DISCOVERY & PREPARATION

Space topics in focus: laying the groundwork for ESA's future activities

ESA'S DISCOVERY & PREPARATION TOPICS IN FOCUS

The Discovery & Preparation elements of ESA's Basic Activities lay the groundwork for ESA's future by performing the first R&D steps in potentially game-changing concepts. The elements also work with industry to develop baseline designs for future ESA missions in all research domains and across all ESA directorates. This brochure presents some of these activities, grouped by focus topic.

The activities are typically carried out by European industry and academia; they submit their novel ideas for space research through ESA's Open Space Innovation Platform (OSIP).

By giving ongoing activities visibility via the Activities Platform and publishing the results of past activities via the Nebula Library, new efforts can build upon lessons learned from past and present activities, avoiding repetition, while triggering partnerships and ideas for future activities.

By investing in innovative concepts, undertaking blue-sky research and supporting the development of disruptive technologies with high commercialisation potential, ESA's Discovery element supports the Agenda 2025 goal to double ESA's investment in 'game-changing' technologies, and increase the share of industry-driven technology developments. ESA Discovery therefore stimulates and accelerates the world-class European space sector, and helps prepare European industry for tomorrow's opportunities.

The Discovery & Preparation elements both support ESA's objective of boosting commercialisation for a green and digital Europe, also set out in Agenda 2025. Several dedicated OSIP calls for ideas have led to a large number of concrete activities across a range of topics serving this goal, as well as others specified by the ESA Director General in Agenda 2025. Among them are studies and R&D activities on the creation of green propellants, space debris mitigation, and climate monitoring, as well as the in-orbit servicing of spacecraft. Other activities contribute to advancing the fields of cyber-resilience, safe launches and secure operations.

Discovery & Preparation are ESA's tools to be ready for the next stage of space exploration – to the Moon, Mars, and beyond – as well as to improve life on Earth for future generations.

The collection of articles in this brochure highlights some of the topics investigated via the Discovery & Preparation elements of ESA's Basic Activities. By no means is this list exhaustive, but it provides a good overview on the large variety of topics covered during the last two years.

The content was first published as 'in focus' articles on the ESA website and is subject to regular updates.

An ESA Production
Illustrations: **Sacha Berna**

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ARTIFICIAL INTELLIGENCE IN SPACE

When we think of robots, we tend to personify these non-human aids and give them human-like features. But any machine with inbuilt artificial intelligence can be a robot. They are used in all kinds of situations, especially where they can alleviate strenuous tasks or complete missions that are too dangerous for a human to undertake.

The term 'artificial intelligence (AI)' comprises all techniques that enable computers to mimic intelligence, for example, computers that analyse data or the systems embedded in an autonomous vehicle. In the past, artificially intelligent systems have been taught by humans, but nowadays it is more common for AI to be achieved through machine learning (ML).

Machine learning teaches machines to learn for themselves. It is a way of 'training' a relatively simple algorithm to become more complex. Huge amounts of data are fed into the algorithm, which adjusts and improves itself over time. This type of artificial intelligence has taken major leaps forward since the dawn of the internet.

Deep learning (DL) is a specialised technique within ML, whereby the machine utilises multi-layered artificial neural networks to train itself on complex tasks like image recognition. This can happen via supervised learning (e.g., feed the system Moon and Earth pictures until it can successfully identify both types) or unsupervised learning, where the network finds structure by itself. Good examples of deep learning are online translation services, image libraries and navigation systems for self-driving cars or spacecraft.

AI/ML in space

AI, and in particular ML, still has some way to go before it is used extensively for space applications, but we are already beginning to see it implemented into new technologies. One area in which the applications of AI are being thoroughly investigated is in satellite operations, in particular to support the operation of large satellite constellations, which includes relative positioning, communication, end-of-life management and so on.

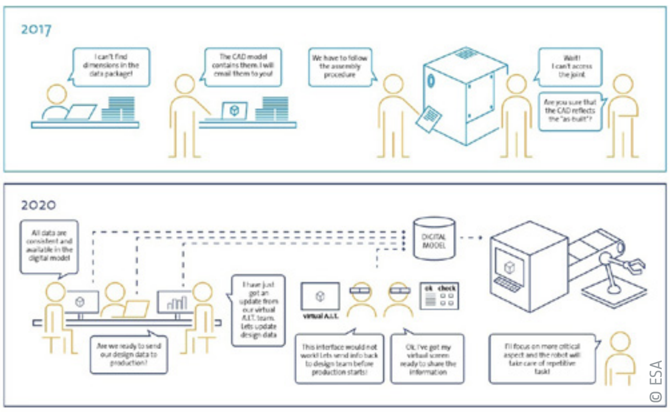
ML systems are also commonly used in space applications to approximate complex representations of the real world.

For instance, when analysing massive amounts of Earth observation data or telemetry data from spacecraft, ML plays an important role.

Potential applications of AI are also being thoroughly investigated in satellite operations, in particular to support the operation of large satellite constellations, including relative positioning, communication and end-of-life management.

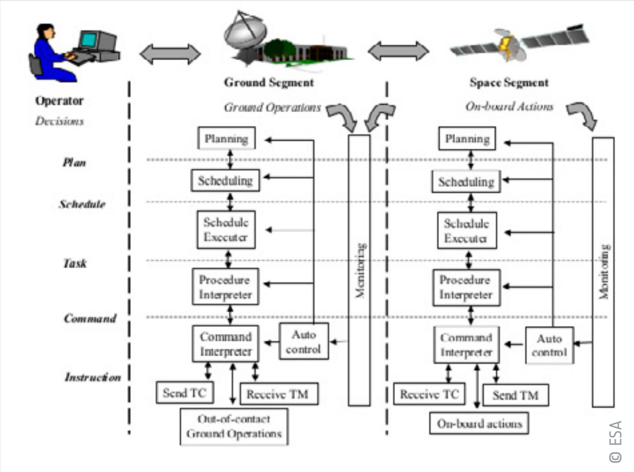
In addition, it is becoming more common to find ML systems analysing the huge amount of data that comes from each space mission. The data from some Mars rovers is being transmitted using AI, and these rovers have even been taught how to navigate by themselves.

Its development has come a long way over the last couple of decades, but the complicated models and structures necessary for ML will need to be improved before it can be extensively useful. AI also currently lacks the reliability and adaptability required in new software; these qualities will need to be improved before it takes over the space industry.



DISCOVERY & PREPARATION ACTIVITIES

Under ESA's Basic Activities a number of studies have looked into using artificial intelligence for space applications and spacecraft operations.



The Discovery element of Basic Activities recently funded a number of studies to develop software, concepts and protocols to push ESA's OPS-SAT mission to its limits. Several of these included artificial intelligence. OPS-SAT spacecraft manager David Evans said that "AI is a broad term for an effectively infinite toolbox, and it was great to see concrete applications using a variety of tools from across the field."

Currently spacecraft need to communicate with Earth to do their job, but developing autonomous spacecraft that use artificial intelligence to take care of themselves would be very useful for exploring new parts of the Solar System and reducing mission costs. An older study on autonomy requirements for future spacecraft constellations identified the necessary technology to improve automation, including autonomous navigation, automated telemetry analysis and software upgradability.

A more recent study focused on the management of complex constellations for which novel automated procedures are being studied to reduce the active workload of ground operators. Automation of both the ground and space segments will reduce the need for human intervention – especially for large constellations, automated collision avoidance manoeuvres could be a real help.

Other studies carried out under ESA's Basic Activities include investigating how a swarm of picosatellites can evolve a collective consciousness, and looking into how artificial intelligence can be used in advanced mission operations and technologies, as well as in innovative security concepts, mechanisms and architectures.

Space technology and space applications produce a huge amount of data, including spacecraft telemetry and product data – the useful scientific data that a spacecraft gathers, for example information about Earth from an Earth observation satellite. Another application of machine Learning is to analyse all this data. One study carried out under ESA's Basic Activities inputted historical mission data into ML algorithms to search for new features useful for future telemetry checking, command verification and procedure writing processes.

▲ Astro drone screenshot

Deep learning systems learn through either unsupervised data feeding or reinforced learning. There are many possible applications of DL, including automatic landing, intelligent decision taking and fully automated systems. ESA's Advanced Concepts Team (ACT) is very active in this area.

In particular the ACT has studied evolutionary computation, which involves writing computer code in such a way that all evolutions are considered. The better results are kept, and the worse are rejected – just like in biological evolution. One application of this has been to calculate the trajectories of the planets.

The ACT has also investigated using ML in the area of guidance, navigation and control. In particular, they looked into using big swarms of small robots that share their information in a network: if one robot learns from experience that a certain manoeuvre is beneficial, the whole swarm learns this. This is called hive learning.

Other examples of AI activities that the ACT has supported include investigating a community science mobile phone app that will improve the autonomous capabilities of space probes and optimising star tracking systems.

ESA-wide applications of AI/ML

Going from these basic activities to real space applications may seem like a big step but ESA is already starting to use AI and ML in its space missions. For example, rovers can navigate around obstacles by autonomously finding their way across 'unknown' fields. Artificial intelligence is also aiding astronauts on board the International Space Station, more details of which can be found in the next section of this article.

ESA's Hera planetary defence mission will make use of AI as it steers itself through space towards an asteroid, taking a similar approach to self-driving cars. Whilst most deep-space missions have a definitive driver back on Earth, Hera will fuse data from different sensors to build up a model of its surroundings and make decisions on board, all autonomously.

Meanwhile on Mars, intelligent data transmission software on board rovers removes human scheduling errors which can otherwise cause valuable data to be lost. This increases the useful data that comes from our planetary neighbour. The same technology could also be used in long-term missions that will explore the Solar System, meaning that they will require minimal oversight from human controllers on Earth.

Satellites orbiting Earth also require more autonomy, as they need to make more frequent collision avoidance manoeuvres to evade increasing amounts of space debris. In January 2021, ESA and the German Research Center for Artificial Intelligence (DFKI) established ESA_Lab@DFKI, a technology transfer lab that works on AI systems for satellite autonomy, collision avoidance capabilities and more.

Furthermore, ESA has gained ample experience using AI to plough through enormous amounts of data to extract meaningful information. This technique has already been implemented in more 'Earthly' applications, including monitoring the number of cars at a shopping centre, predicting retailers' financial performances, monitoring climate change and supporting police forces in their efforts to catch perpetrators.

Earth observation is one area that AI is already being used more extensively. ESA is currently working towards a Digital Twin of Earth, a replica constantly fed with Earth observation data and artificial intelligence to help visualise and forecast natural and human activity on the planet. Furthermore, ESA's 'Rapid Action Earth observation' dashboard is showing how AI can be used to monitor economic indicators – for example, the combination of commercial satellite data and AI has been used to monitor production changes at a car manufacturer in Germany and plane traffic at Barcelona airport. And FSSCat – launched in September 2020 – is the first European Earth observation mission to carry AI on board, in the form of the ϕ-sat-1 AI chip. ϕ-sat-1 is improving the efficiency of sending vast quantities of data back to Earth.

A major challenge for the shipping sector is the safe and efficient autonomous navigation of the seas. An ESA-led project is already applying AI to achieve autonomous situational awareness, enabling a ship to reliably sense its own environment. These AI systems would initially be deployed to support human crews, with crewless ships a longer-term goal.

What are other space agencies doing in this area?

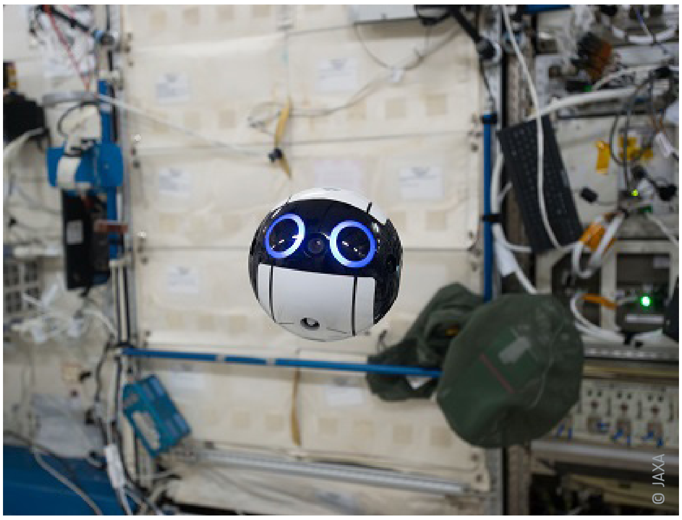
▲ DLR's CIMON

The German Aerospace Center (DLR) has been developing AI methods for space and Earth applications for many years and in 2021 set up an Institute of Artificial Intelligence Security. In 2018 DLR launched an AI assistant to support its astronauts in their daily tasks onboard the International Space Station (ISS). Fully voice-controlled CIMON (Crew Interactive MObile companioN) is able to see, speak, hear, understand and even fly! CIMON returned after 14 months, but CIMON-2 arrived in December 2019 to replace it. CIMON-2 is scheduled to stay on the ISS for three years.

NASA is also using AI for many applications, and has set up an Artificial Intelligence Group that performs basic research that supports scientific analysis, spacecraft operations, mission analysis, deep space network operations and space transportation systems. The Agency investigated making communication networks more efficient and reliable using cognitive radio, which picks out the 'white noise' areas in communication bands and uses them to transmit data; this maximises the use of the limited telecommunication bands available and minimises delay times. It also recently applied AI to calibrate images of the Sun, improving the data that scientists use for solar research. For deep-space exploration NASA has also looked into designing more autonomous spacecraft and landers, so that decisions can be taken on-site, removing the delay resulting from communication relay times.

NASA has also cooperated with Google to train its extensive AI algorithms to effectively sift through the data from the Kepler mission to look for signals from an exoplanet crossing in front of its parent star. This successful collaboration quickly led to the discovery of two new exoplanets previously missed by human scientists. After its initial success the project is ploughing through data from other missions to continue its search for new planets.

Using the wealth of ESA and NASA data from all over our Solar System, the AIDA (Artificial Intelligence Data Analysis) project, funded under the European Horizons 2020 Framework, is developing an intelligent system that will read and process data from space, aiming to bring about new discoveries, reveal anomalies and recognise structures.



▲ JAXA Int-Ball

The Japanese Space Agency (JAXA) also developed an intelligent system that took pictures of experiments in the ISS Japanese module, KIBO. JAXA's Int-Ball operated autonomously and could take pictures and videos. It was developed to promote the autonomy of extra- and intra-vehicular experiments, while seeking to acquire the robotics technology necessary for future exploration missions.

Meanwhile, French space agency CNES is working with French company Clemessy to develop a fluidic systems simulator using AI neural networks, the UK Space Agency has funded a project that uses AI to detect buried archaeological remains in satellite imagery, and the Italian Space Agency even co-founded an AI-focused company.

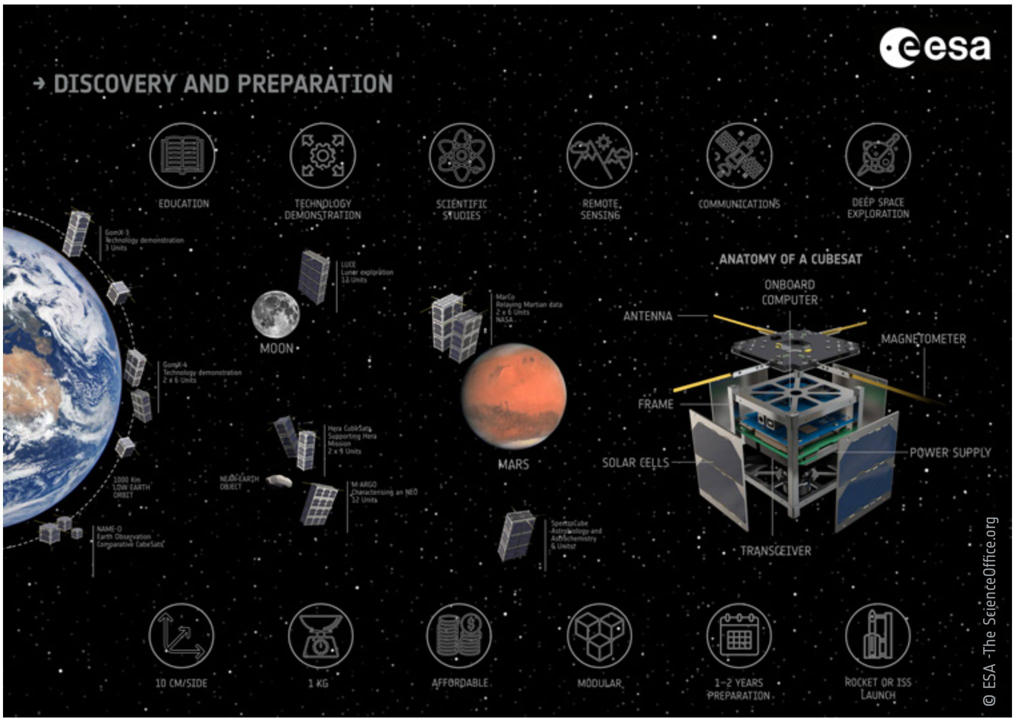
CUBESATS

We tend to think of satellites as huge spacecraft that tower over the engineers who build them. Consider Envisat, SOHO and GOCE – all ESA satellites similar in size to a small bus. But over the last twenty years, miniature satellites called CubeSats have been shaking up the space industry, making accessing space easier and cheaper for those who could previously only dream of it.

CubeSats are typically built up from standard cubic units each measuring 10 cm x 10 cm x 10 cm – just a bit bigger than a Rubik's cube ! The number of units depends on the CubeSat's mission, but tends to be between 2 and 12, resulting in a mass of just 1–10 kg. These little satellites have a fraction of the mass, and cost, of more traditional satellites.

Having initially been developed as educational tools, CubeSats are increasingly being put to active use in orbit for technology demonstration, scientific studies, and even commercial purposes. And just like typical satellites, they are custom built to fulfil the specific requirements of their mission.

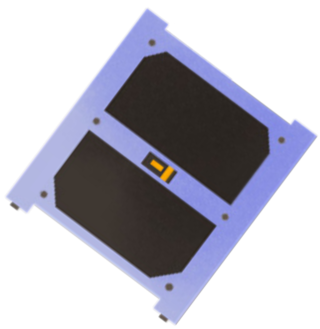
ESA's CubeSats as of October 2018 ▶



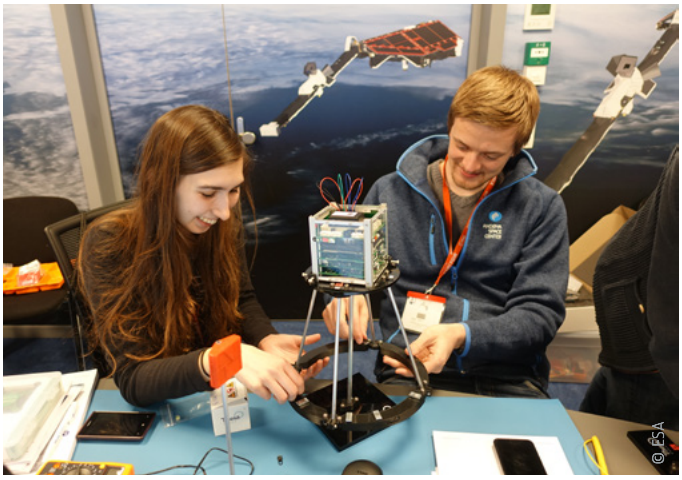
CubeSats tend to hitch a ride into space using extra space available on rockets, meaning lots of launch opportunities and low launch costs. They are packed in a container which, at the push of a button, ejects them into space via a spring system. A similar technique is used to deploy CubeSats from the International Space Station (ISS), where they are launched out of the Japanese module, Kibo.

These small satellites provide affordable access to space for small companies, research institutes and universities. Their modular design means that subsystems are available off-the-shelf from different suppliers and can be stacked together according to the needs of the mission. This allows CubeSat projects to be readied for flight extremely quickly – typically within one or two years.

CubeSats are now commonly used in low Earth orbit for applications such as remote sensing and communications. But as engineers become more familiar with the technology, CubeSats are beginning to venture farther afield. Whether it's to the Moon, Mars, or even further, these tiny spacecraft are certainly changing the game when it comes to space exploration.



Why is ESA interested in CubeSats?



ESA began giving university students the chance to develop their own space mission when it kicked off its CubeSat education programme – *Fly your Satellite!* – in 2013. Many *Fly your Satellite!* alumni have gone on to create their own companies which now form the basis of the CubeSat industry! CubeSat's have clearly proven their worth as educational tools, but ESA is also using CubeSats for professional space missions.

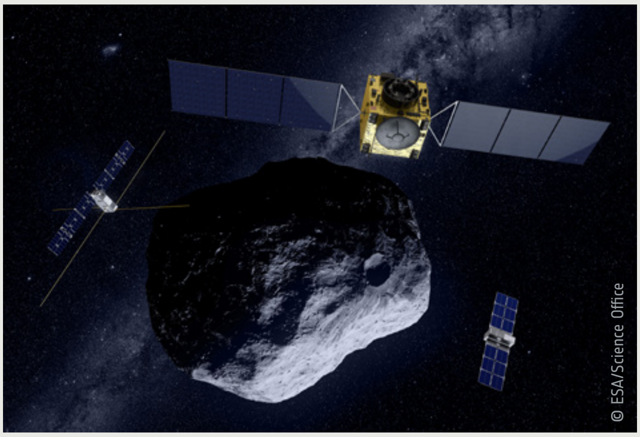
Not only do CubeSats provide an affordable means of demonstrating exciting new technologies, they also drive the drastic miniaturisation of systems and encourage a new approach to spacecraft integration. They can obtain simultaneous in-situ observations of their surroundings and give us an affordable way to deploy small payloads. But perhaps most exciting in terms of science, CubeSats bring versatility to space exploration that could help us find out lots more about the Solar System.

DISCOVERY & PREPARATION ACTIVITIES

Under ESA's Discovery & Preparation activities many CubeSat-focused studies have been funded and 'technology challenges' are regularly opened to get the most brilliant proposals for new space technology.

· Hera mission

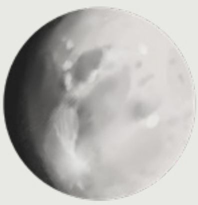
Due to be launched in 2024, Hera is ESA's contribution to the international Asteroid Impact and Assessment (AIDA) collaboration. NASA's DART impactor will hit the moon of a binary asteroid system called Didymos, and Hera will watch the aftermath to study this type of asteroid deflection. Hera has three objectives: to demonstrate technology in interplanetary space, to investigate Near-Earth Object mitigation techniques, and to gain new insight into the evolution of the Solar System. Hera will be accompanied by two six-unit CubeSat explorers, giving European scientists their first chance to operate CubeSats in deep space.



▲ Hera and CubeSats

· LUnar CubeSats for Exploration (LUCE)

To support ESA's lunar exploration objectives, in 2017, ESA challenged European teams to design a CubeSat mission to the Moon. Two winners were selected – one to map meteoroid bombardments and the other to search for water ice and other volatiles at the lunar south pole. The winners worked with specialists via ESA's Concurrent Design Facility (CDF) to develop their mission concepts further. The CubeSats would piggy-back on a lunar transfer vehicle before being released into orbit around the Moon.



▲ Example of a LUCE CubeSat

· SpectroCube:
ESA plans to soon launch SpectroCube, a mission that will travel far from Earth to carry out astrobiology and astrochemistry experiments. The key science objectives of SpectroCube are to assess the impact of space on the biology and chemistry of the building blocks of life.

· M-ARGO
Through the Fly element of the General Support Technology Programme, ESA is developing the Miniaturised Asteroid Remote Geophysical Observer (M-ARGO), a stand-alone deep space CubeSat to meet and characterise a near-Earth object. The concept of M-ARGO was first explored in ESA's CDF via a Discovery & Preparation study. Planned for launch in 2024/5, the mission will test the potential of using miniaturised technologies to lower the entry-level cost of space exploration.

· NAME-O
In 2014, ESA welcomed teams of scientists to design a project that would use cooperative nanosatellites for Earth observation. This resulted in NAnosatellite Multiple channel Earth Observation (NAME-O) — a mission designed to carry out remote sensing using five cooperative nanosatellites.

Discovery & Preparation has supported many studies that have explored new CubeSat technologies, including investigating an anchoring device for CubeSat landers**, looking into the feasibility of a** multi-purpose satellite onboard the International Space Station**, analysing the** impact of spacecraft tracking on the operation and design of small satellites**, and investigating how** increasing number of nano- and micro-satellites will affect impact risk in Low Earth Orbit**.**

ESA-wide use of CubeSats

Over the past ten years, ESA has been putting more time and effort into its CubeSat activities. Roger Walker, head of ESA's CubeSat efforts, explains that "ESA is harnessing CubeSats as a fast, cheap method of testing promising European technologies in orbit".

ESA's first CubeSat project was GomX-3, a mission to demonstrate various signal monitoring technologies, which was deployed from the ISS in October 2015. Consisting of twin CubeSats, GomX-3's successor GomX-4 is monitoring Arctic territory and testing radio links in space across distances of up to 4500 km. One of the twins can also adjust its orbit using cold-gas thrusters, opening up the prospect of rapidly deploying future constellations, maintaining their separations, and flying them in formations to perform new types of measurements from space. GomX-5 is scheduled for launch in 2022 and will demonstrate next-generation constellation related technologies, including electric propulsion and high-speed intersatellite links.

▲ GomX-4 pair

ESA's Directorate of Telecommunications and Integrated Applications launched two CubeSats in 2019 under their Pioneer programme. The CubeSats are trialling novel telecommunications technologies and will be important for the next phase of Earth observation applications. Also in 2019, ESA's Directorate of Operations launched OPS-SAT – an in-orbit testbed for innovative mission control software; in 2021 ESA Discovery funded a number of projects to develop software, concepts and protocols to push OPS-SAT to its limits.

ESA's Directorate of Earth Observation is currently operating FSSCat, a double CubeSat mission for tandem observation of Earth's polar regions. Meanwhile, the Directorate of Human and Robotic Exploration is considering a CubeSat mission to test out a key capability for Mars Sample Return while the Science Directorate is also adapting some CubeSat technologies for operation in deep space as well as studying the potential use of CubeSats in support of planetary science missions. Other ongoing and planned ESA-funded CubeSat missions include:

· RACE – ESA's Rendezvous Autonomous CubeSats Experiment will test out autonomous rendezvous and docking capabilities for CubeSats.

· QARMAN – launched from the International Space Station (ISS) in spring 2020, QARMAN is demonstrating re-entry technologies, particularly novel heatshield materials, a new passive aerodynamic drag stabilisation system, and the transmission of telemetry data during re-entry via data relay satellites in low-Earth orbit.

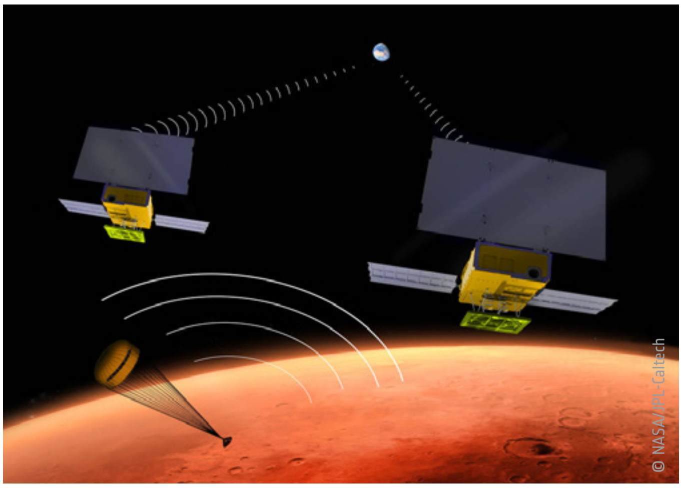
· SIMBA – launched in September 2020, SIMBA is measuring the power of the Sun and the balance between incoming energy from the sun and the outgoing energy from Earth.

- **PICASSO** – sent to space in the same launch as SIMBA, PICASSO is measuring ozone distribution in the stratosphere, the temperature profile of the mesosphere, and electron density in the ionosphere.

- **RadCube** – launched in 2021, RadCube is demonstrating miniaturised instrument technologies that monitor space weather.

- **PRETTY** – PRETTY will demonstrate a novel technique used primarily to detect sea ice, and test a miniaturised radiation dosimeter. It is due to launch later in 2022.

What are other space agencies doing in this area?

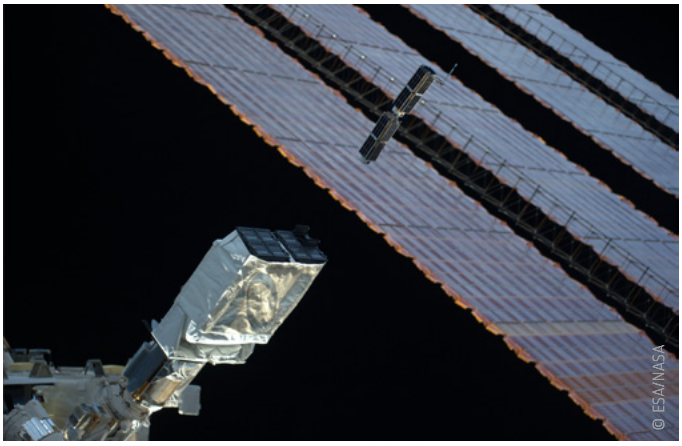


▲ MarCO CubeSats

NASA runs the extensive Small Spacecraft Technology Program as well as the CubeSat Launch Initiative. Previously selected CubeSats have studied near-Earth objects, space weather, Earth's atmosphere and much more.

In 2018, NASA launched its first pair of CubeSats designed for deep space – Mars Cube One, or MarCO. Both satellites hitched a ride alongside InSight, NASA's latest Mars lander. The MarCO CubeSats followed InSight on its cruise through space; each relayed data back to Earth as the lander entered the Martian atmosphere.

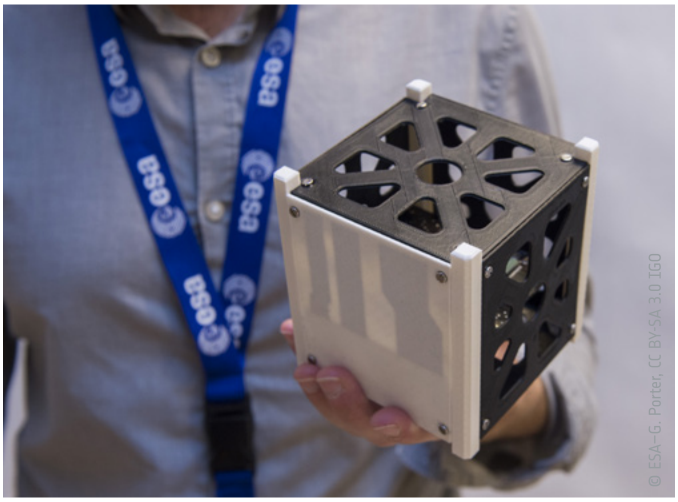
Another NASA CubeSat mission, GTOSat, will observe the forbidding radiation belts that circle Earth, and in 2021 the Agency plans to launch a CubeSat mission to the Moon which will be a pathfinder for the Lunar Gateway. 2022 will be a busy year for NASA – the Agency also plans to launch its innovative mission NEA Scout, which will be the first to use a solar sail for propulsion. When deployed, the sail – square in shape with each side about the length of a school bus – will use solar energy to propel itself through space. This year NASA also plans to launch a constellation of six CubeSats to study tropical weather.



▲ CubeSats launched from ISS

Currently, CubeSats are deployed from the ISS via the Japanese module, Kibo. The Japanese Space Agency has collaborated with the United Nations Office for Outer Space Affairs (UNOOSA) to set up KiboCUBE, a project that offers developing countries the opportunity to deploy their own CubeSats from the ISS. The Canadian Space Agency runs the Canadian CubeSat Project which aims to engage students in real space missions, and in 2016 the Russian space agency developed the world's first CubeSat to be produced entirely with a 3D printer, resulting in a stronger, lighter structure.

A 'PEEK' into the future



▲ Electrical lines in CubeSat body

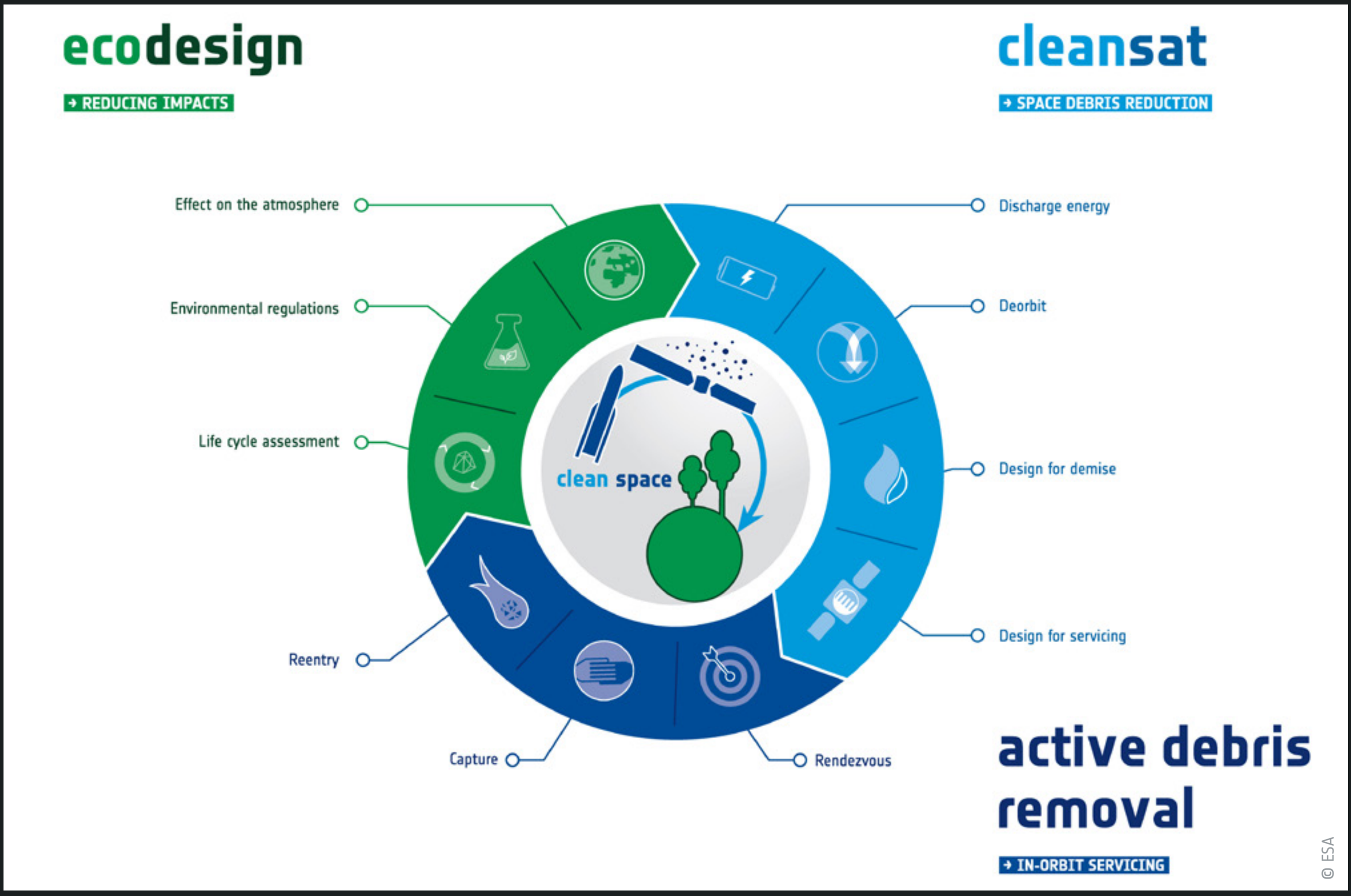
As a first test of a new printable, hard and electrically conductive plastic called PEEK, in 2017 ESA started 3D-printing CubeSat structures incorporating their own electrical lines. In 2020, PEEK was used to transmit a portrait of the Mona Lisa, marking the first step towards a future when plastic printed parts can incorporate their own power and data links within their built structures, instead of relying on separate wiring and circuits. In future, such miniature satellites could be ready to go once their instruments, circuit boards and solar panels are slotted in.

CLEAN AND ECO-FRIENDLY SPACE

As a forward-thinking space agency, ESA is pioneering an eco-friendly approach to space exploration. With the amount of space debris on the rise, and the negative effects of industrial materials, processes and technologies on the environment, it is becoming vital that ESA not only reduces the impact of its own activities, but also sets an example to other agencies.

ESA's Clean Space initiative was set up in 2012 to consider the environmental impact of the entire life cycle of space missions. Clean Space's activities fall into three main areas:

- EcoDesign: addressing environmental impacts and fostering green technologies
- Space Debris Mitigation: minimising the production of space debris
- In-orbit servicing/Active Debris Removal: removing spacecraft from orbit and demonstrating in-orbit servicing of spacecraft



But achieving eco-friendly space exploration requires innovative technologies to be created. As ESA's supporters of novel research, the Discovery & Preparation programme has funded numerous studies that contribute to Clean Space's three main focus areas.

Understanding and reducing the environmental impact of space missions

To scrutinise the environmental impact of each space project, it is important to assess emissions, resources consumed, and the pressures put on human and environmental health over a mission's life cycle.

One of the first steps to achieving this was a Discovery & Preparation study that applied an eco-design methodology to space activities. The methodology investigates the environmental impact of space missions and following this activity, ESA wrote a set of space system life cycle assessment guidelines. A later parallel study, aptly named GreenSat ([1] and [2]), looked into eco-designing a satellite from beginning to end with a maximum reduction of its environmental impact. This is surprisingly difficult, because sometimes minimising environmental impacts at one stage of the life cycle can lead to larger impacts elsewhere.

Several Discovery & Preparation studies have explored the influence of more specific parts of a space mission on the environment. One study investigated the impact of the launch, an especially emission-heavy part of a space mission, which affects all parts of the atmosphere. Spacecraft propellant can also often be dangerous, both because it is often a harmful chemical and because it can cause explosions in space, creating a lot of debris. Another study investigated the benefits of self-pressurised green propellant technology.

▲ An Ariane 5 launch

These studies are important for understanding how to design missions to be as environmentally friendly as possible, and for ensuring that decision makers consider environmental impacts when deciding whether to proceed with a space project.

Minimising the production of future debris

Scientific models estimate that as of September 2021 there are over one million objects larger than a marble in orbit around Earth, and 330 million objects larger than one millimetre (latest figures).

The vast majority of these objects are no longer operational but can be very dangerous; objects orbit Earth so quickly that something measuring just one centimetre wide can expend the energy of an exploding hand grenade upon impact with a satellite. One Discovery & Preparation study simulated satellite collisions to better forecast the future of space debris. Another explored how a spacecraft could detect and track pieces of debris in orbit, and then fire a laser at individual pieces to move them out of the spacecraft's way.

▲ Space debris around Earth

Just like cars drive along designated roads, satellites move along fixed orbits, the most popular of which are geostationary (~36 000 km altitude) and low-Earth (<1000 km altitude). One study modelled the break-up of large satellites and rockets moving along these two space highways to investigate how the overall levels of debris would be affected. They showed that the break-up of large satellites will be the driving factor in the future space environment. Other studies investigated disposal strategies for specific satellites in set orbits, for example satellites in medium-Earth orbit and satellites situated at stable Lagrange points or in highly-elliptical orbits.

But one of the more challenging factors in the realm of space debris is mega-constellations consisting of hundreds to thousands of spacecraft, which are becoming a useful and popular solution for global telecommunications coverage. These offer low-latency, high bandwidth global telecommunications coverage, but the resulting growth in satellite numbers might lead to a corresponding growth in space debris. The MEGACO study sought to understand the complexity of mega-constellations, with a focus on collision avoidance and dealing with satellites that have reached the end of their lives.

▲ Space debris around Earth

One study looked into space debris risks related specifically to propulsion systems and another even explored how a spacecraft could deorbit itself if it fails and becomes uncontrollable. Studies seeking to understand how de-orbiting a spacecraft would impact the amount of space debris, included predicting the likelihood of survival of different objects that travel through Earth's atmosphere.

Removing defunct satellites from orbit

Even if all space launches stopped, the amount of debris would continue to rise because of collisions, which lead to more collisions, and so on. But what if there was a way for us to actively remove space debris?

Clean Space is working on exactly this via its Active Debris Removal/In-Orbit Servicing (ADRIOS) project, which aims to establish a new market for in-orbit servicing of spacecraft, as well as debris removal.

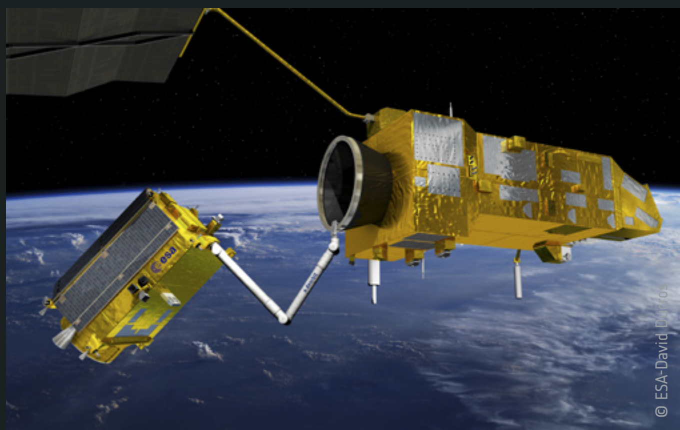
The latest development in the area of active debris removal is ClearSpace-1 – the first space mission to remove an item of debris from orbit. Due to be launched in 2025, ClearSpace-1 will use four robotic arms to capture the Vespa upper stage left in orbit after a flight of ESA's Vega launcher back in 2013. Discovery & Preparation recently supported a study to plan the ClearSpace-1 mission, which will be led by Swiss start-up, ClearSpace.

▲ ClearSpace-1

One initiator of this project was a Discovery & Preparation study carried out in 2013 that looked into how a debris-removal mission could be developed. The study found that the success of such a mission would require substantial progress across multiple technology domains, such as capture mechanisms, guidance and navigation, image recognition and onboard processing. So since then, Discovery & Preparation has supported a large number of new studies to make progress in these areas.

A particularly strong focus has been on finding the best way of capturing a large spacecraft, especially using a net or robotic arm.

One study found that including extra satellites with robotic arms within a mega-constellation would be particularly effective at removing a lot of debris. The same study explored the option of launching a chaser satellite with a net to capture failed spacecraft. Another mega-constellations study looked into how to reduce the number of failures and how to dispose of satellites once they reach the end of their lives.



▲ Capturing a piece of space debris

The DETUMBLING study investigated using a robotic arm to deorbit a spacecraft and COBRa researched how a functioning spacecraft could be used to push a derelict satellite into a lower orbit. The functioning spacecraft would fire its thrusters in the direction of the dead satellite, forcing it to change direction and deorbit. Another study assessed the behaviour of elastic tethers that could potentially be used to deorbit satellites.

To enable active debris removal, distance and orientation estimates of spacecraft should be improved. In 2019 ESA's Advanced Concepts Team ran a competition to use artificial intelligence to do just this.

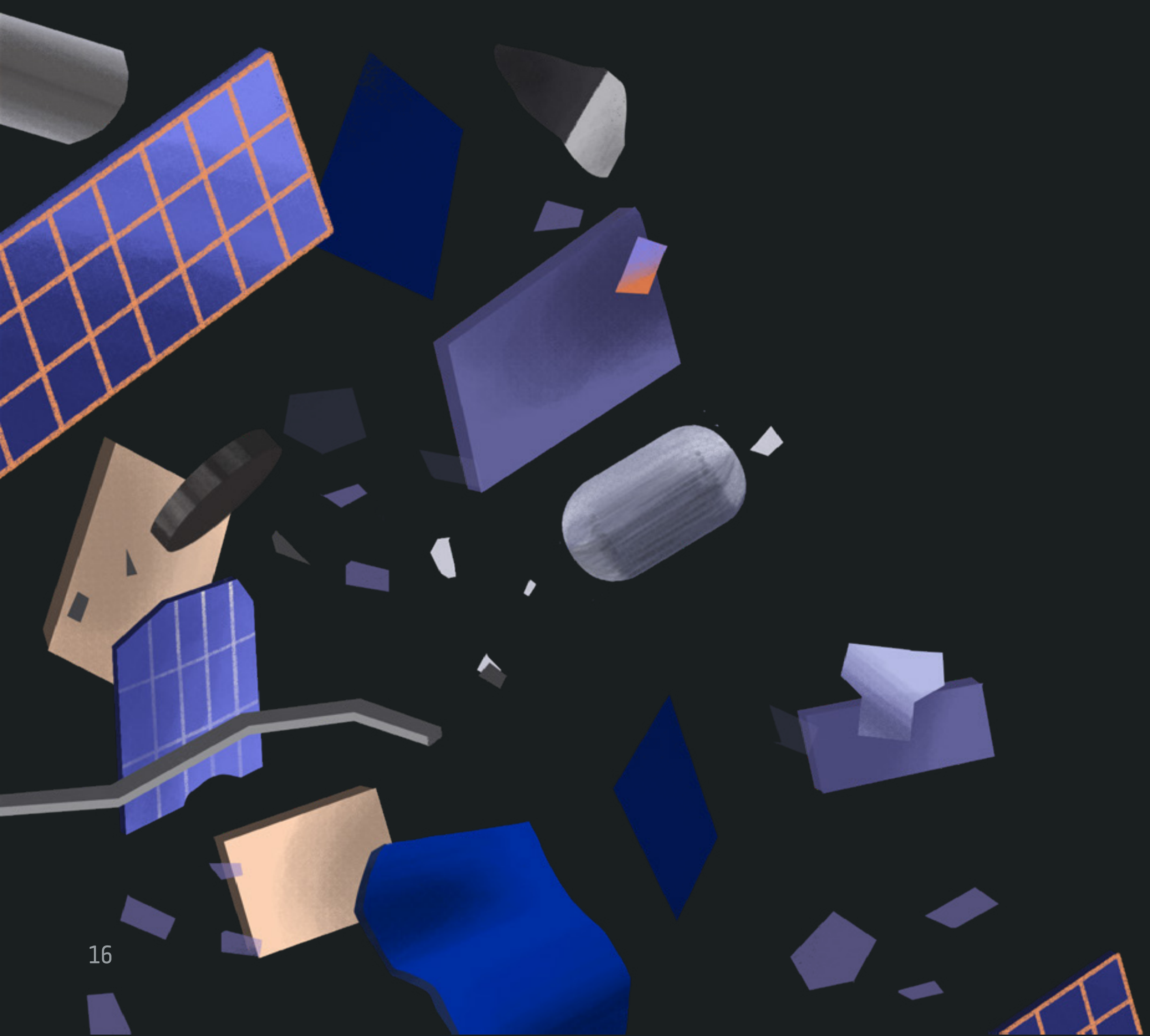
What's next?

To develop Europe's in-orbit servicing capabilities, in April 2021 ESA launched a call for ideas for in-space activities such as refuelling, refurbishment, assembly, manufacturing and recycling to prepare the next mission proposals.

A number of ongoing studies are looking into how to ensure a clean space environment, including one that is seeking to characterise the cloud of debris produced as a result of a collision and one looking at the impact of spacecraft demise on the atmosphere.

Other studies on power and thermal control subsystems, manufacturing processes and ground testing are planned for the future.

In the more distant future, ESA will explore how to design satellites to be recycled, as well as extending the lifetime of missions by repairing them in space. This will keep space sustainable and accessible for the future.

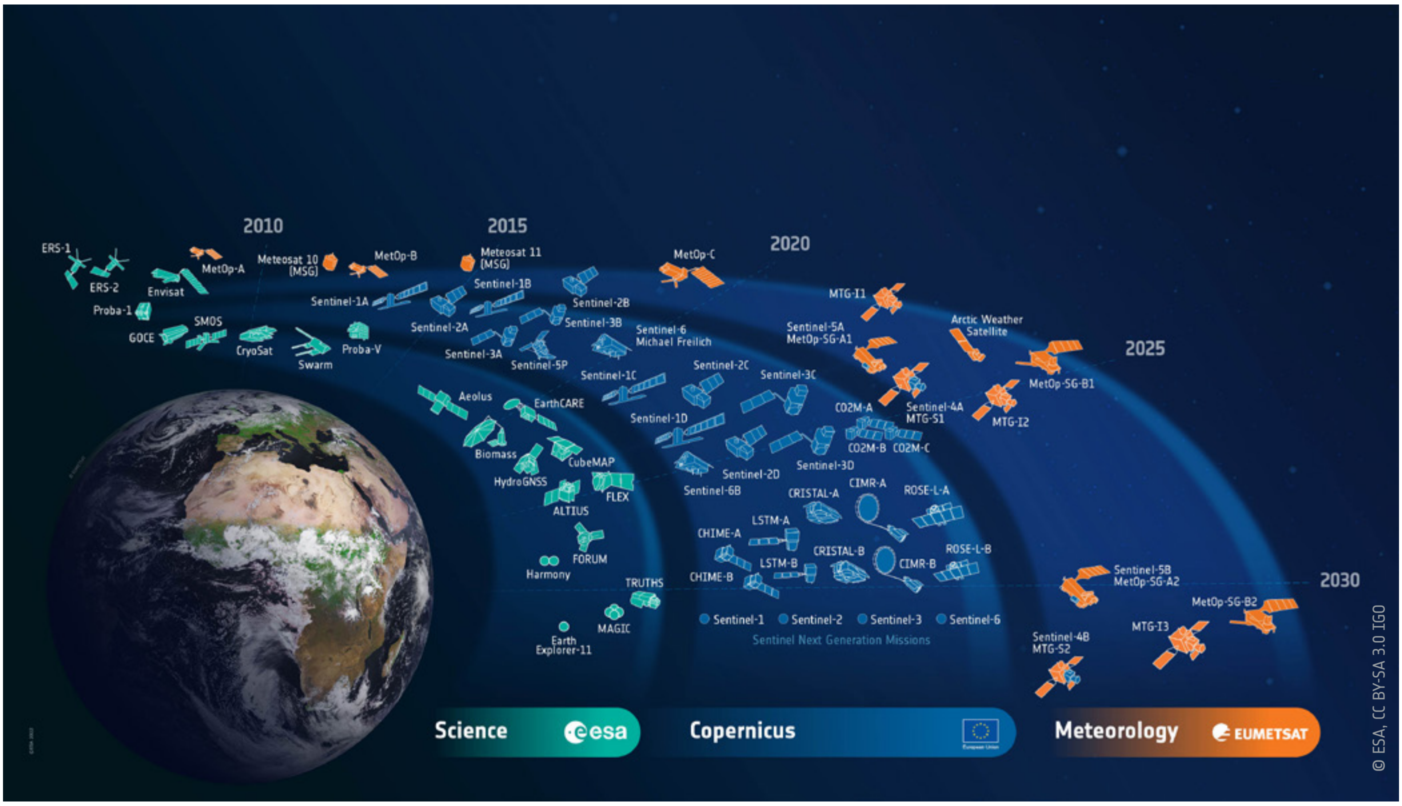


EARTH'S CLIMATE AND ATMOSPHERE

The atmosphere is a complicated yet essential element of our habitat in space, and contains many different chemicals that may be good or bad depending on their location and quantities. Using satellites to scan Earth's atmosphere reveals a plethora of information that is difficult or impossible to see from the ground. From their vantage point high above us, satellites can collect data on the different chemicals to better understand and manage the environment.

Earth observation satellites see the world through a wide enough frame to observe large-scale phenomena. By continuously watching over Earth, they can highlight long-term changes in the composition of the atmosphere, for example to monitor the depletion of the ozone layer due to atmospheric pollution or changing levels of specific greenhouse gases. This can also help us understand more about climate change, and what we can do to reduce it.

Through its [set of Earth observation satellites](), ESA is dedicated to observing Earth from space and supports scientists and policy makers in Europe and worldwide by providing high quality data.



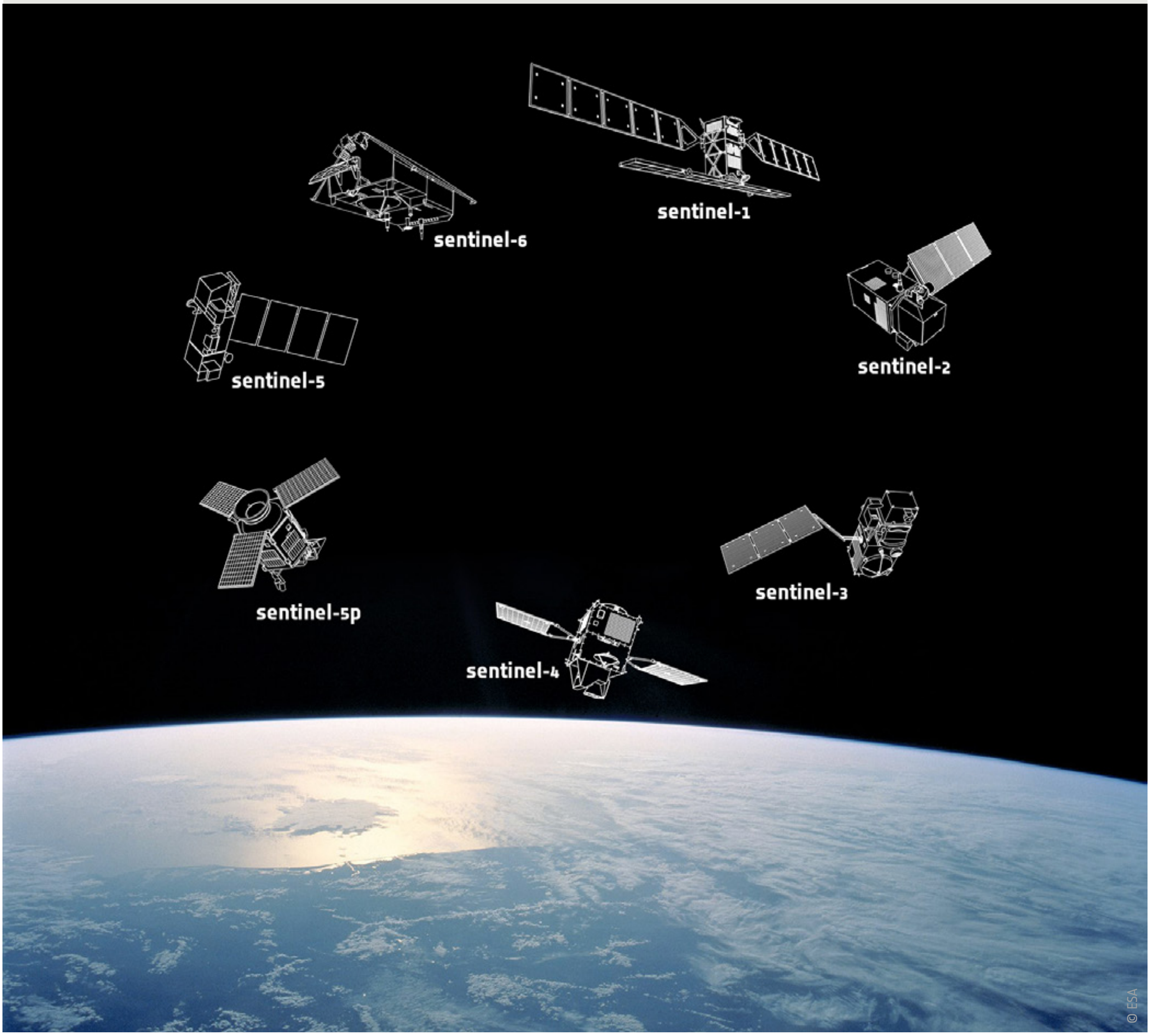
▲ ESA-developed Earth observation missions launched since 2010. Copernicus Sentinel-4, -5P and -5 focus almost entirely on the atmosphere, but many of the meteorology missions also carry sensors that measure the components of the air surrounding planet Earth.

DISCOVERY & PREPARATION ACTIVITIES

ESA is committed to developing cutting-edge technology to further understand our planet, improve our daily lives, support effective policy making and benefit businesses and the economy. Many steps forward in the development of such technology have been made possible by exploratory research into new concepts carried out by ESA's Discovery & Preparation activities.

Discovery & Preparation has contributed to ESA's development of a new set of satellites for the EU's Copernicus programme. Some of these satellites are already collecting and delivering information the programme needs to discover more about our planet, with more satellites still to be launched over the next few years. Monitoring atmospheric composition is a huge part of the programme, especially for the Copernicus Sentinel-4, -5 and -5P missions.

Discovery & Preparation has supported studies that have been instrumental in enabling the Copernicus Sentinels to collect the most beneficial data about the atmosphere and for this information to be used effectively. A study carried out in 2009, for example, presented mission concepts and observation techniques that could monitor the chemistry of the atmosphere, with the key aim of defining the roles of the Copernicus Sentinel-4 and -5 satellites in monitoring air quality and climate protocol. Another study explored how atmospheric pollution can be quantified when scientists use data from Copernicus Sentinel-4 to monitor air quality across Europe and North Africa.

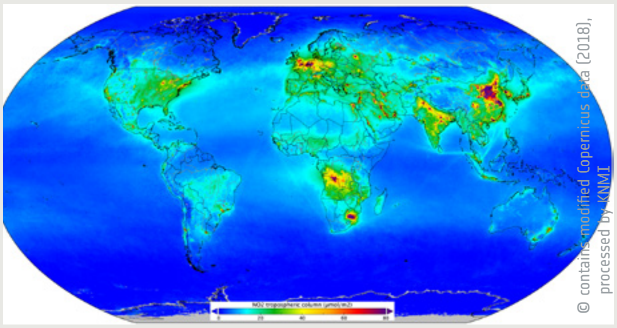


▲ The Sentinel family

Copernicus' Sentinel-5 will keep an eye on air quality, as well as monitoring ozone, ultraviolet radiation and the absorption and radiation of energy by gases in the atmosphere. One early Discovery & Preparation study explored how satellite observations could contribute to working out exactly how much air pollution is human-made to support monitoring of the Kyoto Protocol. Another study specifically investigated how to ensure that instruments measure two of the most potent greenhouse gases – carbon dioxide and methane – as effectively as possible close to Earth's surface. Most recently, through an ESA Discovery study French company SPASCIA improved the ability of satellites such as Sentinel-5 to monitor methane sources and sinks, by identifying and reducing errors in satellite-based thermal infrared measurements of the potent greenhouse gas.

The outcomes of a study that looked into the impact of observations made from a low-Earth orbit on analysing and forecasting the composition of the troposphere are already supporting Copernicus Sentinel-5P, which was launched in 2018, and will support Copernicus Sentinel-5 when it is launched in the mid-2020s.

The Copernicus Sentinels and other satellites that monitor the atmosphere will all benefit from a study that explored how measurements of atmospheric composition from different missions can be combined. This helps scientists to see how global atmospheric composition changes over long timescales.



▲ Worldwide nitrogen dioxide mapped using measurements gathered by Copernicus Sentinel-5P

Whilst the Copernicus Sentinel-1, -2, and -3 missions each consist of two dedicated satellites, Copernicus Sentinel-4 and -5 will be payloads onboard a Meteosat Third Generation and MetOp Second Generation satellite respectively. The Meteosat and MetOp programmes provide weather data to monitor the climate and improve weather forecasts. Discovery & Preparation has contributed to these programmes, for example, through a study completed in 2019 that investigated whether a MetOp satellite could be supported by a radar or lidar instrument to provide even more accurate weather forecasts.

In 2013, Discovery & Preparation launched a SysNova campaign for ideas for missions that would improve our ability to monitor the chemical make-up of the atmosphere. The call was answered by Thales Alenia Space and the University of Leicester, who planned a constellation of nanosatellites that could regularly and accurately measure the amount of harmful nitrogen dioxide close to Earth's surface.

▲ Aeolus: ESA's wind mission

August 2018 saw the launch of ESA's Aeolus satellite, the first mission to monitor the movement of the wind on a global scale to improve the accuracy of weather and climate predictions. Many Discovery & Preparation studies have supported Aeolus, including one that investigated how a mission could study the mesosphere – the 'gateway' between Earth's environment and space – using a lidar instrument. Another established a long-term database of aerosol and cloud lidar measurements to support continuous and harmonised observations over the next decades, and one assessed the operational value of space-borne radar and lidar measurements of clouds and aerosol particles.

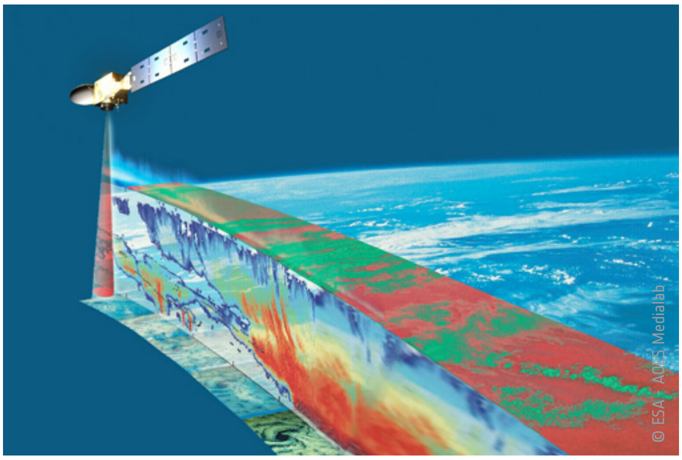
The most recent Aeolus-related study was completed in April 2019, and looked into how Aeolus data could be combined with data from ESA's future EarthCARE mission for climate modelling and weather prediction.

What else is ESA doing?

As a world leader in the field of Earth observation, ESA has been monitoring the atmosphere since the launch of ERS-2 and its atmospheric ozone research sensor in 1995. In 2002, ESA launched the largest Earth observation spacecraft ever built – Envisat – with an instrument dedicated to measuring trace gases in the troposphere and stratosphere, the layers of the atmosphere closest to Earth's surface.

Contact with Envisat was lost suddenly in 2012, and now Copernicus Sentinel-5P is the main atmosphere detective until Sentinel-4 and -5 are launched in the early to mid-2020s. Copernicus Sentinel-5P carries the state-of-the-art Tropomi instrument to map a multitude of trace gases such as nitrogen dioxide, ozone, formaldehyde, sulphur dioxide, methane, carbon monoxide and aerosols – all of which affect the air we breathe and therefore our health and the climate.

Once Copernicus Sentinel-4 and -5 are launched on their Eumetsat-operated meteorological satellites, they will provide information to support European policies. The main services will include monitoring air quality, stratospheric ozone and solar radiation, as well as climate monitoring. ESA has also contributed to the Copernicus Anthropogenic Carbon Dioxide Monitoring (CO2M) mission, destined to be Europe's prime mission for monitoring and tracking carbon dioxide emissions from human activity.



▲ EarthCARE

As well as contributing to the Copernicus Sentinels and Meteosat and MetOp meteorological satellites, ESA has developed a number of Earth observation missions dedicated to scientific research, including EarthCARE, which will shed light on the role that clouds and aerosols play in reflecting solar radiation back out to space and trapping infrared radiation emitted from Earth's surface. Clouds remain one of the biggest mysteries in our understanding of how the atmosphere drives the climate system. Therefore, an improved understanding of the relationship between clouds, aerosols and radiation is one of the highest priorities in climate research and weather prediction.

What are other space agencies doing?

▲NASA's suite of operational Earth science missions

NASA has developed a set of Earth observation satellites, many of which contribute to atmosphere and climate change research. The Orbiting Climate Observatory 2, for example, is currently measuring atmospheric carbon dioxide to characterise sources and sinks of this gas and quantify how carbon dioxide levels change over the course of a year. NASA's Suomi NPP mission is also helping scientists understand, monitor and predict long-term climate change, as well as tracking the spread of unhealthy air pollutants through the atmosphere.

Among other tasks, NASA's Aqua mission collects information about water vapour, aerosols and dissolved organic matter in the air. Terra also monitors the atmosphere, including pollution in the troposphere, the distribution of clouds, and their contribution to the transfer of energy from Earth's surface to the top of the atmosphere, whilst Aura keeps an eye on ozone levels, air quality and climate. NASA's Cloudsat mission measures the altitude and properties of clouds, providing information on the relationship between clouds and climate to help answer questions about global warming.

NASA worked with French space agency CNES on the CALIPSO mission to provide new insight into the role that clouds and aerosols play in regulating Earth's climate. In 2018, CNES launched CFOSAT together with the Chinese space agency, CNSA, that is helping us better understand and predict climate change by monitoring ocean surface wind and waves.

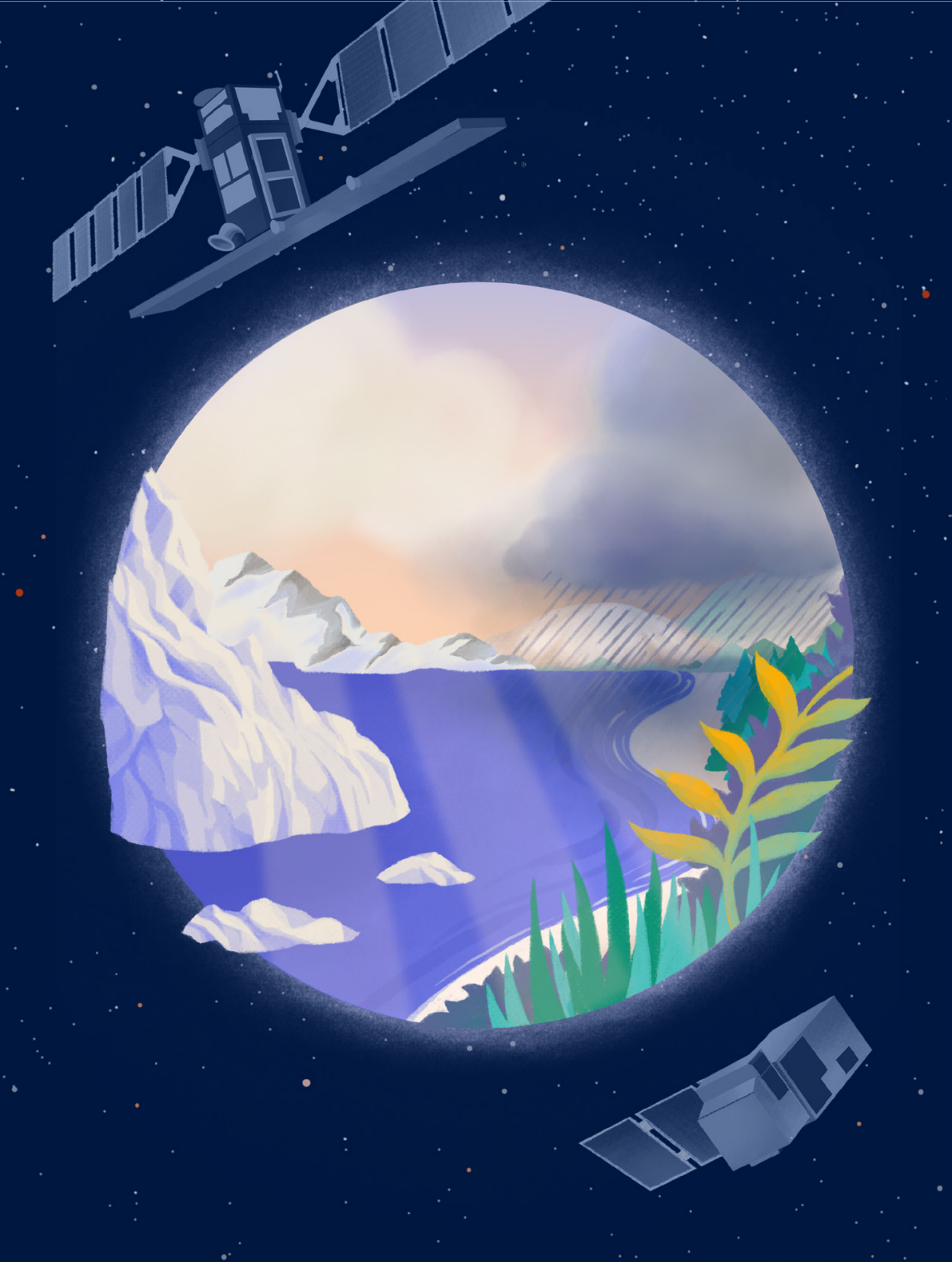
CNSA is also launching the Gaofen series of high-resolution imaging satellites. Several have already been launched and the data they collect is being used for climate change monitoring. Gaofen-5, for example, carries instruments to detect greenhouse gases and investigate the atmospheric environment.

Japanese space agency JAXA oversaw the development of several sensors for NASA's Aqua satellite and jointly implements EarthCARE together with ESA. JAXA's Global Change Observation Mission monitors the global environment to shed light on climate change, and the agency's Greenhouse Gases Observing Satellite is dedicated to monitoring greenhouse gases, including carbon dioxide and methane.

In 2019, the Canadian Space Agency (CSA) launched the three-satellite RADARSAT Constellation Mission to help governments track climate change in Canada and beyond. The mission followed on from RADARSAT-1 and -2 and can capture images more frequently and precisely than its predecessors. The CSA also developed two instruments – MOPITT and OSIRIS – that respectively fly onboard NASA's Terra and Sweden's Odin satellites. MOPITT gathers long-term data on carbon monoxide concentrations and OSIRIS measures concentrations of ozone, aerosols and nitrogen dioxide.

The series of Meteor satellites led by Russian space agency Roscosmos provide many environmental services, including monitoring global climate and measuring the Earth-atmosphere system. The organisation also oversaw development of the Electro-L/GOMS-2 satellite that images the upper atmosphere.

Closer to home, the German space agency DLR launched TerraSAR-X in 2007, providing data to help scientists investigate climate change. The satellite has so far delivered hundreds of thousands of images, and even the first analyses document indisputable details of climate change, including the retreat of glaciers across the globe. DLR also manages plans for the future Tandem-L and recently-launched EnMAP satellites, and works with ESA on processing data from ESA Earth observation missions.



MONITORING EARTH'S SURFACE

Using satellites to scan Earth's surface reveals a plethora of information that is difficult or impossible to see from the ground. From their vantage point high above us, satellites can collect data on the land, ocean and ice caps to monitor the changing environment and support responses to natural disasters.

Images of our planet are acquired continuously from orbit to better understand the environment we live in and help protect it for the future. These images show the world through a wide-enough frame that large-scale phenomena can be observed with an accuracy that would take an army of ground-level observers to match.

And because Earth observation satellites remain in place for long periods of time, they can highlight environmental changes occurring gradually. Looking back through archived data, we can see the steady clearing of the world's rainforests, an annual rise in global sea level and an increase in the number and intensity of wildfires.

ESA remains dedicated to developing cutting-edge spaceborne technology to monitor Earth's surface, and consequently improve daily lives, support effective policy making and benefit businesses and the economy. It does this using a fleet of [Earth observation satellites].

▲ ESA-developed Earth observation missions watch over different parts of the Earth system, including Earth's surface

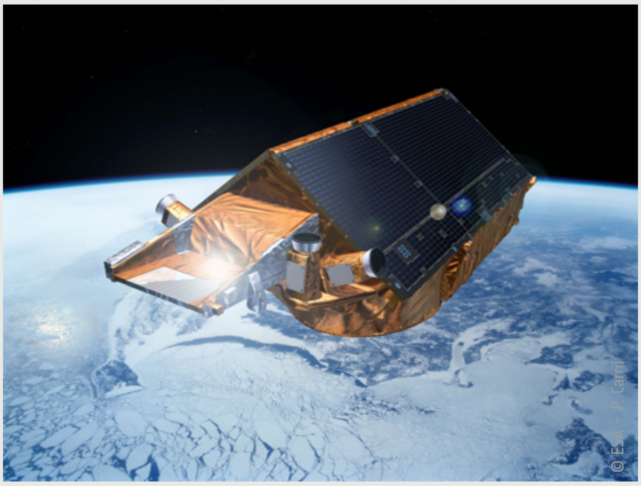
DISCOVERY & PREPARATION ACTIVITIES

To ensure that ESA remains a world leader in monitoring Earth's surface from above, ESA Discovery & Preparation supports novel research to maximise benefits from the Agency's satellite missions, as well as studying the feasibility of new missions.

· Current missions

ESA's Soil Moisture and Ocean Salinity (SMOS) mission is dedicated to making global observations of soil moisture over land, and salinity over oceans. In support of this and other missions with similar objectives, we studied the concept of a soil moisture mission back in the early 2000s, followed by an in depth analysis into how soil moisture could be monitored using optical and radar measurements.

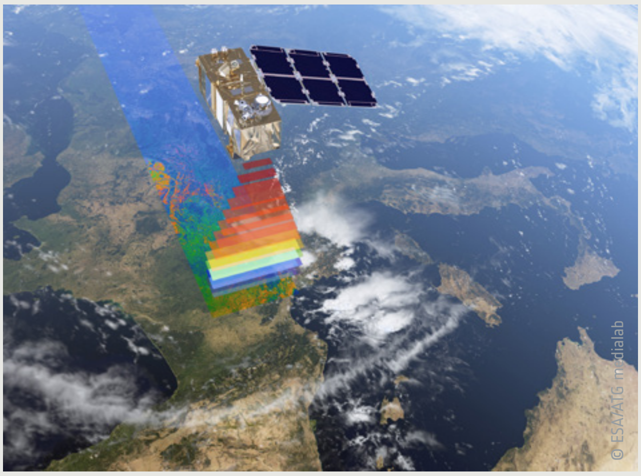
Looking to Earth's poles, CryoSat measures the thickness of polar sea ice and monitors changes in the ice sheets that blanket Greenland and Antarctica; it is a mission highly relevant to addressing questions surrounding climate change and its impact on our planet. The importance of such missions has long been appreciated by ESA and Discovery & Preparation, which first explored a potential sea ice mission at the beginning of the century. A later study investigated how measurements from space, air and ground could be combined to support mapping of arctic sea ice.



▲ Information from CryoSat is leading to a better understanding of how the volume of ice on Earth is changing and, in turn, a better appreciation of how ice and climate are linked

CryoSat isn't ESA's only map-making mission. Proba-V was a washing machine-sized technology demonstration mission that mapped land cover and vegetation growth across the entire planet every two days. A very successful study explored how data from the satellite could be combined with historical climate data to look at the susceptibility of parts of southern Africa to drought.

Meanwhile, the Copernicus Sentinel-1 mission provides radar imagery to help us understand the land and ocean, partly thanks to a Synthetic Aperture Radar (SAR) instrument – a detection system that sends out and receives pulses of radio waves to create very detailed images of the Earth's surface below. Many Discovery & Preparation studies have investigated how SAR can be used to find out more about Earth's surface; Airbus and Diam both used Copernicus Sentinel-1 as an example to explore how SAR on board satellites could cooperate with uncrewed aerial systems to improve our view of Earth from space, and another study explored how SAR data could be combined with navigation data to study tectonic processes in Indonesia.

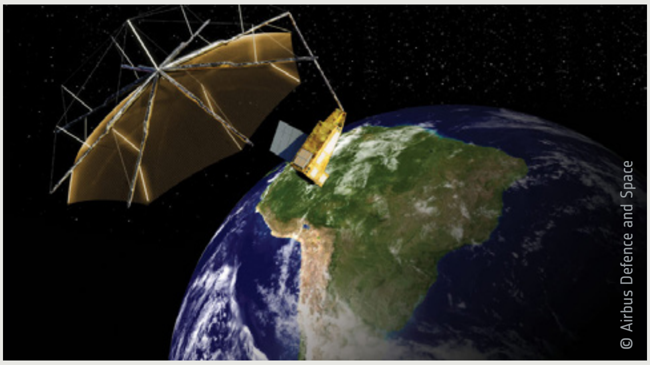


▲ Copernicus Sentinel-2 is monitoring the land as part of the European Union's Copernicus programme

Copernicus Sentinel-2 is also providing imaging – in the optical part of the spectrum – for land monitoring, for example to investigate vegetation, soil and water cover, inland waterways and coastal areas. A study that finished in 2019 developed a model to combine Copernicus Sentinel-1 and -2 data to monitor crops more effectively. Another looked into how data from the two missions could be used for disaster risk reduction and a third developed tools to detect and monitor slow-moving landslides using Copernicus Sentinel-2 data.

· Future missions

Looking to the future, the FLourescence EXplorer (FLEX) mission will map vegetation to measure photosynthetic activity. Discovery & Preparation supported the preliminary concept review for FLEX, as well as a mission performance analysis and a requirements consolidation study. A decade ago, two studies by Deimos Space and the University of Bologna explored how FLEX could work with Copernicus Sentinel-3 on a new way of monitoring photosynthesis to assess vegetation on the ground.



▲ Biomass's five-year mission is to chart the biomass of Earth's forests over time

The Biomass mission will also provide crucial information about the state of our forests. Biomass will look down to Earth through a charged region of the atmosphere known as the ionosphere, which will impact the quality of the images it takes. Three studies in 2016–2018 mapped the ionosphere over Southeast Asia, South America and Africa to support Biomass to collect the best possible data.

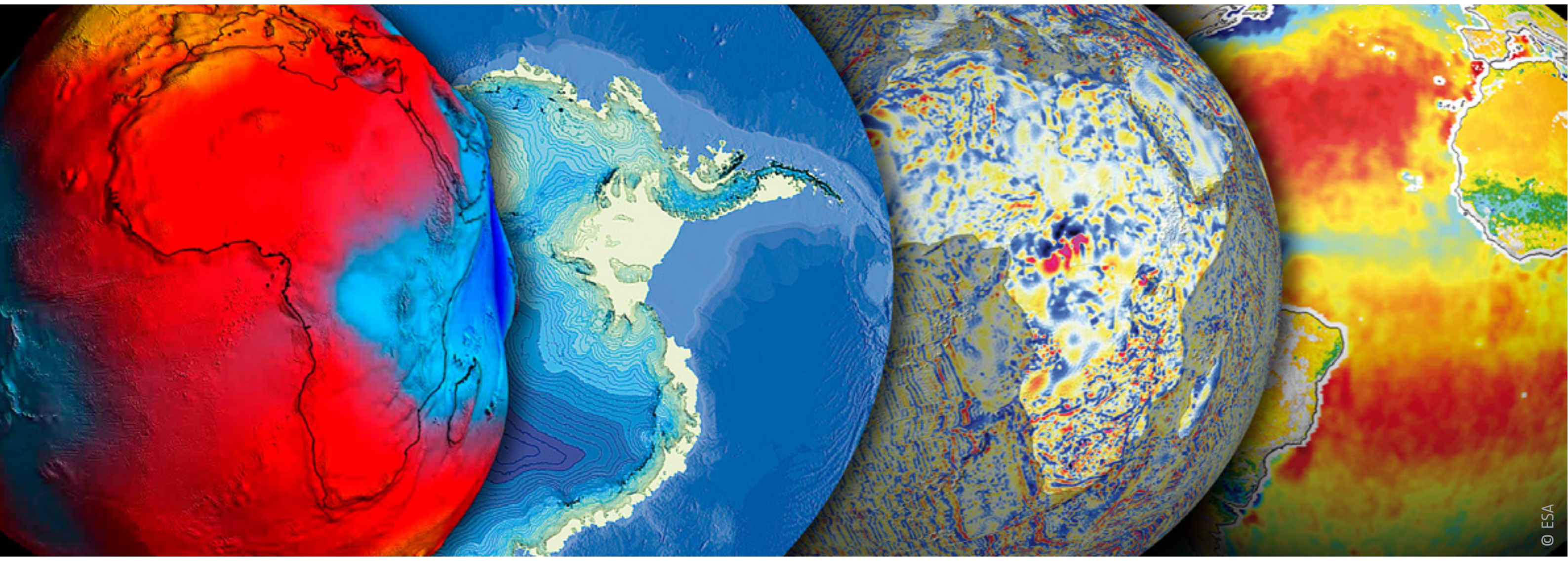
A 2018–2020 study looked into how large 'deployable mirrors' could be actively corrected in space to maintain their perfect shape. Bigger mirrors can capture more light, but the larger they get, the trickier it becomes to maintain a perfect shape. Especially when that mirror is made of multiple segments that fold out once the spacecraft reaches its destination. One mission type that the study focused on was looking at Earth's surface in high resolution from geostationary orbit.

What else is ESA doing?

ESA has been monitoring Earth's surface since the launch of Meteosat-1 in 1977. Although their primary focus is meteorology, several of the Meteosat satellites also contribute to surface monitoring. In total, seven Meteosat satellites were launched as part of the first generation, after which ESA worked with EUMETSAT to develop a second generation of Meteosat satellites to provide more comprehensive and frequent data. A third generation is planned that will revolutionise environmental monitoring.

ESA has also developed and now operates a number of Earth observation missions dedicated to scientific research into Earth's surface, including ice observer CryoSat and soil moisture and ocean salinity monitoring SMOS. Several missions are planned for launch over the next few years, including forest scanner Biomass, vegetation observer FLEX and double-satellite Harmony, which will address key scientific questions related to ocean, ice and land dynamics. These Earth Explorers focus on Earth's surface; several others exist to monitor many different parts of the Earth system such as the atmosphere and magnetic field.

ESA is also developing the Sentinel family of missions specifically for the operational needs of the Copernicus programme. Whilst Copernicus Sentinel-1, -2 and -3 are dedicated to monitoring Earth's surface, Sentinel-4 and -5 focus on atmosphere monitoring and Sentinel-6 measures global sea-surface height. The current suite of Sentinels is being expanded with six new missions, one of which is the Copernicus Hyperspectral Imaging Mission for the Environment (CHIME). CHIME will support EU policies on the management of natural resources, ultimately addressing food security.



▲ Views of Earth from ESA's first four Earth Explorers – GOCE, SMOS, CryoSat and Swarm

What are other space agencies doing

NASA has its own suite of satellites monitoring Earth's surface from space. The Aqua mission aims to improve our understanding of the water cycle, whilst CYGNSS monitors choppy ocean waters during hurricanes to predict wind speed and ocean surges when the storm hits the land. CYGNSS isn't the only satellite supporting natural disasters; Suomi-NPP monitors natural disasters such as volcanic eruptions and wildfires, as well as land cover, vegetation productivity, sea and land surface temperatures, sea ice, land ice and glaciers.

ICESat-2 is NASA's eyes on ice, measuring ice sheet elevation and sea ice thickness to observe changes in Greenland and Antarctica. Terra also monitors ice, as well as the ocean, land and snow. Meanwhile SMAP focuses on soil moisture, detecting where soil is frozen or thawed to improve our ability to monitor and predict floods, droughts and crop yields. And the ECOSTRESS instrument onboard the International Space Station measures plant temperatures to reveal their water needs.

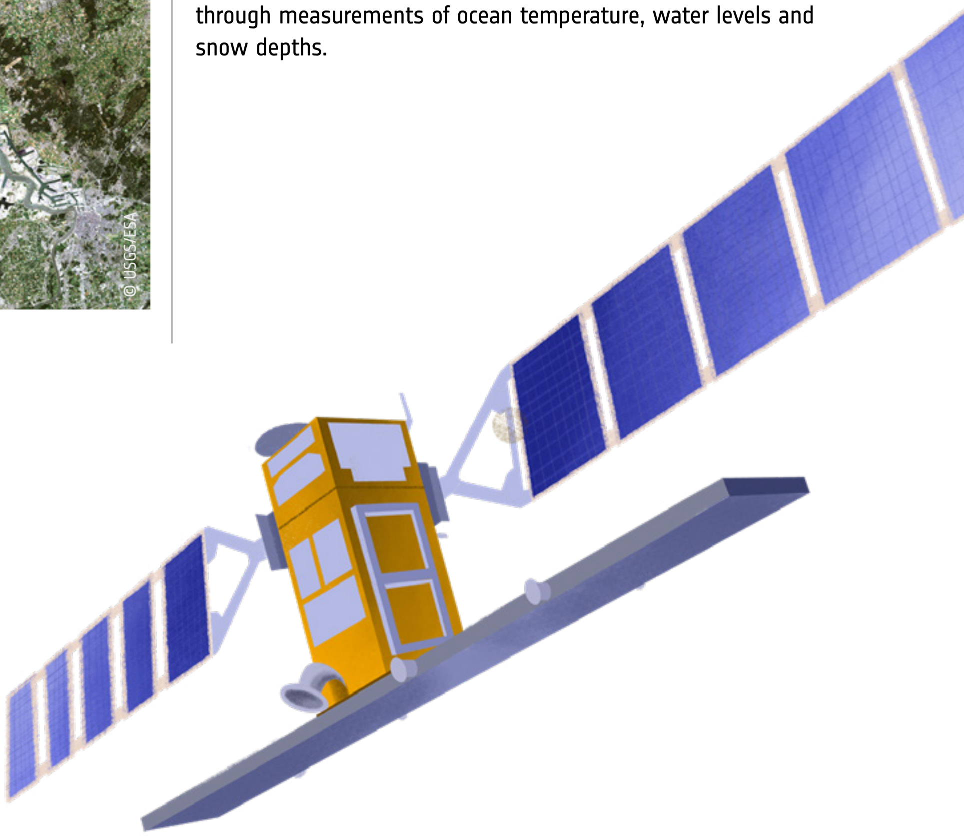
▲ The Netherlands captured by Landsat-5

NASA's Landsat missions provide the longest continuous space-based record of Earth's land in existence. They are a partnership with the US Geological Survey and take very high-resolution images to monitor urban growth, natural disasters, agriculture, forest loss and regrowth, and much more.

NASA also often partners with European agencies on space missions, including a set of satellites developed with French space agency CNES that measure the 'hills and valleys' of the ocean surface. CNES has contributed – including through supplying instruments – to many missions that monitor Earth's surface, including ESA's SMOS, Proba-V and FLEX missions. Through the PEPS digital platform, the French agency also makes Copernicus Sentinel data available to all European citizens.

Aside from having long been involved in processing and archiving data from ESA Earth observation missions, German space agency DLR also operates twin satellites TerraSAR-X and TanDEM-X. TerraSAR-X provides data for a wide range of applications, including studying hydrology, geology, the climate and the ocean, whereas the main purpose of TanDEM-X is to generate an accurate 3D map of Earth's surface. Looking to the future, DLR will soon launch the EnMAP mission to monitor Earth's surface, especially agriculture, forestry, soil and geological environments, as well as coastal zones and inland waters.

Japanese space agency JAXA is also busy monitoring Earth's surface from space. The series of four ALOS missions have been contributing to finding out more about the land and monitoring environmental hazards since 2006. The GCOM satellite pair are respectively used to monitor the climate – including through measurements of vegetation, snow and ice – and water circulation – including through measurements of ocean temperature, water levels and snow depths.

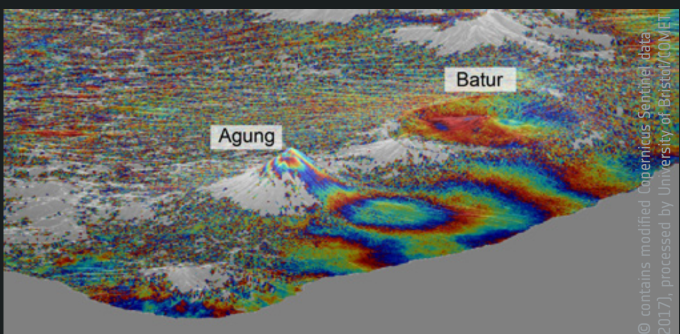


SPACE TECHNOLOGY FOR LIFE ON EARTH

The abundance of data that satellites collect about our planet is not very useful in its original form, but once it is processed and applied to specific situations, it can help solve a myriad of problems on Earth. For example, remote sensing technology can be used to detect environmental changes, satellite communication can assist with remote services and natural disaster management, and human spaceflight has advanced our understanding of medicine.

ESA Discovery & Preparation has supported many investigations into how space technology can be applied to Earth-based challenges. This article focuses on three such applications – forecasting natural disasters, monitoring ocean plastic, and enabling autonomous shipping.

Forecasting natural disasters



▲ Copernicus Sentinel-1 data shows ground uplift around Bali's Mount Agung volcano. The uplift occurred just before an eruption, which was preceded by several small earthquakes. Ground motion indicates that fresh magma is moving beneath the volcano – a sign of an upcoming eruption.

According to Agence France-Presse, in 2010 natural disasters killed 300 000 people worldwide and affected another 220 million. They also caused $120 billion of economic damage. And worryingly, the impacts of disasters are magnifying each year due to growing urbanisation and increasing extreme weather events.

Timely forecasting of natural disasters could help save lives and reduce the impact on the economy. In the past, it has been difficult to predict such disasters, but satellites are able to provide new information to make it much easier.

To achieve this, Discovery & Preparation has supported studies that explore how exactly we can predict natural disasters using satellite data. These studies better inform authorities when natural disasters are imminent, helping them act faster with a more coordinated response.

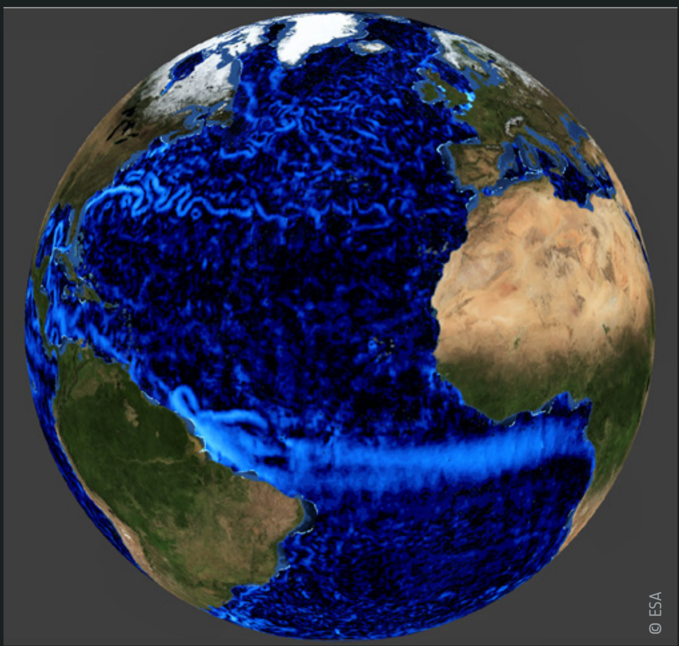
One of the first studies ran under a working group consisting of representatives of space agencies around the world, set up by ESA to research global disaster hotspots. The long-term vision of this group is for space agencies to coordinate their resources so that Earth observation data can be used to forecast all types of natural disasters. The study investigated which space technologies should be developed to achieve this.

▲ Fires in South Africa's Western Cape, which often occur during the dry summer months and are exacerbated by drought. Satellites can be used to spot vulnerable areas.

Following this investigation, another study explored how Earth observation data could be combined with advancements in Information and Communication Technologies to improve natural disaster forecasting. The ideas proposed within the study focused on cloud-based infrastructure, particularly the semi-automatic processing of large amounts of data.

More specific studies looked into how existing satellite data could be used to analyse drought in southern Africa and to study tectonic processes in Indonesia. Indonesia often experiences volcanic eruptions and earthquakes. In the case of one volcano – Mount Marapi – a large-scale eruption that could potentially put 1.1 million people at risk is long overdue, highlighting the need for natural disaster forecasting. By combining SAR interferometry – a technique based on radar – with global navigation systems, space technology can be used to monitor ground movement over time.

Monitoring ocean plastic

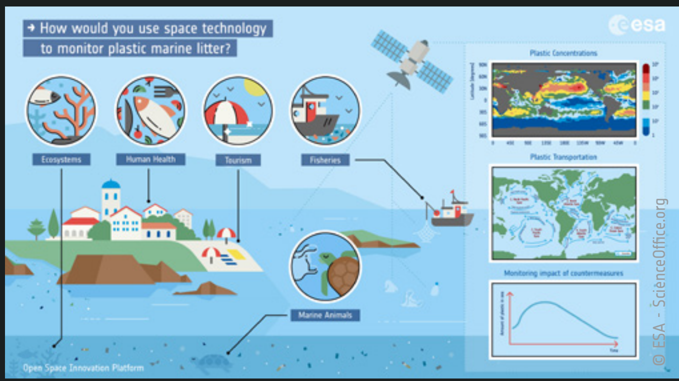


▲ *Simulated ocean surface currents, as would have been expected from ESA's SKIM ex-candidate mission. The satellite would have carried brand-new technology to offer more accurate measurements.*

Approximately 10 million tonnes of plastic finds its way into the ocean every single year. About 70% of this sinks to the sea floor, whilst 30% remains floating on the surface. That's three million tonnes of plastic to potentially wash up on coastlines, affecting not just wildlife but also coastal communities, tourism and the food chain.

Monitoring this plastic can be very difficult from Earth's surface, as it is impossible to see much of the ocean at once. But satellites with very high-resolution cameras and wide fields of view are changing our ability to monitor plastic waste, and Discovery & Preparation is supporting studies that investigate the best way of doing so.

Marine litter has been identified as one of the major hazards to the marine environment. With this in mind, in 2019 ESA's Discovery programme launched a call for ideas through the Open Space Innovation Platform (OSIP) that resulted in a large number of innovative ideas to use space to monitor marine litter.



▲ Satellite measurements of marine plastic litter would add to the existing portfolio of monitoring methods

One of the areas explored in the activities that were funded following this call for ideas (for example, here, here or here) was how satellites could monitor and detect seaborne plastic. All elements that feed into this complex problem have been analysed, ranging from monitoring methodologies (aircraft, drones, satellites) to developing specific instruments for satellites, through simulations to forecast the movement of marine litter through the ocean. The activities laid the groundwork for a thriving community that advances European capability to monitor and thereby more efficiently address the problem of marine litter.

To help primary school students get to grips with how satellites can help detect and reduce plastic pollution in the ocean, ESA Discovery produced a cartoon that follows three pieces of plastic left on the beach.

Enabling autonomous shipping

▲ Space-based services to provide global ship tracking

Just as driverless cars could be the future of the automotive industry, captain-less ships could be the future of the shipping industry. Autonomous shipping has the potential to significantly lower costs, increase safety, solve anticipated crew shortages, and improve working conditions.

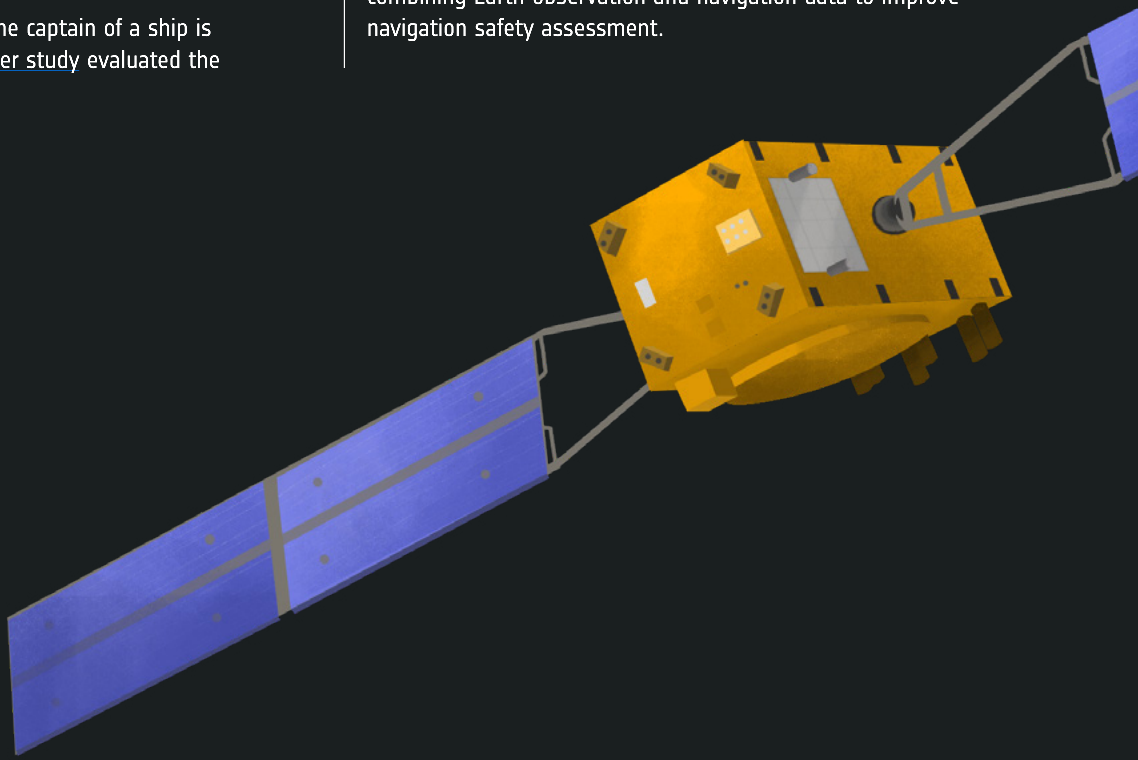
But autonomous shipping relies on an accurate and continuously available navigation system. Discovery & Preparation has supported studies into how to enhance existing satellite navigation systems to enable autonomous shipping, for example by combining them with land-based systems to improve positioning accuracy.

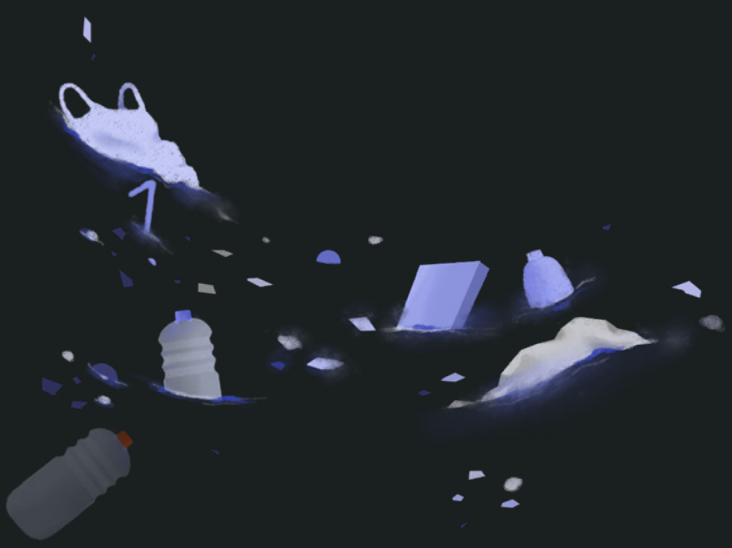
One such study designed a mission that would assist with autonomous shipping thanks to its quick response time and ability to re-image an area very quickly. Applications of the satellite could include routine monitoring of departure points, relocation of ships at sea, ship tracking and monitoring of suspicious activity – like illegal immigration, illegal drug trafficking and piracy !

One of the most difficult times for the captain of a ship is entering or leaving a harbour. Another study evaluated the feasibility of creating a system that would monitor all ships in the harbour to avoid collisions. The system would make use of ESA's Galileo and EGNOS systems to calculate new routes for ships. A similar study focused on the development of a Maritime Adaptive GNSS Safety Concept to support mariners, especially within the vicinity of ports.

The International Maritime Organization runs an anti-collision system for ships which uses data from ground-based sensors. Another ESA-supported study looked into how satellite data could be included in the system to fill gaps in the terrestrial system and ensure worldwide coverage.

Another OSIP call for ideas launched in 2019 sought solutions to enable harbour to harbour autonomous shipping. Five ideas were selected for further research, including one project investigating autonomous shipping in sea ice conditions, one looking into enhancing a vessel's awareness of its surroundings, and one combining Earth observation and navigation data to improve navigation safety assessment.



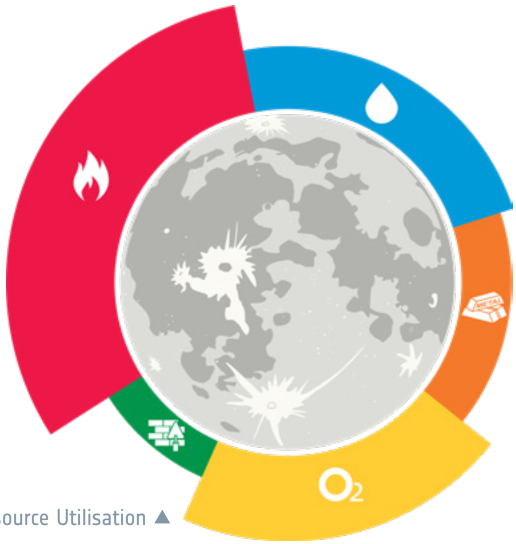


LIVING ON ANOTHER WORLD

Humanity is heading back to the Moon, and this time, we're planning to stay. But for long-term space missions, astronauts would need infrastructure to live and work, to move around, to communicate with Earth, and to produce oxygen and water vital for survival. Taking all this infrastructure from Earth would likely be prohibitively expensive. Instead, we need to figure out how to make it on site.

Using local materials to build infrastructure and produce amenities is known as in-situ resource utilisation (ISRU). Past research in this area has explored and demonstrated fundamental ISRU concepts using a combination of resources found on the exploration site and materials brought from Earth.

ISRU is needed to build a habitat that shields astronauts from harsh environments including thin or non-existent atmospheres, extreme temperatures, intense radiation and even micrometeoroids. It would enable us to build roads to move around the surface, and launch and landing pads for travelling to and from Earth. It could be used to produce equipment that can generate and store energy for producing electricity, as well as antenna towers for communication. And it could produce huge amounts of water and oxygen for keeping astronauts alive and creating propellants for travelling around and eventually coming back to Earth.

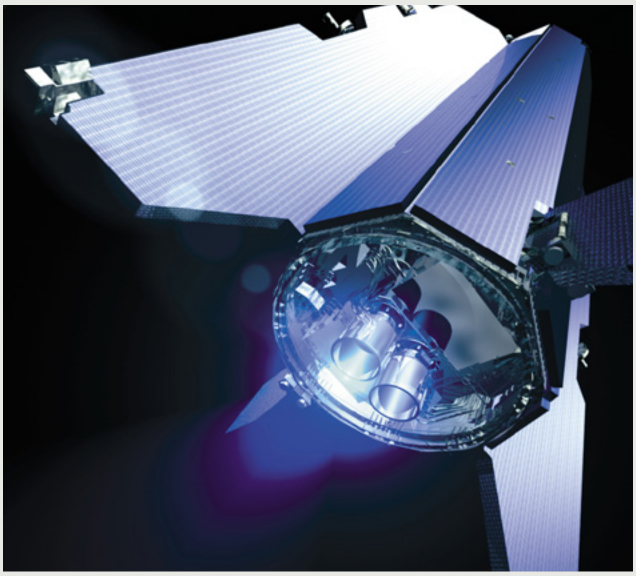


In-Situ Resource Utilisation ▲

DISCOVERY & PREPARATION ACTIVITIES

In 1999, one of the first ISRU-related Discovery & Preparation studies focused on propulsion and power systems, assessing the needs for advanced propulsion in the current century. The study concluded that ISRU could reduce the costs of missions to Mars whilst increasing our capabilities, but that research and development in ISRU technologies should begin right away.

And so, in coordination with all ESA programmes, research continued. A study completed in 2000 focused on the power systems required for future space exploration, including designing an ISRU chemical plant to produce propellant, chemicals for life support, and fuel for surface activities.



A close-up view of GOCE's icon-propulsion assembly ▶

Other studies happening at the same time took a broader look at long-term space exploration, with one considering what architectures and technologies would be required for Mars exploration. The study investigated the possibility of producing propellant and fluids necessary for crew survival – including nitrogen, oxygen, hydrogen and water – from the Martian atmosphere and soil. Another study on the survivability and adaptability of humans to long duration interplanetary and planetary environments also found that ISRU could be particularly useful for producing propellants and life support consumables.

Fast forwarding 13 years, the technology had developed enough to explore more specific ISRU concepts, including a system to collect and store carbon dioxide from the Martian atmosphere and deliver it to a propulsion system. The study, carried out by Airbus, suggested ways in which dust and water could be removed from the carbon dioxide, as well as how it could be liquified for storage.

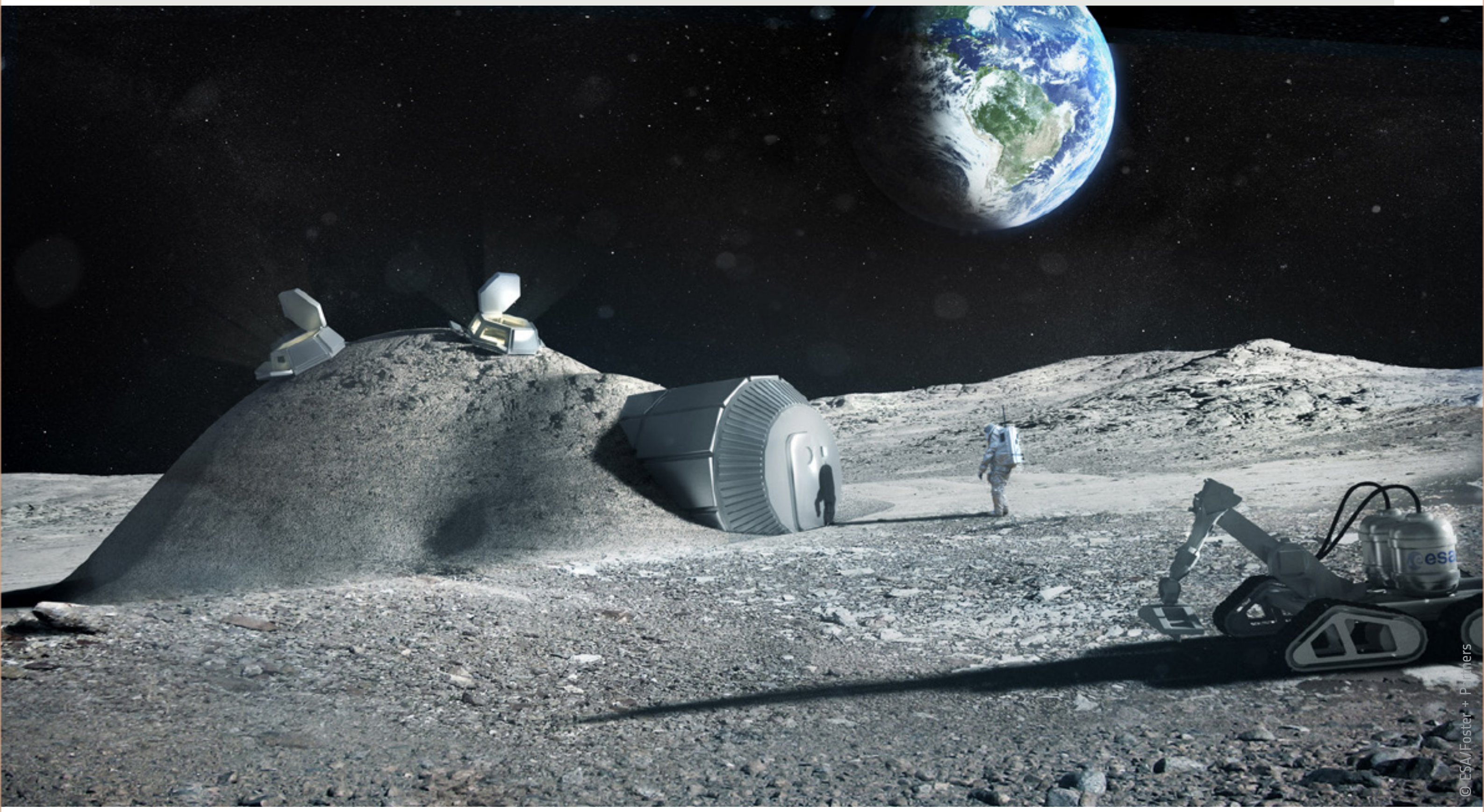
Over the last few years, Discovery & Preparation has supported more research into building infrastructure using lunar soil and more specific methods of energy generation and storage; a recent study explored how lunar regolith could be used to store heat and provide electricity for astronauts, rovers and landers.

One study explored how lunar analogue facilities could support the development of ISRU technologies, including testing the excavation and processing of local materials, as well as how these materials could be used to build structures using processes like 3D printing.

Another confirmed the suitability of lunar soil as a building material, selected a suitable process for printing structures from it, and even designed a printable habitat. And a third recently went one step further and explored how any necessary structures, equipment and spare parts could be 3D printed using lunar regolith, even selecting which specific printing processes would work best.

As an alternative to existing 3D printing technologies, a 2019 study looked into turning lunar soil into fibres to build strong structures. The researchers produced a sample of material to show that it is possible to use this process to make structures that are locally impermeable.

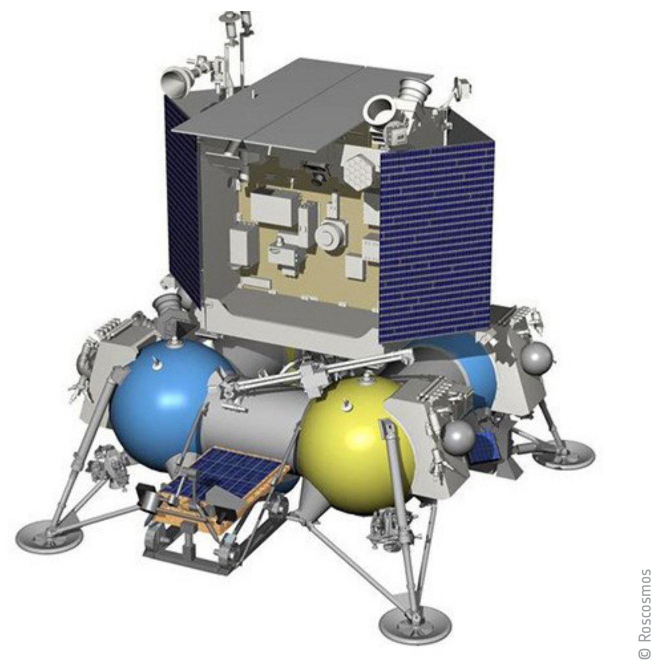
A set of Discovery & Preparation studies recently explored and defined ESA's lunar IRSU demonstration mission, which aims to prove by 2025 that producing water or oxygen on the Moon is possible. One of these studies looked into the system that would actually produce the water and oxygen, proposing a package that extracts oxygen from the soil and uses it to produce water, using a 'carbo-thermal reactor'. Another explored how the system could rely on a lander as a power supply and a third investigated how it could communicate with Earth.



▲ Design for a 3D printed lunar base

What else is ESA doing?

To implement the lunar ISRU demonstration mission, ESA intends to procure mission-enabling services from the commercial sector, including payload delivery, communication, and operations services. In doing so, ESA will both leverage on and further nurture existing commercial initiatives that may find widespread applications in a future lunar exploration scenario.



▲ A computer model of Luna-27, which will fly to the Moon's south pole

ESA is also currently working on the PROSPECT mission, which will access and assess potential resources on the Moon to prepare for the technologies that may be used to extract these resources in the future. PROSPECT will drill beneath the Moon's surface near its South Pole and extract samples expected to contain frozen water and other chemicals that can become trapped at extremely low temperatures. The drill will then pass the samples to a chemical laboratory where they will be heated to extract these chemicals. The mission will operate as part of the Russian-led Luna-27 mission and will test processes that could be applied to resource extraction in the future.

To support the ambition to have a human presence on the Moon sustained by local resources by 2040, in May 2019, ESA published its Space Resources Strategy. The strategy considers what we need to discover and develop to support sustainable space exploration. The strategy covers the period up to 2030, by which time the potential of lunar resources will have been established through measurements at the Moon, key technologies will have been developed and demonstrated and a plan for their introduction into international mission architectures will have been defined. Following the publication of the strategy ESA hosted a workshop to identify the next steps needed to make space resource utilisation a reality.

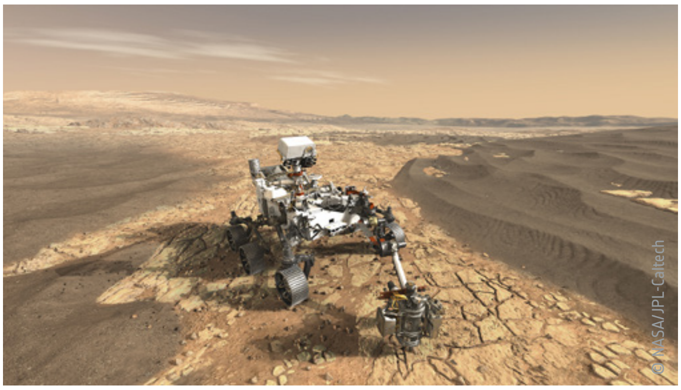
▲ Producing oxygen and metal out of simulated moondust inside ESA's Materials and Electrical Components Laboratory

In 2020, ESA set up a prototype plant to produce oxygen out of simulated moondust. Removing the oxygen from lunar soil leaves various metals; another line of research, therefore, is to see what are the most useful alloys that could be produced from them, and how they could be used on the Moon. The ultimate aim would be to design a 'pilot plant' that could operate sustainably on the Moon, with the first technology demonstration targeted for the mid-2020s.

What are other space agencies doing in this area?

NASA's Lunar Reconnaissance Orbiter already indicated the presence of water ice buried under the lunar soil at certain locations. The orbiter launched with the Lunar CRater Observation and Sensing Satellite that was released from the orbiter and impacted the Moon; observations of the resulting 16-kilometre-high plume showed the chemical make-up of the lunar surface.

The US Agency is also developing several CubeSat orbital missions that will visit the Moon. Lunar Flashlight, LunaH-MAP and Lunar IceCube will aim to find out how much water ice there is and where exactly it can be found.



▲ Artist's impression of the Mars 2020 Perseverance rover

NASA's first Mars lander, Viking, returned important data about the Martian atmosphere, revealing that it is made up of 95.9 percent carbon dioxide. Based on this discovery and information returned by subsequent robotic missions, the Agency has developed technologies to convert Mars' atmospheric carbon dioxide into oxygen to benefit human missions to the red planet. Recently, NASA selected the Mars Oxygen In-Situ Resource Utilization Experiment, or MOXIE, as one of seven instruments that will be placed on the Mars 2020 rover.

Volatiles are substances that vaporise easily and could be a source of water on the Moon. Together with other space agencies, NASA is conducting an international coordination of lunar polar volatiles exploration to increase scientific knowledge, determine the viability of volatiles as potential resources, and to use the Moon as a proving ground for Mars ISRU technologies.

Future China National Space Administration missions are also expected to target lunar polar volatiles as potential resources. China's vision of an international lunar research station, to be established initially as a robotic facility for science and research during the late 2020s and early 2030s may provide an early opportunity for lunar resources to be utilised.

The Russian space agency, Roscosmos, is working with ESA on the series of three Luna missions, including Luna-27, which will host ESA's PROSPECT package. The mission will target measurements in the polar region of the Moon, focusing on cold trapped volatiles that may be found there.

What's next at ESA ?

Through its Open Space Innovation Platform (OSIP), ESA Discovery & Preparation sought ideas on enabling technologies for in-situ construction, manufacturing and maintenance of infrastructure and hardware to support long-term exploration of a planetary body.

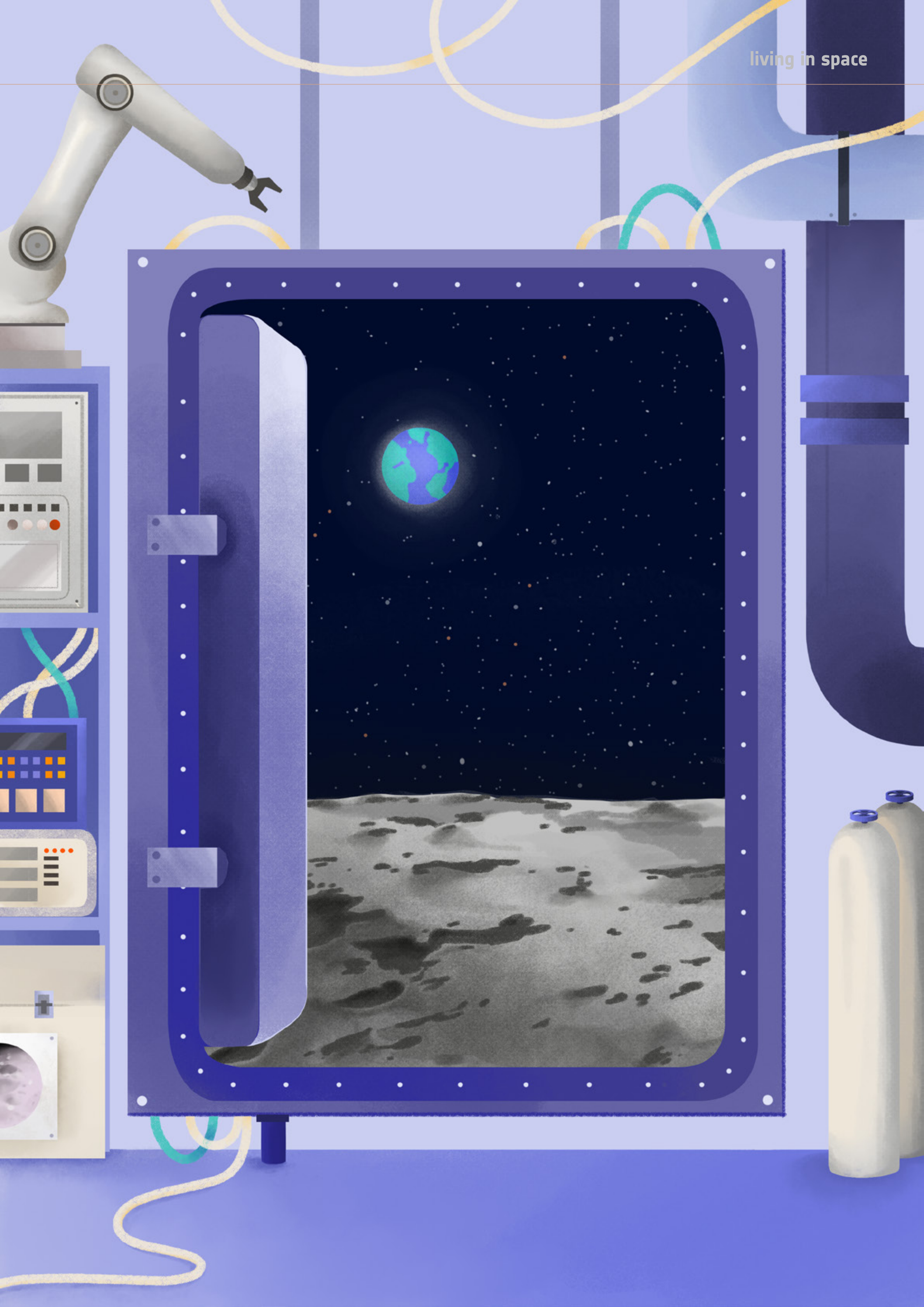
The proposed ideas support the construction of habitats, mobility infrastructure (e.g. roads and landing pads), ancillary infrastructure (e.g. for communication and energy generation and storage), and hardware (e.g. tools, interior equipment, machinery and clothing).

▲ Artist's impression of the Mars 2020 Perseverance rover

Ideas include many novel methods for melting and 3D printing lunar soil, making solar cells from lunar soil, optimising energy storage, finding methods to grow plants from organic waste without needing soil, using lunar soil to build crop-friendly greenhouses, and building infrastructure using space debris. Many of the ideas are now being implemented by ESA as studies, co-funded research projects or early technology development projects. To find out more, visit the results section of this call for ideas.

The use of space resources for exploration is now within reach thanks to advances in our knowledge and understanding of the Moon and asteroids, increased international and private sector engagement in space technologies, and the emergence of new technologies.

Developing technologies and methods to use local resources to support future astronauts remains a challenge, but in doing so we are stimulating innovation on Earth through technology needs as well as new approaches to managing limited resources. This will hopefully help us find new ways to address global challenges and generate near to mid-term economic returns for terrestrial industries.



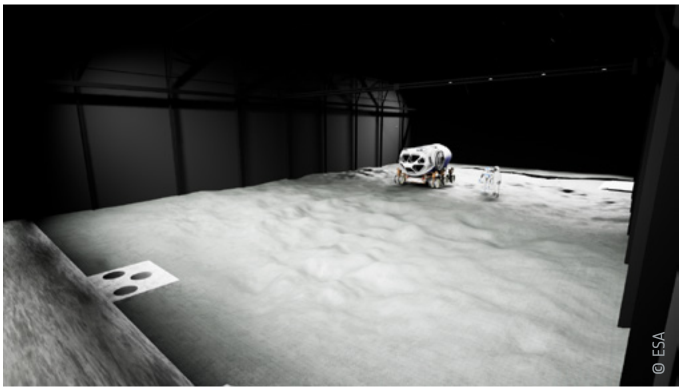
LIVING IN SPACE

Since Yuri Gagarin became the first human to leave Earth in 1961, over 500 intrepid adventurers have made the journey into space. Today, astronauts and cosmonauts from around the world visit the International Space Station (ISS), which serves as a microgravity and space environment research laboratory. Life on the ISS is therefore far from easy; isolated space travellers must deal with the strange sensation of weightlessness and having very little access to fresh food.

Over the last two decades, space agencies have created more comfortable conditions on the ISS, but we need to explore the concept of 'living in space' much further if humans are to ever live and work on another world, such as the Moon or Mars.

The Discovery & Preparation elements of ESA's Basic Activities work to prepare ESA for the future of space exploration. As part of this programme, ESA has worked with academic and industrial partners on a huge number of studies that lay the groundwork for living in space.

Preparing for a space mission



▲ Virtual reality rendering of a LUNA lunar environment

For their own safety, the welfare of their crew and the security of the specialist equipment they control, every astronaut and cosmonaut must go through intensive training before going into space. Training for a mission to the ISS takes years; European astronauts must learn the science behind spaceflight, how to operate equipment, how to deal with weightlessness and even how to speak Russian. When heading further into unchartered territory, even more preparation would be required.

One Discovery & Preparation study that explored how to prepare for a space mission is the Lunar Analogues Study (LUNA). LUNA investigated creating artificial Moon-like environments that could be used to simulate and train for lunar exploration missions. One of the lunar environments that LUNA proposed – the European Surface Operations Laboratory (ESOL) – is now being built at the European Astronaut Centre. ESOL will contain a habitat, lunar terrain, a Mission Control Centre and a communication interface.

A follow-up study investigated converting a deep-sea diving simulator into a model lunar surface; the lunar surface simulator would provide a valuable test-bed for tools and concepts, as well as a location for research and astronaut training.

▲ ESA astronaut Alexander Gerst training for spacewalks in the Neutral Buoyancy Facility

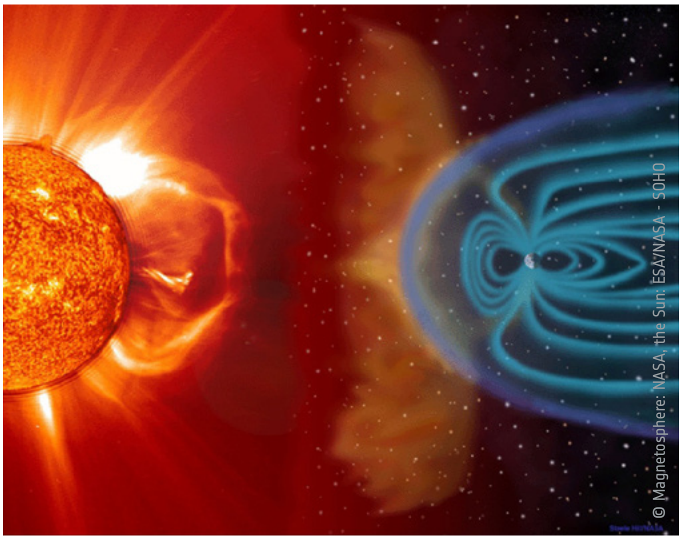
Another study, Moondive, looked into adapting ESA's Neutral Buoyancy Facility (NBF) – a large pool of water in which astronauts neither sink nor float, making it very useful for practising spacewalks outside the ISS. Adapting the NBF for lunar and asteroid mission simulations would involve changing the buoyancy to mimic the gravity of the destination, simulating the terrain and introducing robotic assistance.

Staying safe in space

▲ Equipment sent to Mars is sterilised in advance

Living in space can be risky! Aside from the threats from space debris and malfunctioning technology, space radiation can present dangers to space explorers, lack of gravity can result in physiological issues, and psychological issues can be caused by isolation and confinement. ESA works hard to ensure that astronauts remain as strong and healthy as possible.

One Discovery study, BIOSIS (BIOSafety In Space), reviewed the biological risks to crews due to biocontamination of air and water, and made recommendations for new technology developments that could minimise these risks. BIOSIS recommended engineering an automated biomonitoring system that would prepare and analyse air, water and surface samples.



▲ Earth's magnetic field protects us from the Sun's radiation, but astronauts travelling in space are more exposed

Astronauts on the ISS are exposed to more radiation from the Sun than people are on Earth as they are not fully shielded by Earth's magnetic field. Space explorers travelling further afield will be entirely outside this field and will therefore be exposed to significant radiation. Radiation exposure can damage astronauts' DNA and lead to cancer, cataracts, and radiation sickness. A Discovery study – IPRAM (Interplanetary and Planetary Radiation Model for Human Spaceflight) – estimated the radiation risks involved in missions to the Moon, Mars and asteroids. These estimates can be used when planning future missions to ensure that astronauts remain as safe as possible.

Astronauts spending long periods of time in space will eventually run into medical problems. Carrying enough medical supplies for all possible eventualities would be impossible, so 3D bioprinting of skin and bone could be useful for treating astronauts. One study explored how skin cells and bone pieces could be 3D printed in space.

Building a new home

For long-term space missions, astronauts would need somewhere to live when they reach their destination. Infrastructure is important for sheltering astronauts and scientific equipment from harsh environments, which could include thin atmospheres, extreme temperatures, radiation and micrometeoroids. But it would be expensive – perhaps even impossible – to take all the materials we would need to the surface of the Moon or a planet. For sustainable, long-term exploration we should instead look to local resources available at the destination.

One Discovery study verified the usability of lunar soil as a building material, selected a suitable printing process and designed an infrastructure. Another went one step further and explored how any necessary structures, equipment and spare parts could be 3D printed using lunar regolith, even selecting which specific printing processes would work best. More recent studies have become more specific: one aimed to develop promising robotic fabrication methods that could be used to build a lunar habitat out of fibrous structures, another explored 3D printing of ceramic material in space, and one investigated reusing space debris as a raw material for construction on the Moon.

▲ Design for a 3D-printed lunar base

Many factors need to be considered before building a home on another world. The L-DEPP (Lunar Dust Environment and Plasma Package) studies ([1], [2] and [3]) designed an instrument that could investigate the dusty surface environment of the Moon for better planning of future missions. The Moon has a very weak magnetic field, meaning it is constantly bombarded with solar radiation, micrometeorites and energetic plasma particles which charge up the surface and mobilise dust. The L-DEPP instrument would investigate the lunar dust, plasma, electric field, magnetic field and radio emissions using several different sensors that each have a specific role.

The Moon can reach extreme temperatures – down to -183°C at night! Finding a way to keep potential explorers protected from heat and cold is a huge challenge. One Discovery study looked into creating an intricate energy-channelling system of reflectors to provide heat on the Moon, and one explored how lunar regolith could be used to store heat and provide electricity for astronauts, rovers and landers.

A robotic helping-hand

Life in space can be tough for humans, but robots can be built to deal better with the harsh environment. ESA has a long history of developing robots to explore Mars, including several rovers. Nowadays, robotics is entering a new era in which it works more closely with humans.

▲ When the ESA engineer moves his gauntleted hand, the robotic hand follows in sync

Some activities are particularly difficult for astronauts, for example spacesuit gloves make it hard to perform dextrous tasks. The ADAH (Astronaut Dexterous Artificial Hand) study investigated two scenarios to improve this: one where a robotic system supports or augments grasping and manipulation capabilities, and one where a robotic hand replaces the astronaut hand entirely. In the latter case, the astronaut would operate the robotic hand from inside a spacecraft. ESA has now developed several robotic hand prototypes, and have even designed 'haptic feedback' robots, where an astronaut controls a robot using a joystick or arm exoskeleton, feeling the force on the robotic hand through this piece of equipment.

Other robots can move around the surface of planetary bodies and collect data that would be time-consuming and tiring for an astronaut. The Discovery study Lunar Volatile Resources Analysis Package (L-VRAP) defined an instrument for the first European Lunar Lander to detect, identify, quantify and characterise volatiles in the lunar soil and atmosphere. Creating a robot to do such a repetitive job allows an astronaut to focus on work that requires human levels of intelligence.

Other technologies for helping astronauts and spacecraft operators could make use of augmented and virtual reality. This would help them interact with what they are observing, repairing or building to improve their ability to work remotely. A Discovery study completed in 2019 explored whether augmented reality could be useful for ESA's operations.

The technology that exists today could easily take us to the Moon and beyond, but it is studies like those carried out under the Discovery & Preparation Programme that will make a trip resourceful, sustainable and productive.

What's next?

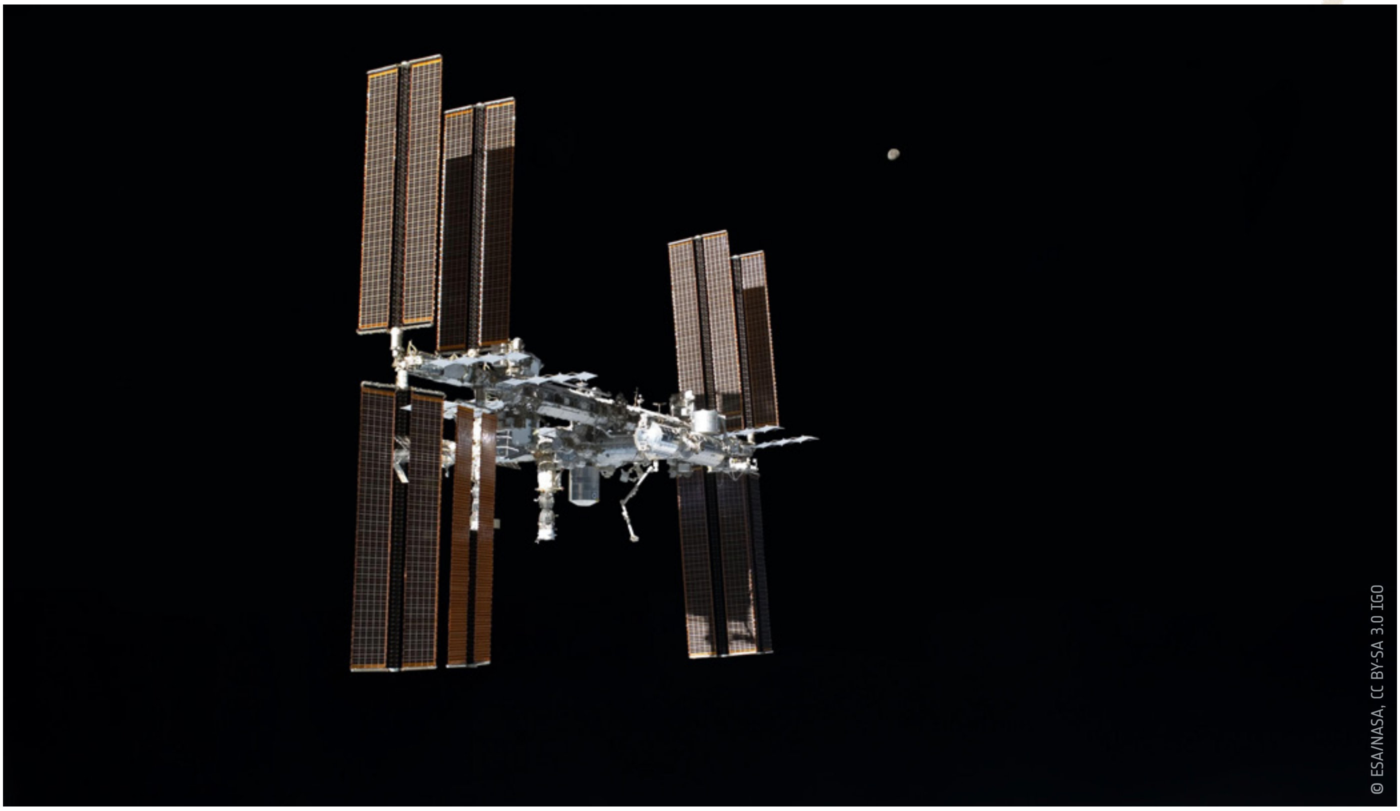
Through its Open Space Innovation Platform (OSIP), ESA has sought and selected ideas to use rovers to explore lunar caves. Aside from being geologically interesting, these locations could be interesting as long-term shelter for future human visitors to the Moon. OSIP has also invited ideas for in-situ construction, manufacturing and maintenance of infrastructure and hardware, to support long term human exploration of a planetary body.

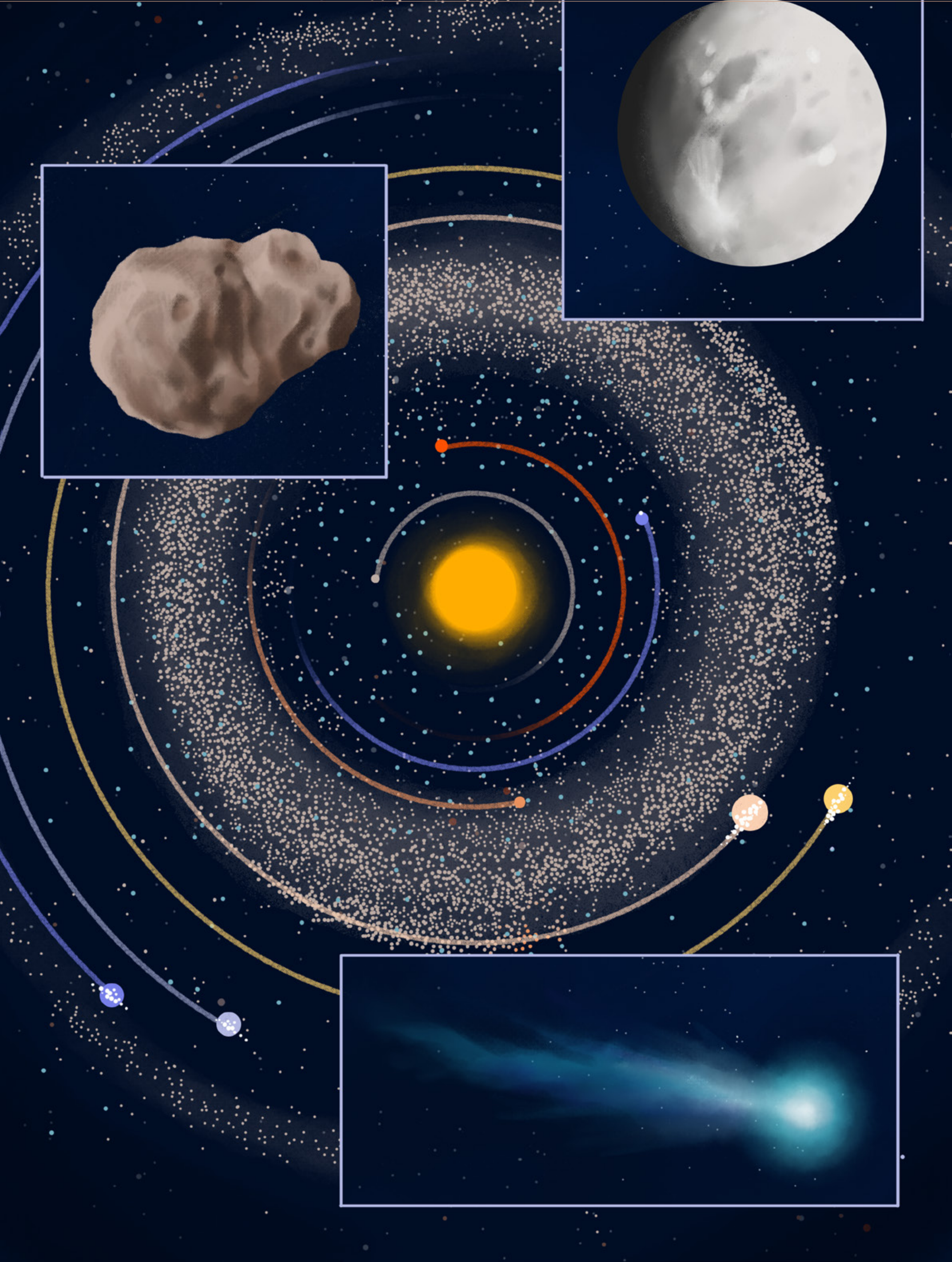
ESA Discovery also used OSIP to seek and select ideas for off-Earth manufacturing and construction. The funded projects explored technologies to shield crews and equipment, help them move around the Moon's surface and generate electricity.

As international teams around the world forge plans to revisit the Moon, ESA is exploring how best to facilitate this exploration. As part of its Moonlight initiative, ESA is conducting deep analyses of the planned lunar missions and further developing possible solutions – both technical and business-related – to provide telecommunications and navigation services for the Moon. An important early step in Moonlight is the Lunar Pathfinder mission.

During the 2020s, a space Gateway will be assembled and operated in the vicinity of the Moon, where it will move between different orbits and enable the most distant human space missions every attempted. Like a mountain refuge, it will provide shelter and a place to stock up on supplies for astronauts en route to more distant destinations. The spaceship will also offer a place to relay communications and can act as a base for scientific research.

Explore ESA's interactive web documentary to discover the why and how of lunar exploration.





ASTEROIDS, COMETS AND MOONS

We have learned a lot from visiting the Moon, and even more from visiting other planets, but what about the thousands of other small objects that share our Solar System? Space agencies have sent several spacecraft to asteroids, comets, dwarf planets and small moons, and have ambitious plans to send more in the future.

Asteroids and comets are believed to be leftover debris from the formation of the Solar System, meaning they can help trace its history. What's more, these objects may have played a vital role in the development of our planet and terrestrial life by colliding with Earth in catastrophic impact events, bringing life-sparking organic compounds. Such collisions were more common in the early Solar System, but small objects can still impact Earth, damaging life, nature and infrastructure.

Such objects may also have brought organic matter to other planets and moons, some of which – Jupiter's moon Europa or Saturn's moon Enceladus, for example – may possess the right conditions for hosting some form of life. For all these reasons, and many more, it is important to study these objects and find out more about them.

ESA missions to asteroids, comets and moons ▶

DISCOVERY & PREPARATION ACTIVITIES

Laying the groundwork for ESA's future activities, Discovery & Preparation supports exploratory research into new concepts. Several Discovery & Preparation studies have investigated different elements of possible future missions to explore small extraterrestrial objects.

Asteroids and comets whose orbits come close to or even cross that of Earth are known as near-Earth objects (NEOs), and they can pose an impact threat. To mitigate this threat, the first step is to search for NEOs and map their orbits. Discovery & Preparation supported a study that explored using star trackers – already on board many spacecraft for orientation calculation – to search for NEOs.

Another challenge we face from extraterrestrial objects is that dust on their surfaces may affect visiting spacecraft, landers and astronauts. The Dusty Plasma Environments study was the first step in developing a set of models that could assess the effects of dusty plasma on future exploration units.

Recent exploration probes and rovers host mini laboratories for in-situ research, but sophisticated laboratories on Earth can perform even more advanced tests. One Discovery & Preparation study explored how to set up a facility on Earth that could safely handle such precious and potentially hazardous samples that were brought back from these space rocks. The investigation was based on previous Mars sample return facility studies.

Another study explored how to land safely on a low-gravity object. It was carried out primarily by the German Aerospace Centre (DLR), who developed the MASCOT lander for the Japanese Hayabusa2 asteroid mission. The study looked into developing a second lander, MASCOT-2, designed to land on Dimorphos (previously known as Didymoon) – one half of the double asteroid target of ESA's Hera mission. Due to be launched in 2024, Hera is one of Discovery & Preparation's great success stories.

Hera will host two CubeSats that will be able to get closer to Dimorphos, whilst Hera examines the aftermath of the impact of NASA's DART spacecraft on Dimorphos' larger partner, Didymos. Being versatile, small and relatively cheap, many Discovery & Preparation studies have investigated how CubeSats could be used to explore smaller space objects. Several of these studies focused specifically on Hera's companions.

Once we've found out more about asteroids, comets and moons, we may start thinking about using the rich diversity of material we find there as energy sources or a means to sustain human life as we venture deeper into space. A recent Discovery & Preparation study compiled a list of potential space resource utilisation missions, performed preliminary risk analyses and proposed a risk assessment methodology. A very forward-thinking study even explored how astronauts could use ESA's Neutral Buoyancy Facility to train for trips to these interplanetary objects, where gravity would be present but very weak. More Discovery & Preparation activities focusing on asteroids, comets and moons can be found in the Nebula Library of studies.

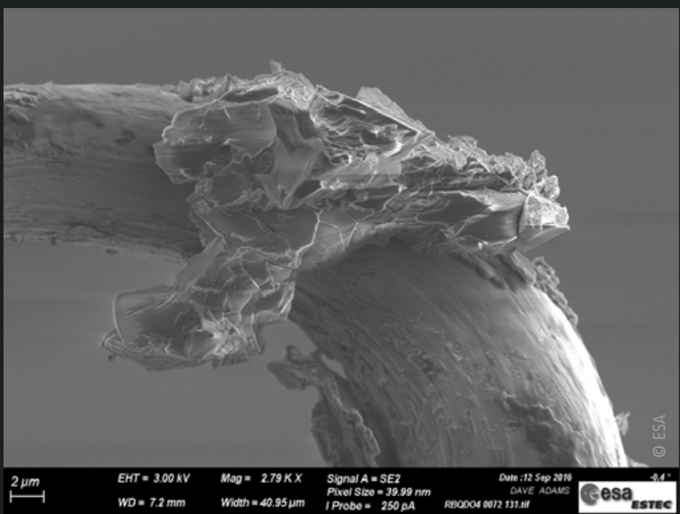
▲ Rosetta and Comet 67P

ESA-wide activities

Hera now falls under ESA's Space Safety activities, which enable Europe to understand and minimise the dangers of risky asteroids, extreme solar events and space debris. The Planetary Defence Office observes near-Earth objects, predicts their orbits, produces impact warnings when necessary, and is involved in potential mitigation measures.

ESA also made history by orbiting a comet with the Rosetta mission. Remaining with Comet 67P/ Churyumov-Gerasimenko for over two years, Rosetta found out a plethora of information about periodic comets, and even released a lander to get closer to the surface of this mysterious object.

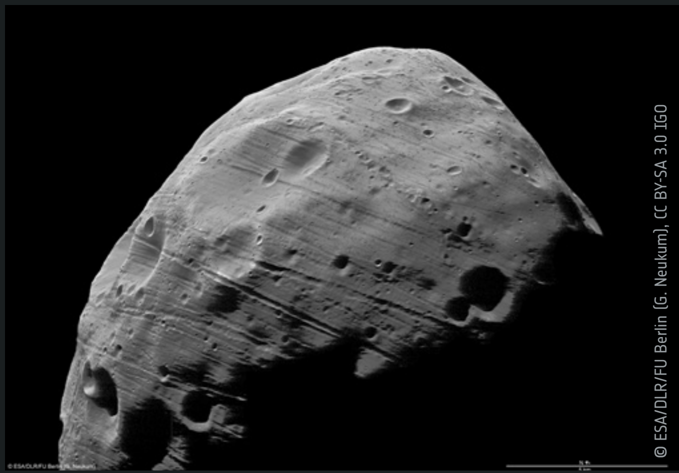
Next, ESA has its eyes on an asteroid. The Agency is working with GomSpace Luxembourg to design the first ever nanosatellite to rendezvous with an asteroid. Due to launch in 2024/5, the Miniaturised Asteroid Remote Geophysical Observer (M-ARGO) will be a 12-unit CubeSat with its own propulsion system. This is being funded though ESA's General Support Technology Programme (GSTP), which is also supporting updates to a tool that will support future ESA lander missions by modelling surfaces of small bodies in our Solar System and providing photo-realistic images.



▲ Microscopic view of a grain of rock from Itokawa

ESA is already involved in asteroid research, through testing three grains of rock brought back from asteroid Itokawa by Japan's Hayabusa mission. This is contributing to our knowledge about the surface environment of asteroids, including offering insight into how the surface of asteroid Didymos will respond to impact.

Planetary missions are also contributing to our understanding of extraterrestrial objects. Whilst orbiting Mars with Mars Express and the ExoMars Trace Gas Orbiter, ESA observed Mars' moons, Phobos and Deimos. Moving further afield, The JUpiter ICy moons Explorer (Juice) mission will investigate three of Jupiter's largest moons – Ganymede, Europa and Callisto – to determine whether any of them may be habitable.



▲ Phobos, imaged by Mars Express

But we don't necessarily need to get close to these objects to learn about them. ESA's space telescopes, including Hubble, have photographed numerous small bodies throughout the Solar System to discover more about their characteristics and orbits. Hubble recently captured an image of a rare self-destructing asteroid, Gaia collected information on more than 14 000 asteroids, Herschel discovered water vapour around dwarf planet Ceres, and the Infrared Space Observatory discovered twice as many asteroids as were previously believed to exist.

What are other space agencies doing in this area?

▲ Hubble deep image of the Universe, photobombed by asteroids that left white trails on the image

Aside from landing on two different asteroids with their Hayabusa and Hayabusa2 missions, JAXA is currently planning a mission to survey Mars' two moons: Phobos and Deimos. The mission, Martian Moons eXploration (MMX), even plans to collect a sample from one of the moons and bring it back to Earth.

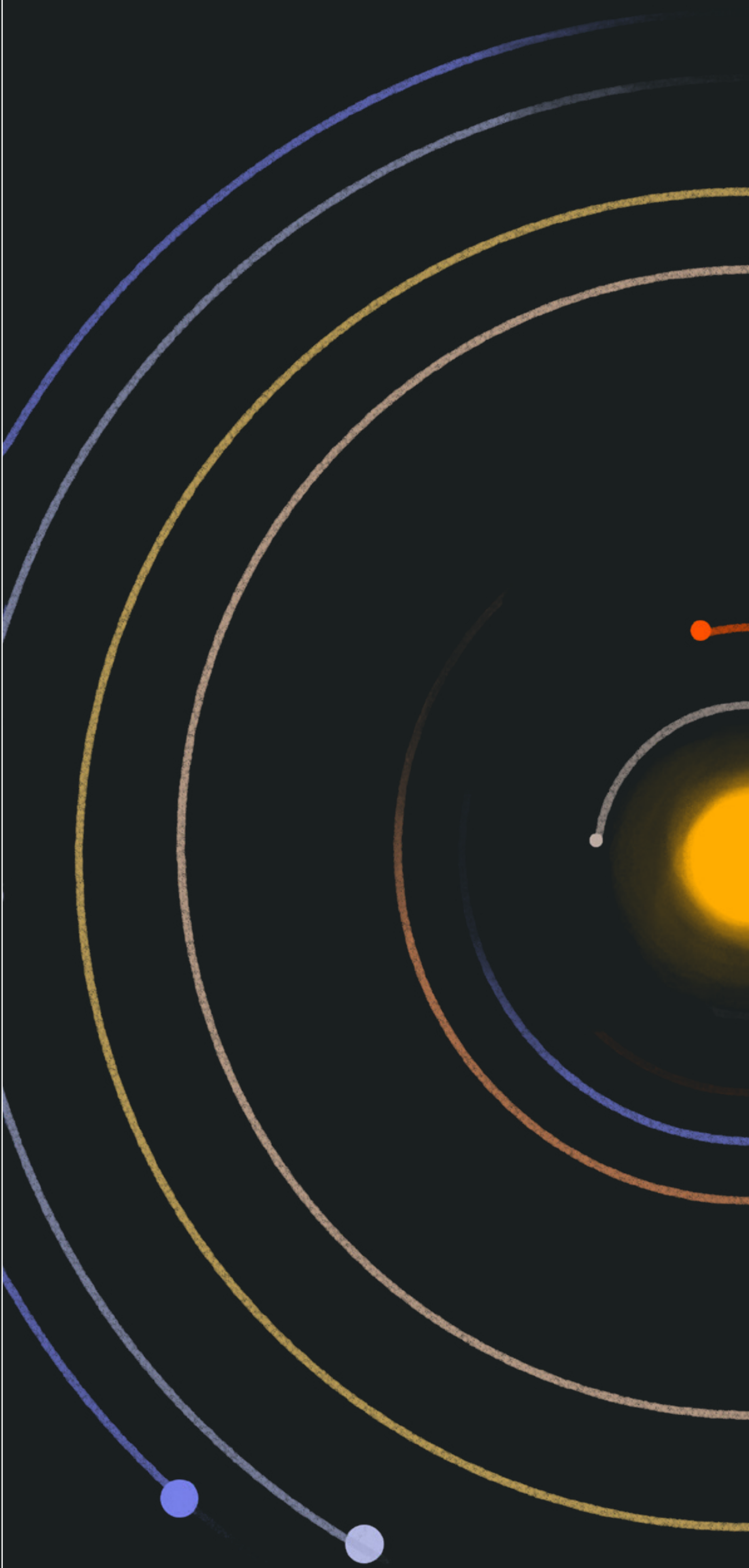
NASA has also visited extraterrestrial objects in the past, with the Dawn mission being the first to orbit a dwarf planet – Ceres – and also visiting the biggest asteroid in the Asteroid Belt, VESTA. Dawn discovered that Ceres was previously an ocean world and found organic material. It also confirmed that Vesta is the source of many meteorites found on Earth.

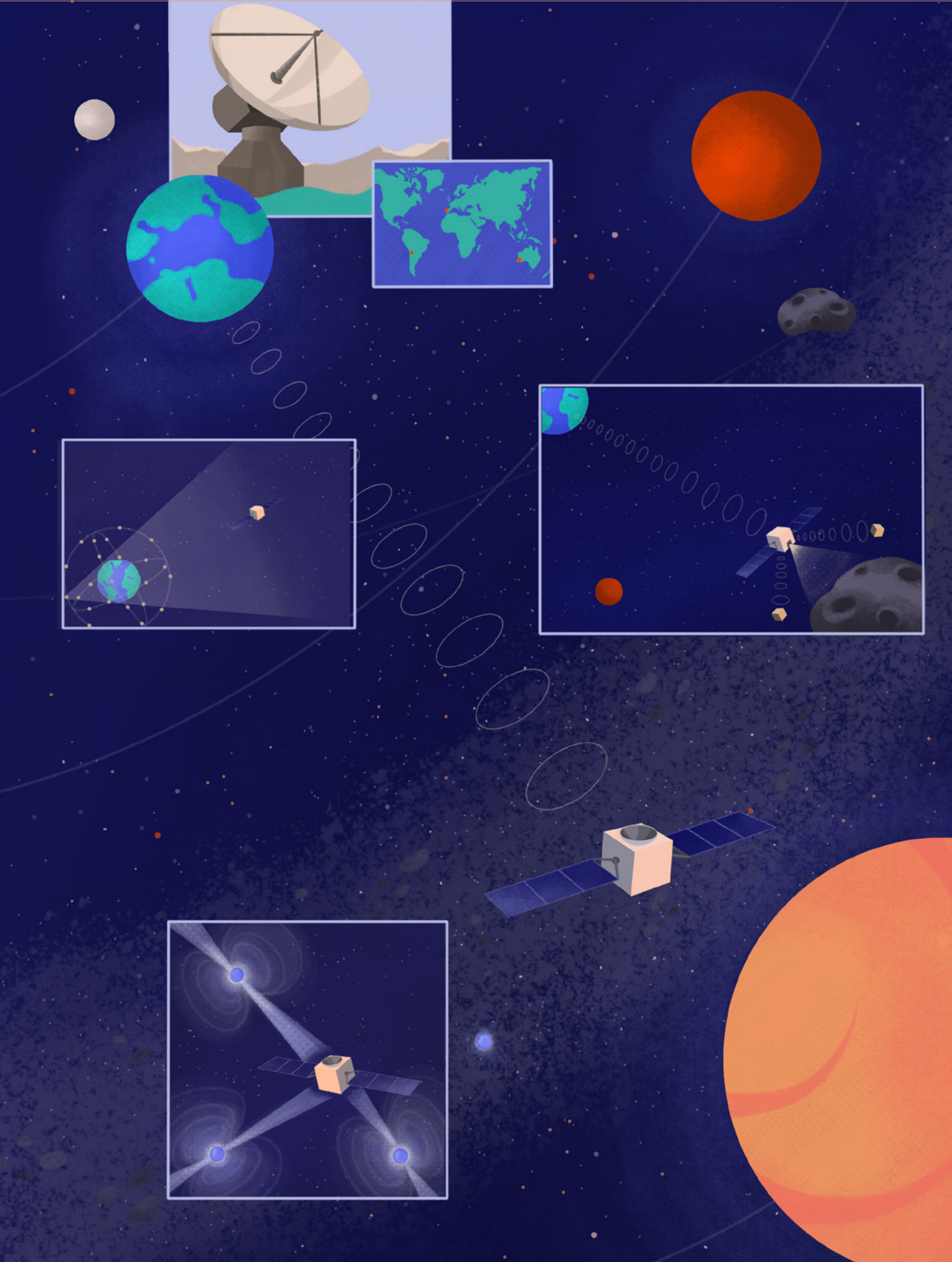
The US Stardust mission collected dust from comet Wild-2, which indicated that comets may have formed very differently than was originally believed. Deep Impact also visited a comet – Temple 1, crashing an impactor into the comet's surface to expose materials such as water ice and organic matter. These results suggest that comets may have played an essential role in the initiation of life on Earth.

▲ Dawn visits Vesta

Right now, NASA's OSIRIS-REx spacecraft is orbiting an NEO. OSIRIS-REx plans to bring back a sample to Earth to support investigations into how planets formed and life began.
The Canadian Space Agency (CSA) participated in OSIRIS-Rex by providing an instrument that is mapping the asteroid's surface, allowing scientists to select a suitable sample site. CSA also developed the Near-Earth Object Surveillance Satellite (NEOSSat), dedicated to detecting and tracking asteroids that may someday pass close to Earth.

And it's not only space agencies that are involved in finding out more about NEOs – the European Southern Observatory (ESO) also dedicates time to this cause. In 2019, ESO's Very Large Telescope imaged a double asteroid that came close to Earth. This provided a good opportunity to rehearse how space organisations would work together if a hazardous NEO ever threatened Earth directly. The project was coordinated by the International Asteroid Warning Network (IAWN), a collaboration between many space organisations aiming to protect Earth from NEOs.





DEEP SPACE COMMUNICATION AND NAVIGATION

In recent years, ESA has designed some of the most advanced spacecraft ever built to reach exotic locations such as the Sun, Mercury, Mars, Jupiter and the Didymos asteroids – a trend that will continue into the years ahead. As missions voyage further from Earth, it is important to consider how we can continue to communicate with them and how they will navigate through space when they are so far from home.

To communicate effectively with spacecraft, we need to send and receive status, navigation and scientific data. This is achieved using ground stations on Earth. ESA operates a sophisticated system of ground stations, including three Deep Space Antennas (DSA) (a fourth is currently under construction) located around the world, providing continuous coverage as Earth rotates.

To ensure that missions meet their science objectives, ESA continues to develop technologies to communicate with them more effectively. This includes the technologies on board spacecraft, as well as those on the ground.

DISCOVERY & PREPARATION ACTIVITIES

Discovery & Preparation lays the groundwork for ESA's short- to medium-term future activities. The Preparation element recently ran the Open Space Innovation Platform (OSIP) Campaign 'What's Next – new ideas for space missions and concepts'. A number of ideas for new deep space missions were addressed, especially supporting future human interplanetary spaceflight, Mars exploration and missions to near-Earth objects.

As part of its provision for future deep space missions, Discovery & Preparation has conducted several investigations into future ESA's space science missions. A study that finished in 2009 developed a system to enhance the operation of these missions – which typically travel relatively far from Earth – through a flexible planning, scheduling and optimisation process. A more recent study proposed an end-to-end mission simulator to improve their efficiency.

Discovery & Preparation has also contributed significantly to ESA's Proba missions, which test new technologies in space. A 2009 study envisaged an interplanetary Proba mission – Proba-IP – to travel to a near-Earth object and validate autonomous onboard guidance, navigation and control technologies.

On top of these general investigations, Discovery & Preparation has carried out more specific studies that focus on individual deep space communication and navigation technologies.

▲ ESA ground station network, with the three deep space tracking stations labelled with yellow boxes.

· Communication – making long-distance relationships work

Communicating with distant spacecraft is difficult. The signals that pass between the spacecraft and ground stations are very weak and because of the large distances, it takes them a long time to travel between the two. It can take up to 24 minutes for a signal to travel between Earth and Mars, for example, and almost an entire day to receive a signal sent by NASA's Voyager 1 – a spacecraft that has travelled beyond the edge of the Solar System.As there are strong constraints for equipment on board spacecraft, a lot of the more complex communications technologies are incorporated into the ground stations. Many Discovery & Preparation studies have contributed to developing such technologies.

A study that finished in 2012 explored the feasibility of developing klystrons entirely within Europe. These devices transform electrical power into amplified radio signals to send commands from ground stations. The study set the requirements and objectives for the development of such a device, as well as defining an industrial environment and potential roadmap for the future. Klystrons are now used in ESA's network of ground stations.

▲ ESA's New Norcia station (Deep Space Antenna-1) in Australia

Another study focused on selecting the best ground station architecture for future deep space missions. By gathering data about the current performance of ESA's Deep Space Antennas, as well as collecting the needs and characteristics of future missions, the study calculated the characteristics of the ground system that would be required to meet these needs. The study noted that communicating with optical frequencies is more efficient than the more traditional radio frequencies.

To reach distant spacecraft or for intra-satellite communication, optical communication is becoming an interesting alternative to radio communication because it allows more data to be transmitted; this maximises scientific return and could enable new types of missions. However, optical signals are affected more by Earth's atmosphere.

Given the increasing demand on downlink data rate to increase science return, in 2016 the Deep Space Optical Communications Architecture Study (DOCOMAS) presented how technology needs to evolve in the future to enable optical communication between a deep space probe and Earth. The study focused on the ground segment, including cloud mitigation strategies. It identified that the key enabling technologies are dedicated optical ground antennas, novel photon detectors and a generic design approach to an optical payload terminal. The concept design was tailored for ESA's Asteroid Investigation Mission (AIM), which has evolved into the Hera mission.

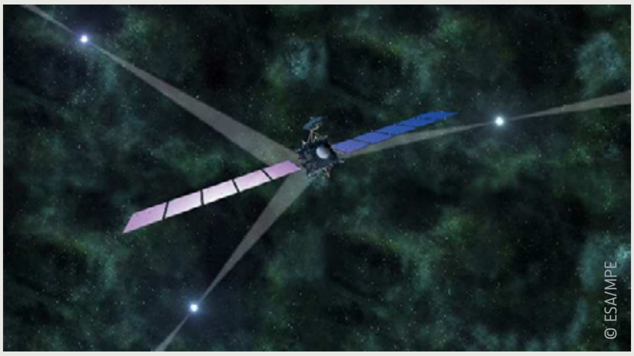
DOCMAS built on the results of an earlier study that focused on developing technologies for communicating with interplanetary missions, including investigating the required optical technologies. With communications being a notorious bottleneck in interplanetary science and exploration missions, the goal was to propose a technology development roadmap to enhance communication capabilities.

Another study explored how ESA's Optical Ground Station (OGS) – usually used for communicating with nearby spacecraft – could be used to communicate with deep space missions.

· Navigation – turning time into distance

Good communication is vital not only for collecting science and status data, but also for navigating spacecraft through the Solar System. To navigate spacecraft we need to know their position, which is no easy feat when they are so far away. But by measuring three parameters – distance, velocity and the angle at which a spacecraft is located in the sky – it is possible to calculate a satellite's position down to a small box-shaped region of space.

One element that is essential to navigating deep space is timing, in particular ensuring that the time on board spacecraft is synchronised with the time on the ground. To calculate where a spacecraft is in the Solar System, we precisely measure the time it takes for electromagnetic waves to travel between the spacecraft and an antenna on Earth. Navigators on Earth then transmit course adjustments. A 2007–2009 study explored forward thinking techniques to synchronise time on board deep space probes for accurate navigation, in particular looking into low-cost options. A parallel study found that an accuracy of ten nanoseconds for a signal passing from a spacecraft to Earth is possible without using an onboard atomic clock.

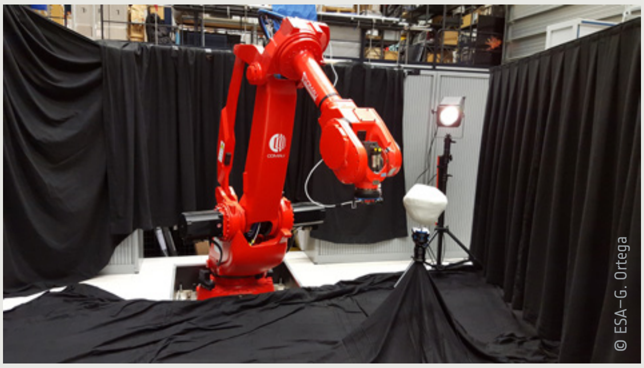


▲ Navigating with the aid of pulsars

Navigating a spacecraft to distant locations requires a team of scientists and engineers using sophisticated radios, large antennas, computers, and precise timing equipment. Whilst the DSAs have been the standard tool for navigating spacecraft in the past, the network comes with limitations and partial autonomous navigation is becoming more common. One method that has been explored more over the past decade is to navigate using pulsars – magnetised, swiftly rotating, dying stars that emit beams of electronic radiation out of their magnetic poles.

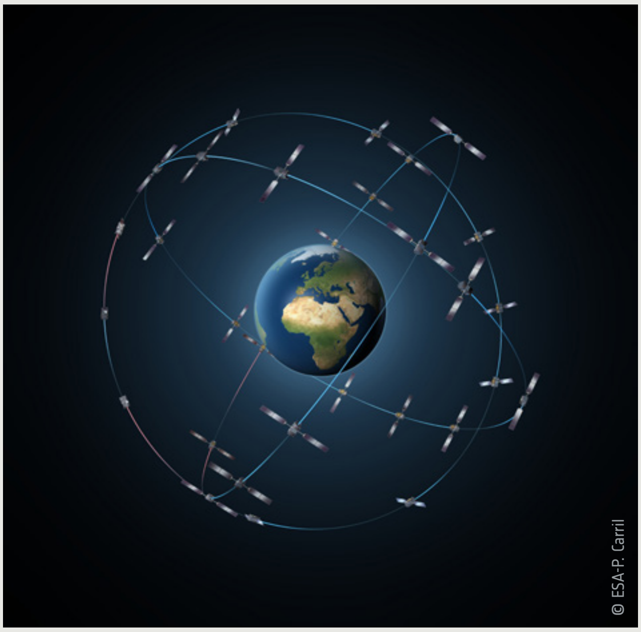
Millisecond pulsars – which have rotation periods of less than ten thousandths of a second – offer the most precise timing standard known. In a kind of celestial GPS, spacecraft can measure the time between receiving each pulse of radiation from three different pulsars, looking for tiny changes in the arrival times to pinpoint its location.

This was still a very novel idea between 2012 and 2014, when Discovery & Preparation supported two studies that explored the feasibility of deep space navigation with X-ray pulsars. The first was carried out by the UK's National Physics Laboratory and University of Leicester, and the second by the University of Helsinki. Among other discoveries, the research found that the benefits of such a technique include increased spacecraft autonomy, improved position accuracies and much lower mission operating costs due to the substantial reduction in the use of the associated ground-based systems.



▲ Preparing the practical test of the navigation of Hera around Didymos

Pulsars are not the only astronomical objects with the potential to be used for navigation. A 2016 study investigated the feasibility of an onboard visual navigation system for ESA's Hera mission (then AIM), which will visit double asteroid Didymos later this decade. The system laid the path towards developing such a system; Hera will use its onboard camera to determine the position of the asteroids with respect to the background stars. Hera will also demonstrate communication with a ground station via an optical link as well as communication between the main spacecraft and two CubeSats.



▲ Europe's constellation of Galileo GNSS satellites

What about making use of Global Navigation Satellite Systems that enable Earth-based navigation to negotiate our way further afield? Navigation satellites orbit around 22 000 kilometres above Earth's surface. As they point down towards Earth, any spacecraft below them are served well by the signals they send out. But around ten years ago, engineers started demonstrating that spacecraft outside the orbit of navigation satellites could also navigate in space using their 'spill over' signal.

In 2012, two Discovery & Preparation studies kicked off to investigate a seemingly radical question: could this spill over signal even be used to navigate our way around the Moon, and if so, what kind of receiver would we need to build to be able to use these signals? The studies – led by Deimos and Joanneaum Research – found that indeed, the signal from navigation satellites orbiting Earth could be used to navigate the Moon's surface. But with the signal being so weak, they concluded that a new type of receiver would need to be built. ESA has now invested in the development of such a receiver, and is exploring whether it could be demonstrated on the Lunar Pathfinder mission.

What else is ESA doing?

ESA has several missions already working in deep space, including Solar Orbiter, ExoMars and BepiColombo. Next year will see the launch of the JUpiter ICy moons Explorer (Juice), which will spend at least three years observing Jupiter and three of its largest moons. In 2024, ESA's planetary defence mission, Hera, will set off to visit an asteroid, in the process discovering more about these rocky objects and finding out if we could deflect an asteroid on collision course with Earth.

ESA's ambitious plans for the next decade of human and robotic space exploration will take us from the ISS to the Moon, a deep-space gateway and a Mars landing. Concrete steps are already being taken towards exploring the Moon; NASA's new Orion vehicle, with a European service module at its core, will build bridges to Moon and Mars by sending humans further into space than ever before.

For all robotic and human missions to the Moon, asteroids, Mars or beyond, at least one DSA is essential for communications. ESA's Operations directorate controls spacecraft – including those voyaging deep into the Solar System – and develops and manages the necessary ground infrastructure. Prior to every mission launch, Operations teams carefully design and build the ground segments that enable engineers to control satellites in space and receive and distribute their data.

▲ ESA's Malargüe tracking station supports many deep space missions

ESA Operations oversees ESA's tracking station network, Estrack, the core of which comprises seven stations in seven countries, including the four DSAs. Furthermore, the directorate is currently operating the tiny OPS-SAT satellite, which is devoted to testing and validating drastically improved mission control capabilities.

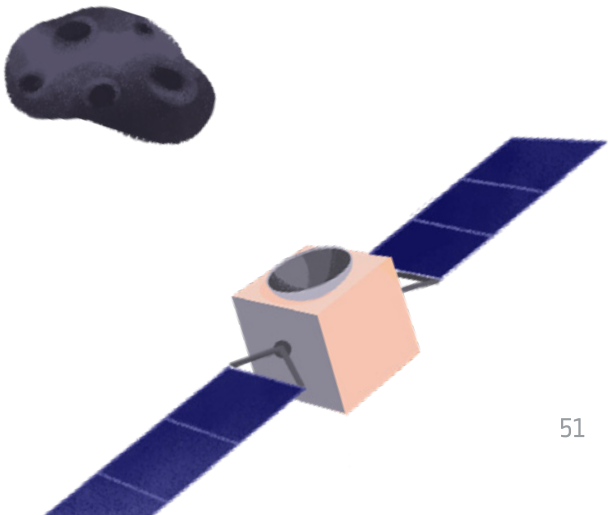
In addition to the daily operation of spacecraft exploring space hundreds of millions of kilometres away, ESA's operations teams continually work to develop new capabilities to support future missions, including flight-dynamics techniques, delay-tolerant networks, deep-space communication technologies and innovative satellite control software and systems.

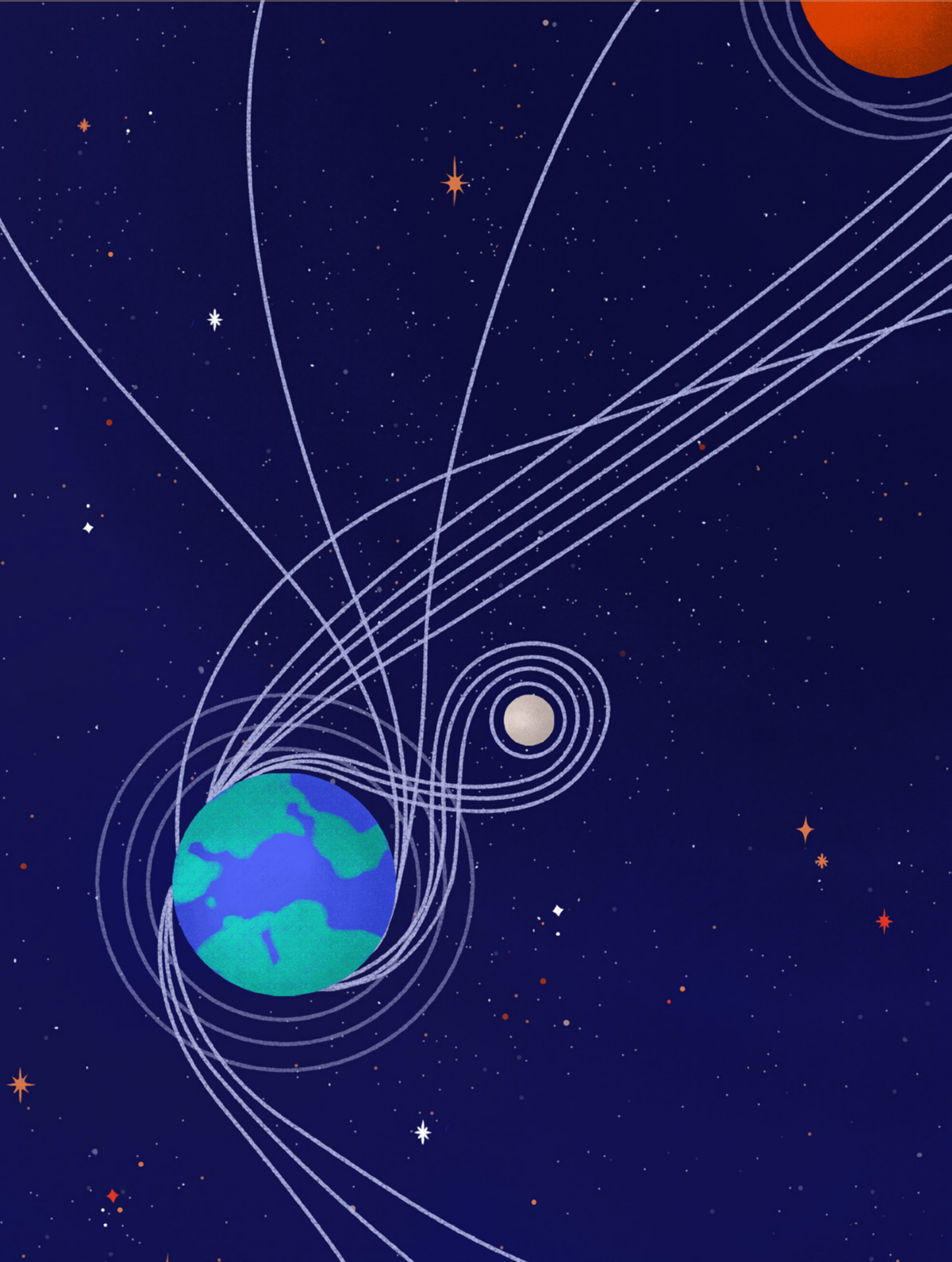
What are other space agencies doing?

ESA shares Estrack capacity with other space agencies, who in return provide tracking services to ESA missions under a number of resource-sharing agreements. These include networks and stations operated by ASI (Italy), CNES (France), DLR (Germany), NASA's Deep Space Network and Goddard Space Flight Center and JAXA (Japan).

For example, NASA's Deep Space Network stations routinely support Mars Express (as well as other, now-completed missions such as Rosetta, Huygens and Venus Express), while Estrack is supporting Japan's Hayabusa-2 mission. In recent years, Estrack has provided support to missions operated by China and Russia, as well as tracking the descent of NASA rovers to the surface of Mars.

Other space agencies are also developing their own technologies for communicating with and navigating deep-space spacecraft. For example, NASA has developed a deep space atomic clock and an X-ray navigation device that determines the position of a spacecraft anywhere in the Solar System, and JAXA has worked on a navigation system using highly accurate 3D radar and navigation guidance control technology for rendezvous and orbit transition to the neighbourhood of the Moon.





PROPULSION: LIFT-OFF, ORBIT ADJUSTEMENTS AND TRAVELLING THROUGH SPACE

The launch of a spacecraft is the start of a new mission and the only means to reach the depths of the Solar System. With reusable rockets becoming a reality, what is ESA doing to advance propulsion technology and make it greener?

Without propulsion, nothing goes anywhere. It provides the extreme acceleration a rocket needs to lift off and release a spacecraft into orbit around Earth or sling it into deeper space. Spacecraft themselves then use their own propulsion systems to adjust their orbits around Earth, travel through space, or make carefully controlled landings on the surfaces of other planets.

European launch vehicles are known for their reliability, but ESA continues to develop new technologies to enable lower-cost, greener and ever more reliable launches. Rockets typically make use of 'chemical propulsion', of which there are two main types: liquid and solid. Whilst liquid propulsion is more efficient, solid propulsion is simpler, safer and cheaper.

• Liquid propulsion combines fuel with oxygen in a combustion chamber. The mixture is ignited and explodes, creating powerful combustion gases. These are propelled from the engine's central nozzle, thrusting the rocket forward. The fuel flow can be controlled and the amount of thrust regulated. Liquid propulsion remains state-of-the-art for the large thrust generated by current launch vehicles as well as in-orbit spacecraft manoeuvres.

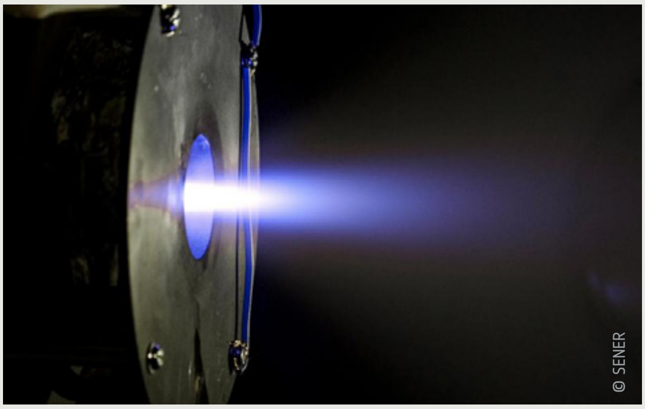
• Solid propulsion works on the same principle as a firework: a pre-mixed fuel and an oxidiser are ignited, after which the thrust cannot be regulated or turned off. Solid propulsion can be useful for 'kick' stages that put satellites into their final orbit.

▲ Chemical propulsion in action during an Ariane 5 launch

One alternative to chemical propulsion is electric propulsion. This more efficient process uses electricity to expel propellant at high speed. Partly thanks to studies carried out by ESA Discovery & Preparation, electric propulsion is an increasingly mature technology. Electrostatic engines in particular are prized for their ability to deliver sustained thrust over prolonged periods of time with limited masses of fuel.

Discovery & Preparation is also exploring more novel propulsion techniques such as lasers, solar sails and nuclear propulsion.

DISCOVERY & PREPARATION ACTIVITIES



▲ A test firing of Europe's Helicon Plasma Thruster, ideal for propelling small spacecraft

· Early studies

ESA Discovery & Preparation invests in novel research to direct the future of space activities. In 1999, the programme supported two study phases that assessed the needs for advanced space propulsion in the following century. Phase 1 of the PROPULSION 2000 study identified the most promising propulsion concepts and techniques for the foreseeable future. Phase 2 proposed development plans for four main mission scenarios: launch vehicles, orbital transfer vehicles, satellites and deep space missions.

A 2002 study explored the power needs of future missions, including for propulsion. It concluded that over the following 5 to 15 years, Europe should focus on developing nuclear propulsion technology as well as demonstrating power beaming propulsion, which typically uses either a microwave or laser beam to propel a spacecraft forward. ESA's Advanced Concepts Team have since explored beam-powered light sails.

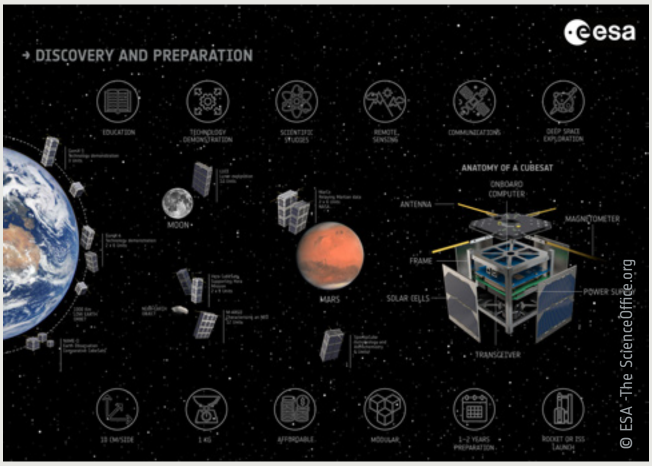
· Electric propulsion

It was around the turn of the century that electric propulsion technologies started looking more attractive; the lifetime of electronics was increasing and spacecraft were able to generate more electrical power.

Electric propulsion is now considered to be a key and revolutionary technology for new generations of satellites. It uses electricity to accelerate a propellant, and unlike chemical propulsion, it requires very little mass. In recent years, it has become a more popular choice for deep space missions; it has been used on ESA's BepiColombo, GOCE and SMART-1 missions.

In 2014, a Discovery study was one of the first explorations of Helicon Plasma Thrusters for space applications. These thrusters use high power radio waves to excite the spacecraft propellant into a plasma state, which can achieve much higher propellant velocities. The study identified missions for which a Helicon Plasma Thruster would be particularly advantageous; it found that missions involving long-term orbiters based on the International Space Station (ISS) would benefit especially, as they could use ISS waste gases as a propellant.

Another study explored the application of the clusterelectric effect to electric propulsion systems. The process involves making electricity from tiny molecular 'snowballs'; it has various benefits for electric propulsion, resulting in propulsion systems that are flexible, lightweight, provide effectively unlimited energy, and have a high thrust-to-power ratio.



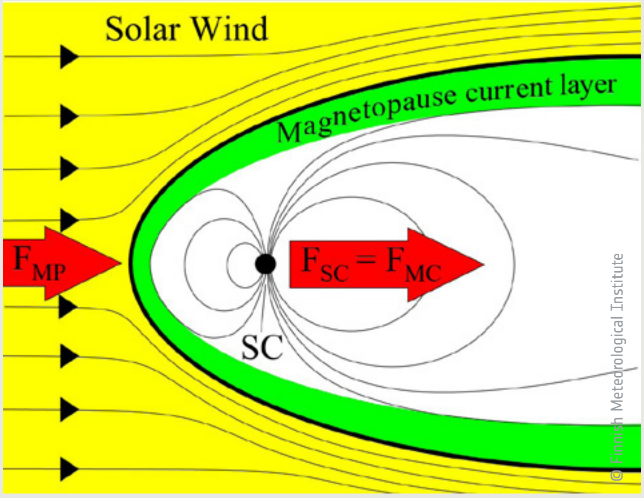
▲ ESA's CubeSats, as of October 2018

In recent years, more and more small satellites have been launched. These often include no onboard propulsion system, which reduces their capabilities and lifetime. TNO, NanoSpace and EPFL recognised that improving the next generation of small satellites required developing miniaturised, highly integrated propulsion systems that met strict mass, volume and power constraints. In a first step to achieving this, through a 2009 study they developed a new electric propulsion system based on microelectromechanical systems (MEMS). The study identified a wide variety of mission scenarios that could benefit from such a propulsion system.

To make electric propulsion systems even more efficient, a Discovery & Preparation study investigated a process that involves accelerating hot plasma through a magnetic nozzle. The study found that this technique could improve the performance of an engine.

Solar electric propulsion uses the electrical power from onboard solar panels. A 2012 study looked into combining solar electric and chemical propulsion to take advantage of the respective benefits of each.

· Other propulsion techniques



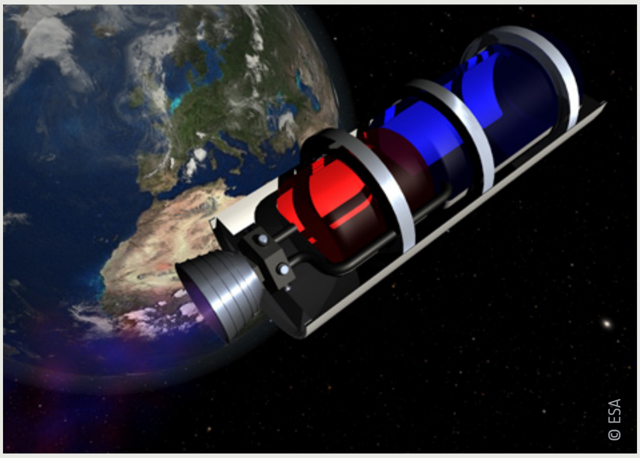
▲ Propulsion through the generation of a magnetic bubble

Solid propulsion was introduced for military uses during the second world war. Since the late 1950s it has been used in many small launchers, including Europe's Vega. Solid propulsion has also been used for orbit adjustments, reorientation, separation and much more. A 2012 study evaluated the current state of the art in solid propulsion technologies and created a tool that can be used to either select existing solid rocket motors from a database or create preliminary designs for new motors.

Solar sails that propel spacecraft through space using the momentum of sunlight are becoming increasingly topical, but what about utilising the magnetic nature of the solar wind? One study looked into the theoretical and technical aspects of two 'magnetospheric propulsion' concepts, where a spacecraft uses an electric current to generate a magnetic bubble around itself that diverts the solar wind.

But it is not all about the success stories. Discovery & Preparation studies are also good for finding out what would not work well. In the early 2000s, controlling gravity for spacecraft propulsion was a topic regularly discussed in scientific publications. A Discovery & Preparation study showed that – even if gravity could be modified – it would bring only modest gains in spacecraft launches, and no breakthrough for space propulsion.

· Sending a spacecraft to sleep



▲ Passivation

Even when a spacecraft is no longer useful, its charged batteries or leftover fuel can trigger explosions, a major source of space debris. To avoid this, ESA is investigating methods of 'passivation'
– ensuring that a spacecraft has no remaining energy on board.

Two parallel Discovery & Preparation studies have been key for developing this concept. The first reviewed passivation requirements and impacts, as well as passivation strategies for current and future missions. The second focused more on the risk of generating space debris due to a failure in a propulsion system, including the specific risk of a non-empty propulsion tank being impacted at high speed.

What else is ESA doing?

▲ Artist's impression of Ariane 6

Ariane is Europe's very own rocket programme, providing Europe with independent access to space. ESA works with Airbus, ArianeGroup and other partners on Ariane, including on propulsion elements. The newest member of the rocket family, Ariane 6, is due for its first launch in 2023.

By 2025, Ariane 6 may be using the Prometheus engine. This ultra-low-cost reusable engine is fuelled by liquid methane and demonstrators are currently being built through ESA contracts. Prometheus could achieve a tenfold reduction in costs compared with the existing Ariane 5 Vulcain 2 engine.

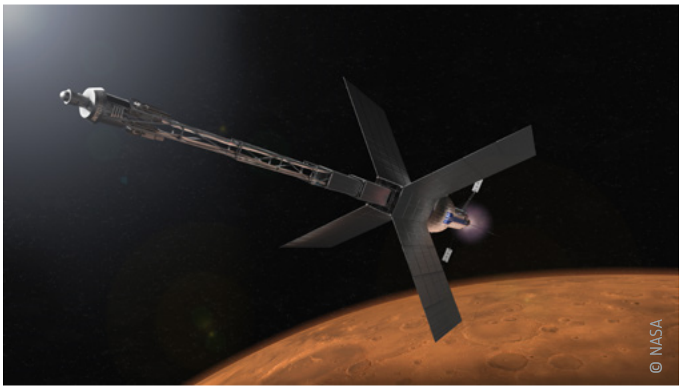
ESA is also developing the Expander-cycle Technology Integrated Demonstrator, or ETID, which will pave the way for the next generation of cryogenic upper-stage engines in Europe. In this innovative design, liquid hydrogen propellant is 'expanded' through cooling channels before being combusted, going from liquid hydrogen temperatures to full combustion in just over a second. Its results are relevant for the reignitable Vinci engine, which has been developed to power the upper stage of Ariane 6.

ESA's dedicated Propulsion Laboratory tests methods of controlling the motion of spacecraft once they have reached space. In particular, the lab has acquired a great deal of expertise on various methods of electric propulsion as well as chemical propulsion systems.

▲ The Expander-cycle Technology Integrated Demonstratora

▼ ESA's Propulsion Laboratory

What are other space agencies doing?



▲ A Mars transit habitat and nuclear propulsion system that could one day take astronauts to Mars

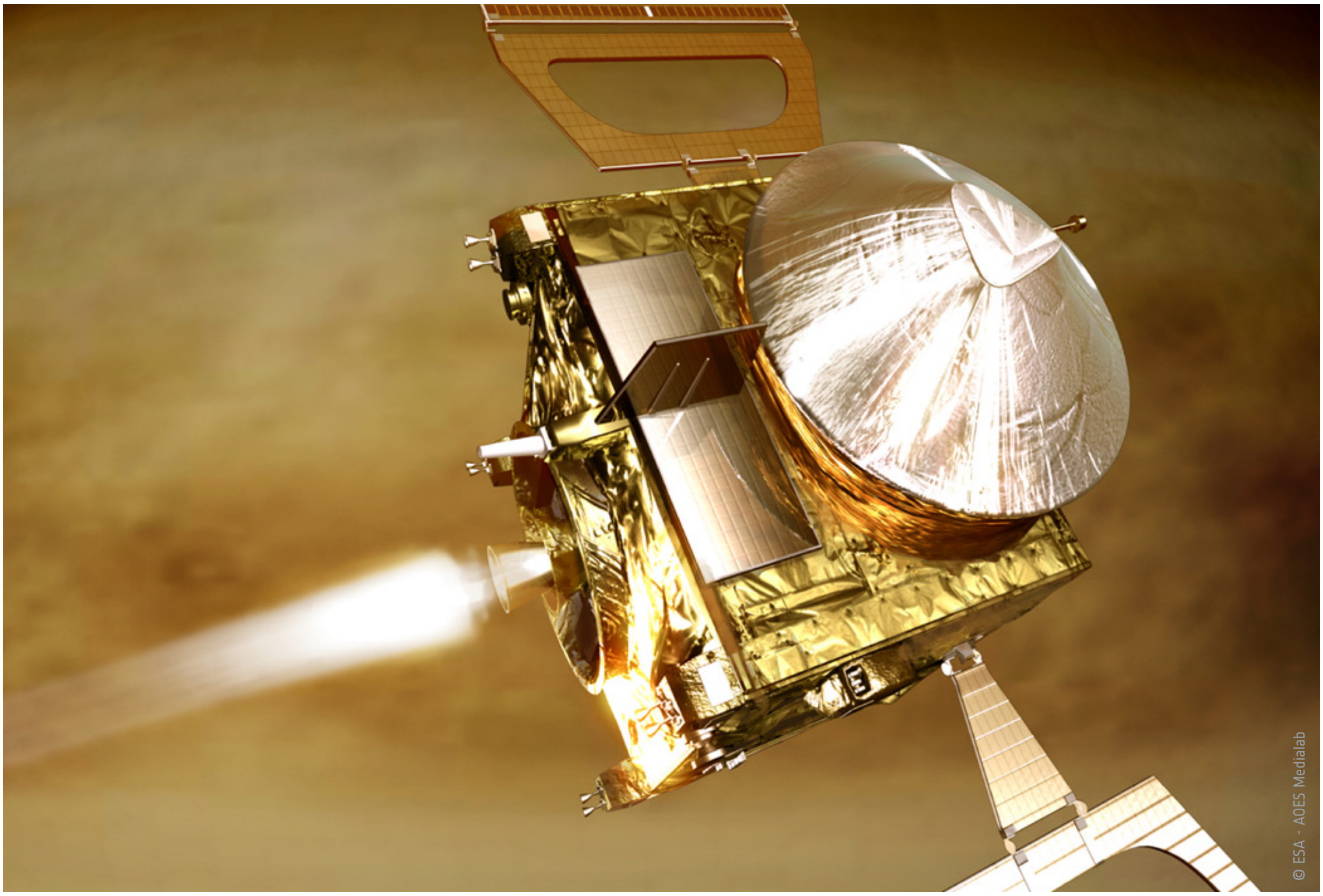
NASA is also exploring electric propulsion; its Power and Propulsion Element for the Lunar Gateway, for example, will demonstrate advanced, high-power solar electric propulsion around the Moon. The US agency is also exploring propulsion concepts for visiting Mars, including a combination of nuclear electric and chemical propulsion, as well as emerging technologies such as nuclear thermal propulsion.

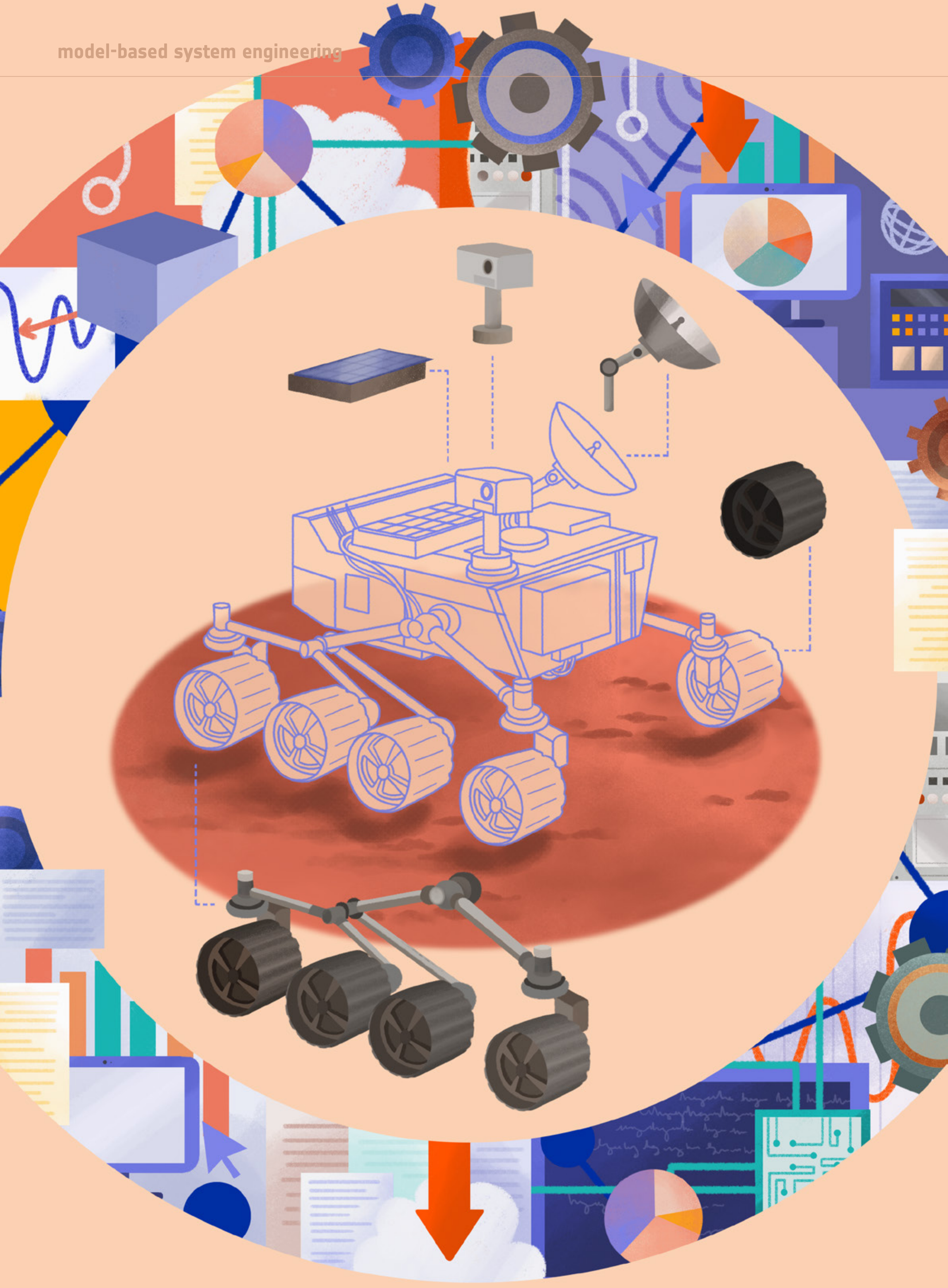
The German Aerospace Center (DLR) is also involved in propulsion, for example the ETID was tested at the Center's Lampoldshausen site. DLR also hosts an Institute of Space Propulsion, where engines for rockets such as the Ariane family have been tested and further developed since 1959.

The operation and marketing of the Ariane programme is undertaken by Arianespace, a commercial subsidiary of French space agency, CNES. CNES supported the design of Ariane 6 and develops the ground facilities in French Guiana that are needed to launch the Ariane rockets.

ESA works with the Italian Space Agency (ASI) on another launcher – Vega. Since its first launch in 2012, Vega has been making access to space cheaper, quicker and easier. It typically carries satellites for scientific and Earth observation missions to polar and low Earth orbits.

The Japanese Space Agency, JAXA, is researching more environmentally friendly propulsion technologies for both rocket launchers and aircraft. Rocket engine research and development is led by the Kakuda Space Center, which conducts research ranging from basics to applications. JAXA even has a dedicated Electric Propulsion Laboratory focusing on the R&D of electric propulsion technologies and related plasma diagnostic techniques. Thrusters developed at the lab were deployed on the recent Hayabusa and Hayabusa-2 missions.





MODEL-BASED SYSTEM ENGINEERING

Targets set out in ESA's Technology Strategy require a fundamental revolution in the way that space technology is developed. Model-based system engineering (MBSE) could be the answer.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Traditionally, system engineering is based on documents, but space systems are becoming too elaborate to manage with documents alone. The workings of a space mission are increasingly complex, entangled, and full of exceptions and dependencies, making text descriptions inadequate to describe their behaviour completely and consistently.

Over a decade ago, ESA began pushing core MBSE technologies and coordinating activities within Europe, with the aim to reduce documentation, make data more accessible, and ensure digital continuity throughout the lifecycle of a space mission, across disciplines and throughout supply chains.

But what exactly is MBSE?

Let's start with systems engineering. Many separate elements go into making a space system, with individual subsystems developed by specialist teams. System engineers focus on the space system as a whole. By incorporating needs and requirements, they design the architecture of a system, define its building strategy and oversee the integration of subsystems, as well as the verification and validation of the overall system, to form the final result.

Model-based system engineering builds a project using models to describe all the different subsystems and elements, rather than documentation. Information that would usually be included in documents is expressed in a more structured and digitally processable way – as diagrams and tables, for example, rather than as words. This allows it to be more easily processed by computers and used within different software tools.

Models can be developed, reused, and they have inputs and outputs. And like the transition from analogue to digital, the transition from documents to models will enable space projects to be much more efficient.

"*The full digitalisation and the transition to model-based system engineering is […] a key enabler to increase the opportunities for in-orbit demonstration and verification.*" – ESA Technology Strategy


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DISCOVERY & PREPARATION ACTIVITIES

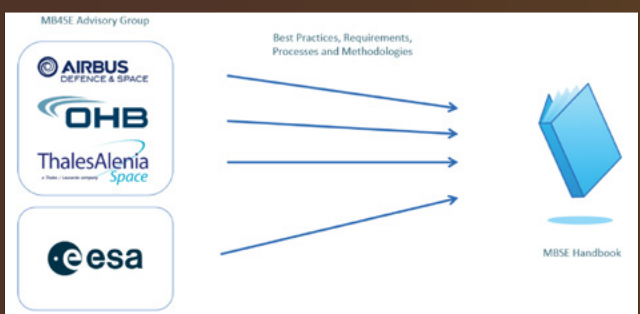
There is some way to go before MBSE can be adopted seamlessly at every stage of every mission. To speed up the process, the Discovery element of ESA's Basic Activities asked industry and academia to propose novel ways to boost the introduction of MBSE into the space sector, and is currently funding 24 projects that develop MBSE further.

In parallel, the Preparation element of ESA's Basic Activities has been supporting the European space industry by applying MBSE in various phases of the preparation of future ESA missions, such as:

- EnVision Science Mission study
- Lunar Communication and Navigation Service (phase A/B1)
- Security And cryptoGrAphic mission (phase A)
- Mars Sample Return (phase B2)

Among the Discovery element activities, in an effort to bring together different approaches to MBSE, GMV combined insights from the three major European space system integrators (Airbus Defence and Space, Thales Alenia Space and OHB System) on their MBSE activities. The aim of this activity was to increase the potential for different MBSE approaches to efficiently work together, and to ensure a seamless exchange of MBSE-related information between different stakeholders. The project proposed and implemented solutions to consolidate MBSE activities in Europe (website).

Other projects funded by ESA's Discovery element followed ideas submitted by industry to a dedicated Open Space Innovation Platform (OSIP) call for ideas. They developed key aspects of MBSE further and applied it in new ways. 83 ideas were submitted, covering a variety of MBSE topics. Of these, seven were selected to be implemented by ESA Discovery as studies, 15 as early technology development projects, and two as co-funded research projects that address more fundamental aspects of MBSE.



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▲ Harmonising MBSE standards

One of these studies has further contributed to ensuring the smooth and efficient advancement of MBSE across the space sector; ESA Discovery supported CGI and OHB to identify a way to harmonise the different approaches of ESA and large space companies, and compile the information into an MBSE best practices handbook.

Through an early technology development project that came out of the OSIP call for MBSE ideas, ESA Discovery funded SpaceCube GmbH to develop a novel end-to-end system engineering portal that supports users to integrate and transfer data across different tools.

A second early technology development project carried out by IRT Saint Exupéry addressed the emerging 'Model-based safety analysis' (MBSA), a natural sequel of MBSE where system and safety engineers share a common system model. Specifically, the project developed the coupling between MBSE and MBSA, focusing on the electronics of a system.

All other activities arising from the OSIP call for ideas are due to finish throughout 2022. Their results will be made publicly available via the Nebula Library.

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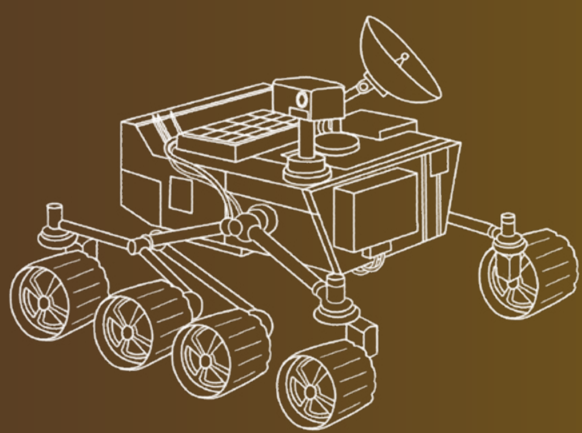
▲ Harmonising MBSE standards

MBSE needs to be used from the very beginning of the mission development process. At ESA, these early steps happen at the Concurrent Design Facility. Since the end of 2021 all Preparation future mission studies (pre-phase A and phase A) have required an MBSE approach by default.



What else is ESA doing?

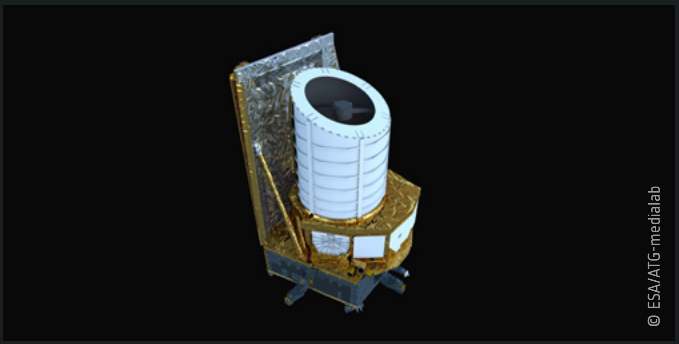
MBSE and the 'Digital Spacecraft' concept more generally, is about drastically changing the way that ESA and industry work together, switching from a 100% customer-supplier relationship, towards a more co-engineering approach. This means that it comes with higher transparency and trust, clearer objectives, and a stronger partnership.

ESA Agenda 2025 outlines the challenges ahead in maintaining and growing Europe's role in the space economy. It states that:
*"ESA projects are characterised by heavy engineering efforts from geographically dispersed teams in ESA and industry. Digital continuity throughout the life cycle of projects allows the substantial reduction of cost and errors, and will shorten schedules. ESA will therefore digitalise its full project management, enabling the development of digital twins, both for engineering by using **Model Based System Engineering**, and for procurement and finance, achieving full digital continuity with industry."*

ESA is coordinating industry to work together despite each company using its own tool. As part of this goal, ESA and industry worked together to create an MBSE technology roadmap in 2019.

In the same year, the model-based for system engineering (MB4SE) advisory group was set up with the aim to deploy MBSE in space projects by coordinating MBSE efforts carried out through ESA R&D programmes and in industry. The group consists of ESA, the French, Italian and UK space agencies, and the German Aerospace Center, as well as three large European space companies – Airbus Defence & Space, Thales Alenia Space, and OHB. It advises ESA on the technical aspects of MBSE research and development and ensures that the efforts of space agencies and industry converge towards the same shared vision.

One example of the MBSE advisory group's work was to define the 'MBSE Hub', a virtualised central space that enables different MBSE tools to work together. A version of the Hub is now being developed by RHEA Group; it will allow the exchange of data between different groups using a common language.

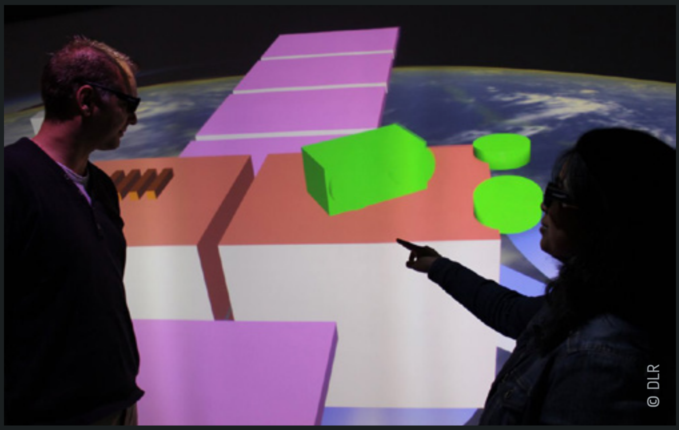


▲ Euclid

ESA is already using MBSE increasingly for space missions. Euclid, Plato, Ariel, ClearSpace-1, TRUTHS, the European Large Logistics Lander, Mars Sample Return and Galileo have all benefited from the approach. Euclid has been in development since 2012 and now forms the basis of how ESA uses MBSE for Science missions.

Another ESA mission that has seen an MBSE approach from the very beginning of its development is e.Deorbit. Although it has now been reborn as a space servicing vehicle, e.Deorbit had aimed to remove a large piece of ESA-owned space debris from orbit in an early demonstration of cleaning up our space environment. MBSE has been used to model the physical architecture, track verification methods, and establish 'single truth' data exchange at a system level; this was a first for an ESA mission, and has been a huge challenge. But it has also been a success, opening the doors to a broader application of MBSE when designing future missions.

What are other space agencies doing ?



▲ DLR models the virtual satellite in their VR lab

The Japanese Aerospace Exploration Agency's (JAXA's) Engineering Test Satellite-9 is a demonstration satellite that aims to achieve next generation geostationary satellite communication. Due to launch later in the 2020s, the project team is applying MBSE to manage the complex operations of the satellite. More generally, JAXA's R&D Directorate is using and accumulating knowledge in MBSE to support future projects.

Meanwhile, the Institute for Software Technology at the German Aerospace Center (DLR) has developed a tool for MBSE called Virtual Satellite. This tool supports the common effort for a uniform digital representation. Continued evolution and integration of the Virtual Satellite software family builds the backbone of DLR's MBSE activities. For example, DLR's Galileo Competence Center is using Virtual Satellite for the modelling of the planned project COMPASSO. On board the International Space Station (ISS), COMPASSO will test optical technologies and compare their performance with existing systems.

Over the past four years, NASA has been laying the groundwork to increase its use of MBSE in its space missions. This process has included providing software licences, interviewing industry, academia and other organisations, and creating a 20-year vision and roadmap for the use of MBSE within the Agency. NASA is also working specifically on several initiatives to advance System Modelling Language – or SysML, the modelling language that MBSE uses to communicate the abstract ideas captured within the models.

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