE) habitat will also be integrated as a module.

Mitigating Risk

Given the risks associated with entering the LEO economy, some stations, rather than targeting a specific business segment, are taking a flexible approach to their design.

By building modular stations, companies can start small in orbit and expand as demand grows. Christian Maender, director of In-Space Manufacturing and Research at Axiom Space, stated that there's not "going to be any one market" that is best to target at first, and flexibility is an important aspect of the Axiom station in development. This flexibility allows for stations to grow strategically to serve customer needs and target specific markets as they emerge, especially as different industries will scale differently in LEO.

Blue Origin describes its own space station, Orbital Reef, as a "mixed-use business park" that can accommodate a wide variety of customers whether their purpose is research, manufacturing, or tourism.[23] Attaching new modules will allow for companies or space agencies to target their own needs without extraneous costs. Brent Sherwood, senior vice president of advanced development programs at Blue Origin, spoke at the 2021 ASCEND conference about how Orbital Reef's flexibility benefits new entrants to space. He stated that "by simplifying at the interface what their module could be" and placing most of the complex technology in the core modules, it "lowers the bar for them to get into space faster".

Nanoracks announced it is partnering with Lockheed Martin and its parent company Voyager Space to launch Starlab by 2027. Mangiuca stated that the station is focused on "user-needs-based design" and is working with existing customers that have the interest and the ability to pursue research in space. The station will be continuously occupied by four astronauts focusing on scientific research. The Nanoracks CEO said that, while space tourism will be a possibility on Starlab, a business model based on science is more sustainable.[24]

Orbital Assembly Corporation is developing multiple series of stations with different uses, but its Voyager-class station is gaining the most interest. These stations will also have an almost entirely tourism-based business model and are described

by the company as a "luxury hotel" in space.[25] The design is unique because of its ring shape that can simulate varying levels of artificial gravity. While microgravity is beneficial for research, it can also be harmful to humans, so including an artificial gravity element in a tourist space destination could mitigate some health risks.

Onward to Deep Space

While the commercial LEO economy develops, some government space agencies have begun shifting their sights to more distant space exploration. Transitioning to commercial space stations in LEO allows NASA to spend more time and money on programs such as Artemis. NASA estimates it will save $1 billion a year — about 25% of its current ISS operating costs — if it invests in commercial space stations.[26] China and Russia are collaborating on a lunar space station as a combination of the two countries' original lunar exploration plans. Russia announced the collaboration of the International Lunar Research Station (ILRS) after turning down NASA's offer to partner with the Artemis program. The location of the ILRS is still unknown, as there are discussions about whether the station should be in lunar orbit or on the surface of the Moon.

Credit: NASA

At a Glance: The Gateway
Partners: NASA, ESA, CSA, JAXA

The first two modules to be launched for the Gateway are the Power and Propulsion Element (PPE) and the Habitation and Logistics Outpost (HALO). NASA has contracted SpaceX to provide the launches and plans to launch both modules at the end of 2024.

The PPE is the 60-kW primary energy and communications module developed by Maxar Technologies. The HALO is the main control module developed by Northrop Grumman and will serve as the living quarters for the initial crew members. Visiting spacecraft and new modules will be attached to the HALO.

NASA is building a lunar station, the Gateway, as part of its Artemis program to return to the Moon. The agency is working with JAXA, the European Space Agency (ESA), and the Canadian Space Agency (CSA) to build and operate the station. The Gateway is intended to be a research facility and a base for lunar exploration activities; crews will be able to dock and live on the station while taking trips down to the Moon's surface as needed. The location of the station will also provide research opportunities in deep space.

However, to develop and test the technology necessary to return to the Moon and on to Mars, agencies still need an accessible microgravity platform. NASA projects that out of four human health research topics necessary for the Artemis lunar landing and eight more topics necessary for Mars exploration, only four will be completed by 2030.[27] After the ISS is retired, commercial space stations offer an efficient platform close to Earth to complete this research, although the Gateway may be used for some extended mission simulations.

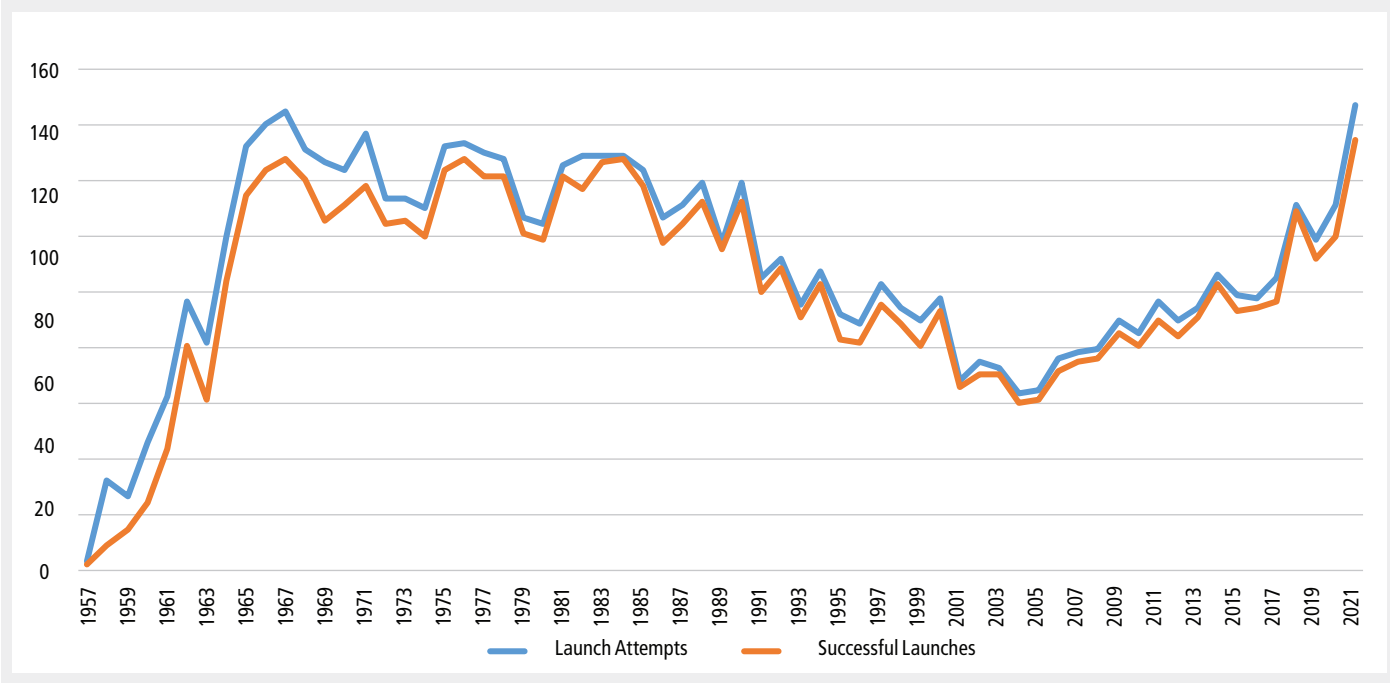
Zoe Hobbs is an economist and research analyst at Space Foundation. She can be reached at ZHobbs@SpaceFoundation.org.

Introduction | *Successful launches soared past annual records in 2021 with 134, beating out the previous record of 128 launches, last met in 1984. Chinese launches grew by 40% and placed the country first with 55 launch attempts in 2021. Commercial missions continued to grow at a faster rate than military and civil government missions. This trend was driven by the United States, which had more than three times the commercial launches of any other nation.*

A SpaceX Falcon 9 stands on the launch pad on Dec. 8, 2021, the night before launching NASA's Imaging X-ray Polarimetry Explorer (IXPE). The Falcon 9 Block 5 was the most-used vehicle of 2021 with 31 launches – and 30 successful first-stage landings.
Credit: NASA/Joel Kowsky

Launch Analysis: 2021 Sets Record for Successful Orbital Launches

Successful Orbital Launches, 1957-2021



Source: Space Foundation database

With a record 145 orbital launch attempts, 2021 climbed past the Apollo era, surpassing the old mark set in 1967 by two launches. The year also beat the previous record for successful orbital launches by six.

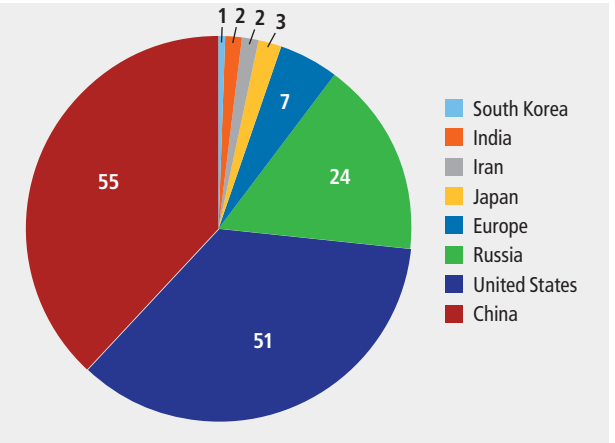
The average number of payloads per launch in 2021 edged out 2020's record mark, up to 11.9 from 10.7. Driving the payload hike were 989 Starlink and 284 OneWeb satellites which rocketed to low Earth orbit to deliver internet services to users below. SpaceX's Inspiration4 was the first commercial orbital launch mission to take to space. Two Russian missions delivered private astronauts to the International Space Station, and 2021 tied for the most crewed orbital launches with nine flights.

Orbital Launch Attempts by Country

Three nations primarily drove the launch increase: China, Russia, and the United States. The U.S. saw a 16% increase in launch attempts in 2021. China recorded a 41% increase. While Russia hit a decade low for launches in 2020, it doubled its attempts in 2021 with 24.

The big three accelerated launches in 2021, but other cooperative space bodies trended down. Europe and Japan launched fewer rockets compared to 2020, and Israel did not attempt a launch in 2021.

Global Orbital Launch Attempts, 2021

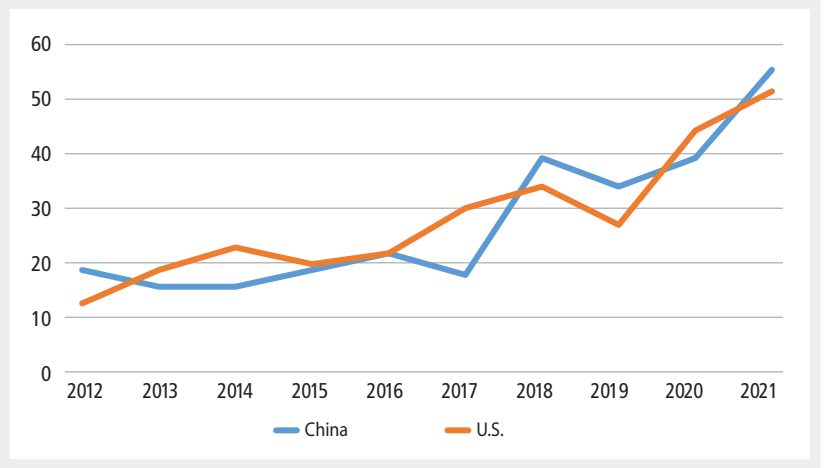


Source: Space Foundation database

The China Aerospace Science and Technology Corporation (CASC), which stated in 2020 that it wished to reach 40 launches in 2021[1], exceeded its goal with 48. China had 55 launch attempts – the most by any country last year. China also reached a milestone of 400 orbital launches of the Long March vehicle family, approaching the records of America's Atlas and Russia's Soyuz families.

China's launches put that nation back into first place for total numbers in 2021, a title it has regularly traded with the United States over the past decade. The U.S. has been first in five years, China has been first in four years, and the two countries tied for the launch crown in 2016.

Total Orbital Launch Attempts by China and U.S., 2012-2021



Source: Space Foundation database

Launch Failure Rate

With three unsuccessful launches, the industry was on track for a relatively low failure rate of 4.8% by midyear, but anomalies hit later in 2021. The year's second half brought seven launch failures and one partial failure – three of which were new launch vehicle flights. The first half of 2021 had looked even better before the Pentagon later confirmed a June 12 launch failure in Iran.[2] While the annual failure rate of 6.9% was lower than 2020's 10-year high of 8.8%, it was still the second-worst year for failed launches in the past decade.

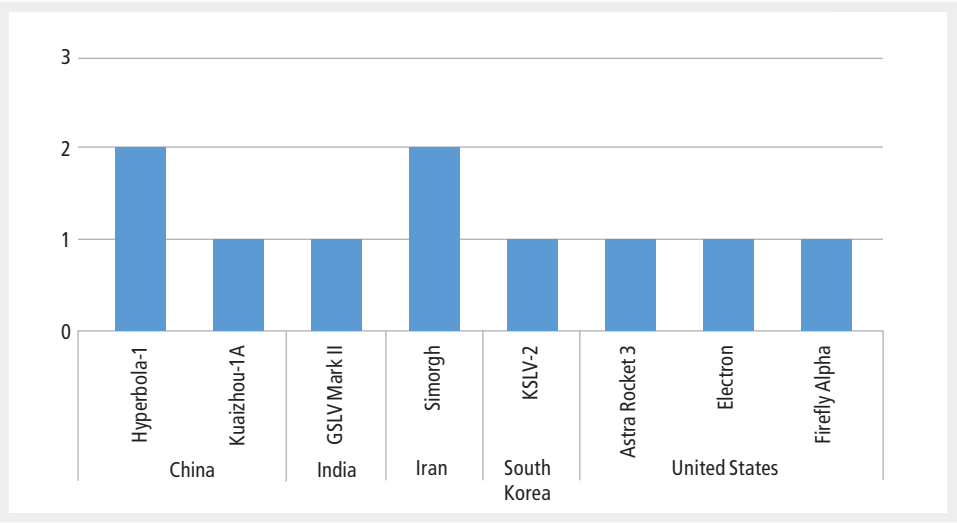
Year	Failure Rate
2012	6.4%
2013	3.7%
2014	2.2%
2015	4.7%
2016	2.4%
2017	6.6%
2018	1.8%
2019	5.8%
2020	8.8%
2021	6.9%

Source: Space Foundation database

China and the U.S. saw similar trends in failed launches for 2021 with three each. China's Hyperbola-1 launch vehicle failed in its second and third attempts after a successful maiden flight in 2019, and Iran's Simorgh rocket failed both of its 2021 launches.

South Korea attempted its first launch since 2013 with the maiden flight of the KSLV-2 but failed to reach orbit. The South Korean launch was one of three attempted launches of new vehicles in 2021, less than half as many as 2020. All three new vehicles experienced partial or complete failure.

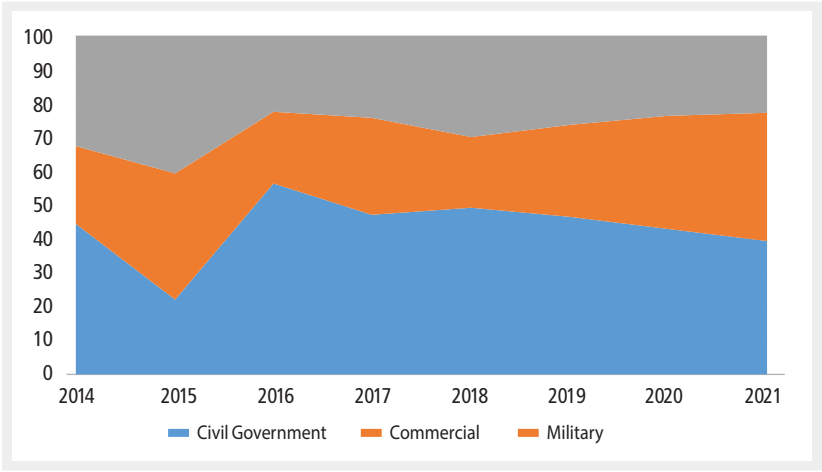
Launch Failures by Country and Launch Vehicle, 2021



Source: Space Foundation database

Reusable vehicle launches reached an all-time high of 32. SpaceX's Falcon 9 Block 5 was responsible for 31 recovery attempts and had a success rate of 96.8%. Rocket Lab's Electron vehicle was launched once in 2021. Although the upper stage suffered a failure, the Electron's first stage was successfully recovered from the ocean. No new operators attempted to recover a first-stage booster in 2021.

Global Launch Attempts by Mission Sector, 2014-2021



Source: Space Foundation database

Orbital Launch Attempts by Mission Sector

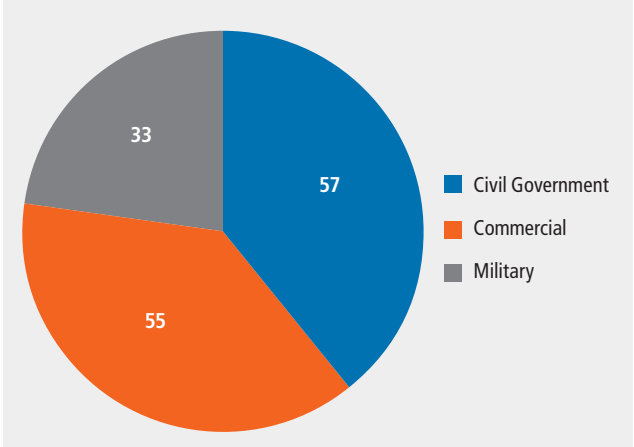
Commercial launch missions continued a three-year growth trend, causing the proportion of civil government and military missions to shrink in 2021. However, the number of launches grew in all three sectors, with commercial missions leading the increase.

The civil government and commercial sectors make up around 80% of all launches and were almost equal in 2021 with 57 and 55 launch attempts respectively.

Commercial missions made up 38% of launch attempts worldwide in 2021. The proportion varied greatly between countries, making up 60.7% of U.S. launches, while China had a more modest 16%. Russia reversed several years of sluggish commercial launch activity with eight launches for the OneWeb satellite constellation in 2021. Russia also welcomed its first space tourists since 2009, with private astronauts on two civil government launches to the ISS.

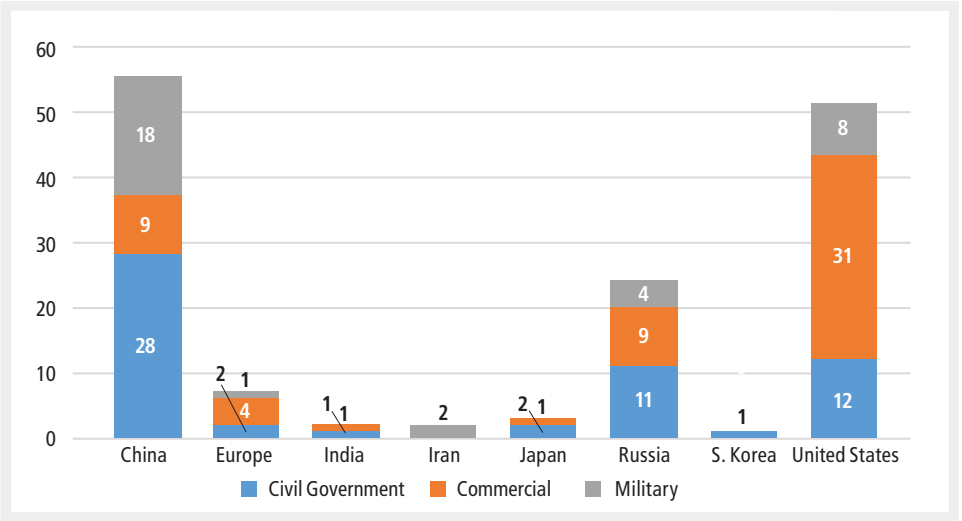
Like commercial trends, military missions widely varied between countries. The sector accounted for about 17% of 2021 launches in Russia and the U.S., while 32.7% of Chinese launches were military missions.

Global Launch Attempts by Mission Sector, 2021



Source: Space Foundation database

Launch Attempts by Country and Mission Sector, 2021



Source: Space Foundation database

Looking ahead to 2022

Orbital launches in 2022 are expected to keep up with 2021's record-setting pace. SpaceX and OneWeb plan to launch more satellites for their mega-constellations in 2022. SpaceX completed the first launch of the year on Jan. 6, sending another swarm of Starlink satellites into orbit.[3] China's space agency announced a goal for 40 launches in 2022, including six missions to complete its space station, Tiangong.[4]

New launch vehicles are expected to rocket to space in 2022, including NASA's planned launch of the Artemis I mission, an inaugural test of the agency's Space Launch System (SLS) after years of delays. SpaceX has announced plans to launch its Starship for the first time, and CASC plans to debut the Long March 6A.

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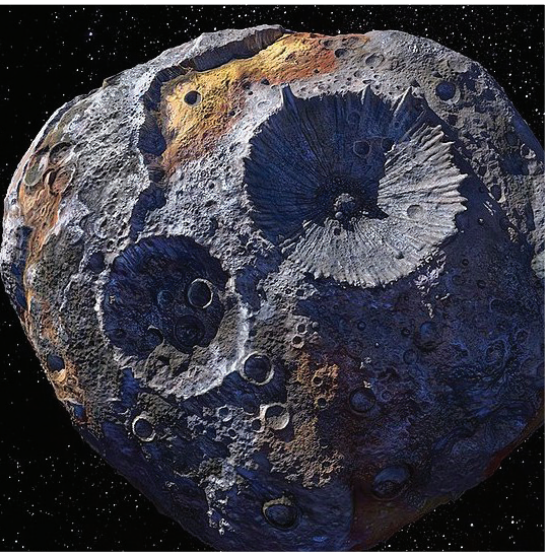


Introduction | *Mankind could soon be able to exploit asteroids to obtain natural resources for use on Earth, gather ingredients for missions in space, and support habitation on the Moon and Mars.*[1] *In the following article, some leading industry experts discuss how to mine in the absence of gravity, how mining could pollute space, and ownership of the resources taken from the asteroids.*

Artist's concept of the asteroid Psyche, believed rich in nickel and iron, and the focus of a NASA mission that launches this year.
Credit: NASA

Asteroid Mining: Potential Develops, but so do Regulatory, Technical Issues

Gathering mineral samples from asteroids is no longer science fiction. Japan has its Hayabusa missions; the United States Osiris-Rex. China and Russia have a joint mission planned, and United Arab Emirates has set an ambitious plan for a 2028 mission to the asteroid belt.

In August, NASA plans to launch a probe to explore Psyche-16, a metal-rich asteroid that orbits between Mars and Jupiter. The asteroid has drawn interest since the 1990s when observations, including pictures from the Hubble space telescope, showed it could be the metallic core of a proto-planet. That could mean Psyche-16 offers a bonanza of riches, with some envisioning a Massachusetts-sized block of iron, nickel, and more valuable metals. Some have estimated its worth at $10,000 quadrillion — tens of thousands of times more than Earth's annual gross domestic product. More recent research found the asteroid may be more rubble pile than a space-based treasure chest. And even if Psyche is as valuable as early assessments suggest, bringing the riches home means a 460-million-mile commute through space with mining equipment that hasn't been invented. NASA's probe will take almost four years to reach it.

Rather than seeking fortune in the cosmos, NASA's Psyche probe could give scientists a look into how planets are formed. The agency said the spacecraft, equipped with cameras, a magnetometer, and a spectrometer to determine what makes up the asteroid, will deliver a "look inside terrestrial planets, including Earth, by directly examining the interior of a differentiated body, which otherwise could not be seen."

But some on Wall Street see financial potential too enticing to ignore once mankind can mine in space.

By 2023, the Asteroid Mining Corporation plans its first mission. While asteroid mining hasn't developed as quickly as expected, the future imagined is beginning to take shape. As progress happens on the technological front, many argue the current legal framework in outer space does not sufficiently address the appropriation, extraction, and utilization of space resources. With potential valuations of trillions and quintillion dollars, concerns also have been voiced that the appropriation and excavation of asteroid resources should be regulated to benefit all nations.[2]

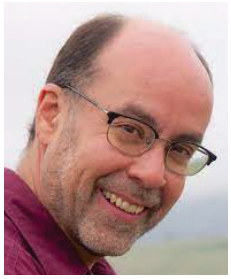

Christopher Dreyer

What's The Greatest Potential For Asteroid Mining?

The value of asteroid mining depends on the asteroid's location and the value of the materials it contains, explained Christopher Dreyer, the director of engineering of the Space Resources Center at the Colorado School of Mines. Dreyer studies space objects with an eye on "value chain from resource identification to production of products."

As in any real estate transaction, asteroid value is tied to location.

"One of the great values of asteroids is that we have them in a location that makes them more usable for the purposes we have in space," Dryer said. "We don't have to launch materials on a rocket. We could mine an asteroid and use the materials to construct things in space. I make a distinction between use in space and return to Earth. Returning materials to Earth is often what people think about when you hear about asteroids and asteroid mining. But making a successful business plan where you're trying to return a valuable resource to Earth, like platinum, for instance, and compete against terrestrial platinum would be challenging."


Angel Abbud Madrid

Angel Abbud Madrid, who heads the Colorado School of Mines Space Resources Center, said a substance that's common on Earth is a mining target in space.

"The resources from asteroids are attractive, because first of all, some of them the carbonaceous ones have up to 20-22% of water," he said. "Water, it's essential for transportation because you can heat it up and use it as steam, you can separate it into hydrogen and oxygen, which is the most energetic propellant known to humans. You can heat it up to a point of a plasma so then you can use it as another way of propulsion. You can use it for drinking if you have humans around and as a radiation shield, so water is probably one of the most important elements from an asteroid."


Jamal Rostami

Jamal Rostami, who heads the Earth Mechanics Institute at the Colorado School of Mines and has worked on a NASA project on mining technology beyond Earth, said finding resources in space for use in space make asteroids an attractive mining target.

"What makes asteroids actually attractive is that you don't have to go there. They come to you," he said. "If you look at it, in this perspective, people think: 'Wait a minute, I don't have to go anywhere. All I have to do is essentially be out there, cast the net, and be able to beam some sort of an exploration system out and look at the components of these asteroids. And if I like what I see, if I like the composition, just go ahead and capture it as it's coming near you.' And that's what makes asteroids very attractive. The fact that they're coming to you, now that you don't have to go millions of kilometers or miles to get there."

What's The Likely Timeline For Asteroid Mining To Move From Experimental To Routine?

"Timelines are hard to predict, but I think the first uses which could become routine would happen in about 10 years," Dreyer said. "Beyond that, I think within 20 years, we'd probably be looking at kind of the similar kind of experimental mining of main belt asteroids. And then that becoming routine, the decade after in the 30-year timeframe."


Tanja Masson-Zwaan

Tanja Masson-Zwaan, deputy director of the International Institute of Air and Space Law at Leiden University, said asteroid mining will likely begin on the Moon.

"I think we are definitely going for using resources in space," she said. "And water on the moon will be the first thing we will be doing that for various purposes: in-situ utilization. But eventually it will be asteroids, it's much more complicated. And possibly, at some point, also bringing them back to Earth. But that's more futuristic than the first steps. It will be incremental."

How Will Asteroids Be Mined?

The answer from Madrid might be "very carefully."

"You do not land on an asteroid, you dock to it," he said. "And so it's going to be an operation, you have to ground yourself, you anchor yourself. So, you're going to have to create techniques that are different from the ones that we use here on Earth in order to excavate, to drill, to extract resources. We can no longer use just normal excavators. There's no traction. And so, you're going to have to become creative."


Ian Christensen

The sheer variety of asteroids in space poses a technical challenge for would-be miners, said Ian Christensen, director of private sector programs at the Secure World Foundation.

"On the technical side, I'm not sure that we fully understand the nature of these bodies, these asteroid bodies, and which ones will have extractable resources and which ones won't," he said. "And then the types of extraction approaches that will be necessary on different bodies. Because one asteroid may be a rocky pile, another asteroid may be a semi contiguous metal body, and another one, maybe a loosely aggregated pile of dust."

Rostami said asteroid miners will need to move quickly.

"The greatest challenge in asteroid capture is that asteroids are moving pretty darn fast," he said. "So, yes, they're coming towards you, but intercepting an asteroid is going to be quite challenging. If you study dynamics, you realize the concept of inertia, which is mass times velocity squared. … Imagine something moving at a speed of several kilometers per second, because these asteroids are typically the product of collision or product of explosion of planets."

Mining on Earth has been a messy business that only in the past century has faced clean-up regulations. Masson-Zwaan said those could come early for space miners.

"To avoid errors that we have perhaps made on Earth with mining or other ventures, we should not go for the tragedy of the commons and think things over early on," she said. "And that also includes the environmental aspects of it."

Which Asteroids Are Most Likely To Be Mined?

There are more than 20,000 asteroids that roam the solar system in orbits between the Earth and sun. These asteroids are generally separated into different classes according to their composition. Mining effort will focus on M-type (metallic), S-type (stony), and C-type (carbonaceous) asteroids.[3] The M-type asteroids are rare but hold precious metals, such as iron

that can be used for manufacturing, gold, and metals from the platinum group. S-type asteroids carry other metals, such as nickel and cobalt but also silicate-based metals.[4] Water for propulsion, life support, and radiation shields can be extracted from the most common asteroid type, the C-type asteroids.[5] Dreyer said these near-Earth asteroids are the most likely targets for mining because they are closest at hand. But that won't make things easy.

"One example (is the) possibility of finding the right asteroid, the right time, the right type, just passing by Earth when you're ready to go," Dreyer said. "If you can't find the right asteroid for that, you need to spend a fair amount of time traveling to the asteroid, then a long time at the asteroid until orbits match up again, and then return. So there's kind of these two branches, you either have these particular types of things you can mine over in less than a year, or you have to spend many years mining the asteroid just to deal with the orbital mechanics."

Far greater than the technical challenge, Madrid said, is the economic one.

"If there is no economic reason for doing this it is not going to happen... If it is just too costly, it's going to make it very challenging to justify the concept of asteroid mining," he said.

How Are Asteroid Miners Regulated Now?

No international regulations currently exist on space mining, which led some nations to implement their own regulations. The United States in 2015 implemented the U.S. Commercial Space Launch Competitiveness Act, which gives businesses and individuals the right to own the resources they mine.[6] Luxembourg, Japan, and the United Arab Emirates have since passed similar laws.[7]

"Their interpretation is there's no conflict between applicable international law and their national laws that say basically asteroids can be mined," he said. "The laws basically say their citizens can mine an asteroid, take the material they've mined, and then transfer ownership."


Andreas Losch

Mining operations have been messy on Earth, tearing up the landscape and sowing toxic waste. At the University of Bern in Switzerland, ethics professor Andreas Losch fears asteroid mining could follow a similar path.

"The greatest challenge is not to mess up again, as humankind likes to … and I'm afraid that this is maybe... that we are partially on track to have the wild, wild west scenario again," he said. "But on the other hand, we have a strong sustainability discussion, and I hope that this discussion will prevail."


Jinuan Su

Jinyuan Su, who teaches space law at China's Wuhan University, said it could take time for laws and treaties to catch up with asteroid mining.

"Law is usually reactive to reality," he said.

The only international law that currently applies is the Outer Space Treaty, a pact between spacefaring nations that prohibited space-based nuclear weapons and blocked nations from claiming

territory on the Moon and other celestial bodies. A battle of what space objects could be deemed celestial bodies looms, Su said.

"That's not a settled question," he said. "And I think this is a question that we should address in the future."

If Asteroid Miners Strike It Rich, How Should That Money Be Distributed?

On Earth, mining firms are forced to share the wealth in the form of taxes and fees. Most of the participants interviewed here voiced concern that imposing a structure that would restrict the growth of this sector is the wrong approach. Asteroid mining companies should have the freedom to develop and not be hindered with tax restrictions, which could decrease investor interest needed to mature the industry.


Temidayo Oniosun

Temidayo Oniosun, managing director at Space in Africa and a member of the International Astronautical Federation, holds a different opinion.

"Some are of the opinion that, we should just allow the industry to grow, allow people to do whatever they feel like, and maybe when the industry grows to like a reasonable extent, then they can bring in policies to help them," he said. "I think that a lot of people think asteroid mining is going to be a win for the entire world. But I don't think so. Because if even American company goes to mine asteroids, yeah, it's gonna be in the news and say: 'Oh, yeah, this is the first time humans will do an asteroid to mine, or whatever'. But I don't think that is a win for Africa, for example. Neither do I think that's a way for people in Latin America, or in Southeast Asia.

"For me…if you go to outer space to mine resources, you should use a portion of your revenue you make from that. So fixed fees. And when I say fixed fees, that means to fix the problems of debris. So if a U.S. company goes to space and mine asteroids, let's say they generate a billion dollars from that. No one is saying they should share the $1 billion with all countries. No. Well, they should be held responsible for certain things like space debris. …This is not just against asteroid mining, this is also applicable to like all space companies that are sending satellites, rockets, and all of it. It's applicable to all of them. A portion, a tiny portion of whatever revenue these guys are making, should go into research and development that addresses the separate issues."

Losch agrees there should be international discussion and agreement about fair distribution of resources from space. "Space is international domain, and so it actually belongs to everyone," he said. "But does that mean everybody can just take everything? That wouldn't work."

Masson-Zwaan said while the 1967 treaty requires shared ownership of objects in space, it doesn't dig into topics like asteroid mining. Because mining in space hasn't begun, laws on the industry haven't been written, she said.

"We should also keep an open eye and not try to put everything down in stone from the start," she said. "Adaptive governance is... a wise approach to such a completely new, very complex, very expensive, very risky business like this is."

Rostami said regulating a business that still seems more like science fiction than fact poses difficulties.

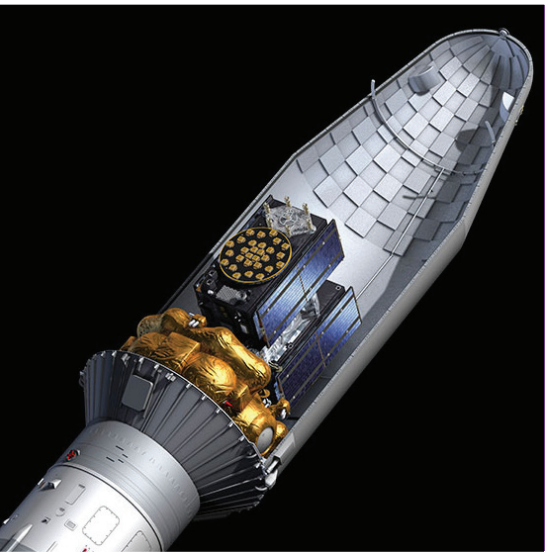
"I'm hoping that in the next few years, we have a better framework of even thinking about it …," he said. "But in reality, until and unless some incidents happen, we cannot even think of the laws beforehand."

How could space mining be regulated?

Some international agreements may provide guidance for space law. Su points to the Commission for the Conservation of Antarctic Marine Living Resources, established by international convention in 1982, and, to lesser success, agreements over international seabeds.

"One of the rationales behind the benefit-sharing argument is that these are the common heritage, common heritage of mankind. And it makes good sense, if we say that the Earth planet is the common heritage of mankind, because we are simply a steward of the planet for our future generations, it would make good sense," Su said. "But when it comes to outer space, are we also the stewards of the whole universe? Do we all own universe, you know, as a whole species? I believe this is a philosophical question. It's not, perhaps not purely legal. And people may have very different opinions, and that would come to very different conclusions as to whether there should be benefit sharing or we should follow a free-market approach."

Corvin Illgner is the co-founder of the SDG 18 initiative "Space for All" and strives for a career in space sustainability. As an intern at Space Foundation, he did research on the topic of fair distribution of asteroid resources, including conducting interviews with the industry leaders quoted in this article.



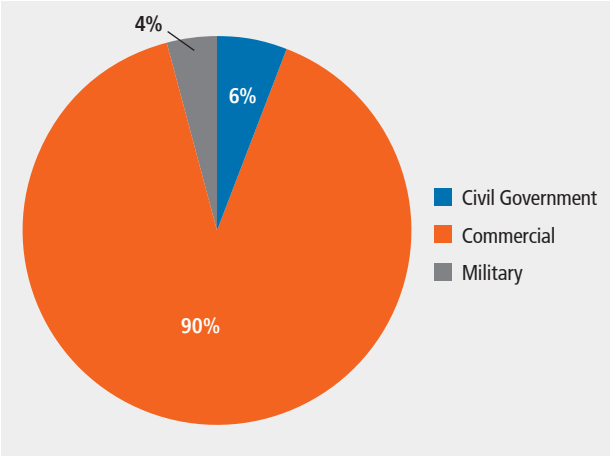
Introduction | *Unprecedented numbers of spacecraft were deployed during 2021. For the year, space operators successfully deployed 1,730 spacecraft, an increase of 29% from 2020's deployments of 1,340. Companies and operators from 33 nations took part in 2021's spacecraft deployments. However, this Infrastructure section of The Space Report will focus on the three countries, organizations, or companies with the largest share of spacecraft deployments in each following section, such as the Spacecraft Mission Segment, Payload Type, and Country Breakdowns.*

Galileos 27-28 seen atop their gold-wrapped Fregat upper stage within their Soyuz launcher fairing. The satellites launched in 2021.
Source: ESA

Commercial Spacecraft Boost Payload Deployment to New High

One hundred thirty-four orbital launches deployed 1,730 spacecraft during 2021. The largest share of those deployments, 90% (1,557 spacecraft), were for spacecraft conducting commercial missions, such as those deployed for Starlink or Planet. Nearly 6% (99) of deployed spacecraft were for civil government missions (such as the James Webb Space Telescope or the Galileo PNT (positioning, navigation, and timing) satellites. Slightly more than 4% (74) were for military missions, such as missile warning or intelligence.

Spacecraft Mission Segment Shares



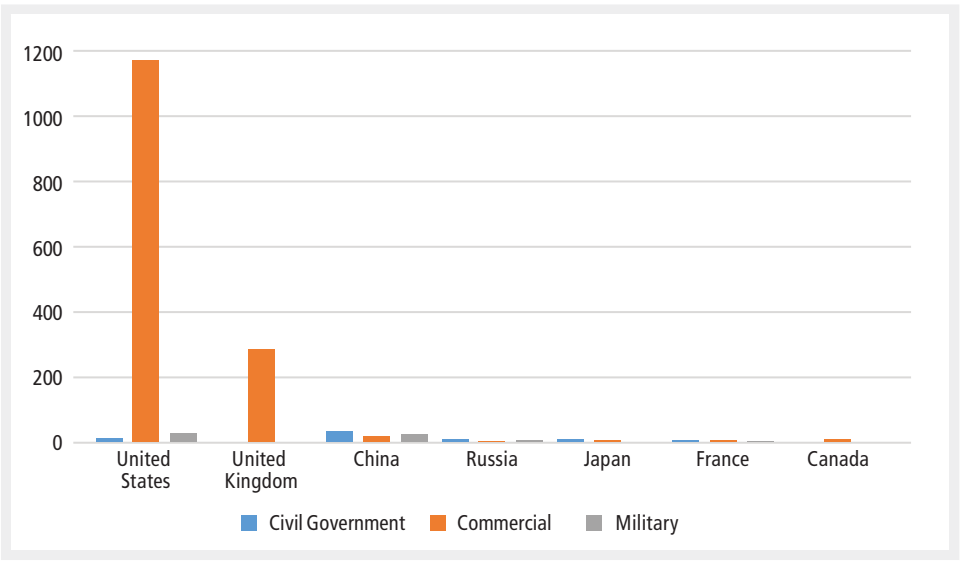
Spacecraft Mission Segment Breakdown

Space Foundation's data-gathering of space industry events and data from primary sources provides about 98% of the data in this report. However, of all of 2021's deployments, the U.S. Space Force's (USSF) online spacecraft database, Space-Track.org, has yet to publish the identity of 39 spacecraft — slightly over 2%. Because of that data gap, this report uses secondary sources, such as news articles and state-run media, to associate the names, missions, and payloads of those remaining 39 spacecraft to fill that gap.

The three satellite operators that deployed the largest share of commercial spacecraft in 2021 were SpaceX Starlink, OneWeb, and Swarm Technologies. Starlink satellites accounted for 63.5% (989) of the 1,557 commercial spacecraft deployed. OneWeb's satellites made up another 18% (284) of all deployed 2021 commercial spacecraft, while Swarm's 76 gave it a 5% share. Civil agencies or companies intertwined with civil agencies deployed the 99 civil government missions during 2021. Of China's 42 civil government missions, the majority (12) were operated by the China Aerospace Science and Technology Corporation (CASC), which took a 12% share of all civil government spacecraft deployments. The Japan Aerospace Exploration Agency (JAXA) followed, deploying 10% (10) of the spacecraft for civil government missions. NASA and Russia's Roscosmos each deployed nine spacecraft for civil government missions. Most of Russia's civil government missions transported crew and supplies to the International Space Station (ISS).

Of the 74 spacecraft deployed for military purposes, China's 35 deployments took a majority with 47%. U.S. military spacecraft deployments followed with 26 (35%), and Russia's four military spacecraft deployments took the third-highest of all military spacecraft deployments with 5%.

Spacecraft Mission Segment Shares by Nation



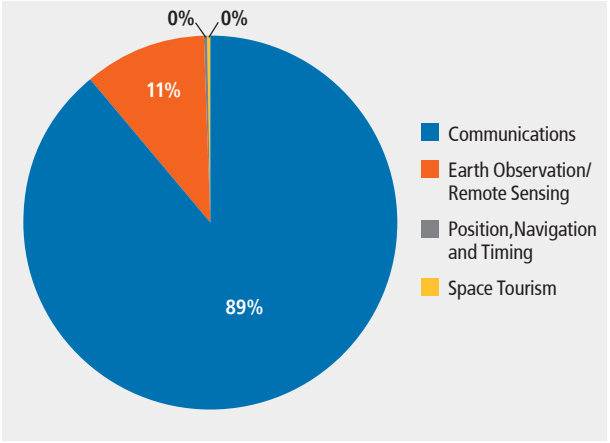
Source: Space Foundation database

Spacecraft Payload Type Breakdown

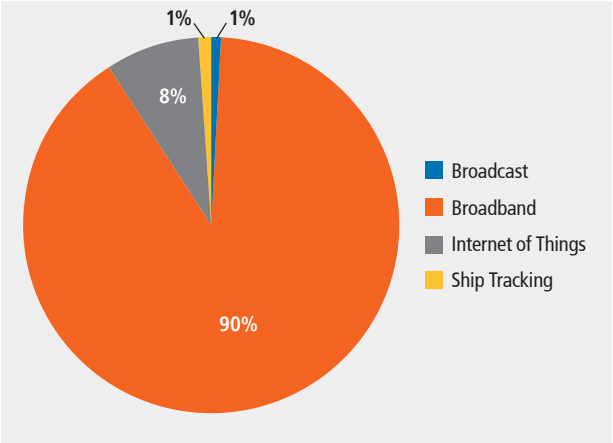
During 2021, communications satellites made up 83% (1,446) of the 1,730 spacecraft deployed. Earth observation and remote sensing (EO/RS) satellites accounted for 10% (172) of all deployed spacecraft in 2021. Other types of payloads, such as those dedicated to PNT, assumed less than half a percent (7) of all spacecraft deployed that year. A new category, orbital space tourism, consisted of three spacecraft deployed for passengers to and from the ISS or on orbits around the Earth.

Slightly more than 88% (1,275) of the communications satellite category consisted primarily of broadband satellites from OneWeb and Starlink. Satellites deployed for Internet of Things (IoT) connectivity were nearly 8% (113) of all communications satellites deployed in 2021. The third-highest share of communications satellites, a little more than 1% (19), were deployed for maritime tracking missions. Finally, the business that once defined the category, large communications satellites deployed into geosynchronous orbit, deployed a little less than 1% (13) of all communications satellites lofted around the Earth during 2021.

Spacecraft Payload Share



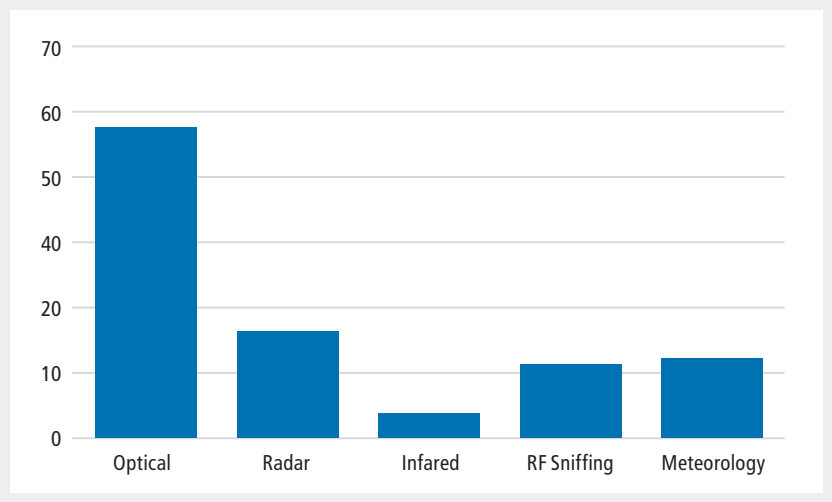
Shares of Major Communications Payload



Most deployed EO/RS satellites, 59% (101), used optical imaging technology. A growing category of satellites using synthetic aperture radar (SAR) to peer at the Earth had over 18% (32) share of EO/RS satellite deployments. Meteorological satellites deployed during 2021 took the third-highest share of EO/RS satellites with 15% (26). U.S. commercial company Spire Global deployed the majority of meteorological satellites (16). Spire's Lemur satellites host multiple payloads. One of those payloads is a GNSS-RO (Global Navigation Satellite System Radio Occultation) detector that sensesand measures PNT satellite signals to aid in weather forecasting.

Twenty-four radio frequency (RF) detection satellites were deployed in 2021, taking a 14% share of EO/RS satellite deployments. RF detection satellites comprise one of the newer and growing categories within the EO/RS satellite segment. These satellites are used to monitor radio frequencies emanating from areas of the Earth. They can be used in tandem with optical

Shares of Major EO/RS Payloads

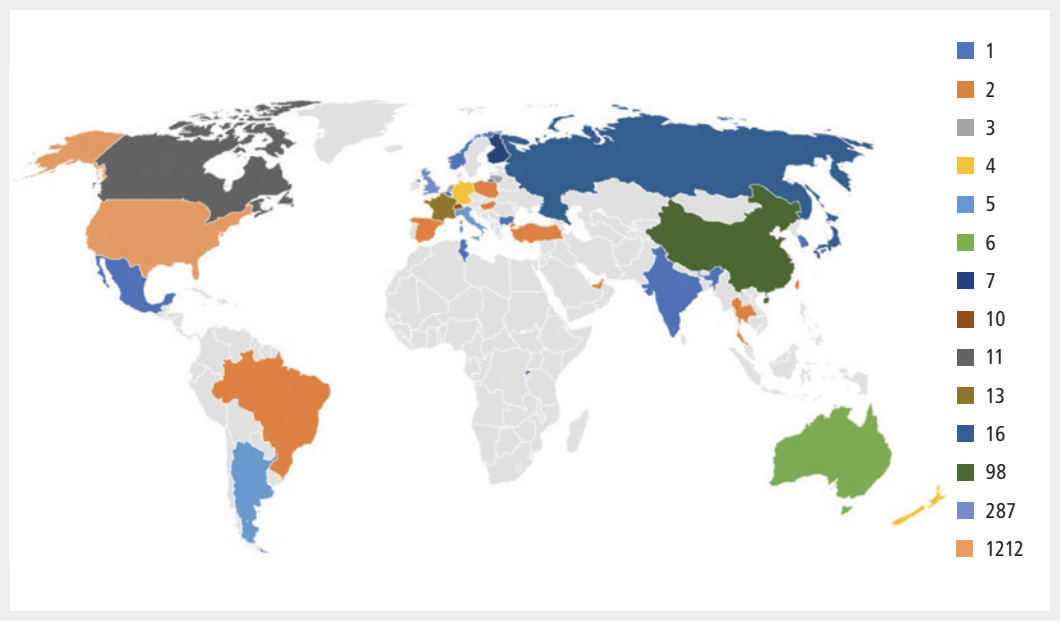


and SAR products for more accurate knowledge of possible illegal activities. One example is monitoring no-fishing zones, where the RF detection satellites verify whether fishing vessels are staying out of those zones. If satellites detect RF transmissions from an area in which they shouldn't be transmitting, satellite operators can request optical imagery or SAR satellite operators gather data from a monitored location as soon as possible and verify whether an authorized ship was in transmitting from it.

Spacecraft Country Breakdown

The operators and activities of three nations accounted for 92% of all spacecraft deployed in 2021: the United States, the United Kingdom, and China. The nation whose companies and agencies took the most significant share of all spacecraft deployments that year was the U.S. Its space operators deployed 1,212 spacecraft, 70% of 1,730 spacecraft deployed in 2021. The United Kingdom's space operators followed with a nearly 17% (287) share of spacecraft deployments. China's space operators took the third-highest share with nearly 6% (98). The space operators of the other 30 nations that deployed spacecraft during 2021 each managed to take less than 1% of all spacecraft deployments.

Nations Deploying Spacecraft in 2021



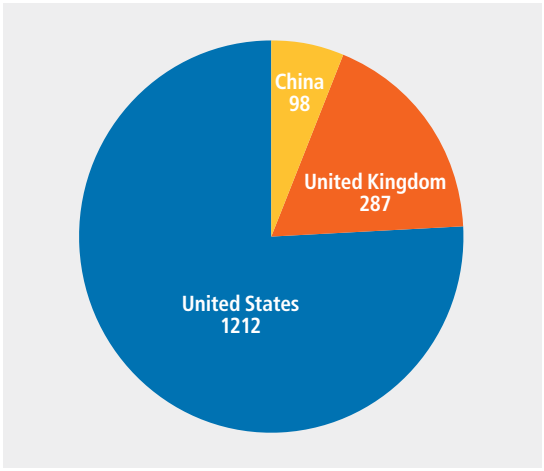
Source: Space Foundation database
Note: Each color corresponds to the number of payloads deployed in 2021 by that nation.

In the United States, one broadband spacecraft operator, SpaceX's Starlink, was responsible for nearly 82% (989) of all U.S. spacecraft deployments in 2021. Swarm Technologies' SpaceBee IoT satellites took the second-largest share of U.S. spacecraft deployments, slightly more than 6% (76), while Planet's optical EO/RS satellites came in third with nearly 4% (48).

All but three (~99%) of the United Kingdom's 287 spacecraft were deployed by OneWeb for its broadband constellation. Different U.K.-based companies deployed the remaining three spacecraft: Inmarsat, Lacuna, and InSpace.

China's largest contributing satellite operator was its military, deploying over 24% (24) of its 98 spacecraft in 2021. State-owned China Aerospace Science and Technology Corporation (CASC) took the second-highest share with 16% (16) of the nation's deployed spacecraft. Chang Guang Satellite Technology Company, a commercial company, took the next largest share of China's deployed spacecraft with 6% (6).

Ranked Spacecraft Deployments: The Three Most Active Nations, 2021



Source: Space Foundation database

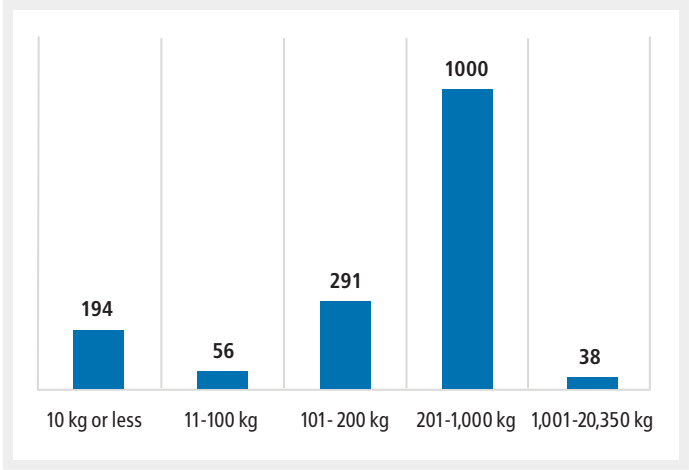
Spacecraft Mass Breakdown

The total estimated mass deployed from Earth during 2021 significantly excludes many of China's spacecraft deployments and U.S. classified spacecraft. Without spacecraft from those categories, the world's space operators deployed an estimated overall total mass of ~507,000 kg, averaging nearly 322 kg per spacecraft deployed. The largest of these was Russia's Nauka module for the space station, with a mass of 20,230 kg. A Proton launch vehicle successfully launched the Nauka into orbit.

Before 2021, the trend appeared to be that spacecraft with a mass less than 180 kg would gain a majority of overall spacecraft deployments. However, that trend began to change in late 2020 and continued to shift during 2021. The number of spacecraft deployed with a mass of 200 kg or less was an estimated 250, 14% of the 1,730 spacecraft deployed in 2021. Those 250 spacecraft accounted for a projected mass of 3,235 kg., barely ½ of a percent of the estimated 507,000 kg deployed into the Earth's orbit.

Operators deployed 291 satellites into orbit — 17% of all deployed spacecraft — with masses ranging from 200 to 101 kg. Their accumulated mass added up to an estimated 43,636 kg, about 8.5% of the overall mass deployed from Earth in 2021. OneWeb's satellites accounted for nearly 98% of all spacecraft within that mass range.

Spacecraft Deployed Per Mass Range, 2021



Source: Space Foundation database

One thousand spacecraft (58%) with masses ranging from 1,000 to 201 kg were deployed in 2021. The total mass of those spacecraft came to an estimated 263,814 kg, 52% of the overall mass deployed for the year. SpaceX's Starlink satellites took slightly more than a 97% share of spacecraft within that mass range.

Compared with the first three ranges, the 38 spacecraft with masses ranging from 20,350 to 1,001 kilograms may seem relatively paltry. However, their total estimated mass of 197,167 kg accounts for 39% of the total mass deployed from Earth during 2021. The largest mass of this range was Russia's Nauka ISS module, with 20,230 kg. The module alone is nearly half the mass (~48%) of the accumulated mass of all of OneWeb's satellites deployed during 2021.

Spacecraft Orbits

Based on data accumulated in The Space Report Online database and Space-Track.org, an estimated 1,715 spacecraft were deployed into low Earth orbit (LEO) — 99% of all spacecraft deployed in 2021. Sixteen spacecraft (~1%) were deployed into geosynchronous orbit (GEO). The majority of spacecraft deployed into LEO, 1,429 (83%), were for communications missions.

John Holst runs Ill-Defined Space, providing analysis of activities, policies, and businesses in the space sector. He worked in the U.S. Air Force, Missile Defense Agency, Cobham, Space Dynamics Laboratory, Space Foundation, and Quilty Analytics.

Introduction | *The S-Network Space Index℠ tracks a global portfolio of publicly traded companies that are active in space-related businesses such as satellite-based telecommunications; transmission of television and radio content via satellite; launch vehicle and satellite manufacturing, deployment, operation, and maintenance; manufacturing of ground equipment that relies on satellite systems; development of space technology and hardware; and space-based imagery and intelligence services.*

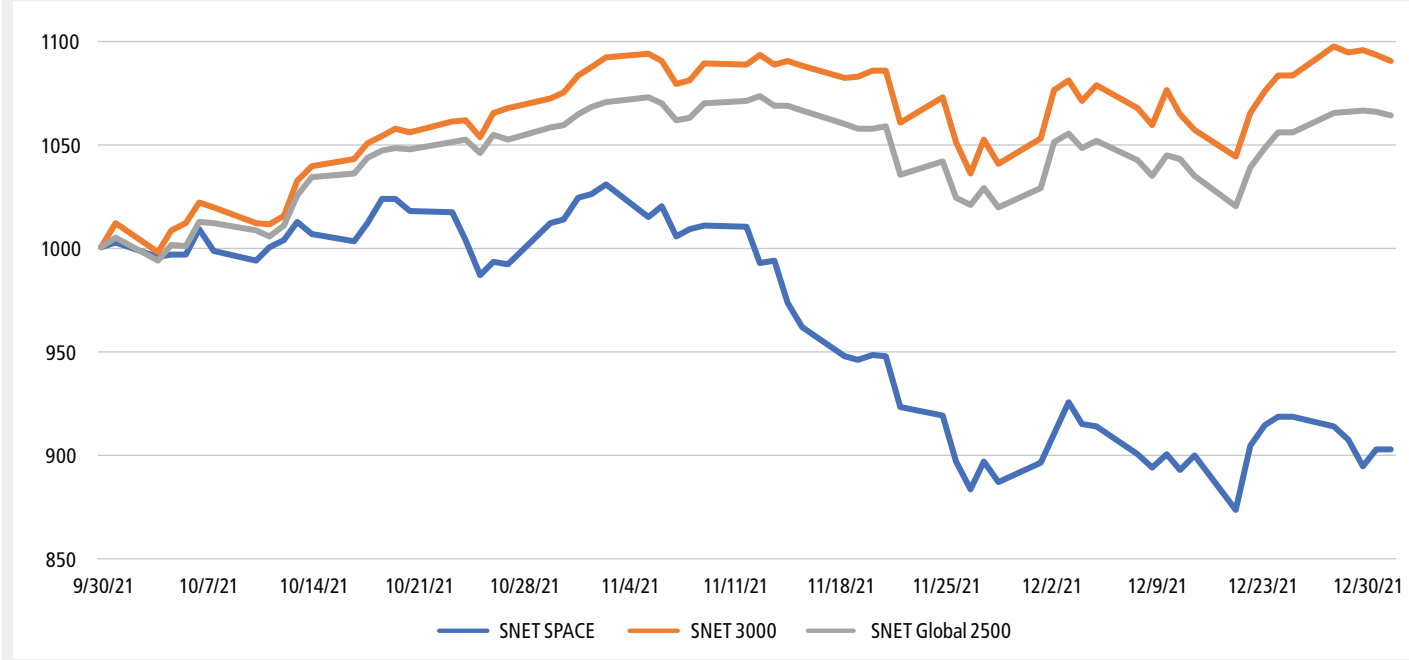
A new component of the S-Network Space Index, Rocket Lab USA, was picked by NASA to build a pair of small satellites for science missions in Martian space.
Credit: NASA, Rocket Lab USA

The S-Network Space Index℠ Q4 2021 Performance

Index Performance

In the fourth quarter of 2021, the S-Network Space Index (SNET SPACE) substantially underperformed other benchmark indexes, declining 9.7%. This compares to a 9% increase for the S-Network U.S. Equity 3000 Index (SNET 3000), which tracks the 3,000 largest (by market capitalization) U.S. stocks. Similarly, there was a 6.4% increase for the S-Network Global 2500 Index (SNET Global 2500), which tracks a combination of the 1,000 largest U.S. stocks, 500 largest European stocks, 500 largest Pacific basin stocks (developed), and the 500 largest liquid Emerging Market stocks.

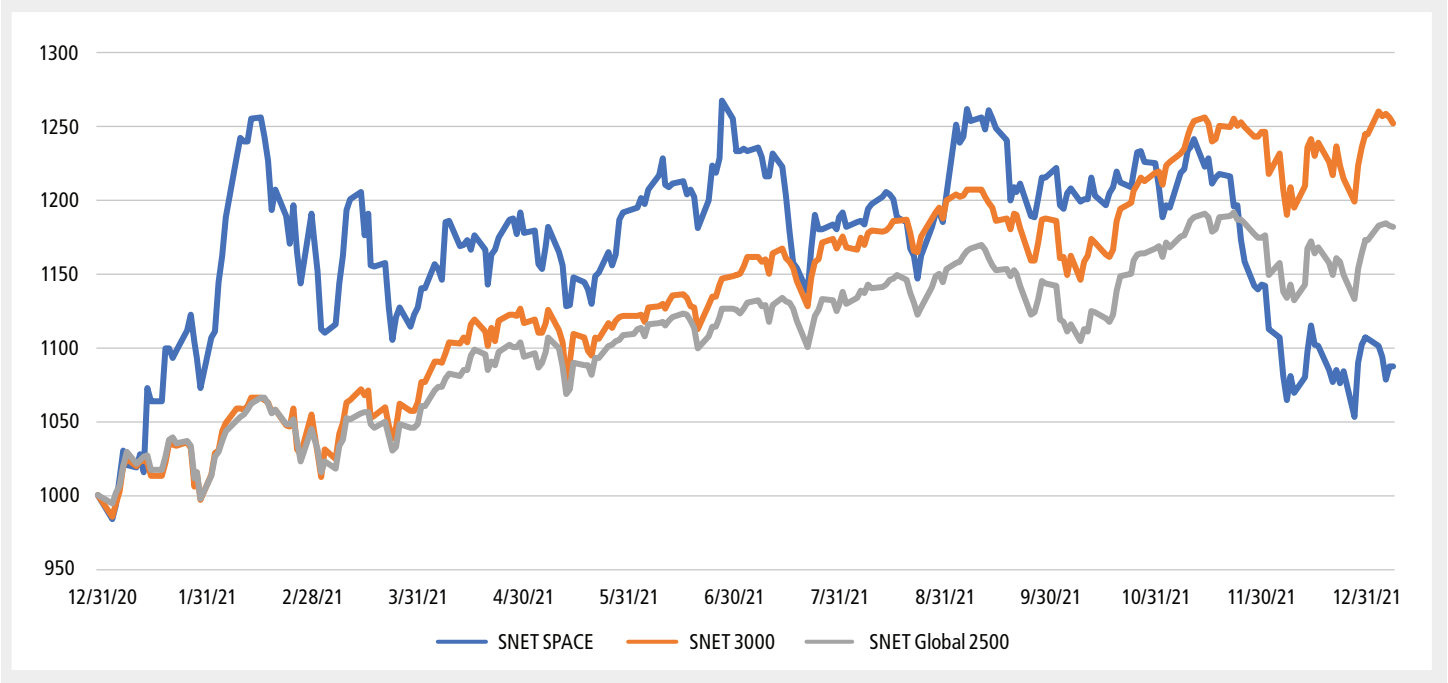
S-Network Space Index vs. Benchmark Indexes, Q4 2021



Note: Performance shown for each index is for the gross total return, assuming all dividends are reinvested.

Assessing the performance of the S-Network Space Index for the entirety of 2021, strong performance early in the year was offset by losses later in the year. While SNET SPACE grew by 8.7%, it lagged behind the other indexes with gains of 25.2% for the SNET 3000 and 18.1% for the SNET Global 2500.

S-Network Space Index vs. Benchmark Indexes, 2021



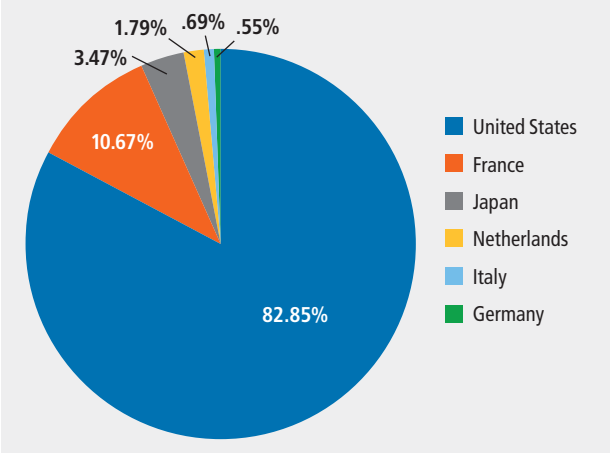
Note: Performance shown for each index is for the gross total return, assuming all dividends are reinvested.

Index Constituents

The space industry is a global one, and the composition of the S-Network Space Index reflects this diversity. Companies listed on U.S. exchanges tend to dominate due to the larger number of companies that meet the financial requirements for inclusion in the index. On Dec. 17, 2021, the index underwent its semi-annual reconstitution — adding new companies and dropping current companies according to the index rules. One minor out-of-cycle change was previously made to the index constituents in November, as satellite communications provider Telesat replaced index component Loral Space & Communications after a merger between the two companies.

The December reconstitution resulted in the highest number of changes to the index since live calculation began in May 2018. Eight companies were added to the index, all but one of which became publicly traded through a SPAC (special purpose acquisition company) transaction. The new index constituents included two launch companies (Astra Space and Rocket Lab USA), two Earth Observation and data analysis companies (BlackSky Technology and Spire Global), two space infrastructure companies (Momentus and Redwire), a quantum security services company (Arqit Quantum), and an optical communications hardware manufacturer (Mynaric, which used a traditional IPO rather than a SPAC transaction to go public). Former index component MDA was removed due to insufficient trading activity for its stock.

Index Weight by Listing Country as of Dec. 17, 2021



At the end of Q4, U.S.-listed companies comprised 82.85% of the weight of the overall index, with France in second place at 10.67%, Japan at 3.47%, the Netherlands at 1.79%, Italy at 0.69%, and Germany at 0.55%.

S-Network Space Index Constituents as of Dec. 17, 2021

Company	Ticker	Country	2021 Q4 Performance
Aerojet Rocketdyne Holdings	AJRD	United States	7%
Airbus	AIR	France	-2%
Arqit Quantum*	ARQQ	United States	19%
AST SpaceMobile	ASTS	United States	-27%
Astra Space*	ASTR	United States	-20%
AT&T	T	United States	-9%
Avio	AVIO	Italy	8%
Ball	BLL	United States	7%
BlackSky Technology*	BKSY	United States	-57%
Boeing	BA	United States	-8%
Comcast	CMCSA	United States	-10%
Dish Network	DISH	United States	-25%
Echostar Holding	SATS	United States	3%
Eutelsat Communications	ETL	France	-10%
Garmin	GRMN	United States	-12%
Gilat Satellite Networks	GILT	United States	-21%
Globalstar	GSAT	United States	-31%
Honeywell International	HON	United States	-2%
IHI	7013	Japan	-19%
Iridium Communications	IRDM	United States	4%
L3Harris Technologies	LHX	United States	-3%
Leonardo	LDO	Italy	-11%
Lockheed Martin	LMT	United States	3%
Maxar Technologies	MAXR	United States	4%
MDA†	MDA	Canada	-42%
Momentus*	MNTS	United States	-61%
Mynaric*	MYNA	Germany	-39%
Northrop Grumman	NOC	United States	7%
Raytheon Technologies	RTX	United States	0%
Redwire*	RDW	United States	-30%
Rocket Lab USA*	RKLB	United States	-24%
SES	SESG	France	-10%
Sirius XM Holdings	SIRI	United States	4%
SKY Perfect JSAT Holdings	9412	Japan	-3%
Spire Global*	SPIR	United States	-73%
Telesat‡	TSAT	United States	-33%
Thales	HO	France	-11%
TomTom	TOM2	Netherlands	33%
Trimble Navigation	TRMB	United States	6%
Viasat	VSAT	United States	-19%
Virgin Galactic	SPCE	United States	-47%
Weathernews	4825	Japan	46%

* Added in December reconstitution, so performance had a low impact on overall Q4 index performance

† Removed in December reconstitution.

‡ Telesat completed its merger with Loral Space & Communications (previously an index component) in Q4 and became a publicly traded company. It subsequently cross-listed on the Toronto Stock Exchange.

The eight constituents added to the index at the end of Q4 mark a shift in the type of space companies available for investment through public markets. Since its inception, the index had been dominated by pure-play satellite operators — mostly in the communications and broadcasting sector — followed by diversified hardware manufacturers. Several companies that focus on end-user equipment, such as Garmin and Trimble, rounded out the index. However, the index methodology was designed to accommodate changes in the space industry, and it easily integrated the new generation of small companies that focus on specific niches such as launch or in-space infrastructure that were primarily the domain of diversified aerospace and defense giants in the past. Virgin Galactic could be considered the first of this generation when it went public in 2019, operating as a standalone launch company and the first publicly traded company focused on human spaceflight. The more recent additions have extended this principle to other segments of the space industry, generally operating with a narrow focus on a specific capability.

The market's reaction to most of these new companies has been negative in 2021, as demonstrated by the fact that all but Arqit Quantum (up 19%) declined in the fourth quarter. Of the companies that went public through a SPAC transaction since 2019,[1] only three ended the year above the $10 price customarily used for issuing the initial SPAC units to investors: Rocket Lab USA, Virgin Galactic, and Arqit Quantum. By contrast, six ended 2021 below $10 per share: Spire Global, Momentus, BlackSky Technology, Redwire, Astra Space, and AST SpaceMobile. It remains to be seen whether the stock performance will improve as the companies continue to make use of the capital raised from their SPAC transactions to mature their service offerings and deliver on the forecasts they provided investors. It is too early to tell whether the companies went public before they were ready or whether the market is currently undervaluing them.

Beyond the performance of individual companies, there is also the question of how portfolio-based financial products are responding to changes in the industry. In the world of exchange-traded funds (ETFs), three products available on U.S. exchanges are intended to provide easy access to the space industry: the Procure Space ETF (ticker: UFO), the SPDR® S&P Kensho Final Frontiers ETF (ROKT), and the ARK Space Exploration & Innovation ETF (ARKX). In terms of methodology, UFO uses the analyst-produced S-Network Space Index as its underlying index, ROKT uses an index compiled through algorithmic processes, and ARKX is an actively managed ETF that relies on its management team's expertise. A detailed comparison of the three ETF methodologies is available in *The Space Report 2021 Q1*.

Disclosure: the author of this section is responsible for production of the S-Network Space Index and consequently has a business relationship with the sponsors of financial products based on the index.

Due to the different approaches to identifying eligible companies and assigning weights within an ETF, the three products are substantially different from each other. Only four companies are found in all three: Honeywell, Iridium Communications, L3Harris Technologies, and Lockheed Martin. An additional 17 companies are found in only two ETFs, and 64 companies can be found in only one ETF. Of the space companies that went public on U.S. exchanges in 2021 and were added to UFO, only Mynaric and Astra Space can also be found in other ETFs.[2] Regardless of the reasons other new companies were not included in ROKT or ARKX, it is clear that space companies cannot assume that the financial media's enthusiasm for their mission will translate into immediate acceptance by financial vehicles such as ETFs (space-focused or not) that are responsible for more than a hundred billion dollars in trade transactions every day.[3]

Holdings of UFO, ROKT, and ARKX as of Dec. 31, 2021

Procure Space ETF (UFO)		SPDR® S&P Kensho Final Frontiers ETF (ROKT)		ARK Space Exploration & Innovation ETF (ARKX)	
Holdings	**Weight**	**Holdings**	**Weight**	**Holdings**	**Weight**
Iridium Communications	5.11%	Aerojet Rocketdyne Holdings	4.15%	Trimble	10.13%
Sirius XM Holdings	5.10%	Northrop Grumman	4.05%	The 3D Printing ETF	7.75%
Maxar Technologies	5.02%	Lockheed Martin	3.97%	Kratos Defense & Security	6.29%
Dish Network	5.00%	Maxar Technologies	3.94%	Iridium Communications	6.09%
Garmin	4.94%	Iridium Communications	3.92%	L3Harris Technologies	5.18%
Trimble	4.92%	Honeywell	3.88%	Komatsu	4.57%
SES	4.91%	Teledyne Technologies	3.84%	JD Logistics	3.97%
Eutelsat	4.73%	HEICO	3.81%	Unity Software	3.45%
Rocket Lab USA	4.70%	Raytheon Technologies	3.80%	Dassault Systemes	3.41%
Viasat	4.69%	L3Harris Technologies	3.77%	Blade Air Mobility	3.32%
Virgin Galactic	4.33%	Hexcel	3.74%	UiPath	3.28%
Arqit Quantum	4.29%	Boeing	3.68%	Amazon.com	3.03%
Echostar Holding	3.06%	Virgin Galactic	3.26%	Netflix	2.96%
AT&T	2.64%	Astra Space	2.76%	AeroVironment	2.90%
Comcast	2.59%	Amphenol	2.61%	Archer Aviation	2.44%
Globalstar	2.58%	TTM Technologies	2.61%	Teradyne	2.42%
Northrop Grumman	2.56%	AMETEK	2.60%	Garmin	2.36%
Astra Space	2.52%	TransDigm Group	2.60%	Markforged Holding	2.14%
Lockheed Martin	2.52%	General Dynamics	2.59%	Deere & Co.	2.14%
Raytheon Technologies	2.44%	II-VI	2.55%	Elbit Systems	1.95%
Boeing	2.39%	KBR	2.55%	Alphabet	1.89%
L3Harris Technologies	2.09%	Ball	2.55%	Spirit AeroSystems Holdings	1.85%
TomTom	1.84%	Fortive	2.52%	Velo3D	1.83%
Weathernews	1.81%	BWX Technologies	2.49%	Lockheed Martin	1.64%
SKY Perfect JSAT Holdings	1.68%	Huntington Ingalls Industries	2.49%	Joby Aviation	1.55%
Telesat	1.59%	Leidos Holdings	2.46%	Palantir Technologies	1.35%
Honeywell	1.53%	Jacobs Engineering Group	2.41%	Synopsys	1.23%
Spire Global	1.31%	Analog Devices	2.35%	HEICO	1.17%
Airbus	0.98%	Viasat	2.35%	Honeywell	1.13%
AST SpaceMobile	0.97%	ESCO Technologies	2.28%	ANSYS	1.11%
BlackSky Technologies	0.80%	Moog	2.24%	3D Systems	1.07%
Gilat Satellite Networks	0.80%	TechnipFMC	2.21%	Airbus	1.06%
Ball	0.77%	Standex International	1.56%	Mynaric	1.06%
Avio	0.66%	Elbit Systems	1.35%	Thales	1.02%
Momentus	0.61%			Teledyne Technologies	0.94%
Mynaric	0.53%				
Redwire	0.32%				
Aerojet Rocketdyne Holdings	0.20%				
Thales	0.15%				
Leonardo	0.05%				
IHI	0.02%				

Key:

Company is in all three ETFs

Company is in UFO and one other ETF

Company is in ROKT and ARKX

In terms of the weights assigned to constituent companies, UFO's reliance on SNET SPACE as its underlying benchmark means that pure-play space companies tend to hold the top positions in the ETF. By contrast, ROKT looks more like a traditional aerospace and defense product, with more than half of its top 10 holdings occupied by large, diversified companies whose space business generates less than half their annual revenue. ARKX's top holdings include a combination of space companies, aerospace and defense companies, and "aerospace beneficiary companies…whose operations stand to benefit from aerospace activities, including agriculture, internet access, global positioning systems (GPS), construction, imaging, drones, air taxis, and electric aviation vehicles."[4] The differences in the holdings and the rankings within each ETF underscore the fact that the space industry is still being assessed by the financial industry, and in many respects the concept of a "space company" is still challenging for markets to grasp. This has implications for whether investors will be patient with emerging companies that are grappling with the technical challenges of space activity or whether they will evaluate such companies using the same criteria as for other industries. The answers to these questions will be hashed out, trade by trade, over the coming years as the space industry continues to evolve and as investors engage with it more deeply.

The S-Network Space Index℠ Methodology

The S-Network Space Index is considered a "pure-play" space index, unlike other indexes that combine space with other sectors such as aviation or defense. The index operates according to a clearly defined rules-based methodology overseen by an impartial Index Committee, as opposed to an actively managed index that operates at the discretion of its managers. In technical terms, it is a modified capitalization-weighted, free float-adjusted and space revenue percentage-adjusted equity index. In essence, it takes into account how much of a company's revenue comes from space-related business and combines that information with a variety of standard financial metrics to determine how influential that company's stock should be in terms of the overall index performance.

To be considered for inclusion in the S-Network Space Index, a company must generate either (1) at least 20% of its revenue or (2) at least USD $500 million in revenue from space-related business. In accordance with the pure-play nature of the index, 80% of the total index weight is assigned to companies whose space-related business generates at least 50% of annual revenue (in practice, most such companies generate 100% of their revenue from space). The remaining 20% of the index weight is assigned to diversified companies that earn the majority of their revenue from non-space businesses.

To further ensure that the companies are substantially engaged in space-related activities, each company must also meet at least one of the following criteria:

- The company was the prime manufacturer (i.e., the contractor responsible for managing subcontractors and delivering the product to the customer) for a satellite in the past five years.
- The company was the prime manufacturer or operator of a launch vehicle in the past five years.
- The company currently operates or utilizes satellites.
- The company manufactures space vehicle components (for satellites, launch vehicles, or other spacecraft).
- The company manufactures ground equipment dependent upon satellite systems.

In addition to its role as an educational and informational tool for tracking the performance of the global space industry, the S-Network Space Index is also designed to serve as a benchmark upon which investment firms can base products

such as exchange-traded funds (ETFs), mutual funds, or other investment instruments. As such, the index rules take into consideration financial criteria such as the average daily trading value of candidate stocks, as well as SEC regulations regarding the minimum number of constituent companies and the maximum weights permitted for constituent companies. The rule book for the index, which describes the complete methodology, is available at http://space.snetglobalindexes.com.

Contact Information and Disclaimer

The S-Network Space Index is maintained by S-Network Global Indexes Inc., supported by space industry expertise from Space Investment Services LLC. For more information, please contact index@spaceinvestmentservices.com

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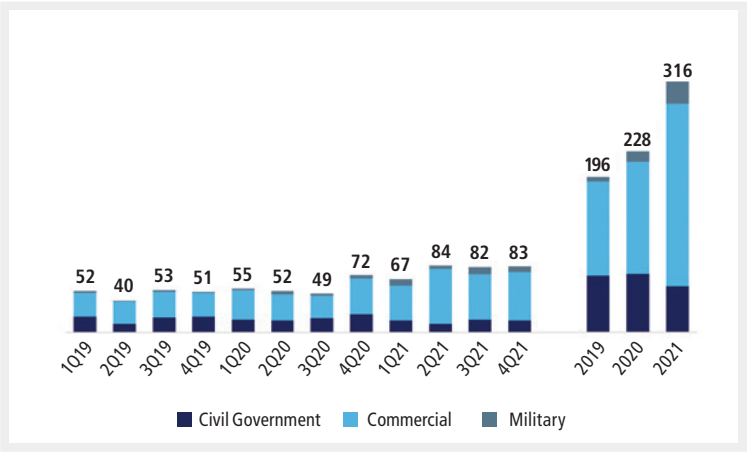
Micah Walter-Range is the creator and manager of the underlying stock index for the world's first exchange-traded fund (ETF) focused on the space industry. As a leading expert on the global space economy, he has authored papers on space-specific topics such as the impact of export controls on the U.S. space industrial base, and cross-sector subjects such as the role of space technology in aviation.

Quilty Analytics: 2021 Q4 Quarterly Transactional Update

Last year ended on consistent transactional footing in the satellite and space sector. In Q4, there were 15 space-related acquisitions/buyouts, 61 private equity and venture equity financings totaling more than $3.2 billion in funds raised, and seven public equity financings (inclusive of 3 pending de-SPAC transactions) totaling approximately $1.1 billion in gross proceeds.

Quarterly and Annual Transactions, 2019-2021



Source: Quilty Analytics

Q4 21 M&A Review

M&A activity was down year over year from 23 deals in Q4 20 to 15 deals in Q4 21. This activity level was generally consistent with the prior quarter's 16 transactions.

Enablement sector activity continued to represent the plurality of subsector activity, representing seven Q4 21 M&A transactions. Rocket Lab, which recently completed its de-SPAC transaction, was particularly active, announcing three such acquisitions: Advanced Solutions Inc. (flight software), Planetary Systems Corporation (separation systems), and SolAero (space photovoltaics).

Also notable during the quarter were two acquisitions of companies with optical communications technology: Space Micro Inc. (majority equity stake acquired by Voyager; Quilty Analytics advised Space Micro Inc. on the sale) and SA Photonics (acquired by CACI). Optical communications, including optical inter-satellite links (O-ISLs), are a foundational technology that will support commercial and defense mega-constellations over the coming years.

Within the satellite communications sector, Q4 21 saw the groundbreaking acquisition announcement of Inmarsat. Viasat is acquiring Inmarsat in a cash-and-stock deal valued at $7.3 billion (as of the time of the announcement), comprised of issuance of 46.36 million Viasat shares, $850 million cash consideration, and assumption of $3.4 billion in Inmarsat debt, in total implying a valuation of approximately 10 times 2021E EBITDA (earnings before intertest, taxes, depreciation and amortization). The outcome appears to be a positive one for Inmarsat's private equity owners (Apax, Warburg Pincus, CPPIB, and OTPP), notwithstanding the headwinds, such as COVID-19, that have occurred since their buyout of Inmarsat in December 2019.

Assuming that the Viasat-Inmarsat transaction clears any regulatory hurdles that arise (notably in the United Kingdom), which it likely will, the transaction is expected to close during the second half of 2022, with the longer-term potential to create a global Ka-band juggernaut. Both companies have strong, insular cultures. Assuming that this risk, network complexities, and other integration challenges can be overcome in the next few years, the combined company will benefit from an unparalleled combination of global GEO breadth (primarily via Inmarsat's network) and capacity depth (e.g., Viasat's high-powered Viasat-3 satellites).

Satcom sector developments in 2021 — including the rise of the LEO Broadband constellations, the pending Viasat-Inmarsat transaction, and new technology adoption in certain corners of the industry (e.g., Anuvu's Astranis micro-GEO order) — will very likely stimulate further competitive responses (i.e., transactions) in 2022. We expect vertical and

horizontal M&A integration strategies to play a role as operators seek to buttress their global network footprints while ensuring access to key end markets, particularly within mobility segments. Notably, Intelsat's impending emergence from bankruptcy, following U.S. Bankruptcy Court confirmation of its reorganization plan in December 2021, will put the company back into the driver's seat to participate in such activities. Likewise, completion of the Telesat-Loral integration transaction, closed in November 2021, provides that company with increased strategic flexibility going forward.
Only one new private equity platform investment was completed during the fourth quarter: J.F. Lehman's acquisition of Narda-MITEQ, divested by L3Harris. Narda-MITEQ offers a range of radio frequency (RF) products and components supporting the satellite communications ground segment, spaceborne assets, and other defense end markets.

Q4 21 Equity Financing Activity Review

Equity financing activity in the space sector posted another near-record high in Q4 21, with 61 private investment equity transactions announced. Private investment activity was broad-based, and Enablement and EO/Geospatial led by transaction volumes with 23 and 16 transactions, respectively.

In the quarter, perhaps the most notable private investment was Sierra Space's $1.4 billion financing. Sierra Space, the offshoot of Sierra Nevada Corp., is focused on commercial space transportation, habitation, and related activities, and has more than 1,100 employees (from SNC) but nonetheless deemed the transaction a "Series A" financing, capturing a $4.5 billion valuation. Sierra Space is one of several companies pursuing the emerging commercial space station market. In December 2021, NASA awarded three companies phase-one contracts for the development of commercial space stations: Voyager's Nanoracks ($160 million award), Blue Origin ($130 million; partnered with Sierra Space and others under the "Orbital Reef" team), and Northrop ($125.6 million).

Investment in LEO Broadband constellations also continued in the fourth quarter, with OneWeb reaping an additional $165 million from Eutelsat's exercise of its previously negotiated option and SpaceX raising an additional $337 million from investors. On the latter front, SpaceX made separate headlines in November with a "leaked crisis" relating to Raptor engine production — although it does appear that SpaceX will conduct its first orbital launch of Starship perhaps late in Q1, following an FAA launch site review.

Other sizeable private investment transactions in the quarter included investments in ABL Space ($200 million for the launch provider), Hawkeye 360 ($145 million for the RF Mapping and RF data analytics operator), Loft Orbital ($140 million for "space infrastructure as a service"), and Astroscale ($109 million for the on-orbit services provider).

There were seven public equity transactions during the quarter, roughly on par with the volume in the prior several quarters but well ahead of activity levels in most other previous years. However, in general, the performance of space public equities did not fare well in the fourth quarter, with our Core satellite and space and frontier space public stock indices down for the quarter overall.

Though it did not raise new capital, Telesat's public listing (its "IPO") should better position the company for future financing events (e.g., for Lightspeed) and facilitate greater M&A flexibility for the operator.

Two de-SPAC transactions were announced during Q4 21: Tomorrow.io (in the weather domain) and Terran Orbital (SmallSat manufacturing and Earth observation).

Announced	Target	Acquirer / Investor	Transaction Size (US$ Mil)	TEV / LTM Adj. EBITDA	Sub-Sector
Acquisitions / Buyouts			**Ent. Value**	**Multiple**	**Type**
10/04/21	Valley Tech Systems (VTS)	Voyager Space	n.d.	n.d.	Enablement
10/05/21	dBmCorp	Maury Microwave, Inc.	n.d.	n.d.	Satcom
10/12/21	Advanced Solutions Inc. (ASI)	Rocket Lab	40	n.d.	Enablement
10/27/21	Santander Teleport ST	FMC GlobalSat Holdings, Inc.	n.d.	n.d.	Satcom
11/02/21	Techshot	Redwire (AE Industrial Partners)	n.d.	n.d.	Enablement
11/03/21	SA Photonics	CACI International Inc.	275	n.d.	Enablement
11/05/21	Orbital Media Networks	LinkUp Communications Corp.	n.d.	n.d.	Satcom
11/08/21	Inmarsat	Viasat	7,356	9.9x	Satcom
11/10/21	VanderSat	Planet	28	n.d.	EO/Geospatial
11/15/21	Knight Sky	NIC4	n.d.	n.d.	Satcom
11/15/21	Planetary Systems Corporation	Rocket Lab	81	n.d.	Enablement
11/22/21	Space Micro	Voyager Space	n.d.	n.d.	Enablement
12/06/21	Orolia SA	Safran SA	n.d.	n.d.	Other
12/13/21	SolAero Holdings	Rocket Lab	80	n.d.	Enablement
12/21/21	Narda-MITEQ (sale by L3Harris)	JF Lehman & Company	n.d.	n.d.	Satcom
Private Financings (Equity) & Related			**Investment**	**Equity Value**	**Type**
10/01/21	Space Crystals	Undisclosed	0.2	n.m.	Other
10/05/21	Rendered.ai	Led by Space Capital	6	3,400	EO/Geospatial
10/05/21	Space Elements	Ira Bell	0.2	n.m.	Other
10/06/21	Muon Space	Led by Costanoa Ventures	10	n.m.	EO/Geospatial
10/06/21	OneWeb	Eutelsat	165	n.m.	Satcom
10/08/21	Beijing Aerospace Satelliteherd Science and Technology Co., Ltd.	Consortium of investors	31	n.m.	Other
10/08/21	Kuva Space	Consortium of investors	4.9	n.m.	EO/Geospatial
10/11/21	Blushift Aerospace	Halmos Ventures	4.0	18	Enablement
10/11/21	Sidereus Space	Led by CDP VC & Primo Ventures	1.7	n.m.	Enablement
10/12/21	CarbonSpace	Led by Rockstart & Yield Lab Europe	1.0	n.m.	EO/Geospatial
10/14/21	AiDash	Benhamou Global Ventures, G2VP, National Grid Partners	27	n.m.	EO/Geospatial
10/14/21	Loft Orbital Solutions Inc.	Led by BlackRock	140	n.m.	Enablement
10/14/21	Ranmoon Mechatronics	ASB Ventures (China) Holdings Ltd	3.1	n.m.	Other
10/14/21	Regher Solar	Undisclosed	5.9	n.m.	Enablement
10/14/21	Space Perspective	Consortium of investors	40	n.m.	Other
10/15/21	Sidus Space	Undisclosed	3	n.m.	Enablement
10/18/21	TrustPoint	DCVC	2	n.m.	Other
10/22/21	Infostellar Inc.	Consortium of investors	6.2	n.m.	Satcom
10/24/21	Satellite Vu	Led by Seraphim Space Investment Trust	20.7	n.m.	EO/Geospatial
10/25/21	ABL Space Systems	Led by T. Rowe Price Associates and Fidelity Management & Research LLC	200	2,400	Enablement
10/26/21	Dhruva Space	Led by IAN Fund & Blue Ashva Capital	2.9	n.m.	Enablement
10/26/21	Fixposition	Consortium of investors	6	n.m.	Other
10/26/21	Hedron	Led by Fine Structure Venture	17.8	n.m.	Satcom
10/26/21	Sofant Technologies	British Business Bank, NetScientific, and Skyrora	1.2	n.m.	Satcom
10/28/21	Sust Global	Led by Hambro Perks	3.2	n.m.	EO/Geospatial
10/29/21	Climate Solutions Exchange	Led by Maughan Capital	0.7	n.m.	EO/Geospatial
11/01/21	SatSure	Led by Baring Private Equity	n.d.	n.m.	EO/Geospatial
11/03/21	Scorpius Space Launch Company	Undisclosed	0.45	n.m.	Enablement
11/04/21	Phantom Space Corporation	Undisclosed	21.6	n.m.	Enablement
11/05/21	Solstar Space Company	Undisclosed	1.3	n.m.	Satcom
11/08/21	Hawkeye 360	Led by Insight Partners & Seraphim Space	145.0	n.m.	EO/Geospatial
11/08/21	Orbital Assembly Corporation	Undisclosed	4.0	n.m.	Enablement
11/15/21	Cosmic Shielding Corporation	Led by Type One Ventures	n.d.	n.m.	Other
11/16/21	Inversion Space	Led by Spark Capital	10.0	n.m.	Other
11/16/21	Hydrosat	Led by OTB Ventures	10.0	n.m.	EO/Geospatial
11/16/21	Fleet Space Technologies	Led by Artesian Venture Partners, Blackbird Ventures, & Grok and Horizons Ventures	26.4	n.m.	Enablement

11/18/21	Cognitive Space	Undisclosed	5.7	n.m.	Enablement
11/18/21	The Exploration Company	Led by Promus Ventures	6.0	n.m.	Other
11/19/21	Sierra Space	Led by General Atlantic, Coatue, and & Moore Strategic Ventures	1400.0	4,500	Other
11/22/21	ADA Space	Led by Hengjian Holding	55.6	n.m.	EO/Geospatial
11/25/21	Astroscale	Led by THE FUND LP	109.0	n.m.	Enablement
11/30/21	Anuvu	Apollo Capital, Sound Point Capital, and Arbour Lane Capital	50.0	n.m.	Satcom
12/01/21	Space BD	Incubate Fund, ANNIVERSAIRE HOLDINGS, SMBC Venture Capital, Mizuho Capital, and Pavilion Capital	9.1	n.m.	Enablement
12/03/21	Smallspark Space Systems	Deepbridge Capital	0.7	n.m.	Enablement
12/06/21	Iceye	Led by Seraphim Space Investment Trust	25.0	n.m.	EO/Geospatial
12/07/21	Skykraft	Adcock Private Equity Pty Ltd & Lennoxgrove Capital	2.5	n.m.	Enablement
12/07/21	Ursa Major Technologies	Led by BlackRock	85.0	n.m.	Enablement
12/08/21	hiSky	ST Engineering	30.0	n.m.	Enablement
12/09/21	iQPS Inc.	Consortium of investors	n.d.	n.m.	EO/Geospatial
12/13/21	Rocket Pi	Hainan Qianyi Fund & Suzhou International Development Venture Capital Holding Co., Ltd.	3.1	n.m.	Enablement
12/14/21	IBISA	HP Insurtech Gateway Limited & Rockstart	1.7	n.m.	Other
12/14/21	Kayhan Space	Led by Initialized Capital & Root Ventures	3.7	n.m.	Other
12/14/21	SatRevolutions S.A.	Virgin Orbit LLC	30.0	150	Enablement
12/14/21	SpaceX	Undisclosed	337.4	n.m.	Enablement
12/15/21	Hypersat	Virgin Orbit LLC	n.d.	n.m.	EO/Geospatial
12/15/21	Stoke Space Technologies	Led by Breakthrough Energy Ventures	65.0	n.m.	Enablement
12/15/21	Teren	Allos Ventures & Ascent Energy Ventures	4.0	n.m.	EO/Geospatial
12/16/21	Helix Geospace	Led by Bloc Ventures	4.0	n.m.	Other
12/17/21	Northstar Earth and Space Inc	Luxembourg Future Fund	45.0	n.m.	EO/Geospatial
12/18/21	Space Forge	Led by World Fund, Type One Ventures, and SpaceFund	10.2	n.m.	Other
12/27/21	PLD Space	Led by Arcano Partners, Aciturri and the Centre for the Development of Industrial Technology	28.2	n.m.	Enablement

Public Equity & Related			**Proceeds**	**TEV**	**Type**
10/18/21	Comtech	PIPE led by White Hat Capital Partners	$100	n.a.	Satcom
10/28/21	Terran Orbital	Tailwind Two Acquisition Corp. (SPAC)	470	1,580	Enablement
11/19/21	Telesat Corporation	IPO (Public listing)	n.a.	2,518	Satcom
11/23/21	Beam Communications	PIPE	4	19	Other
12/06/21	Windward	IPO	46	n.a.	Satcom
12/07/21	Tomorrow.io	Pine Technology Acqusition Corp. (SPAC)	420	729	EO/Geospatial
12/13/21	Sidus Space	IPO	15	n.a.	Enablement

Our Expectations

Satellite and space sector investor interest and transaction activity levels achieved all-time highs during 2021. The overall transaction count for the year was 316 compared to 228 in the prior year (and 196 in 2019). Under the surface, how do we see sentiment and transaction complexion evolving in 2022?

1) **SPACs back to Earth:** In early 2021, de-SPAC activity was reaching record levels. One year later, and today, new de-SPAC transactions are exceedingly difficult to close, and investor redemptions in de-SPAC transactions are very high. We believe there will be few new de-SPAC public space companies arriving in 2022.

   Perhaps more importantly, the space companies that have successfully de-SPACed now must execute to plan. They will be judged (and valued) on their own merits, and some of these companies will see success — though many will not. Traditional factors, including the quality of management, the relevance of the company's strategy/plan, the existence of sustainable barriers to entry/competitive moats, and the successful execution against plan, will separate the winners from the losers. In the meantime, share prices for many of these companies have been under pressure in recent months, driven by a combination of fundamental, market, and technical factors.

2) **Reaching the end-user:** Numerous new satellite systems are being deployed (broadband, Earth observation, and IoT, among others). In 2022, as constellation deployment for many such systems approaches critical mass, the operators will need to identify and pursue new end-customer segments to monetize their satellite systems. Acquisition of downstream players is likely to be one of the tools in operators' toolboxes toward this end.

3) **Sharpening focus on the ground:** Despite billions invested in the space segment over the last two years, the ground segment has been largely overlooked and underappreciated. During the last six months, we have seen a steady uptick in the amount of analysis and review of the ground segment, and new strategic players and financial sponsors are seeking to identify a range of opportunities in these areas. Suffice it to say, the ground segment is critical to overall systems success (whether in satcom or EO, defense or commercial), and we believe that increasing attention will be paid to the ground segment and the RF chain (and optical) during 2022.

4) **From PE platform to add-on focus:** Over half a dozen PE-backed platform companies emerged in the satellite and space enablement sector over the last 18 months. We expect increasing tuck-in/add-on acquisition activity to occur over the coming year as these companies and their financial sponsors seek to build greater scale and synergy.

The year ahead will be an important one for the maturation of the satellite and space sector. As a firm dedicated exclusively to the satellite and space sector, we hope for continued milestone achievement and ongoing success for space sector leaders, key investment programs and constellations, and the best-of-breed startups. Enduring momentum across these three vectors will be vital to cementing a long-term position for the satellite and space sector within the minds and wallets of top-tier investors worldwide.

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This market analysis is provided by Quilty Analytics LLC and Space Foundation research.

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Introduction | *After a 12-year hiatus, space tourism rocketed upward in 2021, with 14 civilians launching into space on orbital and suborbital journeys, double the number of space tourists from all prior years combined. Experts say 2022 will be even busier.*

Tourist Yozo Hirano, Roscosmos cosmonaut Alexander Misurkin and tourist Yusaku Maezawa pose for a photo ahead of their launch to the International Space Station Dec. 8.
Credit: NASA

Space Tourism Took Off in 2021, with More Expected in 2022

Roaring Return for Tourism

After 12 dormant years, space tourism grew so quickly in 2021 that the U.S. Federal Aviation Administration shuttered a program that awarded astronaut's wings to civilian spacefarers in favor of listing their achievement on a government website.

"The U.S. commercial human spaceflight industry has come a long way from conducting test flights to launching paying customers into space," FAA Associate Administrator Wayne Monteith stated on the agency's website. "The Astronaut Wings program, created in 2004, served its original purpose to bring additional attention to this exciting endeavor. Now it's time to offer recognition to a larger group of adventurers daring to go to space."

A SpaceX Falcon 9 rocket carrying the first ever crewed mission with exclusively private citizens launches from Kennedy Space Center, Fla., Sept. 15.
Credit: Space Force

The first tourist in space launched to the International Space Station (ISS) in 2001. By 2009, seven space tourists had flown to space when the industry went into hibernation, according to Space Foundation research. In 2021 alone, 14 tourists flew more than 100 kilometers (62 miles) above sea level, the traditional distance used to define a flight to space.

Landmarks Include Orbital Flight

Blue Origin founder Jeff Bezos kicked off the brisk tourism year in July with a suborbital flight aboard a New Shepherd vehicle. Also on board was Wally Funk, an 82-year-old female aviation pioneer who briefly held the title of the oldest person to fly to space.

"This was a big step forward for us and is only the beginning," Blue Origin CEO Bob Smith, predicted on the company's website after the flight.

In September SpaceX launched the first privately funded mission to orbit with four space tourists, including entrepreneur Jared Isaacman who backed the venture, spending three days aboard a Crew Dragon craft dubbed Inspiration 4.

The Inspiration 4 crew became the first all-civilian crew in orbital space after their September 2021 three-day mission.
Credit: SpaceX

Michael Strahan, second from left, and his fellow crewmates on New Shepard's 19th mission.
Credit: Blue Origin

"During their multi-day journey in orbit, the Inspiration 4 crew conducted scientific research designed to advance human health on Earth and during future long-duration spaceflights," SpaceX stated in a news release.

Under the broader 50-mile spaceflight definition used by the FAA, two more tourists joined the 2021 group, with Virgin Galactic's July 11 flight of Spaceship Two, which carried the firm's founder Richard Branson and five crewmembers to a height of 53 miles (88 kilometers).

Stars Meet Stars

Most blockbuster movies about space are filmed in cozy studios on Earth, but not in 2021.

Russia sent actress Yulia Peresild and filmmaker Klim Shipenko on a Soyuz flight to the ISS in October and used the station as a movie set.

"Russians will be the first in the world to shoot a feature film in space," Russian Space Agency Roscosmos stated on its website. "The film tentatively called 'The Challenge' will be about a girl doctor, who due to dramatic circumstances has a month to prepare for the flight and go to the ISS to solve an important problem."

In December, Japanese billionaire Yusaku Maezawa was joined by filmmaker Yozo Hirano on a Roscosmos flight to the ISS to shoot a documentary about their journey.

The actor most closely associated with fictional exploits in the cosmos, 90-year-old William Shatner of "Star Trek" fame, was filmed during a suborbital Blue Origin flight in October. Daytime TV got a boost when "Good Morning America" co-host Michael Strahan flew to space with Blue Origin in December.

Tourism Boom Expected To Grow

John Spencer, founder of the Los Angeles-based Space Tourism Society, called 2021's achievements "game-changing." "There will be more flights to the ISS with private citizens and more investments in the billions of dollars into space enterprises and space tourism," Spencer said, predicting more growth in 2022 and following years.

The first launch of an all-private crew to the ISS is set for Feb. 28 from Kennedy Space Center in Florida. Axiom Space's Axiom 1 mission is the first of two all-private crewed missions planned by the firm in 2022 under an agreement with NASA. The missions come as Axiom works with contractors to design and build its own commercial space station.Lodging on the International Space Station comes with a galactic bill. According to the most recent price list released by NASA, meals aboard the station run $2,000 a day, trash disposal costs more than $9,000 per pound, and renting the place also entails fees that top $10 million per mission. The fees don't include the cost of travel to and from the ISS.

There are economy-classs options at lower altitudes. In November, Virgin Galactic announced sub-orbital spaceflight tickets starting at $450,000, and company officials said would-be astronauts were snapping them up."Demand for space travel is

strong, and we've been selling seats ahead of the pace we had planned," Virgin Galactic CEO Michael Colglazier stated on the firm's website. "This demonstrates the incredible market for our product and appreciation for the value of the unique experience we offer."

Roscosmos announced in December it plans to step up Soyuz production to meet growing tourism demand, according to the Russian state news agency TASS. SpaceX announced Maezawa is backing a private mission for its new Starship spacecraft that is planned to take passengers on a lunar fly-by in 2023.

"This flight is an important step toward enabling access for people who dream of traveling to space," the firm stated on its website. Spencer said the record-setting tourists flights of 2021 set the stage for growth. "In the future, the year 2021 will be seen as a turning point," he said, "Something like the first mission to the Moon from Apollo." Commercially backed space stations planned to hit orbit in the coming years will drive more tourism, Spencer said. And the well-heeled may someday look on flights aboard commercial spacecraft as something for commoners, he predicted. Decades from now, he predicts, the Earth's wealthiest residents will look forward to "space yachting, modeled after oceangoing superyachts."

If yachting isn't in the future of spaceflight, commuting might be. On its website, SpaceX touts the advantages of using its Starship in place of slower airliners. Flying from Los Angeles to London in a jet can take more than 10 hours. SpaceX says by traveling in the friction-free environment of space, up to 1,000 passengers could go from Hollywood to Buckingham Palace in 32 minutes.

SPACE TOURISTS, 2001-2021

DATE	LAUNCH VEHICLE	AGENCY/COMPANY	DESTINATION	GENDER
28-Apr-01	Soyuz	Roscosmos	International Space Station	M
5-May-02	Soyuz	Roscosmos	International Space Station	M
5-Oct-05	Soyuz	Roscosmos	International Space Station	M
20-Sep-06	Soyuz	Roscosmos	International Space Station	F
7-Apr-07	Soyuz	Roscosmos	International Space Station	M
12-Oct-08	Soyuz	Roscosmos	International Space Station	M
26-Mar-09	Soyuz	Roscosmos	International Space Station	M
30-Sep-09	Soyuz	Roscosmos	International Space Station	M
7-Jul-21	New Shepard	Blue Origin	suborbital	M
7-Jul-21	New Shepard	Blue Origin	suborbital	M
7-Jul-21	New Shepard	Blue Origin	suborbital	F
7-Jul-21	New Shepard	Blue Origin	suborbital	M
16-Sep-21	Crew Dragon	SpaceX	low Earth orbit	M
16-Sep-21	Crew Dragon	SpaceX	low Earth orbit	F
16-Sep-21	Crew Dragon	SpaceX	low Earth orbit	M
16-Sep-21	Crew Dragon	SpaceX	low Earth orbit	F
5-Oct-21	Soyuz	Roscosmos	International Space Station	F
5-Oct-21	Soyuz	Roscosmos	International Space Station	M
13-Oct-21	New Shepard	Blue Origin	suborbital	M
13-Oct-21	New Shepard	Blue Origin	suborbital	M
13-Oct-21	New Shepard	Blue Origin	suborbital	M
13-Oct-21	New Shepard	Blue Origin	suborbital	F
8-Dec-21	Soyuz	Roscosmos	International Space Station	M
8-Dec-21	Soyuz	Roscosmos	International Space Station	M

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Claim Your Seat to Space

Virgin Galactic

Type: Suborbital
Vehicle: Spaceship Two, launched from a mothership
Speed: In excess of 2,500 mph
Ceiling: More than 50 miles
Flight duration: Two hours with several minutes in space
Passengers: Six
Ticket price: $450,000
Book it: www.virgingalactic.com

Blue Origin

Type: Suborbital
Vehicle: New Shepard
Speed: In excess of 2,300 mph
Ceiling: More than 70 miles
Flight duration: 11 minutes
Passengers: Six
Ticket price: Undisclosed, but first ticket auctioned for $28 million, the company stated
Book it: www.blueorigin.com

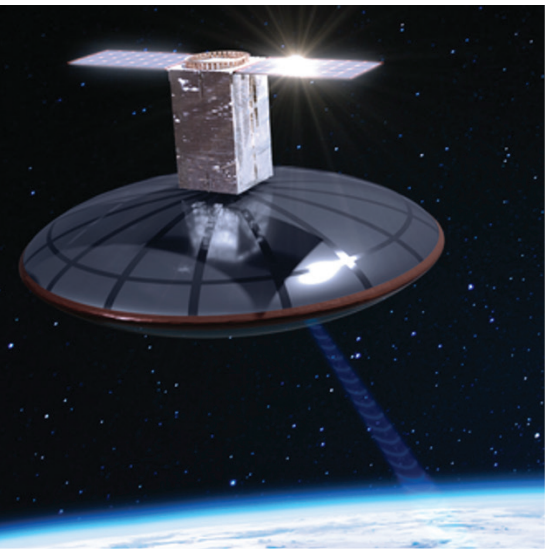
SpaceX

Type: Orbital
Vehicle: Crew Dragon
Speed: In excess of 17,000 mph
Ceiling: More than 367 miles
Flight duration: A recent private orbital flight lasted three days, but can vary
Passengers: Four
Ticket price: Undisclosed, but The New York Times reported tickets could run $55 million
Book it: www.spacex.com

Space Adventures

Type: Orbit
Vehicle: Soyuz
Speed: In excess of 17,000 mph
Ceiling: Capable of more than 20,000 miles
Flight duration: Usually 10 days, but can vary
Passengers: Two Ticket price:
Undisclosed, but reports have quoted prices topping $50 million
Book it: www.spaceadventures.com

Credit: NASA



Introduction | *As world leaders focus on Earth's changing climate, a commercial satellite venture set to orbit in 2022 promises the most comprehensive data from space to better predict weather and give scientists a clearer picture of global warming. The commercial satellites would join a new fleet of planned Earth-observing sensors set for launch by space agencies around the globe.*

This illustration shows a planned radar satellite from Tomorrow.io in low-Earth orbit.
Credit: Space Force

New Commercial Satellites Promise More Advanced Weather, Climate Data

The first of 32 satellites the size of dormitory refrigerators is scheduled to rocket to space in late 2022 and deliver an unprecedented amount of data that an American software firm plans to use to deliver a clearer picture of Earth's changing climate and predict weather for clients from online retailers to airlines.

The Tomorrow.io constellation will be the latest satellites revolutionizing how mankind understands Earth. The new constellation, which is partially backed by a $19.3 million U.S. Air Force contract, will launch as American leaders work to share more data from space — including data gathered by military satellites — with the scientific community.

That new data, from all sources, comes as global leaders look to space to better understand a changing climate on Earth.

"Remote sensing satellites have increased the fidelity of people's understanding of Earth system science and the evolution of the planet's climate," the World Economic Forum explained in a September paper entitled "Space for Net Zero."

With 32 planned satellites, Tomorrow.io, a Boston-based weather software company formerly known as ClimaCell, plans what will be the single biggest weather constellation to date, dwarfing even government efforts. More satellites will deliver more frequent radar views of the atmosphere, allowing hourly rain and wind updates for any point on the planet.

The planned constellation is expected to add commercial horsepower to what have primarily been government efforts to understand the planet and comes as world leaders ponder creating what the World Economic Forum describes as an "Earth Operations Centre" to analyze climate data from space. The Forum found that more than half of "essential climate variables" can only be measured from space.

In Boulder, Colorado, Tony Busalacchi, who heads the University Corporation for Atmospheric Research, said he can't wait to get his hands on the treasure trove of data soon to flow from federal satellites and proposed commercial ventures, including Tomorrow.io's planned constellation.

"The more data we get and the higher resolution, we can drive our ability to predict precipitation," said Busalacchi, whose organization oversees the National Center for Atmospheric Research, the top group in the United States studying climate change.

Tomorrow.io never planned to be in the space business, said Aravind Ravichandran, the firm's director of space strategy. Instead, Tomorrow turned to satellites because existing ground radars cover less than a third of the planet. To make the company's weather predictions work, it needed a wider view.

"The data wasn't available," Ravichandran said.

Putting more radars on the ground wouldn't work, because most of them would need to float in the ocean. Airplanes would do the job, but with rising fuel costs and a constant need for maintenance, they would be too expensive. With commercial launch costs tumbling and technology available off the shelf, Tomorrow decided on space.

"This was the best and most competitive from an efficiency point of view," Ravichandran said.

Once launched, the Tomorrow constellation will be the latest satellites to revolutionize how mankind understands Earth's atmosphere.

The first weather satellites were launched in the 1960s, sending back pictures of clouds on the planet below that could be used to predict weather. Now, increasingly sophisticated satellites can measure carbon dioxide and other gases, detect rising seas, and offer a "better view of the heat budget of the Earth," Busalacchi said.

That "heat budget," which shows how much of the sun's energy is returned to space and how much is retained in the atmosphere, is a key measure of global warming, Busalacchi said.

Busalacchi regularly downloads data from U.S. agencies, including the National Oceanic and Atmospheric Administration, NASA, and the Pentagon's Defense Meteorological Support Program, but getting a clear picture of Earth's climate requires more data than American satellites can deliver. Busalacchi said his agency has worked with nations from France to South Korea to garner more information.

"We have a long history of collaboration," he said, specifically noting work with the European Space Agency and the Japan Aerospace Exploration Agency.

Weather as a Business

Wild swings in weather have made forecasting a more lucrative business, Ravichandran said.

Tomorrow.io executives say its predictions help clients "prepare for the business impact of weather by automating decision-making and enabling climate adaptation at scale."

Tomorrow.io forecasts, Ravichandran said, offer precision that allows clients to foresee supply-chain impacts when weather conditions snarl delivery systems, tangle traffic for commuting workers, or threaten infrastructure. Logistics companies, retailers, manufacturers, and sports franchises have subscribed to Tomorrow.io's services.

The firm, founded in 2016, uses data from weather agencies around the globe. But to get the kind of precision its customers need requires something more, he said.

Radar imagery that can spot rain and wind helps build forecasts, but existing radars cover less than a third of the planet. The biggest blank spots on the planet's radar map are the most vital to long-range forecasting: oceans. Storms gather moisture and strength from oceans, where evaporating water forms clouds. Moist air over oceans can spin into tropical cyclones or head inland to build blizzards. While major weather events draw the most attention, predicting smaller storms that

nurture crops can be vital to agricultural industries. When there's no moisture to spot, the satellites will also help predict drought and wildfire conditions.

Looking down from space, Tomorrow.io's satellites in low-Earth orbit will be able to discern moisture over any point on the planet at least once an hour, Ravichandran said.

"You are going to have hyperlocal forecasting possible for anywhere in the world," he said.

Air Force officials say the satellite data fills gaps that even the Pentagon's array of satellites hasn't filled.

"Global environmental data is essential to effective mission planning and execution of air and ground operations," John Dreher, chief of Air Force Materials Command's Weather Systems Branch at Hanscom Air Force Base said in a statement. "This satellite constellation partnership with Tomorrow.io will give Air Force weather operators a vastly improved awareness of current and forecasted weather conditions."

Busalacchi said he's "bullish" on the role of commercial satellites in helping scientist better understand the planet's climate.

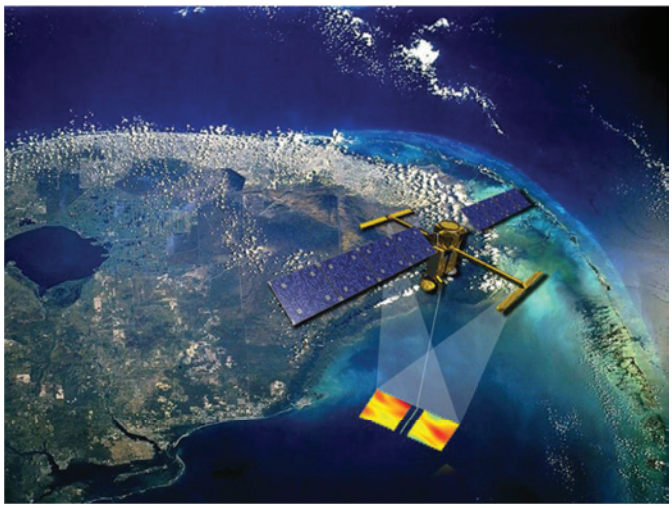
He warned, though, that in order to keep delivering climate data, commercial satellite firms will need to make money.

"The success of this new model has yet to be demonstrated," he said. "The private sector is constrained by the need to make profits."

Space as a Solution

The business of observing conditions on Earth from the high ground of orbit is booming. Northern Sky Research estimated that revenues for Earth observation satellites grew 9.1% from 2019 to 2020, hitting $3.7 billion.

Retired Air Force Brig. Gen. Marty France, who led the Air Force Academy's Astronautical Engineering Department, said he expects the growth in the Earth observation satellite business to continue for the foreseeable future.



Artist's impression of the future SWOT satellite making sea surface height observations. The SWOT satellite is expected to obtain data even through clouds. *Credit: NASA*

"It is nice to talk about the aspirations of exploring the galaxy, but we have enough to do down here to keep us occupied for a long time," said France, who has worked as a consultant for space enterprises since he retired from the Air Force in 2018.

In 2022, NASA, in conjunction with the National Center for Space Studies in France and the Canadian Space Agency, plans to launch the Surface Water and Ocean Topography satellite to study the planet's oceans, lakes and rivers. In early 2023, NASA and the Indian Space Research Organization expect to launch NISAR, a radar satellite designed to survey the Earth's land masses every six days to detect changes. Also in 2023, NASA plans to deliver the Climate Absolute Radiance and Refractivity Observatory to the International Space Station, which is expected to help measure greenhouse gas impacts by determining how much sunlight is reflected from Earth.

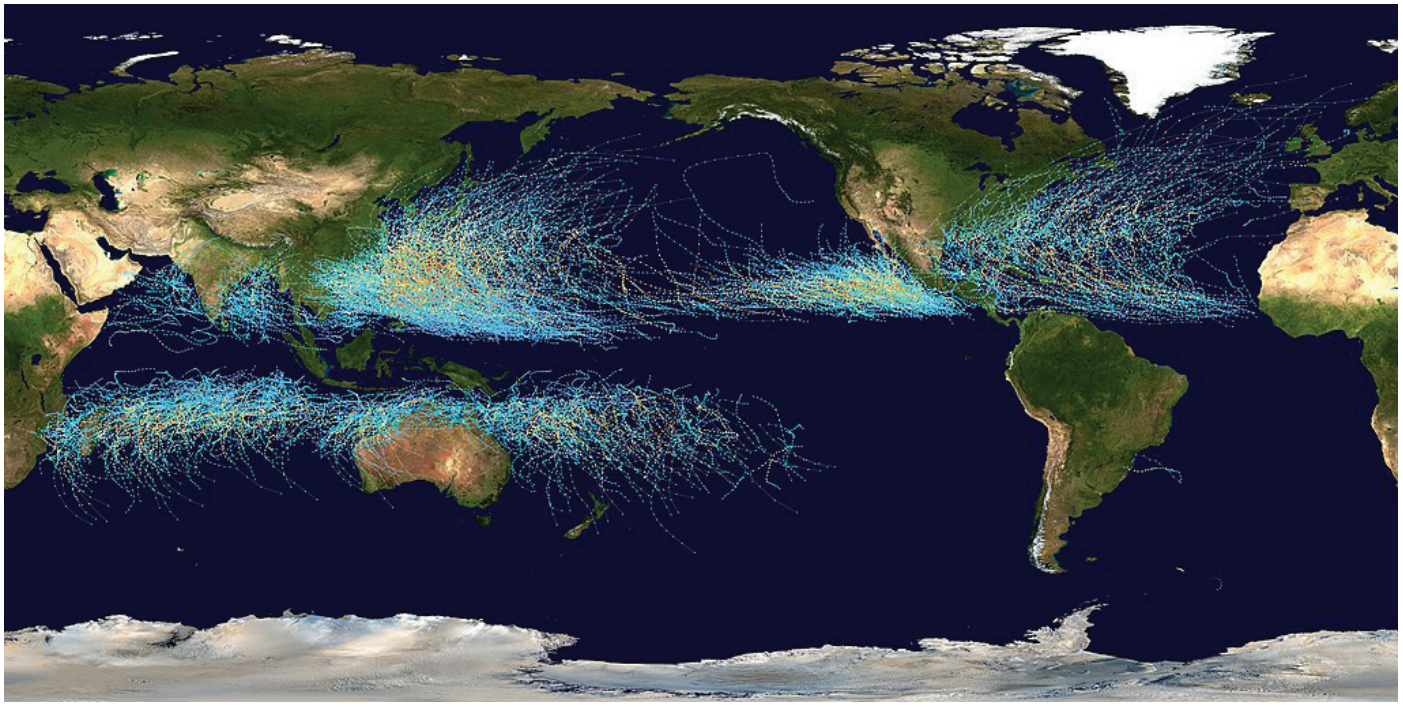
More sensors headed to space will be a boon to scientists on Earth if they can come up with new ways to parse through it all, said Busalacchi.

The sheer volume of data — Tomorrow.io says it already has 700 terabytes worth before its first satellite launches — requires more computing power than even the National Center for Atmospheric Research possesses.

"You hear all the time about how the United States is second or third in medium-range weather forecasting," Busalacchi said, pointing to the European Union's observation systems. "We don't have sufficient computing power. What the National Weather Service does with what it has is impressive, but to really close the gap we really need an increase in computing power."

Chasing Climate Change

Tomorrow.io's satellites are designed to predict weather in small windows of time, Ravichandran said. But they could also be useful for tracking climate, the cumulative swings in conditions over generations or centuries. The 32 satellites could help scientists spot wider trends to learn about rising sea levels, changing rain patterns, and shifting trade winds.



This map shows the tracks of all tropical cyclones that formed worldwide from 1985 to 2005. More advanced satellites will allow for better storm tracking and weather predictions over the oceans and on land.
Credit: Wikimedia

"We will collect data that will be very useful in planet modeling," Ravichandran predicted.

There could be more data on the way.

The Biden administration in December pledged to share more data obtained from space to boost climate research. "Data collected from space helps us improve national preparedness and reduce the impacts of extreme weather, natural disasters, and climate change in a manner that better addresses the needs of vulnerable communities," the administration stated in a document laying out its space priorities.

Retired Gen. France said some military satellites, including infrared cameras in orbit used to spot the heat from missile launches, could offer "big picture" data for climate research. But sharing data from intelligence satellites requires navigating through a minefield of laws and regulations designed to safeguard military secrets.

"We must do more to make it accessible to a larger group of people," France said of climate data gathered by military spacecraft.

Busalacchi said the federal government in the 1990s attempted to free up more military satellite data for climate scientists, but the effort bogged down amid classification concerns.

"I think we need to take a fresh look at what are some of the national assets that can be declassified safely so we can improve our understanding of climate," he said.

Lee

Chasing Climate, Growing Threat

South Korea's Hoesung Lee, who heads the U.N.'s Intergovernmental Panel on Climate Change (IPCC), told a Dec. 6 online gathering of global leaders that the planet's climate crisis is growing more dire, with temperatures up by 1.1 degrees Celsius over historic norms.

"Human influence is making extreme climate events, including heatwaves, heavy rainfall, and droughts, more frequent and severe," he warned. "Climate change is already affecting every region on Earth, in multiple ways. The changes we're experiencing today will increase with further warming." Along with the warning, Lee made a call for better tools to monitor the changing climate.

"I would like to stress here that IPCC assessment reports increasingly acknowledge the need for climate science to explore and tap into all areas and forms of knowledge," he said. "This is a critical component if we as IPCC are to present comprehensive and balanced assessments of the causes, impacts and responses to climate change."

To get that data, leaders are increasingly reliant on satellites.

Former U.S. Vice President Al Gore addresses world leaders in November at a United Nations climate change conference in Scotland.
Credit: United Nations

In November at a United Nations summit on climate change held in Glasgow, Scotland, former U.S. Vice President Al Gore told the assembled world leaders he expects satellites to deliver "an era of radical transparency," by tracking greenhouse gas emissions and other climate conditions.

Gore said information from satellites will create accountability. "When we have actionable information, I promise you the demand for change will grow and grow and grow," he said.

While making profit remains the goal for Tomorrow.io, Ravichandran said his company has partnered with the nonprofit TomorrowNow.org to help shield underserved communities in impoverished countries from the ravages of changing climate and severe weather by delivering better weather predictions.

"It's important to realize the ability to pay is not the same around the world," he said.

The charity claims that 5 billion people worldwide lack access to accurate weather forecasts.

"With advanced weather warnings, people can move to safety and protect their homes, a farmer can accelerate harvest, an emergency responder can be standing by to help," TomorrowNow stated on its website. "And yet, this 'preparedness' is not reality for most people today."

In early December, Tomorrow.io announced a planned 2022 merger with Pine Technology Acquisition Corp. and a proposed $420 million stock offering for the combined firm. Pine Technology is a special purpose acquisition corporation aimed at acquiring firms with expertise in "insurance technology," the company stated in a news release. The new company will operate as Tomorrow.io and trade on the NASDAQ exchange under the symbol TMW.

Busalacchi said the latest push to improve Earth observation from space comes with a new urgency driven by the commercial space race. That could mean more satellites in orbit sooner than could have been imagined a decade ago, he said.

"The rapid turnaround of the private sector is moving us in the right direction," he said.

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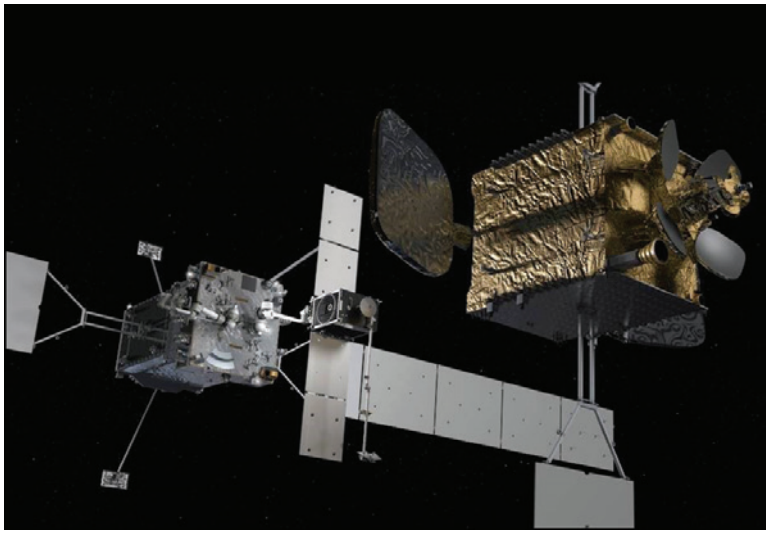
Introduction | *Space sustainability has taken a significant step forward with on-orbit refueling and satellite servicing. A concept that decades ago began with astronaut extravehicular activities is now advancing to a point where no human assistance is needed. New innovations have restored life to old satellites and promise to extend the range of future spacecraft missions.*

Orbit Fab's Tanker-002, mounted on a Spaceflight Sherpa-ES, offers multiple fuel options to satellites in geostationary orbit.
Credit: Orbit Fab

On-orbit Refueling, Servicing Extends Life for Old Satellites, Promises Longer Mission Capabilities with Network of Stations

Somewhere about 2,000 kilometers (1,242 miles) above Earth, the world's first space-based gas station is ready for service. The Tanker-001 Tenzing Fuel Depot reached low Earth orbit (LEO) in June 2021. Three months later, Orbit Fab, the company that developed the depot, announced that in partnership with SpaceX and Spaceflight Inc., it would head another 34,000 kilometers (21,126 miles) higher, into geostationary orbit (GEO), to place its second fuel depot.[1]

Orbit Fab has trademarked its slogan "Gas Stations in Space," but it is not the first company to achieve a satellite refueling in geostationary orbit. Northrop Grumman subsidiary SpaceLogistics in February 2020 docked its Mission Extension Vehicle (MEV-1) to a nearly depleted Intelsat IS-901.[2] Its second vehicle, the MEV-2, docked with another Intelsat satellite in April 2021.[3] A third unit, the Mission Robotic Vehicle, projected to launch in 2024,[4] will have two dexterous robotic arms developed by the U.S. Naval Research Laboratory. The robotic arms will place Mission Extension Pods onto aging satellites, providing six more years of life.[5] All three of the Northrop Grumman vehicles require either a jet pack or a pod attaching to a customer's satellite.



The Mission Robotic Vehicle features two robotic arms that will allow it to attach new fuel pods to satellites.
Credit: Northrop Grumman

Orbit Fab's hardware is a fuel tug and shuttle system that will dock to a satellite, deliver fuel from the shuttle, and then allow the satellite to disengage, much like a ship's tender used to support and resupply other boats and ships at sea. Northrop Grumman and Lockheed Martin Ventures are among the investors backing Orbit Fab's refueling system. Orbit Fab sees market potential in LEO and GEO for satellites, including for the Department of Defense, said Jeremy Schiel, Orbit Fab's co-founder and chief development officer. The greatest potential, he says, may come from space concepts yet to be developed.

"What I'm really excited for is the high school and college student who is just now starting to think about space applications," he said. "They're not bounded by the single-use paradigm we've been

burdened with. They can ask themselves 'What crazy idea can I come up with now that I have a reliable network?' We have so much flexibility now that we're not bound by using only the fuel that you bring up."

Orbit Fab plans to have its GEO tanker in place as early as this year and the first two shuttles in orbit by 2023, Schiel said.

Tanker-01, in LEO, is stocked with high-test peroxide but was meant to be more of a test bed, Schiel said. Tanker-02, once in GEO, will provide multiple types of fuel. The next development phase will be placing multiple tankers and shuttles to create a network of stations Shiel describes as "an orbital highway." That network, he envisions, will allow spacecraft to extend mission life to nine, 12 or 14 missions and will also allow operators to hopscotch through space, connecting with more remote stations that will allow spacecraft to maneuver into cislunar space and beyond.

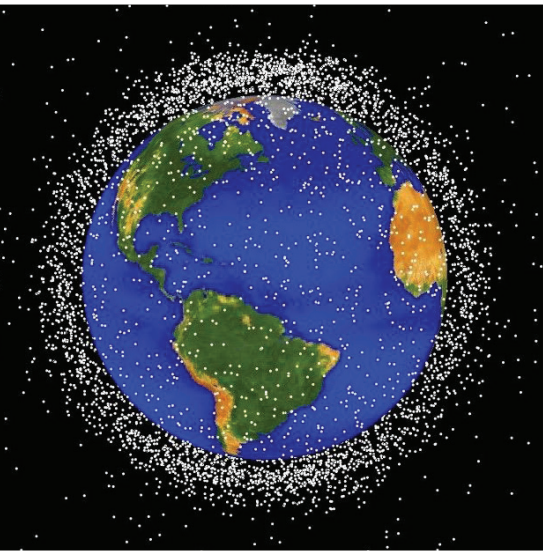
In January, Astroscale U.S. signed the first on-orbit satellite fuel sale agreement for Astroscale's Life Extension In-Orbit (LEXI) Servicer. LEXI is the first satellite specifically designed to be refueled in space. Scheduled for launch to GEO in 2026, LEXI spacecraft will service satellites for commercial operators, the U.S. government, and other world government partners by managing attitude control, momentum management, inclination correction, and even satellite retirement to a graveyard orbit if necessary.[6]

While these fuel depots and satellite servicers are largely in the development stages, Schiel sees their eventual use as a significant shift in space history. "These are major transitions from a global space economy to an in-space economy," he said, noting that the current economy provides goods and services used on Earth. "The transition we're seeing now is of people buying goods and services to be used in space. And that's really exciting." New as it is, it's a future NASA described in detail in its 2010 report "On-Orbit Satellite Servicing Study." In May 1973, NASA restored the new Skylab to full functionality after replacing a thermal shield in space. Twenty years later, the Hubble Space Telescope had corrective optics installed. Both those efforts, however, required astronauts on extravehicular activities (EVA) missions.[7] In 1989, NASA's Headquarters Office of Space Flight drafted a strategic plan to pair the International Space Station (ISS) with an orbital vehicle that would handle refueling, resupply, repair, and system upgrades of satellites. A "space tug" that would handle servicing was cancelled due to budget pressure.[8]

"The proliferation of abandoned satellites poses known hazards to newer members of the constellation and may occupy unique and economically valuable orbital real estate that could be recycled for other uses," the NASA report concluded. "… Satellite servicing is a tool — a tool that can serve as the "master enabler" to create the architectures needed to conquer the next frontiers in space."

The space agency didn't give up on a satellite servicing vehicle. Its three Robotic Refueling Missions, last conducted in 2020, tested robotic refueling.[9] Working with Maxar Technologies, NASA is developing the On-orbit Servicing, Assembly, and Manufacturing 1 (OSAM-1) mission spacecraft. In addition to having robotic arms to assist with fueling and servicing, OSAM-1 will include a payload called Space Infrastructure Dexterous Robot (SPIDER) that will demonstrate in-space assembly and manufacturing. The launch date for OSAM-1 and SPIDER is anticipated for 2024.[10] The European Space Agency also is developing on-orbit technology. In 2021, it issued a €100 million mission proposal for a vehicle capable of a range of in-orbit needs, including debris removal and satellite refueling.[11]

Lesley Conn is senior manager of Research & Analysis for Space Foundation.



Introduction | *As spacefaring nations grow more active in space exploration, the idea of a peaceful exploration and use of outer space starts to fade in the absence of international rules. International cooperation offers the best path to address and clarify these issues. This article explores the debates surrounding the top three space law barriers to the future of international space — the Artemis Accords, the legality of anti-satellite (ASAT) weapons, and space debris mitigation — and offers recommendations on how the United States and other international actors could address these issues.*

This graphic shows the location of space debris tracked by NASA.
Source: NASA

Analysis: Legal Barriers Complicate Future in Orbit

International Dialogue for Artemis Accords

Seeking "a common set of principles to govern the civil exploration and use of outer space," the United States drafted the Artemis Accords, named for a NASA program devoted to building a permanent lunar-orbiting base called the Gateway and a base on the lunar surface where astronauts could mine resources required to fly to Mars.[1] As of Dec. 20, 2021, 14 countries had signed the pact.[2] During her first National Space Council meeting on Dec. 1, 2021, Vice President Kamala Harris announced that France planned to join as well.[3] The Artemis Accords, however, have stirred skepticism among the non-signatory spacefaring nations.

Disagreements on Artemis Accords

Due to the close timeline of moon landings starting in 2024, a perceived sense of urgency surrounds the Artemis Accords. The U.S. Department of State and the re-established National Space Council drafted the pact without going through a more traditional process that would lead to the conclusion of an international treaty.[4] The 1998 International Space Station (ISS) Intergovernmental Agreements took a slower path, with prolonged periods of negotiation that led to an inter-governmental agreement and four Memorandums of Understanding (MOUs) that are binding international agreements.

NASA Deputy Administrator Pam Melroy and Polish Space Agency (POLSA) President Grzegorz Wrochna pose following an Oct. 26 Artemis Accords signing ceremony in Dubai, United Arab Emirates.
Credit: NASA

Though not all of the European Space Agency member states are signatories on the Artemis Accords, ESA and NASA announced Oct. 27, 2020, that the two agencies had signed a MOU to cooperate on the Lunar Gateway.[5] The agreement extends the ISS pact to the Gateway, with ESA providing a habitation module called I-Hab; a second module for telecommunications and refueling called the European System Providing Refueling, Infrastructure and Telecommunications (ESPRIT); and two service modules for the Orion spacecraft. In return, NASA will offer opportunities for European astronauts to fly to the Gateway.[6]

While ESA signed off, of ESA's 22 member states, just four — Italy, Luxembourg, Poland and the United Kingdom — have signed the Artemis Accords.[7,8] Kai-Uwe Schrogl, president of the International Institute of Space Law (IISL), explained that "neither ESA nor the EU nor any European State is pressed to formally join and sign the Artemis Accords" and that though the Artemis Accords are appreciated as policy input for debate, negotiations for the pact must be led in multilateral forums such as the United Nations Committee on the Peaceful Uses of Outer Space (UNCOPUOS). The U.N. Legal Subcommittee recently set up a working group for this purpose.[9]

The European Coordination Committee for the ISS Intergovernmental Agreement (IGA-CC) — with Ambassador Stefano Queirolo Palmas serving as chairman and Schrogl serving as vice chairman — has the challenging task of establishing an intergovernmental legally binding framework for multilateral cooperation beyond Earth orbit.[10,11] ESA members have a pact on using lunar resources to support sustainable lunar exploration, but differing views remain on issues such as non-appropriation, freedom of use, and security.

One such area of disagreement is caused by the implementation of "safety zones." The Artemis Accords define the term as the "area in which nominal operations of a relevant activity or an anomalous event could reasonably cause harmful interference" and explains that this is in line with the principle of due regard in Article IX of the 1967 Outer Space Treaty.[12]

Unless a clear function of these safety zones is carefully articulated to the international community, stressing that these zones don't assert property rights, the zones could be contrary to Article II and Article XII of the Outer Space Treaty stating that the Moon is not subject to national appropriation and installations on the Moon should be open to other states.

NASA is moving ahead with planned Artemis missions to the moon even as diplomats work to bring more nations to an agreement on lunar operations dubbed the Artemis Accords.
Credit: NASA

Next Steps for Artemis Accords

Building on the Artemis Accords' definition of a safety zone and a definition developed by the Hague International Space Resources Governance Working Group — which states a safety zone is an "area-based safety measure...necessary to assure safety and to avoid any harmful interference" — Open Lunar Foundation fellow Alexander Gilbert offered this definition: "A safety zone is one method to meet state obligations under the Outer Space Treaty that defines a geographic, temporal, and/or other delimited circumstance under which a mission operator believes their operational safety requires third parties to commence consultations to avoid harmful interference related risks."[13] Gilbert proposed a safety zone algorithm that defines the activity and operations, functions of a safety zone, and zonal formulation to determine the size and nature of a safety zone through this formula: safety zone = activity + risks from activity + risks to activity. The risks of lunar dust pollution, embedded energy, operations, and other risks associated with a third-party spacecraft at safety zones will also require an international discussion to assess risks.[14,15]

The U.S. has worked to establish a common set of principles as spacefaring nations pursue ambitious goals. However, the U.S. should be open to discuss and negotiate terms of the Artemis Accords with all international actors to avoid complications in the future. One complication could result from safety zones: What will happen when nations that have not signed the accords cannot participate in the zones? Spacefaring states Russia, China, and India haven't signed the accords, nor have African nations or many ESA states. Instead, heads of the Chinese and Russian space agencies signed a MOU in March 2021 to build an "International Lunar Science Station," and announced plans to invite other countries to join.[16] It is imperative that the U.S. negotiates the terms dictated by the non-signatory states and makes it a priority to get major space-capable states on board.

Encouraging Ban on ASAT Weapons

The urgent need to ban ASAT weapons tests became even more apparent on Nov. 15, 2021, when U.S. Space Command confirmed a successful Russian ASAT test in low Earth orbit (LEO). The Nudol ground-based ASAT system destroyed the defunct Cosmos 1408 satellite, creating more than 1,500 pieces of trackable debris that threaten satellites and astronauts on the ISS and China's Tiangong Space Station.[17] Russia's test brought more attention to proposals that would ban use of force in outer space and highlighted the urgent need for international standards on responsible behavior in space.

India's Defence Research and Development Organisation (DRDO) successfully destroyed a satellite in space with its anti-satellite missile on March 27, 2019.
Credit: DRDO

Use of ASAT Weapons

ASAT weapons are usually either direct-ascent or co-orbital systems. Direct-ascent ASAT weapon systems use rockets to put an interceptor on a suborbital trajectory to intercept a satellite whereas the co-orbital systems put conventional explosives in the proximity of a targeted satellite to destroy it.[18]

The first ASAT missile test was conducted by the U.S. in 1959 when an air-launched ASAT missile was fired to intercept the Explorer V satellite.[19] The Soviet Union followed with a series of ASAT trials from 1968 to 1971 and from 1976 to 1982.[20] As a response, the U.S. test-fired ASM-135 missiles from F-15 fighters five times between 1984 and 1986 including in a 1985 test that shattered the Solwind satellite into more than 285 pieces of debris.

After a 20-year break from ASAT testing, China used a direct-ascent ASAT weapon in January 2007 to destroy one of its aging weather satellites, creating a record 3,037 pieces of debris with 79% of the debris expected to linger in orbit until 2108.[21] The next year, the U.S. used a ship-based ASAT missile to down a malfunctioning National Reconnaissance Office satellite. On March 27, 2019, India also conducted an ASAT missile test called Mission Shakti and destroyed one of its LEO satellites.[22]

Legality of ASATs

To this date, four countries have demonstrated their ASAT weapon capabilities. Article IV of the Outer Space Treaty only bans weapons of mass destruction, military maneuvers and weapon testing on celestial bodies.[23] However, "weapons of mass destruction" weren't specifically defined, so there is no explicit ban on smaller weapons outside of orbiting nuclear

weapons. Further, Article IV forbids the testing of "any type of weapons" on celestial bodies, which would not apply to ASAT weapons since they are used in orbit, not on celestial bodies.[24] The legality of ASAT use remains questioned, since it is in clear violation of other articles of the Outer Space Treaty. Aside from going against the peaceful uses of outer space, the debris from ASAT tests violate Article I, which states that outer space should be "free for exploration and use by all states."[25] Such exploration could be hindered by the resulting debris. Article VII establishes international liability on Earth, in air space, or in outer space for a launching state for damage caused by space objects or component parts, which would certainly cover debris from ASATs.[26] Further, Article IX establishes a duty to act with "due regard" to not interfere with other States' activities and to avoid "harmful contamination."[27]

Apart from the Outer Space Treaty, ASATs also violate Principle 21 of the 1972 Declaration of the United Nations Conference on the Human Environment, or the Stockholm Declaration, which states that "States have the responsibility to ensure that activities within their jurisdiction or control do not cause damage to the environment of other States or of areas beyond the limits of national jurisdiction."[28] This principle was reiterated as Principle 2 of the 1992 Rio Declaration on Environment and Development.[29]

Encouraging a Global ASAT Ban

The U.S. should enact a national ban and encourage a global ban on ASAT weapons. During the U.N. General Assembly's First Committee meeting on Nov. 1, 2021, the U.K's co-sponsored resolution to establish a U.N. Open-Ended Working Group (OWEG) on outer space security — part of the Preventing an Arms Race in Outer Space (PAROS) agenda — garnered 163 votes. Eight countries voted against the resolution — including China, Iran, North Korea, and Russia — and nine abstained, including India, Israel, and Pakistan.[30] According to the resolution, the OWEG will convene in Geneva for sessions in 2022 and 2023.[31] As a co-sponsor on the resolution, the U.S. should prioritize encouraging the other countries with ASAT capabilities — Russia, China, and India — that all either voted against the resolution or abstained from it, to initiate a ban on ASAT testing.

The U.S. could take several diplomatic avenues to achieve this initiative. An example of a global non-governmental initiative against ASAT testing is the Outer Space Institute letter to the U.N. General Assembly, calling for a treaty to ban kinetic ASAT tests.[32] The U.S. could also encourage an amendment to the Outer Space Treaty to ban ASAT weapons. The U.S. could also reignite talks on a 2014 Russian and Chinese treaty proposal entitled, "Prevention of the Placement of Weapons in Outer Space, the Threat or Use of Force against Outer Space Objects" (PPWT).[33,34] The U.S. and other nations had dismissed the proposal because it lacked verification methods and failed to restrict the development of ASATs on the ground. Reinvigorated talks on the proposal could offer a way to restart the conversation.[35] Another way could be through the Artemis Accords. Though the accords are not legally binding and do not have any of the three other nations with ASAT capabilities as signatories, through Section three — which commits the signatories to a peaceful exploration of outer space — a specific ban on ASATs could be listed.[36] Whichever diplomatic avenue the U.S. chooses to pursue, a top priority must be to lead as an example and promote a global ban on ASAT testing.

Innovation for Space Debris Mitigation

Of the nearly 8,000 satellites in orbit, including about 1,400 launched in 2021, only around 40% are operational.[37] To date, about 88% of the launched satellites, probes, landers, crewed spacecraft, and space station flight elements have been registered.[38] With these satellites moving along fixed orbits, these "space highways" become increasingly congested with opera-

tional spacecraft, dead spacecraft, and debris, which greatly increases the likelihood of collisions.[39] With many companies and organizations planning to launch mega-constellations of telecommunication satellites in LEO — an already congested corridor — over the next decades, procedures and technologies for space debris mitigation efforts are becoming increasingly urgent.

Recent Mega-Constellations

In April 2021, the U.S. Federal Communications Commission (FCC) voted to approve a SpaceX plan to deploy the first 2,824 of as many as 42,000 Starlink satellites in LEO to offer broadband internet.[40] Verizon partnered with Amazon on Project Kuiper, a constellation of 3,236 satellites, that will provide high-speed internet anywhere in the world.[41] Other companies also plan LEO mega-constellations. Britain's OneWeb is mulling 7,000 satellites and China's Guo Wang's StarNet is planning 12,992 satellites — which could result in a rapidly growing orbital problem until specific international laws and regulations can be implemented.[42]

Guidelines on Debris Mitigation

In 1995, NASA was the first space agency to publish guidelines on mitigating orbital debris.[43] In 2001, NASA and the Department of Defense (DoD) established the U.S. Government Orbital Debris Mitigation Standard Practices (ODMSP), which were updated in 2019. The guidelines provide a reference to promote efficient and effective space safety practices for other domestic and international operators.[44]

Countries such as France, Japan, Russia, and organizations like ESA have since adopted their own guidelines. In 2002, the Inter-Agency Space Debris Coordination Committee (IADC) adopted a consensus set of guidelines accepted by 10 countries to mitigate the growth of orbital debris, which were updated in 2020.[45,46] Based on the work of IADC, the Scientific and Technical Subcommittee of UNCOPUOS also adopted space debris mitigation guidelines in 2007.[47] It is important to also note Article 44 Paragraph 2 of the Constitution of the International Telecommunication Union (ITU): "In using frequency bands for radio services, Members shall bear in mind that radio frequencies and any associated orbits, including the geostationary-satellite orbit, are limited natural resources and that they must be used rationally, efficiently and economically, in conformity with the provisions of these regulations, so that countries or groups of countries may have equitable access to those orbits and frequencies, taking into account the special needs of the developing countries and the geographical situation of particular countries."[48] Together with the U.N.'s 21 guidelines for the long-term sustainability (LTS) of outer space activities, they form a solid foundation that now needs to be built on.

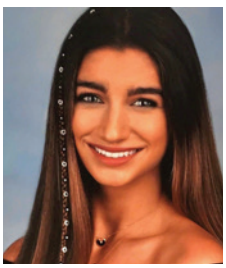
Debris mitigation was also discussed during December's U.S. National Space Council meeting, with Deputy Secretary of Defense Kathleen Hicks noting the DoD's 2021 adoption of five tenets of responsible behavior in space requiring the military to "operate in, from, to, and through space with due regard to others and in a professional manner, limit the generation of long-lived debris, avoid the creation of harmful interference, maintain safe separation and safe trajectory, and communicate and make notifications to enhance the safety and stability of the domain."[49] Deputy Secretary of State Wendy Sherman added that the U.S. will focus on the widespread implementation of U.N. LTS guidelines, and Transportation Secretary Pete Buttigieg announced that his agency was set to offer a new regulation on orbital debris mitigation in spring 2022.[50]

Innovation for Space Debris Mitigation

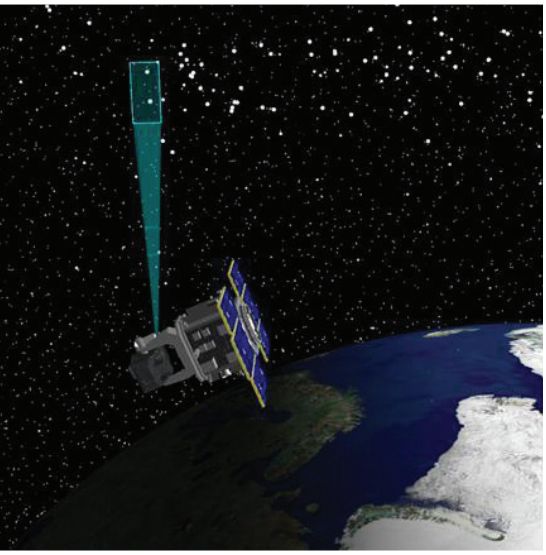
The problem of space debris impacts every spacefaring nation. To tackle the international problem of space debris mitigation, funding innovation and building on the solid foundation of guidelines for space debris mitigation is imperative. During the National Space Council meeting, Vice President Harris announced plans to promote STEM education.[51] While promoting STEM and scientific innovation is an important step, more could be accomplished if funding and resources of spacefaring nations were collectively put toward this purpose. The U.S. could initiate an international program like ESA's Clean Space program to invent ways to keep Earth's orbital environment as debris-free as possible and invite spacefaring nations to help fund nations' university research labs.[52] Thales Alenia Space, for example, has studied Active Debris Removal (ADR) using a chaser satellite to capture an actively deorbiting dead satellite using a net, with both spacecraft burning up in Earth's atmosphere upon re-entry.[53] Another design would use a robotic arm to capture and de-orbit debris before burning up during re-entry. Funding is a major issue for this innovative research; therefore, the creation of an international program with government funding could accelerate finding a solution. In the meantime, though it might be against goals of various satellite providers, government interests, and be a question of national security, it might be a safer approach to create a single mega-constellation to serve the entire world until further international laws have been created to effectively regulate mega-constellations.

International Cooperation lays Foundation

It is of the utmost importance to go about space exploration in a responsible manner. No nation can address these critical issues alone; international cooperation is key to building a strong foundation for the peaceful exploration of space. Debates surrounding the Artemis Accords, the legality of ASAT weapons, and space debris mitigation are unavoidable in the current environment. In order to address these issues, an open-minded approach needs to be pursued; as per my recommendations, the following could be ways to further these efforts: having the U.S. negotiate the Artemis Accords with the non-signatory states, enact a national ban and encourage a global ban on ASATs — either through the Outer Space Treaty, the PPWT, or the Artemis Accords — and initiate an international program by inviting all spacefaring nations to participate and create international funding for innovative research surrounding space debris mitigation.



Tuana Yazici is a Space Foundation space law and political affairs intern. She is also a UNOOSA Space4Women mentee, an International Institute of Space Law prospective member, and is pursuing a master's degree in international administration at the University of Miami. Yazici plans to continue to advocate for greater international cooperation and policy making in space operations.



Introduction | *As a new year in orbit dawns, The Space Report sought a glimpse at the year ahead from aerospace industry leaders, lawmakers and experts. Continued growth of the commercial space sector and missions to the Moon were seen as highlights to come, while concerns over conflict hitting orbit and space debris linger as top concerns. Some of the answers below have been edited for length.*

Guardians at Schriever Space Force Base use Space Based Surveillance Satellites like the one depicted in this illustration to keep an eye on objects in Earth orbit.
Credit Space Force

Leaders Look Up, Look Forward to 2022 and a New Year in Space

Eddie Bernice Johnson,
D-Texas, chairwoman of the House Committtee on Science, Space and Technology

What do you see as the biggest opportunity ahead in space for 2022?
NASA and the space community have a key opportunity to contribute to the climate challenge through observations, research, analysis, modeling, and innovative technologies. The translation of that research into applications that are accessible to a diversity of users can help ensure that the benefits of that work can be shared broadly.

What's the biggest challenge for space in 2022?
Space activity is growing, and many more actors are getting involved in the utilization and exploration of outer space. Orbital debris, orbital crowding, and the risk of collisions in space is a challenge. The safety and sustainability of the space environment is a priority on which we can all come together.

What's coming in 2022 that could fundamentally change how people look at space?
I am thrilled about the James Webb Space Telescope's successful launch and ongoing deployment. This observatory has the potential to rewrite textbooks and open our eyes to the early universe.

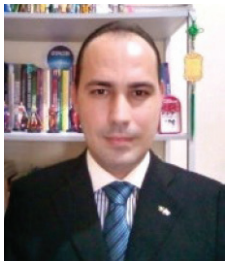
Terry Van Haren,
managing director for LeoLabs Australia, a firm focused on space situational awareness using a global array of radars

What do you see as the biggest opportunity ahead in space for 2022?
I see significant growth in global commercial space enterprises in 2022, with a number of new multi-service constellations going into orbit. SpaceX and Starlink have set the pace, but we will see a myriad of services being based in orbit, which will further fuel the digital transformation being experienced on earth.

What's the biggest challenge for space in 2022?
With the growth of users in low Earth orbit (LEO), space traffic management, debris monitoring, and debris management will become significant challenges for the peaceful use of and sustainment of space. Despite the years of talking, there does not seem to be global leadership or a clear agenda to meet these challenges. We are at risk of further irresponsible acts in space, debris-caused breakups and potential other "black swan" events in orbit.

What's coming in 2022 that could fundamentally change how people look at space?
This year we are going to see a number of new space nations joining the commercial space race. Australia will conduct its first launch attempts since 1957 at potentially three sites, whilst other medium-sized nations will also start launch programs

and grow their space industries. Hopefully, as other nations enter the space race, there will be growing consensus on the responsible and sustainable use of space as the greatest global common for use by all mankind.



Eugênio Preza,
founder and president, EP.SpaceBR, a Brazilian enterprise focused on space education

What do you see as the biggest opportunity ahead in space for 2022?
I see the growth of space tourism.

What's the biggest challenge for space in 2022?
The biggest challenge involves the tests that NASA and other space agencies around the world will initiate for the project of a lunar base.

What's coming in 2022 that could fundamentally change how people look at space?
Soon we will have news from the James Webb telescope — which will reveal great insights regarding space.

Melanie Stricklan,
CEO of Slingshot Aerospace, a Texas-based firm specializing in space situational awareness and simulation software

What do you see as the biggest opportunity ahead in space for 2022?
Space is increasingly complex due to the exponential growth of global launch activity, the proliferation of new data sources, and the ever-growing body of new satellites and debris. As an industry, there are 115,000 satellites planned to enter space by 2030, which means more potential collision avoidance decisions will need to be made. The biggest opportunity for the space industry is to increase space coordination amongst owner-operators by bringing together all the government, commercial and civil space entities onto one platform to help mitigate risks and facilitate safer satellite operations.

What's the biggest challenge for space in 2022?
Space sustainability is a challenge for the industry, as access to the domain is no longer restricted to just large government agencies with billions of dollars at their disposal. Today, government, civil, and commercial agencies all leverage the space domain to offer critical services such as GPS, internet, cell phones, ATMs, television and more. The exponential growth of global launch activity poses a real risk in terms of space sustainability because it also introduces space debris, which continues to grow at an alarming rate as companies launch objects.

What's coming in 2022 that could fundamentally change how people look at space?
Data transparency will fundamentally change how people look at, and leverage, space. The opportunities are endless within the New Space economy, and data transparency will create a safe environment that can nurture new innovations and grow space commerce. There is an appetite for transparency within our community, and there are already examples of data sharing that demonstrate improved knowledge leads to more efficient and improved space safety.

U.S. Rep. Doug Lamborn,
R-Colorado, a member of the Strategic Forces Subcommittee of the House Armed Services Committee

What do you see as the biggest opportunity ahead in space for 2022?
I think we need to really concentrate on hypersonics. The recent test by China was a real wake-up call. We need a better sensor layer than what we have now. And we need to improve our military space architecture to have more resiliency in orbit, at least in low Earth orbit where our satellites can be targeted.

What's the biggest challenge for space in 2022?
I want to see the (U.S.) Space Force really live out its promise as a nimble and agile service that's quick to jump on opportunities. But we have a lingering question over where U.S. Space Command should be located. I think it needs to stay in Colorado Springs.

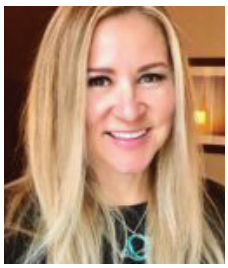
What's coming in 2022 that could fundamentally change how people look at space?
It seems that every few months, or even weeks, something happens in space that wasn't anticipated in years past. It's just too difficult to pick one thing when so much is happening up there.

Masami Onoda
runs the Washington D.C. office of the Japan Aerospace Exploration Agency

What do you see as the biggest opportunity ahead in space for 2022?
The launch of Artemis-1 will be a huge step forward for the Artemis program including Gateway and landing on the Moon, and the journey to Mars and beyond. JAXA's two small probes, OMOTENASHI and EQUULEUS, will be aboard Artemis-1 to demonstrate technologies on and around the Moon. JAXA will be launching the new rocket, H3, this year. The first H3 rocket will be launched with the Advanced Land Observation Satellite 3 (ALOS-3) that will provide continuous observation and data of the globe for disaster management and environmental monitoring. Also, we are selecting a new batch of astronauts who could potentially go to the Moon. There is a busy and exciting year ahead of us.

What's the biggest challenge for space in 2022?
We are still in the middle of the pandemic and that will continue to be a challenge, but despite the difficult times we have never paused our space programs over the past two years. Space programs will not only bring benefits to the economy and society but also have the great power to bring hope and encouragement to humanity and the next generation. This is why we must continue to put our efforts into pushing space programs forward. Together with our international and industry partners, we hope to bring more exciting moments in 2022.

What's coming in 2022 that could fundamentally change how people look at space?
We are starting out with a renewed Basic Space Plan that includes realizing the lunar landing of Japanese astronauts in the latter half of the 2020s. We are also seeing a lot of activities by international and industry partners in the LEO — a transition that is finally happening — that will surely change people's perception of space. Space is becoming an increasingly realistic arena for all of us where we can explore, work and live.



Christina Korp,
self-described "astronaut wrangler" and co-founder of SPACE for a Better World and president of Purpose Entertainment, a space marketing firm

What do you see as the biggest opportunity ahead in space for 2022?
Liftoff of SLS and Artemis 1, and the final Apollo 50th anniversaries — Apollo 16 in April and Apollo 17 in December. It would be a missed opportunity if those missions were not given proper credit and the remaining Apollo astronauts who were a part of those crews don't get recognition. Charlie Duke and Ken Mattingly of Apollo 16 are still alive. Jack Schmitt of Apollo 17 is still here, too. I look at this year as the passing of the torch to Artemis and future missions to the Moon.

What's the biggest challenge for space in 2022?
Even though space seems to be growing by leaps and bounds even during these challenging times, I think the pandemic is still the biggest challenge. Things might be great for the space choir, but outside of space the world is in a place of uncertainty, and in order to attract new talent there have to be new innovative and creative ways to get people to come and work for you. That's tough when people are on lockdown. With every company saying they wants more women this is more difficult with women carrying the load of care for their kids and even taking care of aging family members. So, I hope and pray that omicron passes quickly, and we start to get to a place where we can do more to bring in people from outside.

What's coming in 2022 that could fundamentally change how people look at space?
First, if SLS lifts off and goes to the Moon, that'll be a huge step in a long process of building that rocket. I really hope it moves forward. Other missions to the Moon will get more people to get excited again. I know of some exciting uncrewed missions that are going to happen in 2022, and I see lots of potential to excite the general public and partner with mainstream companies on commercial. These should be the build up to a crew flyby of the Moon with Artemis astronauts in 2023. Again, if SLS is successful with launch in February or March.

Also, I think when Jessica Watkins goes to the International Space Station and becomes the first Black woman to spend several months in space, it will hopefully excite a group of very under-represented people — women of color.

Paul Counet, head of strategy, communication, and international relations for EUMETSAT, the European Organization for the Exploitation of Meteorological Satellites in Darmstadt, Germany

What do you see as the biggest opportunity ahead in space for 2022?
The year 2022 will certainly bring many opportunities for EUMETSAT in the space sector. In the Earth observation sector, the launch of the first of EUMETSAT's "next generations satellites": MTG-I1 (Meteosat Third Generation – Imager 1) will open a new era in terms of Earth observation capabilities. The launch should take place in the fourth quarter of 2022 and is being coordinated by ESA and EUMETSAT.

In the next 10 years, EUMETSAT will renew completely its fleet of meteorological satellites. This next generation satellites will provide new data, but also more frequent, better resolution data to all the EUMETSAT users.

What's the biggest challenge for space in 2022?
New Space will definitely be a game-changer, although it will not start and finish in 2022 — it has already started and will continue to develop after 2022. New Space encompasses two main features: the miniaturization of the satellites and the increased influence of private actors in the space business, with new business models.

What's coming in 2022 that could fundamentally change how people look at space?
New space can be seen as a real democratization of space and access to space: It could thus change how people view the sector. In our field, this means more actors operating satellites and distributing data, which can be both positive and less positive.

On the positive side: EUMETSAT started a test in 2021 by purchasing radio-occultation data from a private actor (Spire). It is the very first time that we have bought private data, although some partners already do it. In 2022 we will evaluate the impact of these data to decide whether we continue or not.

New Space also means a marked decrease in the size of satellites: this miniaturization can have an influence for us. We are currently looking into whether such technologies could be applicable to our satellites that are references against which others calibrate their instruments. We need to be very careful in order to maintain the high quality of our data as this is our main objective. All new technologies have to be weighed against their impact on data quality. For us, more data means more data of good quality, positively impacting the weather forecasts delivered by our member states.

On the less positive side: With more satellites also come more space debris that can be a real challenge for the safe operations of our satellites and data delivery to users.

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Section 1 | Space Infrastructure

The Next Space Stations: Building Blocks of an Orbital Economy

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Section 2 | The Space Economy

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