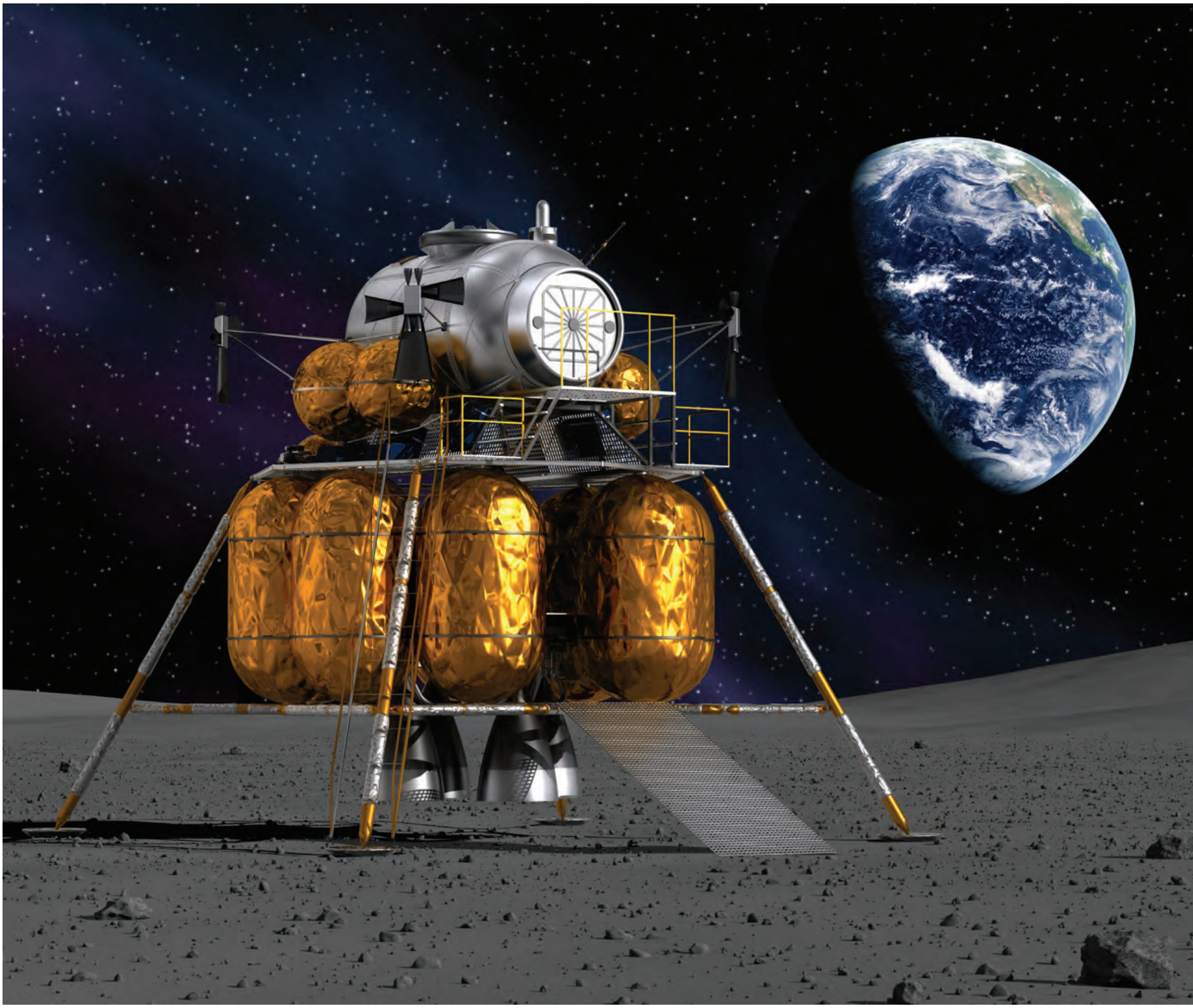
SPACE FOUNDATION

THE SPACE REPORT

THE AUTHORITATIVE GUIDE TO GLOBAL SPACE ACTIVITY

2021

THE 36TH ANNUAL SPACE SYMPOSIUM SPECIAL EDITION



2020 COMMERCIAL REVENUE | LUNAR SUSTAINABILITY | SMALLSATS AND LAUNCH VEHICLES

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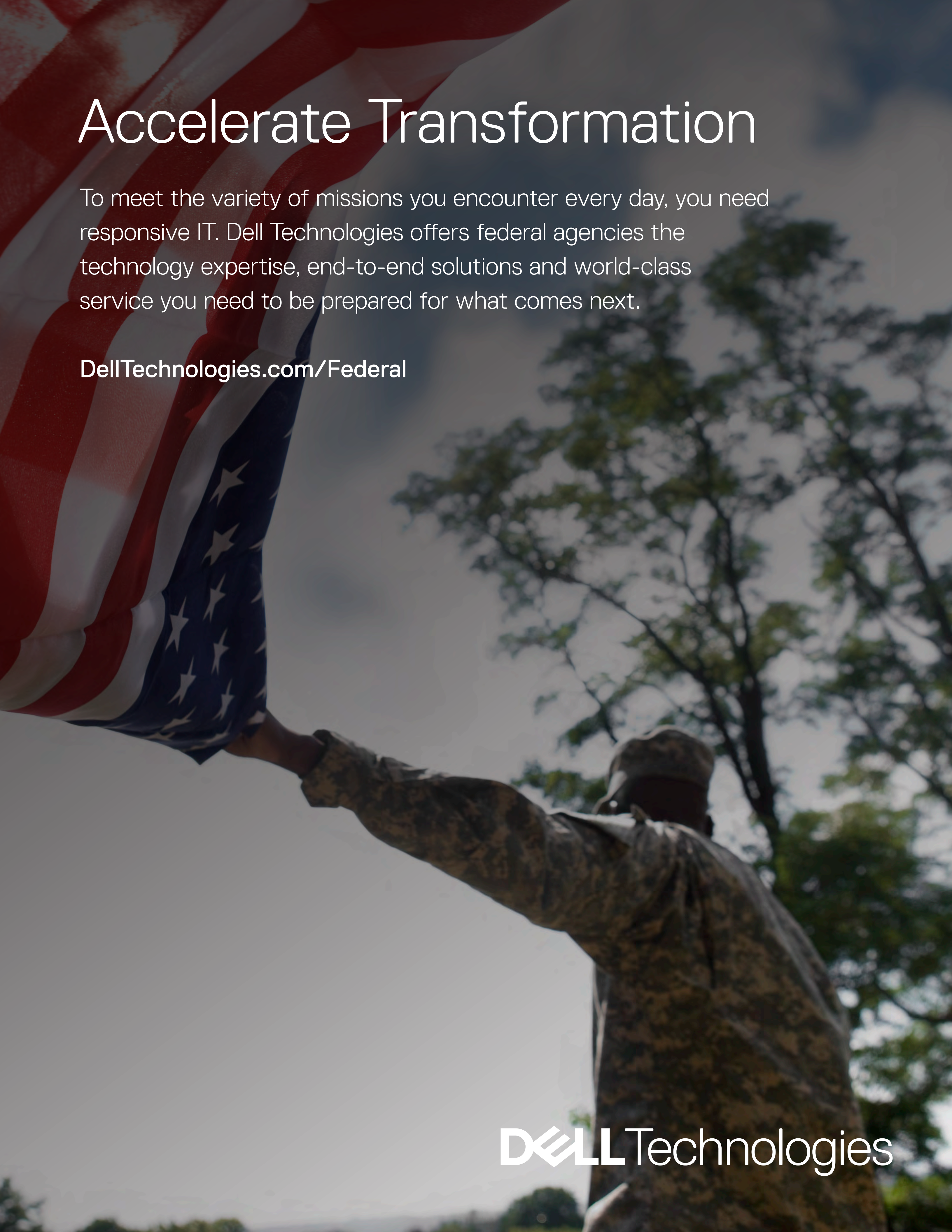
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Small Satellite Mass Categories

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.).

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www.SpaceFoundation.org | For more information, please contact:

Space Foundation HQ:
+1.719.576.8000
4425 Arrowswest Drive, Colorado Springs, CO 80907

Washington, DC:
1700 North Moore Street, Suite 1105, Arlington, VA 22209

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2021 SE

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ABOUT THE COVER IMAGE:
NASA's Commercial Lunar Payload Services (CLPS) program is working with more than a dozen vendors that will soon deliver landers, rovers and equipment to the Moon's surface. Other nations and companies are planning missions, too, making landers such as the one featured in this artist's illustration a regular feature on the Moon.
Credit: 123RF/3DSculptor

Introduction to *The Space Report* | 36th Annual Space Symposium Special Edition

So much of the past, present, and the future potential of space was represented in the July 20, 2021, flight of Blue Origin's New Shepard. Jeff Bezos became the second billionaire that month — after Virgin Galactic founder Richard Branson — to fulfill a lifelong dream of going into space. Bezos and Branson represent the growth and growing influence of private commercial space enterprises.

Bezos in New Shepard
Credit: Blue Origin

Wally Funk, a passenger on the New Shepard flight, and in 2010, the first person to buy a ticket for Branson's suborbital spaceplane, represents sheer perseverance and a singular vision to venture beyond Earth. At 82, she became the oldest person to rocket from the planet. She was eager to go 60 years earlier, when, in 1961, she was the youngest volunteer in the First Lady Astronaut Trainees program. After a series of grueling tests, she was one of the finalists known as the Mercury 13. Her dreams were repeatedly dashed, but she never lost confidence in her belief that she would one day reach space. And in that, she is not unlike so many other people around the world whose personal hopes and dreams are wrapped into a larger goal of scientific achievement, overcoming every obstacle, and becoming part of a new future in space.

A joyous Funk post-flight
Credit: Blue Origin

This edition, a special publication for the 36th Annual Space Symposium, examines where we are as a global space industry and considers the steps still to be evaluated and taken to transform into reality what is envisioned for the future of that industry.

1 | Space Economy

Commercial spending remained the significant driver of the overall global space economy, representing almost 80% of total revenue. Commercial Infrastructure and Support Industries is the smaller of two sectors — the other being Commercial Space Products and Services — but in 2020, Infrastructure and Support Industries showed the greatest growth, increasing 16.4% from 2019. Ground stations and equipment, valued at $118.45 billion, captured more than 86% of the sector, but developing industries, such as on-orbit satellite servicing and human spaceflight, have captured more public attention and investor interest. In February, Northrop Grumman subsidiary SpaceLogistics docked its Mission Extension Vehicle-1 (MEV-1) to a geostationary satellite to provide fuel and thruster capability. Two more MEVs have since launched to extend service to other satellites. When a customer no longer wants service, the MEV can undock and deploy to another satellite. As for space tourism, Virgin Galactic before Branson's flight had sold more than 600 tickets, each costing as much as $250,000, to people in 58 countries. After the flight, as demand grew, some industry observers expect new passengers to pay upward of $500,000.

Commercial Space Products and Services, the largest commercial sector, grew only slightly last year, easing up 1.2% to $219.44 billion. Earth observation satellites showed the strongest growth in the sector, increasing 9.1% to $3.7 billion.

The Space Economy section also provides a recap of 2020 government spending, detailed more extensively in *The Space Report 2021 Q2*, released in July. The majority of nations reviewed, largely influenced by the global pandemic, reduced space spending last year, resulting in an overall 1.2% decline in 2020 to US$90.2 billion.

Compiling global space economy data that Space Foundation has tracked since 2005 finds that in the last 15 years, however, government and commercial spending have propelled total revenue to a 176% gain.

2 | Space Workforce

This two-page spread offers a review and some fresh perspective on global workforce information from around the world, relying on data that is most consistently available from nations that share such information. This feature will allow you track workforce gains from the United States, Europe, Japan, and India and review demographic data.

3 | Space Infrastructure

In this section, two articles probe what will be needed to move beyond initial exploration of the Moon and space. The United States' Artemis program has 11 partners, but China, Russia, Israel, and Turkey also have missions planned, as do a growing number of companies that are public partners or working as independent operators.

As they look to establish permanence on the lunar surface, these nations and companies must consider sustainability on three major fronts — economic, environmental, and infrastructure. Ian Christensen, director of private sector programs at Secure World Foundation, leads the examination of lunar sustainability.

Nuclear power and propulsion are parts of that equation. Chris Beauregard, the former director of commercial space policy at the White House National Space Council, offers a primer on the nuclear applications, some already long in use, that offer the most promise for efficient, powerful solutions for sustainable energy.

4 | Space Policy

As space infrastructure and applications develop, so too must international policy related to government and commercial activities on the Moon and in the rest of space. Michael K. Simpson and Elias de Andrade, both affiliated with the Global Expert Group on Sustainable Lunar Activities (GEGSLA), outline the work of the group, provide examples of how similar initiatives have shaped global policy, and explain how GEGSLA is encouraging participation and input from around the world.

As you read this report

The data presented is a quarterly snapshot of global space activity.
To learn more, daily 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 | *Commercial space activity, undertaken by private industry with little or no government investment, accounts for more than 79.8% of the global space economy. Despite the global pandemic, commercial space revenues continue to grow, increasing 6.6% from $334.75 billion in 2019 to $356.68 billion in 2020.[1] Nearly two-thirds of commercial revenue comes from Space Products and Services such as direct-to-home television and applications that use positioning, navigation, and timing satellite signals. The remainder is generated from Commercial Infrastructure and Support Industries, including satellite manufacturing and launch.*

ESA's 35 meter-diameter dish antenna at New Norcia, Western Australia. Ground stations and equipment, the largest segment of Commercial Space Infrastructure and Support Services, grew 6.4% last year.
Credit: Dylan O'Donnell/Flickr

Despite Pandemic, Double-digit Growth in 2020 in Some Commercial Sectors

Commercial Infrastructure and Support Industries

Commercial Infrastructure and Support Industries revenue totaled $137.23 billion in 2020, an increase of 16.4% from $117.94 billion in 2019. This category includes the products and services provided by the private sector that enable the development, launch, and successful operation of commercial space assets. This includes satellite manufacturing and launch services, as well as space insurance. It also includes revenue generated from ground stations and equipment needed to send and receive satellite signals, and data from commercial space situational awareness firms used to ensure safe operation of space assets in orbit. Commercial human spaceflight revenues also contribute to this total.

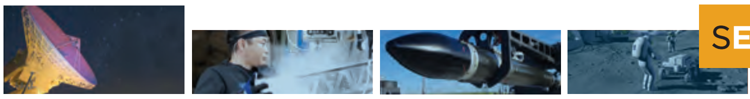
Revenues for Commercial Space Infrastructure and Support Industries, 2020

Agency	Budget	Source
Ground Stations and Equipment	$118.45B	Satellite Industry Association, European GNSS Agency (GSA)
Satellite Manufacturing (Commercial)	$16.17B	Eurospace
Launch Industry (Commercial)	$2.07B	Eurospace
Insurance Premiums	$0.45B	AXA XL, a division of AXA
Space Situational Awareness and On-Orbit Servicing	$0.04B	Northern Sky Research
Commercial Human Spaceflight (Deposits)	$0.06B	News Reports; Public Filings
Total	**$137.24B**	

Launch

There were 114 launch attempts in 2020, 104 of which were successful. The number of launch attempts was 17.5% greater than in 2019. Commercial launches — those carried out for a non-government customer — accounted for 38 attempts and five failures in 2020. This was also an increase from the previous year, up 40.7% from 27 attempts in 2019.[2] This growth is an impressive feat given the impact of the global pandemic during which launches were affected by staffing issues at spaceports, government-mandated shutdowns, challenges of international travel, and delays in payload development and delivery.[3]

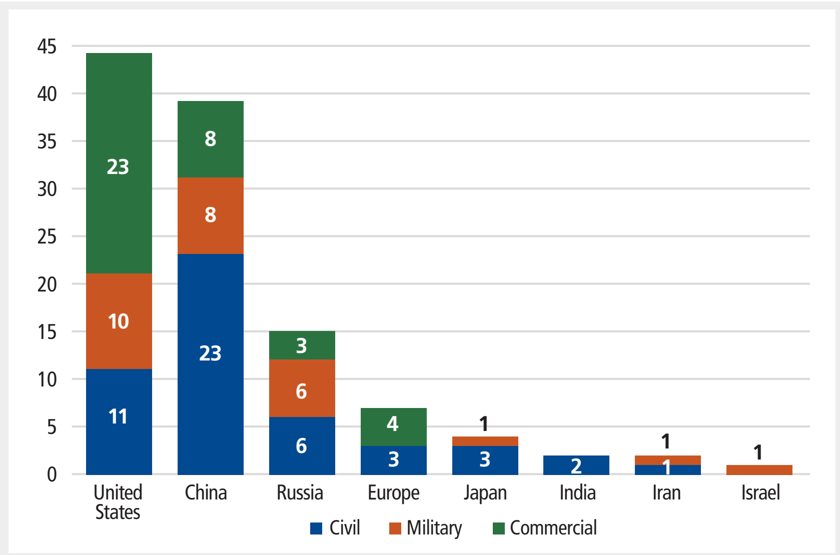
The total market value of launches in 2020 increased 14.2%, to $9.25 billion in 2020 from $8.10 billion in 2019. Much of this growth was due to increases in commercial revenues, which were up 78.5% — growing from $1.16 billion in 2019 to $2.07 billion in 2020. Commercial revenue accounted for 22.4% of the total market value of launches in 2020. The remaining 77.6%, or $7.18 billion, is in government investment and is detailed in the 2021 Q1 and Q2 editions of *The Space Report*. Launch market values are based on estimates provided by Eurospace, the trade association of the European space industry. The model used to estimate these values was updated in 2021, leading to changes in previous year totals, compared to those published in previous editions of *The Space Report*.[4]



The majority of commercial launches that took place in 2020 occurred in the United States, which had 44 launch attempts and four failures. Among the 40 successful launches were 25 SpaceX launches, many of which lofted SpaceX's own Starlink satellites. There were seven successful launches of RocketLab's Electron rocket. The company suffered one launch failure in July 2020 due to faulty electrical connections that caused the second stage engine to cut out too early.[5] The remaining failures included the maiden flight of Virgin Galactic's Launcher One, and the first two launch attempts of the California-based space start-up Astra.[6]

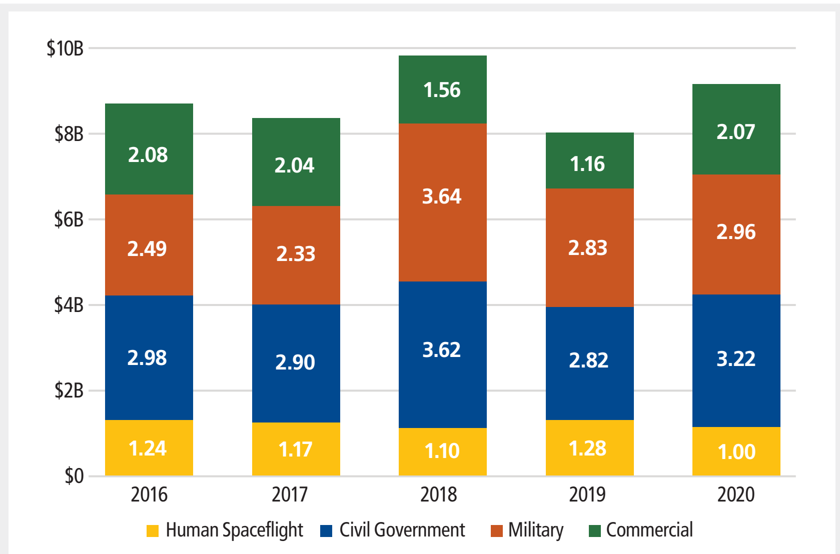
China was home to eight commercial launches in 2020, seven of which were successful. Four of the successes used Long March rockets and two were Kuaizhou rockets operated by ExSpace, a commercial subsidiary of the China Aerospace Science and Industry Corporation (CASIC).[7] ExSpace also experienced a failure, with the maiden flight of its Kuaizhou-11 rocket. The Chinese start-up Galactic Energy successfully launched its Ceres-1 launcher for the first time in November 2020. In Europe, Arianespace had three successful launches of its Ariane-V vehicle and one successful Vega launch. Russia conducted three successful Soyuz launches for commercial customers.[8]

Orbital Launch Attempts, 2020



Source: Space Foundation Database

Launch Services Value by Market, 2016-2020



Source: Space Foundation Database

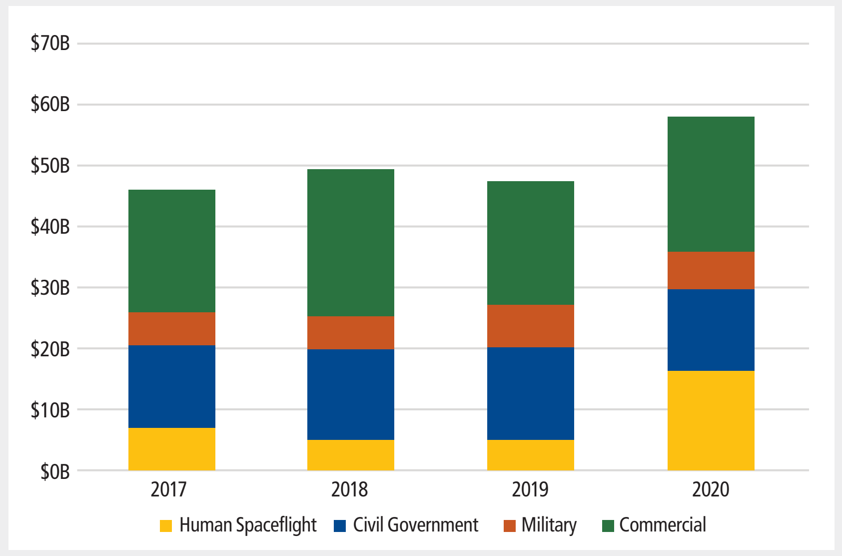
Satellite Manufacturing

In 2020, 1,230 spacecraft launched for the year, an increase of 184% from the 467 launched in 2019. Of these, 1,098 spacecraft, or 89.3%, were commercial payloads. U.S. companies launching large constellations account for much of this volume. In 2020, SpaceX launched 832 Starlink satellites.[9]

Manufacturing revenue associated with commercial payloads launched in 2020 totaled $16.17 billion in 2020, a total more than three times higher than the $4.92 billion associated with payloads launched in 2019. This increase mirrors the dramatic increase in the number of commercial payloads launched in 2020 compared to 2019. Estimates are based on analysis carried out by Eurospace and reflect a new methodology implemented in 2021, leading to updates in previous year totals compared to past editions of *The Space Report*.[10]

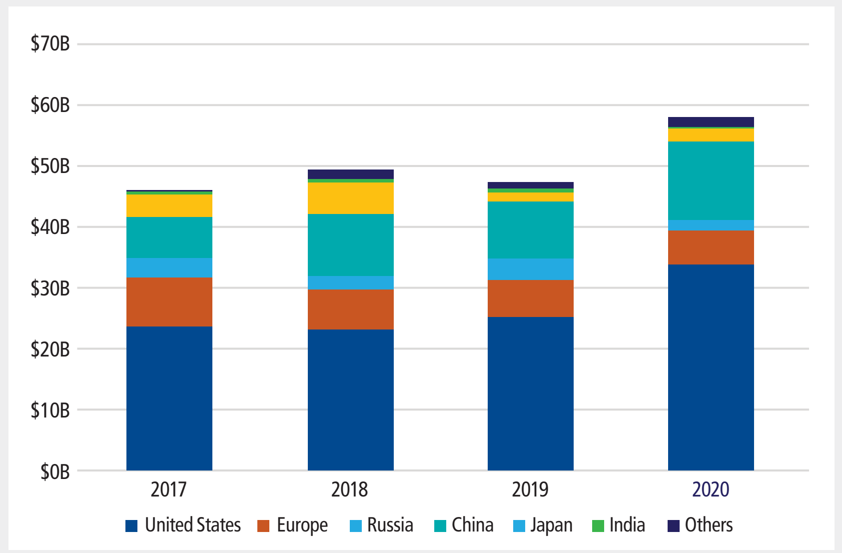
The revenue associated with commercial payloads accounted for 28.1% of total payload revenue in 2020, which was estimated at $57.56 billion.[11] The remaining $41.4 billion, or 71.9%, was associated with government spacecraft, including cargo launched to the International Space Station as part of NASA's commercial resupply services program.

Spacecraft Value by Market, 2017-2020



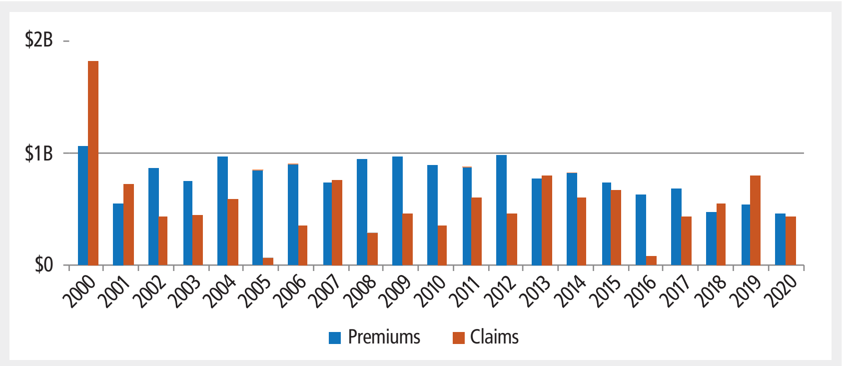
Source: Space Foundation Database

Spacecraft Value by Manufacturing Country, 2017-2020



Source: Space Foundation Database

Space Insurance Industry Estimates, 2000-2020



Source: AXA XL, a division of AXA

Insurance

With its dependence on cutting-edge technologies and need to operate in the remote and inhospitable space environment, space projects always involve some risk. Many companies rely on insurance to help manage these risks. It's possible to purchase insurance for almost all phases of the life of a spacecraft, from launch through operations, but not all operators choose to purchase this insurance. In 2020, 46.5% of launches carried insured satellites. Of the approximately 4,100 active satellites in orbit in early 2021, only 276 are insured. Most of these are in geosynchronous orbit (GEO), where nearly half of all active satellites are insured. In low Earth orbit (LEO), less than 2% of satellites are insured.[12]

The increase in new launch companies and the proliferation of constellations of small satellites creates new types of risks and increases volatility in the market. While the number of small insured launches has been increasing in recent years, many of these new actors do not purchase insurance. For example, SpaceX does not purchase insurance for its Starlink satellites.[13] The increase in risk posed by the increase in objects has led some companies to stop offering collision insurance for satellites in LEO.[14]

After two years in which claims exceeded premiums, space insurers saw net gains in 2020. Premiums amounted to $452.5 million while claims were $427.9 million.[15] Still, insurance rates have increased significantly since 2019, and insurers do not believe they are likely to go down in the near future as the industry continues to adjust to new technologies and methods of operation.[16]

Ground Stations and Equipment

Spacecraft operators use control stations on the ground to send commands to spacecraft and receive information on spacecraft health. Ground-based receivers, including satellite phones, terminals, dishes, and chipsets, allow end users to access data and signals from satellites. In 2020, the revenue associated with these ground stations and equipment was estimated at $118.4 billion, an increase of 6.4% from the $111.3 billion in 2019. Much of the revenue — 71.3% — in this category comes from the sale of global navigation satellite system devices, such as the GPS chips in cell phones. Revenues from GNSS equipment were estimated at $84.4 billion in 2020, an increase of 7.7% over estimated revenue for 2019.[17]

Space Situational Awareness and On-Orbit Servicing

Space is becoming increasingly congested, and satellite operators rely on Space Situational Awareness (SSA) data — information about where objects in space are and predictions of where they will be in the future — to avoid potential collisions. While much of this data comes from government space surveillance programs, particularly U.S. Space Command, commercial providers of SSA data and products have increased significantly in recent years. These companies provide additional data as well as tailored observation and analysis services.

While SSA providers help satellite operators to avoid collisions in orbit or help to diagnose the cause of anomalies on orbit, the on-orbit servicing sector provides services to repair satellites that are damaged or refuel those that are nearing the end of their design life. Since 2000, 77 satellites in GEO have suffered anomalies that could potentially have been addressed with on-orbit servicing and many others could have benefited from life extension services, such as refueling.[18]

The first commercial on-orbit servicing mission — Northrop Grumman's Mission Extension Vehicle 1 (MEV-1) successfully docked with the Intelsat 901 spacecraft in February 2020 and will provide five years of life extension services before moving on to provide similar services to a new client spacecraft.[19] MEV-2 launched in August 2020 and docked with its client satellite in April 2021.[20] Numerous other companies hope to enter this market in the near future. Northern Sky Research estimated global revenues in the SSA and on-orbit servicing sector at nearly $40 million in 2020, more than double the $18 million in estimated revenue in 2019.[21]

Commercial Human Spaceflight

Commercial human spaceflight efforts continue to develop, inching nearer to operational flights. Virgin Galactic sold about 600 tickets at $250,000 per ticket before halting sales following the failure of a test flight. In 2020, the company allowed potential customers to put down a $1,000 refundable deposit toward the purchase of a future ticket. The company ended the campaign after receiving approximately 1,000 deposits. The company hoped to make its first operational flight, carrying founder Richard Branson in 2020, but it was accomplished on July 11, 2021, due to delays related to the pandemic. The company expects to reopen ticket sales after this flight, with higher prices than those offered to early purchasers.[22] Commercial flights are expected to begin in 2022.[23]

Virgin Galactic has also been making efforts to diversify its income streams. In October 2019, Virgin Galactic signed a contract with the Italian Air Force for a research and training flight that will produce $2 million in revenue. In 2020, the company signed an agreement with the Institute of Astronautical Sciences to fly a private researcher who will conduct experiments and technology demonstrations during a suborbital flight. NASA has a similar agreement and has selected a researcher that will test a camera and biomedical sensors. Virgin Galactic officials have stated that new agreements have been priced at about $600,000 per seat.[24] In 2019, the company went public via a special purpose acquisition company, raising additional funds.[25] Revenues for 2020 were reported at $0.2 million, significantly lower than the $3.8 million reported in 2019.[26]

Unlike Virgin Galactic, historically, Blue Origin did not open ticket sales or allow deposits to be made, a situation that continued through 2020. However, in May 2021, the company announced it would hold an auction for a seat on New Shepard's first crewed flight, scheduled for July 20, 2021. The winning bid was $28 million, but days before the flight, the passenger declined.[27] Jeff Bezos and his brother Mark were on the July flight, as was aviation icon Wally Funk.[28]

The third major player in this arena is SpaceX. The company successfully launched humans for the first time in May 2020, in a demonstration flight for NASA's Commercial Crew Program. The first operational flight followed in November 2020 and the second in April 2021.[29] SpaceX plans to launch its first fully commercial flight in September 2021. The flight, called Inspiration4, is funded by billionaire Jared Isaacman, and will include three other civilians, who together will orbit the Earth in the Dragon capsule. Another commercial flight, organized by Axiom space and planned for January, will take three billionaires to the International Space Station, with each paying $55 million for the trip. They will be escorted by Axiom Vice President Michael López-Alegría, a former NASA astronaut.[30]

Commercial Space Products and Services

Commercial space products and services include direct-to-home television, satellite radio, Earth observation, and other businesses that rely directly on space assets. Value-added services built on satellite signals, such as the numerous GPS-enabled apps available on smartphones, also fall within this category. These commercial space products and services account for 61.5% of all global commercial space revenue. The total increased by 1.2% from $216.81 in 2019 to $219.44 in 2020.

Revenues for Commercial Space Products and Services, 2020

Category	Revenue	Source
Position, Navigation, and Timing	$97.11B	European GNSS Agency (GSA)
Direct-to-Home Television	$89.85B	Satellite Industry Association, Public Filings
Satellite Communications	$20.75B	Satellite Industry Association, Public Filings
Satellite Radio	$8.04B	Sirius XM Public Filings
Earth Observation	$3.70B	Northern Sky Research
Total	$219.45B	

Broadcasting

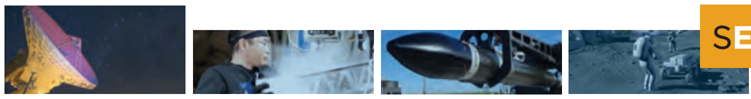
Satellites placed in geostationary orbit circle the Earth at a speed that allows them to appear stationary above one area of the Earth. This attribute makes them particularly useful in broadcasting television and radio signals, which can be received using a dish antenna or satellite receiver on the ground. Satellite television revenue totaled approximately $89.85 billion in 2020, a decrease of 2.3% from 2019.[31]

In the United States, the satellite TV market is dominated by DISH Network and DirecTV. DISH Network generated $12.9 billion in revenue in 2020, an increase of 0.7% from $12.81 billion in 2019.[32] AT&T, which acquired DirecTV in 2015, does not report revenue for its satellite activities separately.[33] However, both companies have reported decreasing subscribers as they face intense competition from other media companies, particularly those like Netflix, Hulu, and others that provide on-demand streaming services online.

DISH TV has responded by expanding its offerings, so that along with access to live TV channels, subscribers also get "DISH On Demand" streaming services and "DISH Anywhere" mobile applications that provide mobile access to content.[34] AT&T announced in February 2021 that it was spinning off DirecTV, along with AT&T TV and U-Verse. The value for the new company is estimated at $16.25 billion, significantly less than the $48.5 billion AT&T paid to acquire DirecTV in 2015.[35]

Satellite TV companies faced multiple challenges from the pandemic. Lockdowns and concern about virus spread reduced the ability of companies to perform in-house service operations. High unemployment and economic uncertainty also decreased the number of new subscribers. Many commercial subscribers, such as sports bars and restaurants were closed or operating at much lower capacity. The companies' own workforces, as well as their supply chains, were also affected by the pandemic, causing delays in service.[36]

Revenue from satellite radio operator Sirius XM totaled $8.04 billion in 2020, an increase of 3.2% from 2019. The company largely acquires customers when the customers purchase new cars. Sirius XM has agreements with every major automaker in the United States to offer satellite radios in their cars, with many including a subscription in the sale



or lease of new vehicles. Shifts in the volume of auto sales due to the pandemic have created challenges and uncertainties for the business.[37]

Position, Navigation, and Timing

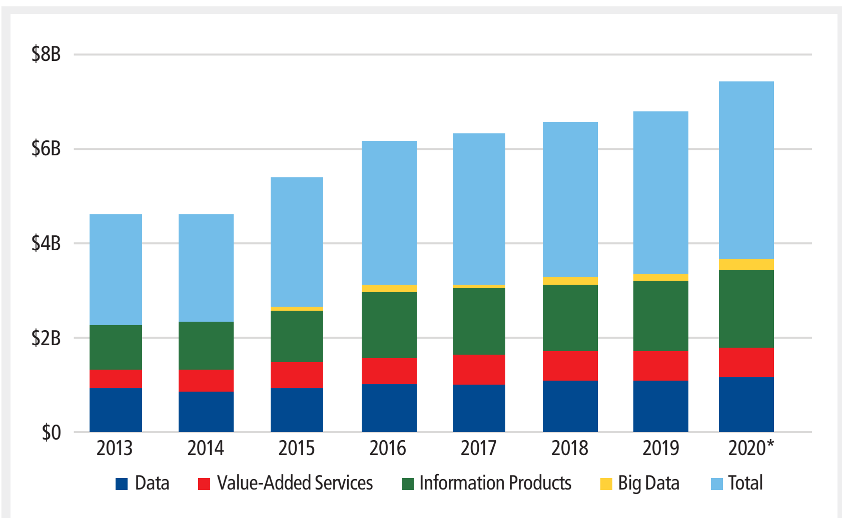
Multiple governments operate global satellite navigation systems, which rely on a constellation of satellites to provide position, navigation, and timing services around the globe. These systems, such as the U.S. Global Positioning System (GPS), are fully funded by governments, and provide these signals free of charge to end users. Many commercial entities have taken advantage of this, generating a vast market of value-added services built on positioning, navigation, and timing satellite signals. The European Global Navigation Satellite Systems Agency (GSA) estimates that the revenue from these value-added services totaled $97.11 billion in 2020, an increase of 6.6% from 2019.[38]

Communications

Communications satellites provide two-way data, voice, and video applications for users around the world with satellite phone and internet services. Traditionally split into fixed satellite services — relying on geostationary satellites and receivers in a fixed location on the ground — and mobile satellite services — using satellites in low earth orbit to serve customers moving around the Earth — this industry has become increasingly diverse in recent years. Companies have invested in a broad range of satellite assets and are targeting a wide array of potential customers, particularly those that operate in remote areas not well served by traditional phone and internet services. Estimated revenue was $20.75 billion in 2020, down 7.8% from 2019.[39]

New to this sector is a wave of companies aiming to use large constellations of small satellites to provide satellite internet. SpaceX's Starlink constellation is the furthest along, with nearly 1,000 satellites launched by the end of 2020.[40] The company began its first public beta test in October 2020. In January 2021, it expanded the beta test to include more areas within the United States, as well as Canada and the United Kingdom.[41] By May 2020, more than 500,000 people had placed an order or a deposit for the service.[42] Competitors OneWeb and Amazon's Project Kuiper have continued development but have not yet begun offering services.

Earth Observation Revenue, 2013-2020

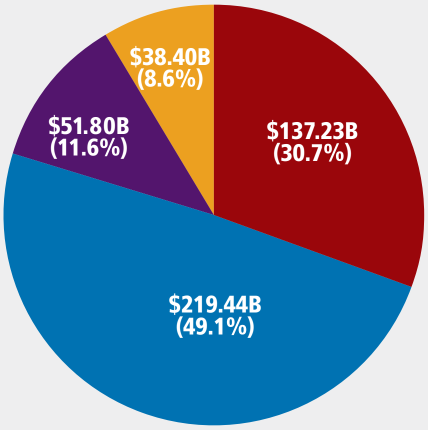


*Estimated Revenue
Source: Northern Sky Research, Public Filings

Earth Observation

Earth observation satellites monitor the Earth from space, collecting a variety of types of data and imagery. Sometimes commercial entities sell the raw data collected by their satellites, but increasingly, companies are finding that value-added services and information products — created by processing the data or adding additional information, are of greater interest to customers. According to estimates by Northern Sky Research, total Earth observation revenues increased 9.1% from 2019 to 2020, from $3.39 billion to $3.70 billion.[43]

Mariel Borowitz is an assistant professor at the Sam Nunn School of International Affairs at Georgia Tech. Her research deals with international space policy issues, including international cooperation in Earthobserving satellites, satellite data sharing policies, and space security issues.



Total: $446.88 Billion

Introduction | *The global space economy reached a new high of nearly $447 billion in 2020, an increase of 4.4% from a revised 2019 figure of $428 billion.*

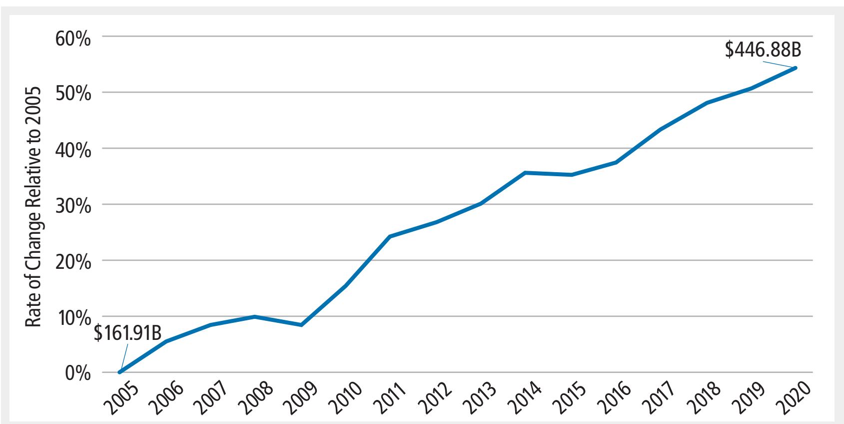
The 2020 figure is 50% greater than a decade ago, and 176% greater than Space Foundation's first such analysis of the 2005 global space economy. As in 2019, nearly 80% of this year's space spending stemmed from commercial revenue, which is divided into two sectors: Products and Services and Infrastructure and Support Industries.

Credit: Space Foundation database

Global Space Economy Climbs Despite Pandemic, Disrupted Government Spending

For the annual analysis of government space spending, Space Foundation reviewed civil government and military spending of 36 governments or cooperative bodies worldwide[1], relying on publicly disclosed budgets, media reports, estimates based on gross domestic product, and, in some cases, correspondence with government officials. The 2020 budget review also includes a review of 2019 actual vs. budgeted expenditures, resulting in revisions for 2019 affecting 13 countries based on actualized figures released later in the year. Space Foundation also added nine new countries and one additional aggregation of smaller African nations[2] to the 2019 analysis because of their inclusion in 2020 data.

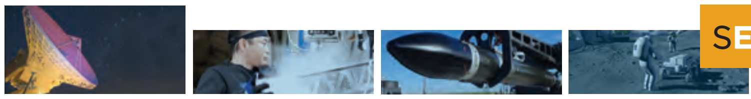
The Global Space Economy, 2005-2020



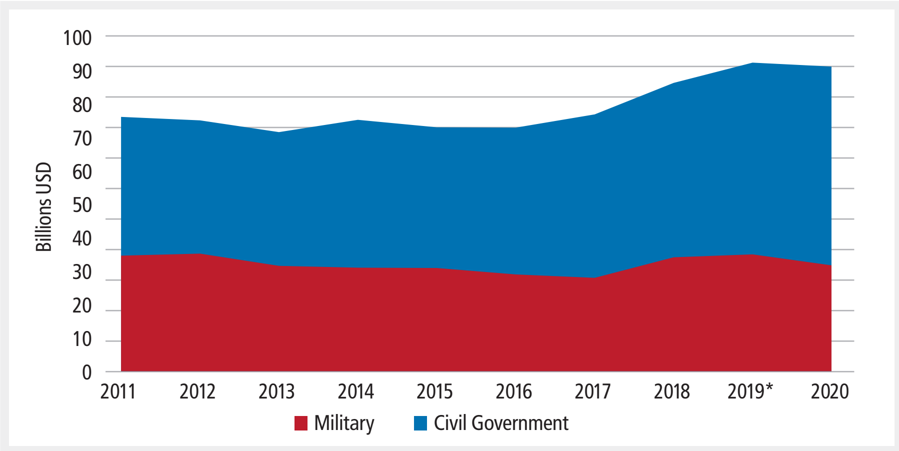
**Revised Figure*
Source: Space Foundation database

Global government space spending fell 1.2% in 2020 to US$90.2 billion from a revised 2019 peak of US$91.4 billion. Just under 58% of this total was allocated to space activities by the United States. For the remaining 42%, Space Foundation analyzed 35 other nations or cooperating bodies spanning the globe. These other nations and bodies comprise the vast majority of space spending. Of these, 17 decreased spending in U.S. dollars in 2020, whereas 13 increased their space spending in U.S. dollars, a reflection of mixed fortunes globally due to the pandemic and subsequent economic crisis. Overall, despite the unprecedented circumstance, nations and cooperating bodies spent 18% more on space in 2020 than they had a decade prior.

Military space spending in 2020, estimated at US$31.4 billion, constituted the smallest share of global government space spending in a decade — only 35%. This figure marks a reduction from 2019, wherein the $34.6 billion spent globally constituted 38% of government space spending. U.S. military space spending comprised more than 80% of global military space spending for the first time since 2011, whereas non-U.S. military space was funded at less than half the

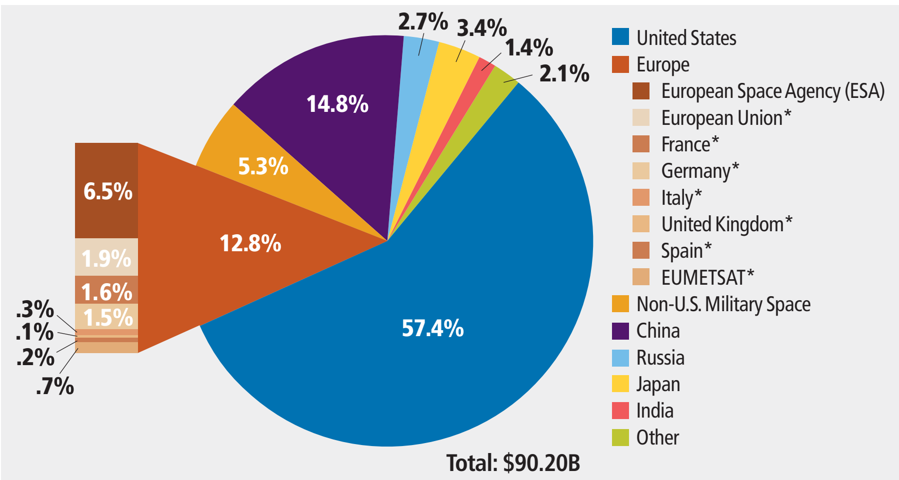


Global Military vs. Civil Government Space Spending, 2011-2020



**Revised figure*
Source: Space Foundation database

Key Global Government Space Spending by Country, 2020



*Note: *Excludes ESA and EUMETSAT spending as applicable*
Defense spending for all Non-U.S. countries is included in 'Non-U.S. Military Space'
Source: Space Foundation database

level it had been in 2019, according to a country-level analysis of six nations spread across four continents: Argentina, Brazil, France, Germany, Japan, and Nigeria.

The top three governments in the global space economy remained the same in 2020: the United States, China, and the European Space Agency (ESA). These three entities constituted more than 81% of government space spending in 2020. The U.S. alone spent nearly 3.9 times as much as the next nation, China, which in turn spent 1.6 times as much as ESA. All three increased their space spending in 2020, the U.S. by the smallest margin of 5.6%, followed by ESA (11.4% in U.S. dollars) and China (17.1% in CNY).

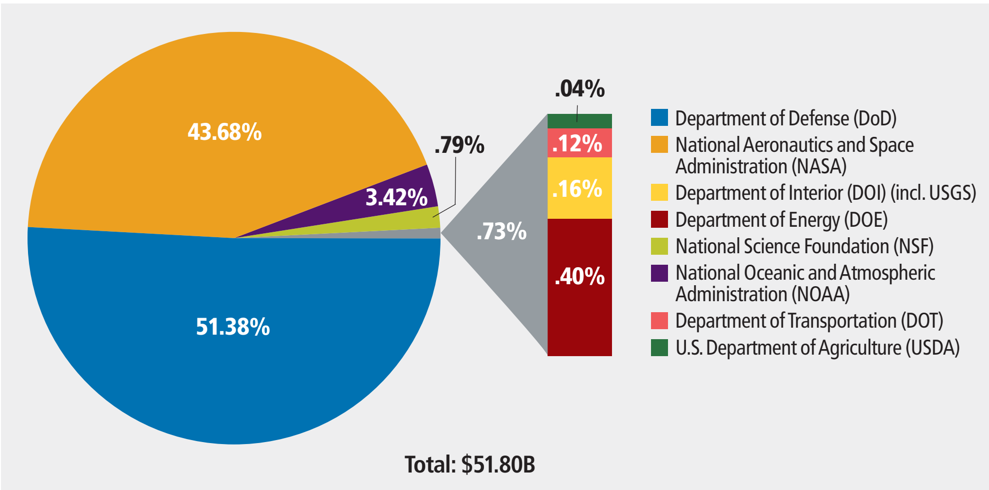
The year's analysis nonetheless revealed notable shifts in the global space economy. Japan's 3% space budget increase in 2020 played opposite Russia's 37% reduction, both based on U.S. currency conversion, to make Japan the fourth-highest contributor to the global space economy, a reversal from 2019. France increased its domestic funding by more than 40% in 2020, leapfrogging Germany and India to become the seventh-largest contributor to the global space economy in 2020 after Russia and the European Union. Lastly, Italy's 37% reduction shifted its ranking from 2019 to land below Canada.

Space Spending in the U.S. Continues to Grow Amid Global Crisis

In addition to dwarfing the investment of other nations, U.S. government space spending proved resilient to the economic effects of the coronavirus, expanding 5.6% to reach $51.8 billion in 2020. This level of funding is more than 12% higher than a decade ago. Of this funding, just over half ($26.6 billion) was allocated to the Department of Defense, with the remainder split between seven U.S. civil space agencies: NASA, the Department of Transportation (DOT), the Department of Energy (DOE), the United States Department of Agriculture (USDA), the National Science Foundation (NSF), the Department of Energy (DOE), and the Department of Interior (DOI).[3]

Funding for these U.S. civil space agencies grew 5% to reach $25.2 billion over a revised 2019 estimate of $24 billion and increased or stayed stable across all except the NSF. U.S. civil space spending figure in 2020 was nearly 33% greater than a

U.S. Government Space Spending, 2020



Source: Space Foundation database

decade ago. The agency with the largest increase in funding was the DOT, home of the Office of Commercial Space Transportation (AST), which spent 77% more in 2020 than in 2019.[4] That said, approximately 90% of U.S. civil space spending in 2020 was allocated to one agency: NASA.[5] Almost 44% of all U.S. space spending was allocated to NASA in 2020 — more than $22.6 billion.[6] This figure is a greater than 5% increase over 2019 and a nearly 23% increase over the preceding decade. The largest share of this budget was allocated to the Science Program, which expanded in 2020 to include Biological and Physical Sciences for the first time. Deep Space Exploration Systems took the next largest share of NASA funding followed by Space Operations.[7] Interestingly, Space Operations was the only top-line item to see a reduction in funding between 2019 and 2020; all other top-level budget authorities grew by at least 3% in 2020. NASA's Space Technology (or Exploration Technology) and Deep Space Exploration Systems (previously Exploration) programs grew the most between 2019 and 2020, each expanding by more than 18%.[8]

U.S. military space spending is often classified; however, the U.S. military made strides in consolidating unclassified space spending in 2020 budget reporting. Between the classified and unclassified procurement and the operations and maintenance of the U.S. Space Force, Air Force, Navy, Space Development Agency, and the U.S. military's Research, Development, Test & Evaluation program, U.S. military space spending increased by more than 6% in 2020.[9, 10, 11]

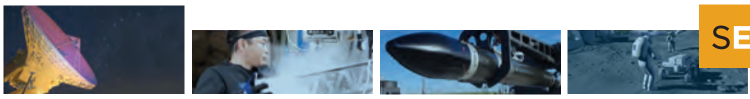
Scott Pace

The Rest of 2021 Holds Promise, According to Space Experts

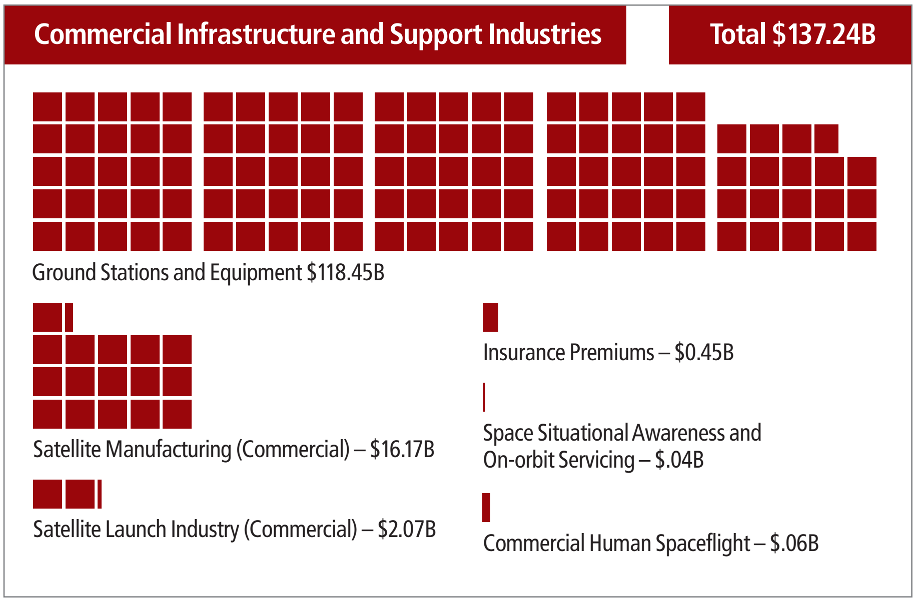
The remainder of the year 2021 promises further growth and evolution in the market. Scott Pace, former executive secretary of the National Space Council, predicts that "while public awareness of commercial space has been stimulated by high visibility space tourism flights and SPAC activities, the real tests for the remainder of 2021 will be in quarterly corporate earnings and market shares for emerging space goods and services."

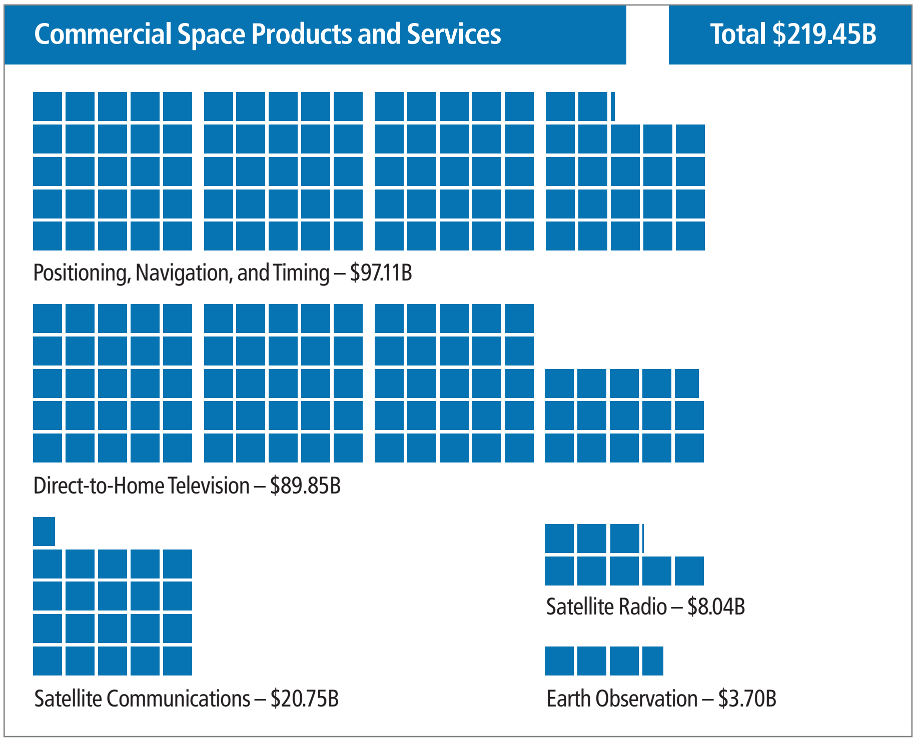
Kevin O'Connell

Former U.S. Office of Space Commerce Director Kevin O'Connell highlighted distinct sectors as being the next to accelerate. "Space is increasingly recognized as a key element, if not the backbone, of the 21st Century information economy," he said. Building this economy "will involve leverage of commercial remote sensing, IoT, and high-speed communications, combined with deep analytics and other technologies." O'Connell also called attention to lunar economic activity, innovative satellite servicing techniques, and space medicine as growing fields of investment to the benefit of all.



Summary of Global Space Activity Revenues and Budgets, 2020



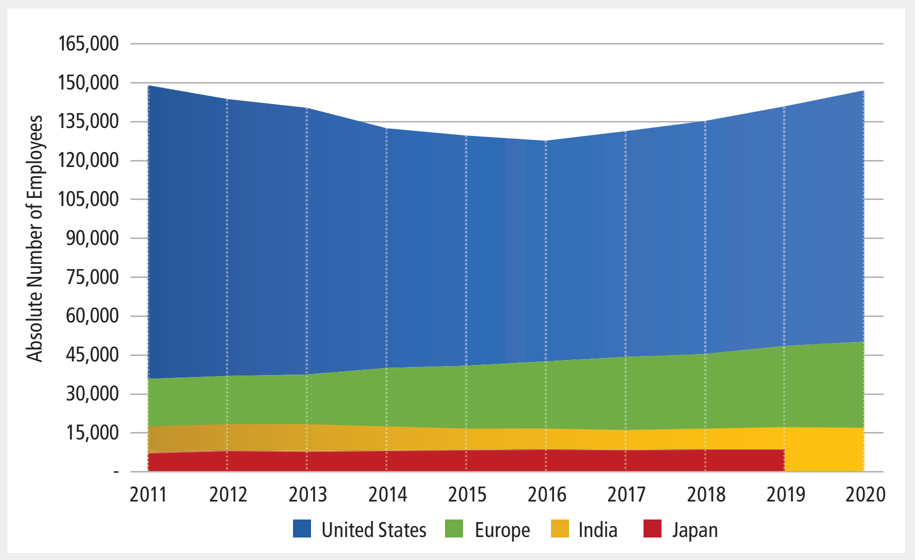


Becki Yukman is a senior data analyst for Space Foundation.

Introduction | *Hiring in more than a dozen nations continued to escalate in 2020 despite the pandemic. A snapshot of key workforce data follows. Analysis of trends in the global space workforce provides insight into the current and future health of the space sector.*

In this May 2021 photo, JAXA Astronaut Akihiko Hoshide stows experiment samples into the minus 88-degree Celsius Laboratory Freezer on the International Space Station. *Credit: JAXA*

Space Workforce Trends in the United States, Europe, Japan, and India, 2011-2020



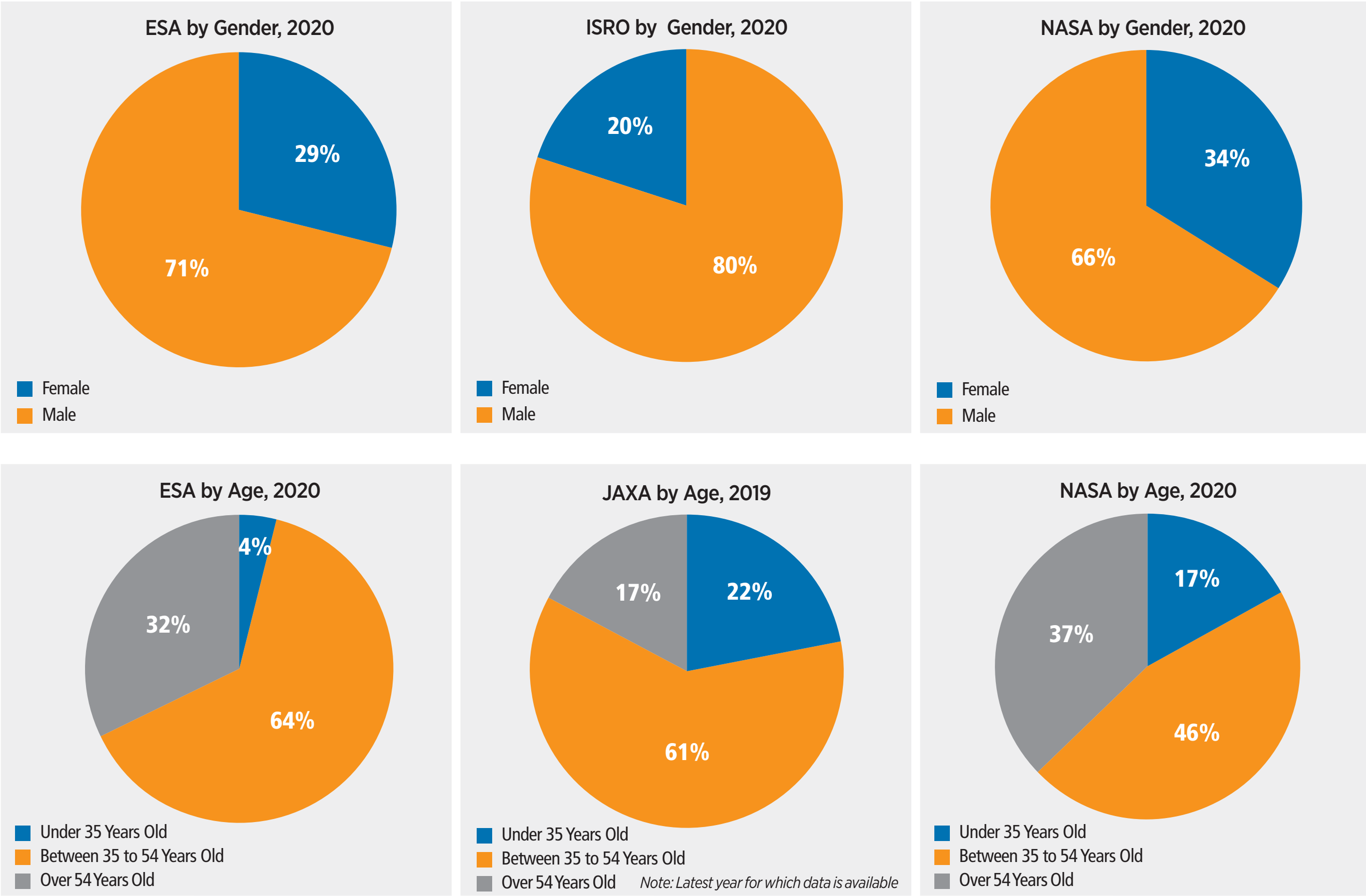
Sources: U.S. Bureau of Labor Statistics, Eurospace, Society of Japanese Aerospace Companies, India Department of Space

The U.S. space workforce grew more than 5% from 2019 to include more than 192,000 workers. The European space workforce included 50,388 employees in 2020, an increase of 3.3% from the 48,766 workers in 2019.

In Japan, the space workforce included 8,725 workers in 2019, the most recent year for which data is available, according to the Society of Japanese Aerospace Companies. While this sector decreased 1.9% from 2018 to 2019, it remains nearly 10% larger than it was five years ago. India employed 17,099 people within its Department of Space in 2020, approximately the same amount as in 2019.

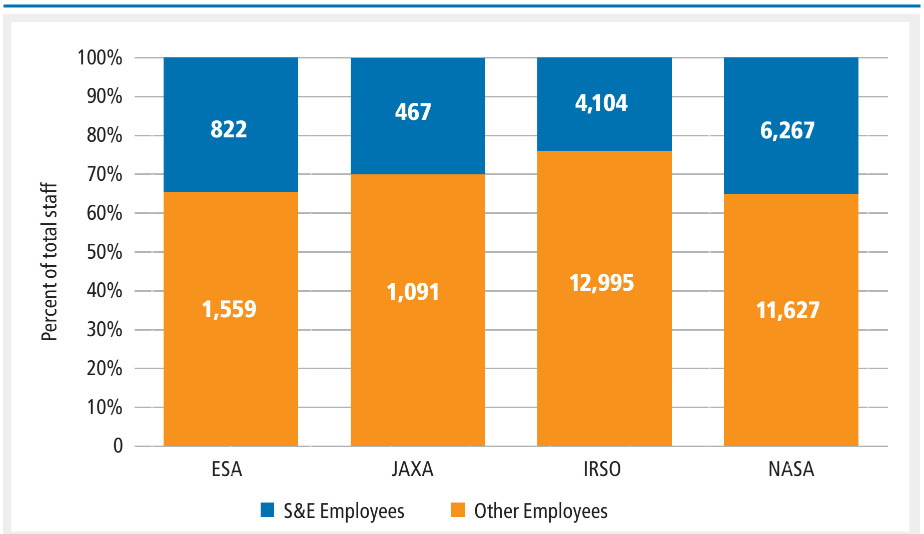
While Russia, China, and other nations also have sizeable space industry employment, they are not reviewed here because of difficulties in consistently obtaining and verifying workforce data.

Demographic Data by Agency for Europe, Japan, India and the United States



Note: Gender information was not available for JAXA; Age information was not available for ISRO.
Sources: U.S. Bureau of Labor Statistics, Eurospace, Society of Japanese Aerospace Companies, India Department of Space

Percentage Split between Scientific Staff* vs Other staff



**Scientific and Technical Staff(S&T) and Scientific and Engineering Staff(S&E)*
Sources: U.S. Bureau of Labor Statistics, Eurospace, Society of Japanese Aerospace Companies, India Department of Space

Introduction | *Inspired by forecasts predicting that thousands of SmallSats will launch over the next decade, launch entrepreneurs have raised billions of dollars and assembled legions of technical experts in a quest to build innovative and cost-effective new rockets. But as the first of these next-generation new entrants reach the launchpad, a new question has emerged: Was all that capital and effort invested in the right design to meet future market demand?*

As the SmallSat market has matured, launch vehicle providers such as Rocket Lab have increased lift capacities. In April, Rocket Lab announced its Electron launch vehicle in 2024 would be joined by the larger Neutron.
Credit: Rocket Lab

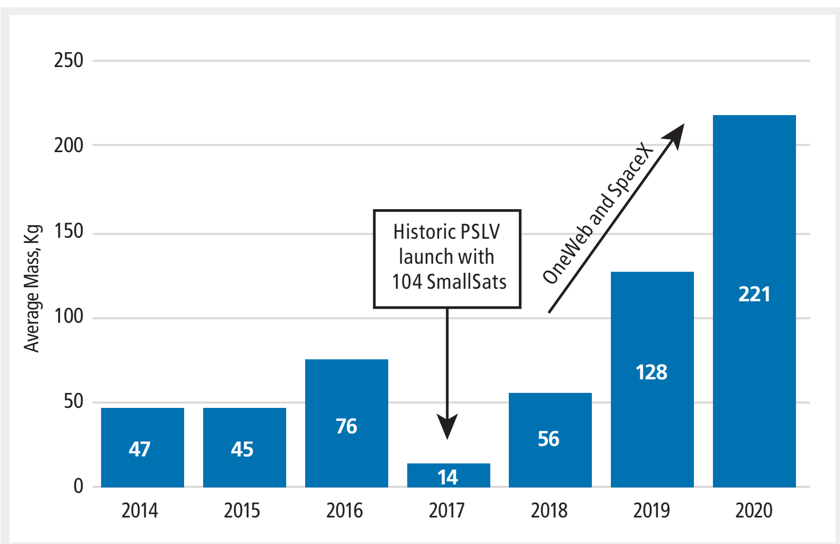
Go For Launch

More than half a dozen preeminent launch startups have redesigned their rockets or announced entirely new vehicle designs as they try to keep pace with rapidly evolving market trends. Are mega-constellations the right focus? Should cubesats warrant dedicated rides to space? What role do small launch vehicles play in a world with rideshares, space tugs, and heavy-lift vehicles?

Can Small Launch Vehicle Developers Keep Pace With SmallSat Trends?

Prior to 2021, Rocket Lab CEO Peter Beck always had the same answer when asked if his company would build a bigger rocket: absolutely not. The company's flagship Electron vehicle – the first of a new generation of small launch vehicles to reach orbit – was right-sized for the burgeoning SmallSat market. The notion of building a larger rocket was so outlandish that Beck often quipped he would eat his hat before building one. But by April 2021, Beck announced that Rocket Lab would build a large, reusable launcher called Neutron with a planned debut in 2024. And, as expected, that hats are "not tasty."

Global SmallSat (<600 kg) Average Mass to Orbit



Source: Quilty Analytics

Why the change of heart? Quite simply, the market moved. When Rocket Lab first unveiled the Electron in 2014, cubesats were rapidly gaining popularity with NewSpace pioneers such as Planet Labs and Spire Global. As the industry began to mature, however, 3Us became 6Us and 12Us as customer demand for higher performance, more sensors, and propulsion necessitated larger buses. SmallSat manufacturers like York Space Systems, Blue Canyon Technologies, and Tyvak Nano-Satellite Systems responded by introducing proprietary bus designs weighing up to several hundred kilograms. Launch providers have inevitably followed that market trend.

Heavy Lift – Been There, Done That

In fairness, predicting launch market demands is a tricky business and not one the industry as a whole has excelled at in the past. Exhibit A was the U.S. Air Force's Evolved Expendable Launch Vehicle program, which funded the development of two separate modular heavy-lift launch vehicles (the Atlas V and Delta IV, respectively), convinced that emerging commercial LEO constellations (in the 1990s!) would provide secondary demand to support these investments. When the commercial market collapsed, the Air Force bowed to reality and let Lockheed Martin and Boeing merge their rocket efforts in 2006 into a new joint venture company, United Launch Alliance.

In some ways, small launch vehicle developers are following in the footsteps of their bigger siblings. Heavy lift launch providers Arianespace, International Launch Services, and SpaceX all increased the performance of their vehicles in response to a prevailing trend towards heavier satellites launched to geostationary (GEO) orbit. Arianespace increased the performance of the Ariane 5 by 1,500 kg from 2009 to 2017. ILS's Proton rocket underwent four phased-design changes from 2000 to 2013 that increased its performance by 600 kg (10.5%) to geostationary transfer orbit (GTO). And SpaceX improved the Falcon 9 by 3,760 kg (~82.8%) over the course of several upgrades culminating in the current Block 5 configuration in 2018.

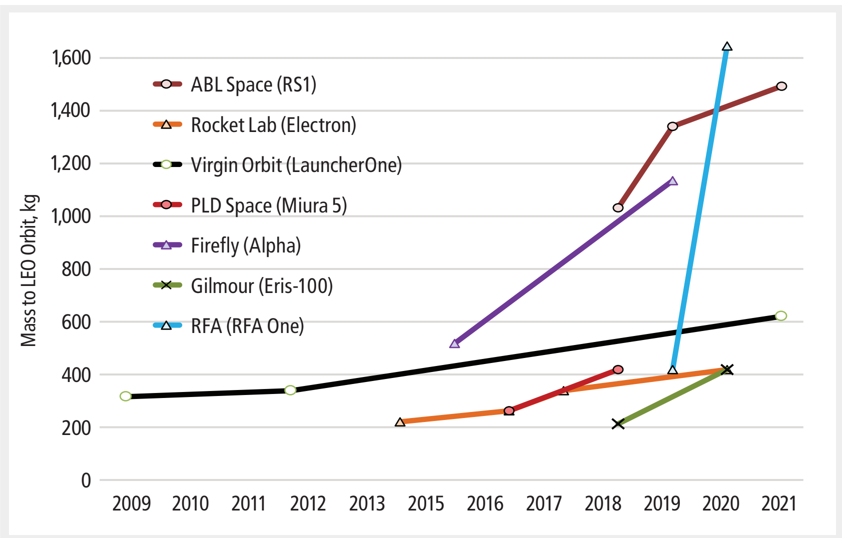
The difference here is that some small launch vehicle developers are undertaking major design changes before ever reaching a launchpad. And because there are many small launch startups – with more than 100 vehicles proposed since 2010 – responses to heavier SmallSats have run the gamut. An analysis of the most prominent Western small launch vehicle startups (by funding and technical readiness) shows two primary approaches to responding to this dilemma.

Vehicle Evolution and Metamorphosis:

Rocket Lab's Electron was initially designed to carry 110 kilograms to Low Earth Orbit (LEO), but the use of electric turbopumps and improvements in battery technology helped boost performance to 300 kilograms. Virgin Orbit increased the size of the engines on its LauncherOne rocket in 2015 and switched carrier vehicles from WhiteKnightTwo to a modified Boeing 747 – two changes that, over the course of 11 years, helped increased its lift performance from 200 kilograms up to the current 500 kilograms.

Sometimes, gradual change is too slow. When Firefly Aerospace emerged from Chapter 11 bankruptcy protection in 2018, it introduced a radically different Alpha launch vehicle, boosting its lift capacity from 400 kilograms up to 1,000 kilograms. Customer input was the prevailing reason. Likewise, ABL Space Systems upped the performance of its RS1 rocket by 300 kilograms when it elected to in-source engines instead of buying them from Ursa Major Technologies. The company further resized the rocket, adding another 150 kilograms of performance for a maximum lift capability of 1,350 kilograms to LEO. Rocket Factory Augsburg, the launch venture spun up by German space hardware company OHB, quintupled the performance of its RFA ONE rocket by switching to a staged combustion design.

Select SmallSat Launcher Mass to LEO Over Time



Source: Quilty Analytics

Starting Over: New Vehicles

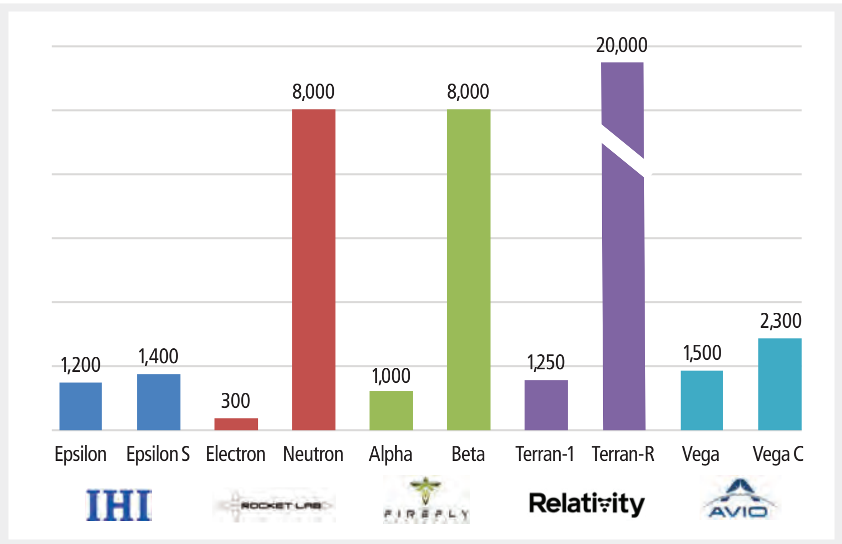
Rationales for new vehicles are as diverse as the rockets themselves. For Avio, Vega C was a natural extension of Europe's push to achieve economies of scale with the Ariane 6. By using the same engine for Vega C's first stage and the Ariane 6 strap-on boosters, Avio achieves economies of scale and can reduce its launch costs. The addition of 700 kilograms of lift capacity was a bonus.

In Rocket Lab's case, Neutron will offer nearly 27x the performance of Electron, with a goal of becoming a mainstay for mega-constellation operators. And Relativity Space, even though it is yet to launch its Terran 1 rocket, recently raised $650 million to kick off the development of a reusable heavy-lift rocket, Terran R, scheduled to debut in 2024.

Mega Motivation

Rocket Lab is not alone in introducing a new, substantially larger vehicle to court mega-constellation operators. Most launch companies upsizing their rockets are hoping to win a piece of the nascent mega-constellation business, which could grow to tens of thousands of new spacecraft over the next decade. Astra CEO Chris Kemp specifically cited Amazon's Project Kuiper constellation as the reason Astra is increasing the performance of its rockets by an order of magnitude (from 50 to 500 kg to LEO). Gilmour Space, Vaya Space, Firefly, and ABL Space Systems have all cited mega-constellations as motivation for upsizing existing launchers or introducing altogether larger vehicles.

Second Act: New Launch Vehicles Introduced by Established Small Launch Companies



Source: Quilty Analytics

But is there a place at the table for small or (increasingly) medium-sized rockets in the mega-constellation launch game? It is too soon to say, but early precedent has largely been elsewhere. SpaceX's Starlink, which accounts for the lion's share of today's mega-constellation projections (whether it reaches 4,000, 12,000, or 42,000 satellites), is all but certain to launch exclusively on SpaceX rockets. OneWeb's 650-satellite Gen-1 constellation is already spoken for, with OneWeb selecting the Arianespace-operated Soyuz. OneWeb had selected Virgin Orbit to launch a portion of its constellation, but backed away from that approach in 2019, resulting in a lawsuit. Telesat has inked an agreement with Relativity for the Terran 1 but will inevitably pair up with heavy-lift providers to carry out the bulk of its launches. Finally, Amazon recently purchased nine launches on the pricey but dependable Atlas 5 after the maiden launch of its expected choice, Blue Origin New Glenn, once again slipped to the right.

This preference for heavy-lift launch vehicles has boiled down to a number of factors, including:

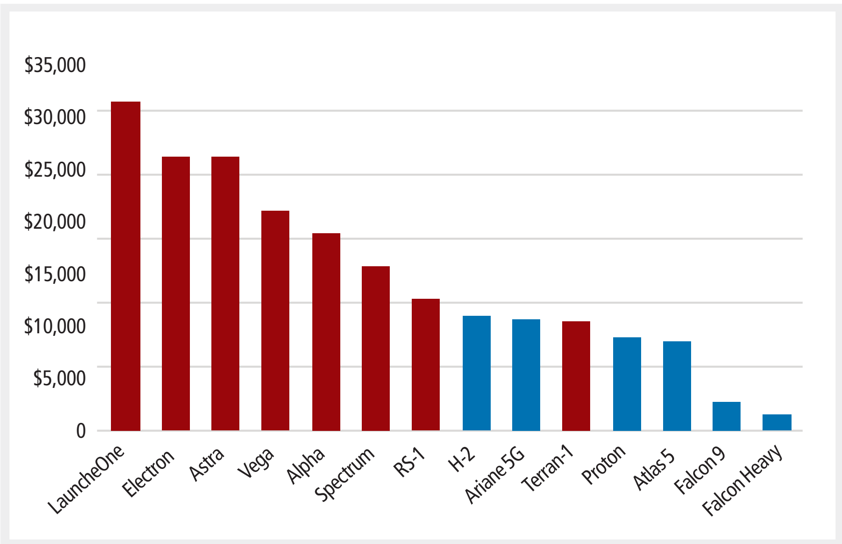
- **Time to market.** Mega-constellation operators require a critical mass of satellites on orbit before they can initiate service. Heavy lift vehicles provide the fastest path to achieving this goal and generating revenues.
- **Filling an orbital plane.** Closely aligned with the preceding point, heavy launch vehicles can typically fill an entire orbital plane rather than piecemealing that coverage through a series of launches.
- **Cost.** As indicated by the chart below, the launch business exhibits strong economies of scale that give heavy-lift vehicles an edge in dollars-per-kilogram to orbit pricing.

Given these challenges, small launchers are unlikely to score top billing on a mega-constellation launch deal, but it is well within the realm of possibility that small launchers will play a constructive role as a "gap filler" launching satellites to complete orbital planes and replacing individual satellites as they fail or deorbit.

Serving the Not-So-Mega Contellations

While the lion's share of mega-constellation launches will likely go to heavier vehicles, small launch vehicles should nonetheless represent a very competitive option for the steady stream of scientific and technology demonstration satellites launched every year, the 60+ SmallSat constellations expected to launch over the coming decade, and a range of other quickly emerging opportunities. Targeting a diverse range of applications ranging from Internet-of-Things communications to optical imaging and weather satellites, many commercial operators have moved past the demonstration stage and are currently gearing up to launch their constellations. Likewise, the U.S. DoD is planning to launch hundreds of LEO SmallSats and is also keen on acquiring a "responsive launch" capability that is well served by small launch vehicles.

Estimated LEO Launch Cost ($/kg) For Select Small and Heavy Lift Launchers



Source: Quilty Analytics

Unlike their much larger brethren, commercial SmallSat operators are targeting constellations that typically range from a dozen to several dozen satellites, often based on cubesat standard (3U, 6U, 12U) or smaller buses in the range of 10-150 kg. Lacking the financial resources of a SpaceX or an Amazon, most of these operators have neither the ability nor the inclination to launch their entire constellation on a large vehicle that could represent a single point of failure for the entire company.

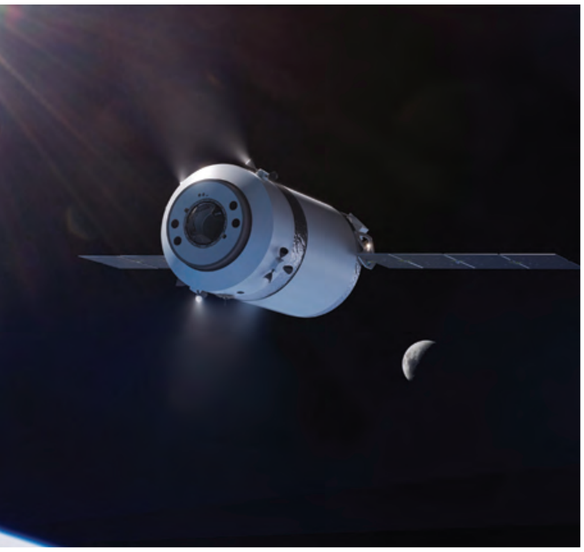
A more likely challenge could come from dedicated rideshare missions paired with an orbital transfer vehicle (OTV). The former provides a cheap ride to orbit, while the latter can provide a last-mile drop-off at a custom orbit, thus preserving spacecraft fuel. While rideshares were historically performed on an ad hoc basis, SpaceX two years ago committed to providing a regularly scheduled rideshare service with pricing well below that of any current or proposed small launch vehicle. If this proves palatable to the market, small launch companies will need to demonstrate schedule reliability, customer responsiveness and price competitiveness with the combined rideshare + OTV cost.

Conclusion

Despite perceptions to the contrary, small launch vehicles are a relatively new phenomenon, with little precedent beyond Orbital Science's air-launched Pegasus rocket and a handful of repurposed Russian ICBMs flown primarily in the 1990s and 2000s. Undoubtedly, the market opportunity looks very different today, but the underlying economic factors that favored large launch vehicles then – namely, economies of scale – still largely hold true today. To be successful, today's small launch companies must use their size and nimbleness to rapidly innovate and outcompete their larger brethren, or run the risk of following the path of the Athena and Falcon 1, two early small launchers that were abandoned before they could establish their ability to compete.

Caleb Henry is a senior analyst for Quilty Analytics

Chris Quilty is the founder and partner of Quilty Analytics.



Introduction | *The Moon is re-emerging as a focus for global space exploration activities at a level and tempo that will surpass the peak of lunar activities during the space race of the 1960s and 1970s. Governments and commercial entities across the globe are investing in a suite of lunar missions. As this occurs, the sustainability — across multiple dimensions — of those activities comes into question.*

Illustration of the SpaceX Dragon XL as it is deployed from the Falcon Heavy's second stage in high Earth orbit on its way to the Gateway in lunar orbit.
Credit: SpaceX via NASA

Three Dimensions of Building Toward a Sustained Lunar Return

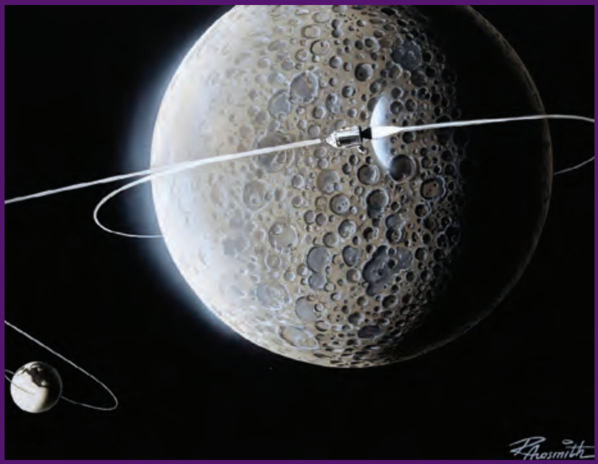
> *The United States shall lead an innovative and sustainable program of scientific discovery, technology development, and space exploration with commercial and international partners to enable human expansion across the solar system and to bring back to Earth new knowledge and opportunities.*
>
> \- National Space Policy of the United States of America, December 2020[1]

Government and private stakeholders across the planet are describing visions and plans for a sustained presence on the Moon — a presence that will require multiple users, uses, and activities to interact and develop in a sustainable fashion. Broadly speaking, the sustainability of continued lunar activities might be thought of in three dimensions: exploration, environmental, and economic:

- Sustainable lunar exploration: including activities, capabilities, and infrastructure
- Sustainability of the lunar environment: including environment impact, heritage and cultural considerations, and safety of operations
- A sustainable lunar economy: including public and private investment; the government's role as a customer; and making a market.

These dimensions frame the most crucial issues about how renewed forays to the Moon must be achieved, matured, and expanded to provide for economic, environmental, and scientific outcomes to the benefit of humankind.

Upcoming Lunar Missions



For the latest list of planned lunar missions, see Appendix 1. Apollo 11 command module orbits the Moon.
Credit: NASA

The Different Dimensions of Lunar Sustainability

Most agencies have become increasingly interested and committed to exploring the Moon's polar regions and in implementing long-term sustainable exploration missions based on international cooperation and commercial participation.

- Global Exploration Roadmap Supplement August 2020[2]

The sustained activities and possible economic expansion envisaged in current planning will not be achieved without efforts to address these three dimensions. How we do as a spacefaring community understand these dimensions of lunar sustainability? How embedded is the connection to sustainable practices in planning for the lunar future? Can we identify and track the types of investments and activities being made to achieve it?

Dimension 1: Sustained Lunar Exploration

In August 2019 then-U.S. Vice President Mike Pence directed NASA to submit to the National Space Council a plan for "sustainable lunar surface exploration and development, including necessary technologies and capabilities to enable initial human exploration of Mars." The resultant Artemis Program Plan for Sustained Lunar Exploration and Development[3] describes a high-level philosophy towards building a sustained lunar presence in which increasingly capable and complex capabilities are developed and fielded in lunar orbit and on the lunar surface. These capabilities include robotic and crewed systems. The International Space Exploration Coordination Group (ISECG), a forum of 26 space agencies, has identified 31 technologies as "critical for future exploration missions."[4]

Achieving sustained lunar (and Martian) activities will require development, maturation, and fielding of these technologies. One method to track or measure activity in sustained lunar exploration is to look at the activities and infrastructure government is funding. Space is still a government-driven market and in this early stage of defining a sustainable lunar presence, government investments will likely drive where private business is applying effort. The types of government investment being made, and its magnitude, will indicate which type of lunar activities will be initially dominated. Government data purchases and exploration science priorities may influence the commercial viability or knowledge for space resources utilization activities.

In this new era of lunar missions, full transparency of government spending from many of the participating nations, including China, Turkey, and the United Arab Emirates, is difficult to obtain. Public records and media reports provide a limited scope of the government investment by other nations:

Global Exploration Roadmap Critical Technologies

The International Space Exploration Coordination Group (ISECG) in 2018 identified these 31 technologies as critical for future exploration missions.
Propulsion, Landing and Return
In-Space Cryogenic Acquisition & Propellant Storage
Liquid Oxygen/ Methane Cryogenic Propulsion
Mars Entry, Descent, and Landing (EDL) (Lunar lander applications too)
Precision Landing and Hazard Avoidance
Robust Ablative Heat Shield Thermal Protection
Electric Propulsion and Power Processing
Mid-and High-Class Solar Arrays
Autonomous Systems
Autonomous Vehicle System Management
AR&D, Proximity Operations, Target Relative Navigation
Beyond-LEO Crew Autonomy
Life Support
Enhanced Reliability
Closed-Loop Life Support
In-Flight Environmental Monitoring
Crew Health & Performance
Long-Duration Spaceflight Medical Care
Long-Duration Behavioral Health and Performance
Microgravity Counter-Measures
Deep Space Mission Human Factors and Habitability
Space Radiation Protection
Infrastructure and Support Systems
High Data Rate (Forward & Return Links)
Adaptive, Internetworked Proximity Communications
In-Space Timing and Navigation
Low Temperature and Long-Life Batteries
Comprehensive Dust Mitigation
Low-Temperature Mechatronics
Low-Temperature Mechatronics (with the Moon as a test bed)
Fission Power (Surface Missions)
EVA/Moblity/Robotic
Deep-Space Suit
Surface Suit (Moon and Mars)
Next Generation Surface Mobility
Tele-robotic Control of Robotic Systems with Time Delay
Robots working side-by-side w/ crew

- Russia announced in May that its Oryol, or Eagle program, would require 1.7 trillion Rubles (US$23 billion) to provide a super-heavy launch carrier, related infrastructure, a landing module and rescue means for its crewed lunar space flights.[5] Its Luna orbiter program will require another 15 billion Rubles (US$195 million) a year for that initiative.[6]

- India has estimated that Chandrayaan-3 will cost 6.15 billion rupees ($86.4 million), compared to the 9.7 billion rupees that Chandrayaan-2 cost. Both estimates include the cost of the spacecraft and its launch.[7]

- The United States, for the Artemis program, has obligated funding through FY2020 of $37.2 billion, with $6.6 billion allocated for FY2021 and another $41.7 billion projected through FY2025.[8] That funding includes expenditures for launch vehicles, human landing systems, habitats, and research and exploration missions.

- Japan has promised 51.4 billion Yen (US$472 million) toward the Artemis program,[9] with funding directed toward technologies for the Lunar Gateway, a resupply vehicle, and a lunar lander.

- South Korea pledged in February to put a robotic lander on the Moon by 2030 and will spend 615 billion Won (US$553 million) this year on that goal and broader space technology.[10]

- Canada joined the Artemis Accords and pledged to spend CAD$2 billion (US$1.4 billion) with NASA on the Lunar Gateway project, including CAD$150 million for a Lunar Exploration Accelerator Program to help develop new technologies to be developed in orbit and on the Moon's surface and will develop a new Canadarm3 to help repair and maintain the Gateway.[11]

- Australia has committed to Artemis as well, agreeing to spend AUD$150 million to support the Moon to Mars exploration program.[12]

Eventually government-developed or -funded systems may provide the basis for shared lunar infrastructure; and operations might be transferred to the private sector. A similar challenge is unfolding in low Earth orbit, as the eventual phase out of the International Space Station, and transfer of capbilities to the private sector, is considered.

Dimension 2: Sustainability of the Lunar Environment

While sustained lunar exploration refers to the activities that will be conducted in a future of continual lunar presence, the Moon's unique physical environment will impact our ability to conduct those activities. And the activities themselves will have impact on that lunar environment — in its physical and cultural aspects. As activity increases in the cislunar environment there is need to develop practices for safe and responsible operations in this domain — both to protect the Moon itself and to enable beneficial science, exploration, and development.

Efforts have begun throughout the space community to identify these practices. In July 2020 NASA updated its planetary protection guidelines for the Moon in anticipation of increased activity and in the interests of sustainable exploration.[13] The Moon Village Association has published a set of Best Practices for Sustainable Lunar Activities and is facilitating a Global Expert Group on Sustainable Lunar Activities (GEGSLA)[14] to develop recommendations to the international community. (See the accompanying article in this edition's Space Policy section for details on this initiative.) The Open Lunar Foundation, under a theme of sustainable governance, has published research on several aspects of lunar environmental management practices.[15] The Aerospace Corporation published a paper in June 2020, Cislunar Stewardship: Planning for Sustainability and International Cooperation, emphasizing the need to develop space situational awareness capabilities and space debris mitigation practices specific to the lunar domain.[16]

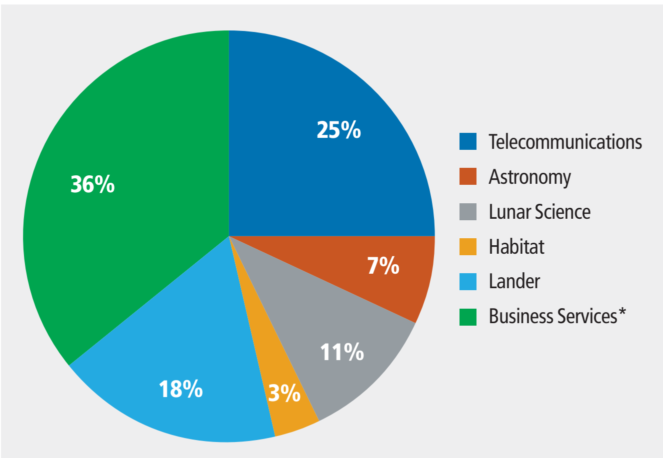
Collectively these analyses begin to identify the environmental management practices that will be necessary to sustain lunar activities. These risks and practices include: space situational awareness, space debris mitigation, lunar dust mitigation, safety zones, interference risks, management of historical and cultural sites, and protection of sites of scientific interest.

Dimension 3: Sustainable Lunar Economy

Many stakeholders see this new wave of lunar activity as a key enabler for the emergence of a larger cislunar economy. United Launch Alliance CEO Tory Bruno has articulated a vision for a "trillion-dollar cislunar econosphere." In this vision, lunar resources, sustained government investment in exploration, the emergence of on-orbit servicing assembly and manufacturing, lead to a multi-trillion dollar in-space economy by the 2040s. Stakeholders within China's state-owned space enterprises have described a vision to develop an Earth-Moon economic activity zone, with some stakeholders describing a potential to create up to $10 trillion in economic benefit value by 2050.[17] While neither of these statements indicate concrete plans or official government policy, they are indicative of the potential space stakeholders see in the cislunar domain.

Developing a sustained lunar economy entails understanding the potential economic activity that might be generated through, and in, the use of the cislunar domain, not as extension of government activity, but by moving from a government-driven market to a business-to-business or business-to-consumer-driven market, in which governments are but one customer type in the marketplace. This entails developing an understanding of the activities and resources that will support sustained growth in profitable space activities, the supplier and customer relationships involved in addressing those market activities, and the policy, legal and regulatory steps necessary to develop a functional market framework.

Survey Results for Distribution of Intended Primary Lunar Services



**Includes areas such as video/image and data storage, insurance and risk management, transport, consulting, autonomous guidance, navigation and control (GNC), and telecommunications standards*
Source: CommStar Communications

Numerous industry, government, and academic studies have attempted to estimate and forecast the potential size or value of the lunar or cislunar economy (or elements thereof). For example, a 2018 market study commissioned by the Luxembourg Space Agency forecasts that "the space resources utilization industry is expected to generate a market revenue of up to 170 billion EUR over the years 2018 to 2045."[18] An April 2020 market study by the consultancy Northern Sky Research "forecasts 140 Moon Missions launching over the next decade to generate $42.3B," with an emphasis on crewed missions.[19]

Each of these studies takes different methodological approaches, different assumptions, or different definitions — and are difficult to meaningfully compare. They all point to considerable potential and considerable uncertainty in development of a cislunar economy. However, most are consistent that government customers will be of key importance in the initial development of commercial capabilities, and that a private market will only emerge following from sustained government investment. Navigating this transition will be a key challenge in achieving a sustainable lunar (or cislunar) economy.

One company, which plans to deliver the first private cislunar communications satellite into orbit in 2023, recently conducted a user survey in coordination with Space Foundation. CommStar Space Communications culled responses from an initial survey pool of more than 4,000 companies, institutions and individuals to ask about planned lunar missions, their communications needs and targeted lunar landing site.

Respondents were allowed multiple responses to mission purposes, with clear majorities presenting for telecommunications and lander activity. In terms of timeline, 50% of respondents plan their missions between 2024-2026, followed closely by 46.4% planning a more immediate goal of a lunar mission before 2023. An expected mission arrival between 2027-2029 was the third-most frequent survey response. Respondents represented businesses in the United States, Europe, Asia-Pacific, South America, and Africa. More than 65% estimated doing five or more missions, followed by 11.5% estimating three or more missions.

Progressing Toward Lunar Sustainability

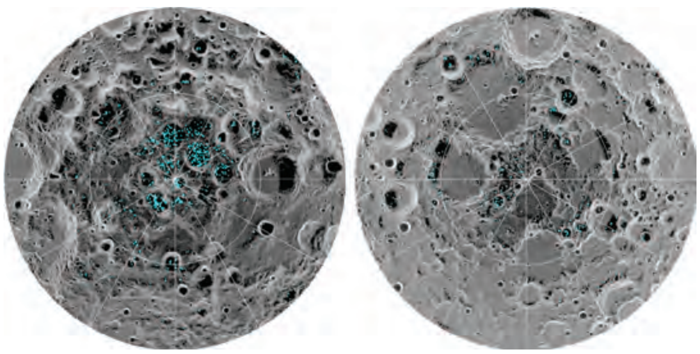
A "new wave of lunar explorations has been emerging in the world, with participants aiming to make sustainable missions to deepen knowledge of the moon and exploit resources there."

- Zhou Yanfei, deputy general designer of China's human spaceflight program, September 2020, Quoted in Space News[20]

If the global space sector is to be successful in achieving a sustained return to the lunar surface, elements of each of these dimensions must be incrementally understood and invested in. All dimensions of lunar sustainability are interdependent: What are we doing on the Moon? How are we doing it? What will it achieve and produce?

Resources vs. Reserves

One of the key resources necessary to support sustained lunar activates is water. Water is of course a critical requirement to support crew operations. Water is also a key resource that can be used to create rocket fuel and potentially catalyze a range of in-space commercial and scientific activities. For example, a 2018 study commissioned by United Launch Alliance identifies "a near term annual demand of 450 metric tons of lunar derived propellant equating to...$2.4 billion of revenue annually."[21] Academic analysis has shown that viable business cases — with positive economic return — can emerge based on lunar sourced propellant. Public-private partnerships with government are shown to be likely to produce greater returns of economic value, however purely commercial business cases are also shown to be possible.[22]



The image shows the distribution of surface ice at the Moon's south pole (left) and north pole (right), detected by NASA's Moon Mineralogy Mapper instrument. Blue represents the ice locations, plotted over an image of the lunar surface.
Credit: NASA

Since 2008 — via data from India's Chandrayaan-1 lunar mission — scientists have known that water ice exists in shadowed craters on the lunar surface.[23] Subsequent missions have provided further analysis. NASA estimates that more than 600 million metric tons of water is present in the polar regions of the Moon, predominately in ice in lunar craters.[24] In October 2020 NASA announced the discovery of water in the lunar regolith, at concentrations "roughly equivalent to a 12-ounce bottle of water trapped in a cubic meter of soil spread across the lunar surface."[25] This finding indicates water exists not only in shaded craters but also in sunlit lunar soil. Yet, as remarkable as the discovery may be, that concentration is less than that of water in the soil of the Sahara Desert.

Just because water exists on the Moon does not mean that the water can be effectively used to support exploration or commercial activities. The terrestrial mining sector refers to "resources" and "reserves." Broadly speaking, "resource" refers to amount of a commodity that exists in in-situ deposits (both known and unknown); a "reserve" is the known part of the resource that can be accessed and used in an economically viable manner.[26] Currently when we speak of water on the Moon, we are speaking of resources, not necessarily reserves.

Efforts are underway to develop further detail on lunar resources. The United States Geological Survey (USGS) has published a Unified Geologic Map of the Moon, which integrates a range of existing lunar geological data to produce a map of the geological surface of the Moon.[27] This map might serve as the basis for further detailed mapping of lunar resources. USGS has already verified that its quantitative methods for conducting resource assessments on Earth can be applied to asteroid mineral resources.[28] The commercial lunar exploration firm iSpace, working with government and academic partners in Australia and Europe, is leading the development of a set of standard terminology and classification categories to describe potential lunar reserves — Lunar Ore Reserves Standards 101 (LORS-101).[29] Based on existing standards in the terrestrial mining sector LORS aims to create a "standard code for reporting space and lunar exploration results, mineral and non-mineral resources (e.g. water), and ore reserves."[30] Such a standard ideally would be used by scientific and industry actors to describe and classify lunar reserves in a manner that promotes transparency and supports a functional marketplace.

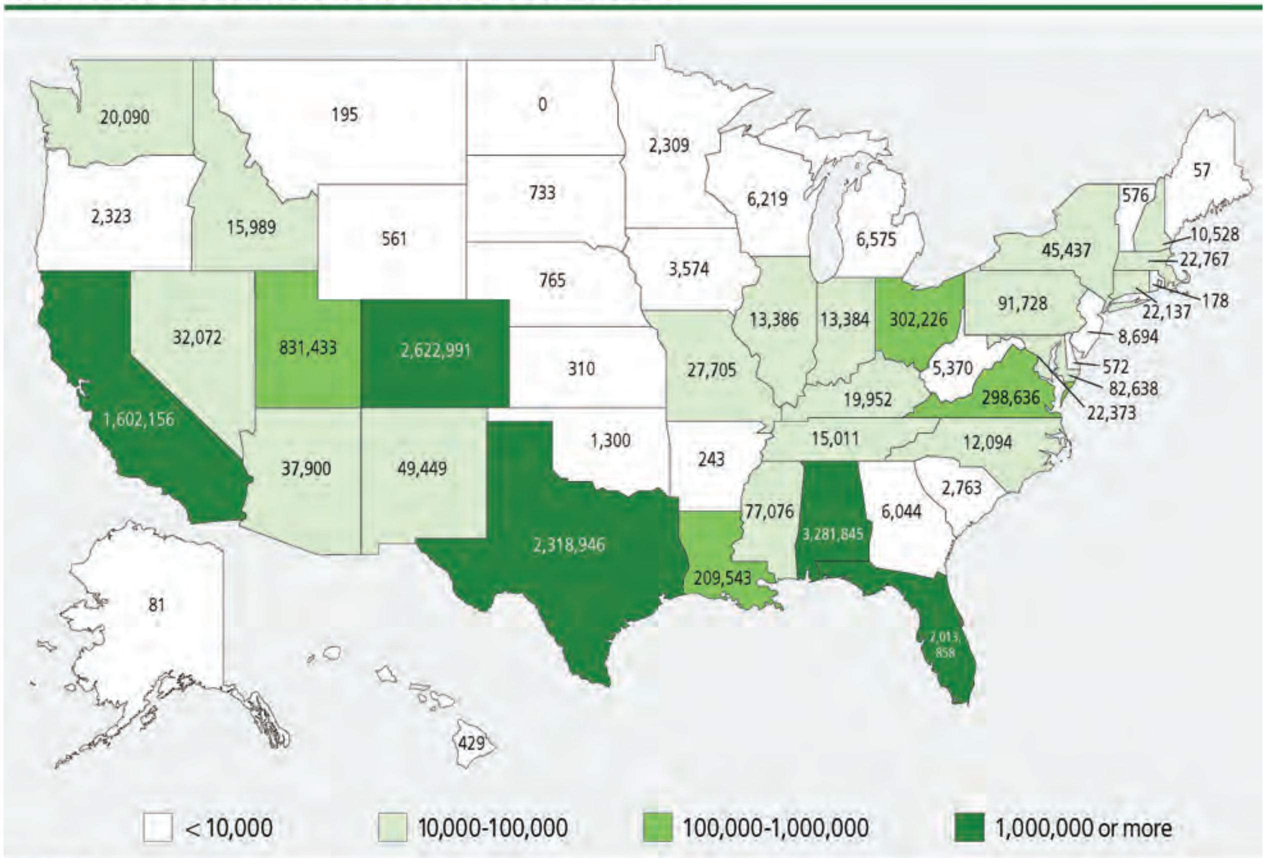
Further efforts to characterize water resources and reserves on the Moon will be necessary to address all three dimensions of lunar sustainability. The locations and sizes of water deposits on the Moon already are influencing the choice of lunar missions and landing sites, and the need to further characterize those deposits will be a key driver of future exploration missions. The presence of water ice in the lunar environment — on the surface and in the regolith — will require balancing scientific and commercial interests, and specific sites of interest or competition may require specialized protection or regulatory practices to manage priority in use or exploration.[31] Efforts to characterize, describe, and access lunar water resources will be necessary to demonstrate economically viable uses, and build business around those uses. Similar efforts will be required for other lunar resources of potential interest — including mineral resources.

Infrastructure Needs for Lunar Operations

Returning to the Moon in a sustained manner requires developing operational capabilities to support continued operations — a different model than the mostly one-off missions that have characterized lunar exploration to date. In July 2020 the U.S. National Space Council noted that "the next lunar explorers will use longer-lasting and more reliable means of habitation, life support, power generation, transmission, storage, surface transportation, and resource extraction and utilization. Surface mobility will enable broader exploration, and reusable vehicles will ferry astronauts and cargo…"[32] Governments are making investments in developing these — and other aspects — of lunar infrastructure. For example, the European Space Agency (ESA) has initiated a set of projects, under an initiative known as Project Moonlight, to provide lunar communications and navigation services. The project aims to provide dedicated telecommunications and navigation infrastructure in lunar orbits and reduce the need for individual missions to dedicate resources and payload space to those services.[33] A pathfinder satellite — Lunar Pathfinder — is under development at Surrey Satellite Technology Limited (SSTL) as public-private partnership with ESA. Due for launch by the end of 2023, Lunar Pathfinder will provide communications relay services for lunar missions and also carry an experimental payload designed to demonstrate the operations of a satellite navigation receiver in lunar orbit.[34] In May 2021 ESA awarded contracts to two competing commercial consortia to conduct concept of studies of lunar satellite networks that might provide communications and navigation services. These networks might ultimately be operated as a commercial service.[35] Since May 2018, China has operated the Queqiao relay satellite in lunar orbit to support its Chang'e-4 lunar mission.[36]

In 2019 Canada established the Lunar Exploration Accelerator Program (LEAP), under the Canadian Space Agency, with a $150 million budget over five years with the purpose of supporting a broad range of lunar exploration related science and technology. In the United States, NASA's Space Technology Mission Directorate has established the Lunar Surface Innovation Consortium (LSIC) under NASA's Lunar Surface Innovation Initiative. The mission of LSIC focuses on communication and collaboration among primarily U.S., commercial, government, academic and nonprofit stakeholders to advance technology capabilities necessary for "successful lunar surface exploration."[37] LSIC has identified six focus areas, indicating key needs for lunar operations: in-situ resource utilization, surface power, dust mitigation, capability to operate in extreme environments, surface access and navigation technologies, and excavation and construction approaches.[38] Addressing each of these areas is complex. For example, an effort under the ISECG has identified an extensive list of Strategic Knowledge

Moon to Mars (M2M) Output Impacts by State (in $ thousands), 2019



Source: NASA
Based on FY2021 Federal Budget

Gaps (SKGs) related to ISRU that must be addressed to enable successful long-term lunar (and Martian) exploration.[39] Sustained funding across a broad base of capabilities will be necessary.

The United States' Moon to Mars (M2M) program, which includes Artemis, represents a significant amount of the current government investment in lunar exploration and its potential for far-reaching economic impact on businesses large and small. Corporations such as Lockheed Martin and SpaceX have won contracts valued at $4.6 billion[40] and nearly $10 billion[41,42] respectively, but a Space Foundation review of nearly $30 billion in NASA contracts shows smaller businesses have won contracts, and NASA procurement officials say more than 2,000 businesses[43] have been awarded subcontracts for products and services ranging from cryogenic propellant management to payload integration and delivery support.

NASA has assessed the economic impacts that result throughout the U.S. national economy from M2M activities,[44] including:

- The total amount of employment generated by M2M activities across the U.S. is more than 69,200 jobs. NASA directly employs 5,563 civil servants to support the M2M program, paying more than $520 million in annual wages and benefits — an average wage of $93,474.
- The M2M program supports labor income of $5.2 billion per year and total economic output of $14.1 billion annually.
- For each million dollars of labor income earned by M2M-assigned NASA employees, an additional $9 million in labor income is generated in the U.S.

This base of contracting investment contributes to economic and exploration sustainability by introducing more participants to lunar activities and working to build an industrial base. These contracts, while not all related to infrastructure, indicate activity in a broad range of capabilities necessary to enable sustained lunar operations. Not all of these contracts will result in successful and long-term viable technology, products, or services. However, tracking the government investments being made across the entirety of the industrial base supporting the lunar program will provide some indication of whether the necessary breadth of capabilities are being developed and supported.

This infrastructure may provide the initial foundation of a sustainable lunar economy — as government investment in a suite of technology developments transitions into government acting as a customer and eventually into a marketplace of private services. In some areas the development of the necessary capabilities to provide the infrastructure for sustainable lunar operations will also help to responsibly manage and protect the lunar environment.

Operational and Environmental Challenges

The Moon is a unique operational and physical domain. Many of the infrastructure investments being pursued are in response to this unique nature — for example, lunar dust mitigation studies or efforts to develop systems capable of withstanding the lunar night. In the context of sustainable lunar operations — operating safely in the context of this unique domain must be a key consideration, including the safety of individual missions and the need to avoid harmful interference with other missions and activities. The Moon also has cultural and historical significance, which increased human activities might disrupt or otherwise affect. As multiple stakeholders become more actively involved on the lunar surface, the need will increase for coordination mechanisms to ensure potentially overlapping and competing uses are balanced. Collectively this group of challenges has led to calls for development of lunar environmental management practices and policies.[45]

This challenge begins in lunar orbit. As more operators become active in lunar orbit, and on the surface, need increases to develop space situational awareness, space traffic coordination practices, and orbital debris mitigation practices specifically for cislunar space.[46, 47] Existing space situational awareness capabilities are challenged to cover cislunar space. A 2020 Memorandum of Understanding between NASA and the U.S. Space Force notes that both organizations are "at current capability limits for extending Space Domain Awareness beyond geosynchronous orbit."[48]

On the lunar surface, management and mitigation of lunar dust is a key challenge. Lunar activities — in particular landings of spacecraft — will create ejecta of lunar regolith and dust. Elements of this ejecta — in particular the dust — can travel long distances in the low gravity environment of the Moon and be potentially harmful to other operations on the lunar surface (and even in lunar orbit).[49] Mitigation of lunar dust as a result of increased activity will be essential in achieving sustainable operations. NASA and other space agencies are funding research into mitigation approaches. One potential approach that has been suggested is the construction of hardened, shared landing pads.[50]

The issue of lunar dust is one example of how lunar activity might pose risk of harmful interference with other activities on the Moon. Other types of harmful interference might occur as well. Some initiatives — including the U.S.-led Artemis Accords and the Hague International Space Resources Governance Working Group — have proposed developing safety zones around specific lunar activities as a means towards reducing the risk of harmful interference and promoting lunar safety.

The suggestion of safety zones points to a broader need to develop practices for deconfliction of activities between stakeholders on the lunar surface. Scientific, commercial, historical, and cultural significance of the Moon must be balanced in an increasingly multistakeholder environment. Practices for doing so will include a mix of policy, legal, and technical approaches, including registries of activities, regulatory and licensing provisions, and information sharing practices. As the Moon is better characterized through exploration efforts — our collective understanding of where overlapping activities and interests emerge will be improved.

Conclusion: Toward a Functional Market

The three dimensions of lunar sustainability and the initial investments and activities in related areas demonstrate the overlapping interests and stakeholders that are a key feature of a sustained return to the Moon. Sustainability itself can be a key driver – and requirement – in international and multilateral discussions of the governance of lunar activities.[51] In many ways the Moon resembles an economic commons, in particular with regard to its resources and uses.[52] The Moon is a shared resource — under the sovereignty of no state, and theoretically accessible to any government, business or entity capable of reaching it. Yet reserves extracted from the Moon may be utilized and owned. Freedom of use is a principle of the Outer Space Treaty, and several states have recognized the ability to utilize space resources (including lunar resources). Yet at the same time, the Treaty establishes that no state can claim sovereignty over the Moon, and by extension cannot unilaterally grant claim to any part of the lunar surface.

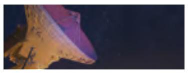
There is need for international coordination and policy to enable a functional and sustainable market on the Moon — that will achieve a balance in all three dimensions of lunar sustainability. Managing rights and access to lunar resources (including regolith, physical sites, and energy) is key toward achieving balance. The legal means to provide certainty to lunar resources utilization claims, to enact protection of cultural and scientific sites of interest, and perhaps to enact safety zones all relate to a central question around priority and access rights to areas of the lunar surface.[53]

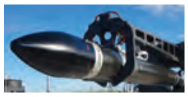
The U.S. Council of Economic Advisers, a policy advisory organization in the Executive Office of the President, has argued that establishing private property rights in space is a key enabling factor for growing the size of the space economy, increasing investor certainty, and producing further benefit from space activities.[54] Private property rights in the lunar context might cover extracted resources, enabling their sale and tradability. It is also suggested — based on evidence from terrestrial extractive industries — that establishing a private property and secure claims system might result in more sustainable environmental practices by reducing the likelihood of a rush to extract reserves under an unclear or uncertain rights regime.[55]

However, the realm of private property rights is not the only system for managing usage and ownership rights. Economic theory provides for approaches to management of common areas through common pool resources and rights in the public domain. These theories address the governance and use of resources in the context of a wider range of stakeholders and interests. The applicability of commons management principles regimes to the lunar context is unclear, and efforts are underway to evaluate approaches.[56] What is clear is that a method to balance stakeholders' interests across the range of lunar activities cannot be implemented by a single country or state alone — it will fundamentally require international coordination. This policy and legal coordination will need to be continued areas of investment — along with business, technical, and scientific investments — to enable a truly sustainable lunar future.

Ian Christensen is director of Private Sector Programs, Secure World Foundation and a fellow at the Institute of Space Commerce.

Lesley Conn is Sr. Manager of Research & Analysis at Space Foundation.



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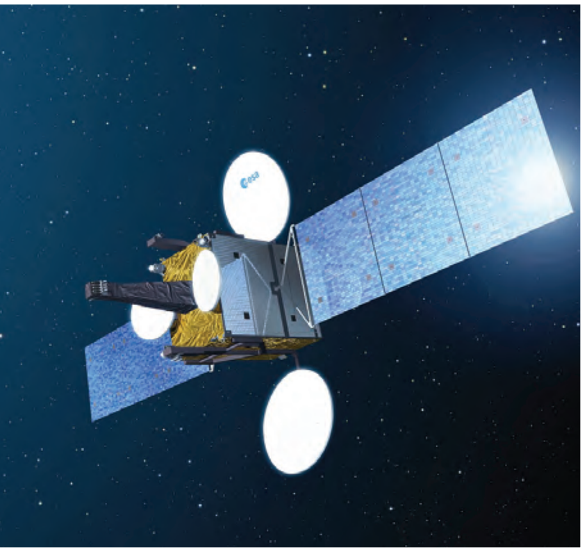
Appendix 1 – Upcoming Lunar Missions

COUNTRY	NAME	EXPECTED LAUNCH	TYPE	AGENCY/COMPANY
Canada	STEM payload	2021	TBA	Canadensys via Astrobotic's Peregrine
	Lunar Exploration Accelerator Program	2022	AI flight computer	Mission Control Space Services via iSpace
	Lunar Exploration Accelerator Program	2022	Lunar camera payload	Canadensys via iSpace
	Lunar Exploration Accelerator Program	2022	Autonomous navigation system	NGC Aerospace Ltd via iSpace
	Robotic Lunar Rover	2026	Polar Rover	Canadian Space Agency/NASA
China	Chang'e 6	By 2030	Robotic probe	CNSA
	Chang'e 7	By 2030	Robotic probe	CNSA
	Chang'e 8	By 2030	Robotic probe	CNSA
EU/Japan/Canada	Heracles/EL3	2027	Robotic transfer/lander	ESA
Germany	DHL	2021	TBA	DHL via Astrobotic's Peregrine
	ALINA	2021	Landers	PTScientists
Germany/Israel	Lunar Surface Access Service	2022	Lander	OHB/IAI
Hungary	Team Puli	2021	Rover	Puli Space Technologies via Peregrine
India	Chandrayaan-3	2022	Lander and rover	ISRO
India/Japan	Lunar Polar Exploration (LUPEX) for water	By 2024	Lander and rover	JAXA/ISRO
Israel	Beresheet 2	First half of 2024	2 landers, 1 orbiter	Space/IL
Japan	Yaoki	2021	Rover	Dymon via Astrobotic's Peregrine
	Hakuto-R	2022	Lander	iSpace
	SLIM	Jan. 2022	Lander and rover	JAXA
Mexico	COLMENA	2021	Micro-rovers	ICN via Astrobotic's Peregrine
Russia	Luna-25	Oct. 2021	Lander	Roscosmos
	Luna-26	2024	Lander	Roscosmos
	Luna-27	2025	Lander	Roscosmos
	Luna-28	2027-8	Lander	Roscosmos
	Oryol (Orel)	2030	Crewed Orbiter	Roscosmos
South Korea	Unnamed	2030	Robotic lander	Korea Aerospace Research Institute
	Korea Pathfinder Lunar Orbiter	Aug-22	Orbiter	Korea Aerospace Research Institute
Turkey	Unnamed	2023	Rocket launch	UAE
	Rashid	2024	Rover	UAE MBRSC via iSpace
UK	Mission 1	2021	"Spider" lander	Spacebit UK via Astrobotic's Peregrine
	Mission 2	End of 2021	Lander	Spacebit UK
USA	CAPSTONE	Early 2021	Navigation cubesat	Advanced Space
	Artemis 1	Nov. 2021	SLS, Orion capsule test	NASA/Boeing/Lockheed Martin
	Peregrine	2022	Lander/ NASA equipment	Astrobotic
	Nova-C	2022	Lander	Intuitive Machines
	PRIME-1	By Dec. 2022	Ice mining equipment	Honeybee Robotics/INFICON/NASA
	Masten Mission-1	Nov.2023	Lander/NASA equipement	Masten
	VIPER	Late 2023	Water explorer	Astrobotic
	Artemis 2	2023	first human-crewed test	NASA/Boeing/Lockheed Martin
	HALO/PPE	2023	Gateway modules	Northrop Grumman/Maxar
	SpaceX dearMoon	2023	Tourism orbit	SpaceX
	CommStar-1	2023	Communications satellite	CommStar/Thales Alenia
	Artemis 3	2024	Human Moon landing	NASA/Boeing/Lockheed Martin



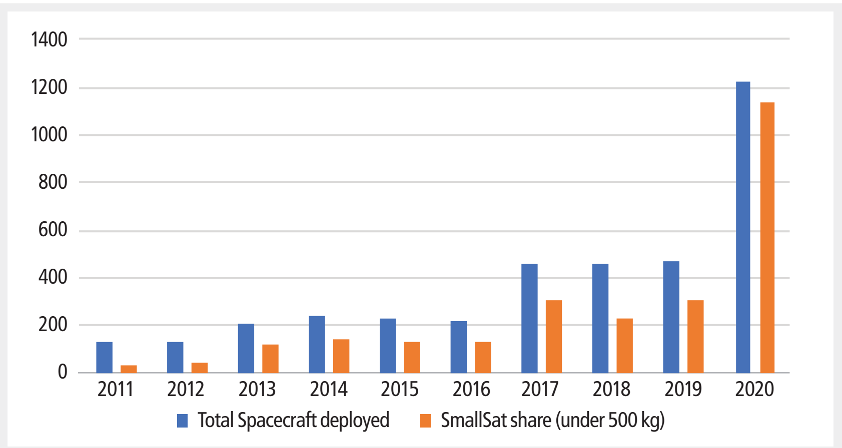
Introduction | *Between 2011 and 2021, commercial business in the global space industry experienced profound changes in the small satellite (SmallSat) sector. In less than 10 years, an ecosystem expanded, catering to commercial SmallSat operators. The sector had origins in civil missions conducted by universities and national space agencies, but the commercial missions have eclipsed those in a big way.*

The Hispasat 36W- marked the first time a German satellite manufacturing company was the prime contractor for a telecommunications satellite. It is entering its fourth year of service.
Credit: ESA

A Growing Ecosystem: The SmallSat Economy

Within 10 years, the SmallSat sector has blown past the activities of larger, more lucrative, legacy satellite operators and manufacturers. As a result, the SmallSat industry involves more nations and businesses while growing into a market of choices. Even more enticing are the competitors' offerings, the choices provided to new operators who then have the luxury of making informed decisions regarding SmallSat manufacturing costs, operations, ground and launch services. The overall result of a mindful operator's decisions could lower its overall capital and operations costs, with some trade-offs.

A Decade's Worth of SmallSat Growth



Source: The Space Report Online database

The dynamic SmallSat space market makes it more affordable for businesses and nations to become space operators instead of space data consumers. Moreover, SmallSat businesses appear to offer characteristics their larger counterparts have always maintained as unobtainable: Satellites can be had fast, cheap, and good — so long as they're small.

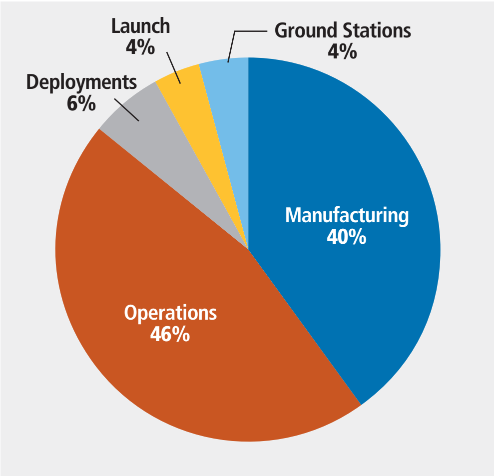
The traditional definition of SmallSats sets an upper limit of 500 kilograms (kg) of mass.[1] They can be any shape or size, but the most recognized sub-set of SmallSats is the CubeSat. Traditional CubeSats use 10x10x10 centimeter (cm—or 3.9x3.9x3.9 inches) as a basic unit. The most common type of CubeSat is typically three of those units in length (10x10x30 cm).

SmallSat Sector Key Activities and Its Participants

The commercial SmallSat sector consists of a range of products and services, supported by key activities:

- Manufacturing
- Operations
- Launch
- Outfitting
- Ground services

140 Operational SmallSat Companies Founded Between 2011-2020



Source: The Space Report Online database

The activities and statistics in this report are only of those commercial SmallSat manufacturing and operations companies that have deployed satellites, not the activities of civil organizations such as NASA, the Japan Aerospace Exploration Agency, or universities. Commercial SmallSat launch service providers (including those that provide ridesharing opportunities) or that have attempted to launch a vehicle to orbit are counted, as are the outfitters (including deployers) that have conducted at least one mission. Commercial ground services, specifically ground stations as a service (GSAAS), have SmallSat operators paying for their services.

Commercial SmallSat activities have grown in share and participants since 2011. For any organization wishing to conduct space missions, SmallSats offer more choices and availability for far less investment than the offerings of heritage space manufacturers. SmallSats tend to cost less than the traditional 1,000+ kg satellites. Their size makes them easy to transport, with some manufacturers configuring SmallSats specifically for more straightforward transport. The majority of SmallSats use common interfaces for mounting to deployers on a space launch vehicle (SLV). CubeSats have standardized dimensions, which makes it simpler to develop deployers for their form.

The large satellite manufacturing business works much differently. Large satellite manufacturers take years (instead of days or weeks) to complete their products. Their satellites cost hundreds of millions of dollars, with some special government satellites occasionally exceeding a billion dollars.[2] For them, the satellites are built good, but not cheap, nor fast. Still, large satellites can do things SmallSats can't because they are larger. For those with money and time to spare, large satellites may be the perfect tools for a mission. They are manufactured to last longer in orbit, sometimes in harsher environments. They have the room to store more power. Optics on a SmallSat can only be so long, but large satellites provide more space for optical payloads.

Of course, the specialized payloads for large satellites are expensive, too. The best SmallSat businesses have learned to repurpose and modify everyday electronics and other technologies to keep prices low while still providing desirable products and services. Others, such as the ground service businesses, are leveraging lessons learned while building out infrastructures that cater to larger populations. For them, the space ground infrastructure business is merely an inexpensive bonus offering to customers.

These, and other reasons, are why commercial SmallSats appeal to nations and businesses with small budgets. Neither has the infrastructure to manufacture, launch, and support large satellites. The changes in the past 10 years allow them to buy large fleets of SmallSats, should they want to, without investing a dime in ground infrastructure and SmallSat manufacturing facilities — commercial SmallSat businesses are already offering those products and services. But businesses within nations traditionally not involved in global space activities have moved in during the past decade, all focused on SmallSat activities and support.

Before 2011, companies from 18 nations were involved with SmallSat activities. By the end of 2020, companies from 32 nations were involved with SmallSats. In addition, nearly 200 companies (~72% of those founded between 2011 and 2020) from those nations were actively manufacturing, outfitting, launching, and communicating with SmallSats.

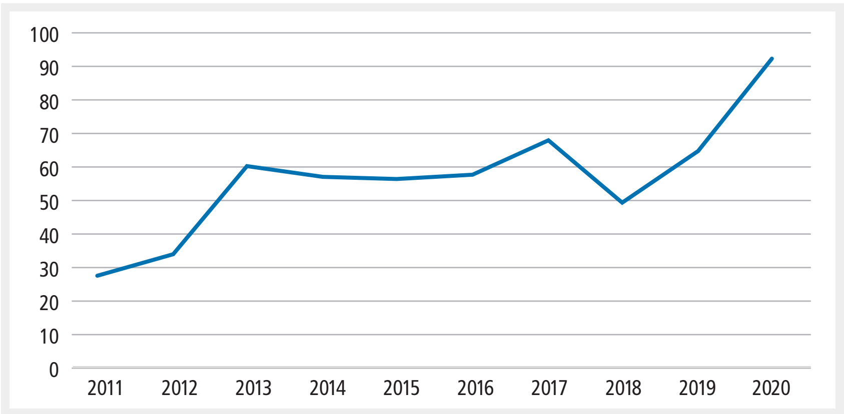
Their activities and growth point to a vibrant, changing market for each essential activity. The SmallSat sub-sector of the overall space industry supports the needs of SmallSat operators with traditional and unexpected business models. As is valid with the "bigsat" market, the mission drives everything in the SmallSat sector.

Those missions form the SmallSat economy. It is not as big as the global space economy, which is based on missions requiring larger satellites, larger launch vehicles, and legacy business plans. But the growth of the past decade points to the SmallSat sector contributing more to the overall global space economy as more companies implement SmallSat business plans. Is this SmallSat economy a precursor of changes that will occur in the rest of the industry? Or will it always be the space industry's smaller sibling?

SmallSats=Small Mass, Form, and Accessibility

The average SmallSat mass during 2011 was nearly 102 kg. In 2020, the average SmallSat mass more than doubled, primarily due to Starlink deployments, to 211 kg.

SmallSat % of Total Spacecraft Deployed



Source: The Space Report Online database

However, the most numerous operational SmallSat configuration orbiting the Earth is SpaceX's Starlink broadband satellite, with a 260 kg mass. Over 1,500 Starlinks are in orbit, and SpaceX is deploying more. Including Starlink, SmallSats made up 92% of all spacecraft deployed during 2020. But SmallSats, even without SpaceX's contribution, are being deployed more often for more missions—nearly 76% of deployed spacecraft in 2020, according to Space Foundation data.

SmallSats Manufacturing

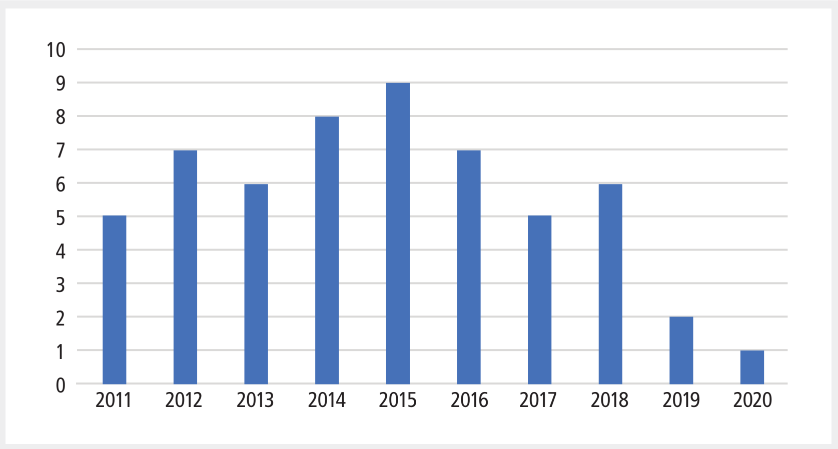
The availability of SmallSats and related SmallSat services today is very different from their availability in 2011. Nations deployed 128 spacecraft during 2011, with SmallSats making up about 27% of all deployments. During that year, civil government missions drove the majority of SmallSat deployments (23). Military missions followed (9), and three SmallSats were deployed for commercial missions. The civil mission share continued to dominate SmallSat deployments until 2014 when commercial missions took 55% (70) of all deployments that year. Commercial missions have continued taking the majority of SmallSat deployments since 2014.

By the end of 2020, a record 1,230 satellites had been deployed. Even with the increased overall spacecraft deployments, SmallSats made up a 92% share (1,133). Of all SmallSats deployed in 2020, 96% were for commercial missions. Not including Starlink deployments that year, commercial missions would still take a majority of all SmallSat deployments — 83%.

A wide range of new and heritage manufacturers offers many SmallSat configurations for interested operators. From 2011-2019, 130 SmallSat manufacturing companies had satellites deployed in Earth orbit. Fifty-six (42%) of those companies were founded between 2011 and 2020. However, 53% (69) of deployed spacecraft come from companies that manufacture the spacecraft they operate, such as Planet, SpaceX, Spire, or OneWeb. Of these 69 vertically integrated companies, 33 do not offer SmallSat manufacturing services to external customers.

SmallSat manufacturers are located within 29 nations. The majority (37%) are headquartered in the United States, with China's manufacturers claiming ~12%. Japan's manufacturers follow with nearly 7%, while the fourth-largest share of ~6% goes to Russian SmallSat manufacturers. Each of the remaining 25 nations has four or fewer SmallSat manufacturers within their borders.

SmallSat Manufacturers Founded 2011-2020 with deployed SmallSats



Source: The Space Report Online database

The satellites that many of these manufacturers offer are far less expensive than those offered by legacy providers. Based on press releases, interviews, and contracts, the table below provides an example of the range of SmallSat costs to customers. Some of the manufacturers have advertised or demonstrated high annual manufacturing rates. All have deployed spacecraft in Earth's orbit.

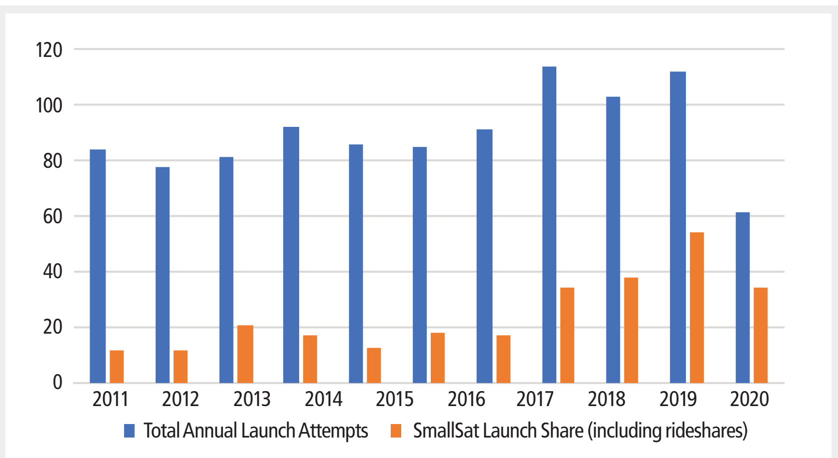
Based on the numbers, a business can buy a constellation of 100 SmallSats and never exceed $1 billion. The more astute businesses may not exceed $50 million, while perhaps having all 100 satellites available to them a half year after signing a contract. Legacy satellite manufacturing companies do not offer comparable price ranges and manufacturing rates.

Manufacturer	Bus	Mass, kg	Power (W)	Propulsion	Life (Years)	Annual Manufacturing Rate	Cost (Million)	Nation
OneWeb	Arrow	200	700	electric	7	730	$9	UK
SSTL	SSTL-Micro	95	200	resistojet	7	<50	$3	UK
Azista/BST	LEOS 50	75	250	electric	5	250	$0.50	Germany/India
Blue Canyon Technologies	X-Sat	200	768	electric	5	200	$3.50	USA
UTIAS SFL	Defiant	50	215	electric	5	<50	<$5	Canada
AAC Clyde Space	Epic (Cubsat)	11	240	n/a	5	~5	$2.25-$2.8	UK
York Space	S-Class	200	3,500	electric	5	1,040	$1.2-$5	USA

SmallSat Launch Services

At the beginning of 2011, launch service providers from eight nations maintained 24 SLV families. The majority of these launch vehicles provided the ability to launch large satellites to a range of orbits, from low Earth orbit (LEO) to geosynchronous orbit (GEO) and beyond. Many of these large satellite launches had spare capacity, allowing launch service providers to offer SmallSat operators a berth, sharing a ride with the larger payload to space. Most of the ridesharing opportunities were for SmallSats with civil or military missions. However, some, such as the Indian Space Research Organisation's Polar Satellite Launch Vehicle (PSLV), became renowned for launching high numbers of SmallSats during rideshare missions.[3]

A Comparison of Regular vs. SmallSat Launches

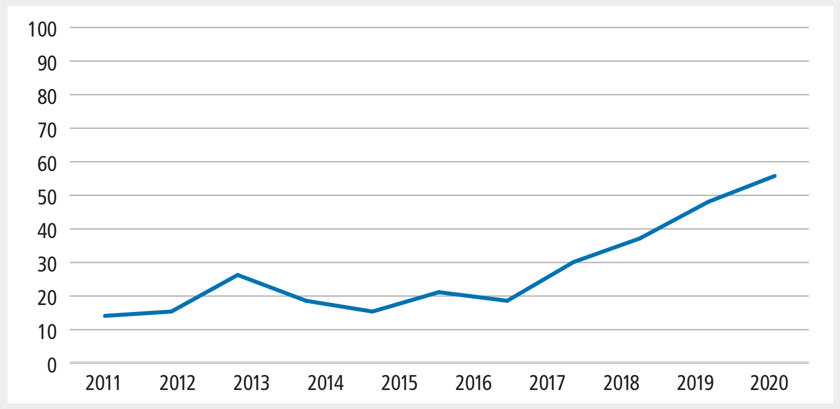


Source: The Space Report Online database

Companies such as Orbital Sciences (now Northrop Grumman), ISC Kosmotras, and Khrunichev provided seven dedicated SmallSat SLVs as 2011 began. Orbital Sciences offered a range of SmallSat SLVs but catered primarily to civil and military needs. As an example, NASA paid about $56 million for a Pegasus launch.[4] As a result, the per kilogram cost of $206,000 for NASA's satellite using the Pegasus SLV is higher than the advertised per kilogram costs of the newer SmallSat-dedicated launch vehicles and launch vehicles providing rideshare services.

More SmallSat-dedicated launch vehicles were introduced between 2011 and 2021. Eighteen new launch vehicles attempted to reach orbit during that time. Of those 18, 13 successfully deployed spacecraft into orbit. At the beginning of 2011, dedicated SmallSat launches accounted for 3.5% of 84 launches attempted that year. By the end of 2020, 35% of 112 launches stemmed from SmallSat launches. As of the end of June 2021, 44% of all 61 launches were dedicated to SmallSats.

% Smallsat Launches from Total Launch Attempts, 2011-2020



Source: The Space Report Online database

The advertised costs for launching with these new SmallSat launch service providers are significantly less than NASA's contract for the Pegasus launch. While the SmallSat-dedicated launch service providers are less expensive than Northrop's Pegasus, they aren't the least expensive launch option for SmallSat operators.

Their portability and the common interfaces enable SmallSats to be launched from nearly any SLV. The number of SLV types (43) that have launched SmallSats demonstrates the concept's utility, whether using dedicated SLVs or rideshare programs. Additionally, the availability of launch platforms, combined with portability and standard interfaces, allows SmallSat operators and outfitters to move from one launch service provider to another if there is a launch schedule delay.

Companies such as SpaceX use these interfaces to offer rideshare options with possibly a more compelling price per kilogram: $5,000. As a result, a SmallSat operator can launch more SmallSats on SLVs with rideshare than they can with SmallSat-dedicated SLVs. On the other hand, SmallSat-dedicated launch service providers may be more responsive to businesses concerned about schedule risks. They also will place a SmallSat operator's satellites in an ideal orbital inclination and altitude instead of one that is "good enough."

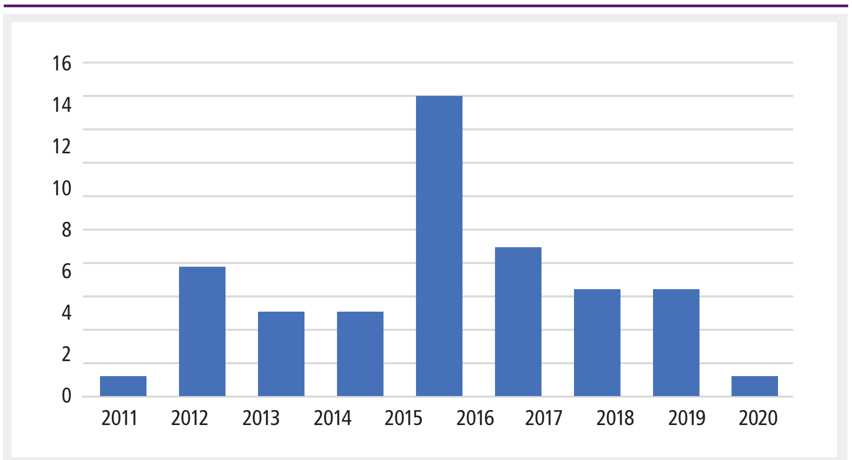
The upshot for SmallSat operators requiring launch services is that it may be beneficial to look for the best deal while understanding some patience and schedule flexibility may be required, especially if the value for the money spent is a concern. At the low end, a burgeoning operator could pay as little as $25 million to launch and deploy 100 SmallSats with a mass of 50 kg each. On the opposite end of that spectrum, virtually no SmallSat operator would want to spend the estimated $1 billion necessary to launch the same number and type of SmallSats with Pegasus — not when there are other options. The table below allows for some useful comparisons.

Provider	LV	Mass, kg (LEO)	Orbit	Nation	Annual Average 2011-2020	Site(s)	Estimated Cost
Arianespace (rideshare)	Soyuz	4,400	LEO-GTO	France	3	1	$16,591
Arianespace	Vega	1,500	SSO-GTO	France	2	2	$30,667
Indian Space Research Organisation (rideshare)	PSLV	1,109-1,700	SSO-GTO	India	3.5	1	$12,942
Northrop Grumman	Pegasus	500	LEO-SSO	USA	1	TBD	$206,000
Rocket Lab	Electron	300	LEO-SSO	USA	5.5	1	$23,333
Roscosmos (rideshare)India	Soyuz	6,600-8,250	SSO-GTO	Russia	14	3	$5,455
SpaceX (rideshare)	Falcon 9	22,800	LEO-GTO	USA	10	3	$5,000
Virgin Orbit	LauncherOne	500	LEO-SSO	USA	1	TBD	$30,000

A new service to the launch business comes from the companies that perform as SmallSat outfitters and deployers. They take advantage of the standardized interfaces SmallSats use for mounting to SLVs. These companies interface between SmallSat businesses and launch providers while providing physical interfaces between customers' SmallSats and launch providers' SLVs. Their services are required for most rideshare missions.

There are eight of these types of businesses that have deployed for their customers. The most recent example of these SmallSat outfitters in action was during the Transporter 2 rideshare mission at the end of June 2021.[5] Transporter 2 launched and deployed 88 satellites. At least four of the eight SmallSat deployment companies deployed satellites during the Transporter 2 mission: Spaceflight Inc., Exolaunch, D-Orbit, and Maverick Space Systems. All deployed SmallSats successfully from SpaceX's Falcon 9 SLV. With current space launch service providers offering rideshare and making tremendous use of these businesses' deployment services, and companies like Rocket Lab planning to launch larger rockets, there may be more opportunities for more deployers.

SmallSat Operators Founded 2011-2020 With Deployed SmallSats



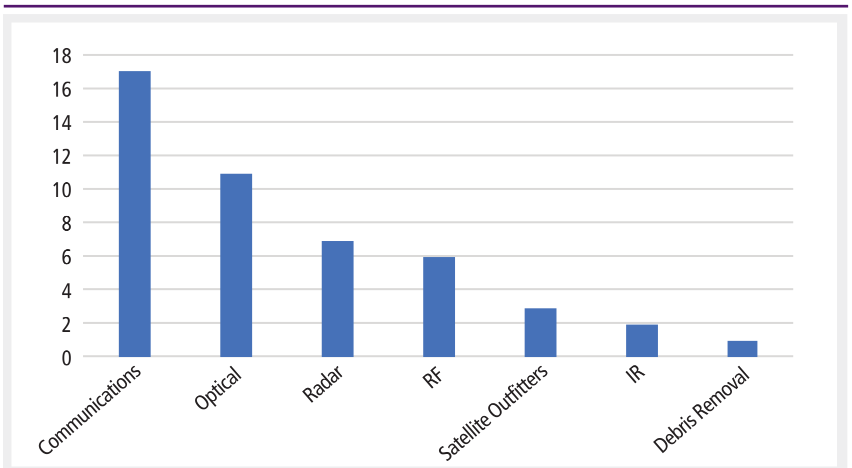
Source: The Space Report Online database

SmallSat Operators

Businesses from 23 nations managed to deploy and operate SmallSats between 2011 and 2021. The nation with the highest share of operators with SmallSats in orbit is the United States, with 41%. China's companies take nearly 10% while Russian companies are the third-highest with 6%. Eighty-four operators have SmallSats in orbit, with 56% (47) founded between 2011 and 2021.

Many SmallSat operators have signaled the intent to, in aggregate, deploy thousands of satellites in the next few years. The operators initially began with optical satellites and have expanded from that mission. The services provided from SmallSats deployed between 2011 and 2021 are communications (IoT, broadband, data relay, etc.), remote sensing (optical, radar, radio frequency (RF), and infrared (IR)), satellite outfitters, and debris removal.

Number of SmallSat Operators Founded After 2011 (with Deployed Satellites)



Source: The Space Report Online database

By the end of 2020, thanks to Starlink and OneWeb satellite deployments, communications SmallSats were the most prevalent SmallSats in the Earth's orbit. Seventeen companies founded since 2011 have become operators of small communications satellites. Newly founded optical (11) and radar (7) remote sensing SmallSat operators each managed to deploy at least one operational SmallSat before June 30, 2021.

The newer missions using radar, RF, satellite outfitters, IR, and debris removal display the SmallSat operators' willingness to experiment with new missions. For satellite outfitters, the operator may not know what the next mission is. These SmallSat businesses provide parts, satellites, communications, and operators for customers interested only in a SmallSat's mission. The customer may be interested in the design and deployment schedule, but outfitters manufacture satellites, run them and pass the resulting data to the customers. Some SmallSat deployers take on a few of the same tasks.

SmallSat Ground Architecture

SmallSat operators' options regarding a ground architecture were initially limited in 2011. First, an operator could build out its ground network, which could cost almost double that of manufacturing and launching satellites. The ground network may be complex because satellites in LEO (in which most SmallSats orbit) require ground stations that must constantly adjust antennas as the satellites pass overhead. Because the SmallSats pass overhead in as little as every 10 minutes, a SmallSat operator must have a network of these antennas to continue receiving critical mission data.

However, instead of building their ground networks, SmallSat operators could go to commercial ground system operators, such as Kongsberg Satellite Services (KSAT) or Swedish Space Corporation (SSC). These dedicated services spent the money to build their terminals and networks (primarily close to the Earth's poles) and are experts in their services. But contact time through those operators tends to be limited and expensive. Ten minutes of a single satellite contact in one orbit could cost a company $500.[6] Consider that one optical LEO satellite orbits the Earth 10-14 times per day and requires more than a single contact per orbit to download large image files and receive new collection targets.

These expenses increase to an unsustainable level for SmallSat operators — such as Planet — seeking to deploy hundreds of satellites. More frustrating for SmallSat operators, ground networks for LEO satellites tended to build most of their satellite terminals close to the Earth's poles. For SmallSat operators with real-time or near-real-time mission requirements, the offerings of commercial ground system operators were unsatisfactory.

However, between 2011 and 2020, six more companies joined the ground station businesses. Four of those five were founded, while the other two were expansions from existing companies in the technology sector. Most of the new companies are promoting ground stations as a service (GSAAS). The concept they are pushing is similar to KSAT's and SSC's offerings (for a price, the satellite operator gets to communicate with its satellites).

However, the new companies offer new services such as flexible contracts, no hidden fees, data encryption, faster data delivery, satellite data processing, and more. In addition, each company has its remote terminals and antennas that are distributed more globally. Their infrastructures give SmallSat operators options with how often their satellites need to communicate, when, and then estimate the costs of their contact plans.

The result of these newcomers is that SmallSat operators do not have to worry about building a ground station network — if they don't want to. Considering some of the advertised costs and new capabilities from the new companies, a few SmallSat operators have already decided to use their services.

Ground Service	Global	LEO	Ground Stations	Antennas	Frequency	Pricing
AWS Ground Station	Y	Y	6	TBD	X, S	$1,650/mo
Atlas Space Operations	Y	Y	10	30	X, S, Ku, Ka	-
Azure Orbital	Y	Y	60	Partner dependent	X, S, UHF	-
KSATlite	Y	Y	12	30	X, S, UHF, Ka	-
Infostellar	Y	Y	-	10	X, S, UHF	~$50-10 min
Leaf Space	Y	Y	12	12-24 (est.)	X, S, UHF, VHF	Monthly or Megabyte-based
RBC Signals	Y	Y	50	80	X	$595/mo
SSC	Y	Y	25	27	X, S, Ku	-

Instant Constellation?

The previous data shows growth. But it also points to unprecedentedly affordable possibilities brought forward The previous data shows growth. But it also points to unprecedentedly affordable possibilities brought forward by a growing and thriving SmallSat ecosystem during the last 10 years, leveraging the products and services that have emerged to support SmallSat operations. For example, satellite operators can use that leverage to build satellite constellations — the province of governments, militaries, and telecommunications companies 10 years ago.

A startup SmallSat operator can mix and match the offerings of SmallSat manufacturers, SmallSat launch providers, and GSAAS companies to fit a specific mission. If cost is no object, then a constellation of 100 SmallSats, each with 200 kg of mass, will cost about $1.5 billion (which is less than the cost of a single military satellite).[7] However, if the budget is critical, a startup can still get a fully capable optical 100-SmallSat constellation with a capable 50 kg mass, on orbit for less than $100 million. Both options include SmallSat manufacturers that advertise they can produce 100 satellites in less than a year.

Adding It All Up

	High	Medium	Low
Launches			
Cost/kg	$30,667	$16,591	$5,000
Total Satellites	100	100	100
Satellite Mass	200	95	50
Launch Total	$613,340,000	$157,614,500	$25,000,000
Satellite Manufacturing			
Cost	$9,000,000	$3,500,000	$500,000.00
Total Satellites	100	100	100
Manufacturing Total (million)	$900,000,000	$350,000,000	$50,000,000
Monthly Cost	$1,650	$595	$595
1 Year Total (million)	$19,800	$7,140	$7,140
X 100 Satellites	$1,980,000	$714,000	$714,000
Total (million)	$1,515,320,000	$508,328,500	$75,714,000

The table above excludes research and development costs for sensors or other types of payloads. For startups, R&D may not be a priority compared to a desire to manufacture and deploy satellites quickly.

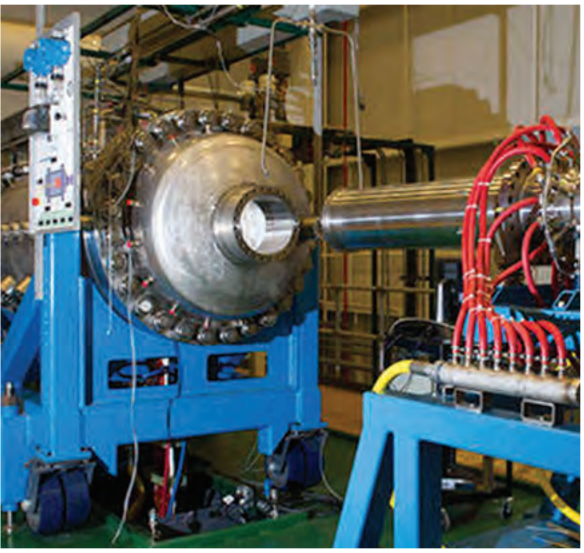
Compared with the prices governments pay for satellites and payloads to implement civil and military missions, even the "High" option may be attractive to specific businesses. However, the higher cost may be less of a temptation for most businesses considering jumping into the SmallSat operations business, especially because both the "Medium" and "Low" options still could yield a capable constellation — depending on the kind of payload and mission a company is seeking to exploit.

The table also emphasizes that the SmallSat business is not yet the moneymaker that is the large satellite business, mainly if operators chose the "Low" option. For example, consider the $1.7 billion price of a single government satellite.[8] About 22 operators choosing the low option would add up to the cost of that single military satellite (all while deploying 2,199 more satellites). Thus, while all the data in this report indicates a growing SmallSat economy, it has a long way to go to contribute meaningfully to the overall global space economy.

The rapid growth, when contrasted with SmallSat's relatively low contribution to the global space economy, appears dissonant. How can something successfully grow but make less money, after all? Commercial SmallSat activity and economic growth may continue, too, if the companies that have yet to deploy satellites successfully implement their plans. This report only covers those businesses that already have operational assets. Hundreds more SmallSat businesses are attempting to break into the SmallSat industry.

Their aggregated SmallSat constellations point to potentially thousands more satellites deployed around the Earth (not including OneWeb or Starlink constellations). Their success, and what appears to be increasingly affordable pricing from SmallSat-supporting businesses, will contribute to the commercial SmallSat economy's growth.

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

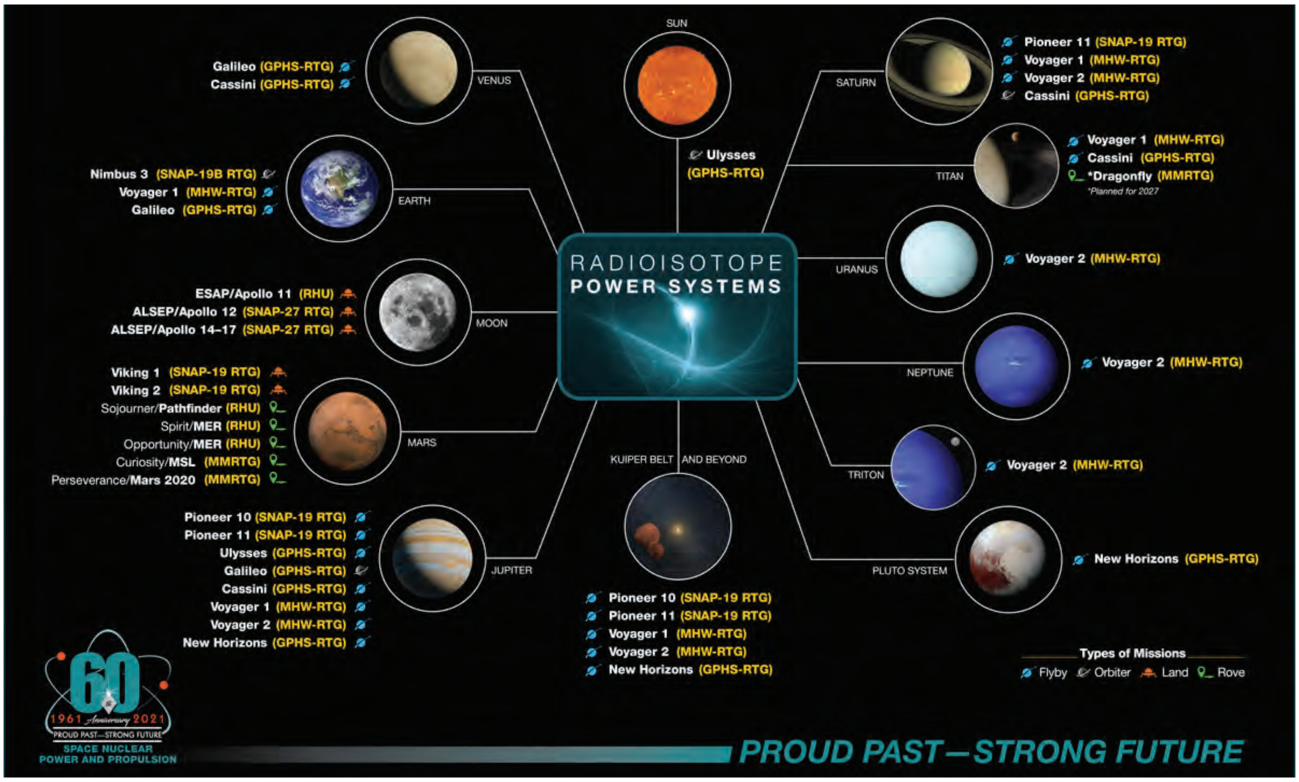


Introduction | *Advancements in space nuclear power and propulsion are essential for maintaining a safe and secure space environment, achieving an enduring human and robotic presence in deep space, and expanding commercial activity in and beyond traditional earth orbits. Thanks to a renewed public and private sector focus, technology is maturing and constraints are being removed at the national, programmatic, and technical levels, but there is more work to be done to develop and demonstrate these game-changing capabilities.*

The Nuclear Thermal Rocket Element Environment Simulator test facility — housed at the Marshall Space Flight Center — safely tests simulated nuclear fuel elements. Such technology could propel human explorers on deep-space exploration more efficiently than conventional spacecraft while reducing crew exposure to the harmful space environment. *Credit: NASA*

Nuclear Power and Propulsion: A Keystone for the Security, Exploration, and Development of Space

Since the 1961 launch of the Transit IV-A satellite, nuclear material has been deployed to enable long-duration spaceflight and exploration of the solar system. The utilization of nuclear material in space is generally based on one of two processes: nuclear fission or radioactive decay. Nuclear fission is the process of splitting an atom to release energy, and radioactive decay is the emission of energy from the atomic nucleus of an unstable isotope. In both cases, technological advancements have provided the ability to safely harness and utilize the resultant energy. Common applications of nuclear material in space are often grouped into space nuclear power and space nuclear propulsion, collectively referred to as *space nuclear power and propulsion* (SNPP). The concept of space nuclear propulsion can itself be split into nuclear thermal propulsion and nuclear electric propulsion.



RHU-heated and RTG-powered spacecraft have visited many moons and most planets in our Solar System; two of them are in interstellar space. Credit: NASA

The first space nuclear applications worth mentioning are the *radioisotope heater unit* (RHU) and *radioisotope thermoelectric generator* (RTG), collectively referred to as *radioisotope power systems* (RPS). These applications utilize radioactive decay to provide heat and electricity, respectively, allowing spacecraft to operate longer under extreme conditions, such as those encountered in planetary and deep space exploration. They have most often been utilized for six decades of uncrewed missions, such as rovers on the surface of Mars, flybys of outer planets, and the Voyager interstellar probes, but they were also brought to the surface of the Moon by astronauts during the Apollo program. While RTGs can reliably provide power below the *kilowatt electric* (kWe)[1] range, which provides an ideal solution for smaller spacecraft, they are limited in their scalability due to low power density and thermoelectric conversion losses.

In terms of heavy-duty space nuclear power generation, *fission surface power* (FSP) is the most commonly discussed application. FSP relies on the same principle as terrestrial nuclear power — the conversion of a fission reaction's resultant heat energy to energy in the form of electricity. In addition to its scalability beyond the single kilowatt range, FSP offers the ability to provide power for systems where solar energy is not sufficient or constant, including areas of the Moon during a lunar night. Therefore, FSP could support a variety of applications to enable a sustainable presence on the lunar surface, including resource extraction, in-situ resource utilization, and environmental control and life support systems.

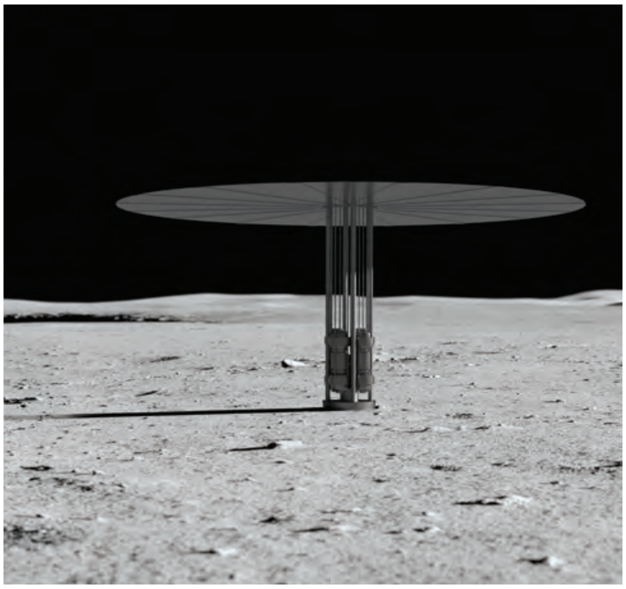
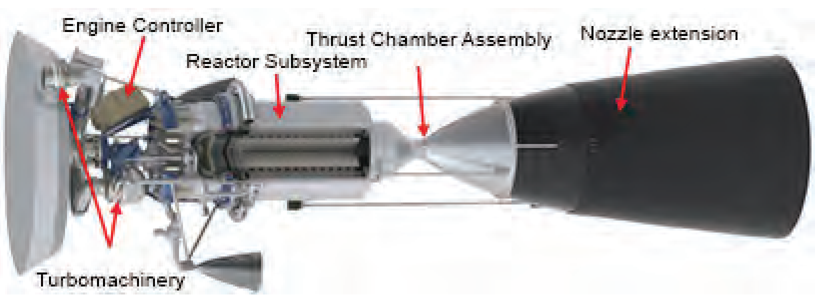


Illustration of a conceptual fission surface power system on the Moon. Credit: NASA

In addition to their ubiquitous use as a terrestrial power source, fission reactors have spaceflight heritage dating back to NASA's System for Nuclear Auxiliary Power (SNAP) program, including the launch of SNAP-10A in April 1965. While this first fission reactor in space was quite large and produced only 500We, its modern counterparts are smaller and more powerful. One such example is NASA's Kilopower Reactor Using Stirling Technology (KRUSTY) experiment in March 2018, which demonstrated in a laboratory setting the ability to produce approximately one kWe. A further demonstration of FSP is expected to take place on the lunar surface in the late 2020s to produce 10 kWe for 10 years.[2] Beyond a demonstration phase, the threshold for paradigm-changing ISRU for applications, such as propellant manufacturing, will likely be measured in hundreds of kWe to several megawatts electric (MWe).

Nuclear thermal propulsion (NTP) systems operate by leveraging the heat energy generated by the fission of uranium atoms to significantly expand a supercooled and condensed liquid propellant, often hydrogen. This extreme pressure is vectored through a nozzle to produce thrust. In space, by virtue of having greater power density for the same mass of fuel, NTP systems are significantly more efficient than chemical rockets and need to carry less propellant for their journey. Because of this, NTP systems have been proposed as a means to reduce the duration of travel in deep space, which can lower a crew's exposure to galactic cosmic radiation (GCR) and allow greater flexibility in mission architectures. In Earth orbits and cislunar space, anticipated civil and national security NTP applications include enabling extended stationkeeping at Lagrange points or maneuvers such as rapid orbital transfers long after their launch.



Digital model of a nuclear thermal propulsion engine assembly. Credit: NASA

The usefulness of NTP has been studied by NASA and the Atomic Energy Commission (now the Department of Energy) since the 1960s through the Nuclear Engine for Rocket Vehicle Application (NERVA) program, which resulted in the development and ground testing of multiple vehicles before being canceled in 1973. While NASA and the Department of Energy have continued to mature the technologies necessary for a flight demonstration for civil applications, the Defense Advanced Research Projects Agency (DARPA) Demonstration Rocket for Agile Cislunar Operations (DRACO) program is also intended to demonstrate an NTP system beyond low Earth orbit by 2025.

Nuclear electric propulsion (NEP) systems harness electrical energy converted from a fission reactor's thermal energy to power a means of electric propulsion, such as ion thrusters. Despite the relatively low thrust produced by electric propulsion, its high efficiency, especially when powered by NEP, can be leveraged to significantly outpace chemical propellants over long distances. NEP is also touted as useful for deep space applications, such as robotic missions to outer planets and interstellar space where the distance from the sun limits the performance of solar arrays, and travel time is not as much as of a constraint as with crewed travel. Similar to FSP, NEP relies on the converted electrical energy of a fission reaction and, therefore, can also count the SNAP program in its heritage.

Commercialization and the Role of the Public Sector

National governments and space agencies play an especially important role in maturing commercial applications and business cases. Like many other boundary cases on the technological frontier, there is yet not a commercial market for space nuclear power and propulsion that doesn't include the public sector as a primary customer. By acting as an anchor tenant, governments can reduce private sector barriers to entry, such as high costs, low demand, low technology readiness, and small addressable market size. The United States, for example, has shifted toward a model of utilizing many commercial space products and services as a default rather than an afterthought.

A recent example is NASA's use of contracts with private companies to develop commercial crew and cargo capabilities. These arrangements often include providing milestone-based payments, utilizing the flexibility of unique contracting mechanisms, and offering non-financial assistance, such as access to facilities and subject matter experts. This type of public-private partnership has proven mutually beneficial to both the government customers and their suppliers. A similar model could be applied to nuclear power in space, especially if governments are willing to support the maturation of terrestrial small modular reactor ecosystems. A viable space economy will require infrastructure, such as a means to create, store, and manage cryogenics necessary for nuclear propulsion, as well as power generation, storage, and transmission for fission surface power. A mature commercial market for those products and services, however, might be decades away, so public sector support will be integral.

In addition to setting precedent and demonstrating leadership, national policy can be used to clarify priorities, reach decision points, send encouraging signals to industry, and offer a means to end the analysis paralysis that often plagues major programs. Policy has also proven to be a major factor in the development of the commercial space sector. For example, the U.S. space enterprise is currently benefiting from a greater degree of alignment of priorities between the executive and legislative branches and an unprecedented degree of continuity in space policy between presidential administrations than in years past. Positive outcomes of the bipartisan and long-term political support for space have begun to manifest in private sector.

Private sector innovation will be crucial in accelerating the maturation of SNPP. At the moment, however, there are but a few stand-alone space nuclear companies, and they are still in very early stages. However, there are terrestrial nuclear companies that now count space as a line of business, such as BWX Technologies, X-Energy, and Ultrasafe Nuclear Technologies, as well as space companies that have begun to foray into space nuclear applications, such as Blue Origin, Lockheed Martin, General Atomics, and Aerojet Rocketdyne.

While it's premature to identify investment trends specific to SNPP, some interest does exist, though a purely commercial market for applications of space nuclear power may be at least a decade away. In addition to an increased government commitment to space exploration, another major factor that may influence private investment in SNPP is the growth of a space economy for products of materials processed in space using energy from FSP, such as energy, water, and propellant.

Internationally, only a few nations have initiated and made significant progress in their space nuclear programs. This is, in part, a function of the size of the cross-section of two already small subsets — nations with domestic nuclear capabilities and nations with a domestic space sector or the ability to substantively partner with others to meet the same ends. Most nations with interplanetary or lunar robotic missions have already or are currently utilized RPS, including the United States, Russia, and China. In terms of space nuclear reactors, the United States and Russia remain the only nations to have launched and operated fission reactors in space. In the coming decades, the United States, Russia, and China have each expressed interest in deploying space nuclear reactors.

To ensure the responsible use of nuclear material in space for all humankind, the United Nations Office for Outer Space Affairs (UNOOSA) Committee on the Peaceful Uses of Outer Space (COPUOS) and its member states have developed a series of principles and a safety framework related to nuclear power sources, among other efforts.[3]

Technology Gaps

Progress on SNPP had been incremental for several decades before a significant acceleration in recent years. However, each application still faces a series of barriers hampering its development, deployment, and widespread adoption.[4] For all space applications, including SNPP, remotely operating crewed and robotic spacecraft in such an austere, distant, and unforgiving environment presents unique challenges. For space nuclear reactors, reliable instrumentation and control systems for modulating reactivity in space will be essential.

To increase the technology readiness of NTP, more work is needed to mature and demonstrate high-temperature materials, such as ceramics and graphites, that are capable of handling superheated gases at several thousand degrees Celsius upon reactor activation. Similarly, advancements in long-duration cryogenic propellant storage at several hundred degrees below zero Celsius are needed to further limit propellant boil-off. An additional technology gap for NTP is the ability to conduct ground demonstrations in a safe, environmentally responsible, and cost-effective manner. While lower enrichment levels are expected to make ground testing more feasible, estimates of the cost and complexity associated with capturing engine exhaust are still substantial. These reactors influenced the DRACO program to opt for low-enriched uranium as fuel, and an on-orbit demonstration rather than integrated ground testing with a live reactor.

The inefficiency of converting a reactor's heat into electricity is a major factor for FSP and NEP. A massive amount of energy, on the order of 90% of the heat generated, is lost in the conversion process and this waste heat must be dissipated. Radiating heat, an ever-present challenge in the vacuum of space, becomes even more difficult at scale. Establishing infrastructure to facilitate the storage, management, and distribution of power produced in space is also an immense challenge that must be overcome in order for more energy-intensive activities to be feasible.

Challenges in Supply Chains, Cost, Production, and Scaling

At present, supply chains for small reactor components, such as those used in many space and terrestrial applications, are still nascent. Low production rates require many components to be custom-built at great expense. For space nuclear applications to be more feasible, production must be scaled up to reach a commercial off-the-shelf level of availability and cost. Due to a significant overlap of components, materials, and workforce, space and terrestrial nuclear applications benefit from the same economies of scale and are impacted by competition with other terrestrial energy sources. Simply put, the increased adoption of nuclear power on Earth lends direct benefits to nuclear applications in space. And therein lies a problem: despite its outsized role in slowing global climate change, nuclear power is at a disadvantage due to higher subsidies offered for renewable energy sources, namely solar and wind.

Project Pele, a program managed by the Department of Defense Strategic Capabilities Office, is developing a demonstration of a micro modular reactor, capable of a single-digit MWe output for several years, to bolster the concept's viability. While its primary purpose is to offer energy resilience for national security by enabling more energy independence for remote and forward operating bases and other mission-critical assets, the follow-on benefits for space applications cannot be overstated. Particularly, the widespread adoption of small modular reactors as a viable energy source trusted by the national security community around the globe would provide ample justification for the development of a commercial marketplace.

There is also a well-founded concern for the limited domestic production capacity of nuclear material, a highly complex, time-consuming, and costly process. High-assay low-enriched uranium (HALEU) with a concentration of around 20% uranium-235 is the preferred material for SNPP applications. It can be produced in one of two ways: It can be "downblended" from highly enriched weapons-grade uranium (~90% enriched), or it can be enriched from a lower concentration. The problem, unfortunately, is also twofold: the U.S. stockpile of highly enriched uranium is limited and not actively replenished, with primacy given to higher-priority uses such as submarines and aircraft carriers, and U.S. policy prevents production capacity above 5% enrichment.

Domestic production capacity is further limited by several factors, not the least of which are the lack of strong domestic demand and an increased reliance on foreign production for the vast majority of uranium.[5] As a result, there is very little uranium enrichment in the United States. Even the primary enrichment facility in the United States, the National Enrichment Facility, is operated by a U.S. subsidiary of Urenco, a company jointly owned by two German energy companies, and the Governments of the United Kingdom and the Netherlands. Recently, however, bipartisan support has been found for funding the establishment of a national uranium reserve, which may foster renewed mining and conversion capabilities. Plutonium, namely the Plutonium-238 isotope used in RHUs and RTGs for space exploration, has faced similar domestic production and reserve concerns,[6] though there are few technological barriers otherwise.

Subsidies to ramp up production and increase the size of, and access to, the nuclear stockpile for the use of space applications likely create a demand signal for the industry and is important for national resilience. Returning to a level of unencumbered production capacity would need to include greater access to nuclear-grade components as well as input material for fuel, both of which are relatively sparse. Similarly, long-term public sector commitments to mission architectures that will rely on reactors, such as a sustained human lunar surface presence, crewed missions to Mars, or long-duration cislunar tugs, would be a massive driver.

Public Perception, Policy, and Geopolitical Considerations

To some, the idea of nuclear materials and rocketry conjures doomsday scenarios. However, such an association is often the result of a lack of information, misinformation, or oversimplification of the prerequisites for safe operation. Radiation is ever-present in our daily lives in a variety of natural sources and, in safe amounts and under proper safeguards, it poses no significant hazard. Like their terrestrial counterparts, space nuclear reactors are built with safety in mind and, in addition, aren't powered on until they are in space.

The general public and policymakers have been comfortable with the material used for decades in RTGs and RHUs for rovers on Mars. In comparison, HALEU is far more benign, enough so that it can be safely handled with minimal protective equipment and does not present the same security challenges. Public perception is tied to policy and effective communication, and both will be a persistent challenge for government agencies and industry, so the translation of technical concepts to layperson's terms is crucial.

The distinction between HEU vs HALEU is an important one. While lower enrichment levels make reactors less efficient and larger, they benefit from a simpler approval process and, thus, are more tenable for use in civilian space applications.[7] The energy density of HEU simplifies some design challenges and allows for more compact and powerful systems, but models indicate that HALEU can be operated with only a minor mass penalty.

Space nuclear applications are not immune to global security and geopolitical concerns, for which HEU is of greater concern than HALEU. Keeping these materials and technologies out of the hands of malicious actors is not an easy task. It's also in a nation's interest to be in the market of selling reactors, including safety and standards. However, there are no major legal constraints, as much as there are nonproliferation concerns. Therefore, although HEU is not considered a weapon of mass destruction, its use for civilian applications is being phased out over concerns that widespread global adoption could ease access for those seeking to weaponize it.

Concluding Thoughts

Many SNPP applications are plagued by a "chicken and egg" problem: They're hard to do because they haven't been done before, and they haven't been done before because they're hard to do. Solutions to many of the challenges mentioned lie in increased funding and more deliberate focus. Specifically, the industry would substantially benefit from sustained, predictable, and dependable demand signals from governments. The terrestrial nuclear ecosystem is also inherently tied to the space sector. Increasing subsidies for the development and deployment of terrestrial nuclear power systems, perhaps on the order of those afforded to solar and wind, would have tangible impacts on the space sector as well.

Space-based demonstrations for nuclear thermal propulsion and fission surface power will be the next decade's most galvanizing milestones. In addition to being a remarkable technology demonstration, programs such as DRACO will also function as policy and political pathfinders to prove their safety and feasibility. When formulating long-term civil and national security space efforts, capabilities are selected from a menu of currently available options. Flight demonstrations of SNPP are crucial to reaching a level of technical, programmatic, and political maturity where they can be baselined more often and stoke demand signals.

Space nuclear power and propulsion are among a growing number of capabilities through which nations' strategic goals can be met, and their effective acquisition, development, and fielding are essential for a sustainable presence in space.

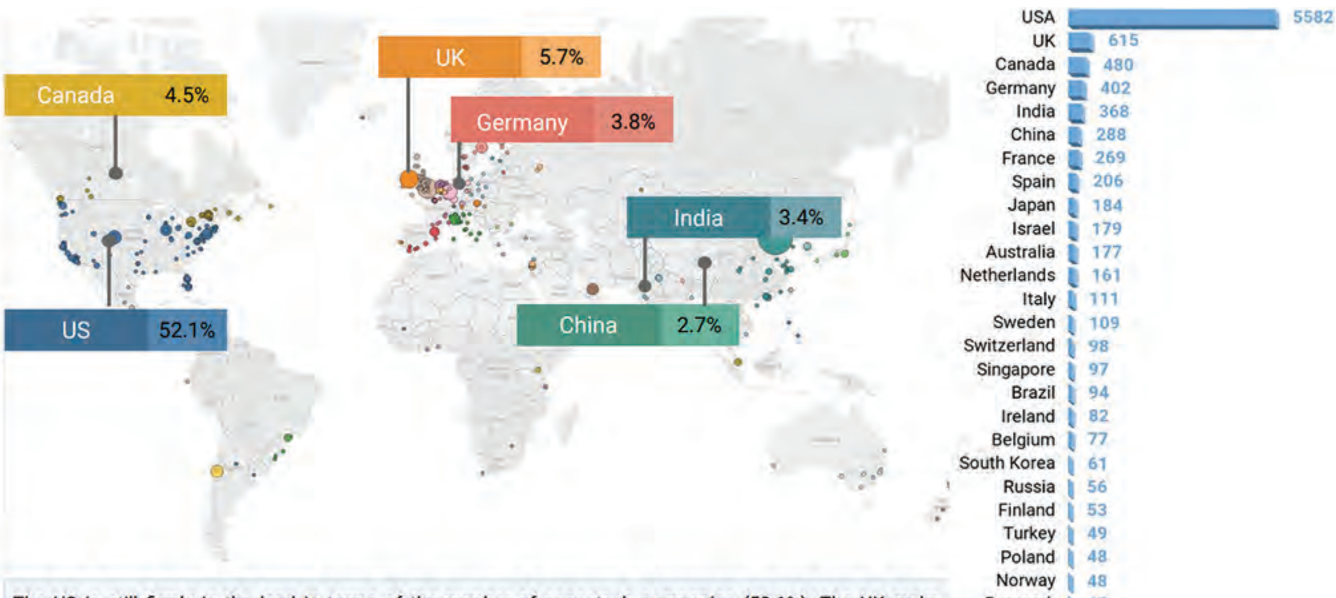
Chris Beauregard is the founder and principal of Aerospace Advocates, a space policy and strategy consultancy based in Washington, D.C. He previously served as policy analyst, policy advisor, and director of commercial space policy at the White House National Space Council. In these roles, Chris supported the development and implementation of U.S. civil, commercial, national security, and international space policy priorities, particularly the removal of undue barriers to U.S. global leadership in space commercialization.

Introduction | *By 2024, NASA intends to land astronauts including the first female on the Moon. The Artemis program is an exciting opportunity for the space industry and all humankind to settle in deep space within the next decades. Even more exciting, the United States is not the only nation venturing into this expanding frontier. 13 other countries have plans for missions to Earth's natural satellite. An international organization is working on recommendations to the United Nations to develop cislunar policies.*

This artist's impression shows a multi-dome lunar base, based on the 3D printing concept. As nations develop plans to explore and eventually inhabit the Moon, there are increasing calls for international policies to determine government regulation and commercial rights. *Credit: ESA illustration*

Getting Along on a Busy Moon

The current $447 billion global space economy[1] is expanding fast. In 2019, before COVID, projections of the UBS Swiss Investment Bank saw it doubling by the end of the decade. Morgan Stanley anticipates that by 2040, the industry will grow beyond US$1 trillion.[2] That growth is pushing developments beyond Earth, making the Moon a very attractive destination for visionary businesses. As shown below, the number of companies sharing that budget and receiving public investment is also increasing exponentially. In the United States alone such enterprises already represent more than 50% of the industry internationally measured by number of companies.



The US is still firmly in the lead in terms of the number of spacetech companies (52.1%). The UK ranks second (5.7%), while Canada, Germany, India and China are in the third place (with 4.5%, 3.8%, 3.4% and 2.7% respectively).

Source: Space Tech Analytics

This increasing number of national projects and private business plans are tracing out a vision of intense human and robotic activities on the Moon for the near future. That interest is not trivial. To leverage the potential of a profitable lunar economy sustainably, the Moon Village Association has proposed and hosted a forum for all major lunar stakeholders to interact, think out loud, and discuss what procedures and working methods may be required to permit maintaining smooth operations for all on and around the Moon. With 36 members and almost 140 observers, the Global Expert Group on Sustainable Lunar Activities (GEGSLA) was launched in February 2021 to serve as a platform of information exchange. The group will operate for two years until it makes its final recommendations to the United Nations Committee on the Peaceful Uses of Outer Space (COPUOS).

Since 1968, when the Outer Space Treaty (OST) went into effect, there has been no recognized sovereign authority over territory in outer space. As a result, no sovereign state can grant territorial title nor decree legislation that applies to everyone inside a defined set of physical boundaries. Although this probably has prevented a mad scramble to claim pieces of celestial territory by the most powerful of Earth's countries, it also leaves a lot of unanswered questions about how people representing different nationalities, cultures, and institutions are going to interact productively as they pursue scientific and profitable activities on the Moon.

Addressing these unanswered questions is the goal of numerous conversations focused on a word that can bring shivers to the spines of some of those pursuing either private business plans or focused national interests: governance. Although used quite frequently in analyzing decision-making processes and operating procedures in both for-profit corporations and not-for-profit institutions, "governance" often awakens fears of "global government" or excessive regulation. For GEGSLA, the term addresses the processes and methods of engagement that show promise for minimizing conflict and mutual interference among those pursuing activities on the Moon. It is in this context that GEGSLA brings equilibrium among governments, established corporations, and entrepreneurs alike seeking some promise of orderly interactions and predictability on the Moon.

Why GEGSLA?

Forums such as GEGSLA provide immensurable sources of information on how multiple stakeholders plan to operate in space. They create a strong sense of community by identifying not only the basis for soft and hard regulatory regimes on technology and policy, but also on several other key issues that will play a role in human interaction in lunar activities. Many stakeholders, for example, have the potential of creating a large number of problems: Space debris on the Moon, and unintentional interference to interoperability are just a few. Therefore, such forums are essential for mitigation and providing a glimpse on how exploration and fair use of the natural resources available in situ on celestial bodies can be monitored and regulated. Although regulation raises concerns among many potential operators of business activities involving the Moon, the lack of regulation keeping erstwhile competitors from doing whatever they want whenever the want is also grounds for substantial worry.

Because everyone working on the Moon would continue to be subject to the laws of their home country, projects involving people from several different nations will need to reconcile potential difference in the legal obligations faced by team members. If it were to occur on the International Space Station (ISS) this kind of issue might be resolved by the Intergovernmental Committee, but no such group exists to address the potentially far more complicated issues presented by the highly varied activities envisioned for the lunar surface and cislunar space.

In this contest, GEGSLA has begun pursing the objective of outlining guidelines for interaction on the Moon that can reduce the number of conflicts and identify agreed-upon procedures for resolving those that do occur. With no delusion of being the decision-making body on such guidelines, GEGSLA seeks to assemble a well-reasoned collection of principles and practices that can be turned over to COPUOS in time for it to begin consideration of them during its 2023 session. With 93 members, COPUOS represents a broadly diverse group of countries with interests in space ranging from ground station operations to interplanetary missions.

As a private initiative with public participation, GEGSLA is following a political trajectory that has proven effective in several previous processes leading to the adoption of space policy principles with broad international support. Some examples may help establish this point: Current guidelines for planetary protection were developed by the Committee on Space Research (COSPAR), which continues to update them. These guidelines have been endorsed by the United Nations General Assembly and are widely followed. Second, space debris guidelines developed by the Interagency Space Debris Coordination Committee were submitted to COPUOS and greatly influenced the text of the guidelines endorsed by the U.N. in 2007. Third, in 2005, a completely private initiative of the Association of Space Explorers gathered a Panel on Asteroid Threat Mitigation that worked for four years to prepare recommendation for addressing threats to Earth posed by Near Earth Objects. Their report was delivered to COPUOS in 2009 and contributed substantially to the General Assembly's endorsement of two new institutions — the International Asteroid Warning Network and the Space Mission Planning Advisory Group. Both have provided the mechanism for coordinating evaluation and contingency planning for addressing asteroid impact threats. Most recently, the Hague International Space Resources Governance Working Group (SRGWG) concluded its work in 2019 and forwarded a set of recommended policy building blocks and a detailed legal commentary on the group's rationale to COPUOS. Both documents are being reviewed as part of informal consultations on space resources within COPUOS's Legal Subcommittee.

Because these expert group processes get attention and political traction, they are an important part of policy making at the international level. Whether it be for adapting business plans to advocating for one's government to take a particular position for or against, being aware of the existence, progress, and eventual recommendations of expert groups is an essential component of addressing the evolving international policy environment in which space commerce will operate in the decades to come.

GEGSLA: The Beginnings

GEGSLA began as an initiative of the Moon Village Association (MVA), a not-for-profit organization established in Austria with an international membership. Although a completely independent organization, MVA was inspired by the idea of Jan Wörner, the former director general of the European Space Agency who used the Moon Village image to emphasize the need for community, productive interaction, and mutual support as a foundation for successful operations on the Moon. After conversations with the U.N. Office of Outer Space Affairs to confirm that expert group input on unresolved questions of international relationships on the Moon would be welcomed, MVA put out an open call for volunteers to serve on GEGSLA.

The call specified that volunteers should express their preference for being members of the group or observers. Members have priority when speaking in GEGSLA sessions with the ultimate responsibility for deciding what recommendations and suggestions will be included in documents to be forwarded to COPUOS. Observers are allowed to view all online meetings of the expert group, comment real time through the chat function, speak with permission of the chairman, and volunteer for service on such working groups as might be established for advancing GEGSLA's progress between regular monthly sessions. As GEGSLA voting procedure is done by consensus, the number of members has been limited to 36 with the goal of facilitating eventual decision-making. No limit has been placed on the number of observers. All countries that volunteered to participate were guaranteed a membership seat at the table unless they expressed a preference for observer status. By the time the two-month period of open call ended in January 2021, 174 people had expressed interest in membership or observer status.

The task of selecting 36 members from this list was assigned to a five-member international evaluation committee. This committee began meeting in January and settled on its final list in February. In the course of its work, members sought a diverse group of selectees not only in terms of gender and geographic connections, but also in terms of professional perspective. Following the approach used by the SRGWG, the committee specifically sought to include members with roots in the commercial sector. To that sector, they added several other categories: government/space agencies, academia, and civil society. Ultimately, the selection included 35 people representing 13 governments, nine commercial endeavors, 10 academics, and three from civil society. In all, 22 countries from six continents were included in the selection. Two important international organizations, UNOOSA and the ITU (International Telecommunication Union) have chosen to participate as observers. Leadership of the expert group was elected during GEGSLA's first meetings, with former Romanian astronaut and UNCOPUOS chairman Dumitru-Dorin Prunariu as presiding officer and Alice Gorman of Australia, Raji Rajigopalan from India, and Kyle Acierno of Canada as deputies.

First Deliverables

On April 19th, 2021, the MVA, as an observer member of the COPUOS, presented its first report on GEGSLA titled "Report of the Moon Village Association on the Global Expert Group on Sustainable Lunar Activities" to the COPUOS Scientific and Technical Subcommittee. The report states that the two most important deliverables of GEGSLA will be a main document titled "Recommended Framework and Key Elements for Peaceful and Sustainable Lunar Activities," and second "Guidelines for Lunar Activity Implementation and Operations" addressing issues such as lunar debris mitigation, benefits sharing, sharing of information, registration of activities, and regulating access to natural resources.

In the main proposal of the report, the MVA also asks for the support of all members of the committee in adopting a new permanent agenda item on the topic of sustainable lunar activities. The adoption will ensure continuity of the efforts. The participation of all COPUOS members will leverage the solid response humanity needs to address the issue of sustainability on the Moon.

The plan is to provide a preliminary draft of both deliverables by early 2022 and the final document by the end of that same year, which is when GEGSLA will complete its activities. The two texts intend to bring forth to the United Nations the needs of the space community and propose solutions for considerations. They are very promising contributions, given the high level of expertise of the members. Hence there is much expectation that the proposals may be incorporated into future guidelines of the committee through the permanent agenda item and a dedicated working group. It is no exaggeration to say that GEGSLA will play a fundamental role in humanity's quest to extend intelligent life beyond Earth, starting on the Moon.

Besides informing COPUOS about the creation of GEGSLA, the report also mentions the early efforts of the MVA for Moon governance, such as the first edition of its Best Practices for Sustainable Lunar Activities, released in March 2020.[3] The edition contains 13 recommendations that reiterate the peaceful utilization of celestial bodies, which is a stated objective in U.N. space treaties, and makes substantive remarks regarding avoiding interference. An example of MVA's perspective is reflected in its recommendation No. 5, Avoiding Harm:

"Space actors are encouraged to take measures to the extent possible:

- To avoid causing adverse changes to the lunar environment or cislunar space, including the harmful contamination of the Moon in contravention of planetary protection policies;
- To mitigate the creation of lunar orbital debris;
- To avoid causing harmful interference with existing or planned lunar activities; and
- To avoid causing adverse changes to internationally endorsed sites of significant scientific or historical interest."[4]

Avoiding harmful interference with existing or planned lunar activities, whether intentional or unintentional, will be crucial for maintaining peace and productive activity beyond Earth. Protecting internationally endorsed sites will assure that areas of scientific and historical interest are distinguished from those for commercial exploration and exploitation. Lunar actors will need to pay careful attention to the four points above to assure a long-lasting, sustainable use of lunar resources and to promote fair competition. Inattention to avoiding harm could lead to major incidents on the lunar surface and might compromise entire space missions and deep space exploration as a whole in the long-term.

While avoiding harm is the core issue being addressed in the MVA document on sustainable lunar activities, Recommendation 8 on space resources and Recommendation 10 on sharing information are also worth attention as they facilitate the understanding of how new ventures on the Moon can be carried out while respecting individual and national rights. The document states that utilization of space resources does not inherently mean appropriation, emphasizing how these activities are in accordance with current space legal frameworks. As such it is reasonably friendly to the foundation of space commerce. Moreover, the report highlights the importance of sharing information about such activities not only to avoid interference but for promoting international cooperation among various stakeholders.

The MVA recommendations for sustainable lunar activities can be downloaded from the association's website and can provide useful insight to the core perspectives behind MVA's interest in launching GEGSLA.

GEGSLA: Work Structure

The MVA's and GEGSLA's first efforts speak much about the way forward with the goals ahead for the next two years. The draft of GEGSLA main document "Recommended Framework and Key Elements for Peaceful and Sustainable Lunar Activities" has three main phases, and members have been divided into four main subgroups. Meetings have occurred monthly and online since February this year.

In the ensuing 10 months, they will work on a large number of pressing topics that ultimately comprise the two most concerning issues already mentioned: avoiding harm and sharing information.

Subgroup 1 – Information Sharing. Within this first subgroup, four topics of discussion have been proposed: Monitoring activities on the Moon to avoid dispute and conflicts of operations; information exchange of activities to promote coordination; the development of a registry of lunar assets, activities, frequencies, etc. (reflecting the Registration Convention of 1976 and Article 5 of the Moon Agreement of 1979); identifying common techniques, common landing zones and spaceport areas.

Subgroup 2 – Safe Operations and Lunar Environmental Protections. This subgroup contains 21 topics, which will subsequently be reduced. Some propose fundamental definitions for "harmful contamination" and "lunar heritage," allowing the further development of codes of conducts. Other topics concern biological waste, pollution, and debris mitigation. Proposal 21 finalizes by fundamentally asking: "decide who will decide which satellites will operate on the Moon (and occupy certain orbits)?"

Subgroup 3 – Compatibility and Interoperability. With eight topics, it is the most technical of all subgroups. It is about developing interoperability standards for mechanical and electric interfaces, shared common stations, and resilience guidelines for the far deep world of cybersecurity. Moreover, it proposes a topic to support the work of the ITU to identify the volume of frequencies on the Moon, signaling this way a possible contribution of the entity on answering proposal No. 21 above.

Subgroup 4 – Responsible Governance. Its nine topics gather regulation proposals for businesses, investments, the public and private sector, the commoditization of space, and the concept of "Moon Commons." It explores the subject of responsible governance and ethical principles based on corpus juris specialis for commerce on the Moon.

A lot is at stake in each single topic, especially with respect to sovereignty. Sharing data of commercial activities may give away information that is often protected by national commercial law on Earth. Countries and companies are not obliged to cooperate on the Moon more than they do on Earth because such a set of binding laws simply does not exist.

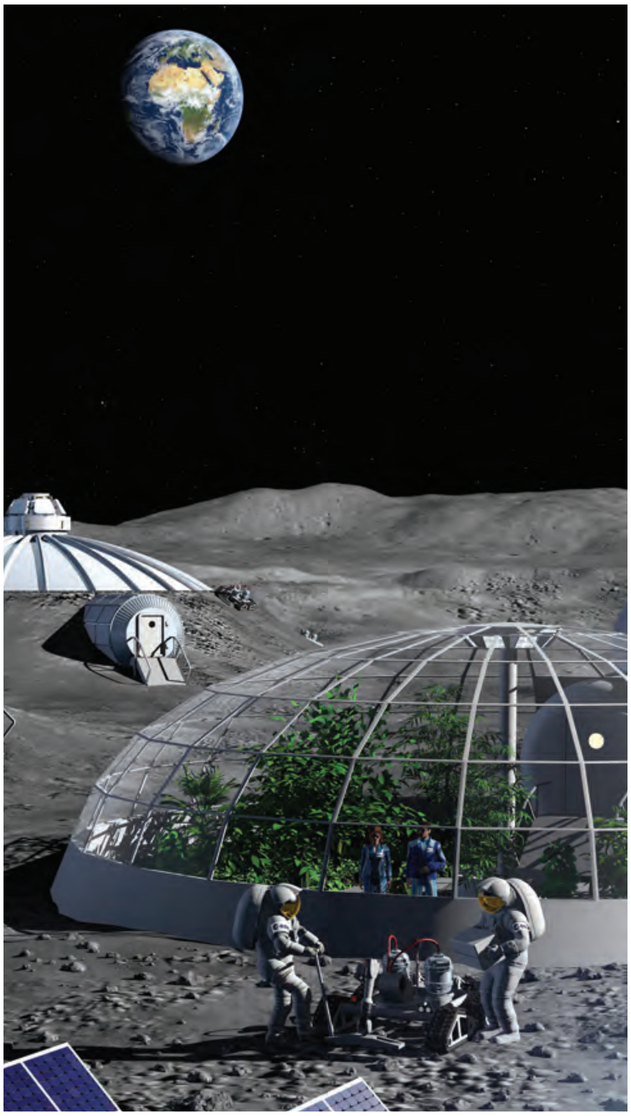
At first, it seems the group is trying to overaccomplish its call. However, the reality is otherwise. GEGSLA has no delusion of being the decision-making body on such guidelines nor does it desire to replace dedicated efforts at the COPUOS. It seeks to add to its contributions. Its means of work, findings, and limitations will be referenced for the development of governance for extraterrestrial commerce for the next decades.

The Moon Is Open For Business

Life on Earth is already very dependent on space applications, and that reality seems destined to increase in the future. Space-based solutions have been expanding across agriculture, transportation, communications, education, and many industries. Exploring and exploiting celestial bodies are part of the drive that will help agencies, companies, and all space actors solve Earth problems. It is with that mindset that Lockheed Martin, Off World, the Luxembourg Space Agency, and the Institute of Space Commerce have sponsored GEGSLA, while representatives of dozens of space agencies, universities, and thinktanks have also committed to the expert group's work.

One company in particular, ispace, has turned its business model toward the Moon, taking a major lead at GEGSLA with its U.S. CEO Kyle Ancierno serving as one of three deputy chairpersons. ispace has been on the top of the Google Lunar XPRIZE competition, raising US$120 million.[5] The company is working to become the first private lunar exploration program with two space missions on its schedule. The missions of ispace to land a rover on the Moon and send high-definition images back to Earth are part of the building blocks of the commercial efforts to spin off developments and provide new products, services, and solutions for society.

With eyes on the future of space commerce on the Moon and beyond, the Institute of Space Commerce (ISC), a North American thinktank affiliated with the International Space University (ISU), and a partner of the International Institute of Space Commerce in Europe, has collaborated with GEGSLA to make space business open for youth. It is the goal of the ISC to



With the anticipated increase in lunar exploration and habitation, there are increasing calls for international law regarding usage rights.
Credit: ESA illustration

make the complex world of space more accessible and manageable to those who will in the next decades take the lead of what has been started. The ISC's goal is another true example of how high-technology is driving education, commerce, and leadership back on Earth, changing lives of youth.

Therefore, even after the work of GEGSLA, the Moon shall remain open for business. The legacy of bringing predictability and governance will continue through the MVA, its sponsors, partners, and participants.

Opportunities for Input

Expert groups are inevitably comprised of a small fraction of those with expertise or interest in the topic under discussion. For those not at the table, this can be frustrating. Fortunately there are ways to be involved with GEGSLA and the issues about which it seeks to make recommendations that don't require a seat at the table.

First, there is the opportunity to become an observer. The number of observers is not limited and participation in this capacity provides immediate insight into the direction that discussions are going and provides an avenue for feedback in near real time. Although observers can be allowed time to speak during meetings, their large number makes that unlikely. Written feedback through Zoom chat or Slack is thoroughly reviewed by the GEGSLA secretariat and its content briefed to the members. Second, with a geographically diverse membership, many people will find one or more GEGSLA members with whom they already have professional relationships. Direct communication with such contacts can ensure ideas and perspectives are not overlooked.

Finally, never lose sight of the fact that any policy decisions emerging from GEGSLA's work will require agreement among governments. That agreement could emerge through the United Nations system or it might take the form of agreements negotiated outside of it. Although broadly supported agreements would provide the most certainty and predictability for business planners and investors, the art of the possible in setting the stage for sustainable lunar activities is not yet clearly understood. This means that traditional paths of advocacy through one's own government will be important once GEGSLA's work is delivered as a final report in 2023.

Conclusion

The next decades can be very promising for space exploration and development if current efforts can find the balance between agreed productive practices and excessive limits. Although much attention will focus on interactions among commercial activities for which there is very little precedent, the deliberations will be extremely important for government-sponsored missions as well.

The recent history of space policy development demonstrates that remaining attentive to the progress of expert groups such as GEGSLA is justified by the impact they have demonstrated, especially in the international arena. This attention is also usefully applied to sponsoring groups such as the Moon Village Association, as in GEGSLA's case, because they often shape substantially the direction of the discussion, especially in its early stages. In the case of GEGSLA, MVA's greatest early impact may be in its commitment to create a group that is diverse in terms of gender, perspective, and geography.

The fact that GEGSLA's deliberations occur in a fishbowl where observers can see ideas emerge — whether worthy of applause or criticism — provides an opportunity to see ideas emerge before they are fully vetted and long before they are solidified into rules or expectations. This provides many opportunities to support or oppose the adoption of recommendations as agreed policy.

For the space commerce community GEGSLA has already proven fundamental for the future of ventures on the Moon. The group is a pioneer of its kind for governance of commercial exploration and exploitation on Earth's natural satellite. Simply by insisting that commercial representatives be present at the table, the group has moved away from the practice of earlier groups that relegated business to its own fora or to groups where international representation of governments was absent to restricted.

As with other similar working groups with high-level experts, there is great anticipation and expectation for the outcome of its main document. Unlike the case with some expert groups, GEGSLA seems to present less cause for anxiety to those who pay attention to its progress.

Michael K. Simpson is managing director of the International Institute of Space Commerce and executive director emeritus of Secure World Foundation. He served on the advisory committee that selected the members of GEGSLA.

Elias de Andrade is deputy director at the Institute of Space Commerce. He is an official observer of GEGSLA.

END NOTES

Section 1 | The Space Economy

Despite Pandemic, Double-digit Growth in 2020 in Some Commercial Sectors

1 These figures are based on data from a variety of sources, including expert analysis and estimates. Past year totals are updated if better data or updated methodologies are developed. The 2019 figure was revised downward from the total of $336.88 billion originally reported in The Space Report 2020.

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Nuclear Power and Propulsion: A Keystone for the Security, Exploration, and Development of Space

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LIST OF EXHIBITS

SPACE FOUNDATION

Thomas Dorame
Senior Vice President,
Space Foundation

RESEARCH & ANALYSIS

Lesley Conn
Senior Manager

Becki Yukman
Senior Data Analyst

CONTRIBUTORS

Dr. Mariel Borowitz
Assistant Professor
Sam Nunn School of
International Affairs,
Georgia Institute of Technology

Shawn Huff
Wendy Perelstein
Web Support

Elias de Andrade
Chris Beauregard
Ian Christensen
John Holst
Michael K. Simpson
Contributing Writers

Dennis Thompkins
Researcher

Steve Edelman
Editor

Design Development Team
ROMIE LUCAS
graphic design & illustration

QUILTY analytics

Chris Quilty
Founder and Partner
Quilty Analytics

Caleb Henry
Senior Analyst Quilty
Analytics

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