McKinsey & Company

The role of space in driving sustainability, security, and development on Earth

Five actions that leaders can take to maximize the potential of the sector and its benefits for humanity.

2022

Contents

__This paper reflects a collaborative effort by McKinsey & Company and the World Economic Forum.__ The information included in this report is a synthesis of the opinions of leaders and experts surveyed in a joint research exercise. It is intended for research purposes only and will not contain, nor is it for the purpose of constituting or informing, policy judgments or advice.

Preface

The space sector is at an inflection point. Technological advances in software, miniaturization, off-the-shelf components, and reusable launch vehicles have combined to reduce the cost of reaching and operating in space. Accessibility has increased, exciting new capabilities have emerged, funders have stepped up, and new private and public players are joining the space sector. Today, the sector is poised to assume a more central role in supporting global security and sustainability, critical global priorities of our age.

Given the evolution of the space sector over the past few years and the increasing importance of space to our daily lives, this seemed like a good time to survey leaders across countries. Our aim is to gain an overview of the space sector today, the direction it is heading, and how stakeholders can influence the sector's future so that it can continue to have a positive impact on society.

One of the major takeaways from our discussions is the need for collaboration. International collaboration has continued for many years in space, with nations working together on ventures such as the International Space Station. The international community can build on this history and maintain space as an arena of coordination, but there is a need to act now.

We are in a critical window for ensuring space is a safe, sustainable, and accessible domain for all; without quick and decisive action, positive outcomes may not be realized. Space already plays a role in accelerating critical sustainability and security agendas. Our findings show it can play an even greater role in advancing these global priorities if the international community further adopts and accelerates the development of crucial space technologies.

We thank the many individuals and organizations from 25 countries who contributed their time and perspectives to this paper. We greatly value the perspectives of these diverse interviewees: approximately 100 top leaders from the private and public sectors, including many C-suite executives and national space agency directors, plus other luminaries from the worlds of government, academia, and the investor community.

As the space panorama evolves, we hope this initiative will foster continued collaboration and dialogue—among those already in the space ecosystem and leaders in other domains, who will no doubt be impacted by humanity's increased activity in space.

We believe these perspectives are just the beginning. We look forward to the journey ahead.

Jeremy Jurgens
World Economic Forum
Managing Director

Ryan Brukardt
McKinsey & Company
Senior Partner

Executive summary

Today, while the public may not fully realize it, the space ecosystem touches many aspects of daily life, abounds with commercial investment and increased commercial use cases, and plays a key role in advancing global sustainability and security priorities. It holds even greater potential for the future.

The sector is at an inflection point; leaders believe that existing frameworks are no longer sufficient to manage the full breadth of today's most pressing issues, including space debris and the commercialization of low-Earth orbit (LEO). Rapid technological progress is unlocking new capabilities, encouraging more commercial funding in space, and making space more accessible for nations and the private sector. These developments are shaking up long-standing operating models and driving a shift from monolithic to distributed architectures. They are also sparking more competition as space becomes crowded, and public and private players scramble to claim finite resources such as orbits and spectrum.

Our findings indicate that the space sector could primarily develop into one of four scenarios with different levels of commercial value generation and collaborative governance:

— **Accessible, self-sustaining space economy:** Global collaboration, widespread funding, and a healthy market landscape lead to unprecedented technological innovation. The space economy helps sustain itself and enhance life on Earth. Effective governance fosters the development of a safe and accessible space domain.

— **Domain of the Titans:** Space activity grows and attracts funding while governance remains rooted in dated, limited frameworks. Space becomes cluttered with debris and becomes a playground for developed nations and ultra-wealthy companies. The full potential benefits of space are not realized.

— **Unrealized potential:** Technical, economic, and regulatory challenges prevent the space economy from fulfilling its potential. Private funding dries up, and innovation grinds to a halt. Traditional applications of space-based communication, Earth observation, and research persist, but a robust space economy with self-sustaining use cases remains a distant vision.

— **National security arena:** A series of space disasters causes governments to reassert primary responsibility for space activity. They respond with regulations that dampen innovation and investor interest. Technological commercialization takes a back seat to national security interests.

Most leaders believe that the self-sustaining scenario would maximize the potential of space. To realize this scenario, they identified five critical actions, all of which would require collaboration among many stakeholders:

1. **Create and implement effective space governance:** Interviewees spoke about a framework for governing space activity being needed to maintain responsible behavior and preserve space as an arena for all. This governance would define and enforce ownership, access, and usage rights for space property while promulgating standards that protect infrastructure, human life, and the environment.
2. **Invest resources and effort in enabling technologies and capabilities:** These are seen as critical to the development of longer-horizon technologies and capabilities such as advanced power and propulsion that can contribute to a sustainable space sector. Many of these investments would likely require patient capital and government support in the early stages of innovation.
3. **Incentivize collaboration among nations, sectors, and industries:** Widespread collaboration is seen as vital to accelerate technological development, make space more inclusive, expand participation, and promote the peaceful use of space. Space has been and can continue to be an exemplar of international cooperation.
4. **Foster a self-sustaining industrial base:** Leaders were clear that government action and the rule of law are critical to helping companies transition from nascent to self-sustaining businesses and fostering the emergence of a private space industry in interested nations. They suggested that governments could encourage private industry maturation by signaling support for the development of commercial space technologies, purchasing services, removing barriers to competition, and educating decision-makers about the potential of space, among other actions.
5. **Leverage the space sector more to advance sustainability and security:** Space-based technology can play a central role in global sustainability and security agendas, provided that the international community adopts and accelerates relevant space technologies, such as Earth observation, carbon capture, and lightning mapping capabilities.

The success of each of these actions depends on global cooperation to develop an accessible, self-sustaining space economy. Success also depends on action at-pace: prioritizing space and furthering foundational governing principles for the sector, ideally in months, not years. By taking the right set of actions today, leaders believe the industry can chart a route for humanity to enjoy the myriad benefits of a peaceful, vibrant, and value-creating space sector.

Background on the development of insights

This paper draws on joint research conducted by McKinsey and the World Economic Forum, with guidance from an industry advisory board chaired by Chris Kemp, founder and CEO of Astra, and Rick Ambrose, former executive vice president of Lockheed Martin Space. It has been informed by interviews with nearly 100 leaders from the private and public sectors, non-profits, academia, and investors, as well as conversations facilitated among groups of industry leaders. Interview participants are listed in the appendix. The following statistics illustrate the breadth of perspectives incorporated:

— Nearly 100 leaders from 25 countries

— Heads of large and small national space agencies

— Leaders from ministries of defense

— More than 30 C-suite executives of new and established space companies

— Academics from 15 institutions

— Leading investors in the space industry

This paper synthesizes their responses and describes a set of options that could help develop a space ecosystem that can yield significant benefits on Earth and in space.

The space sector today

The 20th century space race between the USA and the USSR was primarily a military-technological competition. Each strove to be the first to launch satellites or land on the Moon, while the rest of the world looked on. In that era, technological development was driven primarily by national security interests.

That international competition led to the development of technologies with extensive commercial applications, particularly in satellite communications.[1] Today, space-based technologies play integral roles in our daily lives, for example:

— Satellites enable global positioning systems (GPS), making physical maps largely obsolete. GPS technologies guide everything from Uber trips to autonomous cars.

— Satellites facilitate nearly every financial transaction, from the swipe of a credit card to mobile banking applications.

— Satellites allow for more accurate weather predictions, letting anyone know when to expect rain and giving cities the information to pretreat roads ahead of a snowstorm.

— Satellite data is improving the transparency of actions taken by nation-states. Satellites can give timely visibility into how events are unfolding.

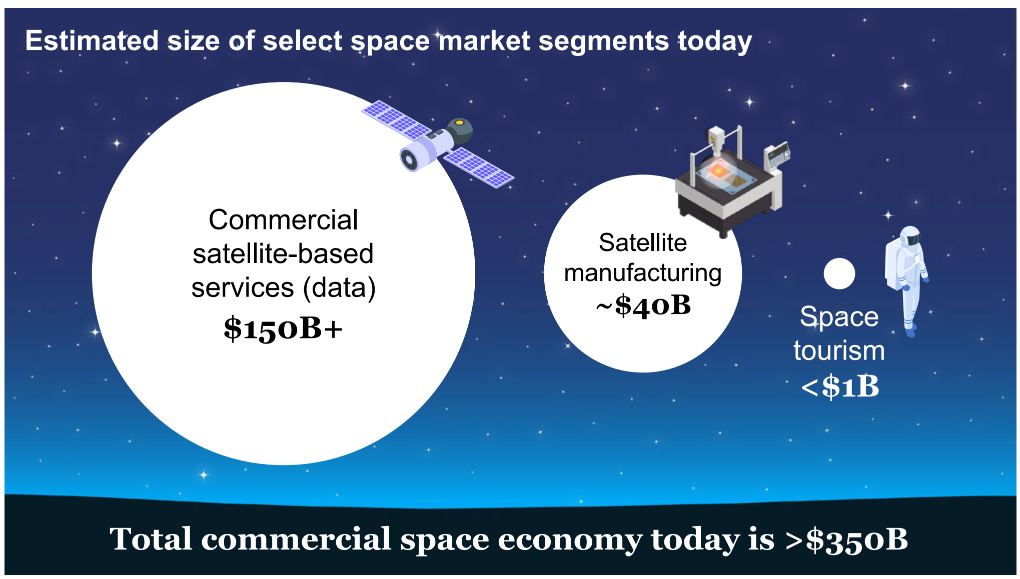
[1] Such technologies were developed and advanced in the late 1950s and 1960s during the Cold War, sparked by the USSR's launch of Sputnik 1 in 1957 (see: Labrador, Virgil. "Satellite communication." *Encyclopedia Britannica,* 17 July 2020. Accessed December 2021)

— The satellite communications industry is worth $65 billion and supports many aspects of daily life, from videoconferencing and agriculture to emissions tracking and the interconnectedness of the Internet of Things (IoT).[2]

We have seen other space applications emerge in recent years, especially as technological advances in software, miniaturization, off-the-shelf components, and reusable launch vehicles have combined to lower the costs of reaching space. While space is still a realm for national security and civil scientific experimentation, rapidly increasing investment from institutional investors, established companies, and ultra-high-net-worth individuals has expanded the range of use cases.

Today, satellite-based data represents more than 40 percent of the space economy *(see Exhibit 1)*.[3] This segment has grown by 15 percent compound annual growth rate (CAGR) over the last five years, driven by massive increases in performance-to-cost ratios linked to Moore's Law.[4] As chips and hard drives get better, satellites can pack more power into each rocket payload.

Exhibit 1: The majority of the space-based economy today is data-driven.



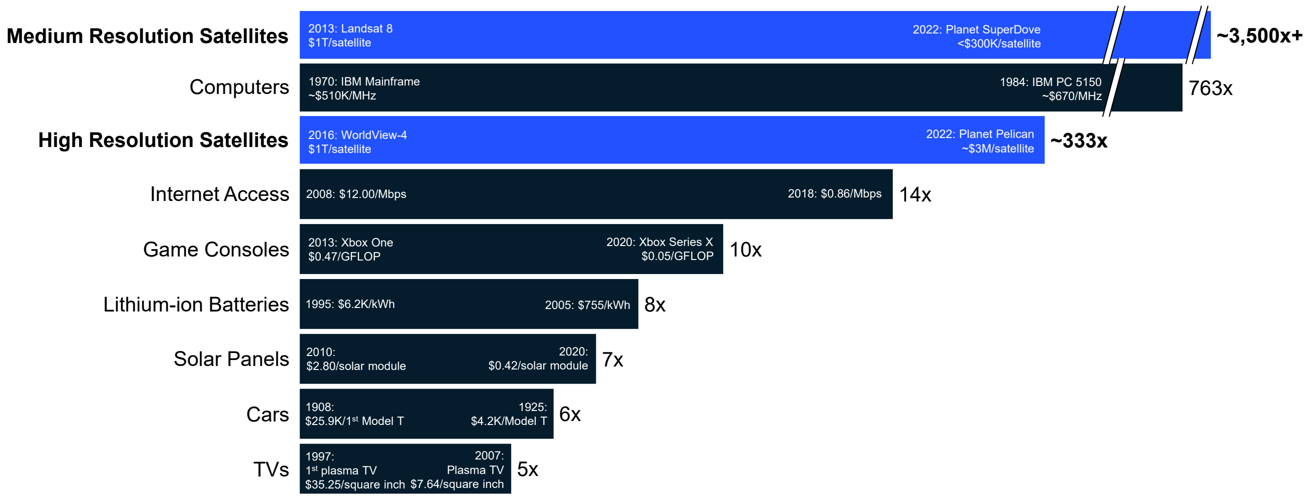
Source: Space Foundation; Northern Sky Research; public press; McKinsey analysis

[2] *Satellite communication market size worth $ 131.68 billion, globally, by 2028 at 9.10% CAGR,* Verified Market Research, October 2021
[3] *The space report,* Space Foundation, July 2021
[4] *The space report,* Space Foundation, July 2021

Over the past five to ten years, satellite cost performance has, in some instances, improved more than 1,000 times, and satellites produce and transport much more data than ever before. There are few parallels for a disruption of this magnitude, except perhaps the transition from mainframe to desktop computing in the 1970s and 1980s *(Exhibit 2)*.

Exhibit 2: Satellite cost performance improvements within a 15-year time horizon far surpass those seen in most other technologies.

Increases in cost performance over time[1,2]



1. Prices are converted to 2022 dollars
2. Comparisons reflect products with similar end-markets; however, they are not meant to construe perfect substitutes. Products may not be comparable on other factors (eg, satellites may not be comparable on data rates, signal to noise ratio, lifetime – however, increase is notable even on other measures such as dollar per bit)

Source: Public press; CPI Inflation Calculator; Center for Strategic and International Studies; National Renewable Energy Laboratory; NCTA; American Enterprise Institute; expert interviews; McKinsey analysis

This disruption is driving new use cases, capabilities, and users for satellite-based data. We anticipate continued growth of this data-based, space-for-Earth economy, but also the emergence of a space-for-space economy of space-based services and products to support life in space. Already, we have observed numerous examples of how space plays a role in different industries *(Exhibit 3)*.

Exhibit 3: The space sector already plays a role in many non-space industries.

Energy and mining
Monitoring methane emissions, informing development of sustainable energy services, providing imagery of mining sites

Agriculture
Monitoring soil, rainfall, and snow cover to inform irrigation plans, predictions of agricultural output, etc.

Pharmaceuticals
Conducting experiments leveraging microgravity (e.g., protein crystallization) to improve pharmaceuticals

Telecom
Providing broadband internet to planes and remote areas, including emergency backup coverage

Automotive
Collaborating on lunar rovers, enabling autonomous driving and in-car entertainment

Transportation
Tracking moving shipping containers, providing positioning and navigation information, monitoring temperature of sensitive containers and road congestion

Consumer
Experimenting in space under specific aerodynamic conditions to inform design and manufacturing of sneakers, soccer balls, etc.

Finance
Leveraging commodities geolocation tracking (e.g., vessels) to inform trades

Insurance
Using radar satellite-based flood monitoring capability to inform risk management and tailor solutions

Tech
Developing in-space computing offerings

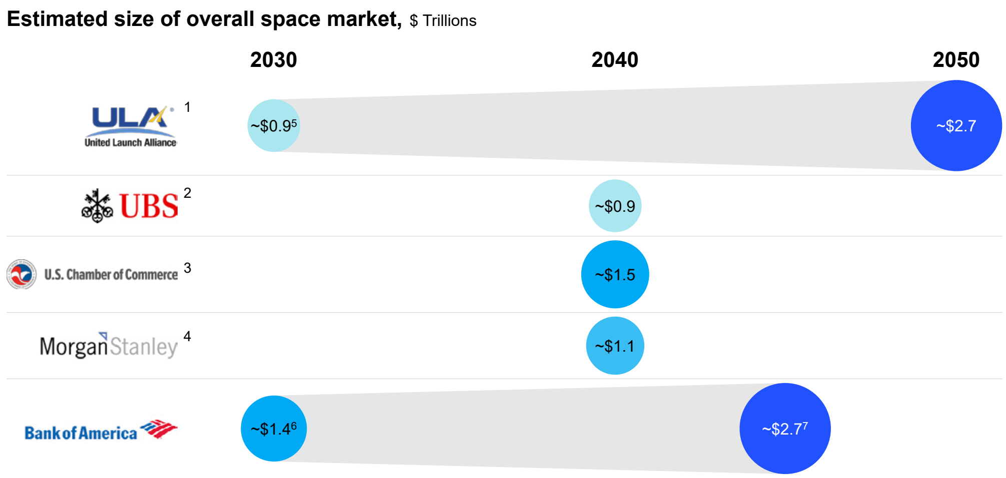
Media
Filming movies on International Space Station

Source: Public press

The timeline for the emergence of new use cases and the development of new customer markets is uncertain, but many experts believe that the space economy will eventually exceed $1 trillion *(Exhibit 4)*.[5]

[5] *ULA Innovation: Cislunar-1000,* United Launch Alliance, 2016; Sheetz, Michael, "Super fast travel from space could be $20 billion market, disrupting airlines, UBS predicts," *CNBC,* 2019; Higginbotham, Brian, *The space economy: An industry takes off*, US Chamber of Commerce, 2018; *"Space: Investing in the final frontier," Morgan Stanley,* 2020; Foust, Jeff, "A trillion dollar space industry will require new markets," *SpaceNews,* 2018

Exhibit 4: There is wide divergence between forecasts of how large and how quickly the space economy will grow in the next 10 to 30 years.



1. *ULA Innovation: Cislunar-1000,* United Launch Alliance, 2016
2. *"Space Tourism: Ready for blast-off?," UBS,* 2019
3. Higginbotham, Brian, *The space economy: An industry takes off,* US Chamber of Commerce, 2018
4. *"Space: Investing in the final frontier," Morgan Stanley,* 2020
5. Report anticipates a space gross product of $900B by 2032
6. Sheetz, Michael, "Bank of America expects the space industry to trip to a $1.4T market within a decade," *CNBC,* 2020
7. Sheetz, Michael, "The space industry will be worth nearly $3T in 30 years, Bank of America predicts," *CNBC,* 2017

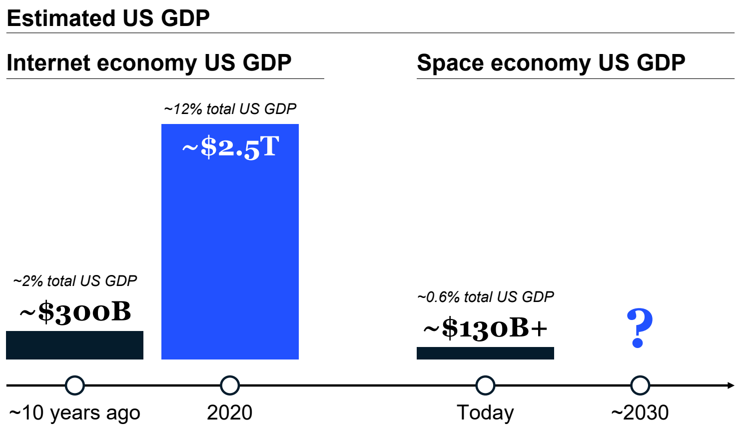
Source: Northern Sky Research; Grand View; Mordor; The Space Foundation; Bank of America; Morgan Stanley; UBS; ULA; public press

The space economy already contributes approximately 0.6 percent of global GDP *(see Exhibit 5)*.[6] In the US alone, in 2019—prior to the sector's strong momentum in the last few years—the space economy already accounted for more than $200 billion of real gross output (0.5 percent of total US real gross output) and more than $125 billion of real GDP output (0.6 percent of total US GDP), as well as 355,000 private sector jobs.[7] Extrapolated globally, this implies about $400 billion of real gross output and $250 billion of real GDP output, numbers which are sure to rise in the coming years.

[6] Based on use of U.S. figures as proxy. See *Updated and revisited estimates of the U.S. space economy, 2012-2019,* Bureau of Economic Analysis, 2022

[7] *Updated and revisited estimates of the U.S. space economy, 2012-2019,* Bureau of Economic Analysis, 2022; *The space report 2022 Q1,* Space Foundation

Exhibit 5: The internet economy GDP provides one frame of reference for contextualizing the space economy GDP.



Source: Bureau of Economic Analysis; Interactive Advertising Bureau; Space Foundation; ResearchAndMarkets.com; World Bank

Countless advancements and breakthroughs in technology, governance, and behaviors are needed for the space sector to realize its full potential, but mindset shifts may be just as important for realizing use cases that we cannot imagine today. For instance, such shifts may include new ways of thinking about sourcing and utilizing data, rethinking the boundaries of a space economy and who it impacts, and engaging non-space companies in the development of the sector. The adoption of 3D printing offers an analogy of how mindset shifts can play out, illustrated in the case study below.

International collaboration has persisted for many years on ventures such as the International Space Station. However, current events are straining this cooperation, causing delays to projects such as European Space Agency (ESA) ExoMars, launch abatements such as Soyuz from French Guyana, and complexities in raw material and component supply chains.[8]

Continued cooperation on space-related ventures is vital to driving innovation and ensuring safe operations in the sector. In recent years we have seen private sector-driven material advances in launch, the first all-civilian mission to the International Space Station, a soaring commercial imagery industry, and more. But much innovation is still needed for the space sector to reach its full potential. Today it costs as much to send water into space as it does to send a human. Until we can change this, many space use cases will remain economically infeasible.

[8] Jeff Foust, "ESA suspends work with Russia on ExoMars mission," *Space News,* March 2022; Stephen Clark, "Russia suspends Soyuz launch operations in French Guiana," *Spaceflight Now,* May 2022; Jason Rainbow, "Satellite supply chains coming under increasing scrutiny," *Space News,* March 2022

A case study in shifting mindsets: 3D printing

3D printing has had a renaissance over the past five to ten years, spurred by desktop printers becoming more affordable. As a result, 3D printing is disrupting a growing range of industries, from fashion to construction to healthcare. However, the development of many recent 3D printing use cases could not have happened without a broad, fundamental shift in the way people think about how things get made.

3D printing drastically accelerated the design process, in some cases, taking iteration times from years to weeks. A traditional risk-averse mindset initially held industries back from recognizing the full benefits and possibilities of 3D printing for some time.[1] But as they embraced the lower costs and faster lead times versus traditional iteration cycles, designers became more likely to take risks, and industries began to unlock new applications.

For example, before 3D printing, gas turbines had a development timeline of over a year, which discouraged innovation and experimentation with the structure of the turbines. The ability to iterate much more quickly lowered the cost of design failures, so designers could use 3D printing to try non-traditional designs. These experiments changed the way gas turbine blades are made. Instead of being made from a single piece of metal, they are now built with a stronger, lighter lattice structure that uses less energy.

As with 3D printing in the gas turbine industry, we expect the space industry to undergo mindset shifts that expand the boundaries of what is possible. In fact, 3D printing is already being used in the space context to make rocket parts, and a 3D printer is installed on the International Space Station.

[1] Mike Scott, "3D Printing Will Change the Way We Make Things and Design Them," *Forbes,* January 2017

The space sector has reached an inflection point

Activity and progress in the space sector have reached an inflection point where commercialization is beginning to outpace governance. The landscape has shifted radically in recent years, and even bigger changes lie ahead *(Exhibit 6)*.

Exhibit 6: The space sector has come a long way and seems poised for future growth.

	Then	Now	Future
Space market size	~$280B (2010)	~$447B	~$1T
Annual private funding	~$1B (2010)	$12B+	$20B+
Countries with space agencies	~55 (2009)	~70	100+
# of space start-ups	~250 (2010)	600+	1,000+
Active satellites	~1,000 (2011)	~4,850	~15,000
Small satellites launched per year	~330 (2018)	~1,740	~3,000+

	Then	Now	Future
Orbit of primary commercial focus	GEO	LEO	Lunar
Space station cost[1]	~$110B (1998)	–	~$5-10B (Potential commercial stations)
Heavy launch costs to LEO	~$65K/kg[2] (Space Shuttle)	~$1.5K/kg (Falcon Heavy)	<$100/kg (Potential Starship)
Launches per year	~75 (2010)	~145	200+
Satellite cost	>$1B (large government satellites)	~$100K (commercial LEO satellites)	<$50K (commercial LEO satellites)
High resolution Earth observation imagery data collected[3]	~30M km^2 (2011)	~175M km^2	>500M km^2

Note: Future reflects estimate by 2030

1. “Then” figure reflects cost of the International Space Station (ISS), for which the first module was launched in 1998; “Future” figure reflects publicly estimated cost of planned US commercial space stations, planned to launch 2024-27
2. Inflation-adjusted
3. Earth observation imagery data reflects <1 meter resolution optical imagery (high and very high resolution)

Source: Union of Concerned Scientists; Center for Strategic and International Studies; Space Foundation; Pitchbook; Crunchbase; Euroconsult; Northern Sky Research; organization websites; public press; McKinsey analysis

There are several indications that the space sector has reached an inflection point:

We are on the cusp of further massive technological progress and new capabilities: Innovations in manufacturing, propulsion, and reusability have made it easier and cheaper than ever before to reach and operate in space. As new private sector companies enter the fray, the pace of innovation has quickened, and launch costs have fallen. In the past few decades, launch costs dropped more than 95 percent, from $65,000 a kilogram (kg) to as low as $1,500 per kg for heavy launch to low-Earth orbit (LEO).[9] Lower launch costs have lowered barriers to entry, leading to significant growth in the number of space companies able to reach and operate in orbit. Progress on mass production, 3D printing, and new super-heavy and fully reusable launch vehicles—designed to make lunar travel more practical and send payloads of more than 100 tons to the Moon—could drive down launch costs even further and open up more possibilities.

Meanwhile, the number of active satellites has doubled over the last two years.[10] By the end of the decade, SpaceX alone is likely to launch more satellites than the rest of the world has sent into space since Sputnik.[11] The pace of launches and volume of at-scale asset production are both increasing. By relying more on software than hardware, designers and engineers have managed to reduce the size and increase the flexibility of space assets. Smaller, nearer-to-Earth satellites have taken the place of some large, expensive satellites in more distant orbits. The advent of artificial intelligence has brought the ability to handle and manipulate huge amounts of data. Looking further ahead, advances in machine learning, robotics, and nuclear propulsion could improve use cases such as global connectivity and emissions tracking, and create entirely new ones, such as large-scale optical fiber production.

What could happen to the launch market?

Fully reusable, super-heavy rockets or recyclable mass-manufactured rockets could reduce launch costs by an order of magnitude.[1] We also anticipate an increasing decoupling of cost and price, which could narrow the competitive launcher set and make the market more attractive for the select few winners.

Overall, we see five main drivers of future launch prices:

— **Launch provider cost structure:** Increased reuse capability, more efficient refurbishment, parts-related cost reductions, and government subsidies may all lower vehicle costs, which could result in lower launch prices.

— **Scale:** As the number of launches increases, economies of scale in production and launch operations will continue to enable reduction of launch prices.

— **Competition:** Launch providers that succeed in lowering their costs may place pressure on other providers to lower their prices to remain competitive, even at the expense of margin erosion. Yet, if declining margins force some players from the market, less competition will enable low-cost players to maintain prices and earn healthy margins. This would lead to the decoupling of launch costs from the prices paid by launch customers.

— **Demand:** In the near-term, constraints on launcher availability put pricing power in the hands of launch companies. By reserving up to 83 launches for satellites from Arianespace, Blue Origin, and United Launch Alliance, Amazon Project Kuiper limits launch availability for others.[2]

— **Below-cost pricing:** Some enterprises may choose to price launches below cost to buy market share. The specter of a price war could deter new, non-subsidized entrants and reduce innovation in rocket development.

1 Micah Maidenberg, *"Elon Musk expects Starship to deliver launches at lower costs,"* The Wall Street Journal, February 2022
2 *"Amazon Secures Up to 83 Launches from Arianespace, Blue Origin, and United Launch Alliance for Project Kuiper,"* Amazon, April 2022

9 Thomas Roberts, "Space launch to low earth orbit: How much does it cost?," *Center for Strategic and International Studies,* September 2020
10 *UCS satellite database,* UCS, December 2021
11 Michelle Yan Huang, Bob Hunt, and Dave Mosher, "What Elon Musk's 42,000 Starlink satellites could do for — and to — planet Earth," *Business Insider,* 2021; Space Environment Statistics, *Space Debris User Portal,* accessed April 2022

All this technological progress is taking place against a changing funding landscape: In the early 2000s, more than 90 percent of space R&D funding came from government sources. McKinsey research shows that commercial sources now provide 30 percent of total space R&D funding.[12] If the current momentum continues, commercial funding could surpass government funding within the next 20 years—a trend that government is largely embracing and is resulting in expanded forms of collaboration, such as public-private partnerships. Private sector funding in space-related companies topped $10 billion in 2021—an all-time high and about a tenfold increase over the past decade.[13] Increased access to capital has fostered a stronger willingness to take risks, contributing to the rapid technological progress in space.

Meanwhile, space activities are increasingly global. Ten years ago, the US government funded 70 percent of global space spending. Today, its share is less than 50 percent.[14]

In the last five years, non-US space budgets have increased by over 130 percent.[15] Global participation in space has grown much more diverse, with approximately 70 national space programs today. Forty nations launched objects into orbit in 2021, double the number in 2015.[16]

At the same time, participants from other sectors such as automotive and logistics have entered the space sector. The number of space-related startups funded and founded each year has more than doubled between 2010 and 2018.[17]

Change is also shaking up long-standing space operating models and architectures. There has been a shift from monolithic to distributed system architectures, most notably as new LEO megaconstellations of thousands of small satellites have gained favor in some areas over large individual assets. Planned megaconstellations from just four companies account for more than 75 percent of the approximately 70,000 satellites planned for launch.[18] And, the International Space Station, which has been in orbit for more than 20 years, is set to be replaced by multiple modern space stations built by governments and private players.

We also see an increased focus on diversifying orbits to bolster terrestrial applications and strengthen resiliency.[19] Players recognize that operating in either geosynchronous equatorial orbit (GEO) or LEO alone can limit their strategic and tactical options. A smooth interface between terrestrial and space-based operations and assets is critical to prolonged operation.

As space activity grows, competition has increased. Public and private players are rushing to claim finite resources such as orbits and spectrum for commercial and national security purposes. Competition for space is limited; trackable orbital debris has increased by more than 80 percent in the last two decades—even before megaconstellations comprised of thousands of satellites began entering orbit.[20] In addition, instead of the old bilateral competition between two major space powers, we now have complex interactions among multiple nations and companies.

---

[12] Ryan Brukardt, Jesse Klempner, and Brooke Stokes, "R&D for space: Who is actually funding it?," McKinsey, December 2021
[13] Ryan Brukardt, Jesse Klempner, and Brooke Stokes, "Space – investment shifts from GEO to LEO and now beyond," McKinsey, January 2022
[14] Ryan Brukardt, Jesse Klempner, Brooke Stokes, and Mary Kate Vaughn, "Space around the globe," McKinsey, April 2022; "The space economy at a glance," *OECD,* 2011
[15] *The space report,* Space Foundation, July 2021; Simon Seminari, "Global government space budgets continues multiyear rebound," *Space News,* November 2019; McKinsey analysis of Statista data on government space programs expenditure from 2014 to 2020
[16] "Online Index of objects launched into outer space," *United Nations Office for Outer Space Affairs,* through December 13 2021
[17] Start up space: Update on investment in commercial space ventures, *Bryce Tech,* 2021
[18] Chris Daehnick and Jess Harrington, "Look out below: What will happen to the space debris in orbit?," McKinsey, October 2021
[19] Sarah Mineiro, "Pentagon: Diversify your orbital regimes," *Breaking Defense,* June 2021
[20] Orbital debris quarterly news, *NASA,* February 2021

Why this time is different

We are in a space renaissance, but some say we have been here before. We saw widespread enthusiasm for the space economy in the 1990s, but projections did not pan out. The widespread rollout of fiber optic cable tempered demand for satellite communication; in addition, lower launch costs were slow to materialize, remote sensing business models did not close, technological challenges remained unsolved, and the bulkiness of hand-held user devices limited uses.

There may be delays and setbacks ahead for the space sector, but we believe the industry is unlikely to follow a similar trajectory. There are five major differences today *(Exhibit 7)*:

1. **Technology:** Massive technological advances have enabled step-change improvements in performance.
2. **Costs:** Many use cases that drive enthusiasm for space sector growth today were conceived ten years ago, but cost structures made them untenable. However, the sector has made significant progress down the cost curve.
3. **Applications and use cases:** In the 1990s, there was a focus on exploration and the development of military and personal communication use cases. The industry is now developing a broader set of viable space-for-Earth and space-for-space use cases.
4. **Sources of capital:** The space sector now attracts capital from many sources and is no longer as singularly dependent on government funding.
5. **Global competition:** Competition among states is likely to fuel demand for space products and services.

Exhibit 7: Today's commercial space sector benefits from advances made across multiple dimensions over the past 30 years.

Technology

Example: Satellite throughput from 5-10 gigabits to >1 terabits per second

1990s-2000s space sector

- **Spectrum usage:** Satellites primarily used lower bandwidth C and L band spectrum, eg, Inmarsat provided 3G speeds from space using L-Band in 2008
- **Satellite throughput:** ~5-10 gigabits/second[1] (limited by spectrum use, data compression, spot beams count)
- **Ground equipment:** Ground antennas predominately connected to a stationary GEO satellite (no LEO tracking ability)
- **Launch frequency:** ~15 launches / year was max observed orbital launch frequency by a single vehicle[2]

Today's space sector

- **Spectrum usage:** Greater usage of higher bandwidth spectrum (eg, Ka, Ku, V)
- **Satellite throughput:** >1 terabits/second satellite planned for 2022 launch[3] (achieved via more spot beams, inter-satellite links, data compression improvements)
- **Ground equipment:** Advancements enable ground antenna tracking of LEO constellations
- **Launch frequency:** Average of 6.8 days between launches by SpaceX in early 2022[4]

Cost

Example: Cost per kg to LEO from >$10K to as low as ~$1.5K

1990s-2000s space sector

Many business cases for new use cases could not financially close:

- **Launch costs:** >$10K/kg to LEO, inflation adjusted[5]
- **Satellite costs:** Predominantly large, exquisite satellites costing billions of dollars (eg, SBIRS satellite cost of >$3B)[6]
- **High resolution Earth observation (EO) imagery:** Average cost of ~$20/km² for optical data and ~$133/km² for synthetic aperture radar (SAR)[7]

Today's space sector

Decrease in costs has expanded business case opportunities:

- **Launch costs:** As low as ~$1.5K/kg to LEO (benefitting from reusability)
- **Satellite costs:** Some small LEO satellites are now being built for ~$100K (in addition to exquisite satellites for specific missions)
- **High resolution EO imagery:** Average cost of <$15/km² for optical data and <$70/km² for SAR[8]

See Exhibit 8.

1 Armand Musey, "Should High-throughput satellites really last 15 years?," *Summit Ridge Group,* September 2016
2 *Orbital Launch Summary by Year*, Space Launch Report, accessed January 2022
3 Evangela Rodgers, "With satellite internet, network capacity is key," *Viasat,* September 2021
4 Sesnic, Trevor, "Group 4-10 brings Starlink to over 2,000 operational satellites," NASA Spaceflight.com, March 2022
5 Thomas Roberts, "Space launch to low earth orbit: How much does it cost?," *Center for Strategic and International Studies,* September 2020
6 Erwin, Sandra, "Is the cost of military space programs going up or down? Depends on how you count," *Space News,* March 2018
7 "Satellite-based earth observation," 4th Edition, *Northern Sky Research,* 2011
8 "Satellite-based earth observation," 12th Edition, *Northern Sky Research,* September 2020

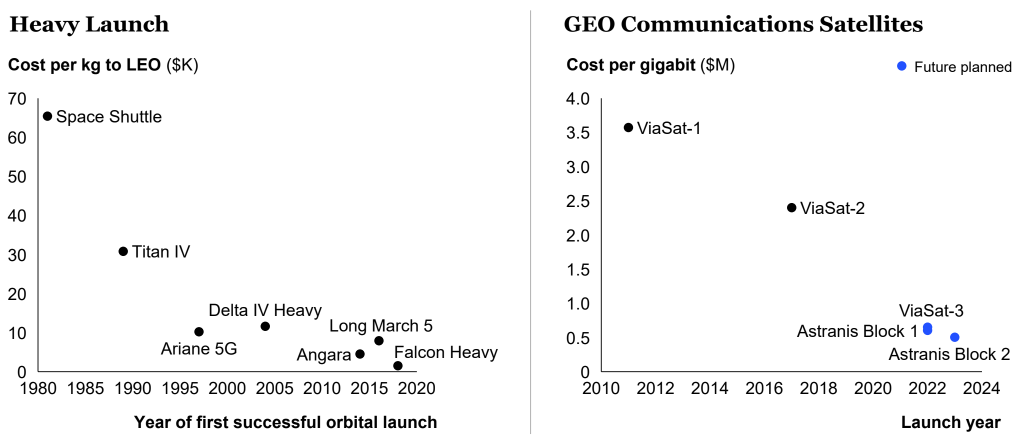
	1990s-2000s space sector	Today's space sector
Applications and use cases	*Example: Commercial satellites from ~40% to ~90% of satellites launched*[1]	
	Demand for scientific exploration drove development of the International Space Station, launch of Great Observatories, and planetary missions **Satellites primarily used for military and personal communication purposes** (~40% of satellites launched in 1990 used for communications) — **High latency** communications (high-and low-bandwidth) — Broadcast — **Earth observation and other activity from GEO/MEO (medium-Earth orbit)** (~60% of satellites launched in the early 1990s were intended for non-LEO destinations)	**Extensive development of new or expanded space-for-Earth use cases** (eg, change detection, emissions monitoring) with pursuit of real commercial value generation potential and customers outside of government and the aerospace and defense sector **Recognition of potential for space-for-space applications** (eg, power generation in space, on-orbit servicing) **Hosted payloads enable much expanded access** to space for smaller players and science missions **Satellite applications span government and commercial sectors,** with ~90% of satellites launched in 2021 being for commercial use cases — **Low-latency,** high-bandwidth communications — Low-cost, narrowband IoT — **Increased activity from LEO** (~98% of active satellites launched in 2021 operate in LEO)
Sources of capital	*Example: Private investor capital from ~$1B to ~$30B*	
	Government programs and large OEM/ Telcos served as primary source of capital (~$1B in private investor capital from 2000-2010) **Global government spend on space was ~$6 billion per year**[2] (early 2000s)	Government funding remains high, but **private sector/investor capital** now covers ~30% of space R&D funding (~$30B in private investor capital from 2010-2020) **Global government spend on space reached ~$92 billion per year**[3] *(2021)*, with more nations investing in space capabilities, including via approaches such as civil-military fusion technology development investment

[1] Numbers in this section were based on McKinsey analysis of data from UCS satellite database and Gunter's space page
[2] Simon Seminari, "Global government space budgets continues multiyear rebound," *Space News,* November 2019
[3] Eric Berger, "US accounts for more than half of global space spending," *ArsTechnica,* January 2022

	1990s-2000s space sector	Today's space sector
Global competition	*Example: Stand-up of US Space Force in 2019*	
	Relaxation of international tensions facilitated international collaboration on space initiatives (eg, International Space Station, Cassini mission)	**Complex global dynamics** can hinder collaboration, but bolster resources for national security space endeavors

Exhibit 8: By moving down the cost curve, the space sector has unlocked use cases that were previously cost-prohibitive.

Sample space cost curves



Note: Satellite lifetime not factored into cost per gigabit. Figures reflect estimates only (based on analysis using publicly stated information and expert estimates). Launch years reflect actual or planned per company announcements

Source: Company websites; public press; expert interviews; Center for Strategic and International Studies; McKinsey analysis

Given the momentum in the space sector today, it is hard to imagine a future where activity grinds to a halt. That said, the pace of development could accelerate or decelerate based on several factors, including market performance, inflation, the proliferation of orbital debris, the rate of demand growth, development and adoption of alternative Earth-based technologies, geopolitical factors, and the pace of technological progress.

Aviation sector development between 1920 and 1950 provides clues for how the space sector might develop over the next 30 years

In many respects, the space sector's development over the next three decades may resemble the maturation of the aviation industry from 1920 to 1950.

The aviation industry of 1920 looked very different than that of today. At that time, aviation was still in the early phases of industrialization. Planes were built of canvas and wood, airports were open fields, and commercial applications were largely limited to the delivery of mail. Within 30 years, however, aviation had evolved to closely resemble the commercial and defense-driven ecosystem we know today.

The 1920s featured innovations in the basic structure of aircraft that set the stage for explosive growth in the 1930s. Airplanes began to be built of lightweight metals, facilitating developments that increased cargo capacity and range. Records were regularly broken for speed and distance, stimulating public interest in the industry, even though air travel was mainly accessible to the wealthy because airplane tickets were prohibitively expensive. Space travel today is also prohibitively expensive, but trips into space are gradually becoming more accessible as launch costs decrease.

For aviation, these developments laid the foundation for the transformational advancements of the 1930s, known as the "Golden Age of Flight."[1] Technological advancements such as fully metal planes with enclosed cockpits, refinement of mass production methods, and increasingly globalized trade networks contributed to the development of the Douglas DC-2 and DC-3 airplanes, which revolutionized commercial air travel. Annual airline passenger volume in the US rose from 6,000 in the late 1920s to more than 450,000 by the mid-1930s to more than a million by 1940.[2] Major airline companies were founded that shifted the focus of the airline sector from delivering mail to transporting multitudes of people across vast distances.[3] The space sector may follow a similar trajectory as super-heavy launch vehicles, fully reusable rockets, mass production, and other technological and scaling advances increase space accessibility and enable more use cases.

In the mid-20th century, extensive military investment supported the rapid development of the aviation sector, leading to the creation of jets.[4] Many of these defense-driven advancements were applied to commercial aircraft, which boosted customer demand for faster and more comfortable air travel. Government investment has long fueled the space sector, and we may see more defense-driven space investments that have commercial applications. For example, satellite imagery plays a key role in defense applications such as monitoring conflicts, but it also can be useful in a range of commercial applications, from crop management to weather forecasting.

By 1950, commercial air travel had become commonplace, and aviation was firmly established as a necessity for defense. Total global aircraft kilometers, that is, the distance flown in a year by all aircraft, had grown from less than 100 million in the 1920s to 1.5 billion, and available seat kilometers, a measure of annual passenger carrying capacity, had increased 130 times from 350 million to 45 billion.[5] The industrialization and maturation of space could follow a similar trajectory. Declining costs and the entrance of new players could create a virtuous circle. As new defense and commercial use cases become feasible, the sector may enter a new phase of rapid growth and development, catapulting the industry to new heights by 2050.

1 "1920-1950," *Timeline Of Aviation*
2 "Early Commercial Aviation," *Smithsonian National Air and Space Museum*
3 "A Brief History of the FAA," *Federal Aviation Administration*
4 "World War II Aviation," *Smithsonian National Air and Space Museum*
5 McKinsey analysis of ICAO worldwide traffic and operations data

Space commercialization outpaces governance

Experts we interviewed talked about how the rapid pace of change in the space sector has overtaken the current international governance regime. The principles for operating in space were largely set forth in five United Nations treaties penned in the 1960s and 1970s. Many leaders feel those treaties provided a solid foundation and still have value, but were not designed to address contemporary challenges such as space debris, lunar property rights, and spectrum usage. They also noted that the treaties do not cover extended commercial activity in LEO and beyond, nor do they specify norms for increasingly important areas of space activity such as Lagrange points—positions in space where balanced gravitational forces tend to keep objects in position. New technologies, applications, and behaviors are straining the existing governance regime.

Survey participants noted that the limitations of existing treaties for the sector could become more glaring as space activity and commercialization intensify. There have already been incidents of close encounters between satellites without the benefit of rules to govern collision avoidance. For example, a recent incident between OneWeb and SpaceX, in which neither party could agree on how to act during a close encounter between their spacecraft, highlighted the need for stronger protocols for collision avoidance.[21] There have been similar near-encounters between national assets and private company satellites, with mixed views on who is accountable for fuel-burning collision avoidance maneuvers.[22] The issue is further complicated because the greatest risk of collision is not due to operational satellites but to inactive or defunct objects or debris.[23]

The United Nations adopted guidelines for space debris mitigation in 2007 and the sustainability of space activities in 2019.[24] However, compliance is voluntary, and actors may ignore them for commercial or financial reasons. The same is true of other frameworks for activities across the space sector, including guidelines issued by industry associations, recommendations from the International Telecommunication Union (ITU), and the principles of the Artemis Accords.[25]

There is a need to address commercialization and governance in space to improve the ability to reconcile challenges like debris and spectrum allocation. The rest of this paper looks

Case example of activity outpacing governance: commercial aviation in the 1950s

There are historical analogies that illustrate the risks when governance stands still in the face of rapid industry development.

In the commercial aviation sector, takeoffs and landings at American airports leaped 13-fold from 1938 to 1956. The air regulations in effect at the time had been written earlier, when aircraft were slower, and there were many fewer flights. Those regulations allowed pilots to ignore air traffic control guidance.[1]

The fatal collision of two commercial airplanes over the Grand Canyon in 1956 highlighted the inadequacy of the regulations. The disaster prompted much-needed modernization of the air traffic control system, improvements in safety technology, and the creation of the Federal Aviation Administration (FAA) to regulate airspace.

The space sector can learn valuable lessons from the history of the airline sector. By preemptively updating its governance structures as the industry evolves and matures, the space sector may be able to avoid destructive and tragic incidents.

1 Tim Queeney, "Fatal airliner collision over the Grand Canyon," *HistoryNet,* September 2020

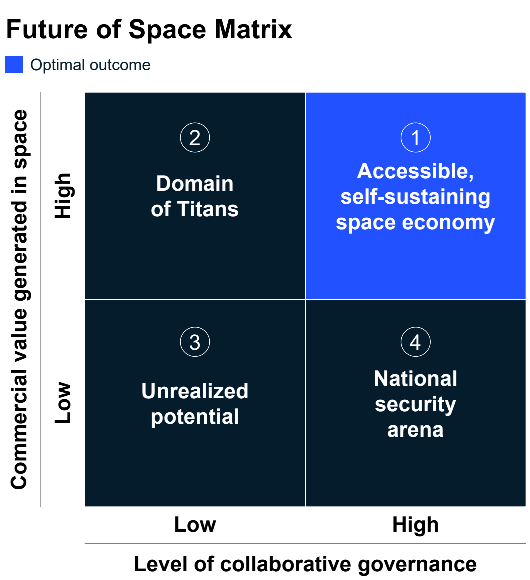
21 Jeff Foust, "SpaceX and OneWeb spar over satellite close approach," *Space News,* April 2021
22 Shreya Mundhra, "50% of 'near miss' collisions, 1600 'close calls': Are Elon Musk's Starlink satellites triggering a space catastrophe?," *The Eurasian Times,* December 2021
23 Kunstadter, C., McKnight, D., Lewis, H., Stevenson, M., and Chatia, R., "LEO risk continuum – providing context to current and future collision risk," *International Astronautical Congress, forthcoming*
24 *Space debris mitigation guidelines of the Committee on the Peaceful Uses of Outer Space,* UNOOSA, 2010; *Guidelines for the long-term sustainability of outer space activities of the Committee on the Peaceful Uses of Outer Space,* UNOOSA, 2021
25 See, for example, Daniel L. Oltrogge and Ian A. Christensen, "Space governance in the new space era," *Journal of Space Safety Engineering,* Volume 7, Issue 3, September 2020

at how space might develop, the vision that the industry would like to achieve, and what could be done to help realize it.

Potential scenarios for the future of space

Leaders we interviewed see the next era for space proceeding primarily down one of four paths, the main determining factors being the degree to which commercial value is generated in space and the extent to which collaborative governance is instituted in the industry. They envision four scenarios based on the interplay between those two factors *(Exhibit 9)*:

Exhibit 9: Four scenarios for how the space sector could develop by 2050.



Below is a summary of trends and perspectives from the leaders surveyed, across the four scenarios:

1. The **accessible, self-sustaining space economy scenario** is marked by unprecedented technological innovation, catalyzed by global collaboration, widespread funding, and healthy competition. In this scenario, the space economy sustains itself and enhances life on Earth through the rapid development of new use cases such as ubiquitous global communications. The space economy expands beyond $1 trillion as effective governance fosters a safe and accessible space domain. For instance, space traffic management is put in place to prevent collisions, and existing high-risk debris is removed. Stakeholders agree on a framework for

accessing space resources that enables an economic return but seeks to prevent skirmishes over valuable sites and limit the development of monopolies. Leaders suggested that effective governance in this scenario could resemble the UN Convention on the Law of the Sea, which more than 160 countries have signed.[26] That may leave some concerns, such as skies becoming too busy and hampering astronomers, but many stakeholders we spoke with see an overall benefit.

2. The **"domain of the Titans" scenario** sees space activity continuing to grow and attract funding while governance stays rooted in dated, limited frameworks. Space becomes more cluttered with satellites and debris as each company or country acts in its own interests. Without effective governance to foster collaboration and accessibility, leaders fear that space could become restricted to a handful of developed nations and ultra-wealthy companies. With participation highly limited, innovation slows down, and space's full potential is not realized. On the other hand, if the space economy grows large enough, some players could become very powerful and shape the rules in their favor. Historical analogies include private companies that held huge political sway in the 18th and 19th centuries, enabling them to resist regulation by legislators and become pseudo-states with their own military forces and tax collection regimes within the territory they controlled.[27] Consolidation of the space sector to a few large players could accelerate progress in the near-term, but the lack of healthy competition would likely prevent realizing the full potential of space in the long run.

3. The **unrealized potential scenario** results when technical, economic, and regulatory challenges impede progress. For example, space activities remain prohibitively expensive for most players. As business cases fail to materialize, private funding dries up, and innovation grinds to a halt. Absent effective regulation for debris mitigation, orbital collisions become commonplace, causing commercial losses and discouraging investors. Traditional applications of space-based communication, Earth observation, and research persist, but a robust space economy with self-sustaining use cases remains a distant vision. In the worst-case scenario, orbital debris becomes so extensive that much space activity ceases altogether.

4. The **national security arena scenario** is prompted by a series of space disasters that cause governments to reassert primary responsibility for space activity. Leaders expect that governments might respond with strict regulations that may provide effective long-run governance, but could also increase the cost of space activities, stifle market innovation, and quash investor interest. Competition to reach the Moon and Mars propels technological developments. However, critical space infrastructure initiatives such as refueling and traffic management receive less attention, undercutting the development of a sustainable space economy. Technological commercialization takes a back seat to national security interests, with many technologies remaining classified.

[26] Chronological lists of ratifications of, accessions and successions to the Convention and the related Agreements, United Nations, May 2022
[27] Dalrymple, William, "The East India Company: The original corporate raiders," *The Guardian,* 2015

Vision of a thriving space economy

Most leaders favor the first scenario of the accessible, self-sustaining space economy to maximize the potential of space.[28] This scenario would have several key characteristics:

Sense and communicate: Space will play an even larger role in how the world communicates and monitors Earth, with satellites continuing to generate and transmit vast amounts of data. Expanded satellite communications infrastructures could help bring affordable broadband services to rural and developing communities, enabling better connectivity among the 40 percent of the global population with little or no internet access.[29] In addition to simply growing the number of assets in orbit, the performance of the space-based communications networks will continue to improve with the smarter use of scarce spectrum. Laser-based inter-satellite links would allow satellites to communicate with higher data transfer speeds and prevent interference or jamming.[30] Other technologies such as cognitive radio enabled by artificial intelligence could facilitate dynamic sharing of spectrum, improving the utilization of frequencies.[31]

Similarly, advances in remote sensing could improve the tracking and monitoring of climate conditions, while tracking emissions on the ground to drive accountability and mitigation.[32] A "digital twin" of the Earth using detailed real-time space-based data could take a more active role in monitoring Earth's climate health and making weather predictions. Near real-time visibility into how landscapes change could help improve the prediction and monitoring of fires, floods, and forest degradation.[33]

This type of insight would not be limited to the climate. Ubiquitous and timely Earth observation data combined with advanced artificial intelligence and machine learning could unlock new business and tactical insights: companies could improve the management of their supply chains; banks could feed new data on crops, drought, and weather into their risk models to make better decisions about loans to farmers; satellites could enable the dynamic management of autonomous vehicle flows; advances in remote sensing could allow public health experts to make more accurate predictions of disease outbreaks and provide early warnings of famines based

---

[28] However, some space industry participants have voiced concerns about increased space activity, for instance, astronomers who are concerned about satellites crowding the skies

[29] For more information, see "Connected world: An evolution in connectivity beyond the 5G revolution," McKinsey Global Institute, February 20, 2020

[30] Stew Magnuson, "*Laser communications to thwart jamming, interception*," *National Defense*, November 2014

[31] "Cognitive radio: The new architecture of space communications," *Aerospace & Defense Technology*, December 2018

[32] "The net-zero challenge," *World Economic Forum*, 2021

[33] Morgan Crowley & Jeffrey Cardille, "Remote sensing's recent and future contributions to landscape ecology," May 2020

on data concerning flooding and droughts.[34] By fusing multiple types of satellite-generated data, including electro-optical (imagery), synthetic aperture radar (SAR), radiofrequency (RF), and hyperspectral, a more complete view of activity on Earth could be created. If this happens, data from satellites will play an increasing role in national security, commercial, and humanitarian fields.

Protect and secure: In the future, space could play a larger role in safety and security than it does today. Ubiquitous and persistent remote sensing could expose the actions of bad actors. Sensing could help deter large-scale drug trafficking or illegal shipping and allow for clear attribution in international incidents, though international standards will be needed to help protect from bad actors exploiting this information.

Space technologies could also help address cybersecurity threats and data concerns. Constellations of satellites could distribute quantum keys to users, enabling safe and secure encrypted communication over terrestrial and space-based networks. Additionally, space could serve as a neutral area, with keys to sensitive data held beyond the borders of any single national government. Satellites could even provide a trusted environment for computation far from concerns of physical tampering or eavesdropping.

Space could also help make nations more resilient to natural disasters. Satellites could offer early detection and prediction for a wide range of threats from wildfires to solar flares, giving governments more time to prepare or evacuate. The recent launch of the DART (Double Asteroid Redirection Test) spacecraft shows that satellite technology could even develop the capability to protect Earth from the danger of asteroid impacts.[35]

From a defense perspective, space continues to be strategically important for nearly every nation. Space-based systems will likely become increasingly resilient and disaggregated to ensure they can survive attacks and debris collisions. The need for mission and system resilience in the face of broad and deep potential threats will likely lead to hybrid architectures. Leaders believe that satellites will need to be secure against man-made threats from physical weapons and cyberattacks. Space-based systems for defense will evolve with new technologies, applications, and operations concepts.

Discover and build: Space will continue to serve as an arena for scientific discovery. The development of new commercial space habitats will make it less expensive to operate in space and pave the way for innovations in fields such as astrophysics, pharmaceuticals, and manufacturing. The ultra-clean, microgravity orbital environment could foster the creation of new products, including semiconductors, pharmaceuticals, optical cables, retinal implants, or even organs, that will benefit people living on Earth. Continued experimentation on in-space manufacturing will likely lead to discoveries that we have not yet imagined.

Space may also be well-suited for heavy manufacturing linked to pollution on Earth today. The solar system can support many times more industry than we have on our planet, and asteroids and other bodies contain a plethora of precious metals that are scarce on Earth.[36] If nations can align on mining rights and the ownership of resources procured in space, we may be able to save

[34] Greevink, Jet, "3 ways satellite tech is helping to transform finance," *GEO Awesome,* 2019; Beatty, Deanna et al, "The future is big – and small: Remote sensing enables cross-scale comparisons of microbiome dynamics and ecological consequences," *ASM Journals,* 2021; "100 earth shattering remote sensing applications & uses," *GISGeography,* 2022

[35] "NASA, SpaceX launch DART: First test mission to defend planet earth," *NASA,* November 2021

[36] Troy Farah, "Made in space: Why Earth's industries might one day leave our planet," *Discover Magazine,* July 2019

Earth's resources by mining in space. And, if we can solve the major logistical challenges, space may someday support scaled solar power generation and fuel production, reducing emissions on Earth. Moving industries like power production into orbit could play a role in reducing global warming and ensuring that Earth can continue to sustain human life.

From technical and commercial perspectives, one of the most widely perceived near-term space manufacturing use cases is the production of ultra-pure optical fiber (ZBLAN), which can carry substantially more data for greater distances (without repeaters) than traditional silica fiber.[37] ZBLAN has already been produced in small test quantities in space and constitutes a promising use case given its value of more than $2 million per kilogram.[38] However, any large-scale manufacturing initiative would still have to solve major hurdles around access to in-space infrastructure and production costs, as well as the cost and logistics of returning the finished materials to Earth.

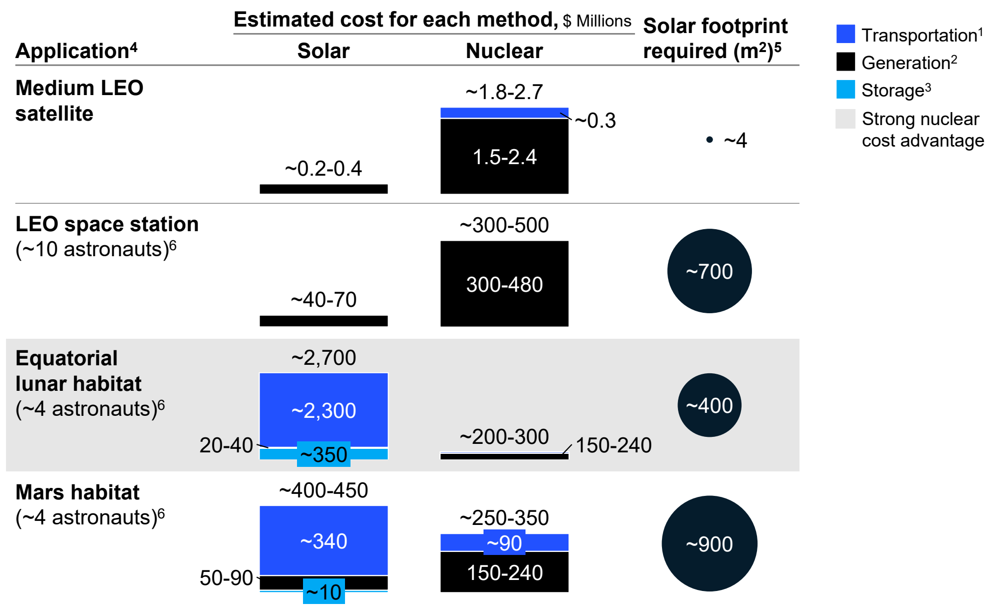
Continued improvements in robotic technology and microgravity-based fabrication could soon enable humans to build unprecedentedly large structures in space, enhancing the pace of technological development and scientific discovery. Larger space telescopes will expand our abilities to search for other life in the universe and understand our origins. A future lunar gateway station could serve as an assembly hub for spacecraft with the capacity to support humans on multi-month journeys to Mars. Instead of designing satellites specifically to survive the rigors of launch, we may be able to build finer and more delicate instruments in space, producing entire satellites in orbit and customizing them for different missions.

However, these new spacecraft and space use cases will require their own power systems. While solar power will continue to be the primary energy source for orbital systems, new power generation technologies will be essential to provide enough energy to sustain habitats on the surface of the Moon *(Exhibit 10)*.

[37] Cozmuta, Ioana, et al, "Breaking the silica ceiling: ZBLAN-based opportunities for photonics applications," Proceedings Volume 11276, *Optical Components and Materials XVII,* March 2020

[38] *Fiber Optics,* Red Wire; Crane, Keith et al, "Market analysis of a privately owned and operated space station," *Institute for Defense Analyses,* March 2017

Exhibit 10: Nuclear power may be the best source of energy for lunar or Mars habitats.



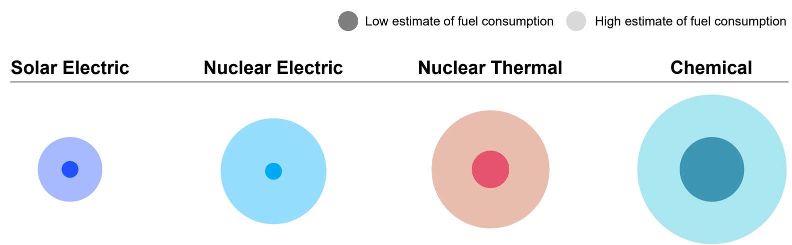
1. Assumes future costs of $500/kg to LEO, $25,000/kg to lunar surface, and $100,000/kg to Martian surface
2. Assumes $3-5M/kW for nuclear based on terrestrial small modular reactor (SMR) costs of $4K/kW and same space/terrestrial power ratio of ~1,000 from solar panels (non-recurring expenses assumed to be spread across >5 units); assumes $50-100K/m² cost for space solar panels
3. Assumes $20K/kWh cost for energy storage
4. Assumes 1 kWe for medium LEO satellite, 100 kWe for LEO station, and 50 kWe each for habitats
5. Assumes panel efficiency of ~20%
6. Assumes nuclear reactor is sited sufficiently far away from humans to avoid large shielding requirements

Source: Public press; expert interviews

Unlike high Earth orbits, where access to sunlight is nearly continuous, the lunar surface experiences two weeks of darkness each lunar night, making the cost of storing energy unacceptably high. Space-based nuclear power could offer a continuous energy source independent of the sun that would also be useful farther out in the solar system where sunlight intensity is much lower. To make space-based nuclear power feasible, we will need to overcome multiple barriers, including the conversion of nuclear energy into electricity, liabilities, and mitigating the risks of launching fissile material into space.

Sustain and manage: Space infrastructure and services will be crucial to enabling new space use cases and could create entire new micro-economies to support other space activities. For example, while many LEO satellites will continue to be replaced relatively frequently, precious assets like telescopes and GEO communications satellites could be refueled, repaired, or even upgraded in orbit. Raw materials from the Moon and nearby asteroids could be used to produce fuel and structural components to support the growing space economy without needing to launch large amounts of material from the Earth's surface. An in-space logistics network could make the transportation of goods in space as simple as shipping a package here on Earth. The development of affordable space logistics services will depend on progress in new propulsion technologies that could enable faster and more efficient space transit *(Exhibit 11)*.

Exhibit 11: Advancements in propulsion technologies are needed to enable rapid space transit.



	Solar Electric	Nuclear Electric	Nuclear Thermal	Chemical
Propellant required to transport a 1 mt payload from LEO to low lunar orbit (LLO)[1], mt	0.1-1.5	0.1-4.0	0.5-5.0	1.5-8.0
Approximate transit time to Mars[2,3], months	24+	~1	~3	~6-9

1. Entirety of spacecraft considered payload except for engine, power system, and propellant; assumes Isp of 1,000-10,000s for electric propulsion, 500-1,500s for nuclear thermal (NTP), and 250-450s for chemical and engine masses of 0.05-0.2 mt for solar electric (SEP), 0.7-2.0 mt for nuclear electric (NEP), 0.7-3.0 mt for NTP, and 0.1-1 mt for chemical; assumes full propellant mass is consumed by end of maneuver
2. According to public quotes from industry experts
3. At the cost of transit times, nuclear propulsion could also expand the range of launch windows to Mars, which are currently constrained to once every ~2 years

Source: Public press; expert interviews

Current chemical and solar electric propulsion technologies suffer from significant limitations. Chemical propulsion may be the best way to reach orbit from Earth for the foreseeable future, but it is relatively inefficient, so large amounts of fuel are needed to achieve significant changes in velocity.[39] In the case of solar electric propulsion, thrust is limited, requiring massive solar arrays to achieve rapid space transit.[40] Nuclear thermal and nuclear electric propulsion could propel spacecraft at much higher speeds, making it more feasible for humans to visit Mars and improving the affordability and cadence of trips within cislunar space.[41] However, nuclear propulsion is not readily available today. It may also carry greater safety risks, and most satellites do not have high enough power requirements to justify it.

39 *6 things you should know about nuclear thermal propulsion,* Office of Nuclear Energy , December 2021

40 Mikulas, Martin, et al, "Telescoping solar array concept for achieving high packaging efficiency," *American Institute of Aeronautics and Astronautics,* 2015

41 Ilin, Andrew V. et al, "VASIMR human mission to Mars," *Space, Propulsion & Energy Sciences International Forum,* 2011

Survive and thrive: By 2050, a much larger and more diverse group of people could work, live, and travel in space. LEO will be home to commercial space stations that serve as hotels for tourists and business parks for commercial activities such as manufacturing and research. Similar habitats could emerge on the Moon, initially spearheaded by government programs but eventually transitioning into centers for commercial activity. As more humans spend time in space, new forms of entertainment could arise as astronauts perform on reality television and play microgravity sports. Settlements such as a Moon base would require many more individuals with specialized roles than the multitasking cadre of astronauts living aboard the International Space Station.

To expand space travel beyond specialized astronauts and ultra-wealthy individuals, we have to lower launch costs. Similar cost reductions and technological advances in life support technologies, and a deeper understanding of the health implications of prolonged stays in space, will be needed to support large-scale, continuous human habitation in LEO and other high-radiation environments beyond the safety of Earth's magnetic field. To minimize the logistics footprint of space inhabitants, we will need to use space resources to generate and conserve the necessities of human life, including water and oxygen – termed in-situ resource utilization. If every meal and breath of air must be shipped from the Earth's surface, the large-scale human settlement of space will not be possible. The NASA Mars Perseverance rover has served as an initial experiment in using space resources for life support by converting CO2 in the Martian atmosphere to oxygen. This process could someday be used to keep astronauts alive in the harsh conditions on Mars.[42]

Maritime law and effective governance of the high seas

20th century technological breakthroughs in navigation, fishing techniques, and ocean exploration dramatically changed how we interacted with and on the high seas. Tensions rose as nations came into conflict over ocean territories and newly accessible resources. The threat of pollution and resource depletion mounted as activity on the seas increased and many fisheries were overexploited.

International leaders soon realized that governance was necessary to maintain peace and protect the usability of the ocean and its resources. This spirit of collaboration resulted in the establishment of the United Nations Convention on the Law of the Sea (UNCLOS).[1]

Individual nations also developed their own governance policies. For instance, United States federal law requires the master of any vessel subject to US jurisdiction to "render assistance to any individual found at sea in danger of being lost," so long as it could be done without endangering the rescuing vessel or passengers.

While not a perfect analogy, leaders believe that lessons from the development of maritime law can guide and inspire the space industry in its own approach to space governance. Specifically, participants believed maritime law teaches us the value of:

- Drafting regulations that are internationally applicable and enforced at the national level
- Clearly defining principles for acceptable behaviors in shared spaces
- Preventing over-exploitation of resources and protecting environments
- Establishing economic zones and ensuring all nations have the opportunity to benefit from resources, territories, and activity
- Implementing processes and frameworks for settling disputes

For member nations, the consequences of non-compliance with maritime law outweigh the perceived benefits. Leaders can try to ensure that such risk-benefit calculations will also favor compliance with space governance frameworks.

[1] *United Nations Convention on the Law of the Sea,* United Nations, 2002

[42] Ackerman, Evan, "MOXIE might be the most exciting thing Perseverance has brought to Mars," *IEEE Spectrum,* 2021

Five actions to enable an accessible, self-sustaining space economy

To realize the full potential of an accessible, self-sustaining space economy, leaders identified five high-priority actions, all of which require some collaboration among many stakeholders, including governments, companies, academia, investors, and citizens.

1. Create and implement effective space governance

To make sure that space remains accessible to all, leaders identified the need for a framework to govern space activity, which includes international regulatory bodies, nations, and commercial players. This governance would be defined and enforced by a forum that creates it or an international standards body with widespread participation. Regulations would seek to encourage space development while making access safe and equitable, as well as encouraging productive activity and development.

In space, any bad action could have long-term consequences for many actors, so respondents believe it is important to have an effective governance framework. Efforts to create such frameworks have already begun, such as via the United Nations Office for Outer Space Affairs Committee on the Peaceful Uses of Outer Space (COPUOS) and the Artemis Accords. Still, experts we spoke with would like a greater effort by a widely-recognized, multi-stakeholder international forum to address critical areas such as:

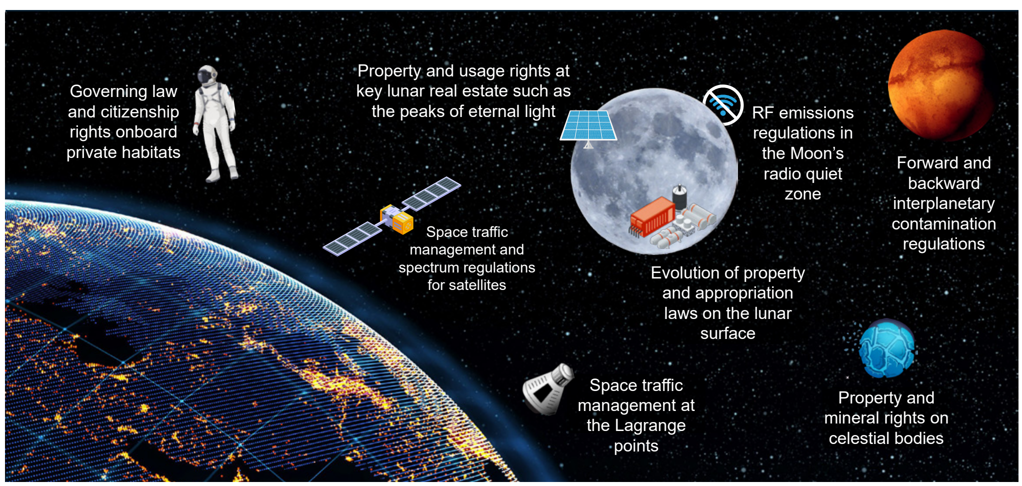
— **Maintaining responsible behavior in space:** A space governance framework could help establish requirements for ethical behavior in day-to-day space activities. To encourage compliance, leaders interviewed believe such a framework could incorporate approaches for enhanced information sharing and coordination among actors.

  This framework could establish a common understanding among states of responsible behavior toward issues such as space debris, ASAT (anti-satellite) tests, space traffic, launch windows, and the militarization of space. Space debris commitments were widely raised as of particular importance, given the proliferation of launched and planned satellites. The lack of ownership of orbits leads to a lack of accountability for debris, incentivizing behavior that threatens to keep space from reaching its potential. Several ideas have been proposed to address problems with existing and future debris, including instituting a "debris removal tax" for companies that profit from space activity; implementing a framework by which companies launching satellites carry insurance to cover the cost of satellite removal; updating the current rule that spacecraft in LEO must be de-orbited after 25 years; instituting a "one up, one down" policy or norm; requiring every satellite to have propulsion capabilities and sensors so that they could automatically perform collision avoidance maneuvers; enacting an incentive system to encourage the removal of existing debris, perhaps by linking the probability of collision to insurance costs; investing in active debris remediation; and increasing investment in solutions for servicing and upgrading existing satellites to reduce the rate at which satellites go obsolete and become debris. Participants think that limits or bans on certain ASAT tests will likely be necessary to limit debris creation and encourage responsible behavior in space, though the details will need careful consideration. The US recently announced that it would end direct-ascent ASAT missile tests and called for other nations to do the same.[43] Nations could also come together to overcome barriers to de-orbiting inactive satellites that belong to other nations. This is important because analysis has shown that the greatest risk to space operations in LEO derives from inactive debris, not operational satellites. Debris-on-debris collisions have twice the debris-generation potential of collisions involving at least one operational satellite.[44]

— **Defining property ownership, access, and usage rights:** A democratized paradigm for space depends on clarity of ownership of space properties and resources, in the view of our respondents. All participants would benefit from a common understanding of who has the right to access and use properties and resources such as Lagrange points, spectrum, and minerals. For some resources like spectrum, current structures such as ITU filings could be leveraged and updated. Clarifying rights around other resources that are under pressure may, however, require the establishment of new international institutions or the expansion of existing ones.

  Leaders see it as especially important to have effective guardrails and centralized governance around the ownership, access, and usage of the most contentious resources to ensure that no single party, company, or nation can dominate access to them *(Exhibit 12).*

Exhibit 12: Leaders suggest that the international community should prioritize the definition of ownership, access, and usage rights for conflict points in space.



There is a pressing need—from the perspective of interviewees—to revise the regulatory regime for spectrum access, to protect against interference and encourage commercial activity. Some stakeholders say that obtaining authorization to access certain spectrums, such as V-band, can take years and be more difficult than developing the satellites themselves.[45] In the US, the FCC

[43] Nandita Bose and Joey Roulette, "US will not conduct direct ascent anti-satellite missile tests, Harris says," Reuters, April 2022
[44] Kunstadter, C., McKnight, D., Lewis, H., Stevenson, M., and Chatia, R., "LEO risk continuum – providing context to current and future collision risk," *International Astronautical Congress, forthcoming*
[45] Michael Sheetz, "In race to provide internet from space, companies ask FCC for about 38,000 new broadband satellites," *CNBC,* November 2021

has introduced streamlined licensing procedures for small satellite constellations to promote innovation and support new entrants. These procedures could serve as a starting point for a regulatory framework that protects ongoing interests and improves the efficiency of launching new systems such as LEO constellations.

— **Developing and promulgating common standards:** Leaders see an opportunity to increase collaboration and efficiency by aligning on recognized standards for space technologies and infrastructures. Such standards could apply to hardware and software, covering everything from spacecraft servicing interfaces to the protocols for sending and receiving data.

  In other industries, a dominant player can sometimes drive stakeholders to coalescence around a particular standard. Yet some leaders think that standards are less likely to emerge this way in the space sector, given the global and fragmented nature of space activities. Private companies have begun to express interest in developing select standards, such as the interoperability of on-orbit spacecraft docking stations, but it is not yet clear how widely they might be adopted.[46]

  Beyond company-driven efforts, leaders see a pressing need for concerted industry collaboration on standards. Already, the International Organization for Standardization (ISO) sets and manages a wide range of space system standards. These could be expanded to encourage interchangeability, the reuse of parts, and real-time communication. Similar standards could be applied to satellite position tracking data to enable space traffic management. Meanwhile, targeted efforts to align standards have emerged within the industry. For example, one group of stakeholders is working to develop and test standards for the internet in space. Standards will become more important as human space travel, including to cislunar and beyond, increases. For example, there would likely be value in spacecraft with different communications systems being able to communicate with each other.

— **Protecting human life, infrastructure, and the environment:** Without appropriate governance, the growing space sector could pose risks to humans and the environment. Internationally recognized mandatory safety protocols for any private or public crewed spacecraft would help protect people traveling into space. Regulatory frameworks could also seek to limit the environmental harm caused by companies and nations launching into space, such as limitations on soot per launch. Also, safety regulations can reduce the risk of accidents that might curtail enthusiasm for the space ecosystem.

2. Invest resources and effort in enabling technologies and capabilities

Significant technological advances have already been made in the space sector, and more are underway. But adequate resources and long-term investments in technologies and capabilities are still essential to achieving the sector's ambitions for space.

Experts named several technologies that will likely play a vital role in developing a self-sustaining space economy and expanding the benefits for Earth from the space ecosystem:

— **Advanced power and propulsion:** Although launch is becoming increasingly affordable with today's technologies, nuclear propulsion may be critical to increasing the speed and flexibility of transportation beyond LEO. Chemical propulsion could power trips to Mars, but frequent

[46] Jeffrey Hill, "Lockheed Martin publishes open-source standard for on-orbit docking," *Via Satellite,* April 2022

voyages to and from, as well as travel beyond it, are likely to require nuclear-powered propulsion. Furthermore, larger-scale activities such as lunar mining and large habitats would demand more power, possibly requiring nuclear reactors to provide power through the long lunar night.

Nuclear propulsion could also bring efficiencies to existing LEO spacecraft. Both nuclear thermal propulsion (NTP) and nuclear electric propulsion (NEP) provide much greater energy density and thrust per unit of propellant than traditional methods, driving improvements in launch weight, cost, and trip time.[47] However, NTP and NEP pose significant safety and environmental risks, requiring technical and potential regulatory advances before the space sector could use these technologies.

— **Downmass or re-entry capabilities:** Improvements in cargo downmass (return to Earth) capacity and spacecraft re-entry, including low-g re-entry and runway landing, will likely be critical to scaling in-space manufacturing. To transport fragile goods, such as ZBLAN fibers or pharmaceuticals from space to Earth, spacecraft would have to maintain cost-effective, highly controlled payload environments during re-entry.

— **Cost-effective means of getting resources in space:** Currently, it costs the same to send essential resources like food and water to space as it does to send a human. On Earth, shipping methods vary based on the value of the cargo. Thus, humans travel long-distance in relative comfort by plane, while packages are transported relatively cheaply, packed into the hold, or by rail, freight, or truck. Today there is only one way to get to space, which is neither efficient nor cost-effective for many cargoes. Technological advancements would be needed to create options for how things get to space or are built there for this to become viable. *(See in-situ resource utilization below.)*

— **AI/ML, cloud computing, robotics, and autonomy:** The space environment is hard on machines and less hospitable for humans. Accordingly, robots and spacecraft will continue to perform most tasks in space. As machines develop greater autonomy, space-based operations could become safer. Advanced artificial intelligence and machine learning could help analyze and drive decision-making based on data sourced from space. As the volume of data grows, more processing will need to be done in an edge environment, that is, in space close to the point of data collection using cloud computing.

— **In-situ resource utilization and life support:** If more people start to live and work in LEO and beyond for extended periods they will need new technologies to stay safe and healthy. Ideally, the technologies would minimize the mass and costs of transporting life-support materials back and forth between space and Earth. To achieve this would involve ways to utilize space-based resources, such as those of the asteroids, the Moon, and Mars, to generate breathable air, water, and fuel for survival.

— **Enhanced cybersecurity:** Satellites have historically been subject to a wide array of threats, including cyberattacks. As the importance and computational complexity of space assets grow, these threats are likely to become more sophisticated. In response, the space sector would need to strengthen its cybersecurity capabilities and defenses. Experts note that standards for all the proprietary and third-party software used in critical satellites could

[47] Matt Williams, "Just how feasible is a warp drive?," *Universe Today,* September 2019

include more rigorous testing, such as cyber range exercises, application security testing, and code scanning. Satellite operators will also need to exercise caution with over-the-air firmware updates since they can be a source of vulnerability.

— **Component improvement and miniaturization:** Continued improvements and standardization of components along the value chain from solar panels to sensors could enable less expensive, more capable, and often smaller space assets.

— **Broadly, mass production:** With practically every space technology, from launch to satellites to infrastructure, much of the sector's task in the coming decade could be to scale production. At-scale production can enable more use cases and improve cost structures.

Government support may continue to play an essential role in driving progress on many enabling technologies, particularly in the early stages of innovation, when uncertainty and timelines can give private investors pause. There may also be areas where industry consortiums or informal partnerships can foster technological advances that benefit multiple sector participants.

3. Incentivize collaboration among nations, sectors, and industries

Over the past couple of decades, global collaboration on the International Space Station (ISS) has advanced the state of space research and exploration. The station has hosted nearly 250 individuals from 20 countries and served as a home base for approximately 3,000 science experiments on topics ranging from disease research to advanced water purification systems. ISS has been a global collaboration success story.[48] Astronauts from many nations have worked together on the ISS.

International collaboration in space has accelerated development and promoted its peaceful use. Today, more nations than ever are participating in the space sector. Governments determine the degree to which they partner for space activity and participate in international collaboration. But none can be excluded from space, and if more countries venture into space, maintaining the spirit of collaboration will be critical.

Leaders widely believe that space should continue to be a place of international collaboration. But for this to happen, the international community will need to decide to preserve space as a collaborative ecosystem.

It may be possible for existing forums and structures to drive collaboration in the sector. For example, the United Nations, World Economic Forum, and industry associations could convene a diverse cross-section of participants to address targeted topics. The World Economic Forum already plays a role in sustainability, and the United Nations does the same with space debris.

There may also be a role for other forums, ideally perceived as neutral parties. For example, interviewees suggested a new international forum to support startups and nations with fewer resources in getting space initiatives off the ground. Some leaders also suggested that a space-specific organization could promote and disseminate norms as ICAO (International Civil Aviation Organization) has for aviation.

[48] *Space Station 20th: First NASA research on ISS,* NASA, September 2020; *Visitors to the station by country,* NASA, December 2021

While collaboration among many or all nations is seen as a positive goal, experts believe it may also make sense to start with what is most achievable. Examples include seeking broad alignment on space norms within nations, seizing opportunities to forge public-private partnerships, encouraging bilateral and multilateral collaboration among nations whose values are already aligned, and aiming for international agreements like the Artemis Accords.

In the survey results, it was clear that the output of such collaboration does not have to be a set of sweeping laws. Leaders think it can be beneficial to establish guidelines or norms. Norms are most effective when there are clear benefits to all, like passing on a given side while driving. Clear communication of the mutual benefits of norms can increase the likelihood they are honored. Additionally, norms can raise awareness of the importance of an issue and prompt thinking on the topic, paving the way for future regulatory action as needed. When establishing norms for space, experts suggest it would be crucial to acknowledge and address perceived drawbacks, such as impacts on near-term profits, and shape the benefits to be ones that all can value.

As the use cases discussed above materialize and the commercial space economy grows, space could become an increasingly important domain for companies outside of aerospace and defense, such as those in the agriculture, pharmaceutical, technology, and manufacturing sectors. Forums that facilitate dialogue between space companies and potential corporate end-users of their technologies and services could benefit all involved. Space startups, which tend to have strong technical skills but less developed go-to-market capabilities, can better understand their commercial markets and user preferences. At the same time, companies outside the space sector could learn how to leverage and apply space technologies in their businesses.

4. Foster a self-sustaining industrial base

Today, many entrepreneurs are working to bring new or advanced space technologies and use cases to market. But to date, few of these new businesses have achieved positive cash flow. Investor support is likely to wane if business cases continue to go unrealized, which may imperil many of today's developing players and slow the pace of innovation in the sector.

To avoid such a scenario, survey participants believe governments can help by acting as critical anchor customers and signalers to provide space startups a path to becoming self-sustaining. In a country where the space sector is already reasonably well developed, governments may have the greatest impact by helping companies improve business performance. In other countries, government could help by encouraging the emergence of a private space industry and helping to foster a talent base.

What it would take—views from leaders we interviewed:

— **Signals of government support of commercial technology development:** To ensure a robust and sustainable space economy, governing bodies should encourage a range of large and small commercial players to participate in the market. These governing bodies would also have a role to play in promoting innovation, such as by encouraging innovation, for example, via offering prizes and funding awards for technological breakthroughs. Meanwhile, some experts suggested that governments could signal their support for commercial space innovation by explicitly stating their intent to purchase commercial technologies. Such statements can go a long way toward enabling space startups to attract investor capital and scale their operations.

- **Government purchasing of services:** To unlock space's full potential, there is an anticipated shift towards service-based models. Here too, leaders believed governments could offer support by adopting the principle of obtaining space-related services from the commercial sector when offerings that meet the government's needs can be procured more cost-effectively and reliably. Such a provision could provide a longer runway for commercial space startups innovating in the sector.

- **Company investment in go-to-market capabilities:** Technological talent abounds in nascent space companies, but interviewees said that business talent is less abundant. This could be one reason why many companies fail to jump from innovative technology incubators to profitable businesses. To counter this, the sector will need to invest in business development talent, take the time to evaluate and prioritize markets, and develop tailored go-to-market strategies for its highest priority target markets.

- **Increased dialogue between space companies and end-users:** End-users will benefit from being educated about the power of space-based products and services to more broadly adopt space technologies. Global non-profits may be well positioned to convene senior leaders from space and non-space companies for education and knowledge exchange. Such forums would also allow end-users to share their needs with space sector players, which could inform product development and ensure that the space sector delivers innovations from which other sectors can benefit.

- **Efforts to attract diverse, high-caliber talent to the sector across regions:** While some nations are racing ahead, many emerging economies are only at the early stages of charting their space ambitions. Diverse participation in the sector will play an essential role in ensuring that the space industry reaches its full potential. Leaders believe governments can lead the way by funding a diverse group of researchers and entrepreneurs and providing opportunities for everyone to access finite space resources, such as launch windows or spectrum.

- **Removal of barriers to competition:** The high cost of operating in space already limits competition in the domain. Any further barriers may stifle innovation, slowing the rate at which technology advances and new use cases are unlocked. In our interviews, leaders suggested that governments may be able to use regulatory actions to lower barriers for new, promising entrants, encouraging and incentivizing more diverse access, for example, to orbital slots.

  Space spectrum is another global resource that will increasingly need to be shared. Here too, some interviewees say that government oversight may need to evolve and improve to democratize sharing. But regulations are not the only device in a government's toolbox. Experts suggest that governments could, for example, fund R&D programs, tailor corporate tax schemes, sponsor the development of new capabilities, and encourage knowledge development. Such levers can encourage the private sector to invest in space technologies, encourage innovation, and attract new players to the ecosystem.

- **Increased education about the potential of space, including for decision-makers:** All too often, end users are unaware of how they benefit from space-based technologies such as GPS. Experts noted that sometimes government leaders and decision-makers also lack a full understanding of the space economy's potential. In that case, they may make decisions and enact policies that unintentionally hinder the sector's development. Thus, the onus is on the space sector to help build a broader understanding of how it benefits individual nations and humanity. With access to this information, leaders can make better decisions that support the development of the sector's industrial base.

— **Cultivation of the broader ecosystem necessary for developing a space economy:** For instance, if insurers were to exit the market, investors might become very reluctant to put their money into space companies. As governments evaluate how they might support the space sector, leaders believe they should cast a wide net and consider the perspectives and needs of every stakeholder.

The next several years will be crucial in understanding how the sector can advance towards a self-sustaining space economy. There may be a delicate balance between pushing for progress and supporting early winners while encouraging new entrants and providing public support for young companies while they mature.

5. Leverage the space sector more to advance sustainability and security

In recent months, the space sector has demonstrated its potential to promote global security by publishing satellite data.[49] Meanwhile, private sector companies, non-profit organizations, and governments worldwide are working to leverage satellite-based tracking to improve transparency on emissions. Some leaders think that the international community can further embrace space-based data to accelerate high-priority sustainability and security agendas.

If the international community decides to adopt and accelerate space technologies such as Earth observation for greater transparency and accountability, experts believe the sector can achieve its full potential as a force for good. A self-sufficient space economy will be of little value if it does not help to sustain life on Earth.

Even as the space sector plays its part in advancing broader sustainability objectives, it should aim to set a good example by committing to employing sustainable practices at the outset and embracing accountability and transparency around sustainable business practices. For example, satellite missions could be given sustainability ratings based on their de-orbit plans and onboard propulsion to enable collision avoidance maneuvers.[50] The industry could apply international sustainability index metrics to missions both pre- and post-launch to drive accountability and support objective decision-making on whether a mission should proceed. These global metrics could be augmented by sustainability requirements, for example, for launch emissions and payload ridesharing. In short, the space sector could show its commitment to a sustainable future by moving decisively toward net-zero emissions and net-zero debris generation in orbit.

Given the increasing contribution of private capital, the space sector's investor base may be particularly well-positioned to help establish high expectations for sustainable practices. Space companies will tailor their actions toward attracting investment. If investors put their money behind sustainable operations, then space companies will likely adopt sustainable behaviors as a core component of their business model.

---

[49] Warren Strobel, "Release of Ukraine intelligence represents new front in US information war with Russia," *The Wall Street Journal,* April 2022; Emmett Lindner, "Verifying images of the war in Ukraine," *The New York Times,* April 2022

[50] *Space sustainability rating,* World Economic Forum

Each of these actions will play an important part in developing an accessible and self-sustaining space economy.

Open communication among stakeholders will be important. It is critical to maintain ongoing, honest discussions about the sector's evolution, including concerns about the trajectory or the pace of progress. As the future unfolds, leaders want to see the sector continuously measuring progress, assessing what is working, seeing where it can go further, identifying issues that need to be addressed, and deciding how to respond to new challenges that arise.

Cooperation is the key to success

Leaders agreed that developing an accessible, self-sustaining space economy depends on robust global cooperation. For this to happen, they said that countries and companies need to align around appropriate rules, norms, and enforcement mechanisms.

In some areas, existing international organizations could play a role in encouraging and facilitating this cooperation. Yet leaders suggest that dedicated new forums may be needed to align stakeholders, advance objectives, and serve as conveners around the key issues for space.

They also suggest that any governing forum should be oriented toward action and speed. With the sector rapidly evolving, stakeholders should resolve the initial challenges in months, not decades. To potentially increase the pace of advancement, some experts said the sector can benefit from actors proposing rules, drafting policies, and clarifying the forum or organization responsible for advancing particular initiatives.

Of course, as the sector grows, disagreements could arise around controversial issues such as mining rights on celestial bodies and the sharing of space situational awareness data. Nonetheless, leaders see an opportunity to move quickly toward alignment on certain foundational governing principles that could provide a basis for resolving more controversial issues.

Effective governance is only one part of the equation. To generate commercial value, actors will have to invest in enabling technologies, for instance, through government programs that would facilitate progress in areas such as nuclear propulsion, where stakeholders broadly agree more investment is needed. In other areas, private companies can accelerate technological progress by cooperating or forming consortia.

Beyond achieving a self-sustaining space economy, leaders want to see a higher standard for the space sector as a force for good. They see the potential for the space sector to help the fight against climate change, give access to information for all of humanity, and provide other tangible benefits for our planet. By taking the right actions today, humanity could enjoy the myriad advantages of a peaceful and vibrant space sector that also creates tremendous economic value.

Appendix: Sources of perspectives

This work has been guided by an advisory board, composed of the following members:

Rick Ambrose – Former Executive Vice President, Lockheed Martin Space *(Co-Chair)*

Chris Kemp – Founder and CEO, Astra *(Co-Chair)*

Her Excellency Sarah Al Amiri – Minister of State for Advanced Technology, UAE; Chairwoman, UAE Space Agency

Josef Aschbacher – Director General, European Space Agency

Shravin Bharti – Founder and CEO, Unbound

Ryan Brukardt – Senior Partner, McKinsey & Company

Vint Cerf – Internet Pioneer; Founder, IPNSIG

Stephen Kitay – Senior Director, Microsoft Azure Space

Will Marshall – Co-Founder and CEO, Planet Labs

Tanja Masson-Zwaan – Assistant Professor/Deputy Director, International Institute of Air and Space Law, Leiden University; President Emerita, International Institute of Space Law (IISL)

It has also greatly benefitted from perspectives shared via interview by nearly 100 leaders, from the following organizations:

Private sector

Accion Systems

ArianeGroup

Arianespace

Astranis

Astroscale

AXA XL

beyond gravity

Blue Origin

Boeing

Delalune Space

Earth2Orbit

Euroconsult

Fleet Space

Hanwha

Hypersonix

ispace

Jacobs

Kratos Defense & Security Solutions, Inc.

Leidos

LeoLabs

Lockheed Martin

Maxar Technologies

Meta Aerospace

Momentus

OneWeb

Orbit Fab

Outpost

Raytheon Intelligence & Space

Rocket Factory Augsburg (RFA)

Rocket Lab

SAIC

Space Hero

ST Engineering

Private sector (continued)

Terran Orbital

The Exploration Company

Tomorrow.io

Ursa Major

Viasat

Virgin Orbit

Voyager Space

Former employees from:
ICEYE, Virgin Galactic

Government

Czech Space Office

Defense Innovation Unit (DIU)

Federal Communications Commission (FCC)

Federal Department of Foreign Affairs of Switzerland

G42

Kenya Space Agency

Luxembourg Space Agency

International Telecommunication Union (ITU)

Intersputnik International Organization of Space Communications

National Aeronautics and Space Administration (NASA)

National Space Research and Development Agency (NASRDA)

National Space Science Agency (NSSA)

Nigerian Communication Satellite Limited (NIGCOMSAT)

Norsk Romsenter (Norwegian Space Agency)

UK Space Agency

United Nations Office for Outer Space Affairs (UNOOSA)

US Air Force

US Space Force

Anonymous space agencies (2)

Former employees from:
Federal Aviation Administration (FAA), United Nations Office for Outer Space Affairs (UNOOSA), US Department of Defense (DoD)

Investors

Blackstone

DCVC

Seraphim Capital

Shasta Ventures

Academic/non-profit

American Foreign Policy Council

Foundation for Space Development Africa

Georgia Institute of Technology

International Institute of Space Law (IISL)

Limitless Space Institute

MIT Media Lab

Observer Research Foundation

Secure World Foundation

School for the Future of Innovation in Society, Arizona State University

SDA Bocconi

Skolkovo Institute of Science and Technology

Smithsonian Institution

Space Industry Association of Australia

Spaceport SARABHAI

The Aerospace Corporation

The Federation of German Industries (BDI)

The University of Texas at Austin

Glossary

Anti-satellite (ASAT) tests – Military demonstration in which a missile system is used to destroy a spacecraft in orbit

Artemis Accords – Set of non-binding commitments on principles for peaceful and responsible civil exploration of the Moon and beyond, signed by a subset of space agencies around the world

Asteroid mining – In-space mining of metals and minerals from asteroids

Bandwidth – Amount of data that can be received, processed, and transmitted by a satellite

Chemical propulsion – Propulsion in which the thrust is provided by the product of a chemical reaction

Cislunar – Region of space from the Earth out to and including the region around the surface of the Moon

Collision avoidance maneuver – Intentional movement (change in velocity) by a spacecraft to mitigate the likelihood of contact with another object in space

De-orbit – To depart deliberately from orbit, usually to descend to Earth

Digital twin – Virtual representation of an object or system, updated from real-time data and designed to accurately reflect the physical system or object

Distributed system architecture – The interaction of multiple satellites to accomplish objectives (as contrasted with a monolithic spacecraft)

Downmass – Payload mass carried down to Earth from space

Earth observation – Gathering of information about the Earth's surface and atmosphere using remote sensing technologies, commonly from satellites

Electro-optical imagery – Photographs captured with electro-optical sensors (which takes light rays and converts them into electronic signals), often via satellite

Fissile material – Material that can undergo the fission reaction and is a key component of potential nuclear propulsion for spacecraft

Frequency – Measure of the range of the electromagnetic spectrum a spacecraft operates in, wherein waves are transmitted to and from the spacecraft. Frequency ranges, or bands, vary in suitable applications and tradeoffs of factors such as bandwidth access and signal degradation

Geosynchronous equatorial orbit (GEO) – An orbit farther from Earth than LEO and MEO, where satellites can match the Earth's rotation, thereby appearing to be stationary over a fixed position

Hyperspectral imaging – The capture of information across the entire electromagnetic spectrum to produce imagery at a level that allows for fine discrimination

In-situ resource utilization – The use of materials found in space to support exploration via generation of consumables to substitute for resources that would otherwise need to be transported from Earth

International Space Station (ISS) – A space station in LEO that hosts astronauts and serves as a scientific lab. The first piece of the ISS was launched in 1998 and the station is a product of collaboration among international partner space agencies

Latency – In the satellite context, the time between satellite observation and the time data are available to users

Low-Earth orbit (LEO) – An orbit relatively close to Earth's surface, and the area of deployment for many satellite constellations

Low-G re-entry – Gentler re-entry to Earth from space than high-G re-entry, enabling fragile cargo to be brought back from space

Lunar mining – Mining of metals and minerals on the Moon

Medium-Earth Orbit (MEO) – An orbit with an altitude between LEO and GEO

Megaconstellation – A large group of satellites designed to operate together to achieve an objective(s) and numerous enough to enable substantial global coverage

Microgravity – Very weak gravity environment in space

Monolithic system architecture – The use of a single spacecraft to achieve an objective

Moon base – Conceptual permanent infrastructure on the surface of the Moon, enabling human activity on the Moon

Moore's law – The principle that the number of transistors in a silicon chip doubles approximately every two years

Nuclear electric propulsion (NEP) – Electric propulsion in which the electricity is derived from a nuclear reactor; being explored for potential use in deep space exploration

Nuclear thermal propulsion (NTP) – Propulsion method that works by pumping a liquid propellant through a nuclear reactor core; being explored for potential use in deep space exploration

Off-the-shelf components – Products that are widely available and do not need to be made-to-purpose

Payload – Portion of a spacecraft specifically dedicated to procuring mission data and relaying such data back to Earth

Remote sensing – Process of obtaining information about objects or areas from a distance, often via satellite

Reusable launch vehicle – Launch system that is designed to return to Earth substantially intact, and is thus able to be launched again

Satellite constellation – Group of satellites working together as a system to achieve a unified purpose

Satellite throughput – A measure of a satellite's bandwidth and efficiency, reflecting the balance of overall data capacity versus speed

Space debris – Human-made objects in space that no longer serve a useful function

Space-for-Earth economy – Goods and services produced in space or using space-based assets for use on Earth

Space-for-space economy – Goods and services produced in space for use in space

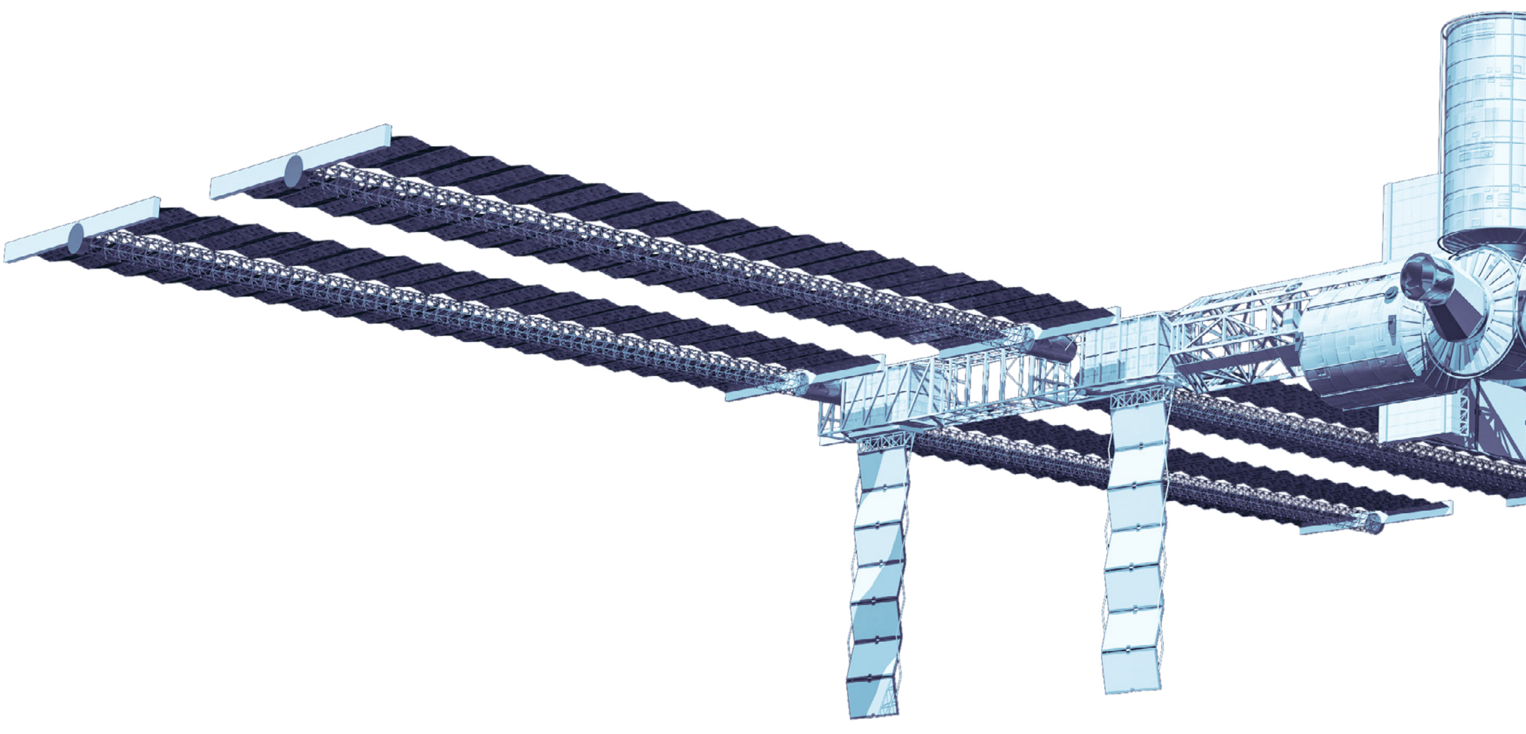
Space situational awareness (SSA) – Domain focused on tracking of objects in orbit and predicting where they will be at any given time

Space traffic management (STM) – Domain focused on safe access, operation, and return of space assets

Spectrum – Radio frequencies satellites use to communicate with the ground or other spacecraft

Sputnik – The first artificial Earth satellite, launched in 1957

Synthetic aperture radar (SAR) – A form of radar data collection, capable of producing high-resolution images in various conditions (including night and inclement weather)



The role of space in driving sustainability, security, and development on Earth
2022

Designed by US Design Center

www.mckinsey.com

@McKinsey
@McKinsey

The authors wish to thank Sarina Carter, Eric Chewning, Reed Doucette, Sam Ezratty, Nikolai Khlystov, Jesse Klempner, Jonathan Li, Kelsi McDougle, Lauren O'Connor, Daniel Pacthod, Brooke Stokes, and Mary Kate Vaughn for their contributions to this report.