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Space 2040:

The Future of the GLOBAL SPACE ECONOMY

Foresight Study
June 2023

“The last big disruption we had in industry was a consequence of space travel. Right, this is when we started building satellites and spaceships to go to the moon or going to orbit. […] But it is one thing to go to orbit to the ISS; it is completely something else to go to Mars and set up shop there, right? The consequence of that is that there's going be this huge injection and advent of new technology. It could be propulsion systems, it could be communication systems – it's just mind blowing – it could be material science. Space is the new frontier. […] Let's say we go to Mars in 2050. All the innovations that have to happen to make that true are the same innovations that can be applied to terrestrial transport. I really think that's something we should all watch out for.”

Ravi Simhambhatla, Avis Budget Group

Foreword by the Author

Dear readers,

Space is an issue that conjures up the imagination like almost no other. One of the earliest science fiction works ever composed is called *A True Story*, by Syrian author Lucian of Samosata in the 2nd century AD. The novella is a satirical account of a journey to outer space, containing some of the first references to extraterrestrial life, the colonisation of Venus and wars in outer space. For many, the notions of space and science fiction are inextricably linked.

It is valuable that space ignites the imagination. In an age where many people's outlook on the future is growing increasingly gloomy due to environmental crises, military conflicts and ongoing wealth disparities, space continues to provide a screen for projecting humanity's hopes and visions. While this is important, it produces a unique challenge when discussing the future of human activities in space: Space is particularly prone to unrealistic expectations. After the enormous acceleration of the 1960s, it would have been hard to imagine that humans still had not landed on Mars. Even in the late 1970s and 80s, when public funding for space had reached its low point, expectations for the progress of space exploration exceeded reality. A 1976 report commissioned by NASA states that "it will be possible by the year 2000 [...] to develop reusable, vertical landing heavy lift vehicles" which will deliver payloads to low-Earth orbit "at a cost of $50 per kilogram, or less."[1] It is only now that this goal is within reach.

How can this report avoid the same pitfalls? Technological developments do not occur free of context. This study thus not only addresses what is technologically feasible, but also explores the geopolitical and societal context in which technological developments take place. The Moon landings of the 1960s and 1970s could have been followed up by more audacious undertakings. Predicting the end of the space race would have required an understanding of the implications of new technologies as well as of geopolitical dynamics. Therefore, this study combines an outlook on geopolitical trends with technological trends, using the methodological foundation of the Delphi foresight method.

While space and science fiction are often mentioned in the same breath, it is critical to stress that space has become a key realm of human activity with tremendous potential for economic development. Satellite navigation, communications systems and earth observation have made space indispensable for the global economy. Easier access has opened up space to new actors, with companies such as automobile manufacturers now possessing their own fleets of satellites. Nearly all businesses, small, medium and large, are already using space to their economic advantage and future trends will drive them to actively engage with space assets and to investigate how they can utilise space to benefit their business models.

Our future in space represents a vision for humanity, but it also represents an enormous opportunity for business and the economy. Have fun reading!

Dr Harald Köpping Athanasopoulos

Senior Consultant of Strategic Foresight

1 James & McDonald (1976)

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EXECUTIVE SUMMARY

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Executive Summary

This foresight study employs the Delphi method to predict the state of the space economy in 2040. After setting up the socio-political context of the late 2020s and the 2030s, it explores six key areas of development: technologies, infrastructures, policy, ecology, exploration and business models. Technical terms are defined in the glossary.

Space Technologies – Reusable Megalaunchers, Diversification of Spacecraft

In the area of technology, the single most important development is the advent of fully reusable megalaunchers in the second half of the 2020s, which will enable a delimitation in the volume, mass, design and applications of spacecraft hitherto unseen. Reusable rockets will contribute massively to a reduction of launch costs, which will open up space to new actors, including many established companies which had not previously engaged with space.

Given the technological convergence that is simultaneously occurring in the space sector, megalaunchers will permit space maintenance, repair and refuelling operations, which will extend the lifespan of spacecraft, contributing to the mitigation of space debris. Spacecraft will become modular, and companies seeking to operate their own satellite can swiftly create their own tailormade asset, which can be launched on one of a diverse and affordable selection of launchers. Responsive space will thus become a reality, with satellites being launched within weeks after being commissioned.

This capability will be given key strategic importance by major space powers. Given the future importance of AI, spacecraft will operate more autonomously, requiring less human control and making space more accessible. During the 2030s, some spacecraft will become equipped with nuclear-powered propulsion, enabling long-duration missions, for example for satellite maintenance operations or for activities beyond low earth orbit.

Space Infrastructure – Cislunar Space, Private Space Stations and Space Manufacturing

In terms of infrastructure, the focus of human activity in outer space will begin to include the space between Earth and the Moon (i.e. cislunar space), which becomes increasingly relevant for commercial and security purposes. Megaconstellations will enable new applications such as satellite internet and nearly real-time Earth observation, also leading to a dramatic increase in the number of active satellites in orbit. The delimitation of spacecraft and reusable rockets will make space manufacturing on a limited scale commercially viable, especially for pharmaceutical and biotech companies. Private space stations provide platforms for commercial research as well as for space tourism and for human spaceflight research by countries who do not wish to invest in their own, independent space stations. By 2040, some of the ground-based computing infrastructure will have moved to space, enabled by the increased accessibility of low earth orbit.

Space Policy – New Space Race, Medium-Sized Powers and Debris Regulation

Space will continue to be a mirror of international relations. The rivalry between a US-led bloc and a China-led bloc will be translated into space, as there will be a new space race between the US and China. This is especially focused on the military utilisation of space and there will be a race towards the acquisition of space superiority. Nevertheless, the relative role of states in space will decline, as commercial endeavours will become the primary drivers of human activities in outer space. Easier access to space will imply that medium-sized powers, such as the United Arab Emirates, Mexico, Israel or Iran, will hold space capabilities similar to those of major powers today. Space will also play an important role in the economic development of the Global South, as the efficiency and environmental resilience of agriculture and construction, can benefit from space systems, enabling leapfrogging. While binding rules on the sustainable use of space are likely by 2040, such rules will not come into effect on the commercialisation of space.

Space Ecology – Space Debris, Traffic Management and Climate Change

During the 2030s, the discourse around sustainability and regeneration will come to include space, as the number of space debris continues to rise, driven by easier access to space and megaconstellations. The growth in the number of spacecraft, and new, service-based business models, will drive forward more effective and comprehensive space traffic management. Large numbers of satellites impact Earth-based astronomy, providing further impetus for investment in space telescopes on the Moon and in free space. Climate change is a driver for the further human utilisation of space, as space assets are instrumental for monitoring climate parameters and mitigating the effects of the changing climate.

Space Exploration – Moon Base, Mars Sample Return and the Search for Life

Humans will return to the Moon in the late 2020s, and by 2040, there will be an American-led base on the Moon. China will be in the advanced stages of its own lunar exploration programme, with a Chinese Moon base scheduled to be launched in the 2040s. There will be a growing market for space tourism, but it will not be a mass market. Human launches into space will continue to represent a small fraction of all space launches. The exploration of Mars will proceed, with the first samples of Martian regolith having been returned to Earth by 2035. A human mission to Mars will be planned for the 2040s. By 2040, we will have a much better understanding of whether life beyond Earth is common or rarer than sometimes assumed. This is enabled by probes to the icy moons of Jupiter and Saturn, as well as by planet-hunting space telescopes, capable of detecting the atmospheric composition of Earth-sized worlds around Sun-like stars.

Space Economy – Growth, Diversification of Actors and New Business Models

By 2040, the total value of the space economy will exceed $1 trillion, and there will have been a massive growth in the number of space launches and spacecraft in orbit. Access to space will have become easier and more affordable, enabling a diversification of actors in space. While space for Earth business models will continue to play a key role, a growing share of space infrastructure serves other space assets, signalling a transition towards space for space. Business models will further shift towards space-as-a-service. The constant availability of Earth observation data will allow space to play a greater role in our everyday lives. This section lists a variety of emerging space business models, including debris removal, space consultancies, space manufacturing and spacecraft MRO.

18 Key Developments in Space by 2040

Technologies

1. By 2040, megalaunchers will have driven down the cost of launching material into space as well as the production costs of spacecraft.
2. By 2040, there will be a diversification of spacecraft in terms of volume, mass and utilisation.
3. By 2040, the routine availability of space rendezvous and proximity operations will enable satellites to be maintained and repaired in orbit.

Infrastructure

4. By 2040, the focus of human activities in space will move on to include cislunar space and exotic orbits.
5. By 2040, there will be several megaconstellations in orbit, contributing to the ubiquity of the internet and Earth observation data.
6. By 2040, there will be several private space stations, serving as platforms for human spaceflight, commercial research and space manufacturing.

Policy

7. By 2040, the race for military space superiority between the US and China will be ongoing, with space being increasingly regarded as a potential theatre of war.
8. By 2040, several medium-sized powers will have acquired space capabilities comparable to those of major powers today.
9. By 2040, there will be binding international rules on the sustainable use of outer space, while there is no consensus on the commercialisation of space

Ecology

10. By 2040, there will be active operations to reduce the amount of orbital debris.
11. By 2040, the growing number of debris and spacecraft will have given rise to increasingly coordinated space traffic management.
12. By 2040, climate change will continue to drive forward the utilisation of space, as space is crucial for monitoring climate parameters.

Science and Exploration

13. By 2040, humanity will possess a US-led human outpost on the surface of the Moon.
14. By 2040, we will know whether life is common or exceedingly rare in the universe.
15. By 2040, space tourism will enable the number of astronauts to reach new orders of magnitude, while not becoming a mass market.

Economy

16. By 2040, the value of the space economy will exceed $1 trillion.
17. By 2040, there will be a slow transition towards space for space as opposed to space for earth.
18. By 2040, there will have been a strong growth of space-as-a-service business models, offering more actors access to space.

TALES OF THE FUTURE

Lisa, 47, Private Astronaut

It starts to rumble. Lisa is strapped into one of 20 seats arranged in a circle around the rocket's central axis. Nervously she stares out of the window, sees nothing except the hazy clouds of the Florida sky. She feels anxious, can tell her heart is beating faster than usual, but remembering her training, she concentrates on her breath. In. Out. The rumbling is getting stronger, a voice in her ear is counting down. Eight…seven…six. She looks at the men and women around her, unidentifiable except by the name tag on their chests and the flag on their suits. Through their face plates she can tell that some are as nervous as her, while others don't seem to mind. Five… four…three. The display in her faceplate says her heart rate is around 95, but that's alright. Just like getting a plane, nothing to worry about, several of these things take off every day. Two… one. She's holding her breath. Lift off! The rumbling is now so strong it's shaking her. As the rocket accelerates, it pushes her into her seat. She holds on tightly to her arm rests and tries to breathe. Passing the clouds already, cobalt blue, still rumbling. The view through the small window is getting darker and darker, everyone is waiting expectantly for it to get darker still. And there it is. Space. Less than three minutes into the flight. A few moments later, the engines shut down, and the rocket is still.

When Lisa started her job at Biopharm, a major pharmaceutical corporation, she had no idea she'd ever become an astronaut. Lisa studied biochemistry and sure, she'd always been interested in crystallisation and perfect protein crystals, but she had never dreamed she'd travel to space. Then, Biopharm invested in space manufacturing. Her experiments travelled to the Biopharm space station three years ago, and finally she was able to conduct the kinds of microgravity experiments she was hoping for. 'Wow, flying to space to fight cancer, not bad!' Lisa's research on perfect enzymes can be used to develop targeted chemotherapy drugs with fewer side effects. Ten years ago, in 2030, Biopharm had carried out research in a small lab hosted by another private station. Trials showed that chemotherapy drugs using enzymes made in space are tolerated slightly better than their Earth-made counter parts. Biopharm decided to scale up production and now has its own research and manufacturing platform in LEO: Biopharm station.

Theoretically, you could remove your helmet and unstrap yourself from your seat a few minutes after launch, once the rocket engines shut down. But in her rocket people unstrap one after the other. Most of her fellow passengers haven't been to space before, and microgravity can be quite overwhelming, so it takes some time. Right now, it just feels weird in her belly, kind of like when you go downhill on a roller coaster. The others, some of them space tourists, are getting up, clumsily moving along the rails on the floor towards a hatch on the central axis. From there, they'll carry on to the observation dome. All she wants to do is get a proper look out of the window. Right now she can only see darkness outside. Her turn. A man moves towards her, helps her release her suit from her seat. "Is it alright if I just have a quick look outside?" He nods, she turns over, pushes herself off her seat towards the small window. Okay, this is too much, sensory overload. The radiance of the blue marble. Weightlessness. Being an astronaut. Her eyes well up.

Lisa gets the hang of being in space quite rapidly. Like her colleague Thomas, who's travelling with her to the station, she's one of the lucky ones who don't get sick. She could have guessed as much. The company that had trained her for space had turned her over in all directions, and she'd never really minded. The flight to the Biopharm station takes around 20 hours. Eventually, the rocket is refuelled in orbit, docks with two other stations and then carries on flying the tourists around the Moon.

After Lisa enjoyed the pleasures of a sleepless night with snoring people in a sleeping bag hanging from a wall, the rocket is finally approaching Biopharm station. Apparently the rendezvous manoeuvre is fully automatised, and after a few twists and turns Lisa's ship has attached to the station. Time to go! Thomas and her get their personal stuff as well as a container full of equipment, entering the space station. The rocket detaches.

Take a deep breath… Lisa feels a bit uneasy about the idea of being in a space station, but then she remembers that there's a capsule hooked on to Biopharm station that can take them back to Earth immediately if anything goes wrong. But that's fine. All will be good. Inside the station Lisa and Thomas have a look around. Thomas has been here before, but Lisa only knows it through VR goggles. It's essentially a large room with around 100 mini labs all the way around its circumference. Inside each lab, there's either an experiment, or they're making enzymes. At the far end of the station, there are the four cubicles they call 'crew quarters'. Not great, not terrible. Lisa and Thomas are greeted by the station's AI, whom they've nicknamed Spaci, for space station communication interface. "Hi, lovely to see you." "Good to be here, Spaci!" Lisa and Spaci had already met in the metaverse. "Alrighty, let's get to work," Lisa says giddily. It's kind of hard to contain your excitement when you realise you're an astronaut talking to a robot on a space station.

Lisa gets her stuff, shoves it in her cubicle, sticks a few pictures of her family on the wall. She hears Thomas doing the same. She has a look around herself. In a room that's totally round it is even harder to loose orientation in weightlessness, but at least they've colour-coded the shelves. On some minilabs there's a screen displaying a company logo. There's other pharmaceuticals, car manufacturers and lots of logos she can't allocate. There are several robotic arms attached along the walls. They're controlled by Spaci. A small round window near the centre of the station is filled with blue. There's a noticeable hum from the ventilation system. She remembers a movie tagline from her childhood, something about space being silent. Well it isn't as silent as she thought it would be.

It's been a long day. The clocks on all space stations are set to Coordinated Universal Time, which is four hours ahead of Florida time and Lisa needs to get to sleep soon, but she wants to have another look at her mission profile first. She gets out her AR goggles, flicking through the air to access her files. Her mission profile appears on a virtual screen hovering in thin air. She's excited, can't wait to get started. But it's late. “Thomas, are you still up?” “Yea, but I'm not so well. I think I'm gonna call it a day. Not hungry either.” Wait, was that a groan? Lisa thought he didn't get sick in space, but anyhow. “Yea, just gonna grab a meal and then I'll be asleep too. Good night!” A few minutes later, Spaci's robotic arm hands her a wrap containing cultured chicken strips and rice in tomato sauce. The food is actually much better than expected and she looks back in disgust at the freeze-dried strawberries she had as a kid – those weren't the real deal. She finishes her meal, clumsily brushes her teeth and Spaci dims the lights. As she slips inside her sleeping bag, she thinks to herself, ‘This has got to be the coolest job anyone's ever done.’

Kamal, 51, Farmer

Monday, April 16, 2040. 6 o'clock. Kamal uses an old-fashioned alarm to wake up each morning. The new ones may be slightly more precise, but he likes the no-nonsense approach of his old Seiko clock. A constant, annoying beep, 60 decibels. Just right. Loud enough for him, not loud enough for Zahra, his wife. He received it from his baba for Eid back in 2002, at age 13. Like himself, his father was a conscientious man.

Kamal reaches for the screen on his bedside table without looking. Nothing. What did they do with it again… He gets out of bed, Zahra still asleep, crosses the corridor and opens the door to his girls' bedroom. They too are still asleep, three heads with black, curly hair sticking out from underneath their sheets. He picks up his screen next to Amira's bed, smiling. She's 10, his youngest. Maryam and Ruqayyah are 12 and 13.

'Alright, let's take a look.' Kamal set up his screen to display the same data every morning. Temperature: 27°C. Air humidity: 52%. Wet bulb temperature: 20°C. Gonna get hot this afternoon. Soil moisture content: 15% pretty much everywhere, except on the banana patch. As usual… Kamal knew that place. He only had okra, no bananas, but on the satellite image it always looked kinda curvy, like a banana, so he called it the banana patch. The software he used could analyse the colour and the texture of the soil there, so he knew it was slightly more sandy than other places. 'You guys will get an extra drink in a bit, don't worry.' All good in his greenhouses. Kamal had set them up back in '36, four years after al-Huma, the Fever. 50°C, wet bulb had been up to 33°C. Most of his harvest hadn't made it. Demand for green houses soared, so he had to wait for a while. CO_2 concentration in greenhouse: 650 ppm, about 150 more than outside.

Ten past six. Fajr prayer. Six fifteen. Shakshuka for breakfast. His wife had prepared all the ingredients the night before, so he just puts them in a pan. Like his grandmother, Kamal uses okra instead of tomatoes. Kind of obvious when you're an okra farmer. Bismillah, he eats it quickly, leaving the rest for his family. Six thirty. Off to the farm, which is just a short drive from Kamal's home.

The sun rose an hour ago, and it's only April, but Kamal feels hot already. He gets out of his pickup, as starlings on a solar panel are chirping cheerfully. There are no clouds in sight. No chance of rain today, but the Euphrates keeps his farm fertile. 'Okay then, let's have a look at the maps.' He gets out his screen. Everyday Kamal checks the same data. Leaf area index: 2.3 average. Vegetation index: 0.8. Chlorophyll content: 32 SPAD units, pretty much everywhere except…ugh, that banana again. Nitrogen content, all good. Pest population per square meter: hang on… Kamal zooms in. The map displays this information at a resolution of 2x2m. Yup, pretty clear there's been a marked increase, which is not unusual for this time of year. A chart tells him which culprit is responsible: aphids. Not unusual either, but higher temperatures have made them more regular visitors. Baba would have just sprayed this field. Effective, but Kamal likes those starlings too much, and he's an organic farmer. He's going to need to drive over to Murat's later to get some lacewings. Kamal's drone will drop them precisely where the aphid population is highest, killing those beasts, and providing a meal for the starlings.

Alright, time to water the banana. Kamal has set up a system of hoses, valves and sprinklers. The software that activates them is linked up to the satellite data, applying water only when and where necessary. His screen is ringing. 'Ugh, what's going on now.' Apparently one of the sprinklers is clogged – unavoidable, but annoy-

ing. But okay, back to work. It's a twenty minute walk to the banana. Grumpily, he sends his drone there in advance to check exactly which sprinkler isn't working. The drone buzzes away, and a few minutes later he's got the information.

He walks across the green field, his greenhouses reflecting the low sun's light in the distance. He admires his okra plants, it's going to be another month or so until they flower, revealing the glowing yellow beauties inside those buds. Alhamdulillah. He's feeling better already. His screen is ringing again. "Good morning, Habibi...sure, bring her over to you mother's...Okay, when will you be home?...Tell them I love them, sorry about that...Yep, have a good one!" There's the sprinkler, not clogged, but broken. Maybe a mouse or some other rodent mistook it for food. 'Gotta print a new one tonight.' He removes the broken sprinkler, replaces the saddle tee with a piece of hose, and instructs a drone to irrigate this place manually.

By the time he gets back to his truck, it's 8 o'clock, plenty of time to check out the greenhouses and to take some soil and leaf samples. Kamal's farm is part of a study to examine the impact of higher temperatures and erratic precipitation on okra farming in Iraq. He's gonna have to send the samples off to a lab in Baghdad. He gets the samples from locations an AI is suggesting based on the satellite data, puts them in sample containers and places them inside a delivery box. A drone will pick them up later that day. Kamal spots a lark drawing circles over his field, the only bird that sings in flight. 'You too are gonna love those lacewings.'

After inspecting the green houses, Kamal drives back home. As he approaches Ash-Shinafiyah, he spots a car without a driver, passing it extra carefully. At eleven o'clock, he's attending a webinar by the company that provides the satellite data. He's got a monthly subscription, and the webinar is free. His house was never hooked up to terrestrial internet, but the small dish on his roof picks up internet from space. Doesn't cost him a single dinar. "With our AI-powered robots, you can say goodbye to your labour problems and hello to a well-manicured farm. Just don't forget to recharge them!" ... "Our satellite imagery is so high-resolution, you can count the number of hairs on your cow's back from space." ... "Did you know that bees can wear tiny backpacks with satnav sensors? It's not just a fashion statement, it's a way to track their movements and improve pollination efficiency."

Sometimes Kamal wonders if they should have changed the humour settings of the AI that probably generated this text. Still, not bad. He remembered how he got his first phone back in '12, at the end of the War. Google Earth didn't work too well in Iraq, but he loved being able to zoom across his family's field, even in low resolution. He would never have dreamed that one day he'd be able to water his okra based on data from satellites. But with all those droughts and floods and after the Fever, he couldn't do without them. Since he used spacecraft for farming all the time, could he call himself a space farmer? He didn't care, he just did. His baba would have been proud to have a space farmer for a son.


BIG PICTURE
BIG PICTURE

While the evolution of the space economy will have a large impact on human development and the global economy by 2040, it will not occur on a vacuum. In comparison to other sectors of the economy, space represents only a small sector, and it is therefore very dependent on trends that will occur in the global political economy.

Acceleration

In a globalised and increasingly technological world, life is proceeding a little faster every day. The availability of information also increases the speed with which people develop and adapt to new things. In both the workplace and private life, we are confronted with at least two realities: one reality is based on our expectations of where we will be in 5, 10 or 20 years. This reality arises from a linear way of thinking, which is fed by our past experiences. It is relatively easy for us to predict that our new-born child will go to school in 6 years, graduate in about 18 years, and earn their own living in about 25 years. It is easy to make such projections because we have experienced our own lives and those of many people around us. We know the context and the systems behind these developments, and accordingly we shape our future expectations. In business, we often follow similar patterns. We look at what our customers ordered ten, five, or two years ago, and we project this development into the future – often by talking to our customers today and finding that they are following the same patterns.

But there is another reality that does not follow a linear development path, but rather an exponential curve. In 1898, Alexander Winton, the inventor who sold the first automobile in the US, was called by his banker with the words, "You're crazy if you think this foolish contraption [...] will ever replace the horse!" Now we look into a future where cars with combustion engines seem outdated and where autonomous driving will soon become accepted. Especially in the field of innovation, development often advances much faster than we can imagine. In the initial phase, disruptive technologies often appear to lag behind existing alternatives, but once a certain point is reached, scaling potential and adaptation speed develop rapidly, leaving behind the prevailing status quo.

Why are we so often wrong when we predict the future? We tend to look at the iterations of a technology and then deal with the errors of a particular iteration. It is usually more helpful to consider an entire category of technologies to determine the intended benefit and the probability of long-term technology diffusion. Video on demand illustrates this quite vividly: When VHS entered the market, film enthusiasts complained about the poor image and sound quality, breaking magnetic tapes, and the decreasing quality of the recording the more it was played. VHS was replaced by DVD, then by Blu-ray, and today it is 'normal' for us to enjoy high-quality video and sound that we stream digitally on large screens in our own living rooms.

Similar – probably much larger – technological advances can be anticipated in numerous areas in the coming years. Various technologies, especially those related to AI and machine learning, are in a stage of development that is approaching a tipping point in the foreseeable future, which leads to exponential growth and adaptation. Whether rendezvous and proximity operations in deep space, autonomous vehicles, robots in logistics and manufacturing, brain-computer interfaces, or medical procedures – the solutions to a variety of challenges are massively influenced by such tipping points. In their convergence, industrial revolution-size upheavals are foreseeable.

New technologies will lead to a paradigm shift in many areas and ensure that exponential growth is redirected and increased in new ways where it seems to be declining. While Moore's Law, which states that the number of transistors on a microchip doubles every two years, seems to be reaching its limits in the face of advances in the electronics industry, initial developments in quantum computing promise a new era in the digital revolution. Unlike classical computers, quantum computers are not limited to computing bits with the values 0 or 1, but process qubits that can simultaneously assume the values 0 or 1 as well as all values in between. They take advantage of quantum mechanical phenomena such as superposition and entanglement and are ultimately able to perform calculations not one after the other, but simultaneously. The enormous potential of quantum computing will lead to changes in a variety of industries, thus enabling exponential growth in a new dimension.

It is obvious that these new technologies and the tipping points of their development bring risks and uncertainty, making a dialogue about the ethical questions of our future development all the more important. Despite its exponential development, the future is made by people. Therefore it is malleable and to some extent controllable. This requires an active positioning in the present, in order not to be surprised or to be pushed into an unpredictable direction.

Times of Uncertainty

For many businesses, the future world will be characterised by the perception of numerous crises and increasing uncertainty. Climate change, which is becoming more of a real threat to prosperity and health, will reach irreversible tipping points in the coming decade. It is already becoming more in wildfires, floods, droughts, and a rapid loss of biodiversity. According to the 2021 IPCC report, a global temperature rise of around 1.5 degrees, which should not be exceeded according to the Paris Climate Agreement, will likely be reached by 2030. Climate-related economic damage and resource scarcity on the planet will reach all nations, including the industrialised countries of the global North, in a new, unprecedented quality, requiring a massive international effort that must be supported by politics, society, and the economy alike.

In the field of the economy, Corporate Social Responsibility, which also includes the ecological level of sustainability, is becoming increasingly important for companies in all industries. At the moment, sustainability is currently considered mainly in external communication and severe cuts to their own business models are avoided. In the future, only companies that actually address the issue or that at least compensate for negative effects will be able to convince their customers and meet societal requirements.

The number of newly founded companies that make the solution of a social or ecological problem the core of their business model is increasing rapidly in recent years. Examples include Ecosia, a search engine that plants trees with every search, Share, a groceries company which donates a portion of its income to developing countries, or Patagonia, which sells clothing that can perpetually be sent in for repair or exchange. These companies operate contrary to linear business logics and profit motives. With the Climate Pledge, many global corporations have committed to achieving zero emissions 10 years before the target date of the Paris Climate Agreement. Since 2007, over 6,000 companies have been certified as B Corporations based on objective standards for their positive ecological and social impact.

Transparency regarding supply chains, resource extraction, and resulting emissions is essential, but increasingly endangered by the global and fragile nature of the existing economic order: At many points, it is still not foreseeable to what extent the quality of life and supply standards of today’s world can continue to exist in the future. Although awareness is growing that climate change is a human-made problem that can only be contained collectively, the looming resource scarcity simultaneously reinforces tendencies towards nationalist strategies to secure one’s own sovereignty.

It hence seems plausible to assume an increasing nationalisation and polarisation of the international community, for example in the form of two geopolitical blocs with China on one side and the USA on the other. Given the increasing scarcity of resources, the probability of a war economy increases, as value creation and technology use are focused on survival in the face of conflicts and crises.

Large amounts of resources would be permanently tied up, being missing elsewhere for the world's digital and sustainable transformation. Technology, multiple ecological crises and ideologies are contributing to increasing complexity, interdependency and uncertainty. Until 2040, this will lead to a significantly greater prioritisation of resilience for individuals, companies, and states. To ensure security, resource independence and the maintenance of supply chains, new (as well as rediscovered) concepts are needed: nearshoring or even reshoring, i.e. the relocation of production to one's own country or continent; multisourcing, i.e. cooperation with several independent suppliers, some of which are also competitors; or the decentralization of production, e.g. through smaller, mobile production hubs. All these approaches become possible strategies that need to be developed depending on individual circumstances. Companies must not only think about resource consumption, emissions, and social responsibility but also about changing customer requirements and newly emerging interfaces between machines and humans.

Data-Driven Economy

One of the most significant changes in the way the global economy will function during the 2030s is based on increasing digitisation and data abundance. The internet and connected technologies such as satellite observation for capturing, storing, and applying various types of data have opened up new possibilities for disseminating information and reorganised interactions between producers and consumers. Overall, a new type of economy is possible, in which market power is increasingly defined not by ownership of material goods, but rather by data as a central asset. Companies like Uber or Airbnb do not own vehicles or properties, yet they sell mobility and accommodation. Google or Facebook do not generate their own content but monetise content by organising it and making it accessible to billions of people. The wealthiest companies are those whose business models consider data as their central asset. Value is generated by the ability to transfer, reorganise, disseminate, share, and exploit data for the development of new, tailored products.

The scope and nature of data sources that capture and transmit information about human behaviour, machine performance, or the state of nature and infrastructure are changing rapidly. Space assets, drones and IoT sensors enable a new data density in (almost) real-time. Even by 2030, the number of connected IoT devices alone is expected to triple to up to 30 billion compared to 2021.

The intelligent linking of data obtained in this way enabled the generation of digital twins, i.e. digital representations of physical reality. Mechanical engineering, maintenance and repair, product development, process design – these processes can be modelled, predicted, and optimised using digital twins, thereby enormously increasing the efficiency and transparency of value creation in numerous industries.

Not only are machines and sensors increasingly interconnected in an Internet of Things, but synergies are also emerging between humans and machines, creating a new layer of reality. With Web 3.0 following Web 2.0 and Mobile Web 2.5, the semantic web is now at a new stage of development. In short, this means the joint understanding of data by humans and machines with the help of artificial intelligence. A computer will not only reproduce data but also understand, classify, and use it for communication with other systems.

In this context, a metaverse is emerging with digital spaces for people to live, communicate, trade, and invest. Social interaction, communication, economics, and consumption receive an additional digital layer, and the understanding of reality is no longer perceived as 'analogue' vs. 'digital', but develops into a melange of online, offline, physical and digital. Billions of investment into research and development for hardware as well as the design of digital worlds and tradable digital goods will bear fruit during the 2030s.

CHAPTER I

CHAPTER I:
SPACE TECHNOLOGIES

This chapter focuses on future space technologies which will facilitate the further development of the space economy. The chapter begins with the increasing availability of heavy lift launch capabilities, which leads to a significant cost reduction for space launches. Furthermore, heavy lift launchers will enable a delimitation of spacecraft in terms of size, design, volume and mass. Space will become significantly more accessible. Lower costs, as well as advances in AI, robotics and propulsion technologies, will enable space rendezvous and proximity operations (RPO) and the commercial viability of space MRO – it will become possible to repair satellites in orbit, making space operations more sustainable. A shift towards a 'good enough' attitude in spacecraft engineering, which is facilitated by dropping launch costs, as well as the constant availability of launch opportunities, will enable responsive space, i.e. the ability to rapidly launch satellites, responding to specific mission requirements, emerging threats, or evolving technological capabilities.

The Starship and Reusable Megalaunchers as Key Enablers

One of the critical developments that is likely to occur by 2030 is the advent of fully reusable megalaunchers, also known as reusable super heavy-lift launch vehicles. Megalauncher is a term that refers to launchers capable of lifting more than 50 tons into low Earth orbit (LEO). There are currently two operational rocket systems capable of this performance, namely SpaceX's Falcon Heavy and NASA's Space Launch System (SLS). However, over the course of the 2020s, megalaunchers will become far more widespread, especially due to the imminent first orbital launch of the *fully reusable* SpaceX Starship.

"One thing that many people don't understand is this: Go and download the Starship user manual, you can get it for free on the SpaceX website. When you look at the user manual you can see the decisive factor. The Starship is not a rocket, it is an actual spaceship."

Robert Boehme,
Planetary Transportation Systems

While the SLS is an entirely expandable system, the Falcon Heavy already has a degree of reusability, as its three first-stage booster rockets are capable of landing. The feature has enabled an enormous reduction in launch costs, as the booster rockets can be reused rather than having to be remade from scratch for every single launch. While it cost 65,400 $/kg to launch one kilogram into LEO using the Space Shuttle, the Falcon Heavy is capable of performing the same feat for merely 1,500 $/kg.[2] This has significantly disrupted the launcher market, and SpaceX has become by far the most important provider for commercial space launches. The reduction of launch costs has arguably been the key driver for the NewSpace sector, allowing new actors to bring new applications into space. Full reusability will cause a further revolution in the space sector.

2 Roberts (2022)

"If the Starship succeeds, it will absolutely be a game changer. We're talking about payloads in the Saturn V class, Saturn V class fairing and fully reusable and something that is big enough for intercontinental travel."

Robert Zubrin, Pioneer Astronautics

According to SpaceX, Starship will bring down launch costs to LEO to $10/kg over the course of the 2020s. While the actual launch costs are likely to be slightly higher, the Starship will nevertheless bring down the cost of transporting material into orbit by at least another order of magnitude.[3] This is enabled primarily by the two key qualities the Starship possesses: full reusability and enormous payload capacity. Starship will be able to transport up to 150 tons into LEO in a single launch. Its volume capacity is 1,000m³, which is equivalent to a stand-alone house.

„I think the principle of heavy reusable launch vehicles will be a game-changer. As that capability becomes mature I think the potential price of one hundred dollars a kilo or less to Low Earth Orbit is feasible in the next 10 years. At that point what you have in waiting are a hundred or a thousand new business models that would become viable literally over a period of weeks from announcement of that launch pricing."

Jim Keravala, OffWorld

Reusable megalaunchers will thus be an important enabler of many of the business models discussed in this report.

One criticism that is often raised, is that many of the foreseen developments in the space economy depend crucially on the Starship. It is assumed that if the Starship fails, the growth of the space economy may continue at a slow, linear pace, while the revolutionary changes enabled by the Starship would fail to materialise. While it is likely true that the failure of the Starship would delay the disruption a reusable megalauncher would produce, SpaceX has demonstrated already that there is no physical reason why a Starship-like craft could not be built. While the Falcon 9 and Falcon Heavy are currently the only available semi-reusable launchers, more than 20 commercial and public actors around the world are currently developing reusable rockets of their own. China's Pallas-1, which is essentially a copy of SpaceX's Falcon 9, has its first flight scheduled for 2024.[4] Similarly, the European Space Agency (ESA) is planning first flight tests of its reusable Themis rocket in 2023 from a new inaugurated spaceport in northern Sweden.[5]

"China doesn't just have one, but several 'private' providers, who do nothing other than copy SpaceX. There are two providers in China who basically just built copies of the Falcon 9."

Robert Boehme,
Planetary Transportation Systems

While the failure of Starship cannot be excluded, nearly all experts who participated in this study expect its success. Moreover, given the American government's commitment to the Starship as a lunar lander within the context of the Artemis programme, it's eventual success is highly likely.[6] Artemis is an international cooperation led by NASA with the intention of returning human beings to the lunar surface by 2025 (although this date is likely to be pushed back to 2027).[7]

3 Scoles (2022)

4 Jones (2023)
5 European Space Agency (2020a)
6 Dodson (2022)
7 NASA (2022a)

Cost Reduction of Spacecraft Enabled by Reusable Megalaunchers

Space is expensive. Over a 13-year period the total cost of the Apollo programme to land human beings on the Moon amounted to $257 billion (inflation adjusted).[8] Space projects such as the James Webb Space Telescope or the International Space Station are among the most expensive items funded by national governments. By 2040 however, the cost of activities in space will fall dramatically. Reusable launchers will decrease the risk averseness that has historically been associated with the space industry. It is obvious that if a launch costs 50,000 $/kg, it is extremely important to make sure that spacecraft are exposed to the most severe tests before they are sent to space. If tens of millions are spent on a launch, it is essential that your spacecraft will function perfectly in orbit. But what happens when launch costs are brought down dramatically?

"And this is of course the exciting part: [reusable launchers] will open entirely new business models. [...] You will be able to use a lot more every day disposable technologies than is the case today."

Robert Boehme,
Planetary Transportation Systems

"I will no longer be bound to taking ten years before I can even launch something, because it is out there and will need to survive somehow for 25 years. That will no longer have to true."

Fabia Höhne Tarragona, OroraTech

If launch costs are brought down, actors in the space industry will be able to take greater risks, no longer having to rely on the most cutting-edge materials and manufacturing methods or the strictest testing procedures. The space industry will need to change its mindset. Whereas previously the highest levels of excellence were required, space actors will need to adopt a 'good enough' mentality, applying production procedures that have long been employed in the car industry. The reduction in launch costs will therefore dramatically reduce the cost of spacecraft themselves, simultaneously shortening development cycles (irrespective of the increasing impact of generative design), which further reduces costs.

„If a failure is not so terrible because you just launch another one and it's not too expensive, then I do think that the cost will go down for these kinds of systems [satellites, propulsion and energy systems] too. So I do think it's a self-reinforcing loop in the right direction."

Bas Lansdorp, NEDPAC

Over the course of the 2020s and 2030s, the cost of all space activities will decrease, enabling ever more actors to participate in the space economy, thereby creating an intensely innovative frontier business culture.

8 Dreyer (2022)

Delimitation: Removing Constraints on Volume, Mass and Design

By 2040, the developments described in the previous sections will have resulted in a growing number of spacecraft in orbit. In 1990, there were 464 active satellites. This figure had risen to nearly 1,000 in 2010 and to almost 7,000 in 2022.[9] Reusable launchers and 'good enough'-quality spacecraft will cause this exponential growth to carry on, causing spacecraft to be made on an industrial scale.

"It will be easier, a lot easier, to access space, to operate in space and also to come back down."

Kai-Uwe Schrogl, European Space Agency

"What I do see, especially with the massive reduction of cost in launch, is that we'll be able to do many more things in space and on celestial bodies like the moon than we have done hitherto for, and mostly because it's now cheaper to do."

John Sheldon, AzurX

9 Salas (2023)
10 ibid.

The reduced cost of space launchers, spacecraft themselves as well as spacecraft development cycles forms a self-reinforcing feedback loop. The cost reduction occurs across the board, enabling access to space to an increasing number of actors. With the risk aversion that has historically dominated the space industry being less of a factor, spacecraft designers can be less conservative, trying out new designs and technologies.

"When the cost of launch goes down, spacecraft designers can be less conservative. And now some of these new ideas will fail, but some won't. And then you'll have more capable spacecraft. The various subcomponents will be more capable or lighter or cheaper or something that makes them more attractive. And so with launches getting cheaper and the spacecraft themselves becoming more cost effective, this is a virtuous cycle, self-accelerating."

Robert Zubrin, Pioneer Astronautics

While this trend will cause an acceleration by itself, technological convergence will cause further acceleration. Physical simulations will enable new spacecraft designs to be tested virtually in minutes using neural networks,[11] and generative design will delimit many of the constraints imposed by human engineering.

11 Bai et al. (2021)

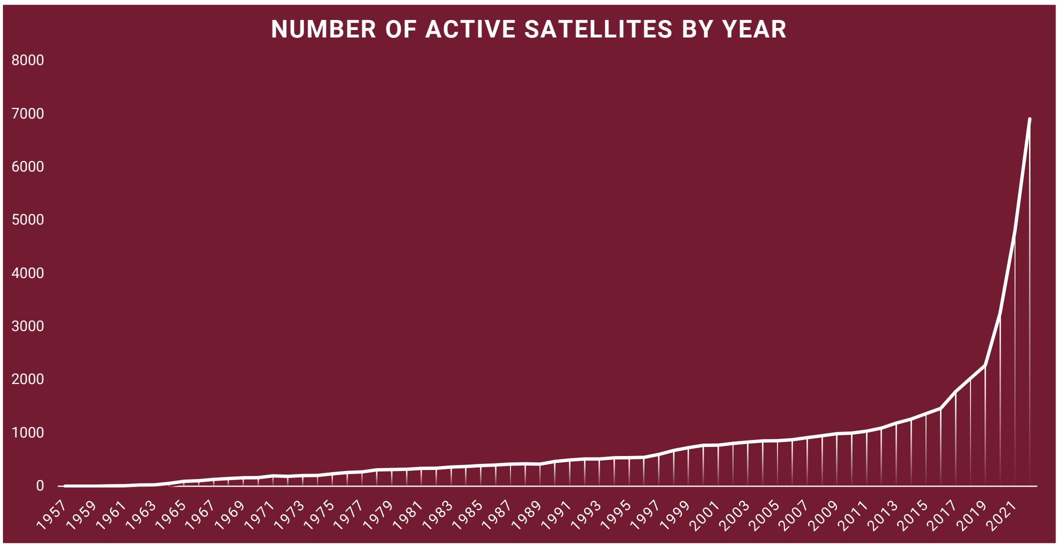


Figure 1: Number of active satellites per year since the dawn of the space age[10]

Apart from design restrictions, reusable megalaunchers carry the potential to remove the restrictions on volume and mass that have hitherto defined the space industry. Spacecrafts have to be built having in mind the dimensions of the launcher. While this will still hold true to some extent, spacecraft designers will be able to be much more liberal than they have ever been. In the same way that lorry containers are able to carry a much greater variety of products than pre-industrial carts and wagons, reusable megalaunchers such as the Starship will be able to carry a much greater variety of spacecraft than any launcher used in the past:

"Using the Starship, SpaceX will not only drive down prices. It is much more critical that they will remove the key restrictions that are currently defining the entire industry. Cost is one restriction, that much is clear, low cost is always a factor. But [the Starship for the first time also removes the restrictions of] volume and mass."

Robert Boehme,
Planetary Transportation Systems

For many businesses, this will imply a paradigm shift, as their considerations on space have previously been severely constrained. Moreover, companies in sectors such as the pharmaceutical industry, biotech, agriculture, energy, mining, logistics, aerospace or construction, will now discover the potential that space offers for their business model.

Diversification of Spacecraft: Miniaturisation, Enlargement and Complexification

The developments described in the previous sections will enable an enormous diversification of spacecraft. This diversification is characterised by three key trends: miniaturisation, enlargement and complexification.

Miniaturisation of spacecraft is not a new trend in the space industry, having been one of the key drivers of the NewSpace age of the 2010s and early 2020s.[12] Miniaturisation in space is a classic example of technological convergence. The technologies required for it, such as increased transistor densities and small sensors, were largely not developed for the space industry. However, when adapted for spacecraft, they enabled smaller satellites with high sensor capabilities. Standardised cubesats, microsatellites and reduced launch costs have allowed actors such as universities and radio amateurs to launch their own satellites into space. The cost reduction brought about by miniaturisation has spawned hundreds of NewSpace startups who now possess the financial resources to build a demonstrator for their projects.

"Especially if you are a NewSpace company your financial resources are limited and you will want to demonstrate your main technology. For that reason, you will first take a small satellite, to tick off that box and then you will perhaps make your satellite a bit larger afterwards, to achieve higher performance and better applications."

Daniel Bock, Morpheus Space

Until 2040, the experts who participated in this study overwhelmingly agree that the trend towards miniaturisation is likely to continue, although miniature satellites will have to be equipped with more manoeuvring capabilities to avoid a build-up of additional debris (see chapter on Space Ecology). A further point to take into account is that small satellites will continue playing an important role because of the physical layout of outer space. Some space applications, such as continuous communication or earth observation systems, require satellite constellations.

12 Neirad (2021)

"One has to consider that we will continue to be bound to orbits and orbital planes. There's the Earth, and there are these different planes and different orbits around Earth where a satellite can be stationed. In our case, we want to take pictures of Earth as often as possible, so it doesn't make sense to use a big Starship, to use a big satellite, because we want to get pictures of a particular place on Earth as often as possible."

Fabia Höhne Tarragona, OroraTech

While some space applications will require large, complex spacecraft, other applications will require a multitude of small miniature satellites. Using a launcher such as the SpaceX Starship, it will become possible to launch an entire constellation of small satellites in a single launch.[13]

Miniaturisation of spacecraft will continue to play an important role in the space industry. However, there are also several factors driving forward the enlargement of satellites. Among those factors are space applications beyond low earth orbit. Given the extremely limited propulsive capabilities of small satellites as well as their limited performance, microsatellites are ill-suited for many applications beyond low Earth orbit.

"In the old days the vision and the strategic considerations of the entire European space field revolved around doing research on nanosatellites and cubesats, because they've realised, 'Oh yes, there is miniaturisation'. But what was totally overlooked was that LEO is merely the first stop. If you want to go somewhere else, you can't do it with a cubesat. Sure, you can do it, and you can probably do it cheaply, but what are you going to do there? You can't do anything with it. You need larger things. You also need larger ships."

Manuel La Rosa Betancourt,
Neutron Star Systems

Larger satellites will therefore play a key role in human activities beyond LEO, which are discussed in more detail later. Nevertheless, once again, reusable superheavy launchers are a key driver of reusable spacecraft, due to delimitation in terms of dimensions. While space startups will still want to build demonstrators, they will be less constrained to do so using a cubesat or another small satellite. At the same time, small satellites will continue to play a vital role due to the need for satellite constellations.

"The trend is enlarging and this is very obvious with Starship as an example of all these launch vehicles really going up in size and allowing much more mass and much more volume. And industry is responding very quickly to this, and we're seeing lots and lots of different types. You could start or pivot into developing capabilities that take advantage of the Starship size launch vehicle."

Dane Rudy, Second Order Effects

As was previously discussed, spacecraft engineers currently place the emphasis of their designs on durability, resilience, longevity and redundancy. The more complex systems become, the more prone they are to errors, lowering their resilience. Given the current space economy, the emphasis on these factors is an absolute requirement, because sending a spacecraft into orbit is expensive. Once in orbit, a spacecraft currently cannot be fixed without a very costly repair procedure (cf. Hubble Servicing Mission in 1993). However, as launchers become cheaper and spacecraft become delimited in terms of mass and volume, the complexity of space systems is going to increase.

"I think that we are going to have significantly more complex and larger structures in space. It will no longer be a problem to construct a manned space station. It will no longer be a problem to build large structures, large spaceships in space. I think that's where we'll be in 15 years."

Daniel Bock, Morpheus Space

Lower costs will to some extent enable the trial-and-error approach that is applied for technologies on Earth to be carried out in space. This will allow for the construction of structures in orbit that are larger than the carrying capacity of a single Starship. Potential applications include orbital factories, space stations and space hotels, which will be discussed in more detail in the chapter on the future space economy.

13 SpaceX (2020)

Diversification of Launchers: Tiny, Enormous, Reusable and Expandable

While the previous sections focused on the impact of reusable very large launchers on the space economy, the diversification of spacecraft will also drive forward a diversification of launchers. In 2030 and beyond, the Starship will not be the only launcher available. While Starship offers ridesharing to smaller satellites, a single Starship launch will not be able to bring satellites to a variety of orbital inclinations, and for many applications, a flexible launch schedule is critical.

Moreover, satellites with military applications are unlikely to be launched alongside their civilian counterparts. States will also want to foster their own national/regional space economies, leaving ample space for a large variety of launch companies:

"What will certainly be the case is that by 2040 there will be 20 or 30 space launch providers."

Kai-Uwe Schrogl, European Space Agency

The diversification of launch vehicles also represents an opportunity for actors outside the United States to position themselves as significant market participants. Europe's Arianespace has historically been the most important commercial launch provider. Due to SpaceX's development of the Falcon 9, Arianespace's market share has dropped dramatically. Nevertheless, Europe's reputation as a highly reliable launch provider still stands. As such, over the 2030s, Europe will likely find its niche elsewhere, for example as a launch provider for small to medium-sized satellites (see section on Europe's role in space in 2040 in chapter 4). Given the numerous activities of companies such as i-Space (China), OneSpace (China), Isar Aerospace (EU), RFA (EU) or Rocket Lab (United States/New Zealand), it is likely that by 2040 all global regions will possess commercial launchers of varying sizes of their own.

Entering the launcher market is not easy and will remain difficult, even in 2040. This is because failure can result in loss of life, environmental damage or the destruction of civilian/military infrastructure. Before a launcher may attempt taking off into space, it requires certification by the national body responsible.[14] Acquiring certification requires procedural experience, which very few actors possess. As of 2023, this represents an opportunity for existing aerospace actors to participate in the burgeoning launcher market by teaming up to invest in launchers of their own.

New Markets for MRO, RPO and 3D Printing in Space

There are two ways MRO (Maintenance, Repair and Operations) is important for the future of the space economy in 2040. Firstly, the availability of reusable launchers that was discussed in the previous sections necessitates a future business model for the maintenance of these launchers, permitting their continued use for space launches. Secondly, reduced launch costs and opportunities for more complex spacecraft will enable satellite MRO (or on-orbit satellite servicing), which involves maintaining, repairing, or refuelling satellites in orbit.

As of 2023, some Falcon 9 boosters have been reused up to 15 times. By 2030, the diversification of launch vehicles implies that the Falcon 9 will not be the only partially reusable launcher available, and the Starship will be fully reusable. After every launch, boosters and rockets will have to be inspected and maintained. Companies will strive to reduce turnaround times to increase their launch frequencies while stabilising costs. This drives forward a business model for launch vehicle maintenance.

14 GAO (2013)

"The advent of used launch vehicles [...] will of course also create business models for the maintenance of these vehicles, all over the world."

Robert Zubrin, Pioneer Astronautics

Of course, MRO for launch vehicles already exists internally with SpaceX, but the proliferation of reusable launchers will also create a market for independent MRO shops. This is especially significant as there will also be a market for used launch vehicles, which will have to be maintained by actors other than the launcher OEMs. Again, repaired and maintained launchers will have to acquire a launch license, which significantly increases the entrance barriers for new participants in the launcher MRO market. This accordingly represents a market opportunity for aerospace actors who already possess experience with certification.

The second aspect of spacecraft MRO is on-orbit satellite servicing. When a satellite fails or runs out of fuel, it is currently impossible to carry out repairs or to refuel the spacecraft. Nevertheless, there is a strong demand for such operations, as it is expensive and time-consuming to design, build and launch a new satellite. Moreover, a satellite becoming inactive can result in competitors taking over market shares, and given the delimitation and diversification of spacecraft, the need for maintenance is going to increase. Therefore, companies and institutions such as Lockheed Martin, Northrop Grumman, as well as SpaceWerx, the innovation arm of the US Space Force, are working on standardising docking systems and developing refuelling capabilities.[15] Over the course of the 2030s, it will become feasible to repair, refuel and maintain spacecraft, thus enabling on-orbit satellite servicing.

15 Erwin (2022c); Albon (2022)

"At the moment, satellites are essentially made and they're frozen in time, if you will. The moment they're launched, they're essentially obsolete. And you might be able to refuel them, but you can't necessarily change the actual payload and sensor itself, they're not designed for them. [...] We're talking about some kind of satellite MRO business model, essentially. And that is developing, especially for refuelling. Of course, the MRO also implies rendezvous and proximity operations, RPO. [...] It's a technological capability that's within reach of major space fairing countries."

John Sheldon, AzurX

Satellite MRO requires the availability of RPO (Rendezvous and Proximity Operations), i.e. the ability of two satellites in space to match their plane, altitude and phasing.[16] Satellite MRO and RPO will become much easier due to technological convergence in the fields of robotics, artificial intelligence, sensor technology and cyber-physical systems. In the early 2020s, remote MRO for aircraft engines began being adopted by major MRO providers using augmented reality displays.[17] For in-orbit satellite servicing, the repairs can be carried out using virtual reality displays coupled with haptic gloves. The engineers will be working on a digital twin of their space asset, and an AI-supported robot will carry out the physical repairs. The satellite rendezvous manoeuvre will be carried out autonomously.

16 Damale (2020)
17 Bjerregaard (2020)

Although only a minority of the participating experts have made this claim, 3d printing may be another method to carry out satellite MRO without the need for rendezvous manoeuvres. Very expensive satellites may be equipped with small 3d printers and the ability to self-repair. When a component breaks down, the on-board 3d printer recreates that component and it is then replaced by a robotic arm. Specific satellites made for 3d printing may be able to produce spare parts on demand. Examples of spare parts that could be 3d-printed include antennas, solar panels, structural components such as brackets or connectors, as well as circuit boards.[18] 3d printing has the potential to dramatically increase the lifetime of satellites in orbit, which contributes to the sustainable use of outer space.

"I can imagine very well that 3d printing in space will be able to help in replacing various components, improve them and repair them. […] I believe that this will simply be able to revolutionise a lot of things, that a revolution is already going on."

Amelie Schoenenwald, European Space Agency

18 Kauppila (2022)

The LEGO Approach to Space: Modularity of Space Systems

In systems engineering, a module refers to a unit with a set of specific interfaces, serving functional goals such as flexibility, evolvability, manufacturability, testability and maintainability.[19] Systems exhibiting modularity are therefore systems that are composed of modules. For the space systems of the future, modularity will be key for enabling the MRO and RPO as laid out in the previous section.

"We need to design satellites to be modular, whereby component parts can be switched out as and when required, either to update the actual sensor itself or the payload as technology allows us, without having to launch a whole new satellite or to repair something that's broken, leaving a satellite stranded in orbit doing nothing. We can then make it operational again and just carry out general repairs and upgrades and so on."

John Sheldon, AzurX

Nevertheless, modularity is not only critical for spacecraft MRO and on-orbit satellite servicing, but also for upscaling spacecraft production. Modular satellites with standardised components and subsystems will drive up the efficiency of production while simultaneously decreasing costs. Responsive space, which will later be discussed in more detail, depends on the ability to swiftly assemble custom-made satellites. Modularity implies that there will not necessarily be warehouses of ready-to-go satellites that will never be used, but warehouses of component parts, which can be assembled as need be on very short notice.

19 Efatmaneshnik et al. (2018)

Modularity of spacecraft will also allow many more players to participate in the space economy. Sensor manufacturers, aircraft OEMs, electrical equipment companies and many more will be able to provide their expertise, producing complete component parts for spacecraft. When RPO capabilities become more widespread during the early 2030s, the ecosystem of the space economy will grow to include a wider array for actors. Companies currently working on modular satellites include Maxar with its 1300 Class platform, NanoAvionics and SpaceWorks. Both ESA and NASA are engaged in research to further explore module architecture concepts.

Digital Twins and Remote Physical Work in Space

Technological convergence in the fields of virtual reality, digital twins, remote-controlled robotics, sensor technology and artificial intelligence will enable remote physical work in space over the course of the 2030s. Human beings will be able to remotely control tools via a virtual reality interface.[20]

"You would have engineers doing very precise operations on a satellite or a spacecraft in deep space, but who are based on Earth wearing a VR headset and haptics doing very, very almost surgery like operations augmented by AI where there is that time lag."

John Sheldon, AzurX

A key technology required for remote physical work are digital twins. Engineers will be able to manipulate these digital twins (in real time if required) in a virtual environment using haptic VR gloves. While the term 'metaverse' is often used to describe these virtual environments, this trend will occur irrespective of whether there is a metaverse or not, as it is driven not only by developments on the space economy but by a need across the board of the manufacturing and MRO sector. Remote physical work will allow engineers working from anywhere in the world without a need to be physically present at the production or maintenance site. This enables OEMs to do much of the maintenance work directly, reducing reliance on independent MRO workshops.[21]

On Earth, the actual maintenance processes will often be supervised by an engineer on site, which will not be possible in space. That is why AI support is critical, especially when there is a time lag (i.e. beyond LEO). AI will suggest which steps to take for a successful maintenance procedure, with human beings supervising tasks and intervening if necessary.

20 Rukangu et al. (2021)
21 Moody (2020)

"If someone wants to work with a test tube, you basically need a humanoid hand. This can only really be done using artificial intelligence, that you can sense everything and that the hand really behaves intelligently. But you also need AI for it to learn intelligently."

Tobias Strobl, AriaX

Much progress is being made in the development of more sophisticated robotic arms and hands, which is driven extensively by demand for new medical appliances.[22] Examples of companies working on these technologies include KUKA Robotics (Germany), Shadow Robot (UK), GITAI (Japan)[23] or the Stryker Corporation (USA). Progress in telesurgery can be translated to other areas of remote physical work, particularly to the high precision operations required for spacecraft maintenance or the replacement of spacecraft modules. Space agencies advancing in this field also include the Chinese space agency, which employs a robotic arm in the construction of its Tiangong space station.[24]

22 Aliouche (2021)
23 Rainbow (2022)
24 Jones (2022)

Autonomous Spacecraft for Collision Avoidance and Activities in Cislunar Space

While autonomous spacecraft themselves are not a new concept, over the next 15 years, three key developments will give this trend new momentum. Firstly, machine learning techniques will enable spacecraft to detect events in the space environment and to react accordingly without delays caused by Earth-based decision making.[25] Secondly, new sensor technology and improved space situational awareness (SSA) will enable spacecraft and operators to detect events with far higher accuracy. Thirdly, the utilisation of cislunar space will cause time lags in communications with Earth to become significantly more relevant.

As will be discussed later in more detail, the outer space environment of 2040 will look very different from the present, as there is going to be an enormous increase in the number of objects, especially in LEO. Spacecraft will need to manoeuvre more frequently to avoid collisions and they will need to be more aware of their surroundings. As the frequency of events and the number of spacecraft grows, it will become more and more difficult for human operators to make decisions, especially as physical and temporal margins shrink. Artificial intelligence will be able to take SSA and satellite sensor data into consideration to avoid collisions.

"Who is carrying out this AI research? There are a couple of companies in Europe that do that. There is for example an Italian company, a startup called Aiko. They develop software, artificial intelligence, that enables satellites to autonomously move and respond. The software uses information from SSA, traffic management, Earth observation, to define the position of spacecraft and to respond quickly or slowly, if a collision potentially occurs."

Manuel La Rosa Betancourt, Neutron Star Systems

25 European Space Agency (2018)

Improved SSA and the tracking of all relevant objects in LEO are a crucial capability before such systems can be implemented (see chapter on space ecology). This will be enabled by advances in sensor technologies:

"I think there will be a certain autonomy in satellites, not only commercial ones, but also to defence. Sensor technology in terms of optical cameras, lidars, infrared will be at a much more advanced stage."

Luisa Buinhas, Vyoma

The trend towards autonomous spacecraft will also be driven by an increasing presence beyond LEO. To explain why this is the case, it is important to note that there is a physical limit to the speed of communication signals. A signal from a satellite to the Earth's surface can only ever travel at the speed of light (300,000 km/s). As of 2023, the majority of spacecraft operate in low-earth orbit, which extends to an altitude of up to 2,000km above the Earth's surface. Communication with these spacecraft is almost instantaneous and there is no significant time lag. The same applies to geosynchronous orbit, where a spacecraft's orbit period is attuned to the Earth's rotation around its own axis. In the case of the Earth, geosynchronous satellites have to maintain a constant altitude of 35,786km. However, this changes in cislunar space beyond geostationary orbit. Cislunar space refers to the area of space between the Earth and the Moon. In these realms distances become too large so that time lags begin to make a difference, requiring autonomous capabilities.

"The only option to remotely operate spacecraft is to communicate with ground control, with Earth, and then to send information to Earth. That works quite well when you're operating in low Earth orbit, but as soon as you're on the Moon, you cannot longer do that. [...] That means that you have to build an infrastructure there that enables the support of autonomous vehicles. You can do that using artificial intelligence, on board computing and things like that."

Manuel La Rosa Betancourt, Neutron Star Systems

As the number of spacecraft in cislunar space grows (see section on cislunar space in Chapter 2), the need for autonomous operations will increase, which will be a major driver for autonomous capabilities.

Nuclear Energy to Increase the Versatility of Spacecraft

In the previous sections, several trends were discussed that pertain to the power of propulsion systems of future spacecraft, including the drop in prices, MRO, RPO and the trend towards enlargement. The manoeuvres involved in RPO operations have energy requirements greater than those which can be provided by traditional solar cells. Large complex spacecraft such as private space stations similarly require large amounts of energy, as demonstrated by the football pitch-sized solar panels currently attached to the International Space Station.

"One of the bottlenecks is energy. At the moment, most spacecraft are equipped with solar panels. Either you have huge areas of solar panels, or you can operate other forms of energy in space more easily, for example nuclear. So let's first start with nuclear fission. That will probably be possible in 15 years."

Daniel Bock, Morpheus Space

One likely method to provide this energy is thus through the more widespread use of nuclear batteries as well as through the utilisation of nuclear fission reactors in space. This trend corresponds to many countries viewing nuclear energy as a viable solution to the climate crisis as long as fusion power remains unavailable. [26] Moreover, investments in nuclear energy occur due to the increasing prices of fossil fuels and volatile raw material supplies.

Preparations for the advent of nuclear fission in space are already taking place, with companies such as Atomos planning to launch a nuclear reactor into space for the first time since 1965.[27] Similarly, NASA is planning to test a nuclear-powered spacecraft in 2027.[28]

26 Hochman & Hochman (2022); Young (2023)
27 Peterteit (2022)
28 Roulette (2023)

"The US are developing their own systems capabilities for the development of power supplies based on nuclear reactors. There is a renaissance going on at the moment. 20 years ago, the utilisation of nuclear reactors was on the level of a feasibility study, but now the US have actually pushed for support and for the development of nuclear reactors for space. And the Chinese are doing the same."

Manuel La Rosa Betancourt, Neutron Star Systems

Future megalaunchers and new space applications are driving a trend towards larger and heavier spacecraft. While objects in space are weightless, they still have mass. The energy required to accelerate an object to a desired velocity is directly proportional to its mass. Therefore objects with more mass will require more energy to be propelled forward. This energy could of course be derived from solar panels, which will vastly increase an object's surface area. However, given the more densely populated outer space environment of the future, more surface area implies greater vulnerability to space debris. Moreover, solar panels provide relatively little electrical energy. MRO spacecraft that regularly change orbital planes and trajectories cannot be powered by solar cells alone, as electric propulsion engines powered by solar cells provide only little thrust. An alternative energy source, such as nuclear energy, thus becomes desirable.

"There's a lot of interesting work being done in nuclear power systems. And this is right now quite a bit of a policy issue. There are companies like Atomos Space who are developing a nuclear propulsion system, but also trying to pave the way for just using nuclear technology in lower orbit as energy sources as well. […] And I think the time is now. The marketplace needs it. And as we get larger and larger space systems, they will require more power. And so it makes it more worthwhile to try to climb over that policy barrier."

Dane Rudy, Second Order Effects

The regulatory issue is indeed a common concern raised in discussions about nuclear energy in space. However, if one actor possesses nuclear capabilities, they will have practically unlimited energy available. The competitive advantage is so great that other actors will be forced to adapt. It is unlikely that the US would sit by if China were to successfully use a nuclear reactor in space and vice versa, especially as nuclear reactors in space are not revolutionary from a technical standpoint.[29]

Other factors driving forward nuclear reactors in space include the increased use of cislunar space and the Moon, and the longer operational lifetimes of spacecraft these steps require. Longer operational lifetimes also needed for greater sustainability in orbit and enabled by satellite MRO . On the Moon, it is very difficult to continuously power robotic let alone human activities using only solar power. This is because the Moon is tidally locked to the Earth, implying that the lunar day takes almost two whole earth weeks. To bridge two weeks of darkness, nuclear power is extremely well suited. NASA's Mars rovers Curiosity and Perseverance already use radioisotope thermoelectric generators (RTGs) to provide electricity.[30] While these are not nuclear reactors, they provide power by converting the heat produced by the natural decay of plutonium-238 to electricity. While this works well for small systems, it is insufficient to provide electricity for more extensive activities on the Moon, or to power electric propulsion systems, which require nuclear fission reactors.

"Our presence in space is expanding in the sense that we're now moving into Cislunar space for routine operations, at the moment, mostly civil and commercial, perhaps military by 2040. And those kind of deep space operations require new propulsion capabilities that are much more efficient and less costly. […] So you could see nuclear-powered plasma-propulsed spacecraft, satellites, and so on that will have very large, very long operational lifetimes."

John Sheldon, AzurX

29 Black & Gunn (2003)
30 NASA (2020)

Finally, some kind of nuclear reactor will become indispensable for activities beyond the Earth-Moon system, such as the human exploration of Mars and the asteroid belt for scientific and commercial reasons. Nuclear powered spacecraft will be able to spontaneously fly to different locations in the asteroid belt to scout for minerals and raw materials. Moreover, nuclear energy can be used to provide electricity for human beings on the Moon and beyond.

"Combined with the advancements of nuclear power on Earth, we'll see the potential of nuclear space propulsion, which can help to open up access to Mars."

Rob Meyerson, DELALUNE SPACE

The simultaneous presence of several drivers makes the availability of nuclear power in space very likely. Furthermore, the majority of the experts interviewed for this study confirm that nuclear power will be used to provide energy to spacecraft by 2040.

Nuclear-Powered Propulsion for More Flexible Spacecraft Operations

While a nuclear reactor in space will enormously contribute to the delimitation of space applications by providing far more energy than solar panels or RTGs, energy does not equal propulsion. For a spacecraft to reap all benefits of nuclear fission, the energy produced ought to be converted into propulsion. There are two ways to achieve this, namely nuclear thermal propulsion (NTP) and nuclear electric propulsion (NEP). NTP involves using a nuclear reactor to heat a propellant, whose expansion can then be used to give thrust to a spacecraft.[31] For NEP, the nuclear reactor is used to generate electricity, which is then used to power an electric thruster such as an ion engine or plasma thruster.[32] In 2040, it is likely that both types of propulsion will exist. While NTP is especially useful for spacecraft with a high frequency of manoeuvres (high thrust, short duration), NEP is most appropriate for spacecraft with a focus on durability (low thrust, long duration). NTP will eventually require for spacecraft to be supplied with new nuclear fuel, which will be possible due to the availability of satellite RPO.

"In space, we are experiencing a moment that there has also been during the industrial revolution. […] The steam engine replaced sailing vessels and then the great industrial nations such as England or the US have positioned and established themselves, because of their ability to carry large amounts of goods from one location to another. In space, this is the area of electric propulsion."

Manuel La Rosa Betancourt, Neutron Star Systems

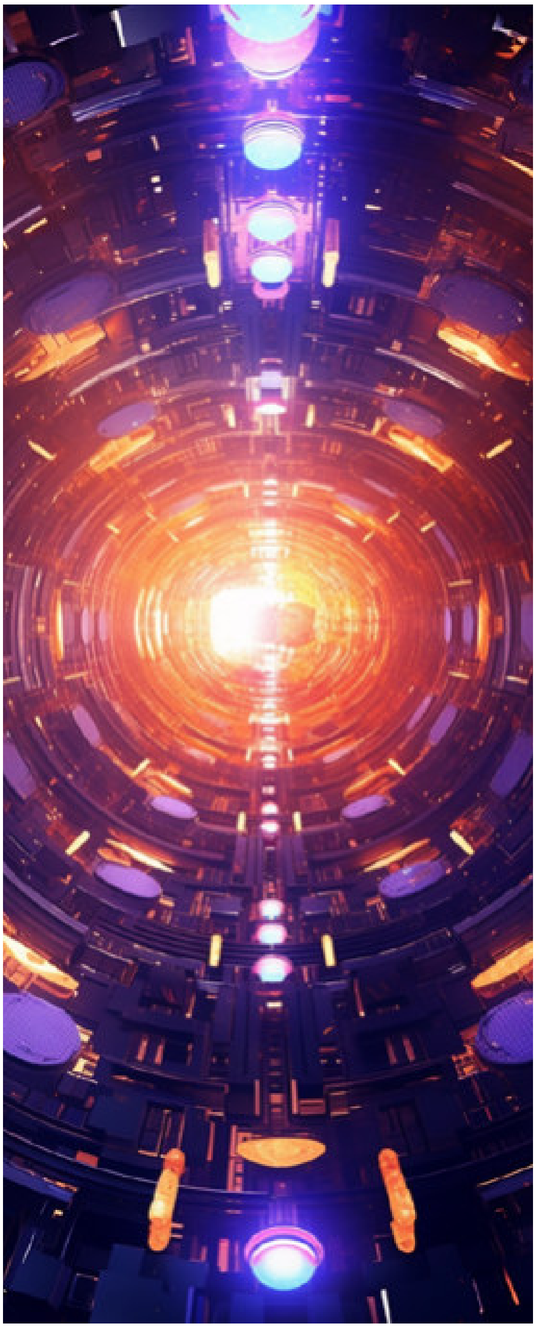
There are countless applications for spacecraft equipped with nuclear propulsion engines: raw material scouting of the asteroid belt, satellite RPO and MRO, long duration earth observation missions. Nuclear electric propulsion will be indispensable for large scale human activities on the Moon and beyond.

31 Gabrielli & Herdrich (2015)
32 Cassady et al., (2008)

"Imagine you want to bring 100 tons or a container to the Moon. This implies to you need 300 tons of fuel to get it there. With electric propulsion you only need a tenth of that."

Manuel La Rosa Betancourt

Apart from nuclear electric propulsion, spacecraft using solar power for electric propulsion will also be significantly more widespread than they are today.



Space-Based Solar Power at the Experimental Level

Especially in Europe there has recently been a renewed interest in space-based solar power, a concept which was extensively discussed during the 1970s and popularised through computer games such as SimCity 2000 during the 1990s.[33] The renewed interest is largely the result of the Solaris initiative by the European Space Agency, which is meant to conduct a feasibility study that could lead to the technology's further development by 2025. China too intends to install a demonstration unit in LEO by 2028.[34]

Space-based solar power involves the installation of large solar arrays in earth orbit. The energy collected by these solar panels is then beamed down to Earth using microwave energy. Lasers could theoretically also be used, but clouds can block them. The renewed push for space-based solar power is primarily the result of three developments:

1. Energy prices on Earth are going up, which may eventually make this form of energy production economically viable.
2. Space-based solar power produces clean energy around the clock, as there is no night-time in space. Moreover, solar panels have generally become more efficient, with efficiency in space being significantly higher than on Earth due to the absence of atmospheric interference.
3. Dropping launch costs also improve the prospects for economic viability.

Nevertheless, according to the majority of the study participants, it is unlikely that space-based solar power will be available beyond the experimental level by 2040. It is included in this report primarily because it is often cited as a potential future space technology.[35]

"I think you should be sceptical about it. There are huge economic and technical challenges. There are significant unknowns and we're effectively talking about a solution, not for this generation, but maybe a solution that turns things around for your grandkids."

Jim Keravala, OffWorld

33 Glaser (1977)
34 Gibney (2023)
35 Black et al. (2022); Woollacott (2022)

There are significant technical challenges to be overcome. The transmission of electrical power 'through thin air' is difficult to implement safely and efficiently. There have been recent experimental attempts to beam 1.6kW of power over 1km, in which transmitters and receivers lost half their input power. For solar power to be viably implemented, 75% efficiency is required.[36] Solar arrays in space will have to be placed in a geosynchronous orbit so that their energy beams can constantly target the same location on Earth. This involves covering 35,000km in a vacuum and several kilometres of the Earth's atmosphere.

Other hurdles involve geopolitical issues. As space-based solar power involves the creation of a high intensively energy beam, there is an obvious dual-use component to the technology. Microwave or laser beams can be turned into directed-energy weapons, and countries may feel threatened by other countries placing such systems in orbit. Having in mind the geopolitical environment of the 2030s, which will be characterised by competing geopolitical blocs, regional conflicts and uncertainty (cf. Big Picture chapter), the deployment of space-based solar power systems becomes less likely.

"The ability to collect so much energy and to focus that on the Earth is as much as a weapon as anything else. Somebody may decide that this is a weapon and we need to eliminate this. As another country at that rate, you may say this is a civilian application, I'm just generating power, somebody else might say, oh, this is just a major weapon that you have put in space. And I feel threatened now."

Narayan Prasad, satsearch.co

Another argument against space-based solar power is that despite dropping launch costs, it may remain prohibitively expensive when compared with fossil fuels, nuclear energy or different types of ground-based renewable energy. While the lack of direct access to fossil fuels will likely cause Europe to proceed with the green energy transition, other global regions will be slower to adapt, continuing to rely on fossil fuels during the 2030s. Space-based solar power involves not only the construction of solar arrays in orbit, which may become more feasible given the advances described in this chapter, but also the construction of facilities to collect the energy harvested in space. These receiving antennas will be several kilometres across, requiring significant land use.[37] It will therefore be necessary to find suitable locations that are not heavily populated or ecologically sensitive, making their construction on the European continent unlikely. If constructed in desert areas offshore, receiving antennas will face the same challenges current technologies are facing.

"As long as oil is plentiful and affordable, that is going to put a kibosh on things like space-based solar power, which is going to be very expensive, even with launch costs falling dramatically."

John Sheldon, AzurX

The majority of study participants agree that space-based solar power is unlikely to become operational by 2040. Hence, it should not be regarded as a saviour in the climate and energy crises humanity is facing during the 21st century. Still, space-based solar power is technically feasible and the hurdles mentioned above will likely be overcome in the second half of the 21st century. As with nuclear energy, an international body could be created to prevent space-based solar power from becoming weaponised. Easier access to space and AI-supported RPO capabilities will facilitate the construction of orbital solar arrays. While unlikely in 2040, space-based solar power might thus eventually contribute to humanity's future energy mix.

36 Clery (2022)

37 Radulovic (2022)

Responsive Space as a Key Space Capability

As with space-based solar power, responsive space is not a new concept, having been referred to in military policy documents as early as during the 1980s.[38] Responsive space refers to the ability of a space programme or system to rapidly adapt and respond to changing mission requirements, emerging threats, or evolving technological capabilities. It is consequently based on a convergence of different space technologies, rather than a single technology.

"At the moment you will need to know a couple of years in advance if you want to launch a satellite. You will have to develop the satellite, which is a unique piece manufactured by hand. Responsive space implies […] that you've got a warehouse, where satellites are stored and where rockets are stored. And then, if there's a crisis, you say, 'Next week I need a satellite that can do espionage – so either optics, or electronics or whatever – launch it on Monday!' At the moment, that is not possible […], but by 2030 it will probably become possible, certainly by 2040, that you can use space very quickly, without these long lead times that we still have today."

Kai-Uwe Schrogl, ESA

As with space-based solar power, the study participants have pointed out that availability of responsive space capabilities is very much dependent on the geopolitical environment as outlined in the Big Picture chapter. Given the rivalry between the US and China and geopolitical uncertainty, space will play a key role in national security. By 2040, space will be firmly established as a fourth arena of military activity, alongside land, sea and air. Responsive space will have become indispensable for states seeking to assert their military capabilities.

38 Sullivan (1988)

"If we're able to manage that shift in manufacturing economics, and governments are prepared to invest in having satellites in storage ready to go at a moment's notice, then yes, we can have responsive capabilities by 2040."

John Sheldon, AzurX

While the availability of responsive capabilities depends on the convergence of a large number of technologies, four of the topics that were discussed in earlier sections of this chapter stand out in particular: the modularity of satellites, space RPO and MRO, decreasing launch costs and cheaper spacecraft.

The modularity of satellites is important in this context, because it implies that responsive capabilities will not necessarily depend on the ability to launch an entire satellite. The satellite may indeed be in orbit already, and a small launcher is used to bring an additional component into orbit. As such, responsive space may involve warehouses of components rather than warehouses of entire satellites.

Space MRO and RPO capabilities in turn are required to install these components on satellites that are in orbit already. Moreover, security actors may require satellites to adjust their orbits due to particular events on Earth such as regional military conflicts, migratory movements and environmental disasters. While nuclear electric and thermal propulsion will become available during the 2030s, not all satellites will have to be equipped with high sophisticated and expensive propulsion system. Specific MRO satellites can be used to 'tug' satellites into the orbital environments required for particular operations. Atomos Space is expecting to launch its satellite relocation, resupply and inspection services during the mid-2020s and other companies are working on similar business models.[39]

As was discussed earlier, decreasing launch costs and cheaper spacecraft go hand in hand. If cheap and flexible launchers are available, this makes responsive space capabilities more likely, as a 'good enough' mentality can then also be established in the military space sector. Military actors will become less risk averse, decreasing the time at which a space mission can be made ready.

39 Rainbow (2022)

It ought to be emphasised that responsive space capabilities are not only relevant for military and security actors, but for businesses as well. Firstly, government agencies are increasingly dependent on private space actors to provide security information, as the war in Ukraine is clearly demonstrating. Private actors will thus in effect provide responsive capabilities to governments. Rocket Lab, a US-based company, is working on a programme designed "to on-ramp commercial and government satellite operators to the Company's 24/7 rapid call-up launch capability and streamlined satellite build and operation options."[40] Other companies working on responsive space include Firefly Aerospace, Northrop Grumman and Virgin Orbit, which plans on using a rocket that can be launched from a flying aeroplane, thereby turning any airport into a potential spaceport.[41]

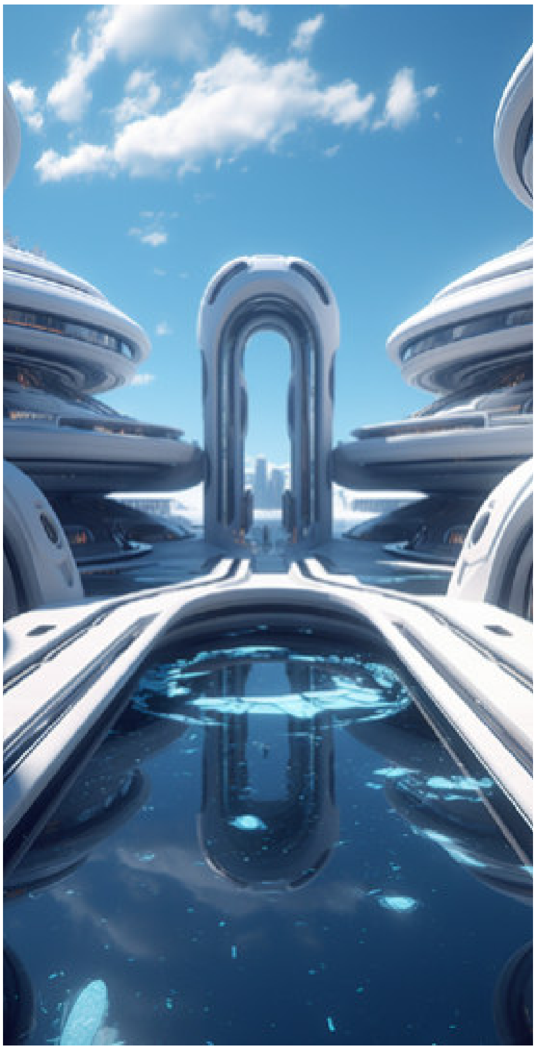
Secondly, as was mentioned in the section on space MRO, inactive satellites can result in losses of market shares to competitors. This applies especially to satellite services that depend on small constellations, where the loss of a single satellite can disrupt the entire system. Many current satellites cannot be repaired using on-orbit satellite servicing, and MRO satellites will only become widely available in the 2030s. Until 2030, replacing a lost satellite is often the only way to restore a particular space service. The time needed to replace the satellite can be critical, thus driving forward responsive space.

Finally, private actors will also require space data such as Earth observation data on short notice (e.g. heat maps, agricultural maps, construction monitoring, supply chain tracking etc.). Providers of such data will therefore also be driven to possess responsive capabilities to fulfil the demands of their clients.

40 Bailey (2022)
41 Ermin (2023)

CHAPTER II:
SPACE INFRASTRUCTURE

This chapter discusses the infrastructures that are enabled by future space technologies. New energy and propulsion systems will allow easier access to exotic orbits as well as new applications in cislunar space. Cheaper and reusable launch technologies and the delimitation of spacecraft are already facilitating the installation of megaconstellations consisting of thousands of satellites. This trend will continue into the 2030s. Moreover, new space infrastructures will include private human space stations, which will in turn serve as testing grounds for orbital factories and space manufacturing. By 2040, some of the computing and data storage infrastructure will have been moved to space. Finally, the chapter discusses how future technologies and infrastructures will lay the foundation for further advances towards space mining.



Exotic Orbits and the Future Geography of Cislunar Space

While space is three dimensional and largely empty, spacecraft cannot easily manoeuvre in space, as this requires enormous amounts of thrust. Spacecraft operations always seek to find the most effective and fuel-efficient way of changing trajectories. Within the solar system, spacecraft move in orbits, either around the Earth, the Sun, the Moon or other celestial bodies. The parameters that constitute particular orbits define the geography of outer space from a human vantage point.

In the future, the advances described in the previous chapter will impact the human geography of space. Space will become more delimited, and many more spacecraft will operate in locations that were previously difficult to access. These 'exotic' orbits may include eccentric orbits, in which a spacecraft's distance from the Earth varies over time.[42] These orbits are currently difficult to maintain because they require more fuel, but advances in spacecraft energy supplies and propulsion technologies will make them more accessible. Use cases for eccentric uses include earth observation, communications, scientific research and space weather monitoring. Earth observation satellites in eccentric and highly elliptical orbits can observe the planet's surface from different angles.

Another orbit which is currently hard to reach is the Molniya orbit, which takes a satellite over the northern and southern poles of the Earth in a highly eccentric ellipse. This orbit is well suited for communication systems requiring coverage of the Arctic regions, for satellite navigation, earth observation of the polar regions, meteorological observation and various military applications, such as reconnaissance and surveillance.[43] The Molniya orbit is difficult to reach because it requires significant changes in orbital inclinations, which are very fuel-intensive. Nuclear propulsion and spacecraft refuelling would make reaching the Molniya orbit significantly easier.

Nevertheless, despite the improved reachability of exotic orbits, human activities in space will increasingly reach beyond earth orbit during the 2030s, which is enabled by new propulsion

42 European Space Agency (2020)
43 Kidder & Vonder Haar (1990)

technologies and geopolitical considerations. Lagrange points and cislunar space will increasingly be used for military, scientific and commercial reasons.

"There will be a rapid race for strategic acquisition of pinch points in Near-Earth Space that are critical. The irony is that despite the vastness of space, there are a few locations that are almost gateways, bridges to the rest of the solar system energetically. So there'll be a race to that."

Jim Keravala, OffWorld

Lagrange points are places in space where objects can sit without moving relative to two other objects that are much more massive, because the gravitational forces balance out. For example, the Earth-Sun L1 Lagrange point is a point in space where a satellite can remain in a stable position between the Earth and the Sun, without using very much fuel to stay there. The Lunar Gateway, which is planned for launch in 2024, is a space station which will provide astronauts with an access point to the lunar surface.[44] The Gateway will be deployed in a highly elliptical near-rectilinear halo orbit, which utilises an Earth-Moon Lagrange point. Lagrange points can also be used for the assembly of larger spacecraft to explore the solar system, for earth observation and space telescopes.

The exploration of the Moon, which will likely intensify over the 2030s, will involve the intensified use of cislunar space.

"So what we're certainly seeing happening is, again, one of the trends that's not technological but mostly geostrategical, is that our presence in space is expanding in the sense that we're now moving into cislunar space for routine operations, at the moment, mostly civil and commercial, perhaps military by 2040."

John Sheldon, AzurX

Exploration and science are not the only reason for increased human activity in cislunar space. China's recent lunar sample return mission and China's successful deployment of a rover on the lunar far side have military implications from the point of view of other actors with interests on the Moon, such as the United States. It is currently not possible to spot a kinetic weapon being fired from the lunar surface.[45] Military actors are not only concerned because satellites in cislunar space are much more difficult to track. Unlike spacecraft in earth orbit, which travel around the Earth in a high repetitive manner, spacecraft in cislunar space will be under the additional gravitational influence of the Moon, which affects spacecraft trajectories, making their behaviour harder to predict. Equipped with nuclear propulsion and megalauncher capabilities, military actors will want to place satellites in cislunar space to establish more secure communications channels, to provide new vantage points for earth observation and SSA, to monitor other actors' operations on the Moon and to defend their own space infrastructure.[46]

44 NASA (2018)

45 Miller (2021)

46 Duffy & Lake (2021)

Megaconstellations to Enable Satellite Internet and Advanced Earth Observation

Megaconstellations are one of the key trends that are regularly cited in studies on the future of the space economy.[47] Megaconstellations are large networks of hundreds or thousands of small satellites that are designed to provide space-based services. Given the proposals of various companies and states, this may result in hundreds of thousands of satellites in orbit by 2030.[48] The space agency of Rwanda has filed a request with the International Telecommunications Union for two satellite constellations comprising a total of 330,000 satellites.[49]

"The actual disruption, which is taking place in orbit right now, is the one about megaconstellations, which however lead to rather negative disruptions, in terms of the sustainable use of outer space."

Kai-Uwe Schrogl, European Space Agency

Megaconstellations are often criticised because they create orbit debris and may therefore lead to certain orbits becoming unusable. This issue will be discussed in more detail in the chapter on space ecology.

At the moment, satellite internet is thought to be the most important use case of megaconstellations. Satellite internet systems such as Starlink are providing global internet coverage, even in remote locations and on high seas. While satellites in geostationary orbit are also capable of providing global internet coverage, they are less suitable for doing so due to issues with latency, capacity and cost. Small satellites in low-earth orbit overcome these limitations. Nevertheless, as long as terrestrial services provide internet access for far less money to the vast majority of the human population, it will remain difficult for satellite internet services to become truly competitive. While megaconstellations will certainly play an important role in the future of the space economy,[50] the majority of the expert panel agrees that they will not replace satellites in geostationary or medium-earth orbits.

Other than satellite internet, potential use cases for megaconstellations include earth observation and navigation services. Sufficiently large networks of earth observation satellites would enable services such as Google Earth to become available in real-time. This in turn has far-reaching implications if distributable ledger technology becomes widely utilised by the 2030s. Space systems could act as connections (or so-called 'blockchain oracles') between the real world and the digital world, being capable of creating a digital twin of the entire planet in the metaverse, tracking supply networks or monitoring weather events, natural disasters, migratory movements and conflicts.

"I don't think there's a need for so many mega constellations which are now being launched. I think companies and countries really need to work together to try to harmonise and leverage each other's resources."

Luisa Buinhas, Vyoma

While the potential of megaconstellations is certainly great, they exhibit various limitations, in particular the dangers they pose to the pollution of the outer space environment. Satellite MRO will play an important role in the 2030s, but in the foreseeable future it is not feasible to maintain and service tens of thousands of satellites belonging to megaconstellations. Given the future modularity of space systems, some study participants have suggested that actors may team up to use megaconstellations for a variety of purposes. A megaconstellation that is used to provide satellite internet may thus also be used as a fleet of earth observation satellites, with different actors sharing their assets. Moreover, some providers may offer the satellite platform as a service, with other actors merely attaching their modules. This 'space-as-a-service' model will be discussed in more detail in the chapter on the future of the space economy.

47 Kalms et al. (2020)
48 Lawrence et al. (2022)
49 Spacewatch Africa (2021)
50 Kinsella (2023)

Private Space Stations as Accessible Labs and Tourist Sites

In the previous chapter, it was demonstrated how megalaunchers will enable a delimitation of spacecraft in terms of mass and volume. However, even without the advent of megalaunchers, the price reduction that has taken place already will enable private actors to operate their own human-rated space stations by the late 2020s.

"My little company Pioneer Astronautics is now majority held by Voyager Space, which is building a private space station. Another group building a private space station is Axiom and also Blue Origin. And there's probably another one that we don't know about. And then there's the Chinese. This kind of stuff is happening."

Robert Zubrin, Pioneer Astronautics

One major driver of this development is the ISS: The International Space Station has demonstrated the need for a research environment in zero gravity. Pharmaceutical corporations and others would like to conduct experiments in space before they place their factories in orbit, but the ISS has very limited capacities for commercial activities. The ISS is simply not designed to be used as a commercial platform.

"So commercial space stations are a really big kind of up-and-coming segment of the space industry that we're watching very closely, at least. And that's going to enable fundamental research to increase the pace of our ability to develop and test new technologies. […] The ISS is a wonderful platform, but it is limited by astronaut time and by space."

Dane Rudy, Second Order Effects

One of the best use cases of private space stations are research laboratories. Private corporations could carry out experiments in the fields microgravity research, life science research and materials science. Much of this research will be directed at preparing for space manufacturing (discussed in the next section), where the activities on private space stations are upscaled to make them commercially viable. However, many of the activities in private space stations will be conducted for the future space economy itself. There is still much to be found out about how to minimize the negative effects of the outer space environment on the human body, and companies may want to do research on how to mitigate the impact of radiation as well as muscle and bone loss. Companies will want to test new spacecraft materials, as well as energy and propulsion systems. As opposed to the ISS, where public and private researchers have to queue for long periods of time before their experiment is conducted, private space stations will enable researchers to respond flexibly to new situations and discoveries.

"You will be able to set up independent space laboratories, being able to carry out research in all sorts of directions, because you will be able to adaptively do different things."

Tobias Strobl, AriaX

In many cases, space companies will provide private space stations as platforms for different government and commercial customers. Companies will be able to use these space stations by remotely operating the on-board equipment and even by sending their own astronauts to space stations. These astronauts will be trained by other actors in the space ecosystems. These private research platforms could host larger laboratories for individual long-term costumers, as well as dozens of small research labs which can be operated continuously from earth. The Axiom Station is the first private space station that is scheduled for launch in 2025.[51] Until the end of the decade, Axiom's ISS section is planned to grow by another two modules. Other companies such as Northrop Grumman, Blue Origin and Nanoracks are also planning on placing private space stations in orbit by the end of the decade. Nevertheless, not all private space stations will be research platforms. During the 2030s, some private companies will also operate their own space stations.

51 Klapetz (2022)

"My company is an R&D company. I would never want to have a situation where my competitors can just be walking through my lab all the time. It's out of the question. But if you can launch a space station or build a space station for $100 million instead of $100 billion, [...] then, hey, $100 million space station, well, that's something well within the budgets of major corporations. There's no reason why BASF couldn't have its own space station, or Pfizer or Toyota. It's not for everybody, but there are organizations that can make investments on this scale and do this. I think it's going to be a thing."

Robert Zubrin, Pioneer Astronautics

While the interests of private companies will be the main drivers of private space stations, there is another important factor which also makes private space stations more likely. By 2030, private space stations will enable human access to space to medium-sized powers. Europe, as well as India, the United Arab Emirates, Japan, Brazil and many other countries, including in Africa, will be able to send astronauts to private space stations for scientific research and national prestige. Medium-sized countries will be able to use private space stations to foster their national space economies, supporting local startups, who will now have platforms available to further develop their business models. Some private space stations can also be used for security purposes. Private space stations will contribute to levelling the playing field between space powers.

"I think that when you have private space stations like Axiom available, you're going to have countries who aren't currently partners in the International Space Station now have the ability to purchase access to an orbiting space station to do research or other scientific discovery."

Rob Meyerson, DELALUNE SPACE

By 2040, the study participants agree that private space stations are going to be common place, and there will be dozens of space stations in orbit around the Earth. While many of these will operate autonomously, being only occasionally visited by astronauts, some of them will hosts scientists and tourists. These space stations will be operated and rented by private companies and governments alike, further contributing to the growth of the space economy.

Space Manufacturing for Pharmaceutical and Biotech Products

Space manufacturing involves the manufacturing of goods and materials in outer space or on the surfaces of other celestial bodies. These goods may be designated for use on Earth or for further use in space. Space manufacturing requires significant resources and infrastructure, but the potential of space manufacturing has been known for a long time.[52]

There are several enablers of space manufacturing that will be available for the 2030s according to the study participants. Firstly, the delimitation of spacecraft volumes and masses brought about by reusable megalaunchers will significantly simplify access to space.

"[One area of interest] is definitely manufacturing in space and actually building material and then bringing it back down for use on Earth. There are obviously quite a few companies working on this as well. They are really fuelled by this shift in perspective, from having to create platforms that are size, weight, power-constrained to really being able to not think as much about the size envelopes or power envelopes."

Dane Rudy, Second Order Effects

A second enabler of space manufacturing are private space stations. When private stations such as the Axiom Station come online, this will significantly accelerate the pace of experiments with space manufacturing.

"The challenge today [is] that the International Space Station is just too difficult to do business with. There is an ISS National Lab organization that determines if your research is worthy of getting on the space station and then you wait years to get the payload approved and launched. It can be done, but it's not at all commercial."

Rob Meyerson, DELALUNE SPACE

52 Phillips & Fontes (1977); Waltz (1982)

There are further trends that will make space manufacturing possible, including satellite RPO, remote physical work and nuclear energy systems. Reusable launchers will be able to dock with orbital factories to pick up and deliver goods made in space to the Earth's surface and to service the on-orbit factories. While space manufacturing stations will operate largely autonomously, advanced human-machine interfaces and robotics will enable scientists and engineers to 'work' in orbital factories remotely. Still, some human missions to space factories will occasionally be needed (see Tales of the Future).

But what are the use cases of space manufacturing? One possible use case involves the production of more perfect protein crystals. In zero gravity conditions, chemical reactions can be controlled more precisely.

"When you observe artificial enzymes at high magnification, you can see that they don't always exhibit perfect crystalline properties. However, conducting experiments on the ISS or satellites, where there is zero gravity, can result in nearly perfect crystallisation. This opens up the possibility of creating much larger enzymes that can grow without limits, potentially revolutionizing enzyme-based applications."

Robert Boehme,
Planetary Transportation Systems

Protein crystallisation in microgravity can for example be used to develop new types of drugs that employ monoclonal antibodies (MABs). These engineered proteins have the ability to bind themselves to substances that cause disease. MABs are involved in some of the top-selling drugs used to fight diseases such as cancer and arthritis. On earth, administering MABs requires long-duration stays at the hospital, but there are ongoing studies by the Merck Corporation that exploit the microgravity environment of the ISS to develop MABs in high concentrations, permitting them to be administered by injection at a doctor's office.[53] Various other research projects into cancer fighting drugs are similarly ongoing, though their pace will be significantly increased by private space stations that are built specifically for the purpose of these kinds of research. The expert panel that participated in this study was divided on whether pharmaceuticals will be produced in space by 2040, but if future experiments show that drugs produced in space are more effective, easier access to space can enable production to be upscaled, thereby becoming economically viable.

Other possible use cases for space manufacturing for earth include the production of more robust carbon nanotubes with fewer defects,[54] or 3d-printing of entire organs for transplants. Due to the fragility of the material, organs printed on Earth can collapse under their own weight during the printing process, requiring the addition of certain chemicals to strengthen the tissue. In space, this problem does not occur as the lack of gravity eliminates the need for chemical strengtheners, allowing the tissue to strengthen properly on its own. This could lead to the production of viable transplant organs in as little as 45 days.[55] Nevertheless, before this is implemented on a larger scale, years of experiments and trials are needed, casting doubts on the viability of this use case by 2040.

Another use case for space manufacturing involves the production of goods for further use in space. This is especially relevant for spacecraft MRO, which was discussed in the previous chapter.

"I am absolutely certain that we will build up large structures that, for example, could print out metallic structures [in space]. This should be possible. I don't think we will just produce everything in space. There are a lot of processes that we can simply do better on Earth, and then we just launch that. But a symbiosis will indeed be the case."

Daniel Bock, Morpheus Space

Moreover, in 2040, space manufacturing may not be limited to earth orbit. Human operations on the Moon will require in-situ production of resources such as fuel, water and concrete. Lunar ice can be melted to produce water, and electrolysis can then be applied to create hydrogen, which can in turn be used as rocket fuel. The steps involved in concrete production are significantly more complex and energy intensive and thus depend on the availability of large power supplies. [56] Using metals that are readily available on the lunar surface, it will also be possible to 3d print metallic structures on the Moon.[57] One company that is working on this is ICON, which recently won a NASA award to do further research on space-based construction technology.[58]

By 2040, the high likelihood of a human outpost on the Moon (see Chapter 5 on space exploration) makes it very likely that a limited form of space manufacturing will exist. However, there is a large degree of uncertainty regarding the possible operation of orbital factories to produce pharmaceutical products. The feasibility of such factories would have to be demonstrated on private space stations, which will take several years. Moreover, experiments will have to clearly prove the improved effectiveness of drugs produced in microgravity. As such, in an optimistic scenario, such factories may become operational by the late 2030s.

53 Guzman (2022); Enemali et al. (2022)
54 Alford et al. (2001)
55 Allman (2020)
56 Reid (2022)
57 Papadopoulos (2021)
58 ICON (2022)

Space Computing: Relocation of Server Farms and Data Storage Hubs to Space

For various applications on Earth, computing power will become a key infrastructure. These applications include the metaverse, which will serve as the future digital architecture, as well as blockchain technology, which in turn will shape the financial architecture of the 2030s and beyond. In the metaverse, digital twins will be used as real-time virtual representations of physical objects. Their simulation requires enormous amounts of processing power. Blockchain technology is dependent on verification algorithms, which similarly require processing power to function. Apart from computing power, many future technologies require data collection and storage. While data storage has become extremely efficient, it still requires physical space, and data is only useful if it is properly analysed and evaluated, which too consumes computing power. Artificial intelligence and quantum computing are three further trends which will impact the IT area over the course of the 2020s and 30s.[59] While spacecraft will increasingly rely on edge computing to carry out some of their data processing faster without having to activate energy-intensive radio antennae, cloud computing will continue to play a key role, and space can contribute to enabling cloud computing in the future.

"I think there will be advances in terms of processing on board and processing in space. And this will really allow us, actually, to move some of the infrastructure that is in the ground today to support satellite operations, to space."

Luisa Buinhas, Vyoma

As discussed in the Big Picture chapter, during the 2030s, the urgency of the climate crisis and energy scarcity will generate an energy hierarchy, where different applications compete with one another for energy allocation. Computer processing is a very energy-intensive technology, as it requires energy not only to carry out its operations, but also to be cooled down. The outer space environment offers suitable conditions to be both. Solar power provides clean energy at higher efficiencies than on earth, and the coldness of space will supply ample cooling. The advent of megalaunchers as well as the capability to service space infrastructure using MRO satellites will make it economically viable to relocate computing power to space.

"…because you've simply got a lot more space. Everyone is always talking about CO_2. Google tested placing its data centre in the ocean for the same reason. These things need to be cooled down in a climate friendly way and at the same time require lots of electricity. Both cooling and electricity are infinitely available in space, with unobstructed access to solar energy from the Sun. This is significantly more efficient compared to Earth, where the atmosphere and day-night cycles can block a substantial portion of useful sunlight."

Robert Boehme,
Planetary Transportation Systems

Another driver for computing and data storage in space are regional conflicts, natural disasters and a renewed emphasis on resilience. During the 2020s, cyberattacks and new AI-capabilities to interpret Big Data will push for server farms and data storage centres to become infrastructures of key strategic significance. To reduce their energy consumption and to secure their physical integrity, some states may decide to move parts of this infrastructure to space.

"It could be that space becomes a hub for storage of data, as an alternative for instance, to physical infrastructures on the ground that are located in geographically unsafe areas of the globe. I do think that some of these data will be transferred to space, not only to the orbital environment, but also, perhaps, to other planets and our Moon. Data will become the gold commodity of the future."

Luisa Buinhas, Vyoma

Some computing power will eventually be relocated to the lunar surface. One driver for this is that the Moon offers protection from the radiation spacecraft experience in LEO, which may produce radiation-induced errors. The Moon is not exposed to the Van Allen radiation

59 Howarth (2023)

belts and server farms could be covered in lunar regolith. Nevertheless, the experts who participated in this study contend that this is unlikely by 2040. It is significantly more probable that computing power will be placed in orbit rather than on the Moon, as lunar server farms or data storage centres require the lunar economy to be in more advanced stages of development. While there is going to be a Moon base in 2040, maintaining a server farm for use on Earth will require a significant amount of infrastructure.[60] Moreover, given the distance of the Moon from the Earth, there is a non-negligible amount of signal latency, making a lunar server farm unsuitable for many Earth-based applications.

60 Tangermann (2022)

Further Advances Towards Space Mining

In the early 2010s, partially reusable launchers and startups such as Planetary Resources caused a hype around the issue of asteroid mining.[61] Harvesting resources off world has enormous economic potential: According to Asterank, which has measured the potential value of over 6,000 asteroids, mining the ten most cost-effective asteroids would generate profits of 1.5 trillion US dollars.[62] Asteroid mining has the potential to move human civilisation to the next level by making resources truly abundant for the first time in history. But will space mining become a reality by 2040?

"By 2040 we will sure have carried out lots of demonstrations. We will have landed, brought back samples to Earth, tried out and validated new technologies. But this will not be happening on a grand scale by 2040, but certainly by 2050."

Kai-Uwe Schrogl, European Space Agency

There are several challenges on the path towards space mining which are unlikely to be overcome by 2040. While megalaunchers, space RPO, modular satellites, the use of cislunar orbit as well as advances in robotics and sensor technologies certainly bring us closer to space mining, the amount of technological convergence required is greater still. While this is by no means an insurmountable *physical* boundary, the mining equipment that is used on Earth will have to be adapted for use on asteroids. Moreover, it will have to function mostly autonomously in a three-dimensional, microgravity environment. Demonstration missions will have to take place to test the feasibility of asteroid mining.

61 Lewicki (2013)
62 Yarlagadda (2022)

"The next thing we'll see are big oil cooperations, big energy corporations, large industrial corporations, big companies such as Siemens or Honeywell and the like, who will actually focus on adapting existing technologies for space systems. And if that indeed happens, you can de facto implement the vision of resource mining on asteroids or planets."

Manuel La Rosa Betancourt, Neutron Star Systems

Another factor to be taken into consideration is the abundance of untapped resources on Earth, which is significantly more accessible than resources on space. For a space mining business plan to close, it will have to be more financially attractive to mine resources in space than it is on Earth. Given the variety of technologies that have to be developed for asteroid mining, this is unlikely to be the case in the short-term future, even if megalaunchers will make space far more affordable and accessible. Bringing spacecraft to LEO is not the same as launching a spacecraft to an asteroid and landing on it. Plans to transport asteroids to orbits in cislunar space, making them more easily accessible, rely on very expensive demonstration missions, which would likely be government funded. No such missions are currently planned.

"Think about this for a minute. Before you look that far out, have a look at Earth. Our planet is entirely made up of rock. A thin layer of water covers 80% of the surface. And we're living on the rest. Here we've dug a few holes, a few kilometres deep. This is not even close to utilizing or even understanding the resources of our home planet."

Robert Boehme,
Planetary Transportation Systems

Given that even the most remote resources on earth are more accessible than space resources, space-for-space business will have to be fully operational before space mining becomes more attractive.

"It's difficult for me to understand yet how current Earth based industries take advantage of [space mining]. Now, I think that changes a lot when we start to think about the space economy as its own unit and building large infrastructure in space. It's a lot easier to go bring material in from the moon or fuel in from the moon than it is from Earth."

Dane Rudy, Second Order Effects

Space resources will be required to serve infrastructure on the Moon or in cislunar space, as it is significantly easier to launch material from the surface of the Moon than it is from the surface of Earth. The Moon's gravity is about a sixth of Earth's, and the Moon lacks an atmosphere, taking atmospheric drag out of the equation. Lunar resources could therefore be used to provide fuel and other material to spacecraft in cislunar space.[63]

63 Hobson (2021)

Mining Helium-3 on the Moon Unlikely by 2040

One often cited use case for space mining is to acquire helium-3 for electricity generation in future fusion reactors. While helium-3 is exceedingly rare on earth, it is thought to exist in larger quantities on the surface of the Moon and other celestial objects.[64] Helium-3 can be fused with deuterium (an isotope of hydrogen) to produce helium-4. This reaction releases large amounts of energy which in turn can be utilised for electricity generation. However, while being a possible driver of space mining beyond 2040, it will not significantly contribute to pushing forward space mining in the near future. Helium-3 production on the Moon is dependent on the commercial availability of fusion power, which is unlikely by 2040.[65] Moreover, most current fusion reactor designs feature the use of tritium rather than helium-3 as a fuel for fusion reactions. Other than helium-3, there are no known resources on the Moon which are not more easily accessible on Earth.

64 Slyuta et al. (2007)
65 Glick (2022)

"It would be music to the ears of any businessmen, government or investor if there was any resource of significant value on the Moon that you could harvest and bring back to Earth. However, as far as we know, there isn't any such significant resource. While the Moon has numerous exciting elements that can be used right there, like for creating titanium structures, rockets, rocket fuel, and water, they primarily serve lunar purposes. Living on the Moon or launching to Mars from there is fascinating, but there's likely not much to discover on the Moon that would be valuable to bring back to Earth."

Robert Boehme,
Planetary Transportation Systems

Beyond Robert Boehme, the vast majority of the experts involved in this study do not see Helium-3 mining as a realistic prospect for 2040.

WILDCARD

Space Mining

It is the year 2039. Space mining giant AstroMine has revolutionised the economy with its innovative approach to mining precious metals and minerals from asteroids. The company's CEO, Sarah Lee, had the foresight to invest heavily in space mining technology in the mid-2020s; a move that paid off handsomely. AstroMine has created a thriving new industry, attracting investors from around the world who are eager to capitalise on the boom in space mining. The company has also generated a wealth of high-tech jobs, from spacecraft designers and engineers to space miners and geologists. The impact of AstroMine on the global economy has been enormous. The company has single-handedly boosted the supply of precious metals, such as gold, silver, and platinum, reducing their market value and making them more affordable for the average consumer. It has also helped to create new technologies, such as advanced solar panels and batteries, which are essential for space exploration and other high-tech applications. However, not everyone is pleased with the rise of space mining. Environmentalists have raised concerns about the potential damage to asteroids and the surrounding space environment. Others worry that the increasing demand for space resources could lead to conflict and competition among nations and companies.

While the study participants agreed that space mining is unlikely to be realised beyond the experimental level by 2040, there exists a minority view which holds that the mining of asteroids will begin soon. Startups such as Netherlands-based Karman+, Chinese Origin Space or American SpaceFab have taken over the lead from the now defunct company Planetary Resources, which was the first serious attempt to jump start the space mining industry.

The potential of space mining is enormous. The value of the resources available on asteroid far exceeds the total value of all raw materials that have ever been mined on Earth. The asteroid 16 Psyche, which is almost entirely made of metal, is estimated to be worth $700 quintillion, enough to give everyone on earth $93 billion.[66] While Psyche is far away, other so-called near Earth asteroids, which orbit the Sun at a distance which regularly brings them close to Earth, are similarly believed to contain raw materials whose value outweighs that of the entire global economy.[67]

In an extremely optimistic scenario, where the price of raw materials from space begins to compete with the price of raw materials from Earth in 2030, it would very soon become cheaper to mine in space than on Earth. As production increases, mining of gold, silver, platinum, palladium, iridium and eventually iron, nickel and silicon, would inevitable cause the prices of these materials to fall dramatically. By 2040, the drop in prices would be so extreme, that supply outweighs demand, causing mining companies to limit their production. Nevertheless, by now the availability of sustainably produced, cheap resources would be revolutionising the economy. Space mining could be driving forward a construction boom around the planet of hitherto unseen proportions. Even climate change would no longer pose a threat, as space resources can be used to build renewable energy planets and carbon removal facilities.

Given this scenario, space mining would soon become a political question, with political movements arguing that space mining has the potential to bring humanity to a state of resource abundance. States would be struggling to find an international agreement on who owns the space resources, with China and Russia using the Outer Space Treaty (see text box) to argue that private institutions cannot claim ownership to materials harvested in space. They call for international legislation on space mining, reserving the right to own space resources to states. At the same time, the United States and the European Union would fall back on their own legislation on space commercialisation passed in the 2010s, allowing private companies to own and sell the materials they produce in space. In 2040, this issue would remain heavily contested.

Apart from the legal question, space mining would pose a number of ethical questions: Is it morally defensible to destroy the unspoilt environments on asteroids?[68] Should there be environmental protection zones in the solar system?[69] How can we make sure that the revenue and benefits generated through space mining are distributed among the entire human population?

While space mining is unlikely to occur become 2040, its advent will certainly bring about a major disruption for the human political economy and society.

66 Smith (2019)
67 Ravisetti (2021)

68 Köpping Athanasopoulos (2023)
69 Elvis & Milligan (2019)

CHAPTER III:
SPACE POLITICS

Having explored the future of space technologies and space infrastructure, this chapter outlines the future politics of space. Human activities in outer space will occur within the context of a new space race between the US and China, which in turn is a reflection of the larger geopolitical picture. Moreover, space will play a growing role for the world's militaries, comparable to navies and air forces today. Owing to the rise of commercial space activities, medium powers will be able to purchase the infrastructure required to access space, giving them a more important role. Finally, while an international legal framework for the commercialisation of space lacks significant drivers, there will likely be internationally recognised regulation on the sustainable use of space.

US-Chinese Space Race

The state of international relations over the 2020s and 2030s is of key importance in determining the state of the future space economy. During the Cold War confrontation between the Soviet Union and the US, geopolitics have been a major driver for the further development of human activities in space. The rivalry between the US and China will likely have a similar impact.

"There is another driver: the geopolitical situation. I don't think that is going to change over the next 50 years. The new space race between the US and China; […] we've already seen this during the 60s between the USSR and the US."

Daniel Bock, Morpheus Space

As of 2023, the United States' capabilities in space exceed those of all other space powers. The US are currently the only actor with partially reusable rockets. The US space exploration programme is the most advanced and it is the only actor with concrete plans with human spaceflight beyond LEO. The number of satellites registered in the US significantly exceeds the combined number of satellites registered in other countries, and, as of 2022, exceeds the number of Chinese satellites by a factor of 5.[70] Moreover, US military capabilities in space significantly surpass those of China in the areas of space-based intelligence, surveillance and reconnaissance (ISR), missile defence, responsive launch and SSA. Nevertheless, China is catching up fast.[71] The War in Ukraine has made the strategic significance of space assets staggeringly evident, as Starlink satellites were used to provide internet access to Ukrainian soldiers, and as private satellite images were used to expose Russian war crimes. This will push particularly China to draw level with the United States in terms of capabilities:

70 Statista (2023)
71 Pal (2022)

"I should also say, by the way, you know, this Ukraine war is going to accelerate the space. Because if you want to know, this is actually a space war. The reason why the Ukrainians are being able to hold their own is because of space capabilities, space based communications, space based reconnaissance, space guided weapons, precision munitions. And it's going to make very clear that the Space capabilities are decisive."

Robert Zubrin, Pioneer Astronautics

Over the course of the 2030s, the strategic importance of space for military operations will increase dramatically. In 2040, space supremacy will be regarded as being on par with air and water supremacy. Satellite communications, navigation, ISR, missile defence and space weapons will be critical security technologies and there will be a race for having the most advanced systems which will involve low and medium-earth as well as geostationary orbits as well as cislunar space to protect critical infrastructure.

"And I hate to define it in in these terms, but who wins this next space race will define the nature of global governance on Earth this century, because access to the high ground militarily and strategically cascades down to your terrestrial surface operations and your economy."

Jim Keravala, OffWorld

The study participants have expressed uncertainty about whether or not China will overtake the United States in terms of space capabilities. If China catches up, the United States will be under pressure to update and expand their own assets. As such, the next 20 years will be characterised by a race rather than by the continued supremacy of the US.

The Centrality of Space for the Militaries of the Future

The first object to be launched into space was the Nazi German V2 rocket, which underlines that space technologies almost irrevocably possess a dual-use component. While earth observation satellites can be used to monitor climate change or to spot earthquake survivors' heat signatures, they can equally be used to watch troop movements or to spot military technology tests. Navigation satellites are utilised for autonomous agriculture as well as for guiding cruise missiles. Space-based communications systems provide satellite television while serving as key security infrastructures for military transmissions. The directed energy beams generated by space-based solar power could similarly be used for hostile purposes.

One key counterspace technology that will shape activities in space over the 2030s are satellite rendezvous and proximity operations (RPO, see chapter on space technologies). If it becomes possible to repair a broken satellite, it is also possible to disable particular satellites without the need to use anti-satellite weapons, thus mitigating space debris generation.[72]

"Of course, the MRO also implies rendezvous and proximity operations, RPO. For the most part, the applications are benign, but there is, of course, always a dark side to these things."

John Sheldon, AzurX

Most satellites in orbit are currently not equipped with sensors that could detect approaching spacecraft. If a hostile spacecraft with RPO capability were to approach a given satellite, the latter could in most cases be disabled with the malfunction being attributed to a technical error. Over the course of the 2030s, satellites will therefore need to develop the ability to defend themselves, which is already possible with the current level of technology. Satellites will need to be equipped with optical sensors to identify hostile spacecraft's physical characteristics, radar systems to track objects in space or infrared sensors to identify heat signatures. Satellites could also possess systems capable of jamming other satellites signals, preventing them from receiving signals from ground-based operators. AI-controlled satellites may be able to carry out their hostile operations autonomously, so some key security infrastructures may be equipped with physical means to defend themselves, such as small directed energy weapons. Of course, AI or ground controlled course alterations are the most obvious way to avoid active confrontations.

"We will probably have technology that is going to emerge that revolves around satellites becoming autonomous decision-makers and defending themselves. So if one satellite sees another one coming close and behaving unexpectedly, probably this satellite could be able to respond to a bad actor."

Luisa Buinhas, Vyoma

Due to the sinking costs of space activities, the number of actors capable of satellite RPO will rise, enabling more actors to be capable of disabling satellites. This will further drive forward the need for satellite self-defence. In turn, while prices are generally sinking, the need for improved sensors and autonomous manoeuvring capabilities will contribute to the decline in prices not being quite as steep as some sources predict.[73] Nevertheless, more accessible RPO may enable space piracy by 2040, i.e. the ability by private actors and criminal organisations to disable or credibly threaten to disable spacecraft in LEO and beyond.

"How do we make sure there is no space piracy? […] When you've got a base on the Moon, we're talking about assets worth billions of euros. Can you make sure that these assets are protected without a military presence, such as spacecraft that ensure that everything is safe?"

Manuel La Rosa Betancourt, Neutron Star Systems

While RPO will certainly play a key role in military operations in space, denial of access is another strategy that may be used by future strategists in the event of a military conflict between two space powers. As space infrastructure becomes more important, countries and private organisations will become capable

72 Harris (2023)

73 Rexaline (2022)

of temporarily disabling that infrastructure, or of making spacecraft and stations physically inaccessible. This can be done through signal jamming, as was already carried out during the Russo-Ukrainian war.[74] The ensuing space race between the US and China will also make both sides capable of denying access to each other's civilian space infrastructure, such as the Tiangong Space Station or a US-led Moon base. Due to the presence of water ice, the lunar south pole is one of the most likely locations of the Moon base, and it is unlikely that the US would allow the Moon base to remain on the lunar surface with simultaneous Chinese science operations in close proximity. The Moon base will thus become relevant for security actors.

"If you have a look at Everett Dolman for instance, he would call this 'Denial of Access', in the sense that you can no longer access a satellite. If you have the option of preventing access to the ISS, or to a Moon base, that would be something quite serious."

Thomas Hoerber,
ESSCA School of Management

Apart from space RPO, satellite jamming and denial of access, it is also possible to directly attack space assets using anti-satellite (ASAT) weapons. Numerous ASAT tests have already been carried out, most recently by Russia, which created a cloud of debris that affected the ISS.

74 Kusumastuti (2022)

"Once you start destroying satellites in space with weapons, the amount of space junk, the amount of other moving parts, becomes exponentially more difficult to track, so anything up there could be hit by its own, other pieces of space junk. That creates a much larger problem than we can even consider right now."

Mark Sudol,
Aerospace Industries Association

While ASAT weapons have existed for quite some time, they have never been used because the actors that possess them would also harm themselves by creating space debris. Military RPO makes the use of ASAT weapons even less likely, because it is possible to achieve the same objectives without self-harm. This in turn increases the likelihood of armed conflict in space, as the risk of unintended consequences is reduced.

"My view of kinetic anti-satellite weapons is that they're not proper military weapons. They're a bit like nuclear weapons; they're political weapons. Maybe the likes of Russia and China test them and it's a signal to others to say, if you encroach on our interests, especially our core interests too much, we're prepared to trash low earth orbit. [...] It's a bargaining chip."

John Sheldon, AzurX

To conclude, space assets have always had a dual-use component and will continue to do so in the future. Space RPO will enable a new category of anti-satellite weapons with minimised fallout. Given that the strategic importance of space infrastructure will increase, the likelihood of the utilisation of these ASAT will increase likewise within a global context characterised by US-Chinese rivalry and limited regional conflicts.

Rise of Commercial Actors and Decline of States

Historically, states have been by far the most important actors in space. The 1960s space race was driven by the desire for national prestige, and the 1990s' project of the International Space Station was a reflection of the increasing international cooperation. Within the advent of the NewSpace era, private companies, research institutions and even individuals have become prominent players in the space economy. Until 2040, the majority of the study participants hold that this trend is going to continue. Commercial actors will likely replace states as the major drivers of human activities in outer space. While states have supported the commercialisation of space and the commodification of space resources, the space economy is developing a life of its own. This includes not only commercial applications with an immediate use-value for Earth. By 2040, most study participants consider it very likely that companies will have landed private astronauts on the Moon.

Moreover, Russo-Ukrainian War has shown that in addition to states, private companies have begun to play a significant role in space military operations. While SpaceX provided satellite internet, Maxar Technologies published satellite imagery. Both companies have thus positioned themselves as siding with Ukraine in the ongoing war. Over the course of the 2030s, private companies will play an ever-more important role, with states relying on them to provide security applications. This will enable many medium-sized powers to maintain similar space capabilities as large space powers. The applications include space launches, SSA, space RPO, space reconnaissance and surveillance, communication services and responsive capabilities.

"It is a very important question whether the state still plays an important role, especially if it remains as impotent as it is right now. [...] I don't really think so. If things remain as they are, I don't think so. In this case I believe that private companies will split things up among themselves."

Thomas Hoerber,
ESSCA School of Management

Nevertheless, despite states' outsourcing of important security capabilities to private entities, states will remain in control of the security-related activities of private companies through contractual arrangements and through exercising their sovereign rights. Moreover, some companies will explicitly declare that their space assets cannot be used for security purposes, as is the case with Bavarian space company OroraTech.

Medium-Sized Powers Catching Up with Major Powers

One key feature of the global political economy of space in 2040 will be that there will be significantly more space powers. Countries such as the United Arab Emirates, Iran, South Korea, South Africa, Australia or New Zealand will have some military and civilian capabilities that are comparable to those of major space powers today.[75] In many cases, smaller economies in today's developing world will also have significant space capabilities, especially if they are characterised by large surface areas. While it is unlikely that these countries will have the capacity to launch human beings into space, they will have several other capacities, such as the ability to independently launch a satellite, earth observation, satellite communications, space RPO, SSA and counterspace capabilities.

"One of those trends will be in maybe 20 years' time, you're going to find very small underdeveloped countries will have, for example, the Earth observation capabilities of more advanced countries today."

John Sheldon, AzurX

The push for smaller countries to become a space power is driven by several factors, including the economic benefits of a national space economy, international prestige, scientific advancement and the increasing importance of environmental monitoring. However, until 2040, military considerations will be the single most important factor causing the rise of medium-sized space powers.[76] The War in Ukraine has made the importance of independent space infrastructure especially obvious. In a conflict situation, states will want to maintain independent access to key infrastructure, such as earth observation and communications satellites.

"You know, I was in both Ukraine and Poland, well, in Ukraine in 2018 and Poland in 2020. And I told people there, you need your own space program. And this is not peripheral, but because, you know, if the Ukrainians had their own reconnaissance satellites right now, they wouldn't be negotiating with the Americans for targeting intelligence."

Robert Zubrin, Pioneer Astronautics

The key enabler of the rise of medium-sized powers is easier access to space. In 2040, there will be a plethora in launch providers around the world as well as a market for used launchers. Medium-sized countries can either group together to support the establishment of a multinational commercial launch provider as a joint venture, or they can purchase used launchers. States that do not possess the economic and scientific infrastructure for building their satellites can order their custom-made modular satellite from satellite manufacturers abroad.

"This is indeed a development […] that would have been impossible five to ten years ago, because it simply would have been too expensive and not accessible for [medium-sized] powers. If costs in the space sector continue to decline, as appears to be the case, given cubesats and the like, this will also start becoming interesting for medium-sized and small powers."

Thomas Hoerber,
ESSCA School of Management

The growing interest of medium-sized powers in space also represents an opportunity to ease geopolitical tensions between the US and China. Non-aligned countries may choose to cooperate with both the United States and China to harvest maximum benefits and to increase their resilience in case of an international crisis.

75 See Townsend (2019) for thoughts on defining 'space power'
76 Weeden & Samson (2021)

"We'll be seeing medium-sized powers […] working with both the Americans and the Chinese, especially on things to do with the moon. I can imagine Saudi Arabia sending astronauts to the moon through Artemis, but also sending astronauts to the moon through the Chinese, just to make the point."

John Sheldon, AzurX

The rise of medium-sized powers will be one of the major trends defining the international political economy of space until 2040.

Space Enables Leapfrogging in the Global South

Easier access to space will enable developing countries to harvest the benefits of space infrastructure directly, which reduced the need to invest in some terrestrial infrastructure. This allows these countries to catch up with developed countries more quickly than otherwise possible. Space can enable leapfrogging in areas such as communication systems, agriculture/forestry, climate change monitoring and disaster management.

While satellite communication is important for security systems, satellite internet will also be able to boost remote areas by providing high speed internet access, thus enabling autonomous systems. Agriculture, forestry, and climate change are intricately linked, and Earth observation satellites are able to monitor forest covers, biodiversity, desertification and changes in soil composition.[77] By 2030, farmers in developing as well as developed countries will be able to precisely monitor crop growth, soil moisture and soil nutrient levels, enabling them to adjust their farming practices. In Europe, much of this is already possible using the Copernicus system of the European Space Agency.[78] Given that developing countries will be hit hardest by the effects of climate change, space is a key enabler for more effective disaster management. Space can function as an early warning system for weather events, floods, earthquakes and wildfires. Flooded areas can be accurately mapped and damaged infrastructure identified. Infrared sensors can spot wildfires and temperature anomalies and assist in search and rescue efforts. Companies such as the German-based OroraTech or US-based Planet Labs are working on commercial Earth observation solutions. OroraTech is focusing on thermal imagery, being able to find temperature anomalies on a resolution of 4x4 metres. Planet Labs in turn produces maps that can be used for agricultural purposes, being able to identify crop stress and to monitor irrigation levels.

77 Rutkovskaya (2022)
78 Jutz & Milagro-Pérez (2020)

"Because at the end in India, […] this is the part of the infrastructure leap or infrastructure disruption that is happening because it's the same thing with mobile phones, right? Because India did not have to a large extent wired telephone that Europe had or the US had and could leap through to smartphones directly to a large extent."

Narayan Prasad, satsearch.co

"I'm thinking of Africa again, microfinance, internet connectivity, perhaps links to renewable energy. […] I think there are lots of opportunities for development."

Thomas Hoerber,
ESSCA School of Management

For developing countries, the ability to 'skip' stages of development by investing in space will be a driver for the growth of the space economy. While legacy systems often slow the adoption of new technologies in developed economies, developing countries have the potential to be faster at adopting the tools that were described in the chapter on space technologies.[79]

"Basically we're saying, we are not using other forms of land-based surveys or other forms of infrastructure and we are directly stepping into a way where this convergence in other industries is enabling space to be used as a sensor again, to be able to then transform industries. So you look at major industries, major digital transformation in other industries happening in India; space will be a part of that. The adoption barrier is much lower […] because legacy systems are not present so much."

Narayan Prasad, satsearch.co

Until 2040, space applications such as agricultural monitoring or disaster forecasting and management will make it easier for developing countries to adapt to the detrimental impact of climate change. Moreover, the lack of legacy systems will allow developing countries to swiftly adopt space technologies for mapping, monitoring and geographic surveys, enabling a degree of leapfrogging.

79 cf. Kabanda et al. (2018) for a similar development in cybersecurity

Continued Role of Europe in Space

The NewSpace economy, which was primarily driven forward by the United States, has led to Europe struggling with maintaining its position in the launcher market. While Arianespace was the most important commercial launcher company up until the mid-2010s, SpaceX has since taken over this position, holding more than 50% of the global market share. Europe's Ariane 5 rocket will see its final launch in early 2023 and its successor, Ariane 6, is struggling with delays.[80] Moreover, Ariane 6 is not reusable and its cost per kilogram is significantly higher than that of SpaceX's Falcon 9. What will Europe's position be during the 2030s?

"As [Germany] and probably also as Europe we continue remaining behind, not having the same level as other great nations. ESA is cooperating with a lot of projects, but we cannot compare our competences and capabilities with those of NASA or China, because the European Union has not set the same priorities."

Fabia Höhne Tarragona, OroraTech

While Europe is now investing in its own renewable launcher, it is unlikely that Arianespace will recover from the advent of SpaceX. The Themis programme serves as a technology demonstration for the successor of the Ariane 6, which will only enter into service during the 2030s.[81] By that time, megalaunchers will have caused launch costs to sink further, making Ariane Next as uncompetitive during the 2030s as Ariane 6 is today. Nevertheless, although Europe's relative position in the launcher market may have declined, Europe will continue to be one of a few global regions capable of supporting a vibrant space economy.

80 Borchert (2023)
81 Patureau de Mirand et al. (2023)

"Having a big European launcher is important, but is that what's going to keep Europe at the forefront of space technology? Since Europe doesn't have a human space launch capability, does the launch part really matter? Or is it better to let the smaller launch companies, like Isar and RFA, be part of the technological engine and maybe focus on some other part of the space infrastructure and make that Europe's big contribution."

Rob Meyerson, DELALUNE SPACE

Over the course of the 2030s, Europe will possess several smaller private launchers as well as its own partially renewable launcher, but it is very unlikely that it will be able to reassert its leading position in the global commercial launcher market. However, based on the expert interviews conducted for this study, there are at least two areas where Europe can lead, namely climate change monitoring and mitigation, as well as space debris mitigation. Given the future modularity of satellites, Europe will support the commercial development of satellite sensors that will help different actors monitor the impact of climate change. As our knowledge about climate change is dependent on space infrastructure, climate change is an important driver of the more intensive utilisation of LEO, as well as of exotic orbits.

One expert also stressed that Europe is seen as a leader in combatting climate change and that it will use this position to become leader in the field of environmental monitoring. If Europe transferred its ecological expertise into space, applying it to space debris removal, orbital regeneration and carbon neutral rocket technology, it could become the champion of the sustainable use of outer space. While it is difficult to predict where Europe's focus will lie during the 2030s, as this also depends on political decisions, the study participants contend that it is likely that Europe will find new niches where it will emerge as a global leader.

Some of the current signposts for this development include ESA's Business Incubation Centres initiative, which supports the development of space businesses throughout the ESA member states.[82] Companies such as German ClearSpace or French Share My Space are pioneering the business case for space debris removal. At the same time, the EU's Copernicus system provides a good foundation for Europe's possible future leadership in the area of Earth observation. Copernicus also involves a variety of commercial actors, such as Airbus Defence and Space and Italy's Leonardo. Since the late 2010s, Copernicus is also open to participation by non-EU member states, including Australia, Brazil, India and Colombia.

82 European Space Agency (2023b)

New Legal Regime for Sustainability in Space

As of 2023, there is only one major international treaty on space that has been signed by all important space powers, namely the Outer Space Treaty (OST).

Outer Space Treaty

The Outer Space Treaty of 1967 has the intention of laying out binding rules for the use of outer space. It has been signed by all major space powers, including Russia, the United States, the member states of ESA and China. Given the Cold War context of its emergence, it is characterised by three major principles:

1. Space is a province of all mankind. No part of space can become the territory of a state.
2. The Moon and other celestial bodies can only be used for peaceful purposes. Testing of weapons of mass destruction in space is prohibited, as well as their placement in space.
3. Countries bear international responsibility for their space activities, regardless of whether they are carried out by public or private organisations.

The treaty also defines which country is considered the 'launching state' of a spacecraft, although this concept has been developed further in the Liability Convention of 1972.

While the Outer Space Treaty was an important achievement in terms of having prevented outer space from weaponisation and being used for nuclear tests during the Cold War, it is very much characterised by its Cold War roots. It makes no explicit reference to the commercialisation of space, which is why there are going to be more debates on a new international space treaty.

"The Outer Space Treaty is actually a paper-thin bubble that has held the peace and stability for half a century. But at some point, its time will come where it will be challenged and it will be either heavily modified or simply ignored by certain actors."

Jim Keravala, OffWorld

The three main developments that are challenging the current legal regime of the OST are space debris, space commercialisation and space militarisation. Space debris is a challenge because it can only be significantly limited through international cooperation, such as a ban on ASAT tests and rules on deorbiting derelict spacecraft. The commercialisation of space is challenging the liability convention. If a private company were to launch a spacecraft from high seas, it is currently the country with which the launching vessel is registered that is liable for damages. Moreover, the OST does not contain clear rules on the appropriation of raw materials from celestial objects.[83] Finally, the militarisation of space will further challenge the OST because of the advent of space RPO. The Treaty is insufficiently clear on what it means by its reference to 'peaceful purposes'.[84]

The experts that were interviewed on this issue are in agreement that by 2040 major space powers are unlikely to agree on new binding rules on the commercialisation and militarisation of space.

"[For rules on commercialisation and militarisation] currently dominant realism would have to be replaced by idealism at the international level. Realism is ultimately caused by the rivalry between the major space powers. The US are constantly blocking the reform of the Outer Spacy Treaty because it's simply not in their interest. They are the strongest, they don't need these rules."

Thomas Hoerber,
ESSCA School of Management

While the major spacefaring nations are unlikely to agree on new binding space legislation on commercialisation and militarisation, medium-sized powers will be pushing for new rules in order to level the playing field between them and the major space powers. The EU/ESA member states as well as India and other rising space powers will call for binding legislation and may even draft their own treaty, but such a treaty will probably not be signed by the United States, Russia or China. This would give such a treaty a status similar to the Moon Treaty, which has only been signed by a very small number of spacefaring nations.

"They [the middle powers] need those rules. […] The middle powers lack the opportunity to be dominant in space or in world. They don't have aircraft carriers and [they] don't have nuclear intercontinental missiles. The EU, or ESA, will never have that. Perhaps India does, but at least in the space area, they will not be on the same level as China or the USA. That's why they need rules.

Thomas Hoerber,
ESSCA School of Management

Nonetheless, while it is unlikely that universally accepted rules will emerge on the militarisation and commercial use of outer space, by 2040 there is probably going to be a legal framework on the sustainable use of outer space. The increasing difficulty in operating in LEO due to space debris is an issue that concerns everyone equally. However, as with climate change, some countries are more responsible for space debris than others. As it becomes increasingly necessary to carry out clean up operations, which will become enabled due to the availability of space RPO, countries may disagree on who bears the cost of these missions.[85] This may delay new legislation, or it may result in discussion on debris removal being postponed. Still, both states and private companies have an interest in rules on deorbiting derelict satellites.

83 Rauenzahn et al. (2020)
84 Hanlon & Autry (2021)
85 Palmroth et al. (2021)

"At the moment, growth is very unregulated. There are a lot of satellites [and] no coordination. [...] I believe we can only wait for legislation and international rules to a certain extent. This also needs to come from industry itself."

Daniel Bock, Morpheus Space

In 2040, the majority of the experts who participated in this study agree that in most countries it will be illegal to launch a satellite that cannot be deorbited. While debris removal operations may lack explicit international coordination, some steps will be taken towards a more sustainable use of space.

CHAPTER IV: *SPACE ECOLOGY*

This chapter addresses the future of the broad field of space ecology, referring to both the state of the outer space environment and to the relationship between space and the environmental crises on Earth. After assessing the development of space debris, it presents a brief analysis of the potential of different scenarios to cause Kessler syndrome. The chapter then goes on to discuss space traffic management, which becomes necessary as the number of required manoeuvres in space increases. The chapter also underlines the impact of the intensified utilisation of LEO on astronomy until finally delving into the role of space in the fight against climate change.

Space Debris as a Threat to the Utilisation of LEO

One of the main technical challenges of the further utilisation of LEO is space debris. Since the beginning of the space age in the 1950s, thousands of satellites have been launched, many of which remain in orbit although they are no longer operational. The US Space Surveillance Network is currently tracking 28,160 objects larger than 5-10 cm in size, which include inactive satellites, spent upper stages, lens covers, launch adapters and thousands of other objects of unknown origin. ASAT tests have increased the number of trackable objects in orbit by up to 25%.[86] Over the next decade, megaconstellations with tens of thousands of individual satellites will further contribute to the generation of orbital debris.

"The problem is the debris, the junk, that are in LEO at the moment. Until 2030 [institutions such as the US Federal Communications Commission[87]] expect up to 60,000 satellites. At the moment you've got 5,000. That means that this is an increase by a factor of ten in the number of satellites. So then the question is, how can you manage this without a cascade that breaks a lot of satellites."

Manuel La Rosa Betancourt, Neutron Star Systems

"Over the next ten years, we are expecting that there will be between 50,000 and 100,000 satellites. Firstly, coordinating all of them will become a problem. And if a few of them collide, you will have a lot more debris."

Daniel Bock, Morpheus Space

Despite space debris growing in significance, the participating experts agree that by 2040 this issue will not become a major stumbling block for the more intensive utilisation of space. During the interviews, four principle measures were identified which will be employed to deal with the problem: (1) debris detection; (2) debris prevention; (3) debris management and (4) debris removal.

Firstly, for space debris to be effectively dealt with, more knowledge on the locations of debris is required. Only a small fraction of an estimated 100 million particles in orbit below 10cm in size are currently catalogued and tracked.[88] During the 2020s, the detection of space debris will become a rising business model, contributing to a growing effort towards effective space traffic management (see appropriate section in this chapter).

"I think anything above paperclip size, I think we will have already detected it by 2040. In fact, I think it will come much sooner."

Luisa Buinhas, Vyoma

Secondly, multiple strategies will be used to prevent the accumulation of further space debris. As discussed in the section on a new legal regime in space, during the 2020s and the early 2030s, many companies will have committed to only launching satellites that can be deorbited. Early signs of this can already be seen as of 2023.[89] By 2040, legislation will be in place in most countries, making it illegal to launch satellites that cannot be deorbited. Reusability of rockets will further contribute to the prevention of space debris. Companies will also pledge not to place disposable satellite parts such as lens covers and other 'packaging' in orbit.

Thirdly, based on more extensive knowledge on the locations of space junk, better strategies will be developed to avoid collisions. By 2035, centralised space traffic management will provide

86 European Space Agency (2023a)
87 GAO (2022)
88 Erwin (2022a)
89 Foust (2022)

satellite operators with early warnings. Satellites will be equipped with additional sensors to detect incoming objects, being able to respond to situations autonomously or at the command of a human operator.

"As on Earth, in terms of the impact and the consequences of climate change, there will be a reorientation towards tidying up space, […] towards controlling the impact, and not so much on mitigation and prevention. […] We will become more tolerant towards space junk."

Kai-Uwe Schrogl, European Space Agency

Finally, by 2030 there will be businesses and government efforts specialising on active debris removal. There are two major drivers for this: On the one hand, space debris is making it more and more challenging to operate on certain orbits of Earth, and both governments and businesses have an interest to reduce these challenges. On the other hand, the more widespread availability of space RPO will enable spacecraft to interact with other spacecraft as well as with orbital debris. 'Harpoons' have been successfully tested as means of catching and deorbiting unused satellites.[90] Other projects are currently conducting tests to magnetically capture piece of space junk and towing them to the Earth's atmosphere.[91]

"I think new business models will emerge which will lead to space remaining profitable. You can see an acceleration of startups and different companies who want to be active in space, who see it as a profitable endeavour."

Fabia Höhne Tarragona, OroraTech

90 Pultarova (2019)
91 Nuttall (2021)

"[Companies] will try to tidy up in space. Until now, we've tried to keep space tidy. In the future we will try to tidy up, which is debris removal."

Kai-Uwe Schrogl, European Space Agency

An additional factor that will contribute to space debris being taken very seriously in the future is space tourism. During the early 2020s, SpaceX and Blue Origin began taking tourists into space. Several other companies will likely launch orbital and suborbital tourist flights in the near future. During the 2030s, space stations for tourists will become commonplace. The increasing number of astronauts will lead to an increased awareness of space debris, as astronauts with substantial material means will be able to witness the impact of orbital debris first hand.

"I think space tourism will help to shine a much brighter light on the problem of space debris. Because people that go and experience even a four-minute space tourism ride are going to recognise that they have an opportunity to do something through advocacy or spending their money in a different way to help solve that problem."

Rob Meyerson, DELALUNE SPACE

In 2040, space debris will remain a challenge, but the majority of the study participants agrees that this will not significantly reduce the accessibility of space. The convergence of the four measures outlined above will contribute towards preventing the space debris issue from escalating and causing orbits to become unusable.

Scenarios for Kessler Syndrome:

Space Debris as a Threat to the Growth of the Space Economy?

In 2013, Alfonso Cuaron's film *Gravity* was released in cinemas around the world. The scifi thriller stars Sandra Bullock as an astronaut stranded in LEO, trying to find her way back to Earth. The film's premise involves a catastrophic chain reaction caused by the destruction of a Russian satellite, which sets off a debris field that collides with other satellites and space stations in orbit, including the space shuttle carrying the main character. The debris field is depicted as a fast-moving cloud of shrapnel that destroys everything in its path and leaves the surviving characters stranded in space.

While unlikely, this scenario is not altogether unrealistic. It is commonly referred to as Kessler syndrome, being named after NASA scientist Donald Kessler, who first proposed the concept.[92] If full Kessler syndrome were to be experienced, some orbits would no longer be usable, significantly hampering humanity's ability to utilise outer space. There are several possible scenarios that could cause Kessler syndrome, such as a military conflict in space or simply an unintended chain reaction. Scientists Jakub Drmola and Tomas Hubik have therefore written a meta-analysis involving several different scenarios to assess whether Kessler syndrome can indeed cause space to become unusable.[93]

Scenario 1: Business as usual and beyond

In the first scenario, current trends are simply extended into the future. Satellite launches continue at the current rate and satellite operators actively interfere to avoid collisions. No sudden events, such as space wars or major ASAT tests take place. By 2066, this scenario would not result in the realisation of the Kessler syndrome, although the risk of collisions is significantly increased. According to the authors, it will take until 2163 for LEO to become so full of debris that the Kessler syndrome sets in. However, it ought to be pointed out that this scenario does not take the advent of megaconstellations, advanced SSA, AI-guided satellite operations and clean-up projects into account. Nevertheless, it does underline that the Kessler syndrome is by no means an inevitability.

Scenario 2: Space war using ASAT weapons

The second scenario revolves around an armed conflict in space involving two major, technologically advanced powers. In this scenario, dozens of satellites are destroyed at some point during the conflict, causing the massive accumulation of debris. This scenario would thus be the outcome in the situation described above. Assuming that around 200 security-related satellites are destroyed using kinetic ASAT weapons, this would still be insufficient to cause Kessler's chain reaction. The probability of satellites being hit by debris is twice as high as before.

Scenario 3: Space war using EMP

If a war escalates further, it is feasible that an electromagnetic pulse (EMP) weapon is deployed in outer space, leading to a massive loss of control over space infrastructure. This scenario is more unlikely than the other scenarios, because an EMP would probably be caused by a high-altitude nuclear explosion. The Outer Space Treaty prohibits the use of weapons of mass destruction in space. However, the impact of an EMP deployment in LEO would be less severe than the large-scale deployment of ASAT missiles. Satellites would become inoperable rather than being torn into pieces, and it is far easier to track and avoid derelict satellites rather than tiny piece of debris. As such, the EMP scenario would not result in Kessler syndrome.

92 Kessler & Cour-Palais (1978)
93 Drmola & Hubik (2018)

Scenario 4: Debris mitigation

In this scenario, efforts are made to clean up LEO to prevent the emergence of the Kessler syndrome. According to Drmola and Hubik, removing 8 inactive satellites per month is sufficient to stabilise the debris population in low-earth orbit. The effort required to prevent the further accumulation of debris in LEO is thus limited.

Kessler syndrome is the outcome of none of the scenarios described above. Even a war in space would not result in a snowball effect. However, what the cited article does not take into consideration is the installation of megaconstellations with tens of thousands of satellites.

"I would also argue that we're in danger, especially with these megaconstellations in low earth orbit with not just thousands, but tens of thousands of satellites. The risk of a catastrophic space debris incident that results in a Kessler-like syndrome where low earth orbit is just trashed and unusable, is very high right now."

John Sheldon, AzurX

Taking Drmola and Hubik's findings into consideration, Kessler syndrome can be avoided if the four measures laid out in the previous section on space debris are implemented: (1) debris detection; (2) debris prevention; (3) debris management and (4) debris removal. The likelihood of Kessler syndrome is further reduced if binding legislation on the sustainable use of outer space is implemented by all major space actors, as is predicted in the chapter on space politics.

Intensified Activities Require Space Traffic Management

During the 2030s, the growing number of satellites and actors in space will increasingly necessitate a coordinated space traffic management system. At the moment, there is no space traffic management system that is in any way comparable to air traffic management. Different countries maintain SSA programmes to catalogue and track objects in Earth orbit. Satellite operators rely on these national programmes to receive accurate information on when to carry out manoeuvres. By the end of the 2020s, this system will no longer be sustainable, requiring a public or private organisation to oversee the space traffic management activities of different national agencies. This will greatly benefit the growth of the space economy making space more accessible for smaller companies operating satellites.

"For 2040, I see the existence of an integrated space and air traffic management system, because there will be ever more movement between airspace and outer space, because it has to be well coordinated so that nothing happens and especially because you need to find proper rules for both spheres. Possible this will be managed by a single organisation in terms of governance, for example by the ICAO, and implemented by control centres that are connected with one another."

Kai-Uwe Schrogl

It cannot be ascertained that a public organisation such as the ICAO will be responsible for handling space traffic management, especially given the covert nature of military operations in space. However, there is a growing number of companies providing services related to space traffic management. Companies such as Neuraspace, Vyoma, Ienai Space and Endurosat deliver real-time tracking information, predict collisions several days in advance using AI and suggest appropriate manoeuvres.[94]

"I do think that space traffic management will become a big business in the coming, maybe in the coming 10 years, 20 years, as we move from our Earth orbits to cislunar and interplanetary space. We will need very good data and very robust algorithms that deal not only with this congestion in space, but with an increasingly diverse nature of stake holders."

Luisa Buinhas, Vyoma

From the statements of the participants of the study it is not clear whether space traffic management will be organised by private organisations in terms of a business model or by state institutions as a public service. Yet taking into consideration the multiple drivers for space traffic management, including space debris and the need for accessibility, there is agreement that space traffic management will be significantly more centralised and coordinated than in the present.

Disruption of Astronomy from Megaconstellations

Since the dawn of the space age in the 1950s, it has become commonplace to notice satellites in the night sky. Spotting the International Space Station, the largest man-made object in orbit, is particularly spectacular, as it can shine brighter than Venus in the hours after sunset and before sunrise. However, megaconstellations and the staggering surge in the number of satellites is increasingly having an impact on the appearance of the night sky.

There exists no easy solution to this problem.[95] Most satellites derive their energy from solar power, and the solar cells attached to satellites reflect the Sun's light to Earth. Even with the availability of nuclear reactors in space, the vast majority of satellites will continue to rely on solar energy. While the naked-eye visibility of satellites is usually confined to twilight hours, astronomy will be very significantly affected by megaconstellations.[96] Large numbers of satellites can interfere with observations by radio telescopes on the ground and contaminate the data astronomers collect.[97] Particularly at risk from megaconstellations will be supersensitive optical telescopes and those designed to survey

94 Russel (2023)

95 Sutter (2021)
96 Bassa et al. (2021)
97 Witze (2020)

the whole sky rapidly.[98] Observing programmes that rely upon data gathered during the twilight hours, such as searches for potentially hazardous asteroids and comets, will be disproportionately affected as well.[99]

"We are not good stewards of Earth orbit, and that leads to other potential issues, [including] astronomy. And that has a deep cultural, as well as scientific resonance around the world. You know, we block out the stars, even the moon. That's actually more significant than people might think."

John Sheldon, AzurX

98 Bartels (2019)
99 Wall (2020)

While artificial intelligence will be able to help clean up images, astronomy will not be the same once more and more megaconstellations are in orbit. This in turn, may be a driver for more astronomy hardware to be moved off world, for example the Lagrange points or to the far side of the Moon.

The Climate Crisis as a Driver for the Space Economy

The climate crisis is the main challenge that humanity is going to be facing over the 21st century. Its impact will transform the economy and ways of life around the planet, having enormous consequences on energy production, mobility, food production and construction. It is therefore impossible to discuss the future of the space economy outside the context of climate change, which can represent a challenge as well as a driver for space. Climate change may slow down the growth of the space economy, as it may be viewed as a vanity project when far more urgent problems exist on Earth. This argument may turn the tide of public opinion against the further exploration and economic exploitation of space. At the same time, climate change may act as a driver of the space economy, as the use of space may be seen as indispensable for tackling the climate crisis.

The majority of the experts who participated in this study agreed that the climate crisis will be a driver for the further growth of the space economy, both within and beyond LEO:

"I personally think that it is a driver, in a good way, to better understand climate change as well as to check whether everyone is sticking to the regulations. Space will be a factor for settings norms."

Daniel Bock, Morpheus Space

"And the reason that the solar system drive is needed is for three primary reasons ultimately. The first is to use the resources of space to improve life on Earth. The second is by expanding off world, we protect our species against risks of existential single point failures. And the third is just the human drive to get out there and explore and to grow, expand and discover. But the most urgent criticality is to improve life on Earth because I don't believe we'll solve the climate crisis without moving out into space and harvesting the resources there."

Jim Keravala, OffWorld

Space will be used in a variety of ways to both mitigate climate change itself and to manage its consequences. Space assets are invaluable on monitoring temperatures and precipitation, especially in remote areas, sea level rise, atmospheric CO_2 concentrations, hotspots of greenhouse gas emissions, changes in vegetation, desertification, soil moisture and many other key climatic and ecological parameters. Moreover, space infrastructure is crucial for determining the locations for renewable energy generation, such as solar and wind power, as well as for monitoring wind farm wake effects.[100] Satellites can also be used to increase climate resilience. Space-supported early warning systems can be used to predict environmental disasters, including wildfires, droughts, floods, heat waves and dust storms.

"Climate resilience is a huge topic. […] We need climate-resilient strategies for things like wildfires and floods, as we've also had in Germany. Is there any way we can predict trends, to slow them down, to set up early warning systems, and how can we do that? And here we're seeing clear trends, not only for space segments, but also for UAVs, balloons, or airplanes, as they're doing in Spain at the moment. And in this regard we're moving towards more sustainability with earth observation and new space technology, because we can do the same things as an airplane with fewer resources."

Fabia Höhne Tarragona, OroraTech

100 Ahsbahs et al. (2018)

Two areas which are going to be dramatically affected by climate change include agriculture and forestry. Satellites can support farmers and foresters through providing data on the health of crops and forests, weather forecasting, disease detection or mapping. Farmers thus also receive valuable input on the more targeted application of pesticides. While many of these applications are already available today, over the course of the 2030s their employment will become more widespread around the globe, which was already alluded to in the section on leapfrogging in the global south. Until 2040, the information provided by satellites will continue to become more accurate, allowing for precision farming, where fields can be watered according to their needs, which in turn helps to save resources. According to the majority of the expert panel, by 2040, the utilisation of earth observation data for farming and forestry will have become as common as using Google Earth images is today.

Until 2040, the climate crisis will continue to be a driver of the further growth of the space economy due to the numerous applications of space assets for monitoring and mitigating the effects of climate change.

CHAPTER V:
SPACE EXPLORATION

During the 2020s and 2030s, the technologies, infrastructures as well as the political context described in the previous chapters will generate new avenues for space exploration, easing access to outer space beyond LEO and enabling new directions for research. This chapter focuses on the future of the exploration of the Moon and Mars, as well as outlining the future of the search for extraterrestrial life. Finally, the chapter assesses the limitations and opportunities of space tourism.

A Moon Base as the Next Step Towards a Multi-Planetary Civilisation

One future trend that incurred great consensus among the participants of this study is the construction and maintenance of a human outpost on the Moon by 2040, which is preceded by a human landing by 2030. Nevertheless, this Moon base will be a research station, much like the stations in Antarctica. It will not constitute the beginnings of lunar settlement.

"I think that there is going to be a Moon base. However, if things continue as they are going right now, this will simply be a research station. I do not believe that its population, or its human presence, will surpass that of the International Space Station, maybe 15 to 20 people, high regarded researchers, who are there to carry out research projects."

Thomas Hoerber,
ESSCA School of Management

"What is very clear, is that there will be a Moon base, and there will be in-situ research utilisation on the Moon. Additionally, space tourism to the Moon is undoubtedly up next on the horizon."

Robert Boehme,
Planetary Transportation Systems

The United States and several partners, notably the European Space Agency, are planning on carrying out a human landing on the lunar surface by 2025. This date will likely slip into 2026 or 2027 and it is dependent on successful routine operations of the SpaceX Starship, which will be used as a landing module.[101] Beyond that, NASA is preparing the Lunar Gateway for launch (see section on the future geography of outer space). The first extraterrestial space station will operate as an orbital platform for expeditions to the surface of the Moon. China too, is preparing for its first lunar landing, which will likely take place during the 2030s.[102]

Although no concrete plans currently exist to set up a Moon base, the permanent availability of a lunar lander and the need to replace the ageing International Space Station with a new prestigious project make this very likely. Moreover, the Moon offers the opportunity to demonstrate several technologies which will be needed for the further exploration of the solar system, especially in-situ resource utilisation (ISRU). ISRU refers to the process of utilising materials and resources found on another celestial body to sustain human exploration and settlement. While it is possible to bring enough fuel to the Moon to facilitate a flight back to Earth, a human landing on Mars will most certainly require the production of liquid hydrogen on the Martian surface. Other technologies that could be demonstrated include lunar mining, space food production or the construction of surface habitats from the lunar regolith (i.e. lunar 'soil'). The Moon is a natural laboratory to further explore Earth's geology history and it is the ideal location of space telescopes, including radio telescopes on the far side of the Moon.

"[You can use it for] science and technology demonstrations. On the other hand, you can also think about resource extraction from the Moon and especially from asteroids, especially when you think about developing helium-3, which you need for nuclear fusion. Is that possible on the Moon? Above all, it is a political, symbolic opportunity."

Kai-Uwe Schrogl, European Space Agency

Another driver for the development of a Moon base is that the Moon could serve as a launching point for the further exploration of the solar system. As the Moon's gravity is only one sixth of the Earth's, significantly less fuel is needed to launch a spacecraft from its surface to Mars or

101 Jovanovic (2022)
102 Jones (2021)

the asteroid belt. A Starship could launch from Earth, fly to the Moon, refuel at the Moon base, and then carry on from there to the outer solar system.

"The Moon itself is actually the better space station, or the better starting point, because it is simply more permanent, it is also easier to maintain, you can just put a new building next to it."

Robert Boehme,
Planetary Transportation Systems

Given these drivers, it is likely that a Moon base will become operational in the late 2030s. This will require the establishment of infrastructure both on the lunar surface and in orbit around the Moon, which represents an enormous business opportunity. The infrastructure needed includes habitat modules, life support system, ISRU systems, resource extraction facilities, power equipment, transportation systems for the lunar surface, maintenance facilities as well as an extensive communications and observation satellite system.

"There will be constellations of satellites to offer services on the Moon. There will also be geopolitical tensions with China [...] and the USA and perhaps other countries. So it'll be essential to have data there [...]. There will be a lot of business on the Moon, I believe especially in 15 years. The next five years are very much focused on LEO, I'd say. But in five years there will be a lot of movement towards the Moon."

Daniel Bock, Morpheus Space

Apart from the traditional space actors, a Moon base will also require contributions from non-space businesses. The Moon Village Association, which was initiated by former ESA director-general Jan Wörner, is trying to reach out to actors who are interested in participating in the further exploration and development of the Moon.[103] The Moon Market offers a platform of products, services and technologies for a lunar settlement. Non-space businesses that could participate in a Moon base include companies focusing on construction, engineering, mining, solar and nuclear energy, robotics, car manufacturing and scientific research. Beyond the Moon base infrastructure, the Moon base also offers an opportunity for space tourism.

"Will there be human Moon base? Absolutely, absolutely, and it will be driven forward mainly by private actors."

Manuel La Rosa Betacourt, Neutron Star Systems

By 2035, there will have been human landings on the Moon by the US, China and private organisations. A US-led Moon base is being established, with China also planning to build its own Moon base during the 2040s.

Moon Base vs. Lunar Settlement

It is important not to confuse setting up a lunar outpost such as a research station with a lunar settlement. While a Moon base denotes that scientists will be assigned to work on the Moon for a limited period of time, a lunar settlement would involve taking up permanent residence. Human settlers would work *and* live on the Moon, which includes hobbies and family life. They would strive towards self-sufficiency in terms of resources such as food, water and breathable air.[104] The purpose of a Moon base on the other hand will primarily be scientific. As such, a Moon base does not imply the beginnings of lunar settlement. In the same fashion, scientists in a research station in Antarctica are not settlers.

Sometimes the terms 'colony' and 'colonisation' are used in the context of the human settlement of outer space. Throughout this report, this term is avoided for its negative connotations within the context of genocide, war and the oppression of indigenous peoples.[105]

103 Köpping Athanasopoulos (2019)

104 Skran (2019)

105 Forganni (2020)

Mars Sample Return and Preparations for the Human Exploration of Mars

In science fiction films, human missions to Mars are often set 20 years in the future. While the 2000 film Mission to Mars predicted the first humans on Mars for 2020, the recent blockbuster The Martian foresaw a human landing on red planet in 2035. Kim Stanley Robinson's Red Mars, published in 1992, suggested it would take another 28 years before a human lander sets down on Mars. Given the trends discussed in the chapters on space technologies and space politics, are we closer to landing on Mars in 2023 than we were in 1990? One key technology which would make a human mission to Mars more realistic is nuclear-powered propulsion.

"We'll see the potential of nuclear space propulsion, which can help to open up access to Mars. As long as Mars is a 210 day transit time, it's not going to be a desirable destination, but when it becomes a 100 day or less transit time, then people will start thinking about it. When Mars is a round trip rather than a one way trip, it's going to be much more desirable."

Rob Meyerson, DELALUNE SPACE

However, in comparison to the Moon, Mars is an exceedingly difficult destination for human space exploration. While the Moon is in Earth orbit and can therefore be reached anytime, it is only possible to launch spacecraft to Mars about once every 26 months. While a human crew on the Moon is never further away from Earth than a few days, astronauts on Mars could be stranded for years in case of an accident. Given the risk-averseness of space agencies since the Space Shuttle disasters, it is unlikely that they would expose astronauts to any risks before all technologies involved have been sufficiently demonstrated. An accident during a mission to Mars would not only end the lives of the astronauts, but also severely damage the public perception of the human Mars exploration programme.

The technologies that need to be demonstrated before a public space agency would support a human landing on Mars include radiation shielding in interplanetary space, ISRU for rocket fuel, long-term life support systems relying on resource recycling as well as landing and take-off from the Martian surface using a human-rated lander.[106] Radiation management beyond LEO can be practiced on the Lunar Gateway space station from the late 2020s onwards. Landing and take-off from the Martian surface will be demonstrated within the framework of the NASA-ESA Mars Sample Return mission.[107] The Mars Ascent Vehicle, which will be used to bring samples of Martian regolith to Mars orbit, will likely land and lift off from the Martian surface in the early 2030s. ISRU for rocket fuel will only be demonstrated on the Moon base during the 2030s. Long-term life support systems have been tried out on the ISS and other past space stations, but not on the surface of Mars, where breathable air will have to be produced on site. While the participating experts were not in agreement on the timeframe of a human mission to Mars, given these factors, a publicly funded human landing on the red planet appears unlikely before 2040.

What about private organisations? Could NewSpace companies such as SpaceX and Blue Origin drive forward the exploration of Mars? While private organisation could be less risk-averse, they will require a business case to seriously consider sending humans to Mars, which is not on the horizon as long as space mining is not commercially and technologically viable.

"And when people went to different continents, the business cases were not always clear. Of course, we were going there for spices, but for people to go there, there was not a bigger business case, there was a company that was shipping them, and they were making money off the tickets. For Mars, a business case of just shipping people there won't work, because you can't just go to Mars and hope for the best."

Bas Lansdorp, NEDPAC

On Mars, a significant amount of infrastructure would have to be provided for settlers to survive in the Martian environment, which is extremely inhospitable to human life.

What about a human landing on Mars beyond 2040? The trends described in this report lay the foundation for making the human exploration of Mars technologically feasible. Moreover, the continuing rivalry between the US and China create the geopolitical climate needed to pursue a human Mars exploration programme. If the ISRU is successfully tested on the Moon, if the Mars Sample Return programme is successful, and if deep space radiation can be managed on the Lunar Gateway, a human landing on Mars during the 2040s is feasible. Beyond that, with the availability of cheap reusable rockets, ISRU and space mining, private companies will initiate the commercial use of Mars.

"The advent of the used launch vehicles [has repercussions for] the entire space enterprise. And that will of course also create business models for the maintenance of these vehicles, all over the world. I think eventually people will make spaceships on Mars. But the entry into that business is repairing them. If you have Starships going to Mars and then being reused to go to the asteroid belt or something, or just to go back to Earth, there'll be repair shops. And eventually people who repair things get into making them."

Robert Zubrin, Pioneer Astronautics

The human exploration of Mars will thus happen, but not within the 2040 time horizon of this study.

106 Starr & Muscatello (2020)
107 Kminek et al. (2022)

More Certainty on the Prevalence of Life in the Universe

While the immediate business repercussions of the research efforts to discover extraterrestrial life are limited, this topic is still included in this report because the discovery of life beyond Earth would have an enormous impact on society, culture, philosophy, religion and humanity's view of its own place in the universe.[108] While it is not possible to predict *if* we will discover extraterrestrial life, as we currently base our expectations on a sample of one (Earth), it is possible to foresee the means available to future scientists to search for life in space.

During the 2020s and 30s, researchers around the world will search for life both inside and outside the solar system. Inside the solar system, one of the most important science objectives is Mars sample return. NASA and ESA have developed a concrete mission architecture to retrieve samples of Martian regolith and the first sample tubes have already been deposited on the surface of Mars by NASA's Perseverance rover.[109] The samples will be collected by the Sample Retrieval Lander in the late 2020s, brought into Mars orbit using the Mars Ascent Vehicle in the early 2030s and sent to Earth using ESA's Earth Return Orbiter. By 2035, scientists on Earth will be in possession of several samples of Martian soil, being able to conclusively determine if these samples contain evidence of life or not. While this will not close the debate on whether life exists on Mars or not, it will certainly provide us with significantly more evidence than there has ever been before.[110]

Apart from Mars, scientists are especially interested in the potential possibility for life in the subsurface water oceans of moons and dwarf planets in the outer solar system. During the 2030s, the European JUICE probe as well as NASA's Europa Clipper will find information on organic chemistry inside the ice moons of Jupiter.[111] By 2040, Saturn's moon Enceladus will likely have been visited by a probe capable of analysing the content of the plumes ejected by its warm subsurface oceans.[112] These missions will provide further information on which of these moons should be investigated further. While there have been proposals to send a nuclear-powered 'melt probe' to an icy world, to directly access the sub surface oceans, this will probably not be accomplished by 2040.[113]

During the 2020s and 30s, several space telescopes will come online which will help us further determinate factors in the Drake equation as well as detect biosignatures beyond the solar system. The Drake equation is a formula used to estimate the number of intelligent civilizations that may exist in our galaxy. It takes into account factors such as the number of stars in our galaxy, the fraction of stars that have planets, the fraction of planets that could support life, the fraction of those planets where life actually emerges, and the fraction of those civilizations that have developed technology that could be detected from Earth.[114] Telescopes such as the Extremely Large Telescope of the European Southern Observatory[115] and ESA's Planetary Transits and Oscillations of Stars (PLATO)[116] telescope will be spotting an increasing number of truly Earth-like planets, being thus able to determine how widespread habitable planets are in our galaxy. Along with the James Webb Space Telescope which began operations in 2022, these missions will also be able to determine the atmospheric composition of exoplanets, finding biosignatures such as oxygen or methane. Another mission proposal involves direct imagining of exoplanets using gravitational lensing.[117] However, before this mission is commissioned, a suitable planet will have to be found.

"This is a mission, which is planned for a 40-year time horizon. […] Satellites outside the solar system are meant to […] build up a telescope using our Sun as a gravitational lens. They use the Sun's gravitational refraction of light to have a giant telescope, to actually take proper pictures of an exoplanet, so that you can see the continents of planets in other solar systems. […] In 15 years, this technology will hopefully be launched and on its way."

108 Kwon et al. (2018); Dominik & Zarnecki (2011)
109 David (2023)
110 NASA (2022b)
111 Lossau (2023)
112 Brinkmann (2022)
113 Hand (2019)
114 Vakoch & Dowd (2015)
115 European Southern Observatory (2023)
116 Deutsches Zentrum für Luft- und Raumfahrt (2022)
117 Jimiticus (2017)

Daniel Bock, Morpheus Space

Lunar exploration and a Moon base will also enable the construction of a radio telescope on the far side of the Moon, where Earth-based radio signals are unable to cause interference. Given that a Moon base will only become available in 2035, such a radio telescope will likely not be ready by 2040. Similarly, initiatives such as Yuri Milner's Breakthrough Starshot are unlikely to be realised by 2040 due to the enormous energy requirements. Starshot would involve the first interstellar probes by accelerating spacecraft attached to a solar sail to a significant proportion of the speed of light using an Earth-based laser.[118]

The search for extraterrestrial life is important regardless of the outcome. If microbial life were discovered on Mars or one of the icy moons, we would know that life independently emerged at least twice within a single solar system. Simple life would therefore be wide-spread in the universe, while intelligent life is likely rare. This discovery would enhance humanity's appreciation of its own position, further boosting environmentalist efforts. If on the other hand humanity fails to discover life beyond Earth by 2040, we will know that life is probably rarer than sometimes presumed. This too would change humanity's vantage point, perhaps strengthening humanity's appreciation of the Earth's unique biosphere.

118 Osterkamp (2017)

Growth of Space Tourism, but not for the Masses

In 2001, Dennis Tito became the first space tourist and until 2020 there have been occasional visits of private astronauts to the International Space Station. In 2021 and 2022 however, more tourists were launched into space than in all previous years combined. Over the 2020s and 30s, this trend is likely to continue.[119]

"I find most of these space tourism projects currently have exorbitant price tags, but they will just become more prevalent and accepted in the future because rocket fuel and launch technology will become cheaper. By 2040, space tourism will become so affordable that you can take a trip to outer space on the weekend and maybe come back just in time for your Monday morning meeting."

Luisa Buinhas, Vyoma

There are various technologies and trends that are discussed in this study report which will enable the more wide-spread availability of space tourism. Most importantly, space tourism is enabled by the availability of commercial human-rated spacecraft as well as by the decreasing costs of space launches. Moreover, during the 2030s, megalaunchers will enable more complex spacecraft, including private space stations. By the end of the 2030s, there will be a human outpost on the surface of the Moon, as well as an extraterrestrial space station. All of these sites represent potential destinations for space tourists.

"If SpaceX can do what they say they want to do with Starship, a behemoth of a launch vehicle that can carry up to 100 people, and you could launch it for 10 or 20 million, then yes, we will have tourists in space. It will be a bit like doing a luxury seven-star hotel holiday for a month for those who can afford it. In other words, most of us won't be able to afford it, but it'll certainly be within reach of more people than it is now."

John Sheldon, AzurX

119 ResearchFDI (2022)

While reports on the future of the space economy sometimes predict that by 2030 space tourism will be so widespread that nearly everyone will personally know an astronaut,[120] there are a number of factors making this unlikely. Firstly, mass space tourism would require permanent infrastructure in space which exists exclusively to serve tourists. While space hotels are theoretically feasible, especially with the advent of megalaunchers and private space stations, they will continue to be prohibitively expensive. While launch costs will drop by at least another order of magnitude, the health and safety measures required for space hotels and human-rated spacecraft carrying tourists are immense. Touristic infrastructure on space or on the Moon will have to be maintained and regularly serviced, further adding to costs.

"You can send Tom Cruise up there ten times, it won't add up. Space tourism? Sure, but that won't be the reason for building a Moon base or a Moon hotel. […] Such a hotel would have to make profit, and I don't really see that."

Robert Boehme,
Planetary Transportation Systems

"There could be a market for tourists in space, if you want to just go up and come down. But I would treat that as Universal Studios and Disney. I would love to go to Universal Studios and Disney once a year. I wouldn't want to go there every day."

Narayan Prasad, satsearch.co

By 2040, space tourism will not constitute a mass market and most people will still not know an astronaut. Nevertheless, the number of people travelling to space every year will have increased by an order of magnitude. These private astronauts will visit space stations and by the mid-2030s, there will be the first space tourists on the surface of the Moon.

"Space tourism is not going to just be about people with cameras going and taking pictures. I think I'd prefer to call them private astronauts and emphasize that they can fly either with their own funding or with their corporation's funding."

Rob Meyerson, DELALUNE SPACE

While space tourism's importance will grow, its impact on the space economy in 2040 is often exaggerated.

120 Kalms et al. (2020)

WILDCARD

Detecting an Alien Civilisation

The year is 2037. The Square Kilometre Array (SKA) is an international science project conceived in the 1990s. It is capable of searching for extraterrestrial radio signals orders of magnitude faster than ever before. The SKA has now been operational for almost 10 years, and these have been 10 years of silence – until now. At first, the signal seemed unspectacular, an ordinary spike on an ordinary survey of a few stars in the constellation Sagitta, but upon close inspection scientists have found that it cannot have a natural origin. The signal's fluctuations appear too artificial and its frequency falls right onto the hydrogen line, which SETI researchers had always predicted is ideally suited for transmitting a radio signal across interstellar distances. Its point of origin is a small, yellow star with Sun-like characteristics around 6,400 light years from Earth. Upon close inspection using ESA's PLATO telescope, a planetary system around this star was discovered, containing an Earth-like planet in the star's habitable zone. The planet is dubbed Sagi after its host constellation. Scientists are now nearly certain that this planet hosts an intelligent species capable of radio communication. But what is the meaning of the signal? Has it been sent deliberately, or is Earth merely picking up an alien radio station? The answers to these questions remain in the dark and scientists cannot make sense of what they are receiving.

While it is impossible to predict when and whether humanity will receive an extraterrestrial radio signal, the chances of such an event are increasing day by day. By 2037, several new telescopes capable of detecting 'technosignatures' will have come online. Yet, a radio signal is not the only candidate for a detection. An optical telescope picking up a laser signal, or the tell-tale signs of an orbital ring around the aliens' star, is equally plausible. No matter how the signal is detected, if it is verified, its impact would be huge.

In the event of First Contact, no international agreements are in place to provide guidelines for possible responses. While governments may initially perceive the signal as a security threat, the vast distances involved will cause calm to prevail. Even a spaceship travelling at 10% the speed of light would need tens of thousands of years to reach planet Sagi. A human response using radio waves would only arrive in 6,400 years. Still, the detection of an alien signal in the same area of the Milky Way would imply that the galaxy is teeming with life. Scientists would be puzzled why humanity appears never to have received extraterrestrial visitors, concluding that it is exceedingly difficult to travel across interstellar distances, even for very advanced civilisations. Nevertheless, governments would likely boost their investment into space programmes and space technologies. Since we know 'they' are out there, space somehow seems more hospitable and less empty. At the same time, governments are concerned that humanity will need to have some kind of defence system on the slim chance that there are hostile species out there.

Meanwhile, the news is inspiring human imagination and the number of UFO sightings around the world explodes. A growing number of people are turning towards religious answers. Especially the Abrahamic religions of Christianity, Islam and Judaism need to significantly adapt their theologies to deal with the discovery. Businesses around the world are making great profits selling merchandise, and billions of t-shirts are made displaying the signal's characteristic spike. The signal has also caused a rapprochement between the super powers. Humanity has found that there are others out there, who will care very little about our national and cultural dividing lines. Like the fall of the wall 1989, the discovery would usher an era of international cooperation and economic growth.

There is an enormous boom for radio astronomy and other SETI methods and the planetary science budgets of space agencies around the world are at an all-time high. The construction of a radio telescope on the far side of the Moon would begin within a few years to receive the signal in higher quality. Giant optical telescopes are constructed on earth and in space, and discovery boosts the deployment of a gravitational lensing telescope to take detailed images of Sagi. Efforts to search for life in the solar system are also greatly increased, as we now know for certain that life will be found if only we look hard enough. A huge science effort would be made to decipher the signal, with ever more people studying astronomy and astrophysics.

Apart from the immediate impact on the global political economy and astronomy, private entrepreneurs too are inspired by the signal's discovery. One company intends to build an arc equipped with an artificial intelligence and samples of the Earth's species, sending it to Sagi. Controversially, another company wants to include frozen embryos in its mission. Others are more ambitious. Space is no longer the dead zone that it hitherto appeared to be. Trillionaires are discussing the construction of generation ships to settle planets around nearby stars. Private and public research funds are flowing into speculative propulsion technologies. The solar system no longer seems to be the limit of human endeavours.

The likelihood of detecting an alien civilisation cannot be predicted. However, if a signal was detected, even if we fail to comprehend it, its impact on society, culture, geopolitics and the economy would be staggering.

CHAPTER VI:
SPACE ECONOMY

This chapter translates the predictions made in the previous chapters of this study into the future space economy. After assessing the growth of the space economy until 2040 and the role of space in our everyday lives, the chapter discusses the democratisation of access to space, highlighting that by 2040, every corporation will need a space strategy. The chapter also discusses the impact of new space technologies and infrastructures on business models. There is a particular focus on the transition towards space-as-a-service business models, as well as the rising significance of business models featuring space-for-space rather than space-for-earth applications. Finally, the chapter lays out a number of future business models in space, assessing them in terms of a variety of factors including lucrativeness, scalability and sustainability.

Growth of the Space Economy Beyond $1 Trillion

Whereas in 2009 the space economy had reached a size of $261.6 billion,[121] it had nearly doubled in size by 2022, being worth a total of $464 billion.[122] If the space economy were to continue on this steady growth trajectory, it is going to reach the $1 trillion mark by approximately 2040. Given the developments described in this report however, it is likely that the future of the space economy will not follow a linear development path.

"We are currently living in times of extreme acceleration, in terms of the space industry. That's why I see major change by 2040, over the next 20 years."

Fabia Höhne Tarragona, OroraTech

While it is often assumed that the space economy will reach $1 trillion in revenue by 2040,[123] according to the experts interviewed for this study, this is probably an underestimate. While some experts foresaw the space economy to grow to over $4 trillion, nearly all agreed that its worth will exceed $1 trillion.

"If you look at the current predictions for the size of the space economy in 2040, you read the figure $1 trillion a lot. I would actually say that's probably an underestimate. Potentially, given that we're now at $434 billion, it'll probably be like $1.3, $1.4 trillion by 2040 if, obviously, things carry on the way they're doing."

John Sheldon, AzurX

The growth that the space economy will experience will also be reflected in the number of spacecraft and space launches. Decreasing launch costs, the availability of fully reusable launchers, the growing number of space applications and megaconstellations are major drivers that will lead to a drastic increase in the number of objects in LEO and beyond.

"I don't believe it will be a gradual linear growth; it's not a straight line. I believe the liberation of economical access to space will be an inflection curve of maybe 24 months and at the two ends of that curve we move from a hundred launches a year to a thousand launches a year at the other end and all those new business models pour into the newly opened frontier opportunities."

Jim Keravala, OffWorld

"In 2040, we will probably have five times as many spacecraft as we have today. And they will all be computer-guided or computer-supported."

Manuel La Rosa Betancourt, Neutron Star Systems

121 Space Foundation (2010)
122 Karasu (2023)
123 Sheetz (2022)

Space Will Play an Increasing Role in Our Everyday Lives

By 2040, space technologies will become even more integrated into our everyday lives, both in a business as well as in a private context. Today, we routinely use satellite navigation services to track our geographic position. We also use satellite images in everyday mapping applications. By 2040, these satellite images will contain more and more layers of information for all sorts of applications. Radar imagery, thermal imaging and hyperspectral imaging will become fully integrated into business applications. Engineers and construction workers will be using thermal images for finding the ideal location of cooling systems. Home renovators will be able to quickly determine sources of heat loss. Farmers will be able to precisely apply herbicides and foresters can spot which areas are affected by disease or drought. Local administration will be able to monitor traffic flows and local heat distribution. The metaverse, as the future digital infrastructure, will enable superimposing this data on physical scenery and objects using augmented reality hardware.

"A lot will be happening and it will become normal, just as GPS and Google Maps have become normal. […] In everyday life, it will lead to us using satellite images all the time, not only with GPS, but on the internet, in telecommunications, in the supply chain; everywhere, continuously, all the time."

Fabia Höhne Tarragona, OroraTech

"It is our big vision that within the next couple of years everyone will get indirect access to space, being able to use space as an infrastructure, in a way that is similar to what he have with the internet, that almost every service, that is being used in everyday life or in businesses, is to some extent a space-based services."

Daniel Bock, Morpheus Space

By 2040, we will be taking further layers of space data for granted, in the same way that we take navigation data or mapping data for granted today. Moreover, given the advent of satellite internet for the mass market, the ubiquity of the metaverse will become dependent on space infrastructure.

Democratisation of Access to Space

A major driver of the growth of the space economy is the democratisation of access to space. This usually refers to the shift in the actors utilising space that was initiated by the NewSpace era. The primary drivers behind this development are dropping launch costs, the increasing diversity of launcher systems and the consequential simplification of access to space.

"It will become easier, far easier, to get to outer space, to operate in it, and to come back down."

Kai-Uwe Schrogl, European Space Agency

Dropping launch costs and investment by the US government in particular have caused a diversification of actors in space. Until 2040, governments will continue to play a crucial role, but other actors are becoming ever more important. As of 2023, this refers particularly to NewSpace businesses, research institutions and billionaires. During the 2020s and 30s, space actors will include car manufacturers, pharmaceuticals, IoT operators, IT companies and aircraft OEMs as well as universities and affluent private individuals. Farmers, engineers, UAV operators, foresters, governments of smaller countries and many others will be using space data and services on an everyday basis.

"I do think that access to space is becoming democratised, such that even individuals or small groups of people now can start having access to space without having to wait for all these big missions and big satellites that are funded by the government. We are moving away from this traditional approach of governments funding large, monolithic missions to actually a decentralised way in which individuals can start using space based on miniaturised technologies for their own applications."

Luisa Buinhas, Vyoma

Every Major Company Will Need a Space Strategy

Over the 2030s, space data will become so widely available and regularly used that businesses not utilising and exploiting this data to their benefit will fall behind their competitors. The majority of the study participants contends that by 2040, every major company and even a significant proportion of medium-sized businesses will need to consider how they can best make use of space.[124]

As of 2023, the list of the world's largest corporations includes the automotive industry, the chemicals industry, construction companies, electronics manufacturers, the financial sector, healthcare actors, insurance providers, oil and gas producers, retailers and telecommunications companies. Space data bear huge potential for all corporations on that list. Automotive companies for example can use satellite internet and navigation satellites to enable autonomous driving. Chinese automaker Geely has launched its own constellation of satellites in 2022,[125] and Toyota has recently invested in Xona Space Systems, a space business working towards high precision navigation signals (<10cm accuracy) that work in all weather conditions.[126] The chemicals industry could use satellite data to spot chemical spills, to monitor greenhouse gas emissions, to track logistics and supply chains or to carry out environmental surveys. BASF and other chemical companies have already set their sights on space to improve the performance of fertilisers for agriculture.[127] Electronics manufacturer Apple has recently introduced a service allowing users to send emergency messages even when there is no network coverage, using Globalstar's satellite constellation in LEO.[128]

124 Brukardt et al. (2023)
125 Yan & Woo (2022)
126 Newcomb (2022)
127 Deter (2017)
128 Rainbow (2023)

"I am firmly convinced that in the future, every corporation will need to develop some kind of space strategy. We are only at the early onset of the earth observation market, of these new data and what you can do with them."

Fabia Höhne Tarragona, OroraTech

During the 2020s, major corporations will be the first to include space assets and data in their business models, and as access to space becomes cheaper and more user-friendly, other businesses will follow suit. Still, until 2040, space will remain a minor albeit important segment of most of these corporations' business models. While it is critical to include space to pioneer new technological possibilities and to avoid falling behind one's competitors, most corporations will not become space corporations in the sense of Blue Origin or Arianespace.

From Space for Earth to Space for Space

One major transition that is going to take place by 2040 is the shift from the space economy being Earth-focused towards being increasingly space-focused. The vast majority of space applications are meant to serve some goal on Earth. Sometimes this goal is set by governments, other times it is set by businesses. Except for some science missions, almost all space infrastructure is meant to serve human beings on Earth. By 2040, space assets will have begun to serve the needs of other infrastructures in space.

"A true space economy I would define as having customers and end users who buy products or services in space for end utilization in space. It's a bit purist, but what it means is that we would have transportation, data, computation, manufacturing, ultimately habitation, people living or working in space."

Jim Keravala, OffWorld

"But what you will have in the future in my point of view is that we'll have satellites serving other satellites, satellites serving infrastructures, and so on. And I think this is probably one of the biggest paradigm shifts that just opens up so much potential in terms of business opportunities. [...] In a way, you would have a new infrastructure that serves the space environment itself instead of humans directly."

Luisa Buinhas, Vyoma

The technologies and infrastructures involved in this transition include satellite RPO, MRO and recycling, space debris removal and SSA using in-orbit sensors. These technologies, and the business models standing behind them, are applied directly to space assets and serve no immediate purpose on Earth.

"In 2040, I think we're going to have a thriving, or the beginnings of a thriving, in-space economy. We talked about the benefits of space for Earth, I think 2040 is when we're going to start to see goods and services being transacted in space."

Rob Meyerson, DELALUNE SPACE

Nevertheless, despite the growth of space-for-space business models, even by 2040, the majority of space infrastructure and spacecraft will continue to serve needs on Earth.

Growth of Space-as-a-Service Business Models

Another significant shift in the space economy concerns business models. In 2023, satellites are tailored products which are commissioned, owned and operated by the same actor. While being rare, it does occasionally happen that satellites are lost on launch. In that case, it is the loss of the company that owns and intends to operate the satellite. Many of the study participants have expressed that by 2040, this business model will be challenged by a space-as-a-service business model:

"For example, I could say that I want to nudge out all of my competitors. And if I have a big enough bank balance and I know my technology is good, now I can call the operator saying, 'Look, you don't give me any money. I'm going to take the risk of building and operating the system. And once the satellite is up and functioning, you can pay me a subscription that is on a monthly basis or a quarterly basis for this asset to provide you the service. And you only pay me the subscription so long as the asset works.' Obviously, it puts the operator in a great position. […] This is true space as a service, right? Where the liability is shifting from the operator to the manufacturer to a large extent."

Nayaran Prasad, satsearch.co

In a space-as-a-service business model, a single satellite could have multiple operators over its lifetime, especially as satellites become modular and can be upgraded as new needs or technologies arise. Satellite operators could also sublet their satellites to other potential users in the same way that science instruments are rented out today. There could also be private space stations that are operated by space businesses and used by different kinds of stakeholders such as universities, pharmaceutical corporations or space tourism agencies. Again, this will make space more accessible, including for small and medium sized enterprises who are not able to operate their own spacecraft. As such, this will contribute further to the democratisation of the space economy.

"We're moving into the direction of satellite-as-a-service, data-as-a-service, software-as-a-service."

Fabia Höhne Tarragona, OroraTech

While the period between 2025 and 2040 will most likely be a transition period with old and new business models coexisting, by 2040, space-as-a-service will probably have become the dominant business model in the space economy.

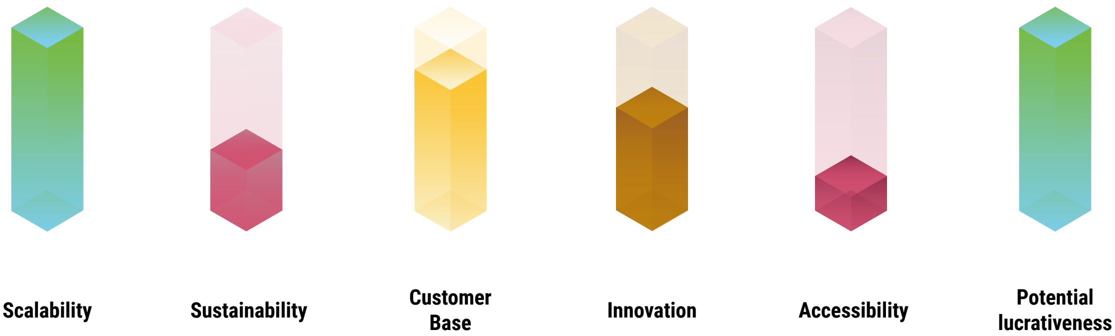
BUSINESS MODELS

BUSINESS MODELS

Space Business Models

This section contains a list of potential future business models in space. In many cases, the lists repeat and summarise points that have been made in previous chapters, stating how technologies and infrastructures can be concretely implemented in terms of a business model. Moreover, summarising the desk research and the interviews that have been conducted for this study, this section assesses each business models based on impact date, scalability, sustainability, customer base, innovation, accessibility and potential lucrativeness.

Satellite Internet



Main deliverables	Customers	Future requirements
Global high-speed internet access using satellite (mega) constellations	private individuals in remote areas, scientists, military	megaconstellations, receivers

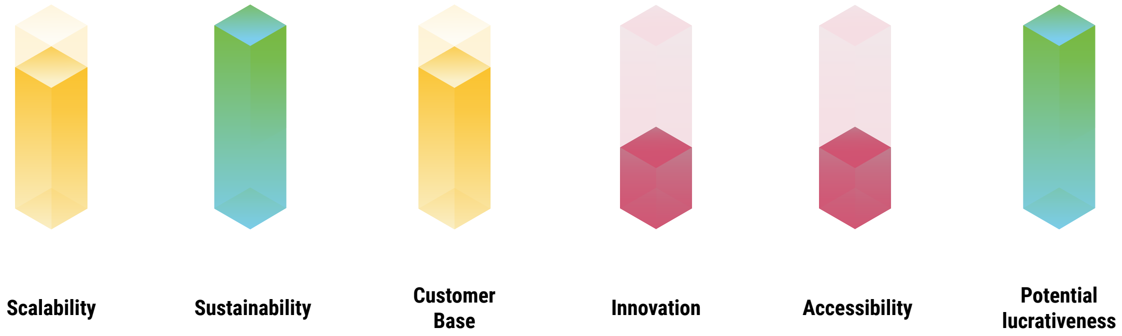
"At the moment, you either have internet via radio transmitters or you have internet via large geostationary satellites. For that you need large stations though, that you need to set up yourself, […] whereas megaconstellations can be used with small terminals. At the moment, you pay less than €2000 to €3000 a year, which is already a huge advantage and you can receive it from practically anywhere. This is huge progress, which will lead to them becoming extremely competitive, also vis-à-vis terrestrial services."

Kai-Uwe Schrogl, European Space Agency

One of the key business models in space for the late 2020s is satellite internet. Apart from SpaceX's Starlink, Eutelsat/OneWeb, Amazon and the Chinese government are similarly investing in satellite internet constellations. While projects such as Starlink focus on universal coverage, other projects such as the OneWeb constellation focus on providing high-speed internet to remote areas.[129] Satellite internet will contribute enormously to the growth of the space economy until 2040. While projections on the magnitude of this contribution vary between 11% and 51%, there is consensus that satellite internet will make up a significant share of the space economy in 2040.[130] By the 2030s, regular access to satellite internet may even be free, with high-speed frequencies being reserved for paying customers. Given that the required initial investment in satellite internet is high, there are however significant market entrance barriers and the number of players in the satellite internet business will likely be limited.

129 Baumann (2022)
130 Space Industry Bulletin (2019)

Earth Observation Data



Main deliverables

Images containing all kinds of environmental data

Customers

farmers, foresters, scientists, architects, private individuals etc.

Future requirements

none

"Sensor technology that also allows for better monitoring of our own planet. And I'm talking here about optical sensors that do monitoring of land regeneration, detection of illegal activities, even tracking of migratory birds and mammals and so on. Looking at, perhaps, shipment and logistics. So, really looking at sensor technology that can do a better reporting of life here on Earth."

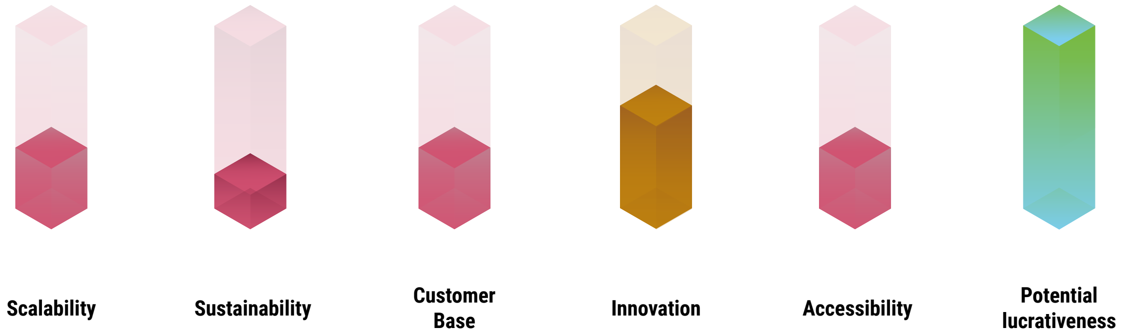
Luisa Buinhas, Vyoma

Having been one of the first commercial space applications, Earth observation is already one of the larger segments of the space economy. Morgan Stanley estimates that its value may rise from currently $2.9 billion to over $25 billion by 2040.[131] Current applications such as mapping, meteorology and climate monitoring will continue to thrive, as climate change will make these data ever more important. However, by 2040, growing, climate-induced demand, miniaturised sensors, dropping launch costs, hyperspectral imaging and AI-supported data interpretation will contribute to the further rise of this segment.

By the 2030s, earth observation systems can even be used to track supply chains, serving as blockchain oracles, i.e. interfaces between physical reality and its representations on the blockchain. In 2040, real-time images of the entire planet across wider ranges of the electromagnetic spectrum will enable applications such as: monitoring crop health and yield; detecting diseases and pests in forests and fields; identifying areas exposed to water stress and nutrient deficiencies; disaster forecasting; monitoring water quality, pollution, wild fires, desertification and sea level rise; detecting minerals and their distribution in geological formations, tracking changes in infrastructure; monitoring tracking flows in heat distribution in cities; monitoring migration flows and many others. Apart from that, hyperspectral imagine has various security-related applications.

131 Dasgupta (2022)

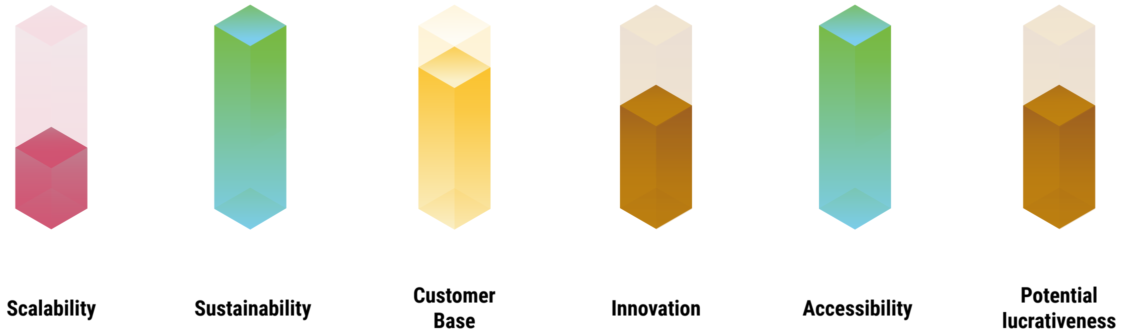
Space Tourism



Main deliverables	Customers	Future requirements
Offering flights to private space stations and around the Moon	affluent private individuals	cheaper human launches

Space tourism is one of the clearest space-related business cases and this report has a section dedicated to it. By 2040, space tourism will have grown significantly, but even then it will only represent a small share of the space economy. In 2040, it is unlikely that companies will built business cases exclusively around orbital space tourism, but all sectors that deal with human spaceflight will be taking it into consideration. As such, the space tourism market has very high entrance barriers. Still, as the number of astronauts grows, these astronauts will have to be trained before their flights into space, which is a potential market niche. Astronauts will also have to be equipped with space suits and security systems, which will also not necessarily be produced by the company offering flights.

Space Consultancies



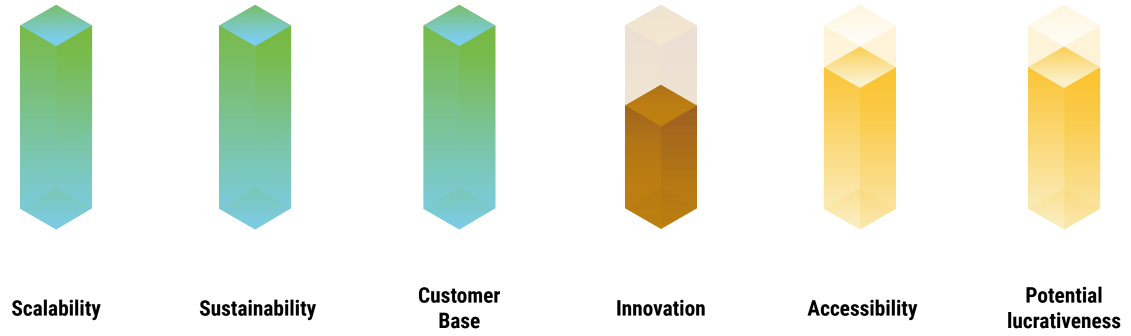
Main deliverables	Customers	Future requirements
Consulting services and discovering how businesses can use space for their benefit	all major corporations, governments, agricultural businesses, aerospace sector etc.	none

"A lot of companies, to be successful, have to either guess at what policy is going to be in play or be strong enough to spend a lot of time working with the FAA and even doing some lobbying to try to kind of inform the FAA and help guide what the policy should be so that it's in their best interest."

Dane Rudy, Second Order Effects

What kinds of space-based services are available? How can my business benefit from space? What legal aspects do I need to take into consideration when becoming involved in the space sector? How can we team up with other actors to create a common space strategy? As all major corporations will need to develop a space strategy by 2040, these questions will become ever more pressing. Space consultancies will advise companies on how to make use of space assets and they will support businesses with combining their strength to lobby in the fields of policymakers and regulators to develop binding rules on the commercial use of space.

Space Traffic Management



Main deliverables

Providing real-time information on space traffic for spacecraft operators

Customers

all satellite operators

Future requirements

SSA

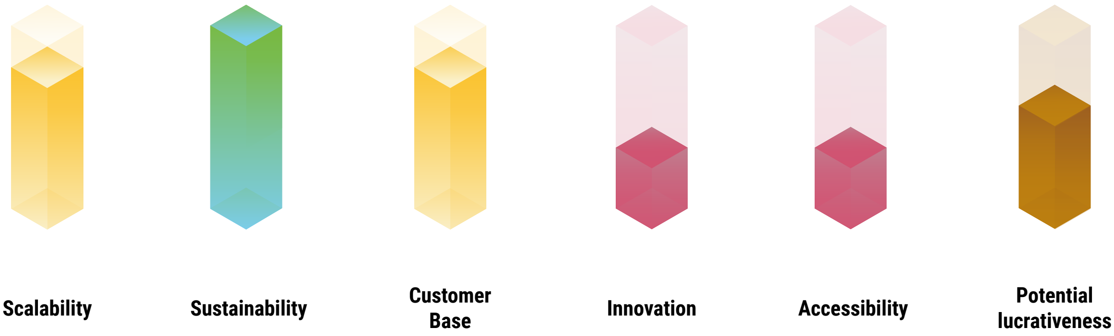
"This is really a problem, and our customers are seeing it. Sometimes you get warning, for example from the US Air Force, forecasting a collision with a satellite with a certain probability. Just to give you an impression: We have customers receiving up to 1,000 notifications per month, that there may be a collision. And that's always a gamble for the operator."

Daniel Bock, Morpheus Space

Given the dramatic growth of the number of spacecraft in orbit, it becomes more and more necessary to have a coordinated space traffic management system. Satellite operators can commission enterprises with collecting the information required to avoid their satellite from colliding with debris or another satellite, as well as with executing the appropriate manoeuvres. Outsourcing this task to third parties saves them time and resources and creates higher reliability. With companies such as Vyoma, COMSPOC, ExoAnalytic Solutions or Kayhan Space, the commercial space traffic management sector is already beginning to emerge.[132] By 2030, this sector is likely to have grown dramatically. This also represents an opportunity for companies specialised in AI, who may execute collision avoidance manoeuvres autonomously.

132 Erwin (2022b)

Construction Monitoring and Planning



Main deliverables	Customers	Future requirements
Monitoring progress on construction sites and providing environmental data	engineering and construction businesses	high resolution imagery

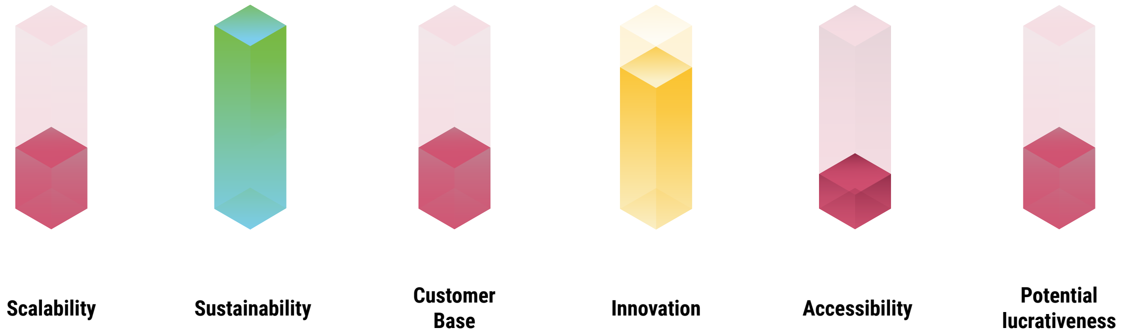
"If you look at trends such as supply chain tracking, climate resilience or building efficiency in construction, you can optimise all of these things using data from earth observation."

Fabia Höhne Tarragona, OroraTech

The increasing availability of satellite data will optime the efficiency of construction, especially in the context of building requiring higher degrees of climate resilience. Earth observation data can be used for selecting the optimal site for construction before time and resources are invested for further planning. High-precision topographic data creates detailed maps of sites for proposed construction projects, helping engineers and architects optimise the planning. Moreover, progress on construction sites can be monitored from space using a variety of instruments, reducing waste, inefficiencies and preventing accidents. Satellite data is especially valuable for underdeveloped areas or for construction projects in remote areas, where it can also be complemented by data gathered from UAVs. As opposed to human reporting, satellite data is independent, objective and less prone to human error. Satellite images of construction sites can also be interpreted by AI, saving engineering firms time and resources.[133]

133 Hawkins (2022)

Debris Removal



Main deliverables

Removing satellites and debris of all sizes from LEO and GEO

Customers

space agencies, governments, satellite operators

Future requirements

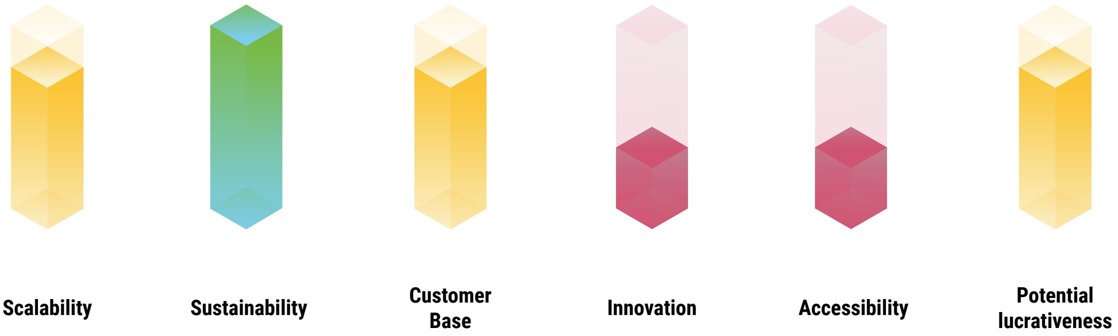
RPO, SSA

"This also means that we will see an entirely new business model, perhaps space debris collectors with some kind of nets or magnets. But there will be a strong increase over the next 10 to 15 years."

Fabia Höhne Tarragona, OroraTech

While the onset of Kessler syndrome by 2040 is unlikely, and while AI-supported debris avoidance strategies will mitigate the worst impacts of space junk, the debris population will have to be reduced to ensure the long-term sustainability of space activities. Governments around the world will launch pilot projects to test debris removal methods, such as nets, harpoons, electromagnetic tethers or laser ablation. For some companies this will generate a limited amount of revenue. For space debris removal to be implemented on a larger scale, international coordination is required, as states will disagree over who will bear the costs of debris removal strategies.

Supply Chain Tracking and Route Optimisation



Main deliverables

Unlimited, real-time logistics tracking around the world

Customers

logistics and shipping companies, military

Future requirements

none

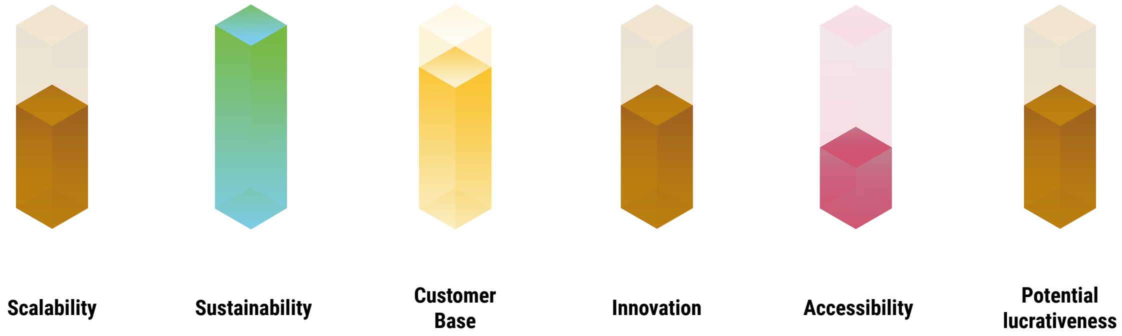
"It is fully integrated into supply chain tracking, allowing you to say where my package is at this point, allowing shipping routes to be recalculated according to the exact location of sea ice, making it easier to choose this route or another route."

Fabia Höhne Tarragona, OroraTach

Earth observation data can be used to track supply chains and to optimise transportation routes. Using radar imagery, such Earth observation data is available in all weather conditions. Satellites can track packages and cargo using telecommunications systems or earth observation data, which has several advantages in comparison with other methods to track goods. Supply chain tracking via satellite provides global coverage, including on high seas or in remote areas. It also provides near real-time coverage, which is not guaranteed if supply chains are tracked using barcoding or physical electronic data interchange. The tracking company needs to have no physical contact with the goods beings tracked. Satellite based supply chain tracking also enhances security for strategic goods, by providing information on suspicious activities such as theft and tampering.

Earth observation data can also be used to improve shipping routes, for example by providing real time information on polar ice coverage, thus enabling shipping via the Arctic Ocean. To reduce the climate impact of aviation, it will become critical to avoid the generation of contrails. Earth observation data can suggest climate friendly routes, which avoid areas where contrail formation is more likely. By monitoring dust development, Earth observation data can further suggest routes that avoid dust abrasion, prolonging the lifetime of aircraft engines and reducing maintenance needs.

Applying Space to Agriculture



Main deliverables

Monitoring environmental data for agriculture and forestry

Customers

agricultural companies, scientists

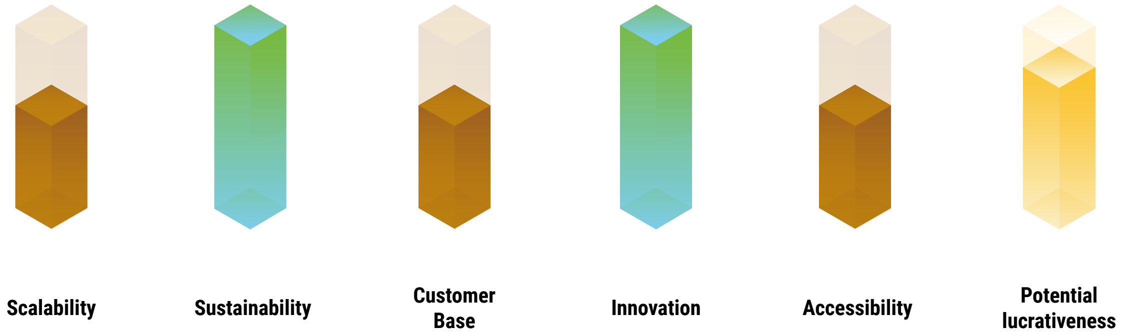
Future requirements

imaging satellites

Using Earth observation data and other space assets for agriculture and forestry is one of the most obvious space applications with great growth potential until 2040. Space data is already being used by governments to assess which farms meet the criteria for subsidy allocation.[134] In the future, farmers will routinely rely on space data. As Earth observation can be used to monitor data on crop growth, temperatures, rainfall and vegetation cover, it can provide the foundation for core yield forecasting. Precise information on soil moisture enables farmers specially water areas with low moisture levels, which is especially important in regions with water scarcity. Satellite data of soil nutrient levels enables the more specific allocation of fertilisers. Pest and disease monitoring contributes to reducing the number of pesticides used.[135] Similarly, foresters can use satellite data in combination with AI to map tree species, estimate wood stocks, detect theft or plan which tree species should be planted in what locations.

134 Dahm (2023)
135 Haynes (2023)

Spacecraft MRO



Main deliverables

Maintaining and repairing spacecraft in orbit and on the ground

Customers

all satellite operators

Future requirements

reusable megalaunchers, AI, robotics, remote physical work

"So you could see nuclear-powered plasma-propulsed spacecraft, satellites, and so on, that will have very large, very long operational lifetimes. By the way, that also means future satellites and spacecraft will also be modular in the sense that you can have a satellite up in orbit for 40 years, but you switch out the payloads routinely. And that's why we're also seeing a lot of satellite maintenance capabilities. So for example, go up, do a rendezvous with a satellite to refuel it or to swap out payloads or sensors or other parts of its operating system as well."

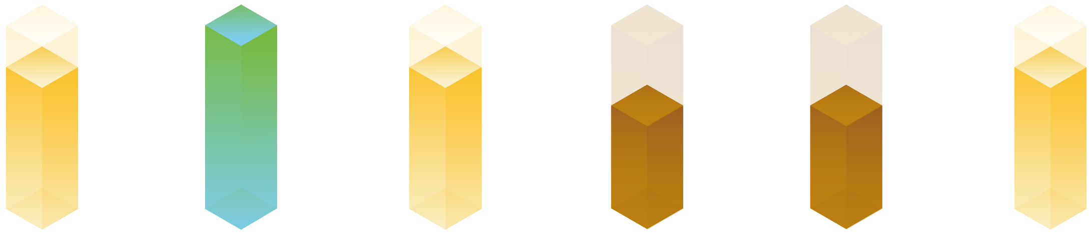
John Sheldon, AzurX

Over the course of the late 2020s and the early 2030s, there will be a significant proliferation of reusable rockets and recycled satellites. To permit these assets to be used effectively, reliably and safely, there will need to be a network of MRO shops for spacecraft. In many parts of the world, the maintenance and recycling of spacecraft will be carried out by independent and sometimes state-operated shops. In other cases, the OEMs themselves will provide the operators with long-term MRO contracts.

Nevertheless, MRO will not only be carried out on spacecraft on the ground, but also on satellites that are already in space. During the late 2020s, specific MRO missions will be required to maintain satellites by replacing seals, retaining rings, plugs and slides, as well as for refuelling. This can dramatically extend a satellite's lifespan.[136] During the 2030s, RPO-capable, nuclear-powered satellites with 3d-printing systems and robotic arms can routinely carry out MRO operations in orbit. The Remote Manipulator System, a robotic arm that is currently in use on the ISS, was built and developed by Canada's MDA Space Missions, CAE and Rockwell International, highlighting the potential diversity of companies involved in space MRO operations.

136 EDI (2018)

Ride-Sharing for Spacecraft



Main deliverables

Several clients sharing a single, modular satellite for their applications

Customers

SMEs, governments of small states

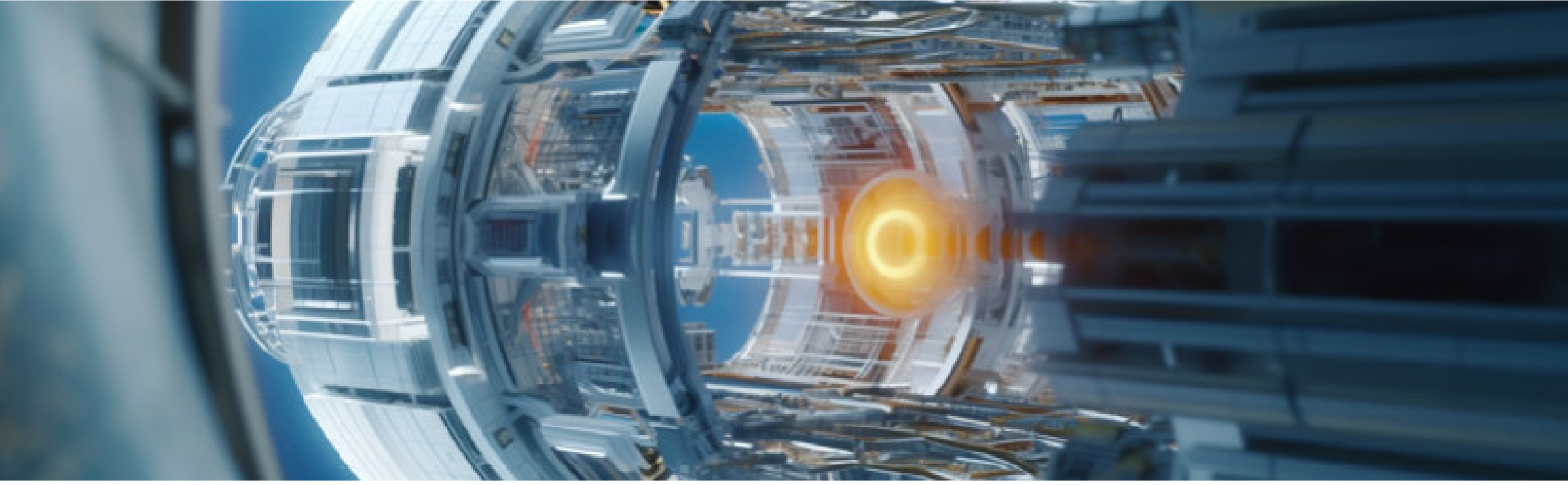
Future requirements

modularity of spacecraft

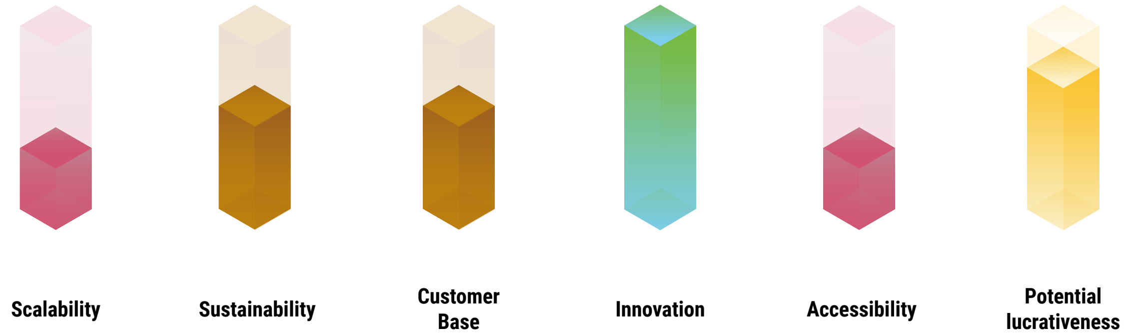
"And you could have the same approach with satellites: rather than having 2,000 satellites, maybe you could have a lower number of satellites, but perhaps with different sensor technology on board, such that you kind of share the satellite, you share the resources of the satellite. It's what we call a 'hosted payload' approach. I think this is a lot more holistic and a lot more resource-efficient than just having all these large numbers of cheaply built satellites launched into orbit that just end up staying there. So kind of the concept of rideshare, but for satellites and say sensor technology. I think this will be a very interesting business model for the future."

Luisa Buinhas, Vyoma

As space assets become miniaturised, delimited, complexified and modular, a single satellite might host a variety of missions and applications. The operator offers the service of providing the platform and manoeuvring the satellite, while various other actors can 'latch on' to the satellite with the modules they require. This will allow access to space to become affordable not only for universities, but for high-schools and private individuals. It will also vastly increase the accessibility of exotic orbits, such as the Molniya orbit, for companies and governments alike.



Private Space Stations



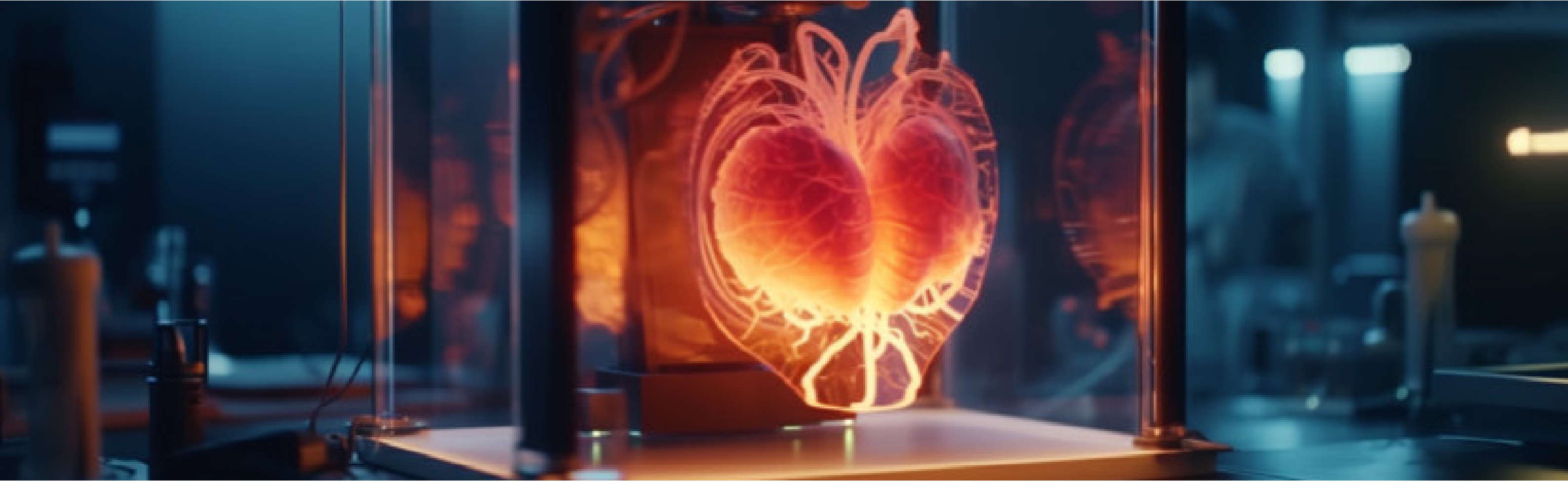
Main deliverables	Customers	Future requirements
Private space stations for tourism, science and manufacturing	pharmaceuticals, biotech companies, medium-sized countries	megalaunchers

"So when Axiom Space exists, a company like Merck or Amgen or Bayer can buy a research module and have dedicated research being done for their purposes and that can be done in a short amount of time when the Axiom Station exists as a private commercial entity."

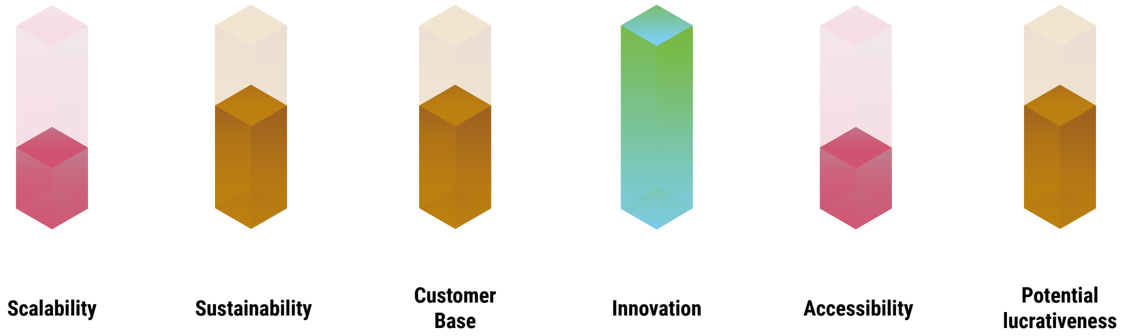
Rob Meyerson, DELALUNE SPACE

Apart from Axiom Space, companies such as Blue Origin, Sierra Space, NanoRacks and Northrop Grumman are similarly planning on launching their own private space stations during the late 2020s and early 2030s.[137] By 2040, there will likely be multiple private space stations in orbit. Applications of private space stations include tourism, scientific research platforms and space manufacturing. Apart from these obvious use cases, private space stations could also be used in film-making, as stages for art performances,[138] for zero gravity healthcare or as waypoints for further travel to the Moon. Nevertheless, the most immediate use case is to use private space station as technology demonstrators for space manufacturing. Companies could rent out small laboratories on their space stations that can be operated remotely by commercial and public actors such as pharmaceuticals, universities and biotech businesses.

137 Kluger (2022)
138 Hopkin (2022)



Space Manufacturing



Main deliverables

Producting chemicals and pharmaceutical products in microgravity

Customers

pharmaceuticals, biotech companies

Future requirements

private space stations, (megalaunchers)

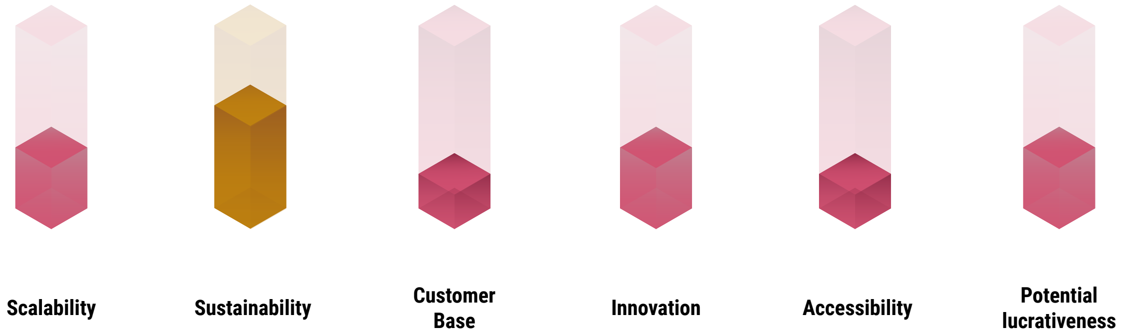
“In the very early stages, it might be enzymes only. In the future, however, we certainly will reach a point where we can accomplish 3D printed organs, printed to perfection in space. At this point, it becomes interesting to say, ‘I’m establishing an entire space bound “3D printing centre” where we are able to print organoids to perfection in space and eventually send them back down on Earth.’”

Tobias Strobl, AriaX

If the research on space manufacturing discussed in the chapter on space infrastructure produces positive results, by the late 2030s, space manufacturing could become commercially viable. Space manufacturing in LEO utilises the microgravity environment to develop structures that are impossible to create on Earth.[139] Initial business models may involve providing small microgravity research platforms for pharmaceuticals and biotech companies to prove the large-scale viability of space manufacturing.[140] By 2040, this may evolve into in-orbit factories.

139 Makaya et al. (2022)
140 Riley (2022)

Lunar Infrastructure



Main deliverables

Communications, navigation and logistics systems for a Moon base

Customers

governments, space agencies

Future requirements

(megalaunchers), Moon base

"The Moon is an almost completely unspoilt piece of rock. There will need to be a huge amount of infrastructure on the Moon and around the Moon to be built up."

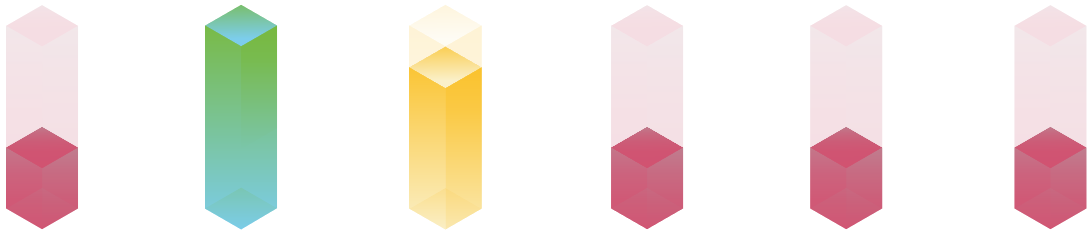
Daniel Bock, Morpheus Space

"And there's more than that... What does it look like, if we want to advance a civilization beyond Earth? How do we feed them? We won't be able to bring everything, nutrition, supplements, to space from Earth. We therefore must be able to provide food grown in space."

Tobias Strobl, AriaX

When a Moon base becomes operational during the 2030s, this will generate a variety of business opportunities. From a technical point of view, a Moon base will require a small telecommunications and Moon observation satellite network, which will have to be demonstrated, built, launched and operated. The Moon base will also require infrastructure to effectively utilise these satellites. While this will likely be implemented by a traditional space business, the technical infrastructure of the Moon base itself, including sanitation, heating and energy systems, could be provided by companies which have hitherto not been involved in the space economy. The Moon base will also be an important testing ground with space mining, and Earth-based mining companies will have to adapt their equipment to test the feasibility of space mining. Astronauts will also have to grow some of their own food, creating opportunities for companies specialising in indoor farming equipment. Further business models on the Moon, including ISRU and construction, are discussed below.

Trading Used Spacecraft



Main deliverables

Buying and selling used spacecraft, including satellites and rockets

Customers

Medium-sized countries, military, major corporations

Future requirements

fully reusable rockets

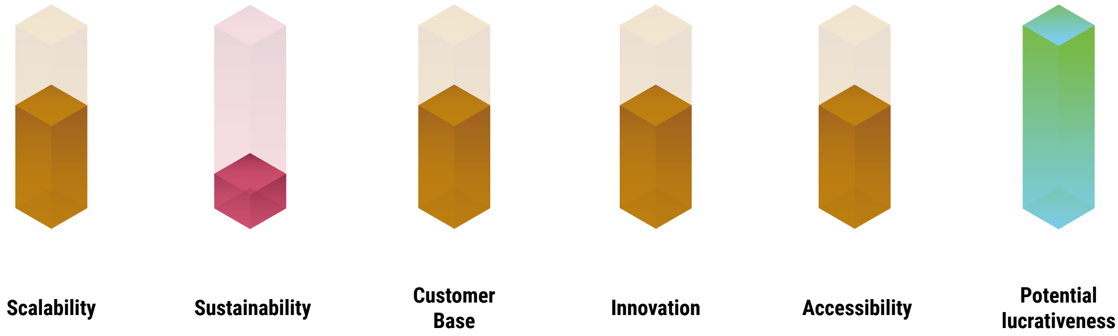
"Now, I mean, think about this for a minute. […] The poor people in the US or Europe have cars. They buy used cars. And they can get them at an enormous discount against the new car price. So there's going to be used space launch vehicles. There's going to be used Starships."

Robert Zubrin, Pioneer Astronautics

The advent of reusable rockets has produced a new commodity in the shape of used boosters and, in the future, used rockets. There has already been an interest by other companies to purchase used Falcon 9 boosters.[141] Once the Starship is routinely used, smaller and poorer countries who are unlikely to ever possess their own rocket manufacturing capabilities may be interested in purchasing used Starships, which creates a market for buying and selling rockets. The dawn of routine satellite RPO manoeuvres and satellite recycling will also create a market for inactive satellites and space debris. Interesting parties may purchase these satellites from their original operators, recycling them to serve new purposes.

141 Klotz (2016)

Point-to-Point Transport



Main deliverables

Reaching any place on Earth within an hour using fully reusable rockets

Customers

affluent private individuals, military, international corporations

Future requirements

reusable megalaunchers

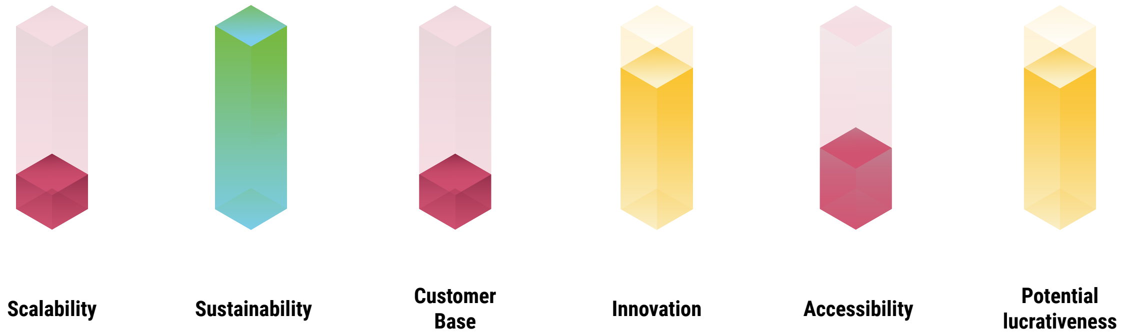
"I think there's an enormous market there for surface to surface transport, not between every city, but between coastal cities. Or because of the noise, okay, but you could have a launch platform 20 kilometres offshore, and tremendous number of cities around the world are on the coast. And they could be linked by this."

Robert Zubrin, Pioneer Astronautics

Point-to-point transport using the Starship or another fully reusable rocket is a potential method for transporting individuals across the surface of the planet in a fraction of the time required by a conventional airplane. According to SpaceX, a trip from New York to Shanghai would take merely 39 minutes, which is highly appealing for customers valuing low travel times. Moreover, the US military has expressed an interest in point-to-point rocket transport, which would, for example, enable delivering air force cargo anywhere on the planet in less than an hour. By 2040, point-to-point rocket transport may thus occupy an important niche.[142] Nevertheless, within the time horizon of this study it has limited potential for scalability for the following reasons: (1) rocket launches are extremely loud and create sonic booms, implying that rocket transport hubs will have to be built at significant distances from population centres or on high seas, reducing their competitiveness vis-à-vis airports; (2) even the most advanced rocket transport hub will have significantly higher turnaround times than an airport; (3) rockets produce more GHG emissions than passenger airplanes;[143] (4) the safety record of the safest rockets is poor compared to aviation; (5) despite dropping launch costs, passenger transportation on rockets will remain too expensive to appeal to a mass market.

142 Smith (2021)
143 Breeze (2021)

ISRU Systems



Main deliverables

Supply ISRU systems for a Moon base and for a human mission to Mars

Customers

space agencies, governments, private space settlement ventures

Future requirements

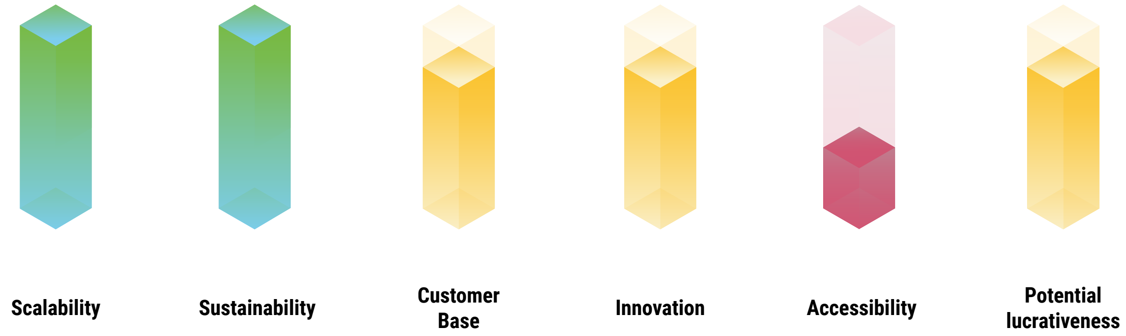
Moon base

"Advancements in material science are crucial when it comes to the exploration of space. We need to address questions around where future colonists will live, what they will wear, what about the whole issue of oxygen supply, […] what will the hoses look like, what materials will hoses be produced from, what will suits look like, etc."

Tobias Strobl, AriaX

ISRU refers to the practice of using materials and resources found in the location where they are needed, rather than bringing them from elsewhere. In the case of a Moon base, this implies using lunar resources for providing water, fuel, oxygen to astronauts using a variety of methods. Oxygen and hydrogen for rocket fuel can be extracted by electrolysing water, which in turn is available on the lunar surface. While ISRU is important on the Moon, it is critical for an eventual human mission to Mars, where the astronauts' lives will depend on it. Until 2040, this business model is unlikely to be commercially driven, as most of the demand will come from governments. Nevertheless, ISRU research will also benefit industries on Earth, where carbon capture and sequestration will likely play an important role by 2040. Moreover, ISRU methods and technologies can be used to extract valuable resource from poluted or contaminated sites on Earth, such as landfill areas or abandoned industrial sites. Companies working in this field are thus potentially suited for providing services and technologies for space ISRU.

Computing in Space



Main deliverables

Data storage and computing in orbit or on the Moon

Customers

IT corporations, governments

Future requirements

reusable megalaunchers

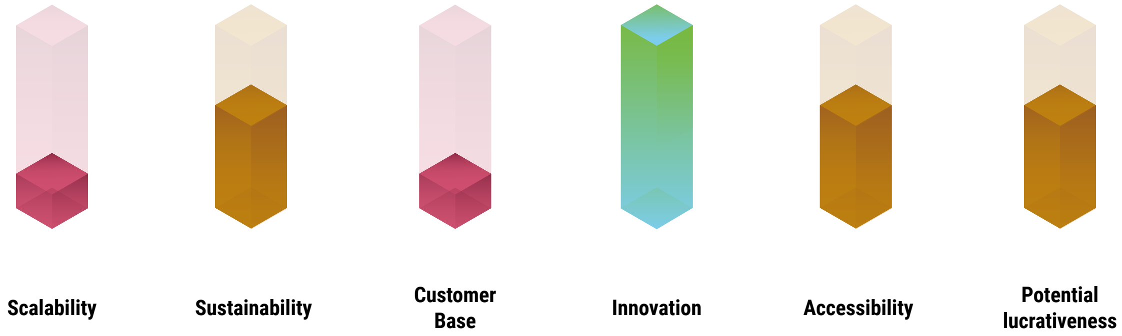
"Another topic are computing centres in space. There is already a large startup that wants to do this."

Robert Boehme,
Planetary Transportation Systems

Over the further course of the 2020s and 2030s blockchain technology, machine learning applications, data analysis, cloud computing, the metaverse, high-end gaming, rendering and scientific computing will require enormous capacities in data storage and processing power. These in turn require energy, which is fiercely competed for in an era where fossil fuel energy is being phased out, while solar and wind power can only provide electricity under the right circumstances. This will increase the competitiveness of computing in space, and major IT and Big Data corporations will consider moving some of their computing power to LEO.[144] In space, solar energy is always available at much higher efficiencies than on Earth and the outer space environment provides ample cooling. Space is also an attractive location for quantum computers which require operating temperatures close to absolute zero, which are easier to achieve in a vacuum.[145] Business models to implement this could involve the provision of data processing or storage centres in space, with customers paying for their utilisation.

144 Limón (2022)
145 Hughes-Castleberry (2021)

Materials for Construction in Space



Main deliverables

Providing construction material for settlements on the Moon

Customers

governments, space agencies, private commercial and space settlement efforts

Future requirements

reusable megalaunchers, Moon base

"Definitely materials science since the conditions and demands of space are substantially different. You need to cope with the harsh environment of space which includes, amongst others, exposure to extreme heat and cryogenic temperatures, high-energy UV radiation, debris impact, and many more. […] There is a myriad of concepts and applications from space bound material science coming back down on Earth. However, in my point of view materials science for materials that are designed to withstand the challenging requirements of space, can become interesting yet crucial.

Tobias Strobl, AriaX

Materials in space must withstand conditions very different from those on Earth, having to be airtight, protect against radiation and provide shelter from extreme temperatures. With the advent of private space stations and a Moon base, there is an emerging business case for companies providing materials and construction elements. Companies such as Sierra Space or Bigelow Aerospace are already working on future space habitats, and there is potential to material science to make these habits cheaper and more flexible.[146] The customer base for such habitats is composed of space agencies as well as commercial space station operators.

146 Northon, 2017

METHODOLOGY

METHODOLOGY

This study employs an adapted version of the Delphi method, a qualitative foresight approach based on expert interviews (n = 20).[147] The composition of the study involved the following steps:

4. Environmental scanning: At the early stages of this study, environmental scanning and desk research was conducted to establish a comprehensive and multifaceted perspective on the future of the space economy, giving way to new avenues of thought regarding its long-term development. This process culminates in the generation of a future forces map, which represents the most important trends, drivers and actor groups that will impact the space economy by 2040.
5. Expert selection: On the basis of the future forces map, experts representing the various actor groups were selected using further desk research. These experts were contacted and invited to participate in the further stages of this study.
6. Expert interviews: The experts participated in a one hour, in-depth, qualitative, semi-structured interview. An interview guide was prepared to assess the drivers and consequences of each trend the experts describe. The experts were also asked to provide their views on major trends for the future of humanity outside the realm of space, as this provides important context for the foresight study.

147 Gordon (1994)

7. Interview analysis: The interviews were transcribed and then analysed using the MAXQDA software to identify drivers, trends and consequences as described by the interviewees. Upon completion of the interview analysis, a series of hypotheses on the future of the space economy was formulated.
8. Online survey: All study participants were asked to participate in an online survey to rate some of the hypotheses that emerged from the interviews on the likelihood of their occurrence. The participants were asked to rate only those hypotheses that were particularly contested or controversial, or which were not held by a majority. The purpose of this survey is to consolidate the interview results and to eliminate contradictory hypotheses.
9. Study report: Based on the interviews and the online survey a study report was composed to summarise and contextualise the findings. The study report extensively employs approved quotations from the expert interviews.

The predictions presented in this report represent the opinions of the majority of the experts that participated in the study. If a quotation is used to illustrate a prediction, that does not imply that the experts who are not quoted do not hold this view. The report occasionally makes predictions which are not supported by the majority of the study participants. If that is the case, it is highlighted in the text.

GLOSSARY

GLOSSARY

ASAT weapons

ASAT stands for Anti-Satellite weapons. These are weapons designed to destroy or disable satellites in orbit around the Earth. ASAT weapons can be ground-based or launched from aircraft, ships, or satellites, and they typically use kinetic, explosive, or directed energy technologies to destroy or disable their targets.

Asteroid belt

The asteroid belt is a region of the solar system located between the orbits of Mars and Jupiter that is home to millions of small rocky objects, known as asteroids. The asteroids in the belt range in size from tiny fragments to large bodies several hundred kilometres in diameter, and they are believed to be remnants from the early solar system that never coalesced into full-sized planets. The asteroid belt is an important area of scientific research, as it provides insights into the formation and evolution of the solar system.

Biosignatures

Biosignatures are measurable indicators of life, either present or past, that can be detected in a given environment. These indicators can include chemical compounds, isotopic ratios, and physical structures that are associated with biological activity. The detection of biosignatures is a key goal of astrobiology, which seeks to understand the potential for life beyond Earth.

Celestial bodies

Celestial bodies refer to any natural object that exists in space, including stars, planets, moons, asteroids, comets, and other objects. These objects are typically composed of various materials, such as rock, gas, ice, and dust, and they are held together by gravity.

Cislunar space

Cislunar space is the region of space between the Earth and the Moon, including the space around the Moon. It is a key area for human exploration and activity beyond Earth's immediate vicinity. Cislunar space is of interest for a variety of reasons, including scientific research, resource utilisation, and human settlement.

Counterspace

Counterspace refers to a type of military capability designed to disrupt or disable space-based systems operated by an adversary. Counterspace operations can include a variety of tactics, such as jamming or spoofing signals from satellites or ground stations, deploying kinetic or non-kinetic weapons to physically damage or destroy satellites, or conducting cyberattacks on space-based systems. In recent years, counterspace capabilities have become a significant area of focus for military powers around the world, as they seek to protect their own space-based assets while also developing strategies to counter potential threats from adversaries

CubeSats

CubeSats are a type of miniature satellite that typically have a cube-shaped design and a size of 10 centimetres per side (1 litre in volume). They are often used for low-cost and low-risk space missions, such as scientific experiments, technology demonstrations, and educational projects. CubeSats can be easily launched into space as secondary payloads alongside larger spacecraft and can operate in various orbits, including low Earth orbit (LEO) and beyond. Due to their small size and modularity, CubeSats can also be used to build larger satellite constellations for Earth observation, communications, and other applications.

Directed energy beams

Directed energy beams are weapons that use focused energy, such as lasers or microwaves, to disable or destroy targets. These weapons produce a high-intensity beam of electromagnetic radiation that can be directed towards a target with precision, causing damage or destruction by heating, burning, or vaporizing the target.

Eccentric Orbits

An orbit in which a spacecraft's distance from the Earth varies over time.

Electromagnetic pulse (EMP) weapons

Electromagnetic pulse (EMP) weapons are devices designed to generate a short burst of electromagnetic radiation that can disrupt or damage electronic devices and systems. EMP weapons can be delivered in various forms, such as nuclear or non-nuclear explosive devices, or high-powered microwave generators, and can potentially cause widespread and long-lasting disruption to communication, transportation, and power infrastructure.

European Space Agency

The European Space Agency (ESA) is an intergovernmental organization created in 1975 to coordinate space activities among European countries. ESA is based in Paris, France, and has 22 member states, including Germany, France, Italy, Spain, and the United Kingdom. ESA does not have the same membership as the European Union and is not part of the EU family of institutions. ESA and the EU are close cooperating partners.

Extraterrestrial space station

An extraterrestrial space station is a hypothetical structure designed to be built and inhabited by humans in space beyond Earth's orbit. It would be a long-term habitation module or research facility placed in a stable orbit around a planet, moon, or other celestial body, and would serve as a base for human exploration and scientific research. The development of an extraterrestrial space station is a challenging engineering and logistical endeavour that requires advanced technologies and sustained investment.

Geosynchronous orbit

Geosynchronous orbit is an orbit around Earth where a satellite completes one orbit in the same amount of time as the Earth rotates once on its axis, approximately 24 hours. This means that the satellite appears to remain fixed in the sky from a specific point on the Earth's surface, making it useful for communication and observation applications. Satellites in geosynchronous orbit are typically positioned at an altitude of 35,786 kilometres above the equator and are often referred to as geostationary satellites.

Interplanetary probe

An interplanetary probe is a robotic spacecraft that is designed to travel to and explore other planets, moons, asteroids, or comets in our solar system. These probes are usually launched into space using rockets and are equipped with scientific instruments and sensors that can collect data and images of the target object. Interplanetary probes can help us better understand the composition, structure, and history of other celestial bodies, as well as the conditions and environment in space beyond Earth.

In-situ resource utilisation (ISRU)

In-situ resource utilisation (ISRU) is a process of using materials or resources available on-site or nearby to support human activities, particularly in the context of space exploration and colonization. ISRU involves identifying and extracting useful resources, such as water, minerals, and gases, from the local environment rather than transporting them from Earth. This approach can significantly reduce the cost and logistical challenges associated with space missions and can enable longer-term habitation or settlement on other planets or moons.

ISR

ISR stands for Intelligence, Surveillance, and Reconnaissance. It refers to a military concept that involves gathering and analysing information about an enemy or potential threat using various methods such as human intelligence, electronic surveillance, and unmanned aircraft. ISR is critical for situational awareness and decision-making in military operations.

Kessler syndrome

Kessler syndrome is a theoretical scenario where the density of objects in low Earth orbit becomes so high that collisions between objects could generate a cascade of debris, rendering the orbit unusable for spacecraft. The accumulation of space debris poses a significant risk to functioning satellites and spacecraft, and preventative measures are essential to avoid a Kessler syndrome scenario.

Lagrange Points

Places in space where objects can sit without moving relative to two other objects that are much more massive, because the gravitational forces balance out.

Leapfrogging

Leapfrogging is a strategy that involves bypassing traditional or incremental steps in development to adopt more advanced or innovative solutions, allowing for faster progress. It is often used by developing countries to quickly adopt new technologies or systems without having to follow the same path as more developed nations.

Low Earth orbit (LEO)

Low Earth orbit (LEO) is an orbit around Earth that is relatively close to the planet's surface, typically at an altitude of 200 to 2000 kilometres. Satellites and spacecraft in LEO travel at high speeds and complete one orbit around the Earth in about 90 minutes. LEO is an important region for many space applications, such as Earth observation, communications, and scientific research. Due to the relatively low altitude, LEO is also the region where most human spaceflights, such as the International Space Station, occur.

Lunar Gateway

A NASA/ESA/JAXA/CSA space station which will provide astronauts with an access point to the lunar surface.

Megaconstellations

Large networks of hundreds or thousands of small satellites that are designed to provide space-based services.

Megalaunchers

Megalaunchers or super heavy-lift launch vehicles are powerful rockets designed to lift heavy payloads into space. They typically have a lifting capacity of more than 50 tons and are used by space agencies and private companies for scientific research, communication, and exploration. Contemporary Examples include NASA's Space Launch System (SLS) and SpaceX's Falcon Heavy. The SpaceX Starship is planned to be a fully reusable megalauncher, whereas current systems are only partially reusable or expendable (i.e. they burn up in the atmosphere upon re-entry).

Microsatellites

Microsatellites are small satellites that typically weigh between 10 and 100 kilograms and have dimensions of less than 1 metre in all three axes. They are larger than CubeSats but smaller than traditional satellites, and are often used for Earth observation, communications, scientific research, and technology demonstrations. Microsatellites can be launched into a variety of orbits, including low Earth orbit (LEO), geostationary orbit (GEO), and beyond, and can operate for several years depending on the mission requirements.

Molniya orbit

A highly eccentric elliptical orbit that takes a satellite over the northern and southern poles of the Earth and is well suited for communication systems requiring coverage of the Arctic regions, for satellite navigation, earth observation of the polar regions, meteorological observation and various military applications.

NASA

NASA, the National Aeronautics and Space Administration, is a US government agency responsible for the country's civilian space programme. NASA's mission is to drive advances in science, technology, aeronautics, and space exploration to enhance knowledge, education, innovation, economic vitality, and stewardship of Earth. NASA's programmes include human spaceflight, space science, technology development, and aeronautics research.

NewSpace

The NewSpace era refers to a new phase in the space industry characterized by the emergence of private companies and entrepreneurs who are actively investing in and developing space technologies and services.

Nuclear Electric Propulsion (NEP)

Nuclear Electric Propulsion (NEP) is a type of rocket propulsion technology that uses electric power generated by a nuclear reactor to accelerate a propellant, typically xenon gas, to produce thrust. NEP has the potential to provide much higher specific impulse than traditional chemical rockets, making it a promising technology for deep space missions that require high efficiency and long duration.

Nuclear Thermal Propulsion (NTP)

Nuclear Thermal Propulsion (NTP) is a type of rocket propulsion technology that uses a nuclear reactor to heat a propellant, typically liquid hydrogen, which is then expelled out of a nozzle to produce thrust. NTP has the potential to provide much higher thrust and specific impulse than traditional chemical rockets, making it a promising technology for future deep space missions.

RPO

RPO stands for "Rendezvous, Proximity Operations, and Docking." It refers to a set of critical operations involved in spacecraft docking or rendezvous with another spacecraft or object in space. Rendezvous involves bringing two spacecraft together in a controlled manner, while proximity operations involves maintaining a safe and stable distance between the two spacecraft. Docking is the final step where the two spacecraft connect to each other. RPO is a crucial part of many space missions, including satellite servicing, space station resupply, and crewed missions. Proper execution of RPO is important to ensure a safe and successful mission.

OEM

OEM stands for "Original Equipment Manufacturer." It refers to a company that designs and produces components or products that are sold to another company to be rebranded and resold under that company's name.

Orbits

The path that a spacecraft or a celestial body follows as it revolves around another celestial body such as the Earth, the Moon, or the Sun.

Planetary Transits and Oscillations of Stars (PLATO)

Planetary Transits and Oscillations of Stars (PLATO) is a space telescope mission planned by the European Space Agency (ESA) to search for exoplanets and study their properties. The mission is expected to launch in 2026 and will observe up to a million stars over a four-year period. PLATO will use the transit method to detect exoplanets, which involves measuring the periodic dimming of a star as a planet passes in front of it. The mission will also use asteroseismology to study the internal structure and properties of stars. By studying a large sample of exoplanets and their host stars, PLATO is expected to advance our understanding of the formation and evolution of planetary systems, as well as the potential for habitability beyond our Solar System.

Radioisotope Thermoelectric Generators (RTGs)

Radioisotope Thermoelectric Generators (RTGs) are devices that generate electricity by converting the heat released from the decay of radioactive isotopes, such as plutonium-238, into electrical energy using thermocouples. RTGs have been used to power spacecraft and other space systems for decades, as they provide a reliable and long-lasting power source in environments where solar panels or other forms of power generation may not be feasible.

Regolith

Regolith is a layer of loose, fragmented material that covers the solid bedrock on the surface of a planet, moon, asteroid, or other celestial body. It can be composed of a variety of materials such as dust, rocks, soil, and other debris, and it is typically created through processes such as weathering, impact cratering, and volcanic eruptions. Regolith is of particular interest to scientists and space exploration enthusiasts as it may contain valuable resources, such as water ice, that could be used to sustain human missions to other celestial bodies.

SETI

SETI (Search for Extraterrestrial Intelligence) is a scientific research area focused on the search for signs of intelligent life beyond Earth. Researchers in this field use advanced technology, such as radio telescopes and signal processing techniques, to scan the cosmos for potential signals emitted by extraterrestrial civilizations. SETI aims to answer fundamental questions about the existence of other intelligent beings in the universe and the possibility of communication or collaboration with them.

Responsive space

Responsive space refers to the ability of a space programme or system to rapidly adapt and respond to changing mission requirements, emerging threats, or evolving technological capabilities. It involves the convergence of different space technologies rather than a single technology. The idea is that space programmes can have a warehouse where satellites and rockets are stored, and in case of a crisis, they can launch a satellite with specific capabilities on short notice.

Square Kilometre Array (SKA)

The Square Kilometre Array (SKA) is a massive radio telescope project in South Africa and Australia that will be the world's largest radio telescope. It will study the universe in unprecedented detail, detecting very faint radio signals from the farthest reaches of the universe and studying objects such as pulsars, black holes, and planets' magnetic fields. The SKA is expected to contribute significantly to astrophysics, cosmology, and astrobiology.

SSA

Space situational awareness (SSA) is the ability to monitor and predict the location and movement of objects in space, in order to avoid collisions and ensure safe space operations.


EXPERTS
EXPERTS

John Sheldon

Partner at AzurX, Research Fellow at ESSCA, Co-Founder of AstroAnalytica

John B. Sheldon, PhD, is a Research Fellow at ESSCA, France. Sheldon is also the co-founding managing partner of AstroAnalytica Ltd., a London-based space research and consulting company, and a partner at AzurX, a Dubai-based space services and investment company. Prior to these positions, Sheldon was the space advisor at the UAE Ministry of Defence in Abu Dhabi, UAE, for five years until December 2021. He has also held other positions, including Executive Director of the George C. Marshall Institute and Professor of Space and Cyberspace Strategic Studies at the U.S. Air Force's School of Advanced Air and Space Studies (SAASS). Sheldon has consulted on national security space and cyber issues for numerous governments and corporations around the world and is also the founding editor (now Emeritus) of Astropolitics. He has published on national security space and cyber issues in various journals and publications. A former British diplomat, Sheldon holds Bachelor and Master degrees from the University of Hull, UK, and a PhD in politics and international relations from the University of Reading, UK. He currently resides in Abu Dhabi, UAE.

Rob Meyerson

Founder & CEO of Delalune Space

Rob Meyerson is the Founder and CEO of Delalune Space, a company focused on developing infrastructure for human exploration and settlement of space. He previously served as President of Blue Origin, where he played a key role in developing the company's New Shepard and New Glenn launch vehicles. Prior to that, he worked at NASA for over 20 years, where he held several leadership positions including the Director of the Human Exploration and Operations Mission Directorate.

Kai-Uwe Schrogl

President of the International Institute of Space Law (IISL)

Kai-Uwe Schrogl is a prominent figure in the field of space law and policy. He is currently serving as the President of the International Institute of Space Law (IISL), a prestigious organisation that promotes the development and understanding of space law at the international level. Schrogl has held several high-level positions in the European space industry and served as the Director of the European Space Policy Institute (ESPI) for more than a decade. He has authored numerous publications and is recognized as an expert in various fields, including space law, policy, and governance. Schrogl's contributions to the advancement of space law have earned him numerous accolades and awards throughout his career.

Thomas Hoerber

Professor of European Studies at ESSCA School of Management

Thomas Hoerber is a professor holding a Jean Monnet Chair in European Studies at ESSCA School of Management with a PhD from the University of Cambridge. He has a particular interest in the connection between history and politics in European integration theory, as well as European sustainability policies and European space policy. His research and teaching domains also include European economics and law, geopolitics, post-war European history and politics, and international relations.

Jim Keravala

CEO of OffWorld

Jim Keravala is the CEO of OffWorld, a company that develops and operates robots for industrial applications on Earth and in space. With over 25 years of experience in advanced technology, he has held leadership positions in multiple aerospace startups and has a strong background in robotics and automation. He co-founded OffWorld in 2016 to develop advanced robotics for resource extraction and infrastructure development on the Moon, Mars, and other celestial bodies. Jim is a recognised thought leader in the space industry, and his work has been featured in various publications.

Narayan Prasad

COO of satsearch.co

Narayan Prasad is a space industry professional with over a decade of experience, currently serving as the COO of satsearch.co, a leading global online marketplace for the space industry. With previous roles at Dhruva Space and ESPI, he brings a wealth of knowledge in spacecraft systems engineering, technology transfer, and business development. Alongside his professional accomplishments, Prasad is also known for his passion for space education and outreach, having co-founded two non-profit organisations in this field. He is a member of the Advisory Board of Satcom Industry Association India, and actively advocates for space sustainability and responsible practices.

Dane Rudy

Director of Programs at Second Order Effects

Dane Rudy leads the Programs and Business Development teams at Second Order Effects, Inc., a technology company focused on the design and development of advanced electro-mechanical systems for aerospace and defense applications. With a background in physics and engineering, Rudy brings a deep understanding of complex technical systems to his role, where he is responsible for managing key programs and driving business growth. Rudy is also known for his ability to build strong relationships with customers and partners, and for his passion for advancing cutting-edge technologies in the aerospace and defense industries.

Manuel La Rosa Betancourt

Co-Founder & CEO of Neutron Star Systems

Manuel La Rosa Betancourt is a seasoned entrepreneur and space industry professional, currently serving as the Co-founder and CEO of Neutron Star Systems, a company focused on developing advanced propulsion systems for small satellites. With a background in material science engineering and business innovation, La Rosa Betancourt has a unique perspective on the technical and commercial aspects of the space industry. He is known for his innovative thinking and strategic approach to problem-solving, as well as his ability to build strong relationships with customers, and partners. Under La Rosa Betancourt's leadership, Neutron Star Systems has become a key player in unlocking the potential of future space missions, with a reputation for delivering cutting-edge technology solutions.

Ravi Simhambhatla

Chief Digital and Innovation Officer at Avis Budget Group

Ravi Simhambhatla is the Chief Digital and Innovation Officer at Avis Budget Group. He has previously served as the Managing Director and CTO of Customer Experience and Transportation at Google and as the CTO at United Airlines, Aer Lingus, and Tesla Motors. He has a strong background in technology and has held various leadership positions in the industry. Simhambhatla is a well-respected technology executive with a proven track record of leading digital transformations in the transportation industry. He is recognised for his expertise in driving innovation and delivering exceptional customer experiences through technology.

Mark Sudol

Director of Environmental Policy at Aerospace Industries Association (AIA)

Mark Sudol is the Director of Environmental Policy at the Aerospace Industries Association (AIA). With over 20 years of experience in Aerospace, Sudol has established himself as a leading expert in his field. He has played a crucial role in developing policies and leading initiatives that promote sustainability and reduce the environmental impact of the aerospace industry. Sudol's extensive expertise lies in identifying innovative solutions to complex environmental challenges while balancing the needs of the industry and the environment. His deep knowledge of environmental policy and regulations has made him a go-to source for insights and guidance in the aerospace sector.

Tobias Strobl

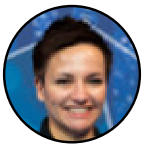
General Partner & Founder of ARIAx Ventures LLP, Professor at Deggendorf Institute of Technology

Tobias Strobl is an entrepreneur, advisor, investor, and professor with a passion for advanced technologies and breakthrough business models. He is the founder of ARIAx Ventures LLP, a venture studio focused on co-creating, developing, and scaling high potential ventures in aerospace & defense, mobility, and life sciences. Tobias is also a professor of international management and venture building at Technische Hochschule Deggendorf (THD) in Germany and an advisor to various space startups and companies.

Luisa Buinhas

Co-Founder & Space Systems Engineer at Vyoma

Luisa Buinhas is an Aerospace Engineer specialising in mission analysis, design, and maneuver optimisation for spacecraft formations. With a PhD from the University of the German Federal Armed Forces and experience in DLR-led mission studies and research internships at MIT, Luisa brings a wealth of knowledge to her role as a Space Systems Engineer at Vyoma GmbH. At Vyoma, she oversees the space program and is responsible for system engineering developments. Luisa's technical skills, innovative thinking, and dedication to advancing the field of space situational awareness and sustainability make her a valuable asset to the company.



Amelie Schoenenwald

Member of the ESA Astronaut Reserve

Amelie Schoenenwald is a member of the ESA astronaut reserve, having been selected in November 2022. She has a diverse background in science, with a doctorate in integrative structural biology, as well as business administration. Her experience includes working as a medical expert manager in the field of rare immunological diseases and as a scientific project lead at the Max Perutz Labs. Her passion for space travel is reflected in her selection as a member of the ESA astronaut reserve.

Bas Lansdorp

Founder & CEO of NEDPAC

Bas Lansdorp is an entrepreneur and visionary in the space industry. He is the founder and CEO of NEDPAC, a Dutch company focused on large scale storage of (renewable) energy. Lansdorp has extensive experience in the aerospace industry and has worked on a variety of projects, including a feasibility study for a human Mars mission. He is also known for his work as the co-founder of Mars One, a non-profit organization that aimed to establish a permanent human settlement on Mars.

Robert Boehme
Founder of Planetary Transportation Systems

Robert Boehme is an accomplished entrepreneur and space enthusiast, best known as the founder of Planetary Transportation Systems (PTS). In working as a team, PTS has become a European aerospace and technology company that provides services in cyber security, electronics, robotics, and software for space. With a passion for exploring new frontiers, Boehme has been involved in several initiatives aimed at advancing space exploration and making it more accessible to a wider audience.

Daniel Bock
CEO & Co-Founder at Morpheus Space

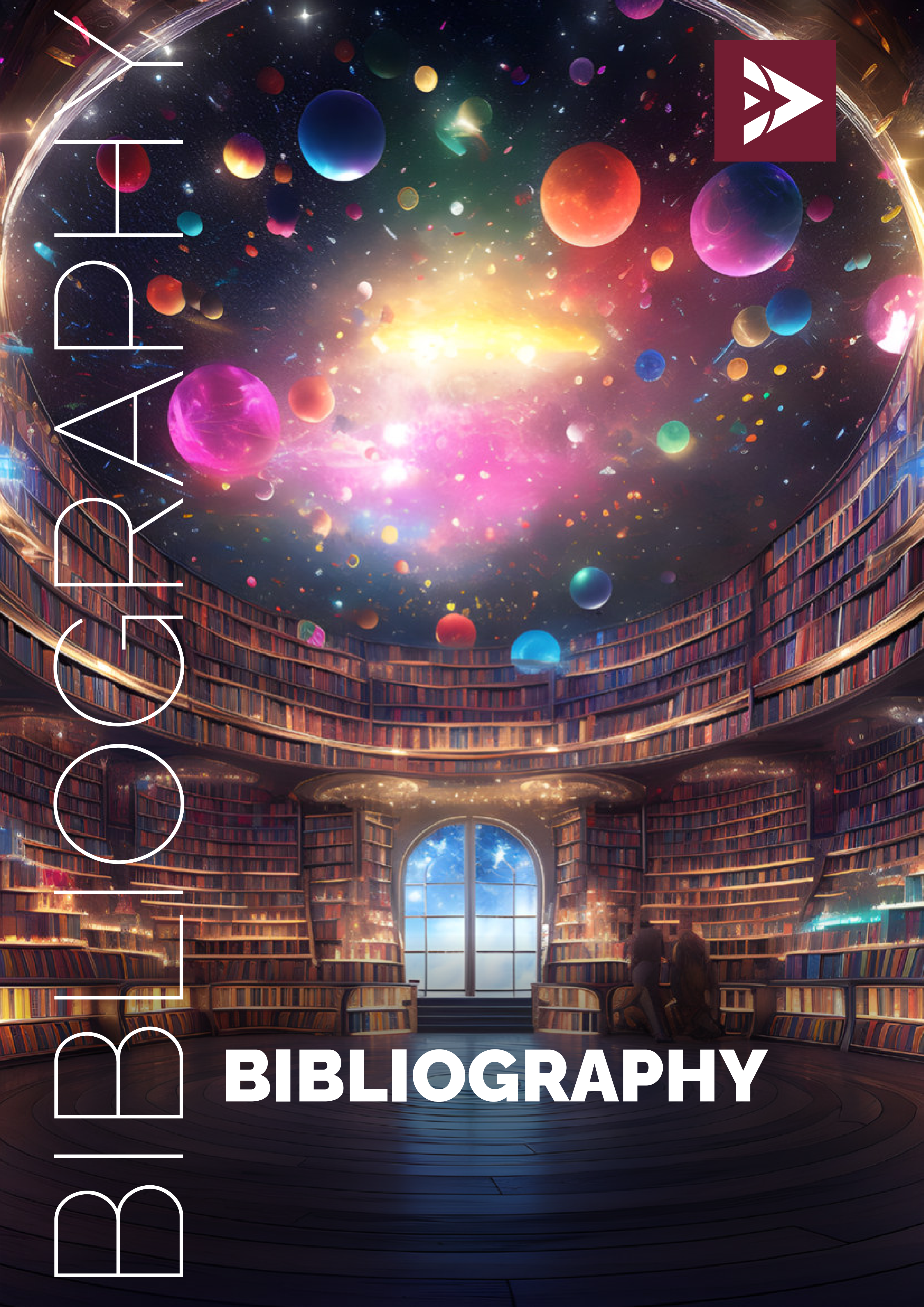
Daniel Bock is the CEO and co-founder of Morpheus Space, a company based in the US and in Germany, that provides mobility solutions for small spacecraft. With a background in Aerospace Engineering from the Dresden University of Technology, Bock has extensive experience in the space industry. Under his leadership, Morpheus Space has grown rapidly, and has established itself as a key player in the emerging market of small satellite propulsion. Bock is a strong advocate for the democratisation of space, and believes that affordable access to space will enable new innovations and benefit humanity as a whole.

Robert Zubrin
President at Pioneer Astronautics

Robert Zubrin is a prominent American aerospace engineer and author who is widely known for his advocacy of the manned exploration of Mars. He is the driving force behind the Mars Direct proposal, which aims to significantly reduce the cost and complexity of a mission to Mars by utilising the planet's resources. Zubrin established the Mars Society in 1998 to promote and advance the goal of a manned mission to Mars, ideally funded by private entities. His expertise in aerospace engineering and passionate advocacy have made him an influential figure in the space industry, inspiring many to support his vision of a human mission to Mars.

Fabia Höhne Tarragona
Operations Manager at OroraTech

Fabia Höhne Tarragona is an Operations Manager at OroraTech, a company specialising in space-based thermal data intelligence. In her role, she oversees the company’s daily operations, manages the development of its satellite technology, and ensures that the company's products and services meet the needs of its customers. With a background in technology and operations management, and experience working in the space industry, Tarragona has a deep understanding of satellite technology and its applications.



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