Space research at DLR

DLR

“I don’t want to believe.
I want to know.”

Carl Sagan
US Astronomer

Content

From rocket propulsion to an outpost in space

Space research has always been a source of fascination and excitement. On 12 November 2014, hundreds of thousands of people all over the world were looking on as the German Aerospace Center's (Deutsches Zentrum für Luft- und Raumfahrt; DLR) Philae lander successfully touched down on the surface of Comet 67P/Churyumov-Gerasimenko. Once on the surface, and 500 million kilometres from Earth, it conducted numerous scientific experiments. Even Google changed the doodle on its homepage to an image of the three-legged lander. Some four years later, on 5 May 2018, thousands of people gathered overnight at the launch site on the US west coast to watch the InSight mission embark on its mission to the Red Planet, carrying DLR's HP^3 – the 'Mole' – on board. Another fascinating cosmic encounter took place months later on 3 October 2018, when the asteroid lander MASCOT reached the surface of the asteroid Ryugu. And it was not alone – two small slides in its interior with the names and good wishes of over 3500 'fellow passengers' accompanied the lander.

A broad spectrum of research topics

Above all, space research makes a significant contribution towards the current challenges facing humankind, such as global change and society's need for more secure and globally available communication networks. The current issues that space research is seeking solutions to include the ever-growing and increasingly disparate amount of data as well as the development and testing of new and innovative technology and its transfer to applications on Earth.

At DLR, 37 institutes are conducting research in the area of space, developing and testing new technologies, and gaining insights that will be of great benefit to society. DLR's Space Research and Technology covers a wide spectrum of research areas. It is not limited to the design and implementation of projects, missions and applications, but also involves the preparation and execution of such endeavours, as well as the effective evaluation and assessment of the acquired data. DLR is system capable in the field of satellites. This makes DLR a trusted and sought-after cooperation partner for space agencies such as the European Space Agency (ESA), the United States National Aeronautics and Space Administration (NASA), the Japanese Aerospace Exploration Agency (JAXA) and the Russian space agency Roscosmos. DLR's partners also include national and international research institutions and industry players.

Maximising the benefits for society

DLR has set itself the goal of maximising benefits of space research for society over the coming decade by drawing upon its expertise and experience. One challenge facing society is the need to monitor global change, and DLR's research into space and global remote sensing can play an important role in this area. Satellite-based Earth observation is the only means of recording change processes with precision and at high spatial and temporal resolution, thus providing the basis for recommendations for action. The development of new technologies to grant Europe independent and cost-effective access to space and enable the reusability of carrier systems is also one of DLR's goals, as is technology transfer from space robotics, for instance, for medicine and nursing. DLR is sending scientific instruments to distant celestial bodies and carrying out experiments under space conditions in order to acquire a new and better understanding of Earth and the Solar System. With new institutes in the field of quantum technology research, DLR is laying the foundations for the application of second-generation quantum technology in space and on Earth, for example for applications in communications and Earth observation. This brochure provides an insight into DLR's current space research and projects.

The world

in transition

Earth is in a constant state of change, and humans often trigger or contribute towards these changes to a significant degree. These include increasing urbanisation, expanding land use for agriculture, not to mention plastic waste in the ocean and other water bodies, the loss of biodiversity, and changes in air quality. Change is also clearly noticeable in the melting of glaciers and the resulting rise in sea level.

As such, monitoring global change and looking for measures to mitigate these effects are becoming increasingly pressing concerns. In 2015, the countries attending the UN COP 21 Climate Conference in Paris agreed that global warming should be limited to a level well below 2 degrees Celsius, and preferably below 1.5 degrees Celsius, compared to pre-industrial levels. The special report, published on 8 October 2018 by the Intergovernmental Panel on Climate Change (IPCC), addresses the consequences of global warming of 1.5 degrees Celsius and looks at measures for combating climate change.

Capturing, evaluating, modelling

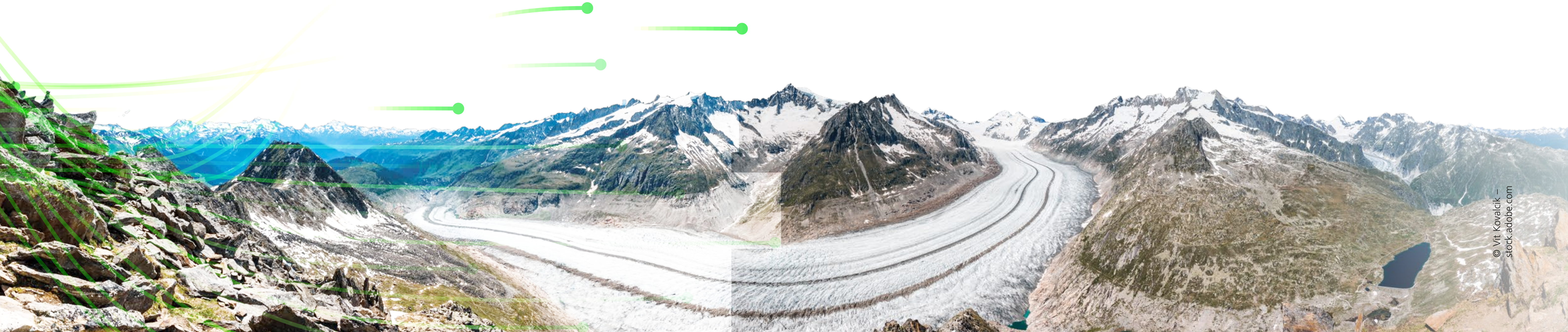
However, the necessary measures can only be taken effectively if the current conditions and change processes are scientifically recorded and evaluated. By the same token, the effectiveness of the measures can also only be assessed objectively if changes to parameters are recorded and analysed. To be able to look to the future, it is important to use models derived from measurements and observations in order to make forecasts based on scientific facts. Objective tracking of change processes also helps to enable sustainable management of natural resources, allowing ecosystems and biodiversity to be protected. Last but not least, precise monitoring of global change is also needed in order to issue timely warnings or provide an appropriate response to disasters such as forest fires, tsunamis and floods. Earth observation from space is the only technology that makes it possible to perform this kind of monitoring globally, comprehensively and with a high level of spatial and temporal resolution and accuracy, and to do so independently of political constraints.

DLR's space research and technology has the unique benefit of extending across all of the necessary infrastructure and areas of research. Satellite missions such as TanDEM-X are operated from DLR's control centres. The data from space are received by DLR's own network of antennas at ground stations in Canada, Antarctica, Neustrelitz (Germany), as well as many other locations. The DLR institutes then process and scientifically evaluate the data. As a national reception centre for data from Earth observation satellites, DLR also manages the German Satellite Data Archive (D-SDA). DLR's Center for Satellite-Based Crisis Information (Zentrum für satellitengestützte Kriseninformation; ZKI) uses satellite and aerial images, as well as other geodata to create information products that can help relief organisations to plan missions in the event of crises or disasters.

Tools for the future

By devising Earth observation missions such as the TanDEM-L radar mission, DLR is advancing research into global change and responding to a wide range of scientific, commercial, regulatory, societal and political needs and demands. In doing so, DLR can draw upon many years of expertise with radar technology, ranging from the SIR-C/X-SAR and SRTM space shuttle missions (1994 and 2000 respectively) to the German TerraSAR-X and TanDEM-X radar satellites.

The huge quantity of high-resolution satellite data on the state of our planet that is captured daily poses a challenge in the field of Earth observation. Conventional methods are ill-equipped to evaluate the existing data effectively. Scientists have long been working not only with satellite data, but also, for example, with data from social networks. This heterogeneity adds another layer of complexity to the steadily increasing amount of data. DLR space research is therefore also exploring the application of Artificial Intelligence methods for evaluating data. To this end, innovative computing infrastructures are being operated and expanded at DLR.

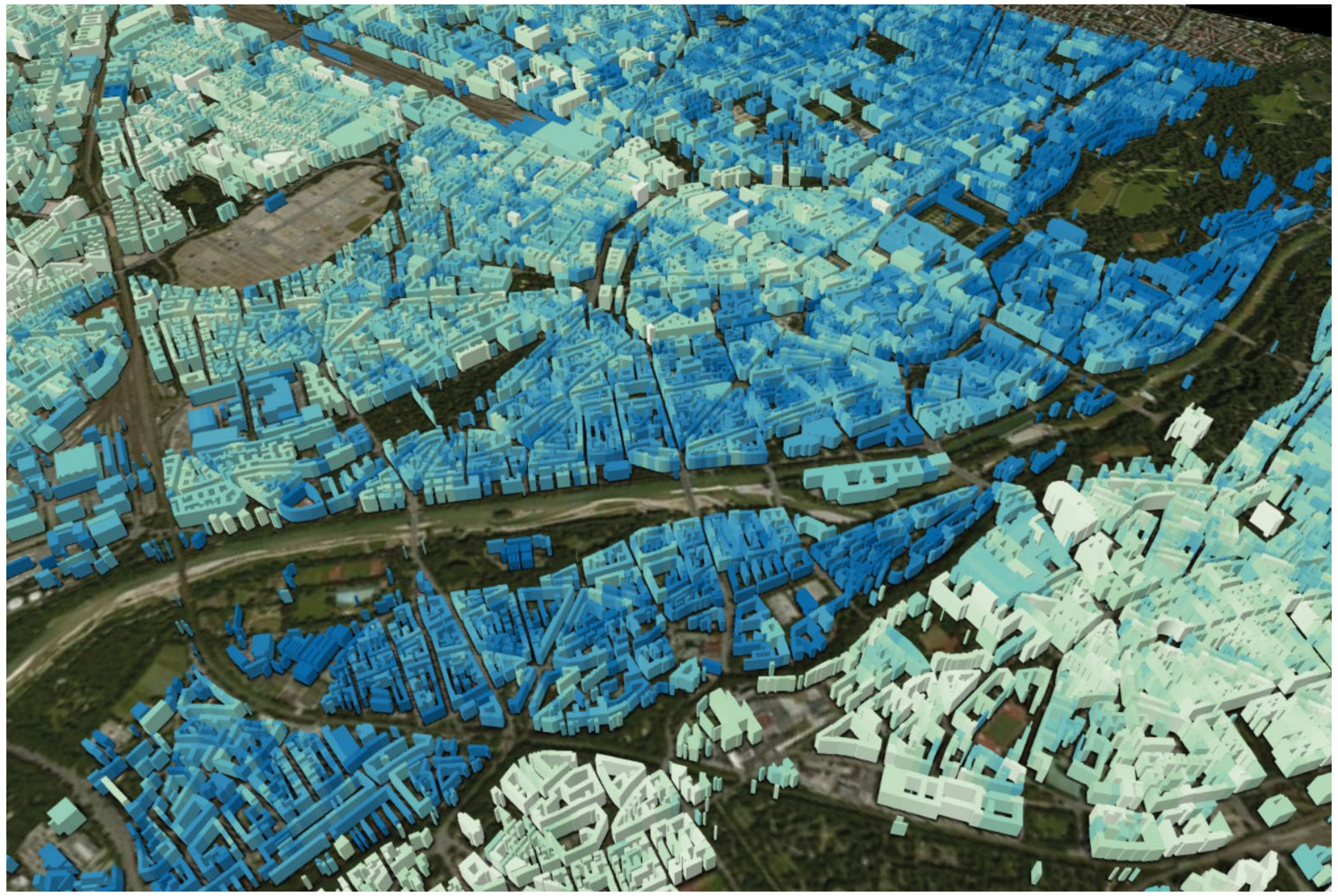


Exploring urbanisation through mountains of data

Photographs of buildings, interiors and food. Comments about politics, weather, or complete trivia. Around 6000 tweets are sent every second, and the content could not be more diverse. Each of these tweets could prove important, as the content, location and time at which it is sent can also provide information about the purpose of a building. Add to this 20 petabytes of data from Earth observation satellites every year, and the veritable art form being practised by DLR scientists becomes apparent: from this colossal quantity of disparate data – optical satellite images, radar images, data from social media – the information that might help to differentiate the use of a building, draw conclusions about population density or improve the organisation of water distribution in developing regions has to be trawled through and linked together with precision. Cities have long been complex structures, and are now home to over half the world's population. On-the-ground exploration and analysis of all urban areas worldwide is simply impossible.

Machine learning

For this reason, the DLR team is conducting research into extracting the right information from these mountains of data. How many buildings are there? How many people live within the area? Basic information like this allows water distribution, education or even health services to be organised more effectively, especially in developing regions. Machine learning, whereby algorithms automatically recognise patterns and regular occurrences, has been used in Earth observation for decades. Over recent years, however, the amount of data and computing power have increased exponentially, while new forms of data, including information from social media or citizen science, have been added to the mix. The scientists are developing new algorithms to ensure that Artificial Intelligence can be used as an effective tool for Earth observation.



3D model of Munich from radar and optical data

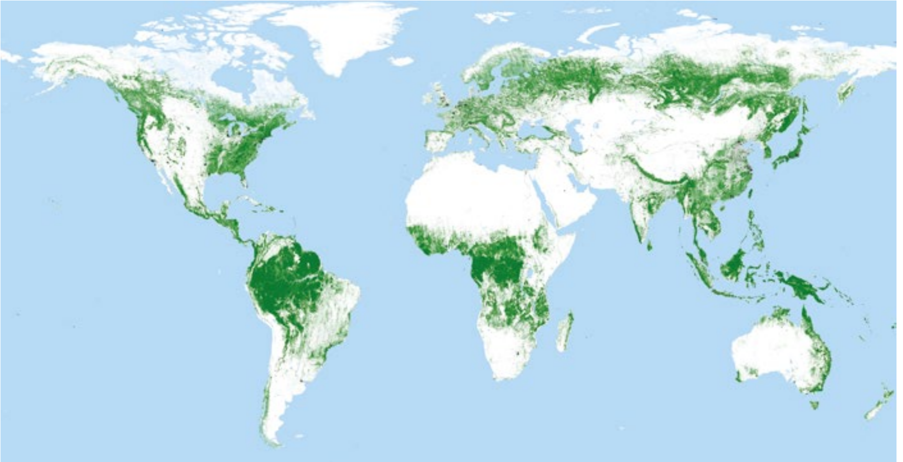
The future of radar technology

With two satellites that record Earth's landmass on a weekly basis and an L-band wavelength to open up new and vital applications for users, the DLR-planned future TanDEM-L radar mission draws upon DLR's many years of expertise with radar technology. TanDEM-L is set to provide detailed information on global change and the dynamic processes associated with it. Changes to forest biomass are to be comprehensively recorded on a regular basis. Earthquake research will benefit from the systematic recording of deformations of Earth's surface, with millimetre precision. Fine-scale measurement of near-surface soil moisture will allow a better understanding of the water cycle. Forecasts for rises in sea level will also be improved by the precise quantification of glacier movements and melting processes in the polar regions.

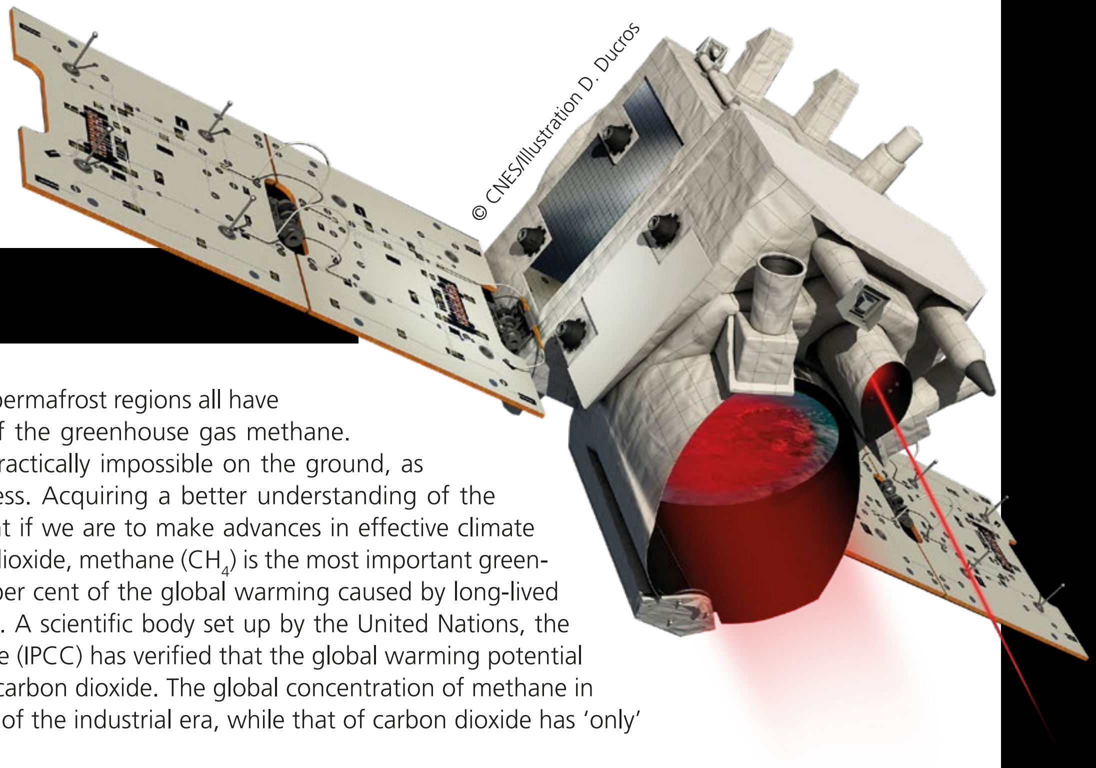
Radar images of the 'green lung'

Satellites use different sensors to look at Earth. These include passive optical sensor systems, for instance in the visible and near-infrared range, active optical systems such as LIDAR (light detection and ranging), and SAR sensors (synthetic aperture radar). DLR has accumulated considerable expertise in the area of radar technology ever since it produced radar images of Earth on two space shuttle missions, SIR-C/X-SAR (1994) and SRTM (2000). Regardless of weather conditions, cloud cover or absence of daylight, the German TerraSAR-X and TanDEM-X satellites are currently surveying Earth. Their data is used to produce a highly accurate digital elevation model of the entire globe. The image of the 'green lung', Earth's forest regions, whose extent is shown in a global map with a resolution of 50 metres, is also a product of the TanDEM-X mission. The DLR scientists processed more than 400,000 data sets to obtain an inventory. For this purpose, the radar experts developed special algorithms that first evaluate each image individually and then combine it into a global map. These algorithms are based on machine learning from Artificial Intelligence. For the first time, this has produced a uniform overview of the rainforests of South America, Southeast Asia and Africa.

The forest map therefore also serves as an important basis for recording global change and recommending the necessary mitigation measures. These findings are crucial for authorities and scientists, as forests are huge carbon stores that need to be preserved and protected against illegal logging. Other potential users come from agriculture, forestry, regional development and land use planning.



TanDEM-X world forest map (left), deforestation of the rainforest in Brazil (right)



Tracking down methane

Rainforests, tropical wetlands and even permafrost regions all have one thing in common: they are sources of the greenhouse gas methane. Conducting measurements of this gas is practically impossible on the ground, as these areas are often very difficult to access. Acquiring a better understanding of the greenhouse gas methane is vitally important if we are to make advances in effective climate protection. After water vapour and carbon dioxide, methane (CH_4) is the most important greenhouse gas and is responsible for about 20 per cent of the global warming caused by long-lived greenhouse gases since pre-industrial times. A scientific body set up by the United Nations, the Intergovernmental Panel for Climate Change (IPCC) has verified that the global warming potential of methane is 25 times higher than that of carbon dioxide. The global concentration of methane in the atmosphere has doubled since the start of the industrial era, while that of carbon dioxide has 'only' increased by 30 per cent.

High-precision measurements

The Franco-German small satellite MERLIN (Methane Remote Sensing LIDAR Mission) will have an unobstructed view of Earth from an altitude of around 500 kilometres. Starting in 2024 and for a period of three years, MERLIN will use a LIDAR (light detecting and ranging) instrument to measure the methane content of Earth's atmosphere with high accuracy. Among other things, these data will be used to create a global map of natural and anthropogenic methane concentrations. The MERLIN mission will also be a further step in determining what is causing the release of this greenhouse gas. Methane is produced by the decomposition of biological material via microorganisms in an oxygen-free environment. Climate change could cause permafrost ground to thaw out and the oceans to warm up, thus greatly increasing the concentration of methane gas in the atmosphere. On the other hand, major anthropogenic sources of methane include rice growing, livestock farming, oil and gas production, mining and landfill sites.

A consortium of companies and research institutes from Germany, France and the Netherlands is involved in the construction of the LIDAR instrument. The active LIDAR can also measure at night and through thin clouds. DLR atmospheric researchers within the Space Research and Technology division are scientifically responsible for the instrument.

Nobel Peace Prize for climate protection

When the Nobel Peace Prize was jointly awarded to Al Gore and the Intergovernmental Panel on Climate Change (IPCC) in 2007, a group of DLR scientists was also honoured by association. DLR climate researchers work on the regular IPCC climate reports, which are provided to political decision-makers as a neutral, objective source of information. They have an ambitious task: to record global findings about the effects of climate change and the risks that it poses, as well as noting strategies for mitigation or adaptation. The United Nations World Meteorological Organization (WMO) also draws upon the expertise of DLR climate researchers who work on the Ozone Report, which is published every four years.

ipcc
INTERGOVERNMENTAL PANEL ON climate change
WMO UNEP

24/7
DLR's ZKI can be activated round-the-clock

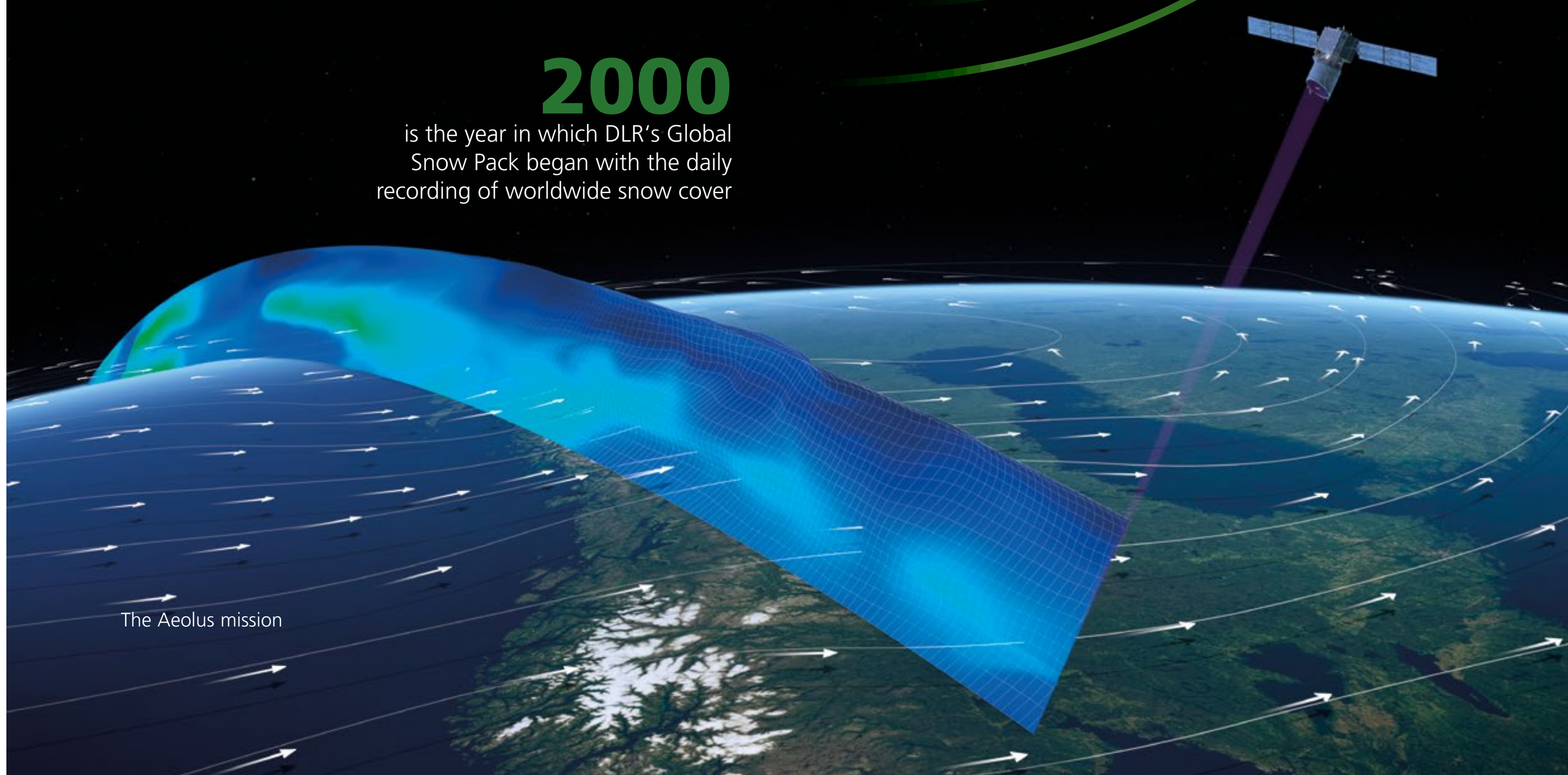
2403
scientists from 70 countries work with TanDEM-X mission data

150 million
square metres have been covered by the TanDEM-X mission

500
institutions make use of DLR's Global Urban Footprint

30
petabytes of data – equivalent to 6,690,000 DVDs – are stored in the Satellite Data Archive at DLR

2000
is the year in which DLR's Global Snow Pack began with the daily recording of worldwide snow cover

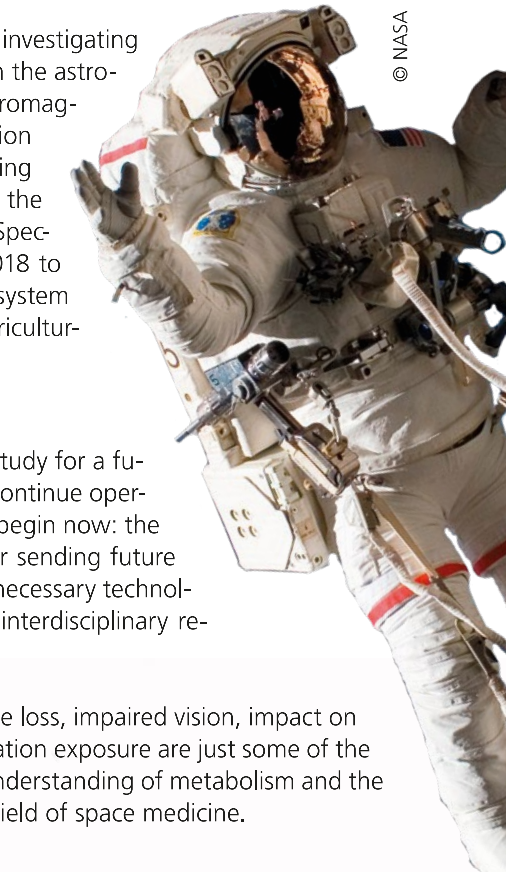

The Aeolus mission

Humans

in space

Outer space begins 100 kilometres above sea level – that is, if you adhere to the definition of the International Astronautical Federation (IAF). This is where aviation ends and space travel begins. Only those who have flown above this altitude are considered to be astronauts. But the Association of Space Explorers (ASE) stipulates another condition: to be an astronaut, a person must have completed at least one orbit around Earth. The first human to fulfil both of these requirements was the cosmonaut Yuri Gagarin, who orbited Earth on 12 April 1961 in the Vostok 1 spacecraft. Astronauts have been indispensable to space research since, as they make an important contribution to conducting a variety of experiments under microgravity conditions. While robots or robotic assistants have become capable of taking on or providing support for various tasks, they cannot replace humans when it comes to research.

Humankind's outpost in space orbits the Earth at an altitude of 400 kilometres. The International Space Station (ISS) is the biggest collaborative project in space. It began on 20 November 1998, when the Russian Zarya module became the first module to be carried into Earth's orbit. The US Unity module was connected to it 16 days later. On 2 November 2000, the first astronauts – the initial long-term crew – moved into their new home. Since then, this outpost in space has become an important part of space exploration, with over 2500 experiments conducted under microgravity conditions by more than 3600 scientists from 106 different countries.



© NASA

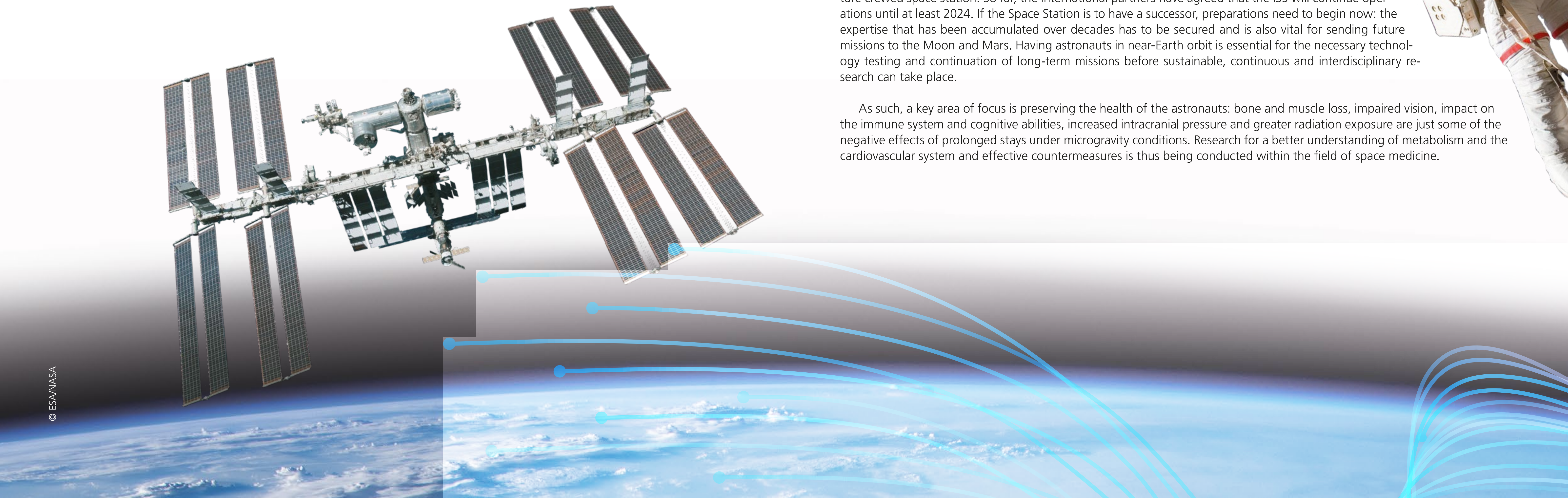
From materials physics to Earth observation

The experiments conducted by DLR on board the International Space Station include investigating the radiation exposure that occurs inside and outside the laboratory module, as well as on the astronauts' bodies. Through materials physics experiments such as those conducted in the electromagnetic levitator (EML), DLR studies solidification processes to make metallurgical production more efficient on Earth. Among other benefits, this could help to optimise industrial casting processes for turbine blades or motor casings. Earth observation can also benefit from the flying space laboratory. The hyperspectral instrument DESIS (DLR Earth Sensing Imaging Spectrometer) was installed on the MUSES research platform on the exterior of the ISS in 2018 to monitor Earth's environment and resources. The data acquired indicate changes to the ecosystem on Earth's surface and make it possible to assess the health of forests, lakes, rivers and agricultural land. These data contribute to the documentation of global change.

Concepts for a successor to the ISS

DLR is preparing for the end of the current ISS through the 'Orbital Hub' concept – a study for a future crewed space station. So far, the international partners have agreed that the ISS will continue operations until at least 2024. If the Space Station is to have a successor, preparations need to begin now: the expertise that has been accumulated over decades has to be secured and is also vital for sending future missions to the Moon and Mars. Having astronauts in near-Earth orbit is essential for the necessary technology testing and continuation of long-term missions before sustainable, continuous and interdisciplinary research can take place.

As such, a key area of focus is preserving the health of the astronauts: bone and muscle loss, impaired vision, impact on the immune system and cognitive abilities, increased intracranial pressure and greater radiation exposure are just some of the negative effects of prolonged stays under microgravity conditions. Research for a better understanding of metabolism and the cardiovascular system and effective countermeasures is thus being conducted within the field of space medicine.



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Female 'phantom' astronauts bound for the Moon

Over 5600 passive radiation detectors, 16 active detectors and a radiation protection vest – this is the equipment with which the DLR space medicine specialists will equip the next two passengers to the Moon. This time two female passengers – Helga and Zohar – will make the journey. Their spacecraft will be the Orion capsule belonging to the US space agency NASA. Their objective is to measure radiation exposure over the course of a 42-day flight. These 'astronauts' on board the first Orion flight around the Moon in 2020 will, in fact, be two female phantoms, 95 centimetres tall and made up of 38 layers in which small crystals will record radiation levels on their journey through space.

Cosmic radiation represents a major health risk to astronauts. Its impact on the human body is a crucial and potentially limiting factor in planning future long-term missions for humans in open space. Over 50 years after the first Moon landing, DLR is developing the MARE experiment (Matroshka AstroRad Radiation Experiment), which will be sent to the Moon with NASA's ARTEMIS 1 mission to determine this radiation risk with greater precision and possibly develop protective measures. During the flight, the 'twins' will differ in only one respect: the Israeli Zohar will wear a radiation protection vest (AstroRad) developed by the Israeli industry partner StemRad, while the German Helga will not.

Several thousand detectors

The two 'passengers' are now being prepared for the MARE experiment at the DLR Institute of Aerospace Medicine. Some 1400 sensor locations are fitted with small passive dosimeters consisting of crystals. The sensors of the active detectors are integrated into the most radiation-sensitive organs of the body – lungs, stomach, uterus and bone marrow. While the passive dosimeters will continuously measure and record the total radiation dose from launch until return to Earth, the active, battery-operated detectors will be switched on during launch and record radiation exposure in a time-resolved manner. For the first time ever, it will be possible to accurately measure the radiation levels that astronauts are exposed to during a flight to the Moon.

The experiment is based on the experience of previous measurements conducted on the International Space Station (ISS): from 2004 to 2011, DLR radiation specialists conducted research using Matroshka, a male phantom exposed to radiation both inside and outside the ISS. Within the European research laboratory, Columbus, DLR is also currently measuring the radiation levels in the DOSIS 3D experiment. MARE's complexity and international collaboration involving numerous universities and research institutions in Austria, Belgium, Poland, Hungary, the Czech Republic, Greece, Switzerland, Japan and the US makes it the largest experiment to determine radiation exposure for astronauts ever to leave near-Earth orbit.

The Orion capsule for the journey to the Moon

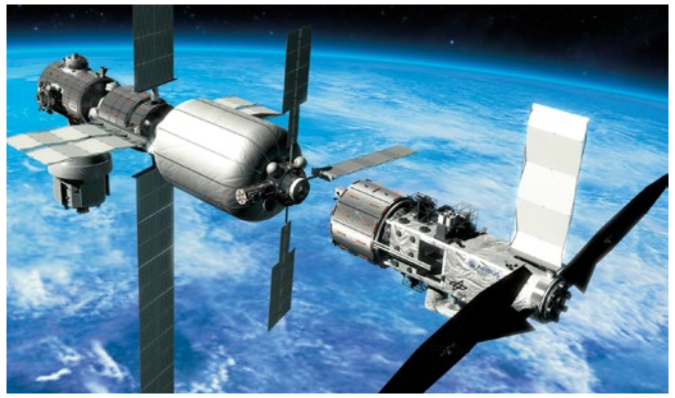
Research for health

The large-scale research facility :envihab, with an area of 3500 square metres, extends across the DLR site in Cologne like a grounded spaceship. The negative effects of gravity can be replicated and countermeasures tested under controlled conditions here. Inside the building are a short-arm centrifuge, a PET-MRI, a hypobaric chamber, physiology and biology laboratories and an area in which the test subjects live during the studies. Research is being conducted in the interests of the astronauts' health, but also to gain a better understanding of the effects of ageing, bedriddenness, immobilisation, and isolation on patients on Earth.

Orbital Hub – research platform in space

The International Space Station (ISS) started out in 1998 with the Russian transport module Zarya, two years before the first astronauts moved in. Since then, the platform has become a laboratory operating under microgravity conditions at an altitude of 400 kilometres. Given the technology it uses, however, the US space agency NASA estimates that it will only be able to continue to operate until 2028. As such, the German Aerospace Center (DLR) has now drawn up a concept for a future research station in low-Earth orbit for the period after 2028.

Called the 'Orbital Hub', it would consist of an unmanned free flyer and a living and service module (base platform). This free flyer would be able to undock from the crewed part of the platform for relatively long periods of time and accompany the crewed section in formation flight, thus ensuring the continuation of experiments without any interference from astronaut activities. The free flyer would primarily contain sensitive experiments that require particularly high-quality microgravity conditions. Externally, the free flyer could be equipped with instruments that have considerable requirements on their orientation and exposure to vibration, such as Earth observation or technology demonstrations.



The modular Orbital Hub with the base platform and the free flyer

Architecture according to user requirements

The habitat for the three-person crew, which includes a laboratory area, is the centrepiece of the basic platform. The docking module on the base is the approach point for any crew or cargo vehicles. Other modules can dock with this module, thus allowing for expansion of the base station. This modular architecture was devised based upon user surveys aimed at defining the requirements of a follow-up model for the ISS. Above all, scientists from a wide array of research fields stipulated that it was vital to be able to monitor experiments in real time and evaluate data on site without having to return samples to Earth.

Cost-effective and sustainable

The future platform in low-Earth orbit, which could be implemented in collaboration with international partners and industry within the next 10 years, should ensure that Europe has ongoing and much more cost-effective access to low-Earth orbit between 350 and 500 kilometres. This would make it possible to conduct research, technology demonstrations and prepare for future exploration. The station can be both crewed and uncrewed, depending on the requirements of the mission. Having a highly functional successor station to the ISS is hugely important given the growing need to monitor and investigate global change. To this end, an 'Orbital Hub' could also serve as a sustainable instrument for climate research. The free flyer would have to be able to dock with existing modules of the ISS during a transitional period. In other words, the decommissioning of the ISS would not mean its end, as some modules would continue to be used.

Terrestrial astronauts at a tilt

If you have ever looked closely at the astronauts floating in front of the camera on the International Space Station (ISS), you will have noticed the effect of weightlessness on the human body: a bloated, pinkish 'puffy face' and thin 'chicken legs' that quickly set in once the body no longer feels 'up' and 'down' due to the absence of gravity. Intracranial pressure and vision can also be impaired. DLR's :envihab research facility allows scientists to get as close to replicating these side effects as is possible on Earth. Over the course of DLR's bed rest studies, healthy participants are usually confined to their beds for several weeks, tilted downwards at the head by six degrees. This slanted position triggers the phenomenon experienced by astronauts during their missions in space, whereby bodily fluids move towards the upper body, while the bones and muscles in the lower half of the body start to lose strength due to immobility. The atmosphere within :envihab can also be modified, for example by increasing the carbon dioxide content in the air. This is the only way to research and understand how to preserve astronauts' health.

As far as the test participants – the terrestrial astronauts – are concerned, participating in the study is as challenging as the missions performed by the professional astronauts in space. There are strict rules: eating, drinking and showering must all be done lying down. Tightly synchronised medical and physical examinations are scheduled every day. A single study encompasses hundreds of hours of experiment time and often well over 100 individual experiments. While targeted countermeasures such as rides on the centrifuge or training on a horizontal sledge jump system are some of the activities in the daily routine for some of the test participants, the control group does not practise any countermeasures. This results in valuable data sets that can be compared to show which measures are most effective at protecting astronauts against the negative effects of weightlessness.

Lying in bed for the sake of science

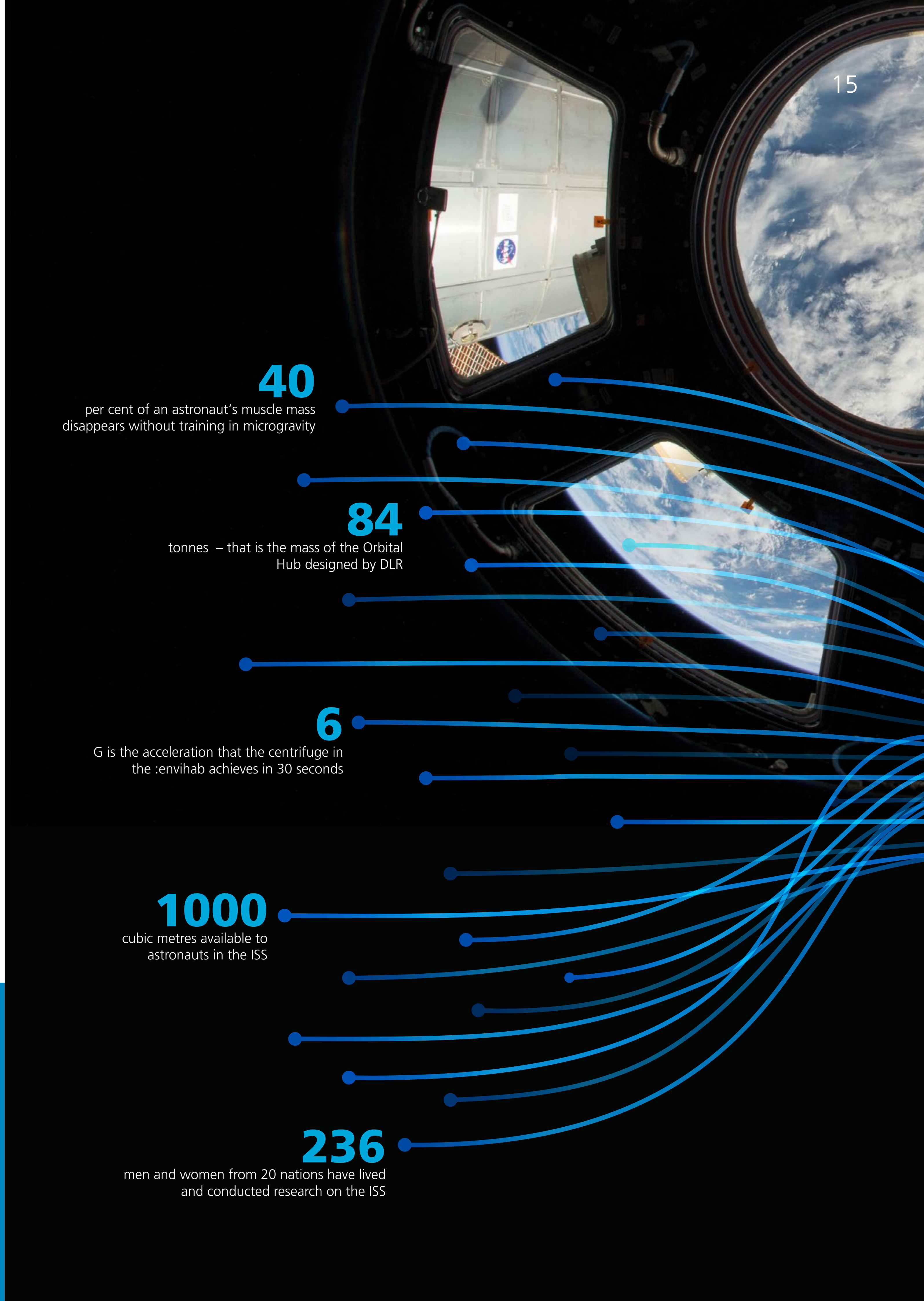
Effective training to preserve health

DLR has carried out a large number of bed rest studies in cooperation with partners such as the US space agency NASA, the European Space Agency (ESA) and various universities and research institutions. The first of these was conducted alongside ESA in 2001. In 2015, the RSL bed rest study tested whether training on a horizontal sledge jump system can reduce bone and muscular atrophy. In 2017, the DLR team worked on the VAPER bed rest study with NASA to investigate visual impairment, intracranial pressure and the physiological and psychological impact of a higher proportion of carbon dioxide in the atmosphere. In 2019, AGBRESA marked the first joint DLR, ESA and NASA bed rest study. In this case, the scientists used rides on the centrifuge to expose the test participants to artificial gravity of 1 G.

Astronauts on the ISS have to complete a two-hour exercise routine every day in order to maintain their health. In future, the use of a centrifuge or horizontal sledge jump system on long-term missions could reduce the time-consuming sports programme currently required in space. Ultimately, the results of the research carried out by space medicine specialists can also help patients on Earth. Being bed-ridden for a long time or treated following severe accidents often has similar effects – muscular and bone atrophy, a compromised immune system or weakened circulation – to the artificially induced physical effects witnessed in the bed rest studies.

From space to :envihab

Since 2014, astronauts have spent their first night back on Earth – complete with gravity, fresh air and silence – at DLR's :envihab facility. Following a long flight in the Soyuz capsule, a landing on the Kazakh steppe and a flight to Cologne via Moscow, astronauts like Alexander Gerst, Andreas Mogensen, Tim Peake and Thomas Pesquet have become participants in an array of experiments. DLR physicians have examined, among other things, their circadian rhythms (sleeping and waking cycle), nutrient consumption, muscles, heart, arteries and bones.



Missions to explore celestial bodies

The Solar System was born around 4.5 billion years ago – but the realisation that Earth revolves around the Sun did not emerge until the 16th century, when Nicolaus Copernicus presented his model. The tentative idea that the structures on Mars might be channels, constructed by inhabitants of the Red Planet, has since been refuted. But many questions remain inadequately answered. How do planets and planetary systems form? What conditions are necessary for planets and moons to become habitable, to be able to sustain life? And how can we discover traces of life? To find answers to these questions, DLR planetary researchers are packing cameras, spectrometers, radiometers and other items of equipment onto orbiters and landers, dispatching them to faraway celestial bodies within the Solar System, and using telescopes to scrutinise extrasolar planets.

Research is ongoing in our terrestrial observatories and laboratories to prepare for these missions or verify their data. In turn, this treasure trove of information is used to create computer models and acquire insights into the composition, structure and age of planetary crusts or the inner workings of these planetary bodies, among other things. DLR is also responsible for the design, development and qualification of instruments, as well as their operation and the evaluation of the resulting data.

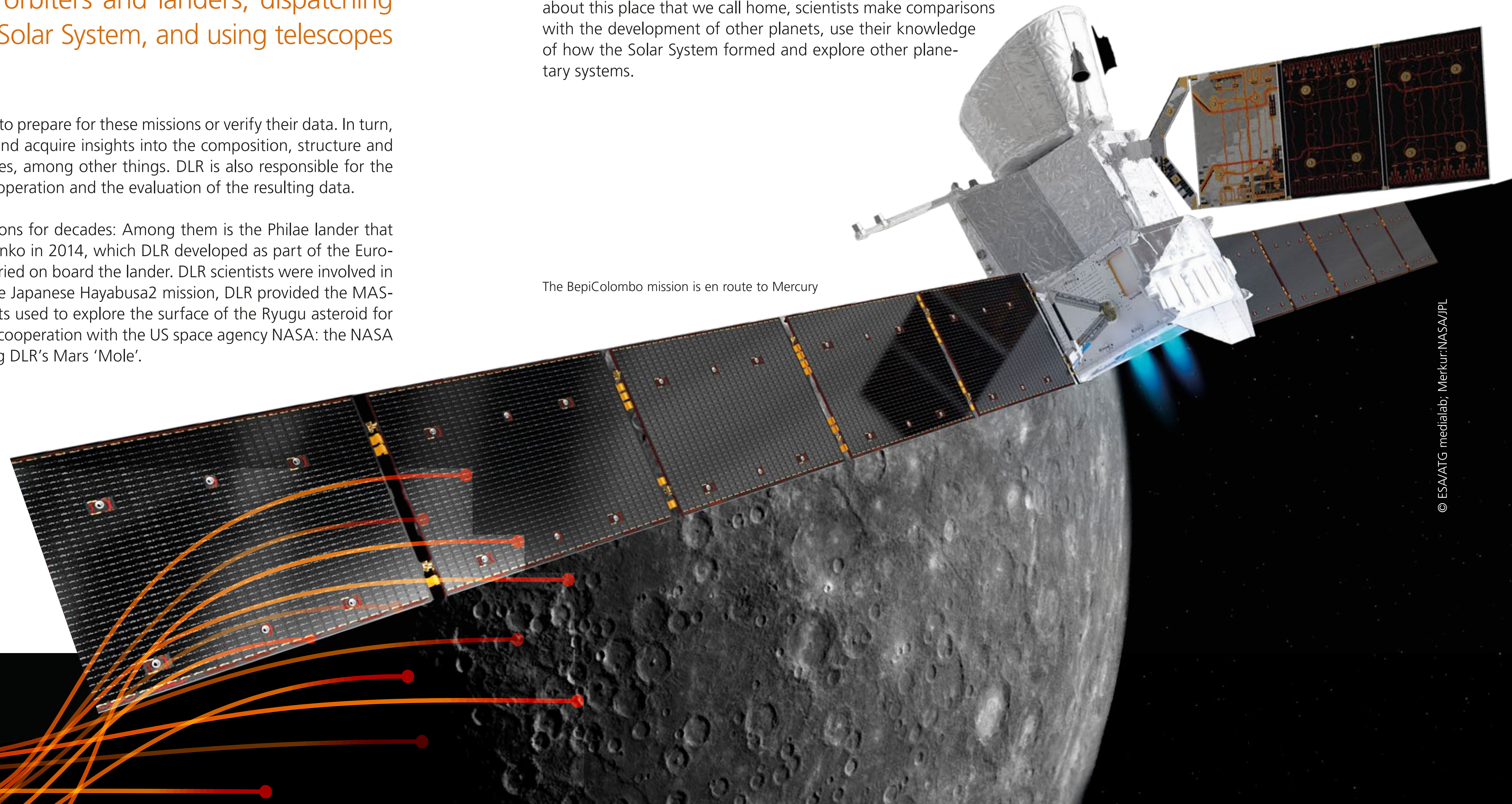
As such, DLR has been an important partner in international missions for decades: Among them is the Philae lander that touched down on the surface of the comet 67P/Churyumov-Gerasimenko in 2014, which DLR developed as part of the European Rosetta mission. It also provided three of the ten experiments carried on board the lander. DLR scientists were involved in developing the instruments fitted to the Rosetta orbiter as well. For the Japanese Hayabusa2 mission, DLR provided the MASCOT (Mobile Asteroid Surface Scout) lander and two of the instruments used to explore the surface of the Ryugu asteroid for 17 hours in 2018. At present, DLR is researching the surface of Mars in cooperation with the US space agency NASA: the NASA InSight landing craft touched down on the Red Planet in 2018, carrying DLR's Mars 'Mole'.

Travelling to icy moons and exoplanets

The next missions in cooperation with international partners are also well on the way to their destinations or are currently in preparation. Among them is the Japanese-European BepiColombo mission, which is traversing space on its journey to Mercury – carrying two DLR instruments on board. The European CHEOPS mission to explore exoplanets is all set to go, while others like PLATO, ExoMars or Mars2020 are in the implementation phase with the participation of DLR. There are plans to dispatch a rover to explore the Martian moon Phobos in cooperation with Japan and France, while DLR will collaborate with the European Space Agency (ESA) on the JUICE mission to investigate the icy moons of Jupiter.

Where possible, DLR aims to carry out global explorations of the celestial bodies. This is achieved firstly using remote sensing equipment from orbit. DLR possesses considerable and longstanding expertise in the mapping of planets and asteroids, as well as the production of 3D terrain models. In the future, research with instruments directly on the surface of the celestial bodies is to be expanded to larger areas: developments such as rovers, which are able to travel long distances autonomously, make it possible to carry out investigations and in-situ investigations at many different locations.

And even if these missions focus on distant planets, there is still one celestial body we learn most about: Earth. To draw conclusions about this place that we call home, scientists make comparisons with the development of other planets, use their knowledge of how the Solar System formed and explore other planetary systems.



The BepiColombo mission is en route to Mercury

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PLATO and CHEOPS – the search for a second Earth

The perfect planet that scientists on the PLATO mission are keen to discover beyond the reaches of the Solar System must meet certain criteria: it should be situated at a favourable distance to its host star and have water on its surface. The PLATO (PLAnetary Transits and Oscillations of Stars) space telescope is scheduled for launch in 2026. Once under way, it will travel 1.5 million kilometres from Earth and observe the sky for at least four years from a position at one of the Lagrange points. DLR scientists are confident that this telescope mission will lead to the discovery of thousands of new planets around sun-like stars. DLR is leading the international consortium, which is looking for a second Earth, but also wants to gain new insights into the development of planetary systems.

The first objective: to find a planetary system similar to the Solar System. For this purpose, 26 individual telescopes mounted on an observation platform will be connected and therefore bundled. The aim is to find planets in the life-friendly, habitable zone of their host stars.

One million stars in sight

In order to discover the distant planets orbiting their bright stars, the scientists use an indirect method: they observe the bright stars. When passing in front of the star's disc during its orbit, known as a transit, the planet will slightly dim the star's light. The mission will observe about half of the sky and study approximately one million stars.

CHEOPS (CHaracterising ExOPlanet Satellite) will once again benefit from work carried out during previous exoplanetary missions like Kepler or CoRot. The space telescope, scheduled for launch in late 2019, will analyse instead of just searching. From some 700 kilometres above Earth, it will direct its gaze at some of the over 4000 exoplanets that are already known and whose sizes range between that of Earth and Neptune. Among other things, DLR is contributing the focal plane module for the image capture sensor and is involved in analysis of data. Measuring the size, mass and density of these worlds will, for the first time, enable their characterisation. Is the planet largely rocky, or does it consist of gas? Does it have an ocean? And above all: how high is the likelihood that this exoplanet might be habitable – meaning it possesses the requirements for the emergence of life as we know it?


The PLATO space telescope will search for exoplanets

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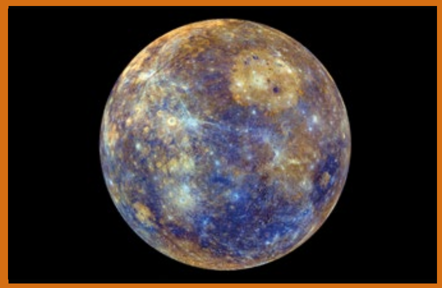


On 20 October 2018, the BepiColombo spacecraft embarked on a seven-year journey. The Japanese-European mission to Mercury is scheduled to arrive at its destination in 2025 and is carrying two DLR instruments on board. The BepiColombo Laser Altimeter (BELA) will use the runtime of millions of laser pulses to deliver the data for a complete 3D model of Mercury's surface. The Mercury Radiometer and Thermal Infrared Spectrometer (MERTIS) is designed to analyse the composition and temperature of the planet's surface. So far, the Solar System's innermost planet has seen little research.

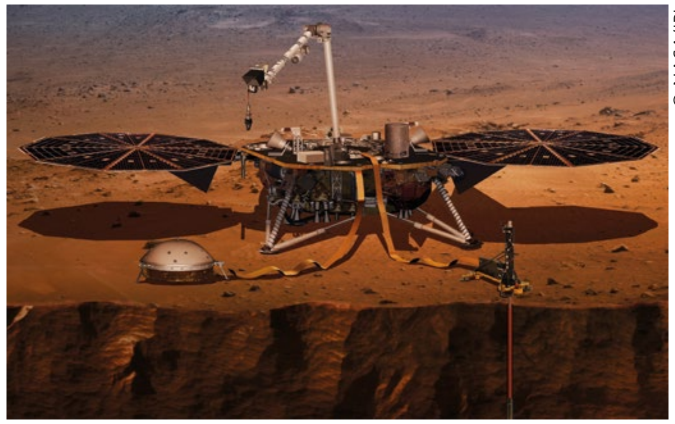
A 'Mole' on the Red Planet

Planetary probes have orbited Mars and analysed it with scientific instruments, landers have touched down on its surface and rovers have explored its terrain – yet the Red Planet is still an enthralling destination for missions. It remains an exciting and equally challenging object for research. Carried on board NASA's InSight mission, the DLR 'Mole' landed safely on the Martian plains of Elysium Planitia on 26 November 2018. The landscape: relatively flat and with few rocks strewn across the planet's surface. These were ideal conditions for the HP^3 (Heat Flow and Physical Properties Package) experiment, designed to hammer its way into the ground to a depth of five metres, dragging a ribbon cable fitted with 14 temperature sensors into the Martian soil. The plan: to obtain constant measurements of temperature and thermal conductivity for one Martian year, equivalent to two Earth years. All the while, a DLR radiometer installed below the lander's platform would measure the surface temperature. By proceeding in this way, the scientists hoped to measure the planet's thermal conductivity and draw conclusions on the Martian 'power plant' and its internal dynamics.

The 40-centimetre penetrometer – known as the 'Mole' – went into action on 28 February 2019. However, it was unable to go deeper than 35 centimetres with its first 9000 blows. Scientists working in the DLR test laboratories then set about experimenting with a variety of sands, rock sizes and an HP^3 model. The goal was to analyse – at a distance of over 228 million kilometres – what could have obstructed the 'Mole'. Photographs were taken during careful 'diagnostic' hammering on the Red Planet and then beamed back to Earth, providing the HP^3 team with some additional clues.

A crater in the wrong place

At present, the engineers and scientists assume that when hammering, the friction on the outer wall of the 'Mole' is not sufficient to absorb the recoil of the mechanism – causing the 'Mole' to jump on the spot without penetrating further into the ground. The team's hypothesis was validated when the holding structure was removed using the robot arm on the InSight lander. Hammering had compressed the soil around the 'Mole' to such an extent that a crater had formed beneath its base. Work is currently under way to develop a method to restore the required friction to the probe with the robot arm. The 'Mole' will then continue to work its way into the surface of the Red Planet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The NASA InSight lander on the Martian surface

DLR's Mars 'Mole' is doing pioneering work and has no precursors in the history of space travel. The only missions to have a similar experiment on board were Apollo 15 and Apollo 17: however, the drill was manually driven up to three metres into the ground by the astronauts.

Terrestrial laboratories for cosmic missions

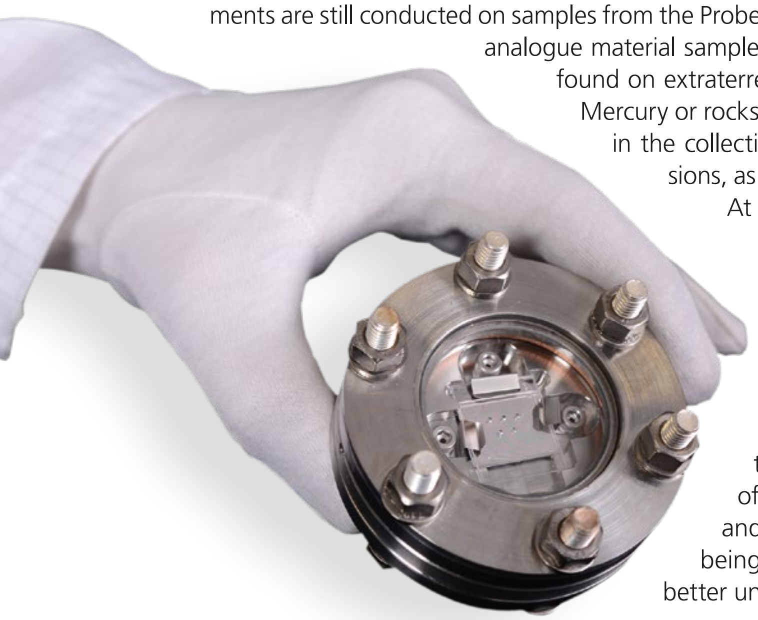
However, meagre in size as the room might be, there is always space for the hot surfaces of Venus or Mars and the icy expanses of Jupiter's moons. The Planetary Spectroscopy Laboratory (PSL) at the DLR site in Berlin is a unique facility that studies planetary analogue materials, that is, substances that might originate from the surfaces of various celestial objects. The laboratory measures spectral data across the entire range from UV to far-infrared, under vacuum conditions and at temperatures of between minus 200 to plus 700 degrees Celsius. The data received provides a means of simulating the surfaces of planets, moons and small celestial bodies in order to determine the properties of extraterrestrial materials.

The laboratory is one of eight in which DLR planetary scientists replicate cosmic conditions on Earth, enabling them to prepare instruments for missions and test them for their voyage through space. The laser altimeter BELA, which is travelling to Mercury on board the BepiColombo spacecraft, was put through its paces in the AIV/Laser Laboratory, while CHEOPS, a mission to exoplanets, was tested and configured in the Calibration and Thermal Vacuum Laboratory. In the Mars Simulation Facility, organisms are introduced to prove, among other things, that they can survive the radiation and atmospheric conditions prevailing on the surface of the Red Planet.

Samples from the Moon, Mars and asteroids

Another laboratory is scheduled to open its doors by 2021, the Sample Analysis Laboratory (SAL). At present, experiments are still conducted on samples from the Probe Preparation Laboratory archives. These hold several hundred analogue material samples that are prepared in sizes resembling those that would be found on extraterrestrial objects. Examples include the fine dust draped across Mercury or rocks from the craggy surface of the asteroid Ryugu. Also included in the collection are samples from the Apollo 16 and Luna 24 moon missions, as well as some meteorites and materials such as nano-diamonds.

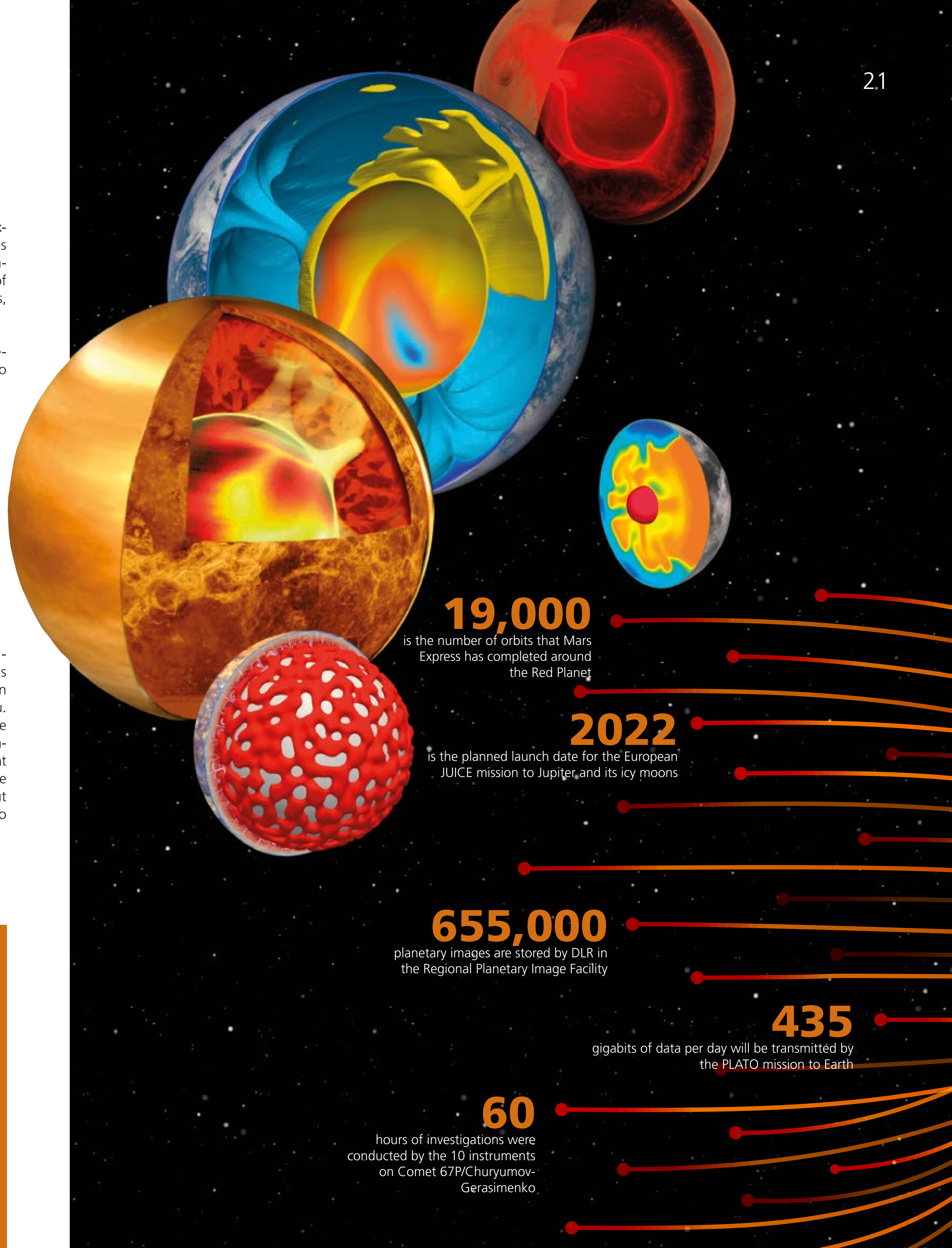
At present, missions are increasingly being designed to bring soil samples back to Earth from remote places in the Solar System ('sample return').For example, in 2023, the US-American OSIRIS-REx mission is scheduled to collect and bring back materials from the asteroid Bennu, while the Japanese Hayabusa2 mission will return to Earth in winter 2019 with samples from Ryugu. Other missions to the Martian moons (Moon-Mars Explorer), the Moon (Chang-E 5 and 6) or to Mars itself also plan to collect extraterrestrial materials for earthly laboratories. With the establishment of a Sample Analysis Laboratory at DLR, it will be possible to analyse and investigate these samples under clean-room conditions without being destroyed. The findings will make an important contribution to better understanding the formation of the Solar System.



Dust particles from asteroid Itokawa

Traversing Titan's atmosphere

NASA's Dragonfly mission is scheduled for launch in 2026 and will bring a helicopter to Saturn's moon Titan. But before it can whisk across the Saturnian moon's surface, its landing capsule will take the heat on some tricky manoeuvres when entering the atmosphere. DLR will use COMARS+ (Combined Aerothermal and Radiometer Sensors Instrument Package) to measure the pressure acting on the heat shield and to collect data on radiation and thermal loads during atmospheric entry. The payload developed at DLR obtained similar data during the European ExoMars mission in 2016, yielding valuable insights for future missions.



Innovation for digital life

The first mobile phone was officially approved in Germany back in September 1983 – it weighed 800 grammes, had a battery life of less than one hour and set its owner back 4000 US dollars. The first text message was sent by a computer to a mobile phone in 1992. In-vehicle, GPS-based navigation systems premiered in 1990. The World Wide Web was developed at the European Organization for Nuclear Research (CERN) in 1989; it was originally designed to simplify the sharing of research findings among scientists. The age of landline telephones, phone boxes or neatly folded paper maps is not that long ago – today, however, digitalisation and the requirements it places on users are front and centre in societal life. Topics such as communications, navigation, autonomy and data security are important areas of DLR space research.

Modern society, with its plethora of digital applications, is highly reliant on communications and navigation: people are using increasingly powerful smartphones for complex applications. Progressive connectivity between people, devices and electronic systems is being developed and tested within Industry 4.0 and the Internet of Things. Vehicles that can navigate traffic with the highest degree of autonomy and safety also need more advanced information and communications technologies. Secure and globally available communications networks will be required to make the smart applications and innovative services mapped out for the future a reality.

Comprehensive and high-performance

Comprehensive roll-out of broadband technology is therefore a vital task and a significant challenge. While this important condition is already satisfied in urban regions, the more rural areas continue to lag behind – laying fibre-optic cables to individual households in remote places is too laborious and expensive. Satellites offer various solutions to this problem and can thus complement existing terrestrial systems. Possible concepts on which DLR is conducting research include extremely powerful optical communications systems for geostationary satellite and stratospheric platforms.

Optical technology will play an increasingly important role in this field. Its benefit: high data throughput – whether via relay satellites or direct connection to the ground. But atmospheric interferences that may distort optical transmission are a drawback. DLR is therefore engaged in extensive research on understanding and controlling both the data rate as well as its stability during transmission.

Fine tuning of time and space

Continuous development of new and more advanced versions of existing technologies is crucial in the area of navigation: not only is satellite navigation used in transport, it is equally vital to logistics, agriculture, construction, the synchronisation of telecommunications networks, power grids, and for financial transactions. New applications and services can only be developed if time and space signals become more precise. DLR believes that modernising satellite navigation is one of the biggest challenges for the future – after all, some of the Galileo satellites have already spent over half their projected lifetime of around 12 years in space. A variety of DLR institutes have joined with other research institutions and industrial partners to pool their resources in the newly established Galileo Competence Center. Incorporated within DLR, it is setting the course for future services, applications and technologies. This also includes the development of future satellite navigation systems such as Kepler.

The increasing presence of autonomous systems in everyday life heightens the risks as well: these systems are extremely vulnerable to manipulation and disturbances, and the consequences are serious. The challenge will be to develop technologies and methods that effectively protect data and signals from deliberate disturbances and spoofing.

Satellite fleet for communications and navigation

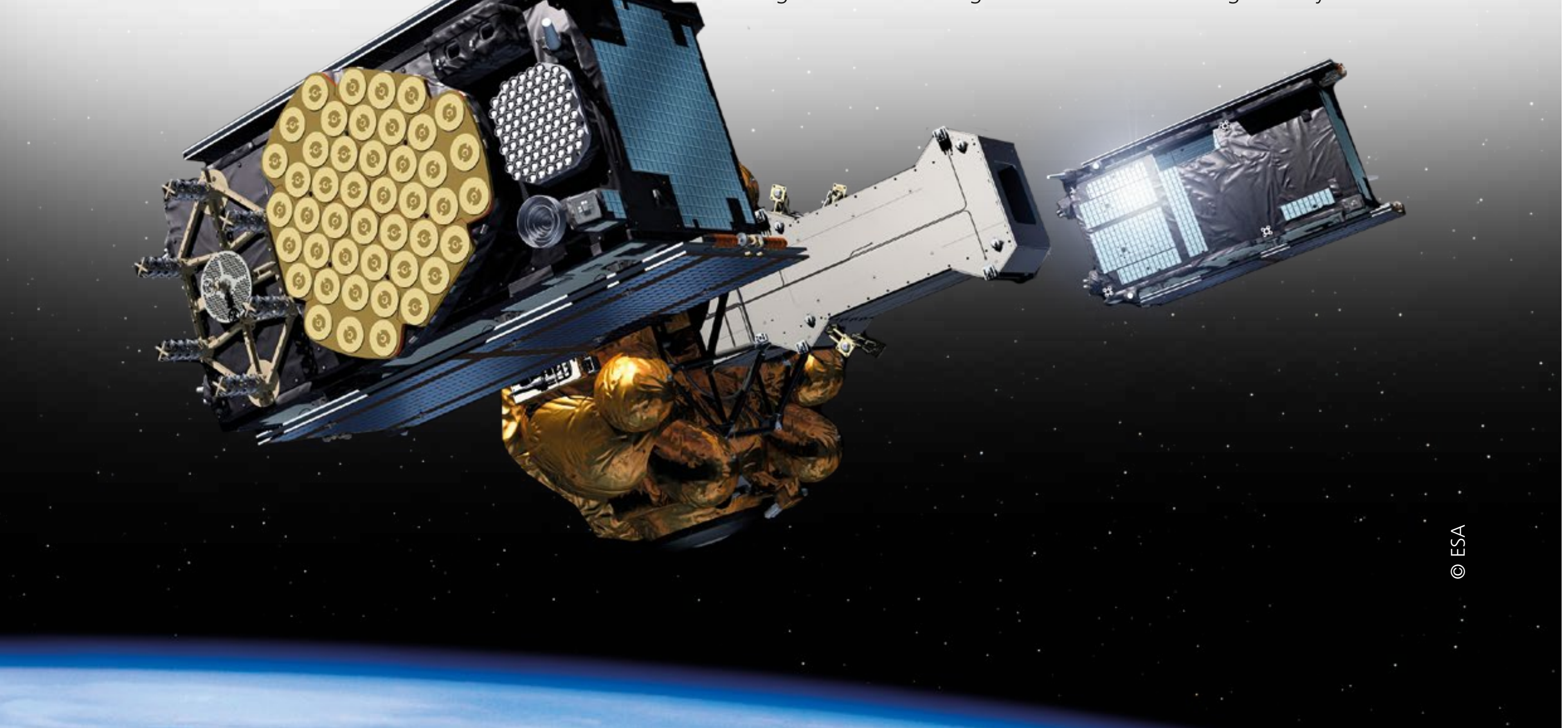
The launch of a Soyuz rocket from the European spaceport in French Guiana at 12:30 CET on 21 October 2011 marked the inception of a new era. Soyuz carried the first two Galileo satellites into space, taking the first steps towards establishing an independent European satellite navigation system. Today, there are 26 Galileo satellites in Earth orbit, but global coverage remains insufficient to enable exclusively Galileo-based navigation. This still requires combination with other systems like the US GPS or the Russian Glonass. Many smartphone users already unknowingly benefit from signals provided by the Galileo constellation. Twelve additional satellites are earmarked for launch between late 2020 and the end of 2022, at which point the system will be complete.

The European Commission approved the first Galileo services on 15 December 2016. Among them were the Search and Rescue Service and the Open Service, a free public platform for the mass market with positioning navigation and timing. Also provided is the encrypted PRS (Public Regulated Service) for entities entrusted with sovereign tasks, such as police forces, fire departments and civil protection. The High Accuracy Service (HAS) provides an extremely precise timing signal that operates within a nanosecond range and enables positioning with an accuracy of up to 20 centimetres. HAS is designed for commercial purposes, for instance within networked agriculture, the logistics industry or the autonomous driving sector. The services are still in the initial phase, which means they operate with precision, but are not universally available.

Pooled expertise

DLR established the Galileo Competence Center in Oberpfaffenhofen to group together expertise in the areas of application, research and operations under one roof. The emerging Competence Center aims to develop fresh concepts and technologies for the next generation of systems, with particular emphasis on using quantum technology as a basis. In doing so, the centre seeks to ensure the superior performance of the Galileo system and hence the technological and geopolitical sovereignty of Europe in the long term. In addition, the new technologies will be demonstrated, tested, validated and put into practical use as rapidly as possible, and the development and implementation of prototype services will pave the way for the emergence of new applications within the wider context of Galileo. These extend from highly precise location services, available at short notice on a global level, to applications for the control of autonomous or automatic systems that satisfy rigorous requirements for resilience, reliability and accuracy.

It is hoped that innovative approaches within the field of quantum technology will eventually make it possible for future generations of navigation systems to pinpoint to the nearest centimetre. Signals will need improved reliability for use in safety-critical systems, and the infrastructure must be made more resilient to prevent jamming (interference signals) or spoofing (falsified signals) attacks. Last but certainly not least, operating the infrastructure needs to become more cost-efficient and less dependent on third-party countries. As such, work on developing the next generation of navigation satellites must begin today.



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From Galileo to Kepler

Although the European satellite navigation system Galileo is not yet up and running, its continued development and successor technologies need to be mapped out. Kepler is a proposal for a third-generation satellite navigation system developed at DLR: the system suggests placing 24 satellites in Medium Earth Orbit at an altitude of around 20,000 kilometres, accompanied by four additional satellites in Low Earth Orbit (LEO) approximately 1200 kilometres above ground. It is hoped that technologies such as iodine-based optical clocks and optical terminals for inter-satellite connections will yield greater precision and integrity. In addition, receivers on the LEO satellites would allow the measurement of navigation signals without atmospheric interference. Unlike today's satellite navigation systems, Kepler can also do without extensive ground-based infrastructure. For instance, it does not need reference ground stations for precise orbit determination and clock synchronisation.

Protecting the digital society

Information technologies, communications and navigation systems, energy supply – hardly any area of today's everyday life functions without digitalisation. It offers society many new opportunities and fulfils requirements, for example, for communication channels that are available at all times or for optimised processes in industrial production. The increasing networking and automation in almost all areas of life, the possibility of high-rate data transmission as well as the use of satellite signals and data for a wide variety of applications ensure technical progress and economic development. However, the degree to which technical systems are networked and the dependence on digital infrastructures also make society vulnerable, because disturbances or falsified data and signals have direct effects in key areas ranging from power supply to security in air, ship and car traffic through to financial transactions.

Anti-jamming and anti-spoofing

The protection of data and signals against deliberate interference and falsification is therefore of considerable importance: The systems to be protected could be deceived in their position or time determination and in the recognition of their environment. These counterfeit navigation and radar signals (spoofing) pose great dangers and can be used, for example, to cause collisions by manipulating position determination or to falsify time signals in financial transactions. The disruption of navigation signals (jamming) creates risks, for example in mobility or energy supply. To prevent this, DLR has set itself the goal of developing and optimising suitable anti-spoofing and anti-jamming measures. In addition, DLR scientists analyse communications and navigation infrastructures and networked systems in terms of attack possibilities and design future architectures and protection concepts to prevent them (security by design).

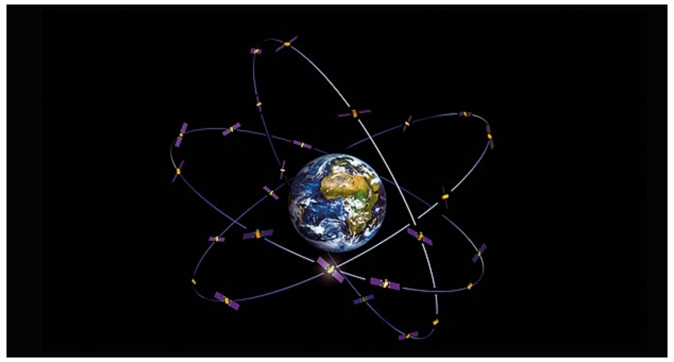
The potential of quanta

Future technological developments such as powerful quantum computers must also be taken into account when protecting vulnerable systems. Since today's conventional cryptographic methods could potentially be broken with quantum computers, DLR is researching methods that will remain secure in the future. This quantum-based approach is one way of ensuring the safety of data and access to systems through the generation and distribution of secure quantum keys, even as technology advances..

Global connectivity

The Broadband Atlas by the German Federal Ministry of Transport and Digital Infrastructure (BMVI) looks quite impressive at first glance: almost the entire map of Germany[1] is marked in green – and nowhere does broadband availability dip below 50 per cent of the households. But things look different if you zoom in on the interactive map. While large cities like Berlin, Hamburg, the region around Cologne, Bonn, Duesseldorf, Munich and Frankfurt offer broadband services to over 95 per cent of households, the rural regions face an entirely different situation. Instead of green and yellow, which would indicate good availability, the areas are marked in grey and blue. This means that the statistics for broadband supply often fall below 10 per cent. Residents in the town of Wustrow in Mecklenburg-Western Pomerania, for instance, are bound to gaze enviously towards Berlin when they look at their data transmission rates.

Global supply of high-speed internet remains a considerable challenge, although communication needs in the modern world are by no means limited to urban centres. Users have high demands when it comes to data rates and availability. But continuing to build terrestrial networks is increasingly becoming prohibitively expensive. Using geostationary satellites to deliver broadband supply to more remote regions appears to be a sensible option. Free-space optical communications play an important role in enabling the transfer of large quantities of data.



Laser-based communications

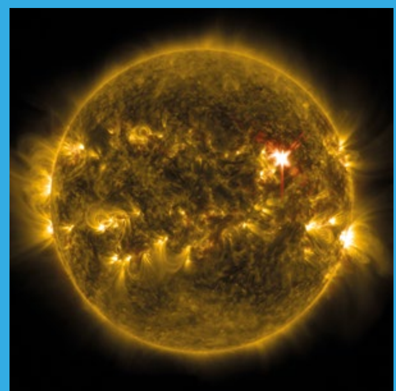
One of the projects that DLR scientists are working on is called THRUST (Terabit-throughput optical satellite system technology). It involves the development of innovative transmission technology for next-generation communications satellites. The THRUST premise: the satellites should link up with the terrestrial internet by means of a laser connection. The aim is to achieve a data throughput of one terabit per second. The Ka band is then used to communicate with users, which is a common frequency for satellites.

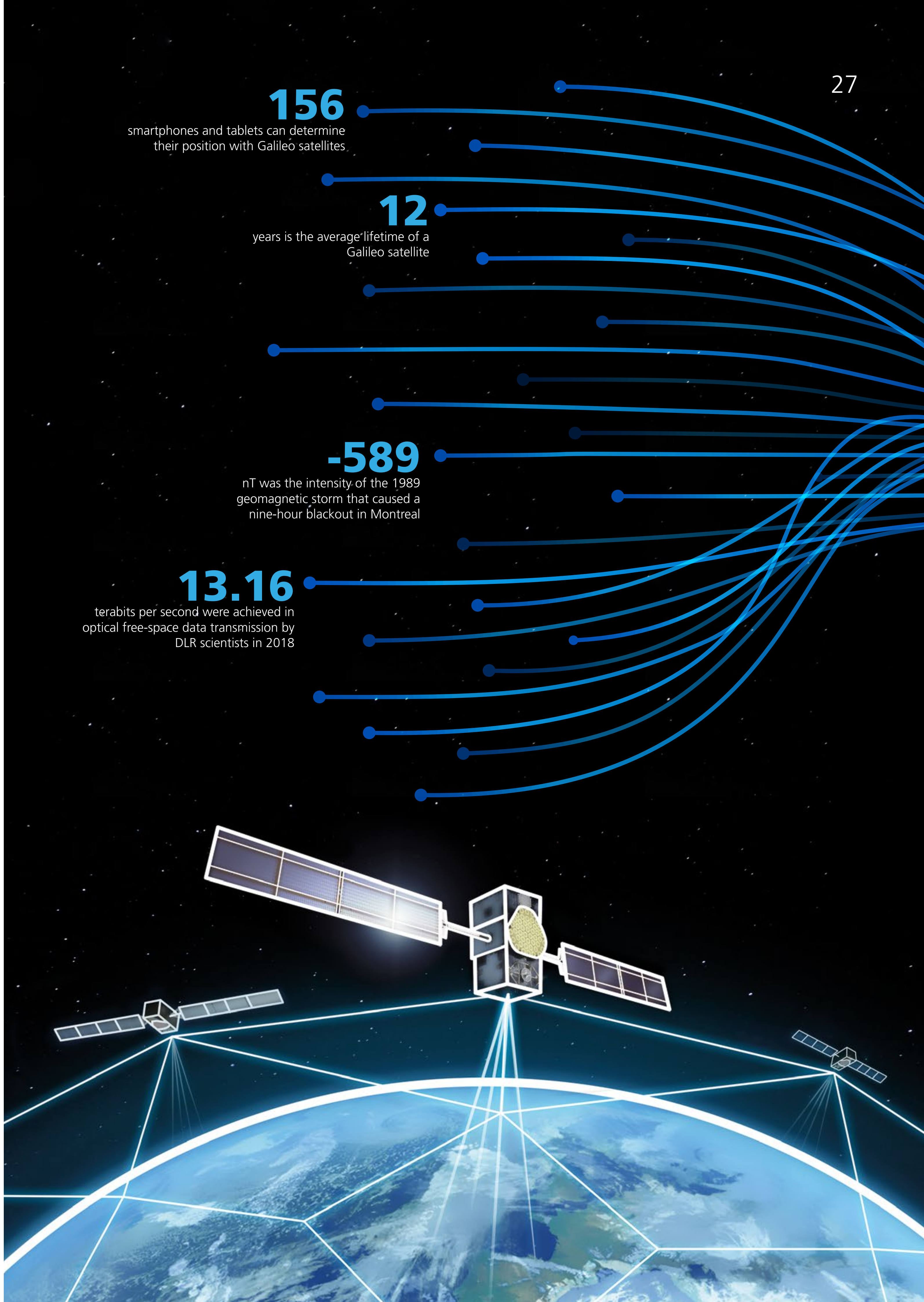
But exploring the feasibility of optical, wireless data transmission in a terabit range is not the only area that requires research. The stability of optical connections is also vital, for instance to operate reliable and failsafe applications within Industry 4.0, smart mobility or civil security. After all, even brief interruptions of just a few milliseconds would lead to the loss of several gigabits of data. Within their research, DLR scientists are therefore seeking to acquire a greater understanding of atmospheric effects and to enable stable laser communications with satellites.

[1] https://www.bmvi.de/DE/Themen/Digitales/Breitbandausbau/Breitbandatlas-Karte/start.html

Protection against solar storms

Solar storms or eruptions can cause interference that impairs the reliable use of communications, navigation and Earth observation systems and that may, for instance, lead to the failure of radio communications within civil aviation. High-magnitude geomagnetic storms can even cause power failures. Established in 2019, the DLR Institute for Solar-Terrestrial Physics collects and processes data on the state of the ionosphere and, in doing so, will lay the foundations for the development and deployment of a fully operational space weather service. It will draw on and process observation data from an array of sensor networks and satellite missions to calculate suitable products for the characterisation and forecasting of space weather. The aim is to improve the protection of technical infrastructure against the effects of space weather.





The conquest of space

The coming years will be crucial for the future of space transport. Competition is becoming fiercer, and the pressure on prices is increasing due to both the development of new launch vehicles and the growth in the private sector. Reusable launchers, new propulsion systems powered by liquid oxygen (LOX) and liquid methane (LCH_4), and global plans for the establishment of satellite constellations will transform our access to space. New technologies must be developed and tested if Europe wishes to ensure that such access is independent and cost-efficient.

Ariane 6, with its Ariane 62 and Ariane 64 variants, is the first step towards a flexible launcher system. But it is already clear that this will not be enough in the longer term. The competition is raising the stakes and is likely to put even more pressure on prices with the introduction of reusable vehicles in the United States.

Compounding the issue is the fact that Ariane 6 had more or less exhausted its potential for performance improvements at the time of its introduction. This is because the launcher is largely built around familiar, proven components that have already fully exploited their performance margins.

DLR's space research programme is therefore prioritising reusability as a means of achieving significantly greater cost efficiency. In particular, the launcher's first stage accounts for a large proportion of costs, and so ensuring its reusability promises considerable savings, upwards of double-digit percentages in some cases. Not only is DLR using the CALLISTO (Cooperative Action Leading to Launcher Innovation in Stage Toss back Operations) and ReFex (Reusability Flight Experiment) projects to explore a variety of reusability concepts, it is also testing the technology in small-scale demonstration flights.

New fuels, new production technologies

With its research on methane-based fuels, DLR is contributing to current developments such as the European technology demonstrator Prometheus – a high-thrust and reusable rocket engine that will be powered by liquid oxygen (LOX) and liquid methane (LCH_4). There are strong arguments for using methane as a rocket fuel, even though it does not yield the same performance as liquid hydrogen. Hydrogen benefits from a considerably greater density in its liquid state, enabling the design of more compact stages.

DLR is also conducting research into environment-friendly fuels known as 'green propellants'. Hydrazine (N_2H_4) has been used in space flight since the 1960s. It can be stored for extended periods and is broken down in simple propulsion systems using a catalytic converter. Hydrazine supports cold starts, which means that the chemical energy to ignite the engine is released as soon as it reaches the catalytic converter. The disadvantage of hydrazine lies in its extreme toxicity for humans and the environment. As a result, elaborate safety measures are required to handle the substance, giving rise to increased complexity and costs. The research community is therefore looking for alternatives that are less hazardous but equally efficient. Among other propellants, DLR researchers are developing, improving and qualifying ammonium dinitramide-based fuels (ADN) and gel fuels.

DLR is further contributing to the area of spaceflight with the development of technologies such as battery-powered pumps, new composite materials and the use of additive layer manufacturing (ALM) for the production of engine components. ALM, for instance, has a variety of advantages for engine manufacture, including significantly shorter production times, which enable complete engines to be delivered within just a few weeks.

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Horizontal or vertical – but always returning to Earth

Cutting costs is key to keeping Europe competitive in the space transport market. In the future, maintaining independent satellite access to space will become an increasingly important goal; however, achieving it will require a paradigm shift in launcher architecture, where reusability will play the biggest role. The first rocket stage accounts for the largest proportion of costs; consequently, ensuring its reusability results in considerable savings, which may even reach the double-digit percentage range. The German Aerospace Center (DLR) is completing two projects in this field: Cooperative Action Leading to Launcher Innovation in Stage Toss back Operations (CALLISTO) and Reusability Flight Experiment (ReFex).

Demonstrator CALLISTO

With CALLISTO, DLR engineers, in collaboration with the French space agency CNES and the Japanese space agency JAXA, are designing a demonstrator that can launch vertically and then land in the same alignment (this is referred to as vertical take-off, vertical landing (VTLT)). CALLISTO is guided using aerodynamic control surfaces during a non-powered phase, featuring a transition from supersonic to subsonic flow conditions. The engine is then reignited to decelerate the CALLISTO vehicle. The landing system therefore absorbs the residual kinetic energy, enabling CALLISTO to perform a safe and stable landing.

Perfecting design, from flight to flight

The CALLISTO project is intended to improve the knowledge about VTLT rocket stages; it will also demonstrate technologies that are necessary to build and market such rockets. The 3.5-tonne rocket is scheduled for take-off from the spaceport in French Guiana in 2022, and additional test flights will follow. The findings from the various flight tests will be used to optimise the design of a reusable space transport system.

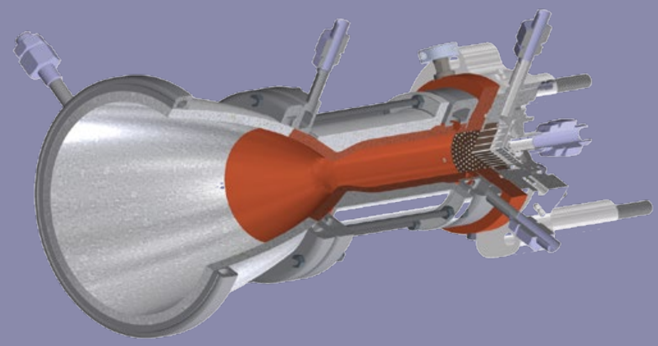
DLR is also engaged in the ReFex (Re-usability Flight Experiment) project, in which it is researching on an alternative approach for reusable launch vehicles with re-entry capabilities. Instead of vertical landing, tests focus on the horizontal landing of a first stage rocket, with autonomous navigation and controlled flight during each phase of the vehicle's mission. The vehicle is stabilised using an active aerodynamic control system, which transforms inputs from the navigation system and the guidance into control commands for the individual actuators. A demonstration flight is planned for 2022 from Woomera, Australia.

Compared to the actual operating system, both demonstrators are quite small, but they will provide key data and insights about necessary technologies. This information will inform a decision on which system would best suit Europe's needs. Developing a new rocket generally takes 10 to 15 years, so the necessary technologies must be made available to keep pace with the stiff competition in the rocket market.


Demonstrator ReFex

AI in engine development

Engineers at the German Aerospace Center (DLR) site in Lampoldshausen acquire valuable data with every test bed experiment. This information can be used in the development and testing of new engines. Data generated through numerical simulations is also valuable in modifying and optimising new technologies. Artificial neuronal networks, which is a special machine learning method, are increasingly being used to combine simulation and experimental data as a means of acquiring fresh insight. This branch of AI has featured in DLR's LUMEN (Liquid Upper Stage Demonstrator Engine) project, as well as other research. As part of research into a liquid propellant rocket engine demonstrator, the machine learning method was used to calculate the dynamics of heat transfer within the cooling channels of the rocket's combustion chamber. The method yielded models that deliver predictions 1000 times faster than equivalent computations, for instance using numerical fluid mechanics.



The search for alternative fuel

Future fuels will face many new demands and challenges, and this is not just concerning the need for improved performance. Advances in the handling and storage of fuels are becoming increasingly important. They also need to be greener, less toxic and more cost-effective. At present, liquid oxygen (LOX)/methane technology is viewed as the most promising fuel combination; it has significant potential in the development of cost-efficient and reusable, high-thrust rocket engines. Current European development projects like Prometheus, MIRA or the Romeo engine are based exclusively on methane as fuel.

Unlike cryogenic hydrogen, methane can rightly be described as 'suitable for storage in space'; its boiling point is around 90 to 130 Kelvin, which means that only passive, thermal insulation of the tanks is necessary. Methane evaporation rates are also considerably lower than those of hydrogen. In addition, compared to liquid hydrogen, methane is significantly less expensive to produce. The smaller tank system, the simpler equipment with only one turbo-pump, as well as the cost-efficient ground infrastructure contribute to these cost reductions.

Conversion for LOX/methane research

Compared to liquid hydrogen, methane also has striking benefits in terms of reusable engines. Unlike methane, hydrogen corrodes material and, in doing so, places limits on engine reusability. The German Aerospace Center (DLR) aims to build its competency in the field of methane. This includes experimental studies and the development of physical models, as well as the numerical simulation of combustion processes and fuel processing. DLR's internal LUMEN (Liquid Upper Stage Demonstrator Engine) project will develop a LOX/methane engine with pump transport system. Once complete, it will be tested at DLR's European research and technology test rig P8. In addition, the current P5 test rig is currently being converted to fulfil the requirements of LOX/methane research. The testing of an additional technology demonstrator with more than 100 tonnes of thrust will also be completed at P5. As a result, from 2020 onwards, suitable infrastructure will be available for testing at the DLR site in Lampoldshausen.

Test of a combustion chamber on the P3 test rig

Space on Earth

When the engine and nozzle are running on the P4.1 test bed at the German Aerospace Center (DLR) site in Lampoldshausen, the conditions are exactly as they would be during a launch procedure. The test material is exposed to a vacuum inside the altitude simulator, as if it were travelling 70 kilometres above the ground. This capability makes the test bed unique in Europe. DLR systems accommodate the entire portfolio of test requirements, from component tests to engine tests, and even the testing of rocket stages. The data collected is used in research and development, as well as for qualification and characterisation processes. Test bed P5.2 became operational in 2019, and is yet another unparalleled facility in Europe. So far, tests have been limited to engines and their components. However, this new system also enables testing of the entire cryogenic upper stage for Europe's Ariane 6 launch vehicle, along with its qualification for space travel.

Typical research in microgravity conditions – conducted on satellites and rockets

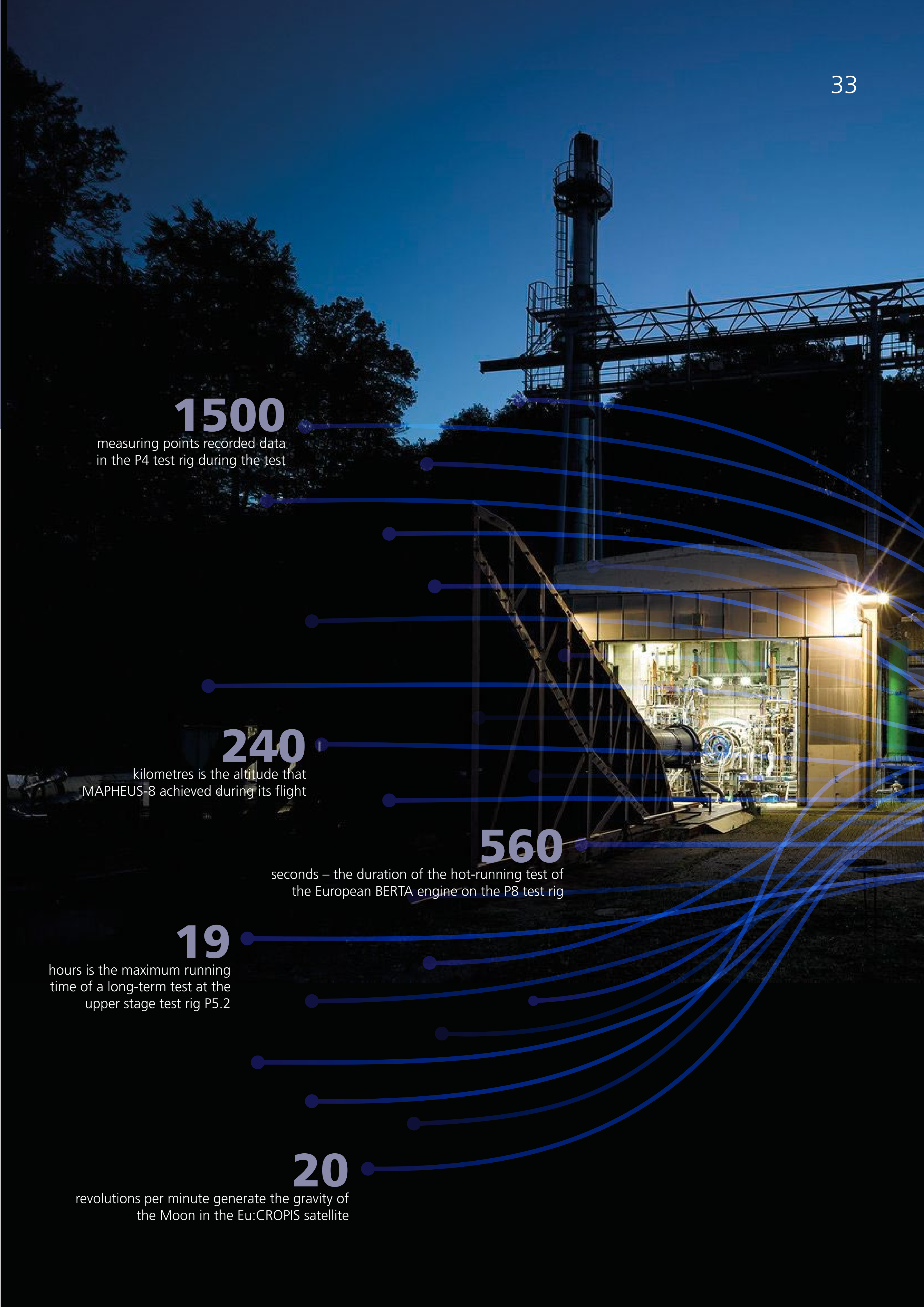
Atmosphere, temperature, vacuum: many of the conditions prevailing in space can be simulated in DLR's terrestrial laboratories and test facilities. However, when it comes to longer periods of microgravity, the laboratories do not fit the bill, despite their cutting-edge equipment. For example, experiments conducted in drop towers only generate a microgravity state of a few seconds. Additionally, DLR's parabolic flight aircraft, in which experiments are regularly performed during flights, can provide 22 seconds of microgravity. But when it comes to addressing scientific questions that require a longer period without Earth's gravitational force, space offers the only solution. Experiments can be exposed to microgravity for up to seven minutes on board high-altitude research rockets. When satellites are used, the duration of the microgravity state is unlimited. This allows experiments involving small furnaces, biomembranes, an electrostatic levitator or biofilters to be operated and tested without the disruptive influences of Earth's gravity. The costs and effort required to complete experiments using rockets and satellites are lower than for those completed on the International Space Station (ISS). As such, these smaller experiments have a greater chance of being conducted in microgravity. Preparations and testing can also be carried out for experiments that will later take place on the ISS.

Rocket technology for experimental flights

DLR's MAPHEUS programme is focused on conducting materials physics experiments under microgravity conditions. As part of the programme, a number of experiments have been transported into space from a rocket launch base in northern Sweden over the last 11 years. Launches are organised and carried out by DLR's Mobile Rocket Base (MORABA) division. As such, MAPHEUS provides scientists with independent, regular access to experiments under microgravity conditions. The eighth MAPHEUS launch in 2019, which incorporated the ATEK mission, fulfilled a dual purpose. Together with various biological and materials science experiments, the 12 metre-high and over 2.5-tonne rocket was itself the subject of research. The science experiments were transported to an altitude of around 240 kilometres. At the same time, the rocket also carried health monitoring systems for critical carrier components, as well as a hybrid casing structure created using a novel method.

Satellites – compact and cost-effective

Another vehicle for transport and living in space was launched to space on 3 December 2018: the Eu:CROPIS satellite (Euglena Combined Regenerative Organic Food Production in Space). Eu:CROPIS is the first mission for the compact satellite platform CompSat, which is a class between small CubeSats and the usual larger satellites, developed and built by DLR. The aim is to test and qualify new satellite bus technologies and to provide a platform for new instruments and experiments. The rotating Eu:CROPIS satellite, whose contents include two greenhouses with trickle filters and tomato seeds, demonstrated the feasibility of inexpensive and effective satellites for the first time. This is intended to be the first in a series of compact satellites. With this strategy, DLR is demonstrating its overall system competence and regularly implements satellite missions for research purposes. The next satellite, COFROS, will test a novel optical clock in preparation for future navigation satellite systems.



Robots

of the future

The job description for the robots of the future is somewhat demanding – it asks for as much independence as possible, as well as the ability to work smoothly and efficiently in a team, alongside co-workers who bring different skills and ways of thinking to the task at hand. Such robots are required to be highly skilled and sensitive. In future, they will be expected to draw upon their intuition, use tools, and understand and assess unfamiliar environments. Of course, they will be equipped with the same level of agility and dexterity that nature has hitherto bestowed only on humans.

Not only are they intended to assist astronauts during their missions; they will also help elderly people or those with restricted mobility on Earth. In industry, they should use their skills to full effect, without ever posing a threat to their human colleagues. Their 'minds' must be sufficient for them to carry out tasks independently, but they must also be able to relinquish their autonomy at any time and execute commands issued by their controllers. The robots of the future will have to be able to deploy all of these capabilities for a large array of tasks in highly challenging environments, whether on Mars, under microgravity conditions, in laboratories on Earth, in disaster zones, or in retirement homes. As part of its space research, DLR is working to ensure that the robots of the future are given these abilities. After all, a robot is only as intelligent and useful as its engineers make it.

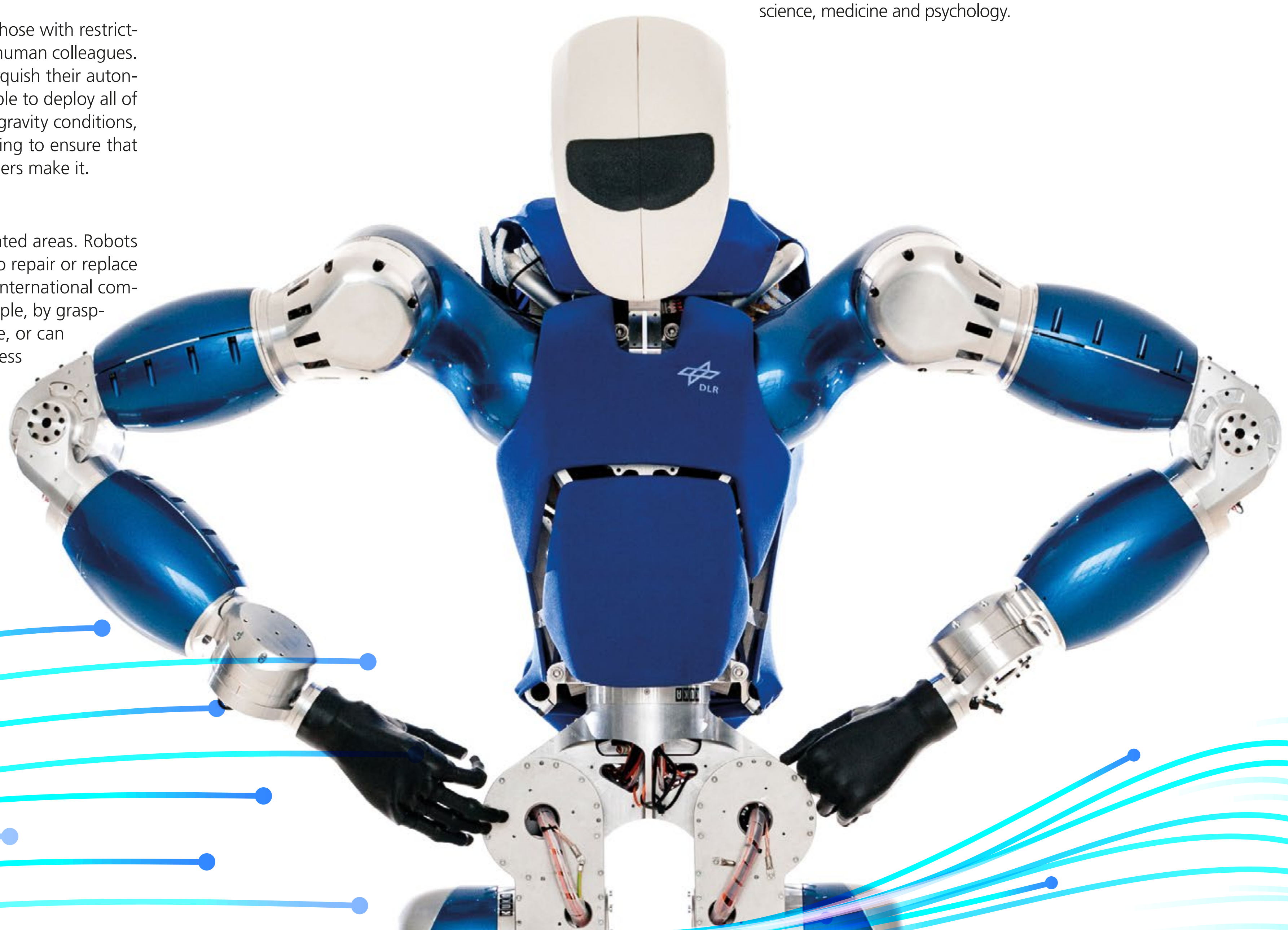
From exploration to maintenance

Robotic systems have many applications in space. DLR is developing and testing technology in several related areas. Robots can be designed to carry out on-orbit maintenance and may inspect and service satellites, but they could also repair or replace scientific payloads. These activities will yield expertise that will become important due to the ever-increasing international competition between commercial satellite operators. DLR is also exploring the removal of space debris – for example, by grasping a tumbling satellite. In addition, robots that are able to assist humans when conducting activities in space, or can undertake hazardous tasks on their behalf, are under development. This increases the safety and effectiveness of astronauts' work. DLR researchers are designing and testing robotic systems to be used for exploration. Rovers will be able to rapidly and independently explore other celestial bodies over a large range while collecting soil samples, which will enable new information to be acquired about the formation of the Solar System.

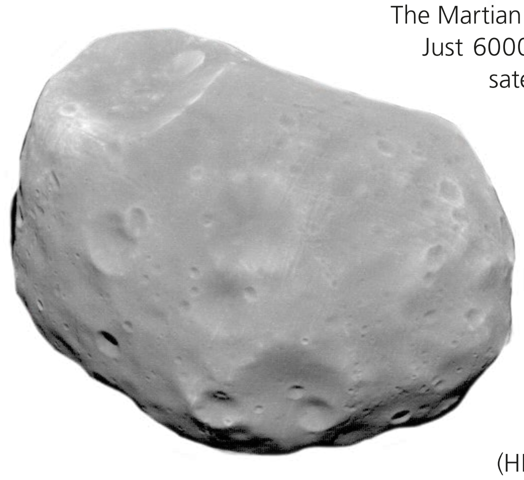
Equipping this hardware with artificial intelligence is crucial for all of these endeavours. Not only must the robots be able to act reliably and autonomously, they should also 'know' and be capable of explaining why they are performing specific actions. This is opening up new possibilities for challenging missions through interaction with humans or in collaboration with a team or other robotic systems.

Robotics for Earth

Spaceflight serves as a test laboratory for robotic technologies that are also vital for addressing challenging situations on Earth. In industry, robots – such as the robotic arms used in car manufacturing – are now commonplace. As part of the process of technology transfer from space to industry, DLR is currently researching the 'Factory of the Future', in which intelligent robots will work in digitalised manufacturing. Personnel in the healthcare sector will also benefit from space research, as robotic technologies are beginning to be used during operations, taking some of the pressure off surgeons. Robots with enhanced sensors – controlled by muscle signals – assist people with restricted mobility to become more independent. Some robots are also used in areas that would be hazardous for workers to access, such as during disaster management and rescue operations. Space robotics, once a single discipline, has now evolved into an interdisciplinary field of research closely connected to biomechanics, neuroscience, medicine and psychology.



Driving on the Martian moon Phobos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The Martian moon Phobos

The Martian moon Phobos is closer to its host planet than any other moon in the Solar System. Just 6000 kilometres separate it from the Red Planet. It remains unclear how this natural satellite, which measures an average of 22 kilometres across, was created. In the distant past, it may have been formed from the debris resulting from a major impact on Mars, or it might have originated in the asteroid belt and been drawn in by the planet's gravitational attraction. In 2026, for the first time, a rover developed by the German Aerospace Center (DLR) and the French space agency CNES will land on Phobos and investigate the moon with four instruments. It will reach its destination as part of the Japanese Martian Moons eXploration (MMX) mission, which aims to land and bring back samples, and is scheduled for launch in 2024.

The scenes awaiting the rover have already been revealed by images from the Mars Express spacecraft, which has imaged Phobos several times from distances of less than 150 kilometres using the DLR-developed High Resolution Stereo Camera (HRSC). The most notable feature of the irregularly shaped moon is its biggest impact crater, Stickney, which measures nine kilometres across. Until now, no attempt to explore the satellite has succeeded; the Soviet Phobos 1 and 2 spacecraft were planned to land there in 1988/1989, but contact with both spacecraft was lost before they reached that stage. The Russian Phobos-Grunt mission, which was launched in November 2011, also ended unsuccessfully, without reaching Phobos.

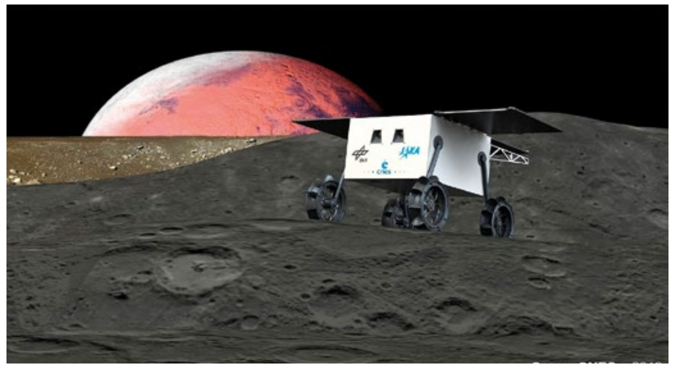
First visitor to a Martian moon

The MMX rover, which weighs only 30 kilogrammes, will therefore be the first visitor to this Martian moon. Upon arrival, it will move across Phobos very slowly on its wheels. Gravity on the satellite is only one ten-thousandth that of Earth. Equipped with solar panels, it will be possible to operate the MMX rover for at least three months on the surface of Phobos.

DLR is making significant contributions to the mission. Two of the four instruments on the rover – a Raman spectrometer and an infrared radiometer – are being developed and built by the DLR Institute of Optical Sensor Systems and the DLR Institute of Planetary Research. These are primarily aimed at examining the surface composition and characteristics. DLR researchers have also been involved in the design of the French cameras installed on the rover and will conduct research using the data that they acquire.

Track depth on Phobos

In addition to transporting the instruments, the rover will also perform another important task. The depth of the tracks that it leaves on the surface will tell the Japanese space agency JAXA about the surface and thus provide information that can be used for sampling with the orbiter. MMX is expected to begin its return journey to Earth in August 2028, while the samples are expected to arrive on Earth in July 2029.


© CNES

MMX rover on the surface of the Martian moon

DLR is largely responsible for the development of the rover. The Institute of Robotics and Mechatronics designed the robotic locomotion system, while the Institute of Composite Structures and Adaptive Systems developed the rover casing. The rover will be assembled at the Institute of Space Systems. After landing, the rover will be operated by DLR's Microgravity User Support Center (MUSC), in conjunction with a control centre in France. Together with other aspects, CNES is responsible for the two camera systems and the central service module on the rover.

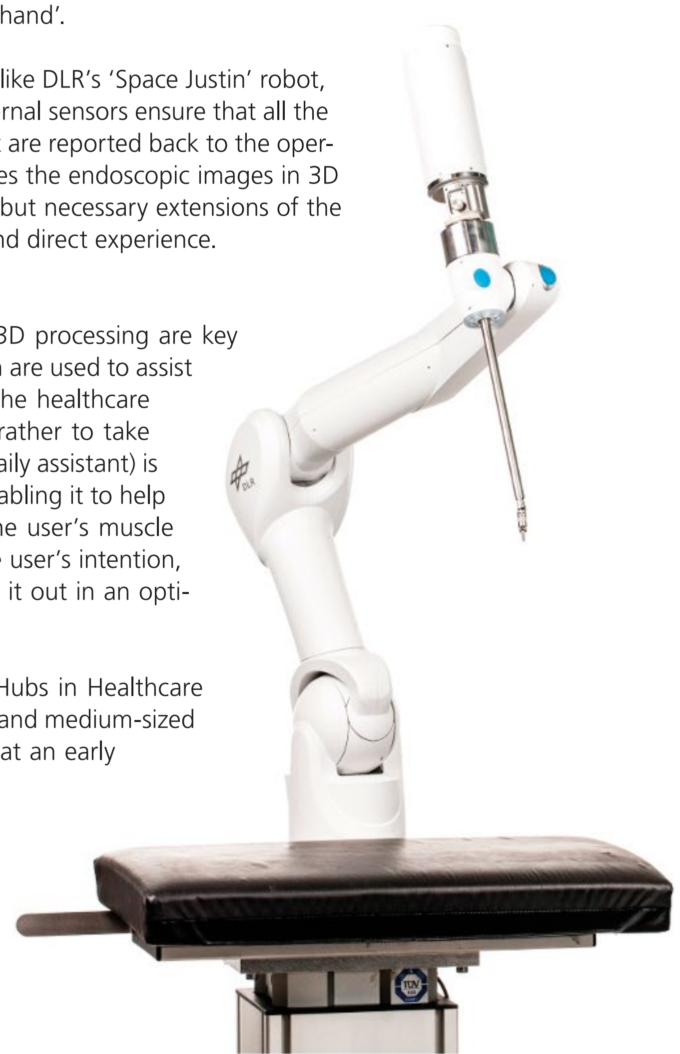
Outstanding mobility

Walking robots could be used for planetary exploration in areas that are difficult to access, such as canyons, craters and lava tubes on the Moon or Mars. Mobile robots could also provide valuable support as assistants in the healthcare sector or as helpers in disaster regions. Humanoid, next-generation walking robots could feature active adaptation of their dynamic motion characteristics, such as stiffness and shock absorption. The four-legged walking robot Bert and the humanoid robot TORO (TOrque-controlled humanoid RObot) are part of the research platforms driving such developments. Two DLR projects – M-Runners and NatDyReL, which have received funding from the European Commission's ERC Advanced Grant – are conducting research into how to make walking robots similar to their biological counterparts. To that end, DLR is bringing together expertise from fields including robotics, biomechanics, artificial intelligence and neuroscience.

Space technology for medicine

The incisions are perfect and the severed blood vessels are sutured with precision. Focused, risk-minimising and stress-free – the 'person' performing these tasks in the operating theatre is not human, but a robot. The DLR-developed MIRO robotic arm assists the surgeon, who controls it via a console. At the same time, the doctor using the controls can feel exactly what the robot's instrument tips are doing, as though he himself were holding them in his hands. MIRO, in turn, filters out slight inaccuracies in human hand movements, performs the surgeon's movements with the utmost precision, and thus optimises the operation. Robot and human work together – 'hand-in-hand'.

The technology for such medical applications comes from space – like DLR's 'Space Justin' robot, the MIRO robotic arm has flexible joints and sensitivity. Numerous internal sensors ensure that all the contacts that the robotic arm makes with its surrounding environment are reported back to the operator's input device in real time. During the procedure, the surgeon sees the endoscopic images in 3D and gently controls the tips of the instruments, not the cumbersome but necessary extensions of the instruments. For the surgeon, this makes operating a more intuitive and direct experience.



Robotic assistance in the healthcare sector

Technologies such as safe human-robot interaction or real-time 3D processing are key areas of research in space robotics at DLR. These developments, which are used to assist astronauts with the exploration of space, can also be beneficial in the healthcare sector. Robotic assistants are not intended to replace humans, but rather to take pressure off patients and medical staff alike. EDAN (EMG-controlled daily assistant) is equipped with a lightweight robotic arm and a five-fingered hand, enabling it to help people with severe motor impairments. It receives commands via the user's muscle signals. The robot also does some of the 'thinking' by recognising the user's intention, adapting the commands that it has received to the task and carrying it out in an optimum way.

As a partner in the international consortium 'Digital Innovation Hubs in Healthcare Robotics' (DIH-HERO), DLR provides its expertise and support to small and medium-sized companies, and in return benefits from getting to know their needs at an early stage. This accelerates the transfer of technology to the market.

Teamwork between space and Earth

The supervisor is flying around Earth at an altitude of 400 kilometres, while the assistant provides support on the ground. In the SUPVIS Justin experiment, those issuing and receiving the instructions are conducting a long-distance relationship of sorts. While the astronaut on the International Space Station (ISS) is orbiting Earth, the DLR robot Justin executes commands in a terrestrial laboratory. To be specific, it decides which actions need to be performed in order to complete the task issued by its supervisor in space. The robot has been provided with the artificial intelligence that allows it to perform such feats by DLR engineers, allowing it to carry out individual sub-tasks independently and without detailed commands. SUPVIS Justin might be smart, but the astronaut remains in charge, via the control tablet PC.

A smart assistant: Justin the robot.

In 2017, such teamwork was tested for the first time as part of the METERON (Multi-Purpose End-to-End Robotic Operation Network) project. 'Rollin' Justin' has previously worked successfully with US astronaut Scott Tingle and the European astronauts Paolo Nespoli and Alexander Gerst. Justin is set to become a member of the team, at least optically, on Mars, in order to inspect and maintain solar panels as independently as possible, task by task, while providing its astronaut in orbit with feedback on the next steps to be taken.

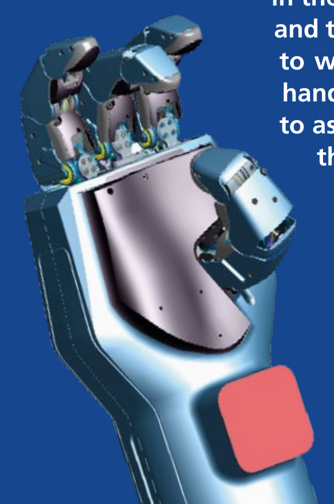
An astronaut's robotic partner

Despite this progress, the tasks that astronauts and robots are expected to perform together have become ever more demanding. In August 2018, Alexander Gerst and Rollin' Justin worked together to maintain a solar power system on the Red Planet. The engineers and scientists then set the human-machine team another test. During the live experiment, they unexpectedly set a satellite receiving system on Mars on fire. Intuitive tablet operation and the smart autonomy of the robot allowed the astronaut and his assistant to replace the burning module successfully.

There are several advantages to using an intelligent, relatively independent robot. For example, a human-machine team is less susceptible to communication delays, as the robot does not need to be controlled continuously. In addition, the astronaut's workload can be reduced by delegating tasks to the robot. During future missions, an astronaut would therefore be able to orbit another celestial body, and from there control a team of robots equipped with artificial intelligence on the surface of that body. In such an arrangement, the robots would no longer serve as just an extension of the astronaut's arm, but would instead be partners on the ground.

Skilful and flexible

Human hands and arms may have many advantages, but using robotic systems to perform certain tasks in space is certainly more cost-effective, and reduces risk. DLR is therefore developing a robotic alternative in the form of the robotic arm CAESAR (Compliant Assistance and Exploration SpAce Robot) and the Spacehand. Together, these come close to matching human capabilities and are able to withstand the harsh conditions of space in long-term geostationary orbit. The robotic hand uses all of the tools that astronauts work with during tasks outside spacecraft in order to assemble, maintain or repair structures in space. CAESAR is a highly flexible robotic arm that can grip onto and stabilise tumbling and non-cooperative satellites. It can do this either semi-autonomously, via teleoperation or through telepresence with force feedback. Both technology developments thus benefit from their predecessors at DLR, including the DEXHAND robotic hand or the ROKVISS robotic arm, which performed tasks outside the International Space Station (ISS) for over five years.



1.91
metres. That is the height of the humanoid Rollin' Justin robot

12
articulated torque sensors give the Spacehand flexibility

100
is the temperature variation in degrees Kelvin that must be endured by the MMX rover on Phobos within one day

5000
millimetres – the maximum length of the CAESAR robotic arm

10
kilogrammes is how little the MIRO surgical robotic arm weighs

Quantum potential

Quanta surround us on a microscopic scale. They can be thought of as tiny packages of physical quantities that cannot be broken up any further. One key example is light. Quantum behaviour on a small scale can result in fascinating phenomena that seem to contradict our macroscopic intuition, borne of our experience of the world of big things. The realisation that the microscopic world that surrounds us can be divided into quanta, known as quantisation, has established quantum mechanics as a branch of physics and turned our understanding of solid states and measurement upside down. One famous instance is the 'Schrödinger's cat' thought experiment, in which the quantum (in this case a cat) exists in two states simultaneously (both living and dead) up until the point at which it is measured (the opening of the box).

Components and instruments that make use of quantum behaviour, known as the 'first quantum revolution', have become indispensable in industry and day-to-day life. They are used as transistors in our mobile phones and electrical devices, in light-emitting diode (LED) displays or as the basis for lasers. Without the quantum behaviour of light, modern communications, data transmission and electronics in general would not be conceivable. The first quantum revolution has long since reached us all.

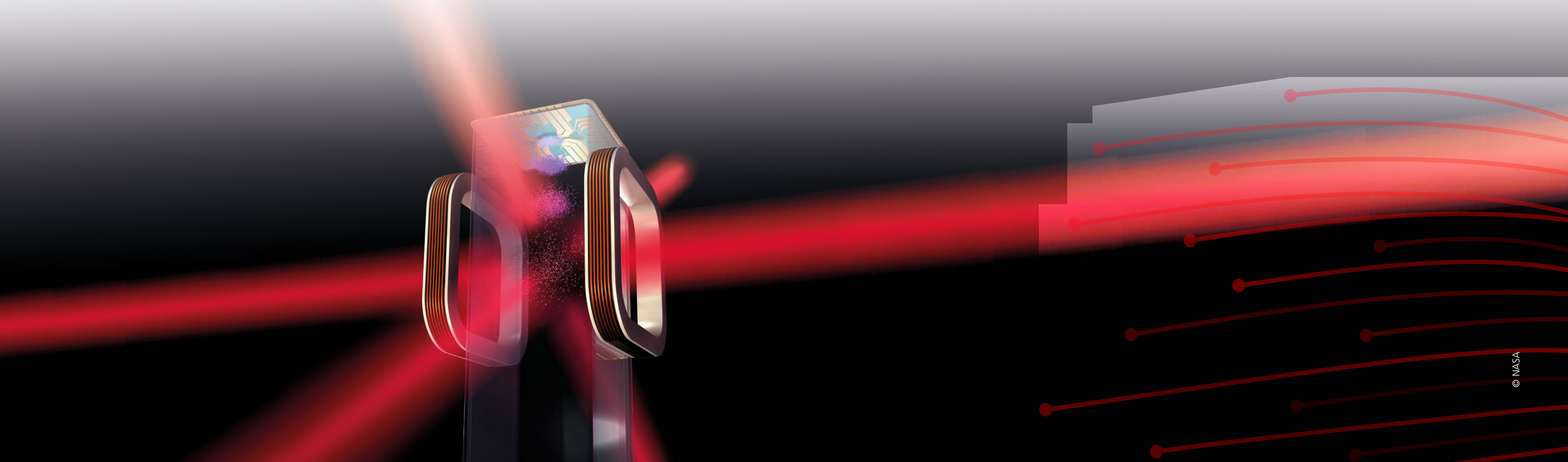
The second quantum revolution

We are now seeing the advent of a second quantum revolution – areas where quantum sensor technology and quantum communications are key. These are based on the manipulation and thus the utilisation of individual quanta of atoms or photons and what is known as the coherence of matter waves. Coherence means that all of the atoms of matter are in the same wave state and behave as a single large wave. This behaviour is manifested in Bose-Einstein condensates (BECs), whereby a large matter-wave of atoms, which have been captured and cooled in a trap, move in a coherent way. If this wave is released from the trap, it can be used as an atom laser. Possible fields of application include holographic projections and, for example, atomic clocks, which are highly accurate timekeeping devices based on the superposition or interferometry of matter waves.

Another important application of the second quantum revolution is quantum computing. This is set to revolutionise the world of computers by massively accelerating the computation of specific problems that are currently impossible to solve using conventional computers. However, due to their considerable potential for performing calculations in parallel, quantum computers can also pose a threat, by cracking encryptions that were previously regarded to be secure.

Quantum technology for space

DLR is preparing for the leap into space for the second quantum revolution by establishing two new institutes that will focus on quantum technology. Research groups are working on the production of larger and more durable BECs in order to make these more useful for practical applications such as quantum sensors and quantum encryption. The first DLR Bose-Einstein condensate 'in space' was generated and tested on a sounding rocket as part of the MAIUS/QUANTUS research projects to investigate the behaviour of quantum condensates under microgravity conditions. This will be taken to the next level by the DLR-planned BECCAL mission on the International Space Station, during which in-depth tests will be conducted under microgravity conditions. DLR will also focus on the challenge of quantum communications and effective encryption using quantum cryptography. New groundbreaking experiments will demonstrate the impact of manipulating a quantum wave on a second, albeit connected, quantum wave 1000 kilometres away. Space research and technology at DLR is thus making an important contribution towards the technological development and security of our entire infrastructure.



BECCAL – experiments with Bose-Einstein condensates on the ISS

Pioneering experiments into different quantum systems are necessary to advance quantum technology for use in space and on Earth. The possibility of generating and studying Bose-Einstein condensates under microgravity conditions is of particular interest, as this may serve as the basis for precision atomic clocks. Low gravity has the advantage that the condensates can be kept intact for a long time. Moreover, the potential for examining the behaviour of the condensates under space conditions is exciting in itself due to the insights that it will provide.

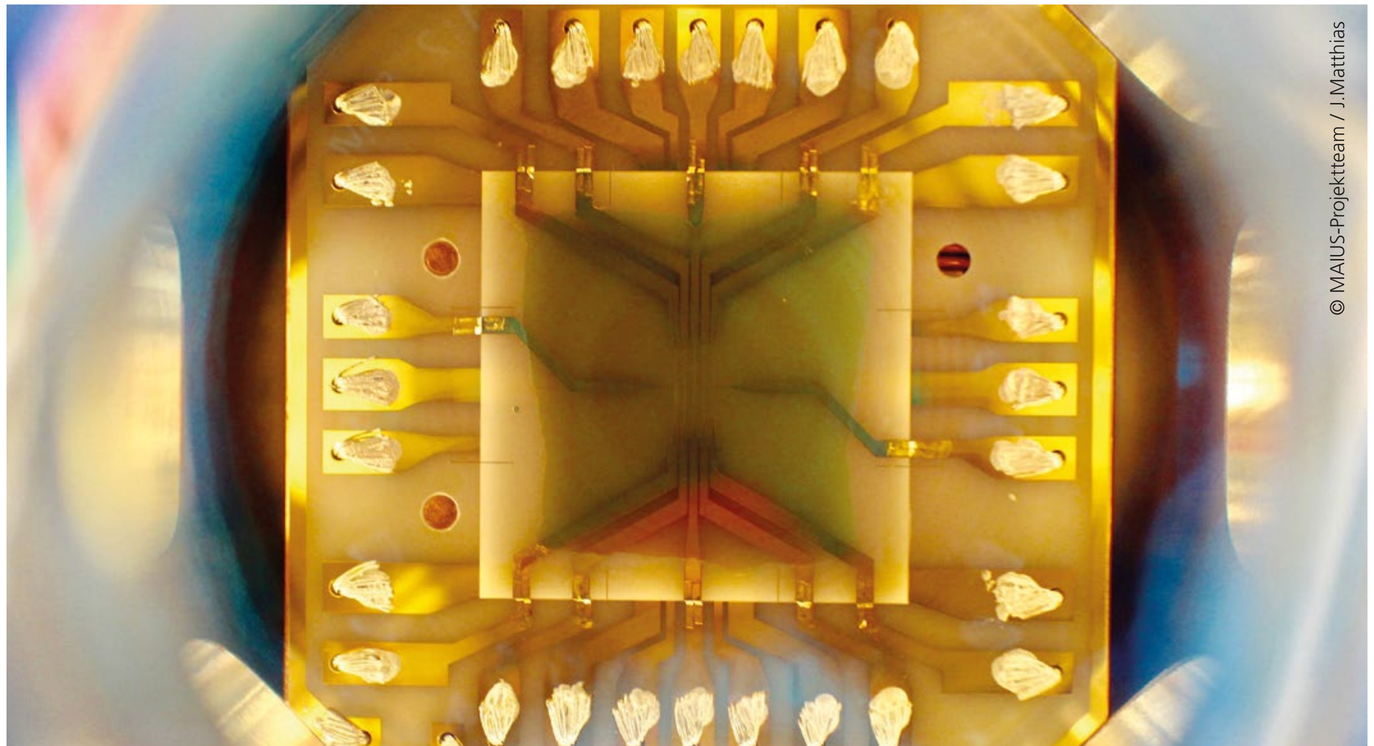
Following the successful generation of Bose-Einstein condensates under microgravity conditions on sounding rocket flights as part of the QUANTUS/MAIUS projects, the next promising step is experiments in space – under microgravity conditions on the ISS, BECs have a lifetime of up to 20 seconds. And that very step will be taken by the DLR BECCAL mission on the International Space Station (ISS). The ISS will make it possible to carry out longer-duration tests under microgravity conditions, including conducting precise experiments relating to atomic interferometry – the superposition of atom waves – for longer times than has previously been the case.

Second-generation technology

In addition to the QUANTUS/MAIUS missions, DLR also collaborates with NASA on the Cold Atom Laboratory (CAL), the predecessor mission to BECCAL. This ISS experiment marks the first steps towards examining Bose-Einstein condensates and atoms in general at low temperatures under space conditions. BECCAL will expand on these experiments extensively with a new generation of quantum-based instruments and devices. Thanks to its two new quantum technology institutes, DLR will play a leading role in the development and creation of this second-generation technology.

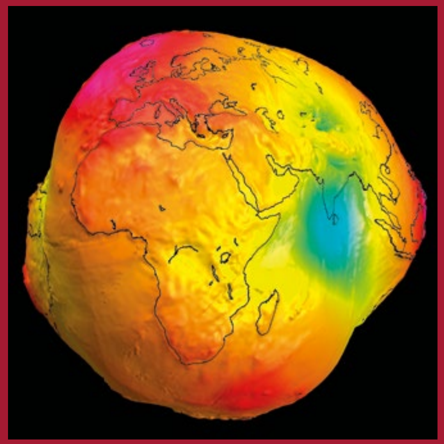
By carrying out missions such as BECCAL, DLR's research and development will lay the groundwork for the application of new quantum-based technology in space. Superposition or interferometry with atom lasers created using Bose-Einstein condensates, for instance, will enable navigation systems based on acceleration measurements, as well as gravimetry for measuring Earth's gravitational field with unprecedented precision. This will revolutionise communications and navigation, and contribute to fundamental research.

MAIUS atomic chip



Acceleration as accurate as never before

Inertial sensors measure acceleration – the rate of change in speed over time. This makes it possible for aircraft or near-Earth satellites to determine both velocity and altitude changes in Earth's gravitational field. Atomic interferometers that make use of Bose-Einstein condensates react very sensitively to accelerations. Inertial sensors based on atomic interferometry and quantum technology can therefore increase the accuracy and stability of acceleration measurements. With a height accuracy in the centimetre range, this makes it possible to measure even the smallest changes in the position of navigation satellites and autonomous air traffic without having to adjust to clocks. DLR is also planning to participate in a follow-up mission to GRACE-FO in order to be able to precisely measure the Earth's gravitational field. The mission will use quantum-optical inertial sensors to observe the distribution of water and plant growth, for example.



Bug-proof quantum keys for digitalisation

Digital solutions and digitally networked devices are becoming an increasingly prevalent part of everyday life and the working world – from communications to Industry 4.0 – not to mention future innovations as part of the second quantum revolution. The potential for breaking existing encryption using quantum computers makes it necessary to devise a new kind of encryption to protect our infrastructure, communications and data.

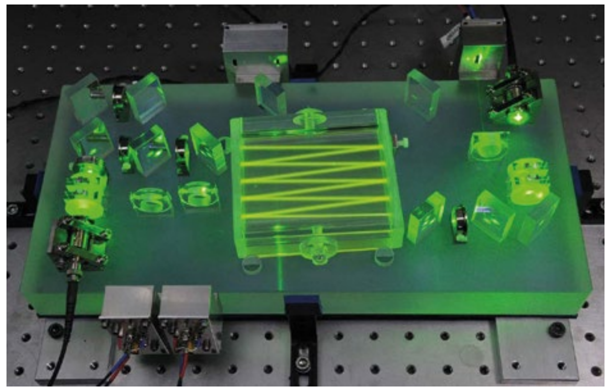
A possible new type of encryption also makes use of quantum effects. This principle is based on the quantum phenomenon whereby measurement affects the state of the thing that is being measured. Superimposed wave or quantum states are therefore reduced to a state, such as 0 or 1, upon measurement. Now, a sender and receiver have a shared, random and secret quantum key that is used to encrypt and decrypt messages. This quantum key is shared between the sender and receiver, and its states are entangled .

Connected over large distances

As the states of the key are entangled, the key on one side 'knows' the state of the key on the other side. If someone now breaks into a quantum-encrypted system and tries to 'read the data', which is in effect a measurement of the state of the quantum key, the key will collapse into a 0 or 1 and the intrusion into the system is detected. This entanglement can be sustained over long distances and can therefore be used for encrypted satellite communications.

As progress is made towards harnessing such technology, being able to demonstrate quantum key communications is one of DLR's major research and development objectives. For future missions – for example within the QUARTZ platform together with the European Space Agency ESA – the same entangled quantum state or wave is to be split. One part will then be taken into space on board a satellite, while the second key remains on Earth. Manipulating the quantum key on Earth, for instance, would then lead to a change in the quantum wave in space, thousands of kilometres away. Such quantum Earth-to-space communications and vice versa would constitute the world's first demonstration of quantum keys used in such a configuration, and would represent a breakthrough for the second quantum revolution.

Using quanta for accurate timekeeping – a new generation of clocks



Clocks determine and provide structure to our everyday lives. Moreover, high-precision timekeeping is essential for communications, navigation and controlling autonomous systems in space and on Earth. Energy grids and financial markets – to give just a couple of examples – require exact time synchronisation. New timekeeping systems are constantly being developed to meet the increased requirements for accuracy. The mid 20th century saw a huge increase in precision thanks to the invention and use of atomic clocks as the time standard. Atomic clocks use the frequency at which an atom's electron transitions between two energy states as a time reference, allowing time intervals to be measured with an accuracy of up to 10^{-15} seconds.

Precision in space and on Earth

The latest atomic clocks thus allow global satellite navigation systems such as Galileo to measure the transit times between several satellites and Earth's surface. Precise positions can be derived from the different transit times of the satellites. In this way, the accuracy of the clocks translates into accurate position measurements. High temporal precision is also vital for calculating exact positional information on Earth, including for the general public.

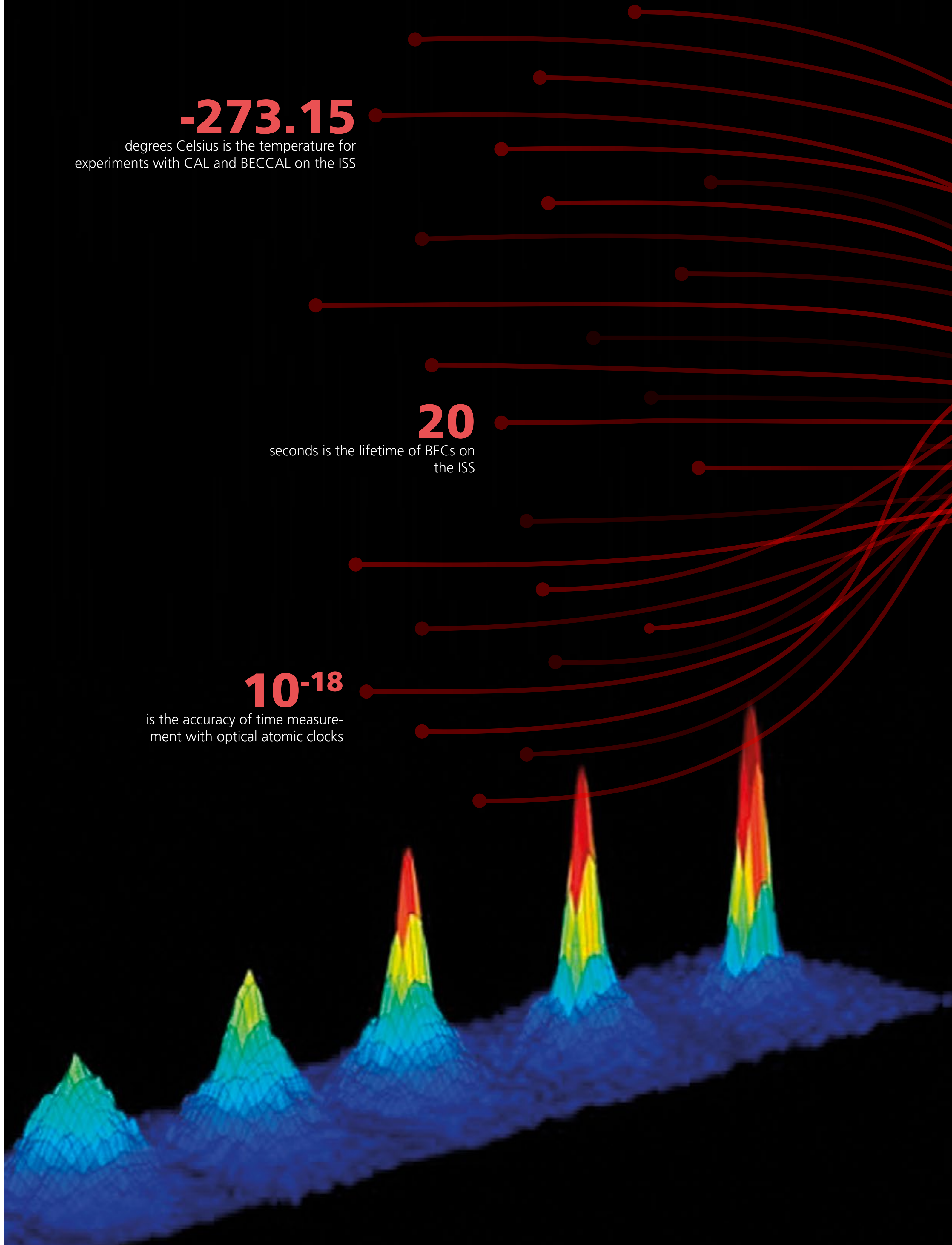
To further develop current communications and navigation systems, DLR's new quantum technology-focused institutes are developing a completely new generation of clocks. Optical atomic clocks with a higher accuracy of up to 10^{-18} seconds and greater stability than 'traditional' atomic clocks are being built. These optical atomic clocks use the frequency transitions of cold atoms at a higher optical frequency – and thus with greater temporal accuracy – as a reference, so they require a precisely stabilised laser for reading the data.

Testing on compact satellites

The optical iodine atomic clocks being developed at DLR are compact and stable over longer periods of time, and are set to be tested in space. The aim is to develop a new global reference system for time that will redefine the second. This kind of innovative reference system will be used for applications in space and on Earth. DLR is designing and planning the COFROS compact satellite mission, which uses quantum optical terminals for the purpose of these tests on atomic clocks in orbit. Further testing and application of optical atomic clocks could also take place on the International Space Station ISS and in constellations of future navigation satellites as part of DLR's ADVANTAGE project.

The microscopic world

The laws of our macroscopic world appear to no longer apply in the tiny scale of the quantum world; indeed, quanta behave in fundamentally different ways depending on the situation. In experiments they demonstrate behaviour that either corresponds to that of waves – with superposition or interference – or that of particles localised in one place. This is known as wave-particle duality. Light can thus be detected either as a single photon or as a wave of a particular frequency or wavelength. This means that quanta and their states can also overlap like waves in the sea or even jointly assume the same wave state. This leads to other fascinating phenomena like coherence and entanglement. In the event of coherence, several particles are in the same state as part of a bigger matter wave. Interestingly, deflection to one particle can cause the same deflection to all of the other particles in the same coherent state, as though they were all part of a single new 'big' particle. Similarly, in entanglement, particles are in a state that depends on other particles, so that the particles 'are aware' of one another. In theory, they can do this over distances of any size, which opens up completely new pathways for communications and encryption.



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