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FRONTIERS: SPACE

Five Big Ideas Shaping Tomorrow's Off-World Economy

There was a time when space exploration seemed like a thing of the past. Since the final Apollo mission blasted off for the Moon over 50 years ago, humanity has not ventured further than low-Earth orbit.

But that's all changing. Space exploration is back on the agenda, partly driven by the rise of new global space powers to rival the US and Russia. Since the turn of the millennium, the ambitions of China's space program have accelerated; it has put astronauts into orbit, landed rovers on the Moon and Mars, and constructed a manned space station. India, too, has been making notable progress. In August 2023 it became the first country to land a rover at the lunar south pole, and has launched a probe into solar orbit.

A new space race is underway—and the longer-term ambitions are even grander than before. The US and China both want to establish a permanent presence on the Moon, and are planning crewed missions to Mars.

There's another crucial difference between this new era of space exploration and the last: The involvement of private enterprise. "Increasingly, private companies are launching rockets, deploying satellites, and undertaking the kinds of orbital activities that not long ago would have been the domain of governments," says Willem Sels, Global CIO of HSBC Global Private Banking. These companies are winning contracts to supply technology to national space agencies as they embark on their missions. But the private sector is also conducting missions of its own, contributing in a multitude of ways to a marketplace that is on course to be worth more than $1 trillion within two decades.

The emerging space economy comprises new types of businesses that would have been impossible until recently. Many of these use innovative satellites to provide services—wireless internet, say, or advanced imaging—to customers on Earth. Others are more experimental, devising new forms of technology for new applications altogether—and just possibly changing the paradigm of off-world activity in the process.

Investors have taken note, with funding rushing into the sector. "One of the difficulties is that quite often the stocks on the stock market don't give you much exposure to these ideas, and so you need to go to the private market," says Sels. "It's one of those examples of where private equity can have a role to some extent in portfolios." He cautions that those who go down this path should be prepared to play the long game. "This probably needs to be capital that you can put away for a number of years. As the adage has it: People underestimate the things that happen in 10 years, but overestimate what happens in two years."

So, what are the trends that could become increasingly interesting? This edition of Frontiers shines a light on five big ideas that are transforming space. All of them are enjoying serious venture capital flows and are attracting attention from credible experts. For each one, we've interviewed a specialist to hear why they're excited about the prospects, but also to explore what challenges still need to be solved.

Those stories are:

Perhaps it's no accident that, right now, space seems to have captured imaginations. "It's been an unusual few years, and many people are wondering about their purpose in life," says Sels. "Space exploration is about progress and discovery, but on a more philosophical level it's about meaning—what it means to be human. For entrepreneurs and investors, getting involved in these ideas is often about more than making money, it's about participating in something more profound."

Meet the expert

Willem Sels
Global CIO of HSBC
Global Private Banking

WHY 'LIVING OFF THE LAND' WILL BE CRUCIAL TO FUTURE SPACE EXPLORATION

As humanity ventures further into the solar system, harvesting resources in space for use off-world will be essential

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or every kilogram that lands on the Moon or Mars, around 7.5-11 kg has to be launched from Earth. This is not only costly—equipment, rocket fuel, personnel—but it is time consuming, and that's before you factor in the duration of the spaceflight. The less that has to be sent up, and the less frequently that has to happen, the better.

That's why, as humans seek to venture beyond Earth, astronaut-settlers on new worlds will need to harvest local resources in order to stay for the long term. This is something wholly new to the space community, and until relatively recently was considered science fiction.

Previously, during the Apollo program, NASA's missions to the Moon were solely "flags and footprints" forays. Astronauts went down to the surface of the Moon, walked around, planted a flagpole, scooped up some rocks, and flew back to Earth for parades and parties—all within a few days.

Heralding the coming era of space exploration, NASA's Artemis program aspires to go back to the Moon this decade with a view to establishing a long-term presence—"for scientific discovery, economic benefits, and inspiration for a new generation of explorers"—and then using what has been learned to send astronauts to Mars by the late 2030s or 2040s. NASA is studying the potential for using local resources in situ at both locations. "We are going to have to learn to be less Earth-dependent," says Niki Werkheiser, the Director for Technology Maturation for

"WE ARE GOING TO HAVE TO LEARN TO BE LESS EARTH-DEPENDENT."

Niki Werkheiser, Director for Technology Maturation for NASA's Space Technology Mission Directorate

NASA's Space Technology Mission Directorate. "That means being able to use the local resources in whatever ways make sense. This could include consumables for the crew, such as oxygen and water, propellant for fuels, or materials for construction of things such as landing pads, roads and potentially even habitats. Longer-duration missions further from Earth become much more feasible when we can use those local resources to help us live and operate so far from home."

An array of private companies are working on techniques and equipment for off-world "in-situ resource utilization"—or ISRU, as this field is known—with a number focused on filling technology gaps for organizations such as NASA on a public-private partnership basis. This is separate from the prospector-style notion of mining precious metals or chemicals in space for sale on Earth, but a European study estimated that the ISRU industry alone would generate market revenue of up to €170bn by 2045, and forecast that the spillover technologies from ISRU projects would be worth €2.5bn over the coming 50 years.

So, what resources are we talking about, exactly? During the Apollo 11 Moon landing, Earth famously heard the lunar landscape described as "magnificent desolation", but in truth there are likely some valuable materials to be found there. Perhaps most intriguingly, lunar scientists believe there are large deposits of water ice at the poles of the Moon, in permanently shadowed craters where ice from comets has accumulated over billions of years. NASA, as well as China with its separate lunar program, plan to soon send a series of science missions to explore these polar regions and assess the feasibility of harvesting this ice. If it exists, the water could be used not just for human consumption, but also broken down into air to breathe, as well as used for rocket fuel in the form of liquid oxygen and liquid hydrogen.

This won't be straightforward. The phrase "lunar ice" calls to mind sheets of frozen water, but the reality is more complex. The ice is mixed into the soil-like rocky deposits, known as regolith, that cover the lunar surface. That means it will need to be extracted and purified. NASA is considering various concepts for how this set-up might operate. One involves a system with four key elements.

"THE WATER COULD BE USED NOT JUST FOR HUMAN CONSUMPTION, BUT ALSO BROKEN DOWN INTO BREATHABLE AIR AND ROCKET FUEL"

First, an excavator to mine ice-rich regolith at the base of a crater. Second, a water extraction unit to heat the regolith and remove the water by sublimating it into vapor, before freezing it for storage in water tanks. Third, mobility platforms to drive those tanks out of the crater. And, finally, a production plant at the top of the crater to extract and store the hydrogen and oxygen.

It's not just about ice. The lunar surface is also rich with metals and silicate. While these can be useful, they can create hazardous conditions; the abrasive lunar dust tore away at the spacesuits and boots of the Apollo astronauts. However, these materials can also be employed for a variety of applications, such as laying down smooth landing pads for spacecraft or building solar cells to generate energy. "A particularly key capability for enabling a long-term presence on the Moon is power generation and storage, because the lunar day-night cycle results in 14 days of continuous sunlight followed by 14 days of continuous darkness," says Werkheiser. This means that the technologies would have to be robust enough to endure extreme temperatures, while providing power throughout that whole cycle.

"If we can extract metals and silicates from the lunar surface, then we could use them to make solar cells and wires for solar arrays and transmission cables," she says. "These kinds of novel technologies will be essential for surviving the long lunar night." One private company is experimenting with "fake" regolith on Earth to prove that if lunar soil is melted at high temperatures—around 1,600 degrees Celsius— the required elements can be separated out in a reactor using electrolysis.

Mars takes the need for harvesting local resources to the next level. While astronauts can reach the International Space Station in a few hours, and the Moon in about three days, Mars takes at least half a year. Most of NASA's roundtrip missions to the Red Planet will put astronauts beyond Earth's reach for a minimum of 18 months.

Mars has its share of resources, too, including ample water ice at its poles. Unlike the Moon, the red planet also has a thin atmosphere. While the surface pressure is extremely low, and requires astronauts to wear spacesuits, there are some useful gasses in that atmosphere. Harnessing them is

"THESE KINDS OF NOVEL TECHNOLOGIES WILL BE ESSENTIAL FOR SURVIVING THE LONG LUNAR NIGHT."

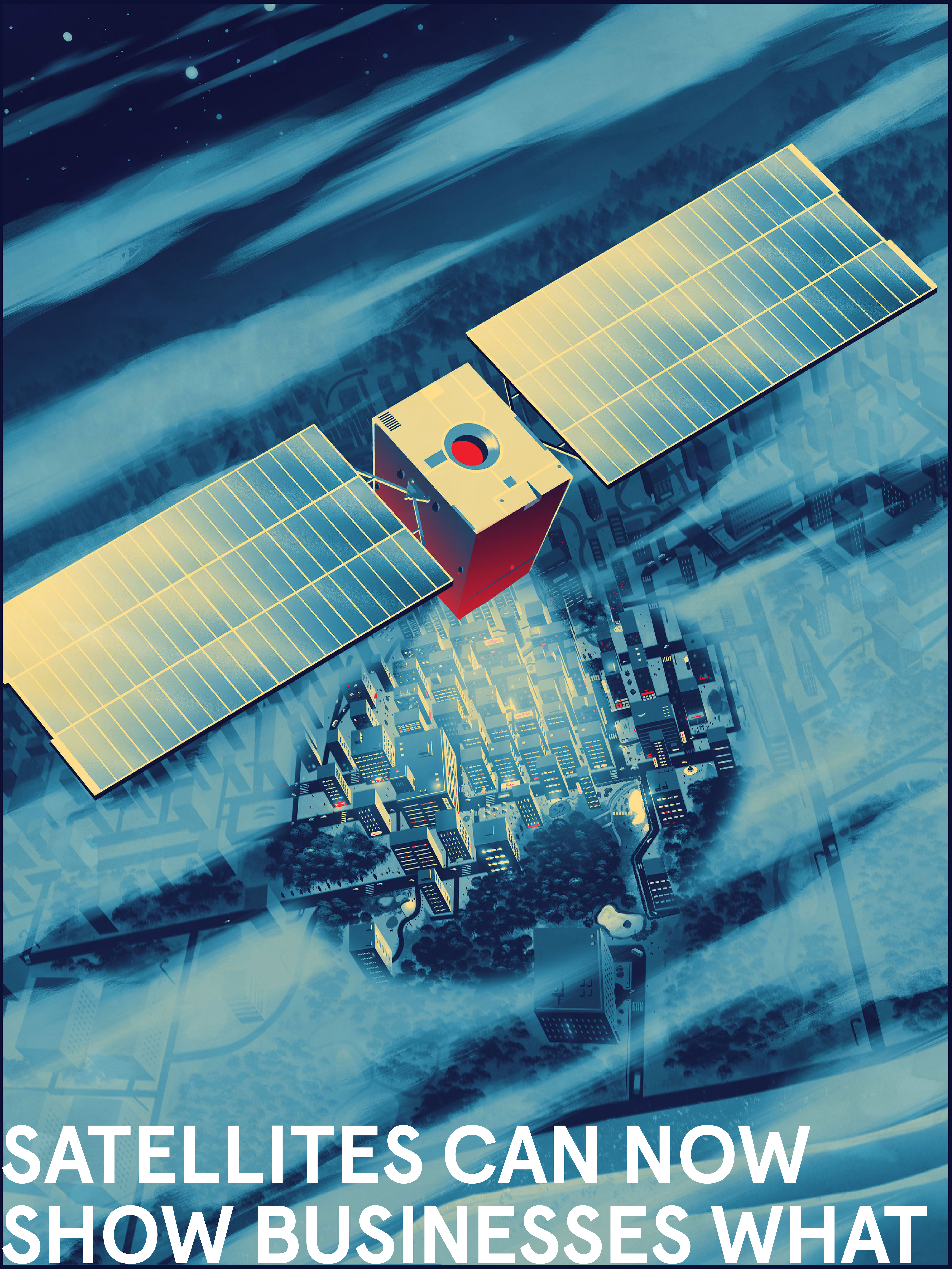
Niki Werkheiser, Director for Technology Maturation for NASA's Space Technology Mission Directorate another key area of experimentation. NASA, for example, has had a demonstrator, named MOXIE, hitch a ride on its Mars Perseverance rover. Since landing on Mars in 2021, MOXIE has used an electrochemical process to split out more than 122 grams of oxygen from the atmosphere's carbon dioxide.

There are myriad challenges to overcome with a manned Mars mission, but one of the biggest is having enough propellant on Mars for the return trip to Earth. Bringing all of that fuel from Earth to Mars for a voyage home is likely to be cost- and mass-prohibitive, so producing propellant on-site, perhaps in the manner showcased by MOXIE, could be vital.

"The ability to harness these in-situ resources to make propellant for transportation to and from Mars truly has the potential to be mission-enabling," Werkheiser says. "The fact that we are now starting to actually test these technologies in space is very exciting."

Meet the expert

Niki Werkheiser is the Director for Technology Maturation for NASA's Space Technology Mission Directorate, where she leads the advancement of mid-readiness level technologies for future space missions.



SATELLITES CAN NOW SHOW BUSINESSES WHAT THE HUMAN EYE CAN'T SEE

Dark? Cloudy? Snowy? 'Synthetic aperture radar' satellites can peer through it all, and this new sector is booming

Imagine a satellite image. You’re probably thinking of something taken by a high-res camera pointing down at the Earth—a bird’s-eye photograph. And that can be immensely useful for everything from navigation to city planning, but it has limitations. At any given moment, about half the planet is cloudy, and about half the planet is under the darkness of night. For real-time events, having the capability to “see” any point on the planet whenever you want to see it is incredibly important.

That’s why an alternative way of looking at the Earth has recently been making waves in the commercial world. Synthetic aperture radar (SAR) satellites don’t have lenses but radio antennae. These send out electromagnetic pulses and record the echoes as they bounce off the Earth’s surface. The echo data is then processed to produce an image. Because those pulses have much longer wavelengths than visible light, they can penetrate the likes of cloud cover or snow, and darkness is irrelevant. This means that multi-dimensional images of the surface’s structure can be taken at any time without fail, enabling persistent observation.

A number of companies are now running SAR satellites and offering access to their data “as a service” across a range of fields. “It is especially useful for environmental monitoring, for example, particularly to chart deforestation,” says Shay Strong, Vice President of

“IT IS ESPECIALLY USEFUL FOR ENVIRONMENTAL MONITORING, PARTICULARLY TO CHART DEFORESTATION.”

Shay Strong, Vice President of Analytics for SAR satellite-operator ICEYE

Analytics for SAR satellite-operator ICEYE. “Rain clouds make this difficult in locations like the Amazon.” The technology has also assisted in the monitoring of natural disasters, such as volcanic eruptions or earthquakes. The SAR sector is currently in a growth phase, with one estimate forecasting the global SAR market size hitting $10.7bn by 2032.

So how did we get here? Governments developed SAR decades ago, originally for military surveillance. But several powerful and persistent trends have led to this imagery now being made available to a broad array of business customers. For most of the history of spaceflight, only governments and traditional space contractors could afford to build satellites. They were large and complicated spacecraft, often costing hundreds of millions to billions of dollars. But no longer. Just as technology has trended smaller on Earth in recent decades, with miniaturization leading to powerful computers sitting in our pockets, so too have satellites gotten smaller. In addition, companies have started taking a more commercially minded approach toward building satellites, using off-the-shelf components and designing more for efficiency and cost.

Another key trend is the diminishing expense and time involved in getting a satellite into orbit. The advent of private rideshare rocket rides has been a game-changer. Dozens of small satellites can be bundled together on a single launch, splitting the cost among many customers. The end result of all of this has been an influx of new companies and private capital aiming to disrupt low-Earth orbit with commercial satellites that can offer valuable services for the planet’s inhabitants. It is the boom area of the emerging space economy.

New markets have duly coalesced, but until recently Earth observation services have depended mainly on visible light. That changed around five years ago when the first private companies to offer SAR opened for business. Finland’s ICEYE, which has raised a total of $304m in funding, was one of those companies.

Today, the company has a constellation of 27 SAR satellites. Putting aside the difficulties of working with sensitive components and overcoming computational challenges, this kind of radar imaging is inherently complex

“THE SAR SECTOR IS CURRENTLY IN A GROWTH PHASE”

because it has to work around a fundamental physics problem. Theoretically, producing high-resolution images from very long-wavelength radio waves requires a huge antenna (in the jargon, a huge "aperture")—in fact, one so enormous it would be impractical. That's where the "synthetic" bit of synthetic aperture radar comes in. As the satellite moves over a target, it receives multiple echoes. By combining these into a single image it can achieve clarity equivalent to having an aperture as large as the distance the satellite has traveled in that time. And that is the key to a further advantage of SAR. Since it is able to map the physical structure of the Earth at such high resolution, comparing two images of the same target can reveal surface changes on the millimeter scale.

ICEYE offers this data to organizations engaged in everything from managing floods and wildfires to monitoring sea ice or ports. It has proven especially valuable to insurance companies trying to make claims assessments following a natural disaster.

"The big insurers spend a tremendous amount of money to send a person out with a clipboard to check the aftermath of an event," says ICEYE's Shay Strong. "And it happens not just for floods, but after fires and large wind-storms. It's fraught with uncertainty because you're sending out someone who could be tired and rushed, perhaps making accidental biased decisions. ICEYE is helping to automate this process through quantitative observations so insurers can be faster to respond to clients, and pay claims more equitably."

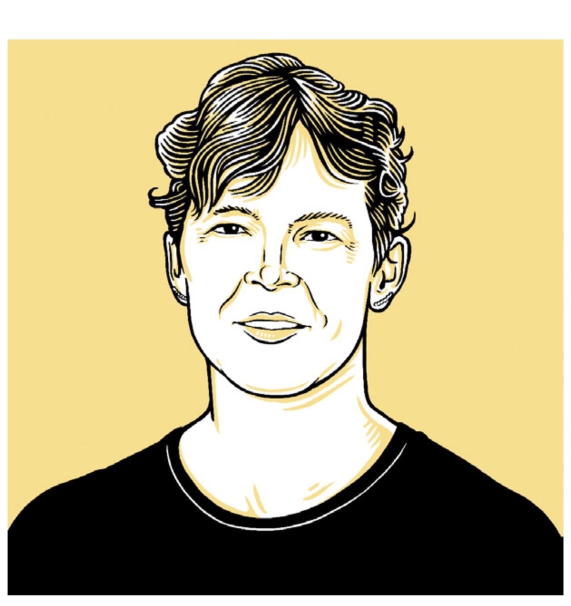
Initially, the focus for ICEYE was developing the radar technology and deploying it into space. The company believed it would just sell the data raw. But pretty quickly, says Strong, ICEYE realized that the true value lay in applying machine learning and additional analytics to help companies and governments get actionable information out of that data.

"Unlike with an optical image, few people understand the complexity of the information they're looking at in an SAR image," says Strong. "It looks and feels like an optical image in many ways. But there's a tremendous amount of challenge with interpretation of the underlying physics." And as ever, where there are challenges, there

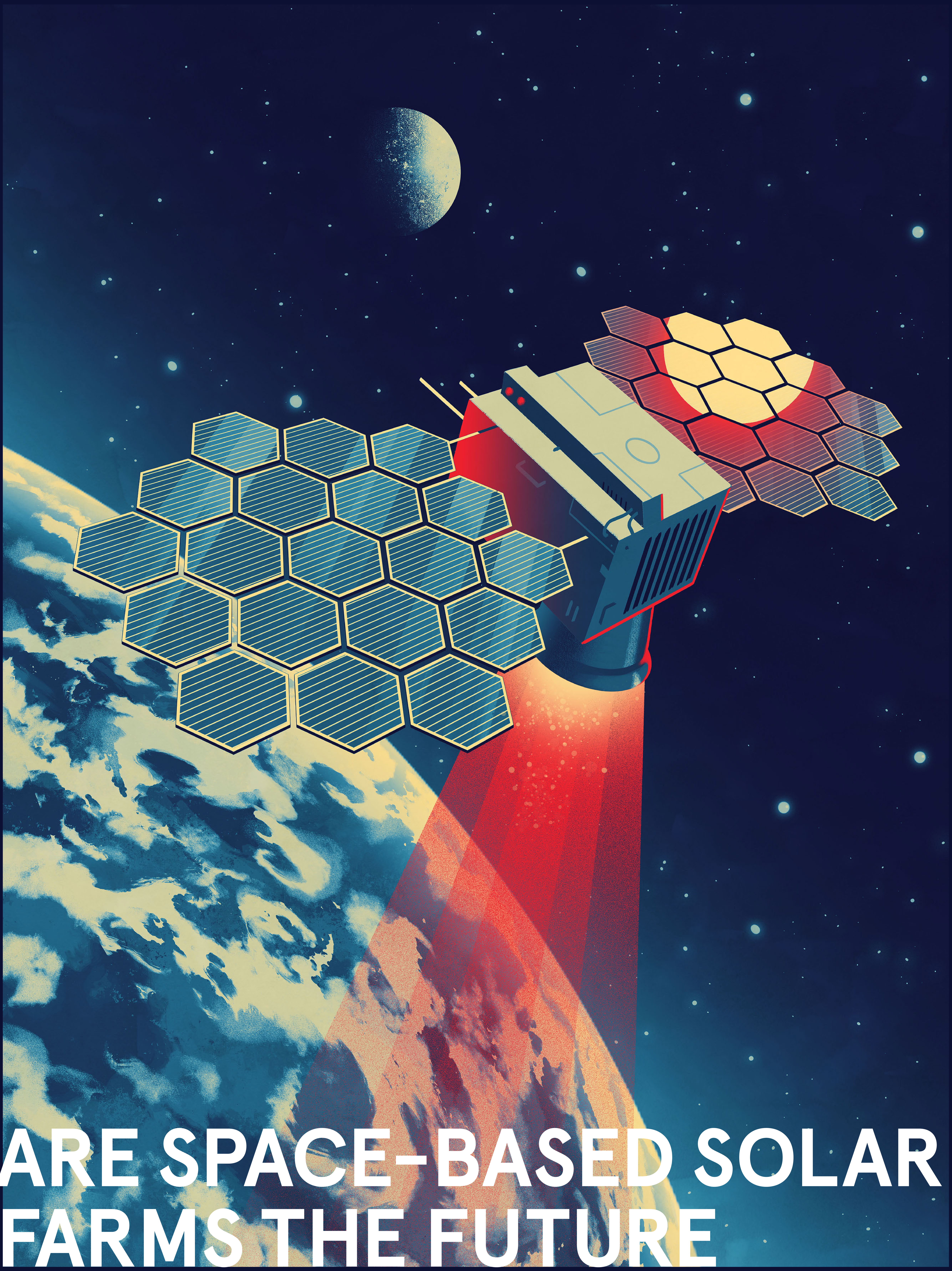
"THE ADVENT OF PRIVATE RIDESHARE ROCKET RIDES HAS BEEN A GAME-CHANGER"

are opportunities. "What we're doing now, is making that data more useful—and I think we are going to see continuing advances on that side of the equation. In particular, identifying and then building the critical solutions that benefit from this information. SAR imagery, and the solutions leveraging it, is a mechanism to quantify the impact of the changing Earth."

Meet the expert



Dr. Shay Strong is the Vice President of Analytics for SAR satellite-operator ICEYE, where she leads development of natural catastrophe solutions based on high-resolution SAR imagery.



ARE SPACE-BASED SOLAR FARMS THE FUTURE OF CLEAN ENERGY?

The idea is enjoying more attention than ever—but there are major challenges to overcome

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he idea of collecting solar energy in space and beaming that power to Earth is not new. In 1941, Isaac Asimov published a short sci-fi story called Reason, in which humans do just that. Over the decades that followed, scientists and engineers have revisited the concept periodically. But what *is* new is that space-based solar power may now be technically and economically feasible.

That's what a European Space Agency (ESA) engineer named Sanjay Vijendran realized when he started assessing the concept in 2020. A new generation of reusable rockets had begun to address the need to get lots of solar panels into space for a reasonable cost. And, at the same time, private companies were bringing down the cost of satellite production.

"It seemed to us that many things were coming together to make the business case close," says Vijendran.

The timing was opportune in other ways. Europe was seeking alternative energy sources to break its dependence on other countries for natural gas and other fossil fuels, and public surveys were expressing desire that space agencies prioritize projects that help address problems here on Earth. Developing a space-based solar array to provide a renewable, carbon-neutral source of energy hit the sweet spot of giving the European Space Agency a grand ambition that met the continent's growing concern about climate change.

The space agency's council approved the creation of the SOLARIS initiative in November 2022, and tapped Vijendran to lead it. Its first task is to carry out a full analysis

"MANY THINGS WERE COMING TOGETHER TO MAKE THE BUSINESS CASE"

Sanjay Vijendran, lead engineer, European Space Agency SOLARIS program to determine whether Europe should start investing billions of euros into the technology. If it moves ahead, this will likely happen during the second half of this decade.

The ESA is not an outlier in wishing to explore space-based solar power. In the UK, a government-endorsed initiative is bringing together more than 75 organizations around the idea, and, in 2023, the government injected £4.3m into eight projects aiming to develop relevant technologies. In the US, the government has awarded a $100m contract to the private sector to launch a prototype this decade. And in China, work is reportedly underway to launch a trial solar array in 2028. By one recent estimate, the global space-based solar power market could be worth $3.4 billion by the end of 2031.

In theory, space-based solar power is straightforward. Satellites orbiting far above Earth's atmosphere collect solar energy and convert it into current, and this energy is then beamed back to Earth—many projects are looking at doing this via microwaves. That energy would then be captured by large antennas, converted back into electricity, and sent to the grid for residential or industrial use.

"This would offer a range of advantages over terrestrial solar power," says Vijendran. "That's especially true in Europe. Days are shorter. There is often cloud cover. Solar irradiance during the winter can be very low." In space, none of these are issues. Space-based solar panels can capture high-intensity, uninterrupted solar radiation at scale, meaning it could become a "baseload" source of energy, providing power constantly to meet day-round demand, much like nuclear power now.

However, the challenges of this approach are myriad. First of all, such an array of solar energy collectors would need to be huge. One concept being considered by the ESA is a constellation of dozens of very large satellites located in geostationary orbit, 36,000 km above Earth. Each of these satellites would be ten times more massive than the International Space Station, which took more than a decade to assemble in low Earth orbit.

Then there are the technological challenges, such as wireless power transmission. This has been demonstrated on Earth, with kilowatts of energy sent over a matter of a few kilometers. But for space-based solar power, this

"SPACE-BASED SOLAR POWER WOULD OFFER A RANGE OF ADVANTAGES OVER TERRESTRIAL"

Sanjay Vijendran, lead engineer, European Space Agency SOLARIS program transmission would need to occur over tens of thousands of kilometers, with gigawatts of energy. The receiving antennas would need to be huge, measuring hundreds of meters to kilometers in scale.

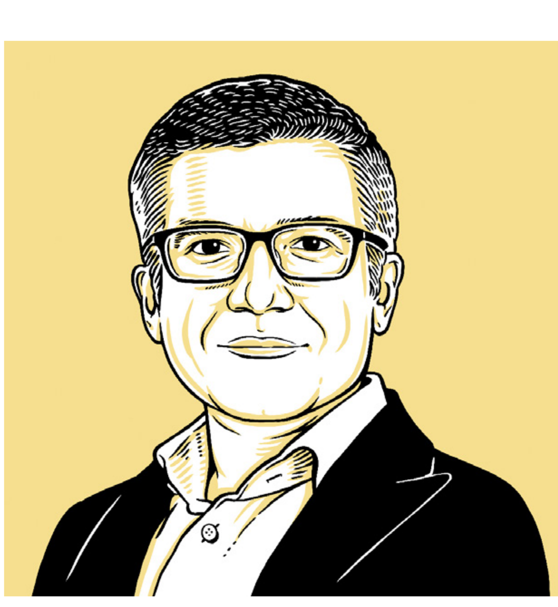
"That's just so far removed from anything anybody has done on Earth or in space, so we're bound to find problems along the way," says Vijendran. "But it's not like somebody's tried it and failed. So we just need to get on with working on expanding the transmission power and the size of the antennas, and solving the problems that will come with being able to coordinate all of these elements in a controlled way to form a beam, and send energy safely and accurately across large distances."

Beyond the technological challenges, there is also the issue of cost. It is far, far cheaper to just set some solar panels out in your backyard and plug them into the electricity grid on Earth than it is to launch them into space, beam the power across great distances, and convert it into usable electricity.

Vijendran says that this is not comparing apples with apples, since the nature of the electricity provided is not the same. Space-based solar power would be reliable; Earth-based solar is unreliable. But in practice he sees the two working together. "Having a space-based source of baseload power will help accelerate the roll-out of terrestrial solar and wind, reducing the need for large-scale storage solutions," he says. "So it helps resolve major challenges the current industry faces to transition to a fully clean energy system."

In other words, Asimov's short story may yet prove to be prescient.

Meet the expert



Sanjay Vijendran is the lead engineer for the European Space Agency's SOLARIS program, working on research and development of space-based solar farms.

HOW CELESTIAL ‘GAS STATIONS’ COULD UNLOCK THE SPACE ECONOMY

Orbiting propellant depots are in development, and they could reinvent how we operate beyond Earth

In 2021, we got a glimpse of the future.

That year, Colorado-based Orbit Fab launched a new kind of object into low-earth orbit. Named Tanker-001 Tenzing, this 35 kg satellite was a fuel depot: It contained a supply of propellant made from concentrated hydrogen peroxide. The aim? To test a concept for in-space satellite refueling—and edge closer to a whole new approach to space exploration based around permanent infrastructure.

Traditionally, every satellite launched into orbit carries all of its fuel with it. The satellite uses this fuel for pointing itself in the right direction, maneuvering for maintenance and shifting orbits. And, when the propellant runs out, that's the end of the line for the satellite—even if it is healthy in every other respect. The option of refueling that satellite, and extending its lifespan, is therefore valuable.

Civil and military space agencies around the world are interested in orbital propellant depots, and a number of companies are experimenting with how this technology might work. What's more, for the first time, new satellite designs are starting to include a refueling port as a standard option. The US government has taken note of Orbit Fab's progress, and awarded it a $13.3m contract to provide hydrazine fuel for US Space Force satellites in orbit around the Earth. "The government is really driving this," says Orbit Fab's CEO Daniel Faber, a serial space-

"ORBIT FAB'S AMBITION IS TO STATION PROPELLANT DEPOTS AT A VARIETY OF DIFFERENT ORBITS"

sector entrepreneur. Orbit Fab has raised more than $30m in venture capital funding; a recent study estimated that the global in-orbit refueling market will approach $1.1bn by 2032.

Propellant depots have potential applications well beyond satellites. They could help rocket builders take on longer missions, because fuelling up a rocket's upper stage in space means less mass to get off the ground first. In the future, new forms of activity—such as the in-space assembly of items that are too large for a single rocket—may entail platforms and infrastructure that will also need fuel. And perhaps, one day, novel operational paradigms could emerge, where refuellable space tugs could ferry people and items between Earth-orbit and lunar-orbit.

A 2021 study put the value of a single kilogram of fuel in orbit—which could be purchased on Earth for a few dollars—at $800,000. If sending payloads into space can now cost as little as $1,000 per kilogram, there is a clear business case for companies to collect, store, and transfer propellant sent up from the surface of Earth. "When I saw that study, I knew we had to build this business," says Faber. "It's just a phenomenal opportunity."

Orbit Fab's ambition is to station propellant depots at a variety of orbits. To refuel, a satellite or spacecraft would dock with one of these depots, before a system the company has designed called RAFTI (Rapidly Attachable Fluid Transfer Interface) would enable propellant to move across. Although Orbit Fab likes to use the metaphor of visiting a "gas station" to describe this set-up, it's more akin to an aircraft getting refueled in-flight. The company has a launch coming up in 2024 to demonstrate its capabilities, and the plan is to commence its US government contract in 2025.

Ultimately, the amount of fuel that can be delivered in orbit will be determined by the size of the propellant tanks, the rate at which it can be transferred, and the length of time the fuel can be stored. For hypergolic propellants like hydrazine—which spontaneously ignite when mixed with an oxidiser—storage even for years is relatively easy. For cryogenic propellants such as liquid hydrogen—which require cooling to extremely low termperatures—storage is much more challenging. Hydrogen boils at

"A 2021 STUDY PUT THE VALUE OF A SINGLE KILOGRAM OF FUEL IN ORBIT—WHICH COULD BE PURCHASED ON EARTH FOR A FEW DOLLARS — AT $800,000."

-252.9 degrees Celsius, and although space is typically very cold, when hydrogen tanks are in sunlight they can heat up rapidly, causing the hydrogen to evaporate. But since hydrogen is the most efficient propellant for moving around in space, NASA and the US Space Force both have programs working on cryogenic fuel storage and transfer.

As the space economy matures, so too may the propellant depot model. “In the near term, all of the fuel that the depots store will come from Earth,” says Faber. “But, by around 2040, I expect resources to increasingly come from the Moon and asteroids.”

The wider business ecosystem this picture implies may include activities that would provide further opportunities for companies operating fuel stations. Consider manufacturing; microgravity enables the production of unique alloys and compositions, which presents new manufacturing possibilities that space companies are already trialing. Orbital labs may also potentially need propellant. “The ability to do things in microgravity that you can’t do on Earth is going to drive the economy in space to be absolutely enormous,” says Faber. “The real question is how long it takes, and what’s the path to get there.”

Meet the expert

Daniel Faber is the founder and CEO of in-space refuelling services company Orbit Fab. He has over 25 years’ experience of space technology leadership as an engineer and entrepreneur.

SPACE JUNK IS A HUGE PROBLEM. IT'S ALSO A BUSINESS OPPORTUNITY

The more we do up there, the more we have to clean up after ourselves. But how?

O**uter space is very, very big. However, the region in which** the commercial space sector typically operates—usually within a few hundred kilometers of the surface of the Earth—is relatively finite. And we're filling it up at an increasingly rapid rate.

In 2017, the total number of satellites launched during a single year exceeded 300 for the first time. By 2020, humanity crossed over the threshold of 1,000 satellites and spacecraft in a single year for the first time. In the year 2023, alone, approximately 3,000 satellites will be launched into low-Earth orbit (LEO). If that sounds unsustainable, well, just wait. The majority of this growth in satellite launches has come from a single US space internet constellation. But this will soon be joined by further vast internet constellations from the US, Europe and China.

This dramatic growth in constellations follows more than six decades of launches by nations and private companies during which the upper stages of rockets were often left derelict in orbit. What's more, anti-satellite weapons tests have showered debris into LEO, and older satellites have broken apart. There's now more than 9,000 tonnes of man-made material whizzing around up there: About 25,000 objects larger than 10 cm, with a further 500,000 between 1 cm and 10 cm. And some of it is starting to collide, creating an even more congested environment. The hypothetical doomsday scenario, known as the Kessler

"THERE'S NOW MORE THAN 9,000 TONNES OF MAN-MADE MATERIAL WHIZZING AROUND UP THERE"

effect, would be if space junk hits a critical mass leading to a runaway cycle of collisions that cause further collisions and renders LEO unusable.

"We really need to be paying closer and closer attention to how we're using the orbits where all our objects are, and open our minds to move away from a single use, throw-away culture in space towards a more circular economy," says Dr. Clare Martin, Executive Vice President of Astroscale U.S., an on-orbit services company. "The things we're doing terrestrially, we need to consider for orbit as well. Can we reuse things? Can we repurpose things? Can we recycle things? It's a different level of thinking about how we use the environment today."

Martin is a space scientist who has modeled and studied debris for more than two decades, and says she is most concerned about explosions in orbit, such as when nations shoot down old satellites to prove their offensive capabilities in space, or when two objects in orbit collide. Ground-based operators can track old rocket second stages or defunct satellites using optical telescopes or radars. But catastrophic events introduce an element of chaos.

"When there is an explosion or a collision, and you generate lots and lots of small pieces, that's a lot harder to track," she says. "It takes something just the size of a pound coin, traveling at the speeds that you get in the orbital environment—around 28,000 km/h—to completely destroy another spacecraft. So it really is the small stuff that's the biggest threat. But that small stuff is generated because we leave the large stuff there, and we don't remove it responsibly."

Astroscale, globally headquartered in Japan, was founded in 2013 to begin providing solutions to the space junk problem. Its next mission will launch in late 2023 to demonstrate the capability to rendezvous in orbit with a spent rocket upper stage. Astroscale's spacecraft, called ADRAS-J, will approach a derelict rocket stage and take photos to characterize it.

A separate Astroscale project offers insight into how the company is thinking about debris capture methods. The UK Space Agency has asked Astroscale to design a mission to remove two defunct satellites from orbit by

"IT TAKES SOMETHING JUST THE SIZE OF A POUND COIN TO COMPLETELY DESTROY ANOTHER SPACECRAFT."

Dr. Clare Martin, Executive Vice President of Astroscale U.S.

2026. Named COSMIC, Astroscale's mission concept involves a spacecraft with a robotic arm grabbing one satellite, moving it into a disposal orbit and releasing it to burn up in the Earth's atmosphere. The spacecraft would then go on to do the same with the second object.

Astroscale has raised more than $380 million in funding, and belongs to an emerging sector of private companies focussed on the space debris problem, although the company has also diversified into other areas besides. A recent report forecasts that the "active debris removal" market will be worth $600m-$1.5bn globally by 2030. Astroscale's method is one of a number of possible ways to deal with space junk. Startups and researchers have proposed a range of ideas including using a net to catch larger objects for controlled or uncontrolled re-entry, firing high-energy lasers either in space or from Earth to nudge objects in new directions, or deploying vacuum-cleaner style "sweepers" to capture space junk.

Tackling space debris is becoming an increasing priority for governments. Japan, the United Kingdom, and Europe are all funding missions to demonstrate "active debris removal" capability. Additionally, this year, the United States Senate advanced legislation that establishes the "intent to close commercial capability gaps and enable potential future remediation missions for such orbital debris".

For the first time, then, Earth is taking baby steps to start mitigating the space junk issue. "We need to broaden our mindset as an industry and think about how we are using space," says Martin. "I see it being a very, very vibrant economy going forward. The change, just in my career, has been phenomenal. From when I first started working I had a choice of maybe three companies to work for in the UK—now there are many, and I see that trajectory continuing. It is touted to be a trillion-dollar economy in the next decade. To truly get there, though, we actually have to embrace the logistics in orbit, and think and use space in a different way."

Meet the expert

Dr. Clare Martin is a space scientist and the Executive Vice President of on-orbit services company Astroscale U.S. She has a specialism in space debris.

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