TECHNOLOGY 2040:
A VISION FOR THE EUROPEAN SPACE AGENCY

→ THE EUROPEAN SPACE AGENCY

Acknowledgments:

With thanks to Andrew Norman, Harriet Jarlett, Sean Blair and all those who contributed their expertise.

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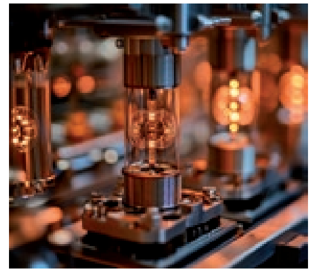

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FOREWORDS

"This vision, which my colleagues, the European Space Agency's engineering experts, have built sets up exactly the space future we wish to build. Europe has a very strong space industry and we work with some of the best companies in the world. Our Agency's engineers work daily with that industry and know what we need to be able to provide strong space capabilities. This document lays out to industry, to our Member States, to the public exactly where we want to be in the decades to come and the directions for how to get there. The vision fully supports and enhances the Strategy 2040 and together these documents will help to consolidate proposals, support the decisions to be made at CM25 and improve implementation after CM25."

Josef Aschbacher
Director General
European Space Agency

We stand at the threshold of the next great frontier. Europe is on the precipice of an exciting new chapter in its space journey and the European Space Agency (ESA) stands ready to enhance its role on the global stage while also deepening its connections with both established and new actors in space exploration.

With the global space economy projected to reach almost 1 trillion Euros by 2040, Europe must ensure that its space companies are leaders in innovation and sustainability, driving the green and digital transformations essential for our economy and Europe's competitive edge. ESA is ready for the challenges of this future and committed to making space a vital tool for solving Earth's most pressing problems. At the heart of this are the technologies it develops. ESA's R&D has always been about bold ambition, unrelenting innovation and unyielding curiosity. Launching a mission in 2040 requires us to anticipate what technologies will be needed and start their development now. As we look ahead, to the year 2040, ESA will be on board with a rapid evolution of technology that will redefine our understanding of space and humanity's role within it.

This document harks back to a historical one from ESA's inception, the blue books, which laid a roadmap for how our Agency's R&D would meet the demands of future missions.

I am proud to introduce ESA's Technology Vision 2040, a response to a rapidly changing landscape that supports ESA's ambitious and far-reaching goals. The Vision proudly supports ESA's Strategy 2040, enabling innovative and next-generation technologies and systems for a more connected and safer future for Europe's citizens.

As we look ahead, to the year 2040, ESA will be on board with a rapid evolution of technology that will redefine our understanding of space and humanity's role within it.

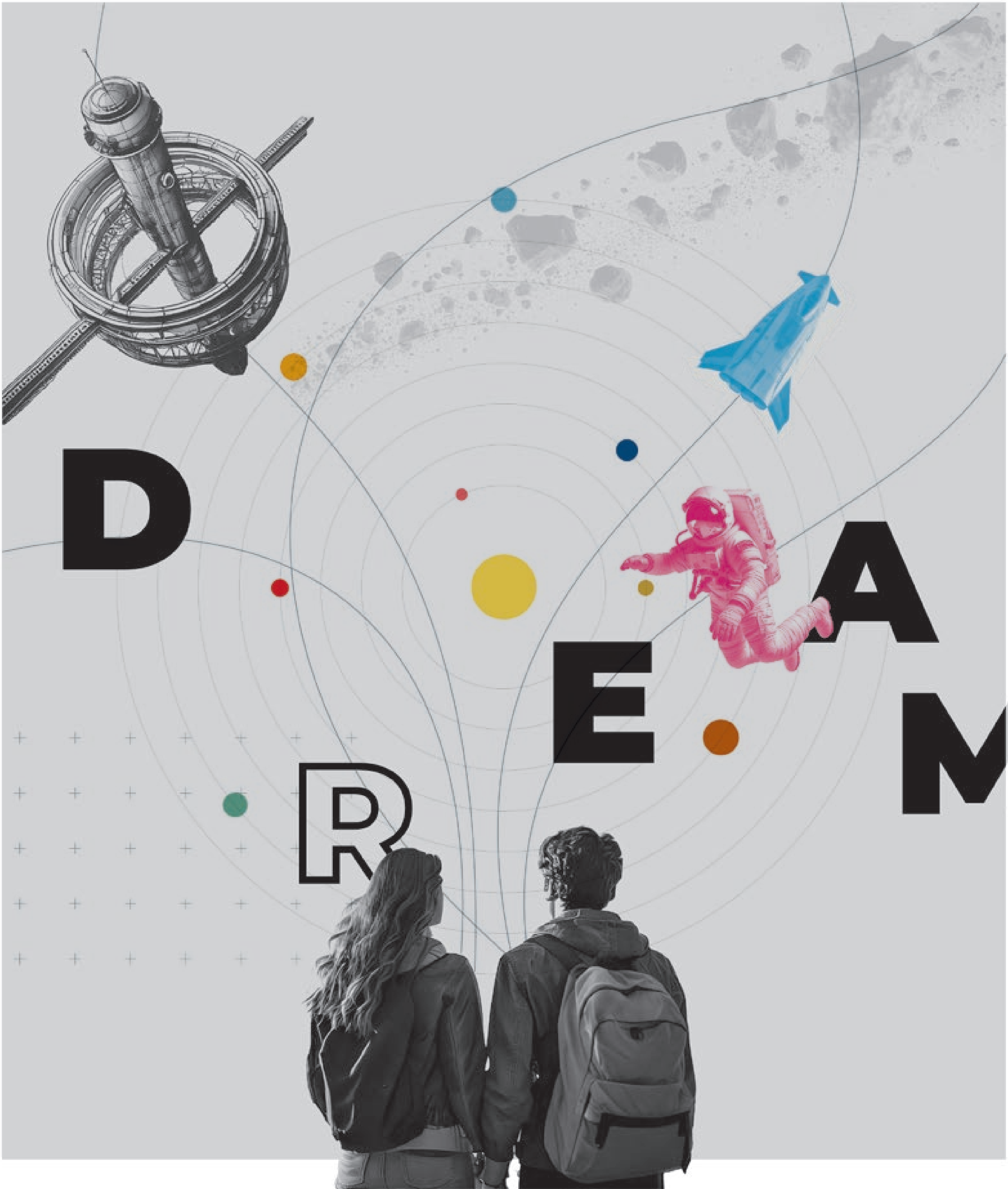
Dietmar Pilz
Director of Space Technology, Engineering and Quality
ESTEC – European Space Agency

In a rapidly shifting geopolitical and technological landscape, the European space ecosystem must make itself not only excellent but resilient and indispensable. Expanding into space is not a luxury but a necessity and space is no longer a frontier — it is a territory. It unlocks unknown resources that open new markets and enable scientific breakthroughs, which leads to technological and industrial leadership and long-term economic resilience.

This Technology vision is not simply a roadmap — it is a call to action. It outlines the critical technologies that will enable strategic autonomy, reduced cost and sustainable and secure access to space. Whether that's in advanced materials and manufacturing or innovative propulsion, quantum technologies or AI-integrated autonomy. Our space infrastructure must be built for resilience, with supply chains independent of non-European constraints, ready to adapt and scale through serialisation and modularity. By 2040, we envision a resilient European presence across Earth's orbits and the Solar System: self-sustaining habitats, in-orbit manufacturing, zero-debris systems and seamless, secure communications and navigation constellations. Hypervelocity transport, VLEO-based Earth monitoring and a circular, autonomous space economy will enable faster missions, safer exploration and surveillance, deeper scientific return and access to new strategic markets.

This document details how we can inspire, focus and align the best of Europe's capabilities, whether from industry, academia or national space agencies, towards a shared technological future. Just as early ESA technology developments shaped the foundations of Europe's space ambition, this vision defines the next leap -- one where ESA and its partners foster an integrated, sovereign and secure space economy. Our objective is clear: to make Europe a decisive and enduring architect of, and in, space.

Tommaso Ghidini
Head of Mechanical Department



DREAM

INTRODUCTION

Embarking on any journey into space is essential for the advancement of humanity. By exploring – and settling – in space, we drive technological innovation, identify valuable resources and inspire global collaboration. This endeavour not only addresses pressing challenges on Earth, including resource scarcity and environmental sustainability, but also pushes the boundaries of our knowledge and capabilities.

Expanding into space ensures the long-term survival of our species, providing new habitats and opportunities for growth. It fulfils our innate desire to explore. Why would we not go?

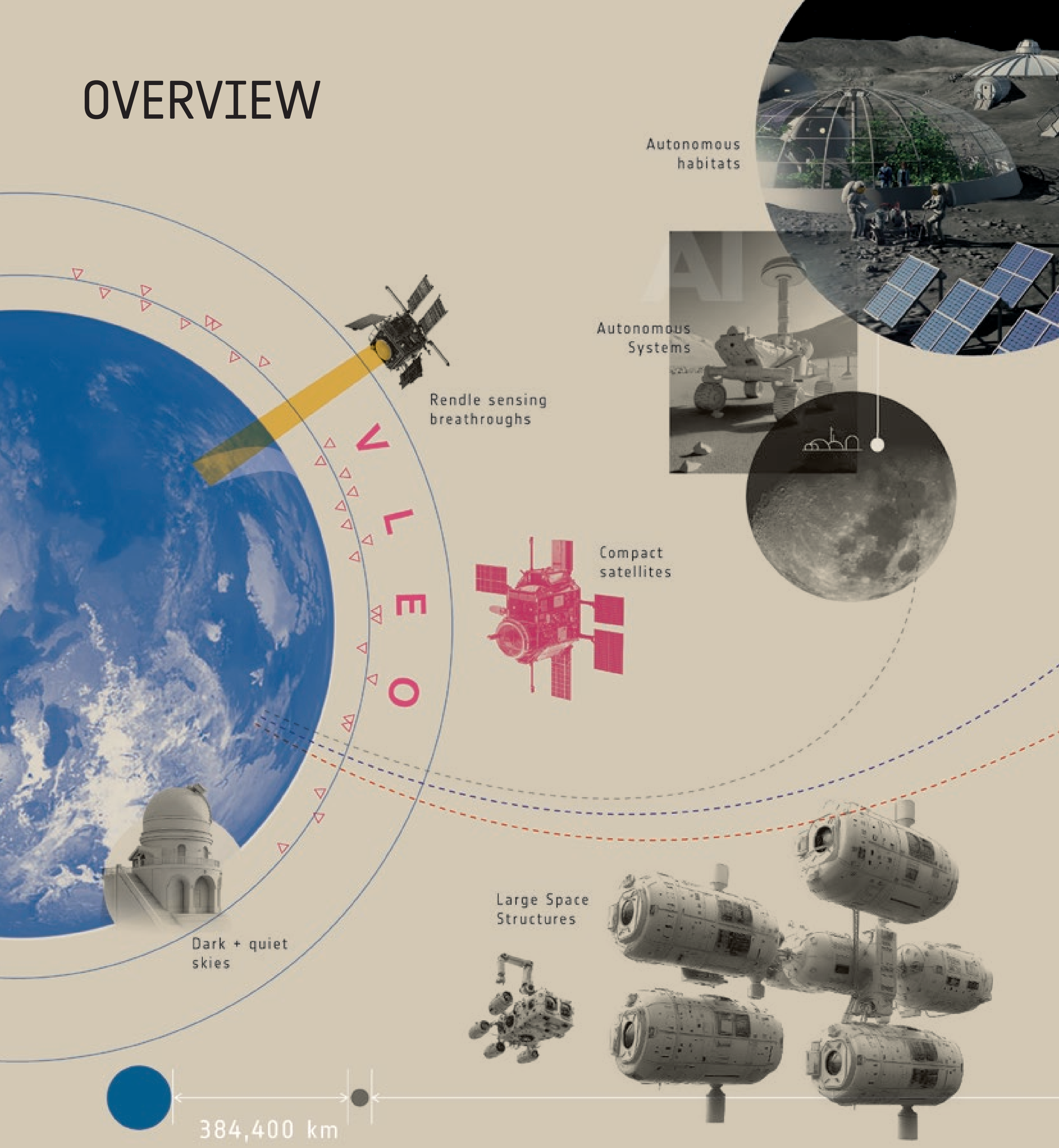
Journey with us as we head into space in the year 2040. Humanity's presence in space will have reached unprecedented heights, with a circular and sustainable space economy thriving, leaving zero debris footprints. In Very Low Earth Orbit (VLEO), high-speed vehicles will navigate space with precision, taking advantage of new remote sensing capabilities. Large space structures will no longer be bound by terrestrial manufacturing, instead being assembled in the vacuum of space through in-orbit self-assembly techniques.

Our Solar System will be connected by a robust internet, enabling seamless communication between Earth, satellites, and distant spacecraft. Robotic and human missions on the Moon and Mars will uncover new frontiers and valuable resources. Comet bodies and asteroids will be mined, their materials helping to reveal our Solar System's history.

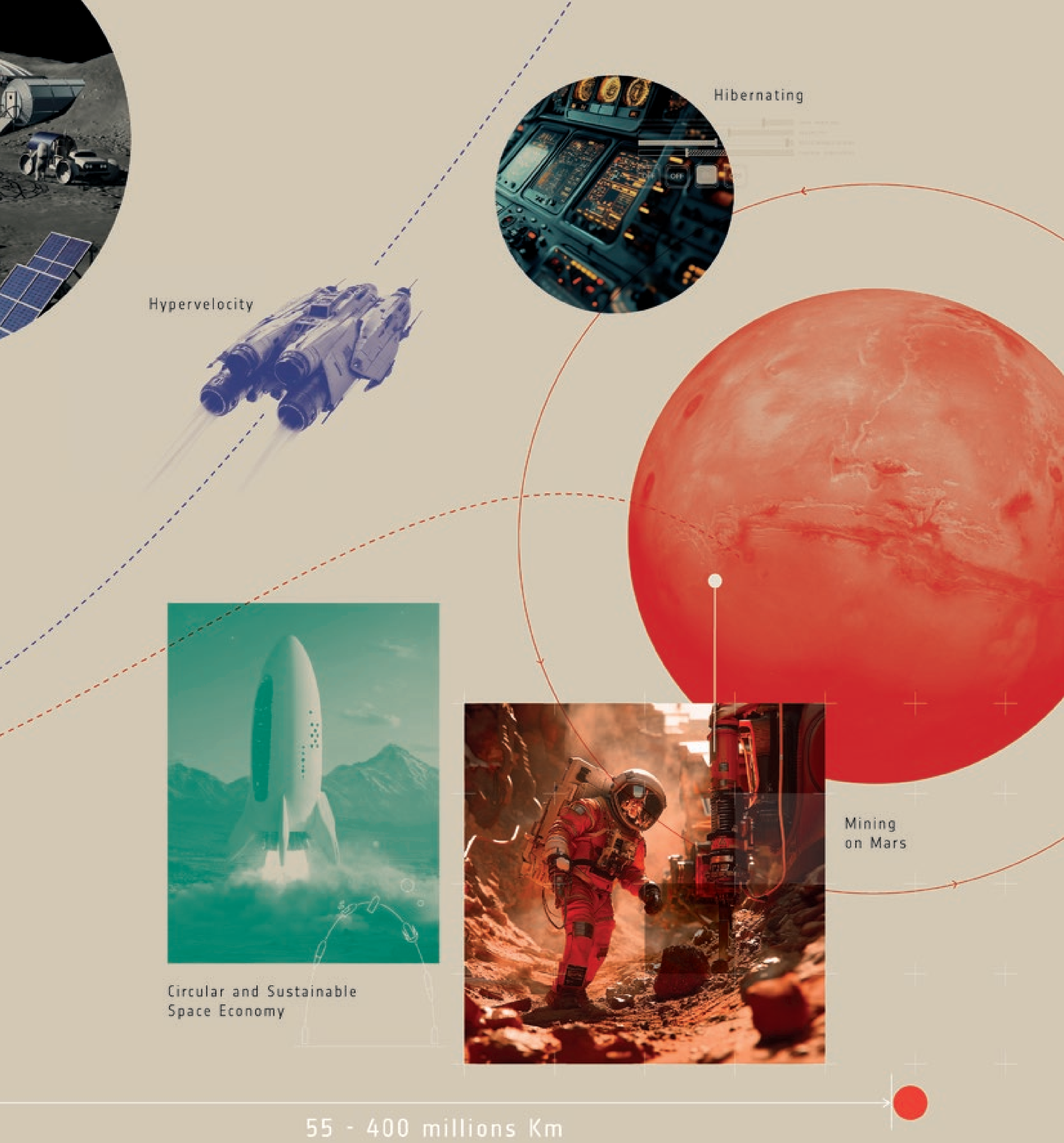
Satellites will be designed to minimize their impact on Earth's ecosphere, with all stages of their life cycle carefully managed to ensure environmental protection. Energy-efficient solar power systems and deep space travel innovations will ensure sustainability in the harshest environments.

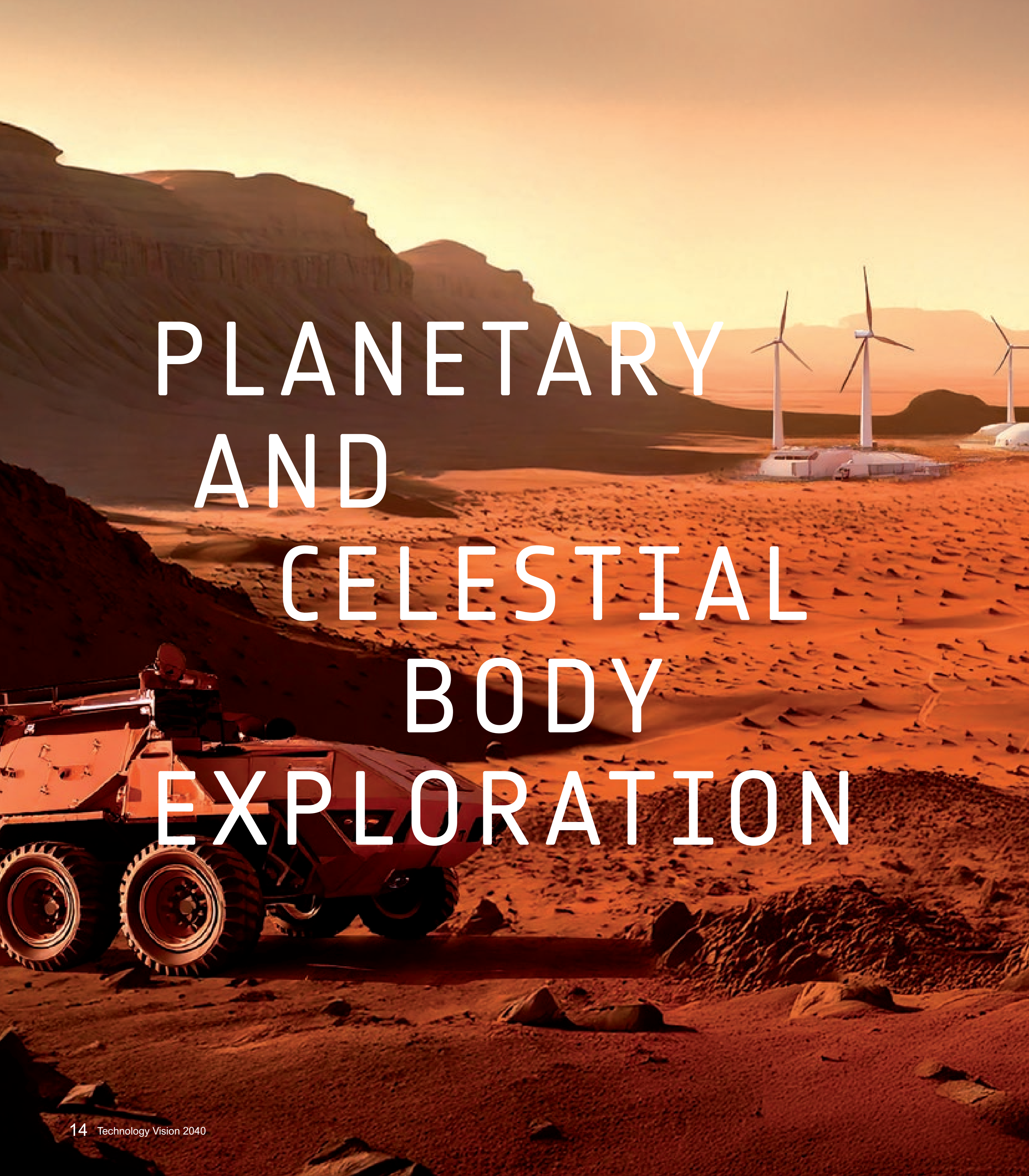
Human habitats in orbit, on the Moon, and on Mars will be self-sustaining, supporting life with advanced technologies. In this new era, humans will thrive among the stars, marked by innovation, sustainability, and a relentless pursuit of knowledge. The cosmos will no longer be a distant frontier, but a home.

OVERVIEW

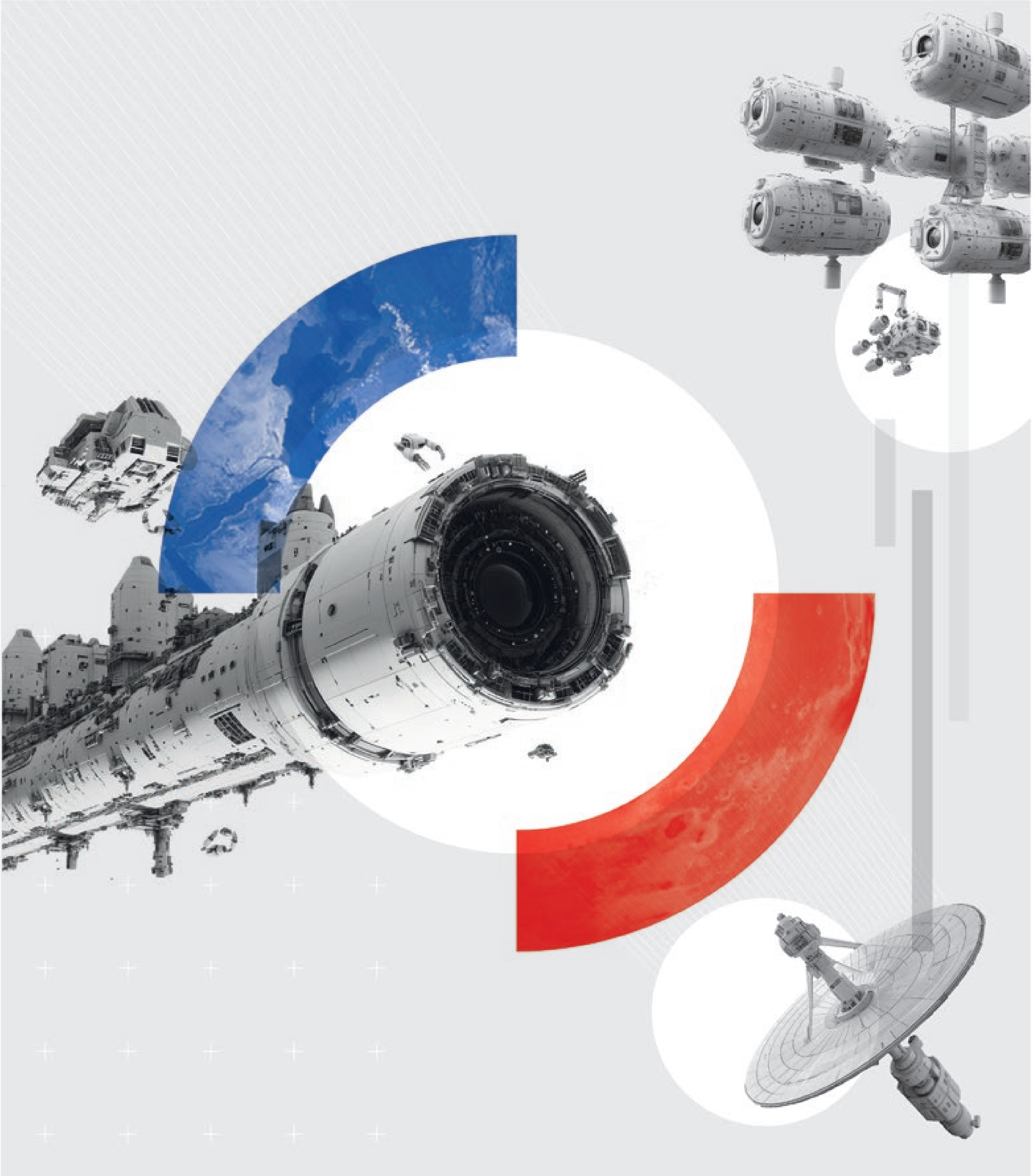


Autonomous habitats
AI
Autonomous Systems
Rendle sensing breathroughs
VLEO
Compact satellites
Large Space Structures
Dark + quiet skies
384,400 km


Hibernating
Hypervelocity
Circular and Sustainable Space Economy
Mining on Mars
55 - 400 millions Km



PLANETARY AND CELESTIAL BODY EXPLORATION



ASTRO ARCHITECTURE: PIONEERING LARGE SPACE STRUCTURES

Vision:

Large space structures are no longer bound by the limitations of launch vehicle dimensions. Either unfolded in space or manufactured and assembled directly in orbit – or on the surfaces of the Moon or Mars – these mammoth constructions can be as big as they need to be. This has widened the scope of space activities, as arrays of giant antennas or lenses can now survey the Universe and habitats more closely resembling towns than today's International Space Station.

Chokepoint into orbit

Today, anything destined for space needs to make it through the chokepoint of its launcher fairing, while also being equipped to endure the violent forces inherent to launch. The largest structure in orbit, the 450 tonne International Space Station, was assembled out of dozens of separate payloads requiring 42 launches and hundreds of hours of spacewalks. The tennis-court-sized James Webb Space Telescope was painstakingly – and expensively – designed to fit within its Ariane 5 fairing like a model ship in a bottle before unfolding in space.

The alternative already exists: on-orbit manufacturing, assembly and deployment will allow for significantly larger structures, constructed directly in space, without needing to withstand the rigours of lift-off. Spacecraft, satellites or instruments built in space would offer higher performance and wider design possibilities. Freed of current design constraints, in-orbit assembly would offer an attractively blank slate: on-demand production of spacecraft structures, customisation and flexibility would become feasible, offering tailored solutions for specific mission requirements, and reduced development times and costs.

Enlarged antennas and modular architectures

This approach can be applied to a broad range of applications including orbital antennas and lightweight telescopes of greater sizes and performance, novel modular architectures for solar arrays or thermal management systems, optical and radio frequency antennas, and extensive infrastructure for orbital or surface exploration.

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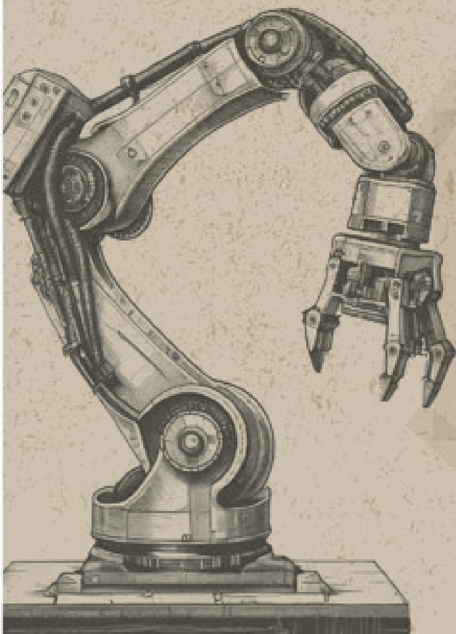
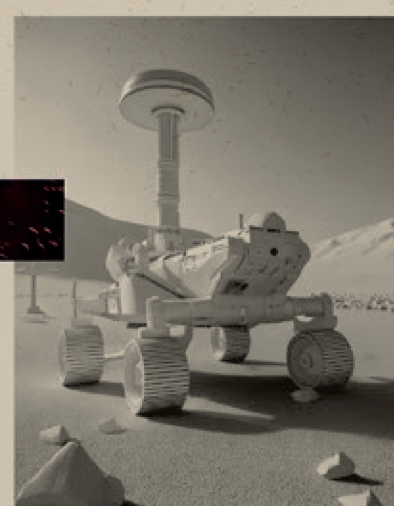
Key technologies

- Expandable space structures manufacturing (deployable, inflatable structures)
- In-situ manufacturing processes and dedicated feedstock materials
- Advanced robotics for assembly
- Supporting technologies for functional verification
- Technologies for orbital assembly operations and control of very large structures
- Enabling technologies for long term sustainability and circular space economy



"It is in our nature to explore, to reach out into the unknown. The only true failure would be not to explore at all."

Ernest Shackleton, explorer



PIONEERING NEW GROUND: IN-SITU SURFACE EXPLORATION AND CAPABILITIES

Vision:

Europe has established a robotic or human presence on many sites across the Solar System, extending from the surfaces of the Moon and Mars to comets, asteroids and even the moons of Jupiter. Scientifically and sometimes economically active locations will enable returning samples to Earth for in-depth study, with some utilising in-situ resources for the expansion of surface infrastructure in a cost-effective manner.

Living off the land

Space is not one destination but many, such as the surfaces of planets, asteroids and comets. In 2014 Europe made history when Philae made the first comet landing, from ESA's Rosetta probe, while the Aurgonaut Luna Lander is in preparation and ESA's ExoMars Franklin rover will touch down on Mars in this decade. Each one its own challenging mission but with scientific secrets and usable resources that will enable future explorers to work towards self-sufficiency. 'Living off the land' will be vital in establishing a permanent human presence on the Moon or Mars.

Going to work on planetary sufaces

Planetary surfaces are not just hard targets for landing, they are challenging environments to sustain any operations. Novel technologies will be needed for scientific interrogation of these new environments, prospecting for resources and assessing whether it is possible to exploit reserves. These instruments must be capable of withstanding extreme temperature, radiation and dust exposure with robotic means to move and navigate autonomously, or handle samples for in-situ processing and analysis. Long-term human habitats require even more technological developments, whether thats oxygen and metal extraction, turning regolith into 3D printing filaments or accessing ice deposits for life support, propellant production and energy extraction. Communication will also be key, necessitating novel approaches for space-based antenna phased arrays, or energy- and mass-efficient radio frequency equipment. Finally, quite new terrestrial testing approaches will be needed to validate these systems ahead of them being used at their target environment.

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Key technologies

- Resource processing and handling technologies
- Excavation, feedstock acquisition and beneficiation
- Environment adapted surface mobility and autonomy (aerial, legged, hybrid systems...)
- Instrumentation for cryogenic environment
- Deep space communication capabilities
- Enhanced environment testing, monitoring, and forecasting methods
- AI to enable systems with higher autonomy

“Earth is the cradle of humanity but one cannot live in the cradle forever.”

Konstantin Tsiolkovsky,
Scientist and Space Pioneer

SPACE OASES: AUTONOMOUS HABITATS BEYOND EARTH

Vision:

Humans dwell in plentiful habitats in Earth's orbit and also on the Moon, Mars and far beyond. These habitats are resilient and self-sustaining with efficient resource management, closed-loop life support systems, smart materials, in-situ manufacturing and resource utilisation. This allows inhabitants of these space oases not only to survive but thrive.

First steps into space

To date, human habitation in space has been limited to orbital stations in low-Earth orbit. Individual crew members stay in orbit for comparatively short periods – around six months at most. And these habitats are far from self-sustaining, requiring regular resupplies of air, water, food and propellant. Crewed surface exploration has been limited to a few days on the Moon.

Independence from Earth

The next steps in human exploration will involve longer stays and farther destinations. Key to the success of these undertakings will be the creation of more permanent infrastructure with increased independence from Earth. This will require the circular management of resources combined with high-velocity logistics – such as with mass drivers shooting supplies cheaply into space – and advanced life support systems, innovative energy sources and maximum utilisation of local resources. Plus these settlements must operate without degrading surrounding extraterrestrial environments – otherwise what is the point of exploring?

As a baseline, these habitats must protect astronauts from the harsh conditions outside, calling for smart radiation shielding materials as well as sensing capabilities to forecast, monitor and mitigate variable hazards such as micrometeoroids. Maintaining the physical and psychological wellbeing of their inhabitants demand advances in medical systems, equipment for extra-vehicular activities, as well as contamination detection, control and prevention. Designing these habitats will demand innovation in design, testing and system engineering capabilities for complex systems, in-situ manufacturing, repair and recycling, as well as innovative end-of-life management approaches.

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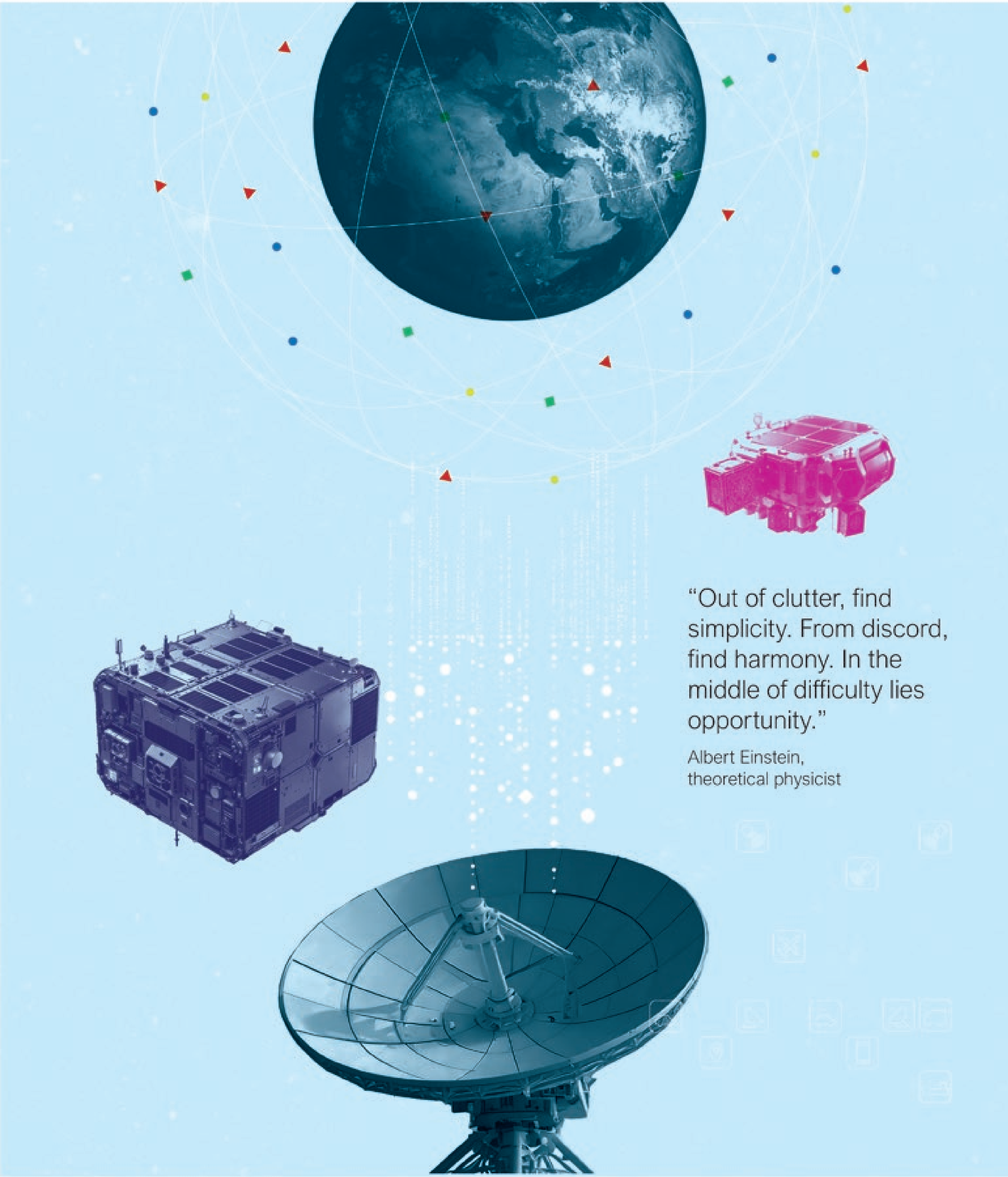
Key technologies

Autonomous resource production and management (e.g. Advanced life support systems, synthetic biology, In-Situ Resource Utilisation, energy storage and power production systems)

Crew integrity (e.g. smart materials, In-situ and real-time contamination control and prevention, physical augmentation spacesuits, biophilic designs and architecture, Virtual Reality/AI crew assistance, cobotics and guided diagnostics)

Life cycle of habitat systems (e.g. in-situ manufacturing, Life Cycle Assessments, Model-Based System Engineering of complex systems, Circularity by design, autonomous systems and robotics)

A TECHNOLOGY REVOLUTION ON EARTH FOR SPACE



> "Out of clutter, find simplicity. From discord, find harmony. In the middle of difficulty lies opportunity."
>
> Albert Einstein,
> theoretical physicist

ULTRA COMPACT HIGH PERFORMANCE SATELLITES

Imagine:

The sky is raining data. At any given moment, mammoth constellations of European-made satellites are variously acquiring, processing and distributing vast amounts of data related to all facets of daily life at many orders-of-magnitude higher and denser throughput than the best of 2025's orbital infrastructure. This has been made possible by a generation of ultra compact high-performance satellites, doing the maximum possible amount of work for every gram of mass.

The size of a spacecraft is a critical factor in determining launch costs, which directly impact the overall mission expenses. To reduce costs, the satellite industry is focusing on creating ultra-compact, high-performance satellites. Achieving this requires a complete overhaul in how satellites are conceived and built, incorporating new technologies that allow for more efficient use of space.

Wastes of space in space

Traditional satellite platforms often waste valuable space. Components, typically produced independently by various manufacturers, are not standardized in terms of size, leading to inefficient use of internal space. Electrical interfaces are often overly complex, resulting in the need for frequent adjustments to the system architecture. The wiring, or harness, connecting these interfaces is routed ad-hoc through the free space between units, leading to wasted volume and larger spacecraft than necessary.

Shrinking down satellites

To create ultra-compact satellites, the mechanical architecture needs to be optimized by standardizing unit dimensions and minimizing unused space. This leads to a more efficient thermal management system. By standardizing mechanical, thermal, and electrical interfaces, units can be aligned with homogeneous dimensions, resulting in a compact, uniform platform architecture. The propulsion subsystem must be re-engineered to fit this smaller form factor. Additionally, deployment elements such as solar arrays and antennas must be compact and foldable for launch, or alternative body-mounted, non-deployable solutions must be explored. Payloads will also need to integrate both radio frequency analogue and digital functions into highly compact electronics.

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Key technologies

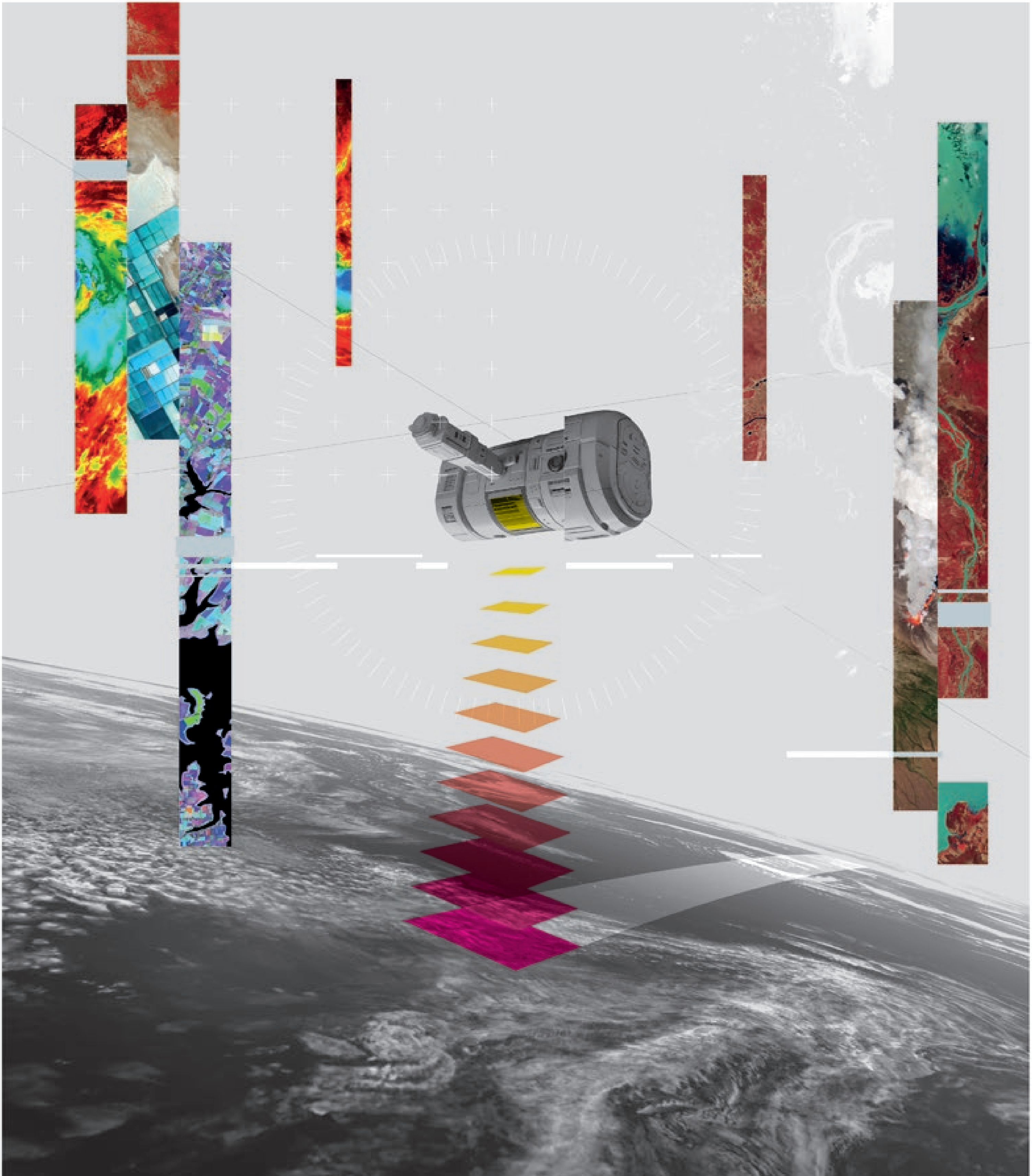
Standardised mechanical architecture, unit dimensions and subsystem electrical interfaces

Advanced integration of payload functions using microelectronics, mixed signal, optical and radio frequency technologies

Advanced payloads featuring Software Defined Radios

Very compact foldable solar arrays and antennas

Thermal systems embedded in the structure



PEERING INTO THE FUTURE: BREAKTHROUGHS IN REMOTE SENSING CAPABILITIES

Vision:

The world about us and the wider cosmos are being observed as never before. Space-based arrays are always watching, embedded with intelligence resembling a planetary-scale nervous system. Their optical and radio-frequency remote sensing capabilities extend across the electromagnetic spectrum – while quantum-based sensors probe still further. Remote sensing instruments and sensors have undergone orders-of-magnitude jumps in performance and in sensitivity, agility, availability and scale. The chief challenge is now the sheer scale of available data; on-board intelligence is essential to deliver optimal value-added information to users.

Remote sensing is a way of collecting and analysing data to get information about a target from a distance – using the properties of electromagnetic waves emitted, reflected or diffracted from the target locale to yield useful information. This technique – used in spaceborne astronomy, planetary science and Earth observation - allows the probing of the universe that is beyond our reach, and to perform extensive spatio-temporal monitoring at planetary scale. One key target of remote sensing is our own planet Earth; Europe is indeed the largest producer of terrestrial remote sensing in the world, through the Copernicus Sentinel fleet of satellites. The outputs of remote sensing have found numerous scientific, political, economic and societal uses; indeed, our world is scarcely imaginable without these ongoing insights from orbit.

Widening our view

In the years ahead our view will only widen, thanks to advances in sensing technologies, such as ultra-broadband/multi-frequency sensors or astrophotonics, along with the novel observing windows opened via quantum sensing of, for instance, gravitational fields. Intelligence will be embedded at all levels: smart sensors will be able to process images as they acquire them, thanks to system-on-a-chip integration. Flexible payloads will actively adapt their configuration and sensing modes as needed, smart missions and on-board intelligent processing will overcome the bottleneck of satellite data downlinking to formulate and despatch key insights immediately. Cost-efficient observing solutions will benefit from packaging sensing technologies into smaller volumes and by developing vicarious calibration systems that tie their observations to reference missions – without requiring lengthy tune-ups from the ground. Remote sensing will also benefit from the use of signals of opportunity from the ever-increasing number of transmitters in orbit, in the same way that current 'reflectometry' satellites utilise reflected satellite navigation signals. This will drive the global observing system into its next massive scale-up.

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Key technologies

- Distributed instrumentation and synthetic aperture imaging
- Quantum sensing
- Smart sensors and cognitive payloads
- Modular optics and miniature Radio Frequency sensors
- AI techniques for payload data processing
- Ultrastable optical architectures

"Artificial intelligence will reach human levels by around 2029. Follow that out further to, say, 2045, we will have multiplied the intelligence, the human biological machine intelligence of our civilisation a billion-fold."

Ray Kurzweil, computer scientist and author

TOWARDS HIGHLY AUTONOMOUS SYSTEMS REVOLUTIONISING SPACE MISSIONS

Vision:

The very concept of mission control is going the way of the dinosaur. Autonomous spacecraft no longer need gatherings of humans to shepherd them from a distance; they have intelligence of their own and they are using it in novel ways. Large-scale swarm constellations of satellites – among other distributed space systems – work together to achieve impossible goals for any single satellite, including the formation of high-resolution virtual telescopes or even self-assembly into larger physical structures. Multipurpose robots leverage their intelligence to infiltrate previously off-limit environments: the depths of craters, caves or even subsurface seas.

Operating beyond human oversight

Autonomy in space terms means that spacecraft, robotic rovers and other systems can perform tasks and make decisions independently of human intervention. Higher levels of onboard autonomy will enable new types of missions, while reducing the resources needed on the ground. There are still challenges to overcome before more complex mission goals can be achieved, including the issues of: communications delays, which are particularly relevant for deep space missions; time-critical operations where every second counts, such as changing orbit; environmental uncertainty where we do not know the conditions the mission will find itself in; complex physical interactions; juggling power constraints and computational resources; and ensuring safety and reliability.

Machines that learn

Addressing these challenges requires the integration of cutting-edge technologies across several areas, addressing the kind of adaptability, flexibility and learning that humans take for granted; the ability to sustain extended duration operations without ground intervention; intelligent decision making for onboard planning, health monitoring and reconfiguration; autonomous collaborative operations; optimised power, communications, data processing and computational resources plus structural self-healing and reusability of space assets.

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Key technologies

AI-based on-board planning / re-planning / reconfiguration and fault direction, isolation and recovery, FDIR

Robust and Adaptive Attitude and Orbit Control Guidance Navigation and Control (AOCS/GNC), on-line system identification, distributed control

Real-time optimised guidance, high precision entry, descent and landing

Robotics: high speed / long range roving, aerial & surface mobility, task learning, robotics & GNC collaborative control for Close proximity operations

Deep space and Optical Navigation, including relative navigation, vision-based navigation and event-based navigation, attitude sensors, cameras, lidar


DATA HANDLING
TELEMETRY
TELECOMMUNICATIONS
CONTROL SUBSYSTEMS
ON
OFF
OFF
ON
OFF
60
120/80

ENERGY-EFFICIENT HIBERNATION SYSTEMS FOR DEEP SPACE SURVIVAL

Vision:

Losing light the further we rove from our Sun is no longer a limiting factor to deep space travel, as individual elements of a mission can be placed into hibernation when not in use. This 'deep hibernation' approach reduces power consumption by up to 70%, opening up broad new expanses to solar powered exploration.

Enduring the outer dark

ESA's solar-powered Rosetta mission would have been impossible without hibernation. In June 2011 the whole comet-chasing spacecraft hibernated for 31 months as it cruised out to a distance of nearly 800 million km from the warmth of the Sun, beyond the orbit of Jupiter. Then, as Rosetta's orbit brought it back to within 'only' 673 million km from the Sun, there was enough solar energy to power the spacecraft fully again. In January 2014 a pre-programmed internal 'alarm clock' woke up the spacecraft to continue its mission.

The darkness of the outer Solar System has traditionally set limits on the use of solar arrays. Available solar power decreases by the square of the distance to the Sun, meaning that deep space missions need very large solar arrays to provide a bare minimum of power.

Energy-efficient hibernation for future missions would adopt an 'à la carte' approach: the overall power consumption of the spacecraft would be minimised by dynamically powering on or off the various electronics subsystems as they are needed at any given moment.

À la carte hibernation

The hibernation concept would also need to be applied to avionics, data handling and telemetry, telecommunications and control subsystems, along with mission payloads. Ultra-low power hibernation timers could activate these sub-systems either via a wake-up telecommand or a preset timeline. The telemetry downlink subsystem would need to be taken out of hibernation periodically to communicate onboard health and science results. The payload data would be processed on-board to reduce its volume, further reducing the power required for its downlink. The thermal subsystem would be optimised for very low and changing power dissipation levels.

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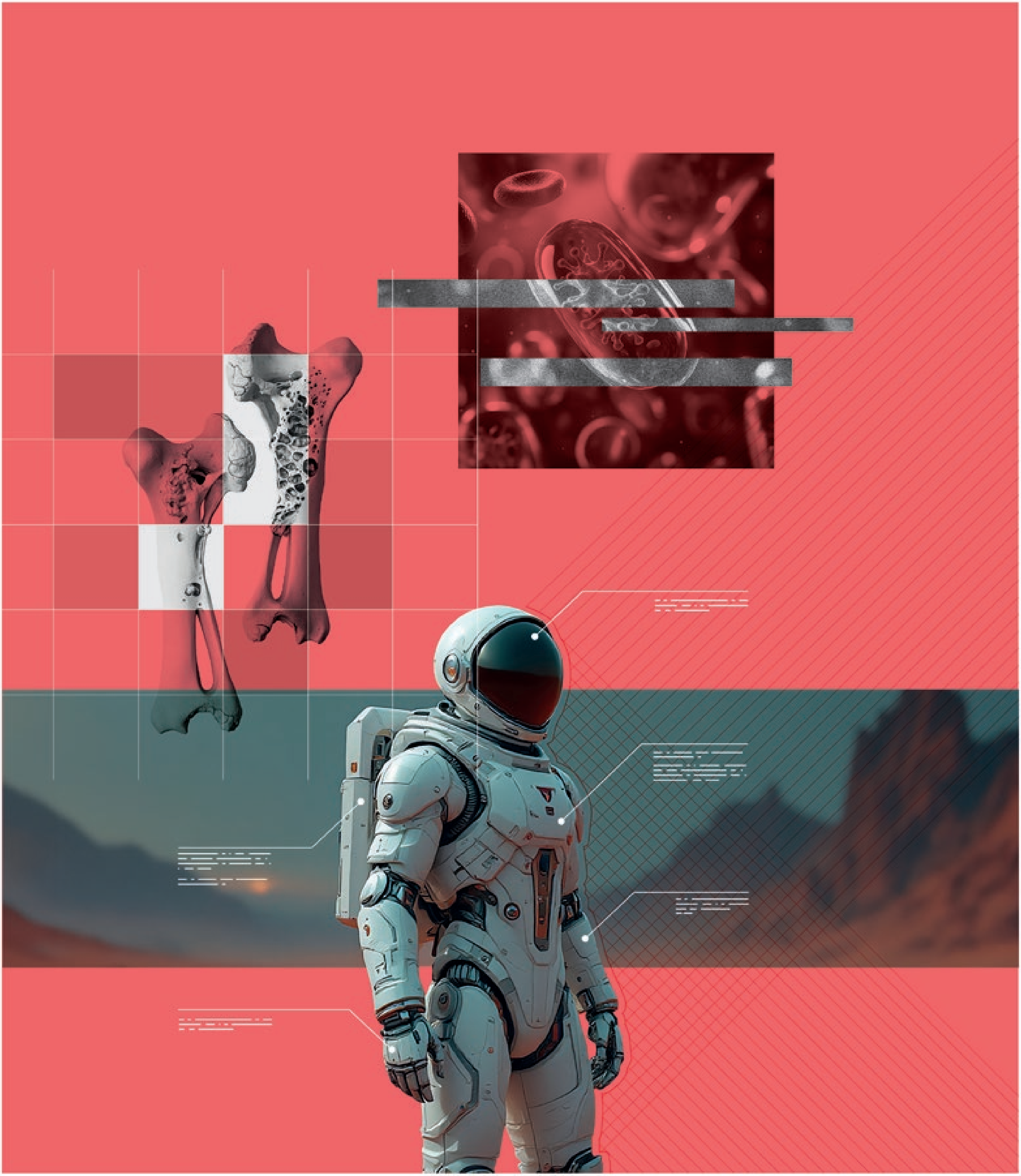
Key technologies

- Low power / idle state microelectronics; Low-voltage power delivery
- Functional hibernation avionics: Dynamic hardware and software concepts
- Enhanced spacecraft autonomy and Fault Detection, Isolation and Recovery supported by AI / Machine Learning
- Thermal subsystems for low dissipation platform



X-PLORERS: HUMANITY'S EVOLUTION

Vision:

Humankind has evolved into an interplanetary species, conducting extended deep space travels while establishing permanent homes on celestial bodies. This development has been made possible by enhanced life support, performance and mental well-being technologies. Day-to-day living on an interplanetary crewed exploration mission is scarcely more demanding than a comparable high-end profession back on Earth.

Humans: the weakest link

A space mission, like any complex system, is only as strong as its weakest element – and for any crewed spacecraft, that ends up being its human crew. We have not evolved to tolerate spaceflight challenges including prolonged microgravity, radiation exposure and isolation. Heading farther from Earth is only going to make these issues worse but the answer lies in a comprehensive programme of space adaptation. Advanced multipurpose countermeasure systems will fight muscle wasting and bone demineralisation caused by microgravity. Space radiation may trigger acute radiation sickness while also increasing long-term cancer risk making it a critical concern for long-duration missions. Personalised protective measures will attenuate cellular damage and these explorers will have medical autonomy to ensure early detection and management of medical issues.

Reduced exposure to hazards

The extensive isolation and confinement inherent to long-term space travel impacts psychological well-being and team dynamics. Engaging immersive experiences and emotionally intelligent digital assistants will alleviate the crew's sense of isolation and help team cohesion. In addition, automation and robotics technologies will break the routine of repetitive actions, support dangerous tasks, minimise exposure to hazardous environments and reduce overall crew workload. Finally, optimal nutrition – via the production of fresh and/or tailored food – will become as essential as physiological and psychological countermeasures.

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Key technologies

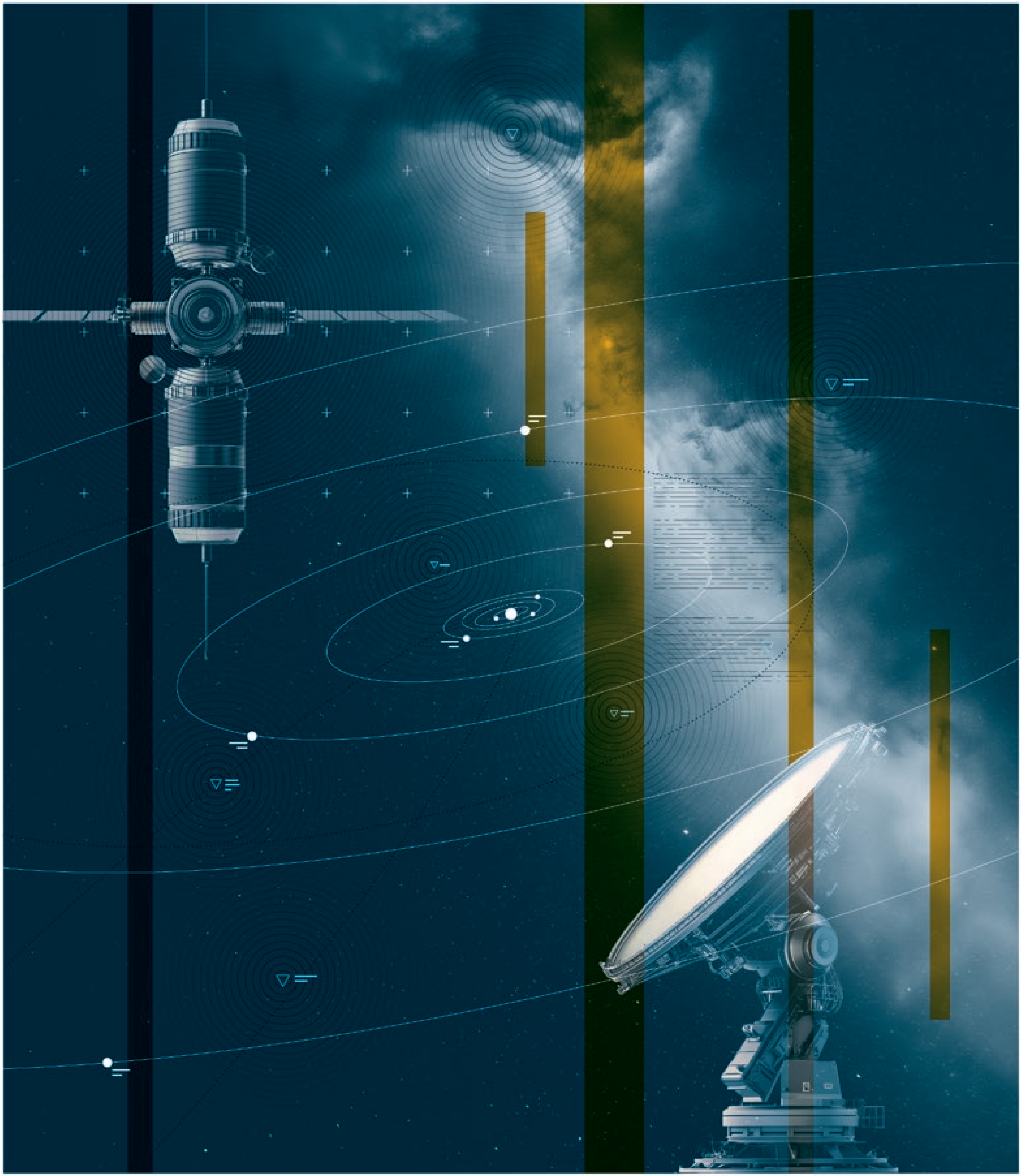
Advanced life-support systems (e.g. cutting-edge bioreactors for consumables production (O2, nutrient-rich food), 3D-printed food, bacterial and cell-cultivated food, synthetic biology, torpor/hibernation technologies).

Advanced medical systems to enhance human performance & health monitoring (e.g. advanced pharmaceuticals, personalised medicine, AI-driven and robotic training devices, decision-making tools and smart assistants)

Advanced design, training & operations technologies (e.g. augmentation exoskeletons, robotic synergistic assistants, advanced spacesuits, simulators)

Advanced mental well-being and entertainment technologies (e.g., eXtended reality coupled to AI)

NEAR EARTH AND DEEP SPACE TRAVEL AND COMMUNICATION



SOLAR SYSTEM INTERNET, NAVIGATION AND COMMUNICATION SYSTEMS

Vision:

The internet has expanded far beyond Earth, with a space-based internet made possible by a European backbone. Deployed communications and navigation systems stretch across the Solar System, providing secure and interoperable services to the European Space Agency and other missions. This integrated "system of systems" combines networks, services and assets from both institutional and commercial entities, enabling universal communication and ubiquitous navigation. As a result autonomous, low-cost space missions are becoming feasible, as since they fly, manage and operate themselves.

Scaling up communications and navigation:

Traditionally, space communications have relied on pre-planned, point-to-point communication links. However, this approach struggles to scale effectively. A more automated, networked communication system, modeled on the terrestrial internet, is crucial for building sustainable space infrastructure. Similarly, space-based Positioning, Navigation, and Timing (PNT) systems will enable autonomous navigation across the Solar System, reducing reliance on Earth-based infrastructure.

The European Space Agency's Moonlight initiative is already taking the first steps toward providing common communications and navigation services for lunar missions, with plans to extend to Mars. PNT and communication systems are interdependent, and expanding both beyond the Moon and Mars is critical to supporting autonomous space missions throughout the Solar System.

Overcoming disruption for expanded reach:

The Solar System Internet will depend on interoperable, secure communication and PNT systems to ensure consistent and coordinated expansion. This system will build on initiatives like Moonlight and MARCONI for Mars. Ensuring interoperability between different systems is vital. Disruption Tolerant Networking concepts will bridge diverse communication technologies, while scalable deep-space PNT systems will enable precise navigation and time synchronization across the Solar System.

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Key technologies

- High-throughput RF and Optical Communication systems for space and ground
- Precise Deep-Space Positioning, Navigation and Timing systems
- Massive Distributed Formation-Flying satellite systems for high-gain beamforming
- Disruption Tolerant Networking
- Scalable and Resilient Communication and Navigation system architectures

VERY LOW EARTH ORBIT (VLEO)

Vision:

High-speed broadband connectivity is available from almost anywhere on the planet, with speeds comparable to terrestrial cellular networks, provided by European constellations of telecommunications satellites in very low Earth orbit. From that same vantage point, optical and radar Earth observation satellites provide very high resolution imagery of our planet's ever-changing face with much less mass and power than their higher-altitude 2020s counterparts.

Space is slow to start. At altitudes between 100 and 400 km, known as very low Earth orbit (VLEO), the atmosphere remains very much in evidence, triggering significant aerodynamic drag and erosion from highly reactive free oxygen atoms that eat away at unshielded satellite structures.

The closer the better

The principle is straightforward: reducing the distance to the ground from VLEO significantly improves the performance of antenna or optical instruments, leading to very low-latency high-throughput telecom links to small user devices and improved ground resolution for optical and radar Earth observation. The radiation environment in VLEO is much more benign, enabling the reuse of cheaper ground technologies rather than space-qualified parts. As an added benefit, VLEO is inherently self-cleaning: once a mission ends, atmospheric drag would pull it back to Earth.

Material improvements

To start operating routinely at VLEO, materials and coatings must be selected that can resist continuous orbital-velocity interaction with atomic gases and especially atomic oxygen. One final challenge is that to provide practical Earth coverage at such low orbits, large-scale satellite constellations are necessary on the scale of hundreds or thousands of units, implying a dramatic step-up in mass production capability.

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Key technologies

Satellite Platforms with low atmospheric drag and demisable materials

Architecture and technologies for mass production

Compact Electric Propulsion Systems for long lifetime and with small aspect ratio

Development of Air-Breating Electric Propulsion (ABEP) system, for lower VLEOs

Materials and coatings resistant to Atomic Oxygen

Payloads for Telecomm, SAR, and Earth Observation, such as TIR and Hypespectral


“The only way of discovering the limits of the possible is to venture a little way past them into the impossible.”
Arthur C. Clarke,
Author and Futurist

HYPERVELOCITY ENDEAVOURS: FROM EARTH TO DEEP SPACE AND BACK

Vision:

Space exploration moves faster now. It is possible to fly high speed vehicles in a safe but precise manner from Earth to destinations across space and back again. This capability has enabled efficient and affordable ground-to-orbit transportation, fast and safe logistics from low- to geostationary Earth orbit and beyond, as well as low-cost human spaceflight and sample return missions set on targets across the Solar System.

Achieving hypervelocity flight regimes would remove many current spaceflight obstacles, inlcuding duration, recurring costs. It would enlarge human and robotic access to distant regions of the Solar System and accelerate the pace of scientific discovery. Mastering hypervelocity regimes will allow enlarged payloads to be deployed onto other planets and the return of greater mass to Earth. It will also support the growth of in-orbit industrial ecosystems and commercial initiatives, resulting in a much higher launch cadence and more affordable space transportation concepts, such as reusable spaceplanes. This would in turn widen access to weightlessness and non-terrestrial environments.

Making hypervelocity happen

Several functional needs are first required. The vehicle has to be accelerated to ultra-high speeds, involving technologies such as air-breathing or detonation engines to exit the atmosphere, along with nuclear or high-performing electrical propulsion for interplanetary propulsion. This requires technological advances in aerothermodynamics and guidance, navigation and control. Secondly, being able to accelerate is useless without the ability to brake, demanding advances in control surfaces, shape modulation, hypersonic retro-propulsion and high-precision entry, descent and landing. Thirdly, the journey must be survivable for the vehicle, its payload and crew. This demands reusable, lightweight, high-temperature materials, structures and mechanisms, radiation and debris shielding plus robust life support.

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Key technologies

- Advanced mechanical-thermal-propulsion high speed flight systems in harsh environment with constrained control authority
- Advanced interplanetary space vehicle architectures enabling higher delta V
- Smart geometries, robust materials and mechanisms along with morphable geometries
- Autonomous GNC for high-speed vehicles with enhanced flight safety features

SUSTAINABLE SPACE

CIRCULAR AND SUSTAINABLE SPACE ECONOMY

Vision:

Space debris is a long antiquated concept. Why waste material that has been expensively hauled into orbit? Instead a circular economy has taken root in space, leaving a zero debris footprint around Earth. More than half of all the mass launched to (and beyond) Earth is recycled. It is now the space industry standard to design and launch satellites with a neutral impact on Earth's ecosphere across their production, operations and disposal re-entry phases.

Circular thinking for Earth orbit

ESA is already a pioneer in sustainability, thanks to its Eco-Design and Zero Debris policies.

The space sector must mitigate its environmental impacts on Earth's ecosystem, by minimising energy consumption, its use of rare materials and polluting processes. ESA is already a pioneer in sustainability, thanks to its Eco-Design and Zero Debris policies. Yet, with the unprecedented growth of the space sector achieving true sustainability requires the kind of circular thinking increasingly seen on Earth: a holistic approach addressing all phases of a project chain. The ability to repurpose and recycle materials in orbit is not only key to sustainability but will also enable new markets and capabilities and add additional commercial value to space assets. Unlocking such potential requires major technological breakthroughs, advanced processes and novel designs.

Today most of the materials used to deploy a space system are disposed of in just a few hours; reusable launch systems are essential to a circular approach, along with standardised interfaces and interoperability to enable in-orbit services. Completely new design concepts could emerge – including modular, repairable and reusable systems – no longer constrained by the need to fit everything on a single launch.

Mitigate Environmental Impacts

Today, spacecraft failures generate debris that remain in orbit for hundreds or thousands of years. So robust designs to prevent failure and limit debris generation are paramount for space sustainability. There are already around one million items of debris in the centimetre scale in Earth orbit, lethal to operational missions, which will need tracking. Non-reusable parts will require disposal in a manner causing no on-ground risk and minimising atmospheric impacts.

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- Understand and mitigate environmental impacts on atmosphere and oceans
- Sustainable materials, processes and MAIT for satellites and launchers production
- Technologies to support Reusable launchers
- Robust satellite designs to prevent in-orbit failures, collisions and break-ups
- Innovative satellite designs for in-orbit AIT (of equipment, systems and subsystems)
- Tracking of cm scale debris and implementing effective collision avoidance strategies
- Implement fully demisable designs for satellite (platform and payloads) and upper-stages

"To confine our attention to terrestrial matters would be to limit the human spirit."

Stephen Hawking, Theoretical Physicist

DARK AND QUIET SKIES

Vision:

Everyday life has been revolutionised by resilient services from space, provided via global satellite constellations, without sacrificing astronomers' views of the wider Universe. A specific European supply chain has been established to enable the interference-free and responsible exploration of outer space by protecting our dark and quiet night skies for astronomical research and their associated cultural and societal significance.

Low-orbiting satellites invading astronomy

Previous generations of astronomers termed asteroids 'vermin of the sky', because the fast-moving space rocks marred long exposures and blocked views of the interstellar phenomena that researchers were really interested in. Today asteroids have been rehabilitated scientifically; instead many of today's astronomers would retarget this damning phrase towards satellites – especially low-Earth orbit satellites that leave scratch-like signatures on optical and radio astronomy acquisitions as they pass across the heavens.

Protecting the heavens

As the population of low-Earth orbit is set to expand massively, in the shape of mega-constellations it has the potential to provide important services and benefits to the population of planet Earth. This expansion in numbers must be accompanied by responsible protection of astronomical research and the natural night sky that is our human birthright. Ensuring this preservation of dark and quiet skies will require the coordination of industry, research institutions and space agencies combining their efforts and performing targeted technological innovations.

As a world-class leader in space technology and a central international space player, ESA is uniquely positioned to lead this crucial technological endeavour, engaging with the broader astronomical and space communities to ensure future generations can continue to explore and appreciate the wonders of the Universe.

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Key technologies

- Materials, coatings, and surface treatments with low signatures in optical and radio frequencies, including advanced manufacturing of nanostructured, electrochromic or dielectric materials, functional films
- Low signature design optimisation for most critical subsystems (including drag-sails, and large antennas)
- Agile satellite operational modes
- Improved coordination and tracking systems for satellites

SUPPORTING TECHNOLOGIES

To realise these ambitious goals, a range of supporting technologies will play a vital role. Innovative propulsion systems, such as ion thrusters, will offer efficient means of travel. Advanced manufacturing techniques, including 3D printing and in-orbit assembly, will reduce the cost and complexity of building large structures in space. Quantum technologies will enhance our communication systems and data processing capabilities, while AI-driven innovations will enable smarter, more efficient space operations. Deep space power sources, including nuclear and solar technologies, will provide the energy needed for long-duration missions. Robust security and resilient space systems will protect our assets from threats, while cost-reduction technologies will make space exploration more accessible and sustainable. Smart ground operations will ensure that missions are optimised from launch to completion.

INNOVATIVE PROPULSION

Vision:

Our Solar System is becoming a smaller place as innovative propulsion technologies bring new destinations into reach. New, more efficient, space propulsion systems have enabled new classes of missions, including crewed and cargo missions into deep space, all while minimising environmental impacts. As absolute achievable velocity increases, a probe to a neighbouring star becomes conceivable within a manageable human timescale – involving a journey time of mere generations, rather than centuries.

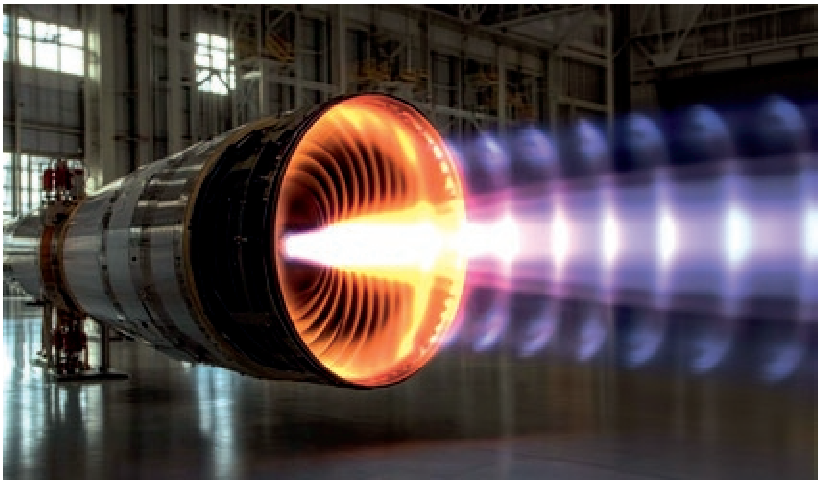
Newton wrote the law of spaceflight

The principle that allows humankind to fly through space was first spelt out in the 17th century, in the shape of Isaac Newton's Third Law of Motion: "For every action there is an equal and opposite reaction." Applying sufficient force in one direction will result in a movement in the other direction – most dramatically in the form of rocketry. Novel in-space propulsion technologies are worthy of exploration as well, such as atmosphere-breathing electric thrusters beamed energy propulsion, long-term storability of propellant, current-generating tethers or nuclear electric and nuclear thermal engines.

Propulsion is a strategic space technology, and continuous advancement in this domain remains fundamental to maintain Europe's leadership in the global space economy. In the short term, the need is for improved performance, increased reliability, flexibility, demisability, high production rates and fast times to market and low cost.

Looking further ahead, innovative propulsion involves novel technologies with much higher performance, environmental friendliness and lower cost, able to expand space logistics capabilities and enable ambitious new missions and applications not only in Earth orbit but also far beyond.

Innovative propulsion has clear interactions with other themes, such as Very Low Earth Orbit, Hypervelocity endeavours, Deep Space Power Generation, Advanced Manufacturing and Materials of the Future.



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Key technologies

Green and low-cost propulsion technologies, e.g. long-term storability of Hydrogen Peroxide, Beamed energy propulsion, Tethers

Water Propulsion for asteroid belt In-Situ Resource Utilisation as well as hydrazine replacement on LEO satellites

Atmosphere-Breathing Propulsion to enable operation in extremely low orbits

Very-High-Power Electric propulsion to enable large cargo missions

In-space Cryogenic Propulsion to enable long-term space missions

Nuclear Propulsion (Thermal and Electric) to enable large payload crewed or cargo deep space mission

QUANTUM TECHNOLOGIES

Vision:

Novel quantum sensors embedded in space-based networks of quantum devices enable new applications and scientific discoveries. Networks of atomic clocks connected via laser offer exquisitely precise satellite navigation while supporting fundamental science and metrology – the measurement of measurement. Space-based quantum sensors provide unprecedented measurements of gravity and electromagnetic fields for Earth observation, inertial navigation and fundamental physics. Quantum entanglement connects quantum computers, sensors or clocks, further boosting their performance and reach.

Strange science of the very small

Quantum physics is based on counter-intuitive properties where atoms or photons can be in a superposition of states acting more like waves instead as particles. Quantum technologies set out to utilise such exotic behaviour for more powerful computing, ultra-precise timing, secure information sharing and high-sensitivity sensors.

Connected quantum devices

ESA has been developing quantum technologies for a quarter of a century. Its long-term vision is to create powerful next-generation clocks and sensors while moving towards networks of connected quantum devices.

Optical clocks and ultra-high-performance time and frequency links will enable new testing of general relativity and particle physics, while also probing the time variations of fundamental constants and hunting for dark matter. Intercontinental clock comparisons will pinpoint tiny shifts in Earth's gravity while space-based optical 'master' clocks will support time standards beyond the limits of ground infrastructure. Compact laser-linked atomic clocks will enable greatly enhanced satellite navigation performance and resilience.

Quantum sensing also represents a significant opportunity for enhanced space-based observations of Earth and other planets. Quantum sensors employing cold atoms can operate as inertial sensors or gravimeters. And quantum sensors based on excited 'Rydberg' atoms can measure the electromagnetic spectrum with very high sensitivity. Diamond-based magnetometers possess intrinsic vector-measurement capability with very low mass and power. Quantum entanglement is a unique way of connecting quantum devices, but only space-based networks can provide long-distance quantum connections and entangled quantum computers, sensors and clocks can have vastly increased performance.

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Key technologies

Quantum sources and receivers

Atomic and optical clocks

Lasers, optics and electronics for time and frequency transfer and atom manipulation

Cold atom interferometers

Quantum sensors based on Rydberg atoms and nitrogen-vacancy centre

ADVANCED MANUFACTURING AND MATERIALS OF THE FUTURE

Vision:

Advanced manufacturing and novel materials have revolutionised spacecraft performance and design. Digital manufacturing, supported by novel machine learning techniques, has become the industry standard. The application of AI and smart chemistry means that space missions are effectively designed down to the molecular level, with the autonomous generation of innovative processes and groundbreaking alloys and chemical formulations to meet any given mission requirements. Sustainable biobased processes minimise terrestrial environmental impacts while out-of-Earth manufacturing enables the construction of space hardware in space and on planetary surfaces, spinning off more sustainable manufacturing technologies for use back on Earth.

Materials make the space mission

Materials make the space mission: this has always been the case, and future missions look likely to rely on advances in materials science as well as manufacturing technologies more heavily than ever. Developing new materials with tailored intrinsic properties will enable novel functions and prospects for space exploration. AI and machine learning will enable researchers and engineers to swiftly select the most promising materials and design concepts during early trade-offs, slashing the costs of development and testing phases.

This approach also encompasses generative designs for future platforms or payloads – which are 'grown' rather than conventionally designed – to end up with bioinspired (or entirely unprecedented) shapes, enhancing the overall system performance of coming space missions.

Advanced manufacturing will also minimise the environmental impacts of the space industry, ensuring an efficient and economical assembly, integration and testing process. Another crucial aspect is the ability to gather critical data for quality assurance, ensuring high performance and reliability of the hardware. The use of digital twins and virtual testing further reduces the need for extensive testing to qualify materials, processes and hardware, shortening development cycles and enhancing efficiency.

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Key technologies

- Development of coatings for dark and quiet skies
- System level impact of advanced manufacturing for ultra compact high-performance satellites
- Development of advanced materials and processes for innovative propulsion
- Smart chemistry
- Sustainable biobased materials and processes
- Development of materials and structures for protection against space debris, atomic oxygen and other environmental effects
- Development of dismantlable satellites for in orbit recycling
- Development of in orbit and in planet printing processes for In-Situ Resource Utilisation

DIGITAL REVOLUTION FOR SPACE

Vision:

The process of digital transformation has reshaped the space sector, just as it has the rest of terrestrial industry. Digitalisation permeates all space engineering, operations and downstream activities. A coherent, interoperable digital thread facilitates formal traceability, analysis, data exchange and round-trip engineering across disciplines, lifecycle phases and supply chains. Supported by advanced modelling, optimisation, simulation and visualisation technique, high-fidelity digital twin representations of systems and the space environment is enabling cost reduction, quality improvements and advanced analytics throughout the space ecosystem.

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Key technologies

Model Based Systems Engineering

Digital Continuity, Big Data, Artificial Intelligence and Semantic Ontologies

eXtended Reality (Augmented, Virtual, Mixed)

Digital Twins for space systems and environments

Multidisciplinary design, analysis and optimisation tools and methods

Going digital for greater performance

The common purpose of most space missions is to acquire data and information, but the very process of creating missions – through design to building and testing – itself yields potentially valuable and actionable data with the potential to guide future enhancement.

Digital transformation is a multi-step process. First came digitisation – the act of taking physical (or analogue) data and making it digital and therefore digitally shareable – based on the use of software to replace paper-based activities. Next comes digitalisation, where the resulting data, and the insights they inspire, form the basis of ongoing improvements – often applying tools such as AI, Machine Learning and Model Based System Engineering.

Guiding real-world activities

In the space sector, the initial goal is to develop an interoperable digital thread, composed of distinct digital artefacts and data sources, supported by advances in 'semantic ontologies' – the organisation of meanings – to power digital twin representations of space systems.

Above this robust digital architecture, advanced multiple domain optimisation techniques can be applied, such as generative design approaches and Large Language Models. AR and VR may guide human physical movements in real-world cleanrooms, enhancing assembly and testing. Newer digital advances will also enable fresh design and operations modalities: applying quantum computing, for instance, will allow the faster optimisation of complex interplanetary trajectories.

AI-DRIVEN INNOVATIONS IN SPACE TECHNOLOGIES

Vision:

Just as there are many more AIs in space than there are human astronauts, AI now plays much more of a role in the engineering, operations and exploitation of any given space mission than do human beings. The integration of AI has been a transformative leap forward, enabling new missions, shortening the time to launch, lowering operational costs and supporting the rapid development of applications to process the ever-rising ‘space data lake’.

AI added to human intelligence

At their most fundamental, space missions represent the extension of human intelligence beyond Earth. AI will magnify this concentration of intelligence still further, sitting astride the entire engineering, operations and data exploitation phases of spacecraft. Applying AI will create numerous opportunities for exploring space and turn the ‘faster, better, cheaper’ mantra into routine reality.

Spacecraft design and construction are extremely complex engineering processes that involve the intertwining of multiple disciplines – and operating missions in-orbit is inherently challenging. Applying AI to the entire mission lifecycle will shorten hardware and software verification times while enhancing performance and reliability. AI-powered platforms and payloads such as edge processing accelerators, data storage and processing units will enable new in-orbit capabilities including in-space servicing, assembly and manufacturing.

AI will be a particular game changer in mission operations, helping spacecraft operators to manage space assets as they grow in number and complexity. AI will be used to automate health monitoring and control and boost the level of onboard autonomy.

AI can also be instrumental in analysing large-scale datasets, leading to scientific discoveries and innovative commercial applications. It will also enhance the performance and reliability of satellite systems while enabling the in-space generation of final products issued from the fusion of multiple spacecraft – resulting in reductions to downlink bandwidths and operational costs. Finally, AI will accelerate the exploration of space by providing cognitive assistance to astronauts and making crewed spacecraft systems more autonomous and performant.

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Key technologies

Mission definition, requirement production and consolidation, cost estimation;

System and subsystems design, analysis, manufacturing, coding, testing, verification, and validation;

Predictive analytics, real-time decision-making support, and autonomous problemsolving capabilities for operators and astronauts;

Autonomy of constellations, rovers, probes

SECURITY FOR SPACE SYSTEMS

Vision:

The billions of euros invested in in-space systems and supporting ground infrastructure can truly be considered a safe investment: security protection mechanisms have adapted to a dynamic environment of novel mission concepts and services, more complex space system architecture and evolving threat scenarios to ensure that what we have, we hold: Europe's space assets will always remain under Europe's control.

Insecure assets

Satellites orbit hundreds or thousands of kilometres away from Earth; it is therefore tempting to consider them as inherently secure purely through their physical remoteness. This would be a mistake. Any space asset is connected to Earth, and that connection makes it vulnerable. In 2023 the US Air Force invited 'white hat' hackers to hack one of their satellites as a test of security. In the event, three teams succeeded.

In real life, this would mean attackers could compromise or misuse a space system's functionality, access protected information or disrupt operations. The risk of such incidents must be minimised.

Defences on all sides

Securing a space system implies a combination of architectural and operational measures and technological elements, distributed across ground, space and user segments plus those elements interconnecting them. Principles like attack surface reduction, segregation and defence-in-depth must be at the heart of any solution and extended to the infrastructure's entire perimeter. As technology and threats against space evolve, so must the security measures.

Achieving robust security requires continuous innovation and adaptation, and the integration of cutting-edge technologies and mechanisms, including physical, cybersecurity, cryptographic related, and surveillance security measures.

The resources needed to implement advanced security systems are substantial, therefore standardised products that could become available off the shelf and offer benefit to multiple concepts and missions, should drive the technology development.

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Key technologies

Generalised RF Link protections against jamming and spoofing

Quantum resistant / Post Quantum Cryptography

Scalable and Agile Security Protection solutions

Defence in depth and Cyber resilience for space assets

Increased situational awareness and incident handling capabilities

RESILIENT SPACE SYSTEMS

Vision:

Europe's space infrastructure is in space to stay, no matter what natural phenomena – or malevolent human actions – might occur around them. Hard times are when these resources are depended on the most, so our satellites are engineered to maintain their essential operational capabilities in adverse natural or human-made conditions, to go on working reliably even when already damaged.

To keep on keeping on

Resilient systems are those that can go on operating, even as conditions worsen about them: to keep on keeping on. They can recover from foreseeable changes in their environment thanks to the systematic imagining of worst-case scenarios back in their design phase, to guide the holistic implementation of risk management and contingency planning.

What does resilience for our space systems require in practice? ESA needs to have secure and traceable supply chains, resilient against counterfeits or espionage, providing us with the tools and means to reliably design, produce, utilise and dispose of our satellites. This also includes new ways to ensure information security throughout the entire supply chain prototypes or subsystems are being designed and manufactured in outsourced facilities.

Space surveillance combined with novel quality approaches

Furthermore Europe needs accurate and available Space Situational Awareness, including space weather measurement and modelling, space object tracking and communications monitoring to prevent jamming and spoofing of satellites and other instruments. Satellites also need to be equipped with countermeasures and redundant elements as insurance against failure.

Current tools and techniques to design for reliability need to be advanced further, employing new quality methods to ensure our designs possess no unforeseen weaknesses that might lead to a loss of capabilities. This includes assessing the dependability and safety of AI-based systems.

This theme is also closely linked to the sustainable use of space, and the disposal of assets after their end of life, because the resilience of space systems is ultimately dependent on the condition of their surrounding environment.

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Key technologies

Future of AI and MBSE Product Assurance, new quality tools and methods.

European Sovereignty on Space Products, Materials, and EEE components.

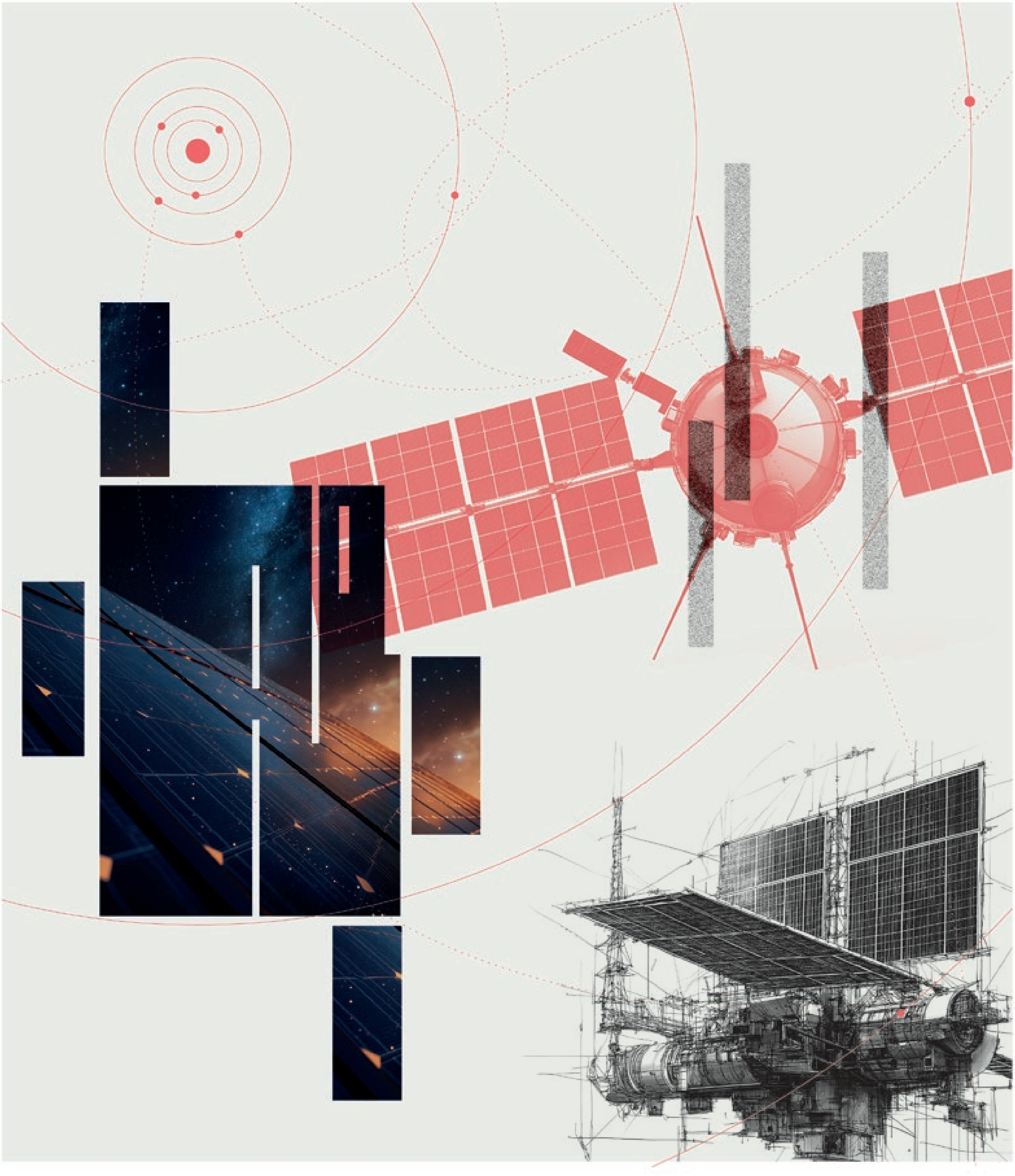
Space Environment Monitoring, Data Analysis, and related design improvements.

Evolution of standards for new needs and regulations, upgraded to new processes, techniques, and methods.

Future testing capabilities, including high-energy irradiation facilities for component testing.

Systematic in-situ measurement data collection and enabling digital twins and environmental multi-scale simulation and modelling.

Novel methods of designing and assessing redundancy, especially in constellations



DEEP SPACE POWER SOURCES

Vision:

Space exploration is no longer constrained by the darkness and cold prevailing at the fringes of our Solar System. A new portfolio of deep space power sources permits missions to penetrate to gloomy regions illuminated by just 1-3% of the sunlight of Earth orbit and just a couple of dozen degrees Celsius above absolute zero.

Denizens of the Sun

By happy accident the photovoltaic cell was invented in 1954, just three years shy of the Space Age. As a result, our satellites and spacecraft are denizens of the Sun – the vast majority of them have always relied on solar energy to function.

Accordingly solar cells have become a basic enabling technology for space, a pillar of European non-dependence, and their capabilities have evolved enormously. Silicon semiconductors have been supplanted by gallium arsenide and now gallium nitride to reach higher power levels, while multiple layers of cells are routinely stacked atop each other – these 'multi-junction cells' being tuned to differing bands of the light spectrum.

Heading into darkness

But current technology is hitting hard limits. ESA's Juice mission to Jupiter runs on 24 000 solar cells across 85 sq m of solar arrays – half the area of a volleyball court, or the average living space of a UK home – but will only produce the equivalent power of a hair dryer at the Jupiter system.

To make future deep space missions possible, multiple power sources will have to be combined. Firstly, futher advancements in solar array technology will be crucial, including ultra-thin and flexible solar arrays incorporating mirror- or lens-based 'concentrators' to focus available light.

Power storage suitable for the deep space environment will also be required, entailing non-rechargeable batteries with high specific energies as well as rechargeable batteries able to go on functioning reliably close to absolute zero. Solid oxide fuel cells will ensure reliable power supplies for high-power electric propulsion systems.

Nuclear electric propulsion will also be essential for deep space exploration, helping reduce overall transfer time, while radioisotope heater units, RHUs, can maintain thermal control in cold environments by continuously generating heat through radioactive decay. For electrical power radioisotope thermoelectric generators, RTGs or Stirling radioisotope generators, RSGs, can be employed.

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Key technologies

- Large solar arrays with Low Intensity Low Temperature cells and concentrators
- Nuclear power (electrical and thermal) for innovative propulsion and thermal control
- Batteries (primary and low-temperature secondary cells)
- Primary Fuel Cells based on Solid Oxide Fuel Cell (SOFC)
- Advanced power conditioning and distribution units

MORE FOR LESS: TECHNOLOGIES FOR COST REDUCTION

Vision:

Each euro invested in space goes much further than ever before. Ever more capable virtual models, standardisation and automated series production has lowered development, production and testing costs to previous unimaginable levels. In combination, these developments have allowed spacecraft to do much more for much less cost, resulting in vastly increased yet more affordable space capabilities.

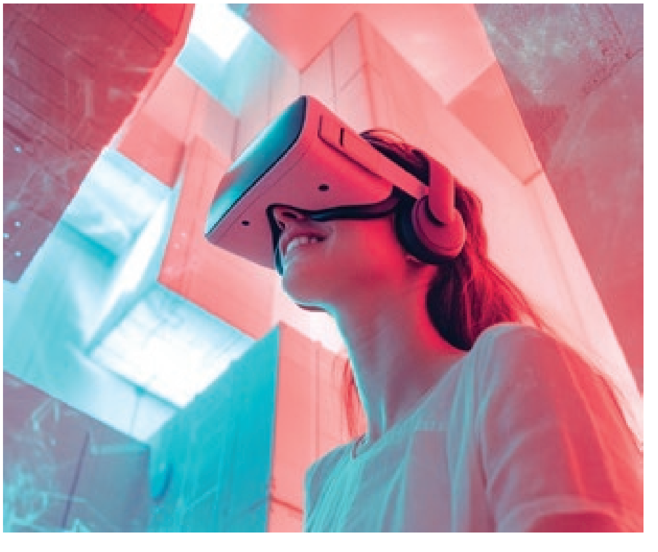
Putting a price on space

Space missions are expensive, have long development times, and are prone to cost increases and schedule stretch. The benefits of these missions, in terms of scientific return or services, can take many years to materialise once a new project has been given the green light for full implementation. Some concepts never even get to this stage, due to a lack of budget and/or too high cost for the expected return.

Changing this situation involves improving the value-for-cost ratio, either by increasing the value of missions and applications – in terms of scientific return, achievable resolution, data rate, constellation size and so on – or reducing the cost and duration of development, production, launch and operations. The best would be to achieve both at once.

Technology breakthroughs will enable space missions to do far more than today using novel materials, equipment and configurations. More effective and efficient design techniques enabled by VR, AI, advanced digital modelling and standardisation of interfaces and products will speed up engineering iterations and allow faster convergence to the most optimal design. Advanced automated production and more efficient test methods will shorten production times.

On the performance side, these smarter, cheaper satellites could be employed in conjunction to boost coverage, resolution and overall data availability, with in-orbit processing meaning that the practical value of the products reaching Earth increases enormously.



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Key technologies

- Immersive Visualisation
- MBSE as Digital Continuity Enabler
- AI-powered Digital Design Assistant
- Building blocks for Software
- Game-changing production of optical systems
- Cooperating Payloads with different satellites
- Fibre-based imaging
- Smart Chemistry
- Cooperating Payloads with flight formation / swarm
- Massive Formation-Flying High-Accuracy Metrolog

SMART OPERATIONS GROUND SEGMENT

Vision:

Spacecraft require smarter and more sophisticated ground segments than ever before. Those ground segments allow fully autonomous and secure operations of Europe's assets in space, enabling seamless access while facilitating unprecedented data downlink rates and daunting mission destinations, even for the most challenging and 'distributed' missions – made up of multiple individual platforms in space.

Footprints on the ground

Operating any space mission is only possible through its ground segment. The total number of missions is growing, and mission system architectures are becoming more complex, requiring constant innovation in ground segment technologies. While ESA's Rosetta comet chaser was operated with a 91-kbps data rate, the Euclid space telescope requires 55 Mbit/s – a six hundredfold increase.

ESA is already providing cutting-edge ground segment systems and software but continuous advances are essential to keep up with the needs of the missions. Ground segments will enable resilient semi to fully autonomous spacecraft operations, incorporating AI and cybersecurity. They will be multi-mission native and arrangeable in the cloud as needed.

Instead of segregated systems, distributed operations systems will support multi-operator driven, interconnected mission concepts enabling missions such as lunar return. Human-machine interfaces will completely transform to facilitate more intuitive and efficient operations.

Space communications solutions will evolve from radio frequencies to optical communications links across all distance regimes from low-Earth orbit to as far as Saturn and beyond. Relay spacecraft around moons & planets will network data streams from multiple spacecraft in 'trunk lines' back to Earth.

Space debris surveillance and precision tracking via radar and optical systems will allow for collision avoidance from Earth to the Moon. Laser-enabled space debris mitigation will allow for low-cost active debris removal, and highly complex orbital dynamics technologies will enable the most daunting mission trajectories, enabling a whole new array of destinations for Europe s missions while maintaining planetary protection.

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Key technologies

- Autonomous and intelligent space asset operations data systems
- Secure Cloud-native distributed ground segment – Mission Systems at the click of a button
- Next-generation Human-Machine interaction technology
- Arraying of Deep Space stations – for punctual performance maximisation
- Optical Deep Space stations – trunk lines with Moon and Mars
- Laser station for low cost space debris manoeuvres and removal
- Highly complex orbital dynamics systems

PLANETARY PROTECTION FOR SUSTAINABLE AND RESPONSIBLE SPACE EXPLORATION

Vision:

A combination of robotic and crewed missions has significantly increased humanity's presence in outer space. We can now explore the Solar System like never before—establishing a sustained presence on the Moon, searching for life on Mars and the Icy Worlds, and preparing for crewed missions to the Red Planet. Europe leads the way in sustainable and responsible space exploration, with planetary protection at the core of its efforts.

Preservation of life in all forms

Ensuring that scientific research related to the chemical evolution and origin of life in our Solar System is not compromised and preservation of the Earth's biosphere from the return of unsterilised material from outer space has always been a priority for space exploration. This is the discipline of Planetary Protection (PP), and its mandate has been given by the United Nations - Outer Space Treaty (1967), Articles VI and IX.

As space becomes more accessible, new actors are investing in space and planning to launch complex, innovative missions. However, ESA's responsibilities towards its Member States and the international scientific community to protect pristine environments of the bodies we aim to explore, as well as safeguarding Earth's environment and public health, remains the same.

Evolution of best practice

Planetary protection practices, initially developed for the Apollo missions, must evolve to meet the needs of ambitious missions. The ESA "Explore 2040" vision articulates precise plans for the next decades, aiming to increase European autonomy and leadership in space. The complexity of such missions calls for a modernisation of planetary protection toolkits and the need to preserve collections of relevant samples in a consistent and standardised way.

The current culture-based methods used to verify biological contamination for space missions are unable to identify the overall biodiversity on space hardware, determine microorganisms of concern, and ultimately assess contamination risks. Similarly, for chemical contamination, there are no validated tools available to assess the risk of volatiles for scientific investigations.

In contrast, a systematic use of non-cultured, DNA-based technologies, aided by AI for contamination predictions and development of new statistical models to assess biological and chemical contamination risks, will enable a transition from current prescriptive approaches to risk-informed decision-making frameworks. Developing the technologies above will give Europe increased flexibility when implementing planetary protection, while fulfilling ESA's corporate obligations to conduct sustainable and responsible robotic and human explorations.

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Key technologies

Metagenomics, molecular biology techniques

AI-driven phenotypic / contamination predictions

Curation of samples

Bayesian statistics (applied to safety and contamination)

Probabilistic models for assessing contamination risks

Standardised biological and organic databases

FOCUS TECHNOLOGIES

Now we have laid out the themes we can see there is a clear focus around key technologies needed for space exploration. Together the themes focus on enabling autonomous, efficient and sustainable space exploration and habitation. The use of AI for robotic control, task learning and problem-solving appears in multiple lists, as does in-situ manufacturing processes and dedicated feedstock materials, particularly related to space habitats and long-term sustainability. There is an emphasis on smart materials and biophilic design as part of maintaining human integrity during long-duration space missions and it is also clear standardised interfaces and modular payloads will become increasingly more important. At the heart of these advancements is a commitment to creating a more sustainable and circular space economy, ensuring that we not only explore but also protect the vastness of space for future generations. Here we delve into the groundbreaking technologies and key technological advancements needed to drive the next generation of space exploration.

1. Expandable & Modular Space Structures

- Deployable and inflatable structures
- Orbital assembly operations and control of large structures

2. In-orbit manufacturing and assembly integration

- Autonomous Systems & Robotics
- Advanced robotics for assembly, exploration, and autonomous operations (surface, aerial, roving)
- Autonomous resource management (e.g., bioreactors, synthetic biology, energy storage, ISRU)
- Robotics for deep space exploration and close proximity operations (e.g., task learning, GNC collaborative control)

3. Advanced Propulsion Systems

- Compact electric propulsion systems for long-duration missions
- Air-breathing electric propulsion for low VLEOs
- High-speed flight systems for harsh environments
- Advanced interplanetary space vehicle architectures

4. Resource Processing & Surface Operations

- Excavation, feedstock acquisition, and beneficiation
- Resource processing and handling technologies
- Environment-adapted mobility for surface exploration (aerial, legged, hybrid)

5. Energy & Power Systems

- Energy-efficient systems for deep space survival (e.g., hibernation technologies)
- Sustainable power systems (solar, nuclear, deep space power sources)
- Advanced thermal subsystems and low-dissipation platforms

6. Communication & Navigation Systems

- High-throughput RF and optical communication systems
- Deep-space positioning, navigation, and timing (PNT) systems
- Distributed formation-flying satellite systems for high-gain beamforming
- Scalable and resilient communication architectures

7. Life Support & Health Systems

- Autonomous Resource production and management (e.g., Advanced Life Support Systems, 3-D printed food, synthetic biology for future space applications)
- Medical systems and health monitoring (e.g., AI-driven training devices, personalized medicine)
- Spacesuit technologies (augmented, exoskeletons) and advanced training systems
- Mental well-being and entertainment systems (eXtended Reality, AI assistants)

8. Sustainability & Circular Space Economy

- Sustainable materials and processes for satellite and launcher production
- Reusable launch systems and in-orbit services for recycling and refurbishment
- Mitigating environmental impacts on Earth and space ecosystems

9. Advanced Materials & Coatings

- Low signature coatings for optical and radio frequencies
- Nanostructured, electrochromic, and dielectric materials
- Materials resistant to atomic oxygen and environmental factors
- Robust, morphable materials and mechanisms for space structures

10. Advanced Sensors & Payloads

- Distributed instrumentation and synthetic aperture imaging
- Quantum sensing and smart cognitive payloads
- Modular optics and miniature RF sensors for deep space observations
- AI-driven data processing for scientific and operational payloads

11. AI & Machine Learning for Space

- AI-based planning, reconfiguration, and fault detection/recovery systems
- Real-time optimisation for mission guidance, entry/landing, and autonomous operations
- Machine learning for predictive maintenance and resource management

12. Space Environment Protection

- Low-atmospheric drag satellite platforms with demisable materials
- Satellite systems with minimal space debris and environmental impact
- Enhanced tracking and coordination systems for satellite operations
- Digital twin technology

13. Testing, Verification and Simulation

- Advanced testing, monitoring, and forecasting methods for space environments
- Functional verification technologies for systems and subsystems
- Life cycle assessments and model-based systems engineering

14. Advanced AOCS/GNC Systems

- Real-time optimisation for mission guidance, entry and landing and autonomous operations
- Autonomous GNC for high-speed vehicles with enhanced flight safety features
- Technologies for orbital assembly operations and control of very large structures