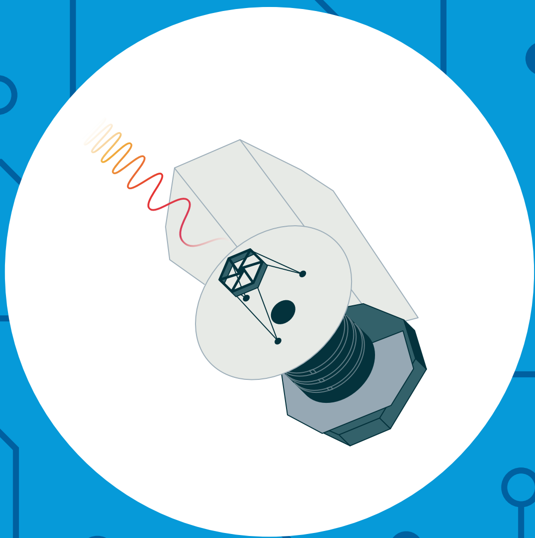
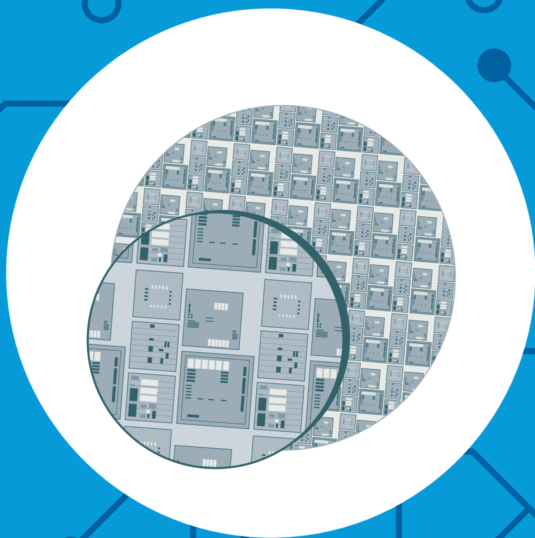
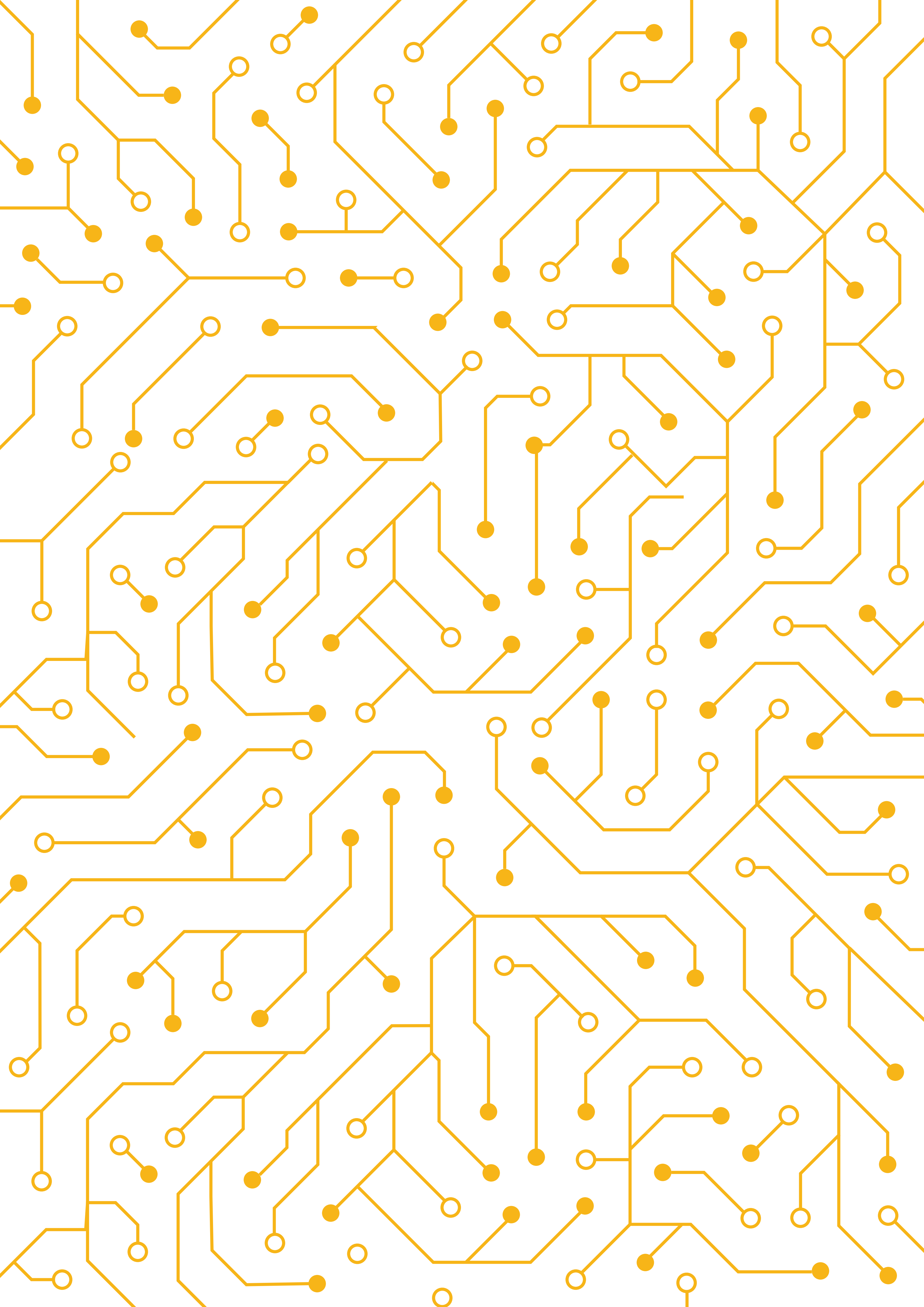




ESA'S TECHNOLOGY STRATEGY

Version 1.2, September 2022



ESA'S TECHNOLOGY STRATEGY:

Developing the Technology which will enable the next major technological and commercial disruptions

This update of the technology strategy guides the planning, development and implementation of all technology development activities prepared, conducted and coordinated by ESA.

It has been developed involving all internal technology development stakeholders and shareholders, including consultations of ESA Member States and Cooperating States as well as space industry. The strategy has been issued by the ESA Director General following a consultation of the ESA Executive Board in August 2022.

→ TABLE OF CONTENTS

A CALL FOR ACTION

EXECUTIVE SUMMARY

Challenges, Opportunities and Targets ... 7

TECHNOLOGY STRATEGY

1 THE CONTEXT FOR SPACE TECHNOLOGY DEVELOPMENTS

1.1 Objective ... 10
1.2 Agenda 2025 and Accelerating Space ... 10
1.3 Methodology ... 11
1.4 Space Economy ... 11
1.5 Related Mega Trends ... 15

2 FROM MISSION NEEDS AND TECHNOLOGY INNOVATION TO TECHNOLOGY THEMES

2.1 Mission Needs and Technology Innovation ... 17
2.2 Cots and EEE components ... 19
2.3 Advanced manufacturing ... 20
2.4 Digital design-to-produce, digitalisation ... 21
2.5 Clean space/sustainability ... 23
2.6 Cybersecurity Technology ... 24
2.7 Quantum technologies ... 25
2.8 In orbit servicing & construction ... 26
2.9 Innovative Propulsion ... 27

3 TECHNOLOGY DEVELOPMENT TARGETS

3.1 30% Improvement of Spacecraft development time ... 28
3.2 One order of magnitude improvement of cost Efficiency with every generation ... 28
3.3 30% Faster development and adoption of innovative technology ... 29
3.4 Inverting Europe's contribution to space debris by 2030 ... 29

4 TECHNOLOGY PORTFOLIO STRATEGY

4.1 European Space Technology R&D ... 31
4.2 Technology Non-Dependence ... 31
4.3 Esa Technology Portfolio Management ... 32
4.4 Enabling Core Technology for Space Mission Needs ... 33
4.5 Enhancing Technology ... 33
4.6 Game-Changing Technology ... 33

MISSION NEEDS AND TECHNOLOGY INNOVATION

5 MISSION NEEDS

5.1 Science and Exploration Technology Needs ... 36
5.1.1 Science ... 36
5.1.2 Exploration ... 37
5.2 Space Safety Technology Needs ... 41
5.3 Applications Technology Needs ... 43
5.3.1 Telecom ... 43
5.3.2 Earth Observation ... 45
5.3.3 Navigation ... 48
5.4 Enabling and Support Technology Needs ... 49
5.4.1 Space Transportation ... 49
5.4.2 Operations ... 52
5.4.3 Space-based solar power ... 52
5.5 European Space Industry Technology Needs ... 53

6 TECHNOLOGY INNOVATION

6.1 Electric, Electronic, (Micro-) Electro-Mechanical and Photonic Systems ... 55
6.2 Structures, Mechanisms, Materials, Thermal ... 58
6.3 Avionics Systems ... 59
6.4 Electric Architecture, Power and Energy, Electro-Magnetic Compatibility ... 62
6.5 Radiofrequency & Optical Systems ... 65
6.6 Life & Physical Science Payloads, Life Support, Robotics & Automation ... 69
6.7 Propulsion, Space Transportation and Re-entry Vehicles ... 72
6.8 Ground Systems and Mission Operations ... 74
6.9 Digital Engineering ... 75
6.10 Astrodynamics, Space Debris and Space Environment ... 77

→ A CALL FOR ACTION

EXECUTIVE SUMMARY

CHALLENGES, OPPORTUNITIES AND TARGETS

The successful implementation of this strategy is essential to achieving the goals of ESA's Agenda 2025, and implementing its technology development ambitions.

The space sector is in the midst of rapid, fundamental change. This change is triggered by a mature, increasingly diverse and vibrant industrial base and sustained high market growth driven by new commercial opportunities and the full-scale integration of space into modern economies. The result is a profound shift in the underlying requirements and drivers of space system design from performance (for one-off missions and prototypes) to cost and schedule.

In parallel, the digital revolution is transforming industries and markets. To best serve the interest and needs of its stakeholders and shareholders – while continuing to undertake cutting-edge technology activities for science-driven missions – ESA needs to invest now and focus its technology development and engineering efforts to seize these opportunities.

By spinning-in, investing in and embracing digital engineering throughout all the design, development and exploitation phases, ESA will drive the technological base of the European space sector to draw full benefit from this technology: For the reduction of cost; to reach shorter, more agile development cycles; and to enable innovative technology to be adopted into space systems much faster.

This will allow the achievement of the four concrete and measurable ambitious targets related to development time, cost efficiency, and sustainability, while shifting the implementation focus in line with Agenda 2025 on the 30% faster development and adoption of innovative technologies.

The implementation of this strategy requires substantial investment in skills and tools for technology R&D at ESA. It extends beyond the engineering community with impacts on procurement and processes, addressed via the ESA transformation process.

→ TECHNOLOGY STRATEGY

1 THE CONTEXT FOR SPACE TECHNOLOGY DEVELOPMENTS

1.1 OBJECTIVE

ESA develops the technologies needed for Europe's space activities. The development of the most suitable technology, on time and according to the right specifications, enables Europe to achieve its ambitions in space, in particular the objectives outlined in Agenda 2025.

This strategy implements the directions provided by the ESA Director General for technology developments prepared, conducted and coordinated by ESA.

1.2 AGENDA 2025 AND ACCELERATING SPACE

The Agenda 2025 defines ESA's priorities and goals. Its implementation plan outlines the actions being taken by ESA to achieve these goals and increase Europe's relevance in the fast-growing space sector.

With Agenda 2025, ESA's Director General calls for "a new mission statement that focuses its space excellence to propel society out of the current health, economic and climate crisis into a more sustainable, fairer and more resilient society". Space contributes much more than just data, navigation signals, or connectivity. It connects the dots to provide information and intelligence. It creates an uplifting spirit, engaging young generations in new and visionary projects, and unites Europe through common dreams and ambitions. It makes the case that "investing in space is investing in the future of Europe through smart answers to complex cross-disciplinary questions and challenges. Investing in space is investing in people and in the science and technology required to be a global actor". This ambition has been underlined by the mandate given to the ESA Director General by Council at its meeting in Matosinhos on 19 November 2021, to take forward the development of three accelerators: Space For a Green Future, Rapid and Resilient Crisis Response and Protection of Space Assets.

Agenda 2025 underlines the importance of space technology developments to achieve Europe's strategic goals. It specifies that ESA will update its "overall procurement approach and technology strategy to serve commercialisation and innovation targets", and "shift the implementation focus of its Technology Strategy to achieve 30% faster development and adoption of innovative technologies." It furthermore specifies that by "adopting an open innovation approach, ESA will double its spending on game-changing technologies and enhance in-orbit demonstration and validation opportunities, together with the European Commision" and that "ESA will increase the industry-driven technology development share of its technology portfolio".

Agenda 2025 specifies that "technology is the key enabler of all major technological and commercial disruptions. Reusability and on-board intelligence have disrupted the launcher sector, [while] miniaturisation and standardisation have disrupted telecommunications and Earth observation. It is now time to shape and grow the disruptive technologies of tomorrow." The document also initiates the launch of "three new technology R&D initiatives on innovative propulsion, in-orbit servicing and construction, and quantum technologies." This 2022 update of the ESA Technology Strategy implements this strategic shift and direction.

The Technology Strategy provides the guiding elements, the technical topics and the direction for ESA's technology development activities. It will allow ESA to provide the expertise needed by the European public sector and private sectors.

1.3 METHODOLOGY

This update of the ESA Technology Strategy takes into account the substantial evolution of the global and European space sector (Section 1.4), the already identified general megatrends shaping modern economies (Section 1.5) and the changes in mission and user needs reflected in the short- to mid- term plans for ESA programmes and projects (Chapter 5). It also reflects the technical progress needed in all key technical domains via the updated mid- to long- term technology innovation (Chapter 6). This update provides a new emphasis for the technology development targets (Chapter 3) according to Agenda 2025 and reflects the progress towards achieving these targets.

In preparing this update, ESA has reassessed which technology themes take priority according to mission needs and technology advances. This involved grouping technologies into 93 action lines, which were reviewed with application domain experts and assessed with respect to: their relevance, the needs of future missions, Agenda 2025, and the technology strategy targets.

This prioritisation and a subsequent clustering according to common technology areas is reflected in the present strategy in Chapter 2.

The first release of ESA's Technology Strategy identified COTS electronic components and digitalisation as critical to achieving the strategy's targets. Their importance has been underlined by this assessment. Concerning electronic components, the assessment resulted in the need to extend the focus from COTS electronics components to EEE components.

In line with Agenda 2025, a new emphasis on quantum technologies has been added, with an increasing number of mission concepts considering the use of quantum devices e.g., for measuring gravity (Section 2.7). Innovative propulsion and in orbit servicing and construction are emphasised in the updated advanced manufacturing cross cutting initiative (Section 2.3) and in the new versions of the competence domain strategies contained in sections 6.6 and 6.7.

The document represents a consolidated strategy with the understanding that the continuous adaptation to changing user needs and integration of new technological capabilities needs to be an integral part of any successful technology strategy implementation process.

1.4 SPACE ECONOMY

1.4.1 Trends

The space sector is at a crossroads of massive changes while also breaking all-time records, with more than 1800 satellites launched in 2021.

The institutional demand from increasingly ambitious governmental programmes continues to dominate the space market (in value) and governments remain the largest funding source of most space technology developments.

In parallel the fast commercialisation of space, supported by U.S. commercial-supply oriented policies, is leading to record levels of private investments into mainly U.S. commercial space businesses. Notably benefitting from governmental technology developments and from a fast adoption of technologies, practices, and business cultures from the ICT sector, new entrants into the commercial arena are disrupting part of the space ecosystem, challenging traditional actors of the global space markets with new space approaches. In this context, well-funded, growth-oriented U.S. commercial space companies identify state-of-the-art European space technology businesses as attractive take-over candidates, putting European technology sovereignty at risk.

While the commercialisation of space took off in the U.S., the New Space revolution has been mirrored in other space powers, such as China and Japan, and accompanied the entrance of new space actors, such as the United Arab Emirates.

At the same time, the world faces critical challenges, with an unprecedent need for a more sustainable, greener and digital global economy. ESA's Agenda 2025 emphasises the benefits of using space to support the recovery of European economy and society towards more resilience and sustainability. It calls for a strong European space ambition using Europe's expertise, technical and scientific excellence as well as industrial capacity, to counter the threats and fully seize the opportunities brought by this new societal and economic context, as expressed in the form of accelerators by ESA Member States in the 2021 Matosinhos manifesto[1].

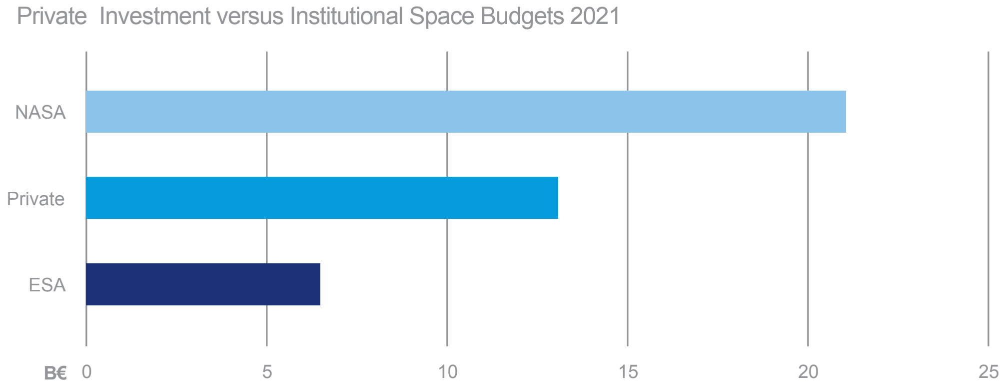


Figure 1 - Private Investments have become a significant contributor to space[2].

1.4.2 Space Economy in Key Figures

The OECD defines the space economy as the full range of activities and the use of resources that create value and benefits to human beings in the course of exploring, researching, understanding, managing, and utilising space.

Space activities are usually structured along two main segments: upstream manufacturing, launch and ground segment activities; and downstream operations and services. The space industry operates upstream of the value chain that flows downstream to the end-users of space-based capabilities.

Current drivers of the global space economy include:

- Ambitious exploration programmes by leading space-faring nations that support high-level institutional investment and state-of-the-art technology developments, using new procurement schemes and funding instruments;
- Continuously growing expectations of cost-effective solutions supported by the new space ecosystem, with more responsibility on the private sector, more agile business models and faster innovation;
- Booming private investment in space companies leading to new entrants in the sector, with increasing commercialisation expectations and attractiveness in taking a share of new space markets (e.g., ISRU, in-orbit servicing, micro-launchers); and
- A clear vision of space as a critical solution for economic recovery and towards the building of a more resilient and more technology-independent European society.

In 2021, 1819 spacecraft were put into orbit, another all-time record with an increase of 44 per cent compared to 2020[3]. This increase is largely due to the launch of more than 989 satellites by SpaceX and to the more than 280 satellites deployed for OneWeb.

In 2021, institutional space budgets (civil and military) reached €78.2 billion, representing a 4 per cent increase compared to 2020 and continuing their growth path with a 6 per cent CAGR over the past five years[4]. While the top five spending countries still account for 83 per cent of the worldwide public investment in space, a growing number of new nations are investing in space capabilities.

1. J. Aschbacher. The Matosinhos Manifesto: Accelerating the Use of Space in Europe; 19.11.2021, available at https://vision.esa.int/the-matosinhos-manifesto-accelerating-the-use-of-space-in-europe/
2. ESPI, Report 83 - Space Venture Europe 2021, June 2022. https://space-economy.esa.int/article/134/espi-space-venture-2021-entrepreneurship-and-investment-in-the-european-space-sector
3. Euroconsult Market Monitoring Reports, 2021.
4. Euroconsult, Government Space Programs, Digital Platform, 2022. The European private investment numbers cannot be compared directly, or in absolute terms, with the private investment figures at the global level due to the slightly different way of accounting used.

Private investment in space continued its surge in 2021. Investors provided a new record of €12.2 billion to private space ventures, a step increase of 86 per cent compared to 2020. This amount is largely driven by massive funding rounds from OneWeb, SpaceX, Sierra Space, and Relativity Space.

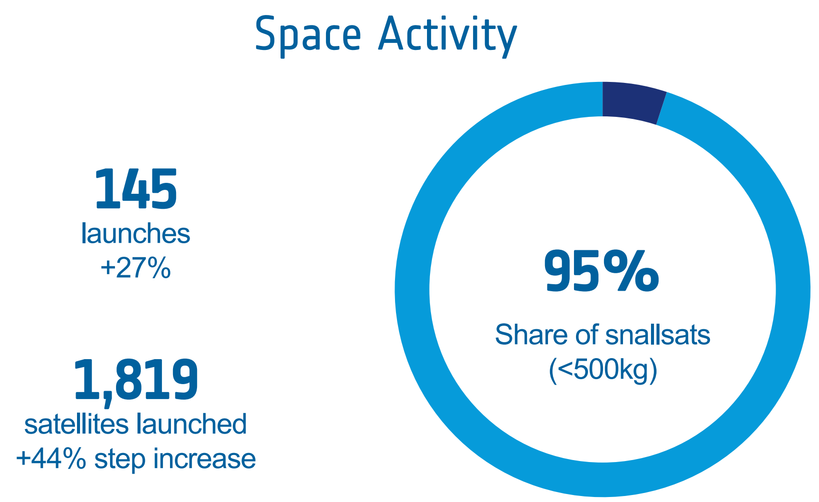


Figure 2 - Global Space Activity 2021.

Private investment in the European space industry[5] reached €611 million in 2021, posting a continuation of last year's growth yet at a slower rate (14 per cent)[6]. In 2021, 44 per cent of the overall private investment was concentrated in the top five deals.

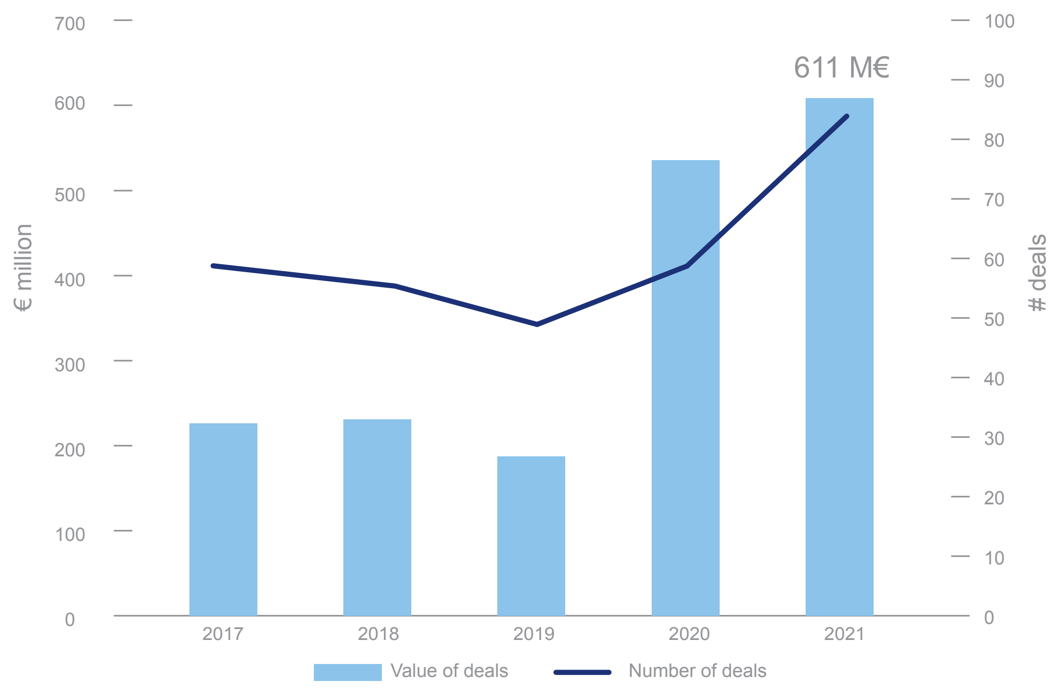


Figure 3 - Number and value of annual deals in European space start-ups 2017-2021[6].

5. (counted as investment in European space start-ups younger than 10 years, whose business tends to feature innovative concepts and models and which has not yet reached business maturity)

6. ESPI, Report 83 - Space Venture Europe 2021, June 2022. https://space-economy.esa.int/article/134/espi-space-venture-2021-entrepreneurship-and-investment-in-the-european-space-sector.

The global upstream market value is generated by revenues from satellite manufacturing, launch services and the ground segment. Estimated at €29.6 billion in 2021, it represents a 6 per cent increase compared with 2020. In 2021, continuing the industry trend of the past years, 95 per cent of all satellites launched were smallsats (<500kg). The development of recurring and low-cost systems reduces the average costs for both manufacturing and launch. The lowering entry barriers lead to rising competition in the field without a guaranteed demand increase. The European space upstream industry generated revenues of €7.5 billion in 2021, capturing 25 per cent of the global market[7]. Manufacturing and launch revenues appear to recover well from the covid-19 crisis.

Space Upstream Market Value

World

29.6b€ +9%

Manufacturing ↑

Launch ↑

Ground Segment ↑

Europe

7.5b€ +19%

Space Downstream Market Value

World

250b€ +1%

Satcom ↓

Navigation ↑

Earth Observation ↑

Europe

60b€ -1%

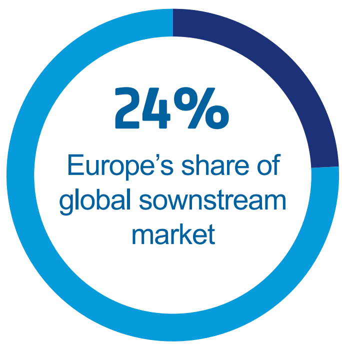


Figure 4 - Space upstream and downstream market value in 2021[8].

Overall, the downstream market saw a minor growth of 1 per cent compared to 2020 with a recovery of the GNSS market, continued decrease of satcom and sustained growth of EO. Overall, global revenues on the downstream market are estimated at €250 billion in 2021, accounting only for commercial revenues. Similarly, in 2021, European commercial downstream revenues posted a small increase, with a 2.4 per cent rise over 2020, generating €60 billion total in revenues.

7. European upstream sales will be updated in the final October publication of the Space Economy Report, after Eurospace Facts and Figures publication in June 2022. The current figure is provisionally based on Euroconsult data.

8. Euroconsult, The Space Economy Report 8th Edition, 2021.

1.4.4 European Reliance on Commercial Markets

New Space has led to smaller, narrow-focused satellites and reduced launch costs, which has lowered the entrance barrier to space and increased the pace of innovation[9]. Supported by new, commercial-supply oriented U.S. policies, this has multiplied the number of actors ready to take risks to profitably serve the growing public and private markets. The U.S. boom in commercial space – strongly supported by the U.S. government – has not only triggered similar policies in Japan and China, but has also compelled some European companies to establish business in the U.S..

Commercial and export sales of the European space upstream industry have been declining since 2017, primarily due to the slowdown of the geostationary orbit satcom market segment. While expectations are high regarding the trend towards constellation systems, the associated potential revenue remains to be demonstrated. The downturn was amplified in 2020 with the closure of the European space port in French Guyana, which, according to Eurospace, resulted in an overall €400 million loss in terms of commercial and export business[10].

These markets are very important for the European upstream industry, which enjoys only a relatively low institutional demand compared to other leading space nations (U.S., Russia, China, Japan and India). Commercial and export customers have been making up for more than 75 per cent of European launch and manufacturing activity (in tons, on average over the period 2016-2020). This is underlined as well by the net positive European space systems trade balance, with exports estimated at €20.3 billion by Eurospace over the past decade (2011-2020).

The dramatic increase in international competition and reduced profit margins require the European space industry to reduce the cost of its commercial space systems. The update of the ESA Technology Strategy addresses this need, supporting industry with specifically pushing technology developments that help reduce production costs and increase production rates, while fostering state-of-the-art innovation and technology development that generate both unique capabilities and contribute to increasing European sovereignty.

1.4.5 Competitiveness of European Space Industry

The priority technology development needs of the European space industry are described by Eurospace, the main European space industry trade association, with a particular attention to the competitiveness of the European space industry. These needs and priorities have been taken into account in the development of this strategy (Section 5.5).

1.5 RELATED MEGA TRENDS

A wave of new technologies is emerging that is shaping economies worldwide. These technological megatrends have an effect on progress on a global scale and will fundamentally affect the performance of space missions as well as the way space missions are designed and operated.

1.5.1 Big Data

The exponential increase in affordable computing power and ubiquitous sensors have led to extremely large data sets that may be analysed computationally to reveal trends, patterns and associations that are not otherwise obvious. Big data enables new analytical applications based on machine learning. Earth observation satellite data sets are large by their very nature. The European Copernicus programme is one of the largest open data providers, already enabling entirely new business applications as well as insight into the Earth’s land, water and climate systems. Increasingly, the data generated by spacecraft are being combined with data gathered through terrestrial sensors to provide richer, previously un-available insight, knowledge and services. Data are becoming the core of businesses and growth offering space manufacturing industry new opportunities to improve their competitiveness in existing markets and to open up new ones.

9. ESA Agenda 2025, 2021.
10. Eurospace facts & figures, Key 2020 facts, Press Release, July 2021.

1.5.2 Digitalisation and 'Industry 4.0'

Advanced manufacturing technologies such as additive manufacturing and the various aspects of digital engineering are revolutionising the way products are conceived, manufactured and qualified. They are at the heart of Industry 4.0 and the smart factory approach to faster product cycles and small batches, with an economy of scale similar to mass production.

These technologies represent an opportunity for more efficient space mission design and implementation, capable of transforming the industry, adapting and rebuilding industrial supply chains and, in the process, regaining manufacturing capabilities that have previously been lost in Europe. They allow the transitioning from the traditional 'design, build and then test' approach based on the intensive and expensive use of documentation to the more agile 'analyse then build' approach with incremental developments.

1.5.3 Artificial Intelligence

Artificial intelligence (AI) is at the core of most current digital disruptions, accelerating competition and speeding up digital transformations. Worldwide, public and private sector investment in AI is still growing fast, with the primary investors being the digital giants. The largest share goes to machine learning, characterised by its multiuse and nonspecific applications, followed by computer vision, natural languages, autonomous vehicles and smart robotics (retail and manufacturing) and virtual agents (services).

ESA has been at the leading edge of academic AI research related to space. Φ-sat-1 included the first AI to be carried on a European Earth observation mission. To avoid downlinking less than perfect images, the Φ-sat-1 artificial intelligence chip filters them out.

1.5.4 Cybersecurity

Global annual cybercrime costs are estimated at one trillion dollars and are expected to substantially increase over the coming years. These include damage and destruction of data, financial theft, theft of intellectual property, theft of personal and financial data, embezzlement, fraud, post-attack disruption to the normal course of business, forensic investigation, restoration and deletion of hacked data and systems, lost productivity, and reputational harm. Cyberattacks are considered the fastest growing crime in the U.S. and are increasing in size, sophistication and cost. To prevent damages, both private and public enterprises are increasing their information technology security spending.

Space systems, interwoven with critical terrestrial infrastructure, are not immune to cyberattacks. Cybersecurity therefore has become a critical requirement for space systems. ESA has engaged in a number of technology activities in support to cybersecurity, including the creation of a new cyber security centre.

1.5.5 Quantum technologies

Quantum technology is in the process of moving from laboratory testing to early applications. It makes use of some of the properties of quantum mechanics, especially quantum entanglement, quantum superposition and quantum tunnelling, for practical applications such as computing, sensors, cryptography, metrology and imaging. The fundamentally different way of interacting with quantum systems promises entirely new applications as well as revolutionary advances in performance in existing ones.

Following Agenda 2025, ESA has started a new quantum technology initiative (Section 2.7) and engaged in a range of state-of-the-art quantum technology activities from cold atoms for atomic clocks to quantum encryption and quantum metrology.

2 FROM MISSION NEEDS AND TECHNOLOGY INNOVATION TO TECHNOLOGY THEMES

2.1 MISSION NEEDS AND TECHNOLOGY INNOVATION

The analysis of different user needs (Chapter 5) combined with the evaluation of the evolution of technology innovation and the resulting capabilities according to ESA's 10 competence domains (Chapter 6) has led to a list of recurrent technology needs, which are grouped into priority technology themes, described in this chapter. These themes are embracing, using and benefitting from the general technology related trends (Section 1.5) but shape them into structured themes specific to space activities. They are essential to achieving the concrete technology targets described in Chapter 3.

Key technology development needs of the different space applications are linked to advanced manufacturing processes and materials. These are necessary to support the commercial telecom and Earth observation sector's need for increased flexibility and reduced production costs (Section 5.3.1) and for the miniaturisation and increasing demand for faster standardisation of Earth observation platforms and payloads (Section 5.3.2). Advanced manufacturing processes and materials are essential for the development of the advanced optical instruments and payloads required for space science missions (Section 5.1.1) and to meet the reliability and reduced structural mass requirements for future exploration missions (Section 5.1.2). Similarly, Europe's space industry has underlined the need for technology advances in new materials and manufacturing processes for their competitiveness (Section 1.4.5, Section 5.5). Many of these technologies and processes have been developed in and for other sectors. The European space industry needs to benefit from their faster spin-in.

The advanced manufacturing, digital design-to-produce, clean space/sustainability and cybersecurity themes were already identified in the 2019 version of the Technology Strategy and are being pursued. Advanced manufacturing (Section 2.2) bundles and focuses these needs into actionable, concrete and coherent technology development roadmaps, ensuring cross-fertilisation between the various related technology development streams and application cases. Based on a long-term vision, ESA has been the global pioneer in introducing sustainability in space activities. The responsible, sustainable use of orbital and other resources has since become a prime concern for the economic viability of some telecommunication missions (especially mega-constellations), Earth observation businesses and the service reliability of navigation constellations. Sustainability and especially the issue of space debris has been highlighted as a priority need by European industry and one of the frequently voiced priorities of the public. The clean space/sustainability theme (Section 2.4) integrates associated technology developments to the point where the space environment can be left in an even better state for future generations. Section 5.2 describes the needs of the dedicated programmatic pillar of space safety and security.

The digital design-to-produce theme (Section 2.4) addresses the spin-in and demonstration of the core technologies enabling a digital engineering process flow from design to operations and data exploitation. While some technologies and processes might be transferred unchanged from terrestrial sectors to space system engineering, others will need some adaptation and adjustment.

The integration of space systems with larger ground systems increases the vulnerability to cyber attacks. Technologies and methods to enhance the cybersecurity level of space and ground systems have been identified as an increasingly important need for space transportation systems (Section 5.4.1), for future telecom (Section 5.3.1), Earth observation (Section 5.3.2) and navigation (Section 5.3.3) missions, while representing generally a concern for practically all space missions. Cybersecurity requires a range of activities across different fields including cyber threat monitoring, detection and reporting, incidence analysis, cyber defence management, behavioural, educational and organisational in addition to technical and engineering aspects.

The cybersecurity theme (Section 2.6) intends to group all cybersecurity related technology and engineering activities. These include, in addition to technologies for the above activities, additional technology developments in the areas of cryptography (including quantum cryptography) and optical communication technologies.

As announced in Agenda 2025, ESA has added three new cross-cutting technology development themes: Quantum Technologies (Section 2.7), In-Orbit Servicing and Construction (Section 2.8) and Innovative Propulsion (Section 2.9).

Further technological themes will be added as certain shared technology development needs between different applications and programmes are seen to emerge and attain sufficient maturity to be pursued in targeted and feasible development processes (e.g., technologies for space based solar power plants Section 5.4.3).

In addition to the technology needs identified in the specific domains of (Section 5.3), science and exploration (Section 5.1) and space safety and security (Section 5.2), increasing the competitiveness of European space activities requires a faster introduction of new technologies into future space systems, which necessitates dedicated efforts to bring them to maturity either when they are issued from space-dedicated developments or when they are imported from non-space domains.

Operational space missions require technologies to be either already demonstrated in space or at high Technology Readiness Levels (TRL). This reduces the overall mission risk as well as risks of delays and costly overruns, which potentially lead to the conservative tendency of re-flying proven, yet no longer state-of-the-art, technology. This applies equally to newly developed technologies and concepts and the spin-in of terrestrial commercial off-the-shelf (COTS) components.

Faster and more frequent in-orbit demonstrations of new technology

The objective of in-orbit demonstrations (IOD) is to progress up the TRL ladder to level 9 and to deliver products, techniques and technologies that are qualified on ground and validated in orbit. Through IOD, new products and technologies are operated in the operational environment and interfaces of user missions, reducing risks and consequently raising further future buy-in, which is especially critical in all cases where the space environment is hardly reproducible on ground.

There are two further and increasingly important drivers to perform IOD. The first is to flight-proof specific techniques required to deliver a product or a service. In this case, it is essential to validate the final performance of the system and hence its commercial viability. Second, for high value missions, it is important to showcase a precursor of the final system to alleviate risk and justify development budgets for the operational system. In these two cases, the IOD often equates to the complete mission.

This new approach to space missions (prototype, IOD, operational mission) is putting IOD at the centre of the space technology development and risk mitigation process. Targets for IOD/in-orbit validation are common in all fields where innovation takes place:

- The IOD of technology and products serves to provide flight heritage, bringing technologies to TRL9 and make products available.
- The IOD of techniques demonstrate feasibility and performances of future planned services (e.g., AIS and ADS-B as past examples), new research in remote sensing, science, space weather, and new operations of space systems, rendezvous, formation flying, servicing, optical communication, etc.
- The IOD of architecture and system concepts demonstrate entirely new concepts such as future missions based on cubesats or the massive utilisation of COTS.

IOD has also proven to be a viable mechanism for the introduction of newcomers in the space industry and to facilitate New Space approaches to missions. Therefore, regular and accessible IOD opportunities are particularly important.

Main challenges for IOD have been access to space, cost and finding flight opportunities. With an increase in the use of small missions, ESA is developing an offer based on Vega and Ariane 6 to provided ride-share opportunities for small missions. These opportunities need to be accompanied by technology developments that allow the faster, more flexible and more systematic integration of new demonstration payloads, including onto operational spacecraft.

To optimise the IOD offer to industry, standardised IOD payload interfaces and similar development processes are necessary. This will benefit in particular new space missions across non-traditional domains such as servicing, debris removal and planetary defence.

System Engineering and Quality Management

The 10 Competence Domains and their respective technology innovation plans (chapter 6) require thorough system engineering and quality control across all projects and development activities. These are especially important as space system developments have been moving from space system engineering to integrated system-of-system engineering – with space being only one part of larger interconnected systems. Quality management will be especially essential to allow ESA to more systematically spin-in terrestrial technologies and offer a tailored risk management capability.

Following the methodology used to update the Technology Strategy presented in Section 1.3, the following sections describe the updated main priority technology themes.

2.2 COTS AND EEE COMPONENTS

Electronic components are the fundamental building blocks of any spacecraft. The quality of the electronic components used on a spacecraft is a determining factor for their reliable operation and performance throughout the mission life.

Usage of COTS components in space is the ultimate spin-in (as the direct use of available items) and is fast gaining acceptance due to the increasing pace of technology progress and innovation outside the space domain. The wider utilisation of COTS-based technologies is driven by the high performance required for space missions associated with the increasing cost and schedule pressure and the new approach to mission qualification and risks typical to New Space approaches. COTS in its wider sense not only includes electronic components, but also complete elements and processes.

However, while spin-in of terrestrial COTS components holds the promise of harnessing leading-edge performance with significantly lower costs, especially for large procurements, there remains a strong reliance on fully ESCC (European Space Component Coordination) qualified EEE components, as technical systems are only as strong as their weakest link and most space hardware is inaccessible for repair. EEE component activities will be supported by the development of a sovereign European supply chain, including specifically via a new EEE European Sovereignty initiative (chapter 6.1).

Evolution and usage of COTS

The increasing utilisation of COTS in space, as currently demanded by industry and operators, requires support from technology programmes to evaluate their suitability for space applications. In this context, mitigation measures from the design (e.g., redundant circuitry) or hardware point-of-view (e.g., coating or other environmental protection technologies) to adapt the systems to the use of COTS is necessary.

ESA has undertaken steps to assure that COTS can be utilised on a wider scale than previously foreseen, accompanied by efforts towards an assured supply chain for fully space-qualified components, as mission scenarios will be more diverse and cannot be separated into either fully COTS-based or fully-qualified components-based missions.

In ESA's technology development programmes, this is dealt with through three stages: "Develop" for initial investigation, "Make" for the last steps before acceptance for space and "Fly", when proof in orbit is required to assess the final behaviour of a COTS part in space.

ESA is currently developing recommended COTS practices, in coordination with national agencies, industry and operators. A new ESA mission classification, which addresses the requirements based on the risk profile of the mission, serves as a baseline to introduce COTS-based technologies for future ESA missions.

2.3 ADVANCED MANUFACTURING

With the Advanced Manufacturing Cross Cutting Initiative, ESA identifies and spins-in disruptive materials and manufacturing technologies already available in non-space industry[11]. The resulting advantages are faster processes, shorter lead times for systems and sub-systems production, increased design flexibility and associated cost benefits. Key technology pillars include additive manufacturing, advanced composite materials, solid state joining, surface engineering and electronic materials and assembly. More recently, Smart Manufacturing and Off Earth Manufacturing have been included. Smart Manufacturing has become enabling, and in many cases game-changing, for space applications due to the strong need to manufacture large and very large constellations, telecommunication modular platforms, navigation/Earth observation recurring products, and the target to reduce costs and production times associated with launcher manufacturing and verification. For Off Earth Manufacturing, ESA aims to foster and support the development of manufacturing and assembly technologies for implementation in space and on extraterrestrial surfaces. This covers the development of new materials for on-orbit/on-planet manufacturing and recycling (including the reconditioning of space debris for construction purposes), the associated processes and verification/testing methodologies as well as the supporting space robotics.

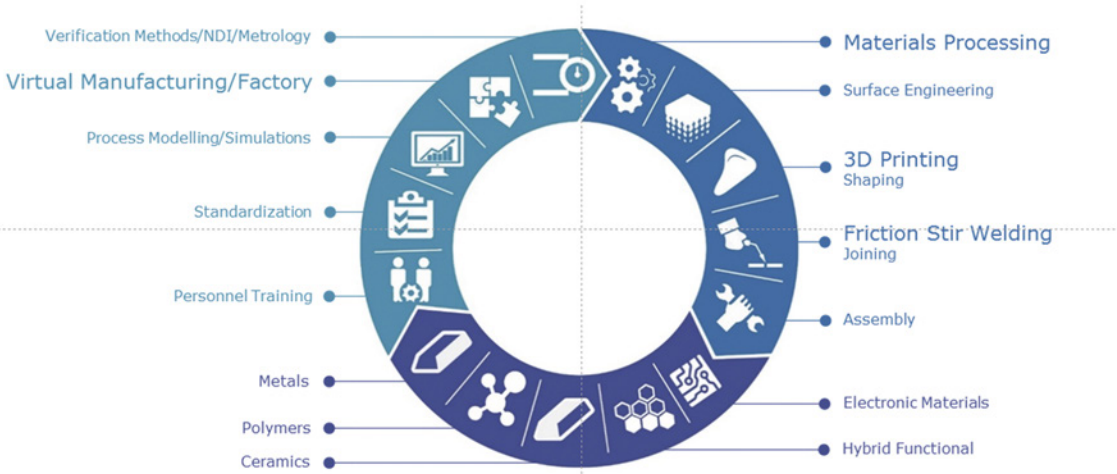


Figure 5 - The Advanced Manufacturing Cross-Cutting Initiative.

Since the introduction of the initiative, over 200 activities (approx. 88M€) have been funded across all of the ESA technology programmes, many of which are in the domain of additive manufacturing, composites materials, digital manufacturing and virtual testing, advanced forming and NDI technologies. A large number of these disruptive materials and processes continue to expand across all business sectors, including aeronautical as well and land transportation. Europe is in a very strong position, with many of the advanced manufacturing leading industries having their headquarters in Europe and key space companies having begun adopting advanced manufacturing as standard techniques. However, the market is evolving very quickly with annual growth rates of up to 40% and the global competition necessitates ongoing development to maintain and expand Europe’s competing and leading positions.

With this initiative, ESA will continue to stimulate the space industry supply chain, improving cost, schedule and sustainability, while maximising the performances of the final space products. The overall goal is to consolidate Europe’s leadership in advanced manufacturing technologies for space applications, with a significant return of investment extending also to highly profitable non-space industrial sectors.

11. GSTP Element 1 “Develop” Compendium 2019: Advanced Manufacturing, ESA-TECT-PL-015900, Iss. 1, Rev. 0, 28/10/2019.

Figure 6 - Compliant mechanisms developed by CSEM in a test configuration.

2.4 DIGITAL DESIGN-TO-PRODUCE, DIGITALISATION

Digital technologies have radically changed businesses, industries and societies. Digital engineering is currently enabling a revolution in the way spacecraft are designed, developed, tested and operated. The centre of the process is based on an integrated, digital model-based approach, which allows the shift from the traditional, lengthy document-centric design-build-and-then-test process to a model-centric analyse-and-build process more suitable to the new space environment.

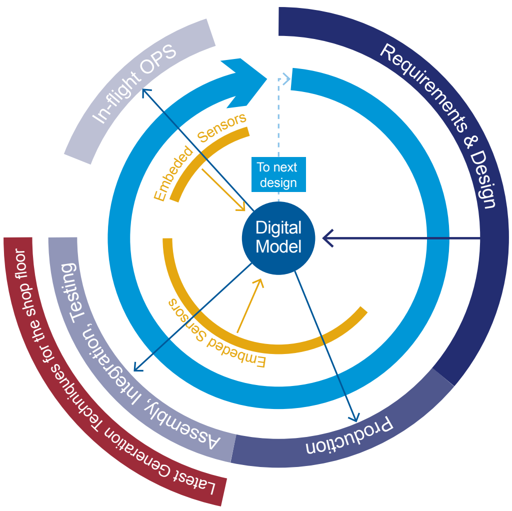


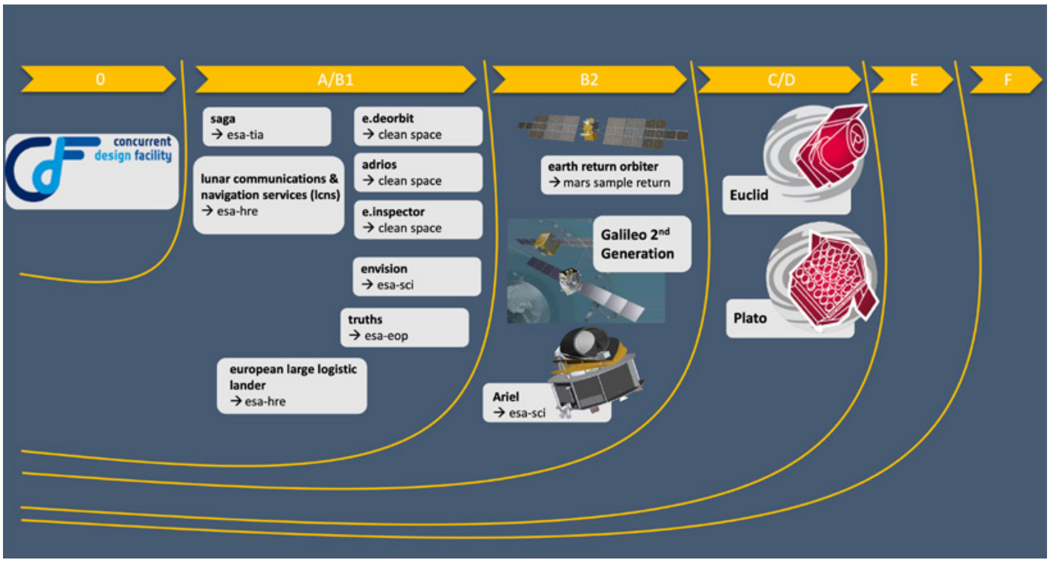
Figure 7 - Digital Design-to-Produce - Key components.

Model Based System Engineering (MBSE) and the digital spacecraft (extended beyond system engineering) are important contributors to the improvement of development time and cost efficiency targets. In particular, industrial actors have recognised the added value of MBSE in streamlining the design, development, deployment and verification of space systems. Design justification and traceability are major benefits gained from adopting MBSE. MBSE furthermore improves communication between stakeholders, such as by facilitating the exchange and reporting of physical architecture and system budgets with customers and automating previously tedious tasks performed using documents.

To increase the speed of introduction of MBSE, ESA has funded dedicated additional MBSE work packages[12] for early mission phases, which have allowed industry and ESA to gain valuable experience and lessons learned in several different systems and subsystems of actual missions.

Several ESA missions have acted as forerunners and seen the investigation, development and adoption of novel MBSE techniques, such as Euclid, Plato or Galileo 2nd Generation. The number of missions and mission studies adopting MBSE at system level increased from three missions in 2016, to 12 missions in 2021. This effort and the experience gained in the process have allowed a) the introduction of MBSE as the default baseline approach to all new mission studies funded by the Preparation element of the Basic Activities; and b) to identify the key challenges such as the interoperability and exchange across domains of expertise and among stakeholders, that will be addressed through a move towards a homogenous MBSE approach.

MBSE and the Digital Spacecraft are important contributors to two of the four development targets of the Technology Strategy: “30% improvement of spacecraft development time by 2023” and “one order of magnitude improvement of cost efficiency with every generation”.



ESA will continue supporting the evolution of standards for digital engineering – incorporating and harmonising all the relevant elements currently being developed. It is important to consider that, while there are still some technology development steps to be taken, the successful implementation of a fully digital engineering process, centred around models instead of documents, crucially depends on the continued willingness of programmes and projects and industrial contractors to embrace this approach.

Moreover, design-to-produce is especially important for the development of space systems intended to be fully integrated into modern economies, to serve new customers and integrate with diverse ground networks and smart devices. In this context, competitiveness and time-to-market need to drive the development. The focus of this initiative is therefore on technologies and processes to reduce time and simplify manufacturing, assembly, integration and testing.

12. Funded by the Preparation element of the Basic Activities.

Some of these technologies and processes are part of the smart factory concept of Industry 4.0, which rely on fully exploiting digitalisation, automation, interoperability and large sensor data analytics. To facilitate the introduction of this concept into space, ESA is continuing to support the space industry in the setting up of partnerships and pilot projects with specialised non-space actors for a rapid adoption of smart factory approaches to space. The initiative benefits from the leading expertise of European SMEs in related technologies such as embedded sensors, virtual, augmented and enriched reality, smart glasses and integrated scanners. The initiative also calls for a change in mind-set, customer involvement, frontloading, preparation of sequences, anticipation of anomalies and usability.

2.5 CLEAN SPACE/SUSTAINABILITY

In support of the new safety and security programmatic pillar and its clean space initiative, ESA develops technologies to secure the future of space activities by protecting the environment. Several lines of action are pursued: eco-design, management of end-of-life, and in orbit servicing with a focus on active debris removal.

Eco-design

ESA has been a pioneer in the field of eco-design since it has been actively working on understanding and finding ways to decrease the environmental footprint of space missions, from their design to their disposal, for the past decade. This process started with the adaptation and application of the environmental life cycle assessments (LCA) to its activities and progressed with the development and publication of the space system life cycle assessment guidelines and of the LCA database. The LCA allows the identification of environmental hotspots and the development of innovative solutions to decrease the environmental impact. Applying eco-design to space missions means to design them while taking into account their environmental impact and fostering the use of green materials and manufacturing processes, while engaging proactively with European environmental legislation, such as REACH.

The way forward is to further consolidate the existing framework, extending the LCA database and guidelines. The objective is for the LCA and eco-design approach to be applied to more projects and missions since the beginning, so that the environmental impact can be considered in the decision-making process.

Management of End of Life

A key aspect for space sustainability is a proper management of the end of life of a spacecraft to minimise space debris production. The traffic increase in Earth orbit calls for a fast evolution of space debris mitigation requirements and their global implementation. A “zero debris” objective has been defined by the DG as the aim to consistently and reliably remove ESA missions from valuable orbits around Earth immediately after they cease operations and apply a net zero pollution strategy for objects in space by 2030. With this ambitious objective, ESA aims to lead by example, and European large system integrators are setting management of end of life as a main driver for the evolution of their platforms.

Through the CleanSat initiative, ESA has set up a proactive and coordinated approach with system integrators and suppliers to harmonize the requirements and to mature end of life technologies. Specifically, ESA’s Earth Observation Programme has implemented design-for-removal requirements in all recent Copernicus Expansion missions. As several of these technologies have matured and are close to qualification, progress at subsystem and platform level are needed to integrate those building blocks in a coherent way. ESA is promoting the development of new Zero Debris platforms for future missions in line with ESA’s Zero Debris objective. These platforms should integrate the heritage technologies from CleanSat activities and go beyond the current state-of-the-art to include features such as full platform design for demise, modular implementation of controlled re-entry, system resilience improvement and preparation for removal in case of failure in orbit. This coordinated systems level work is foreseeing the involvement of both integrators and suppliers and promoting the swift development and integration of innovative technology. The scope of this activity is being prepared in close coordination with industry.

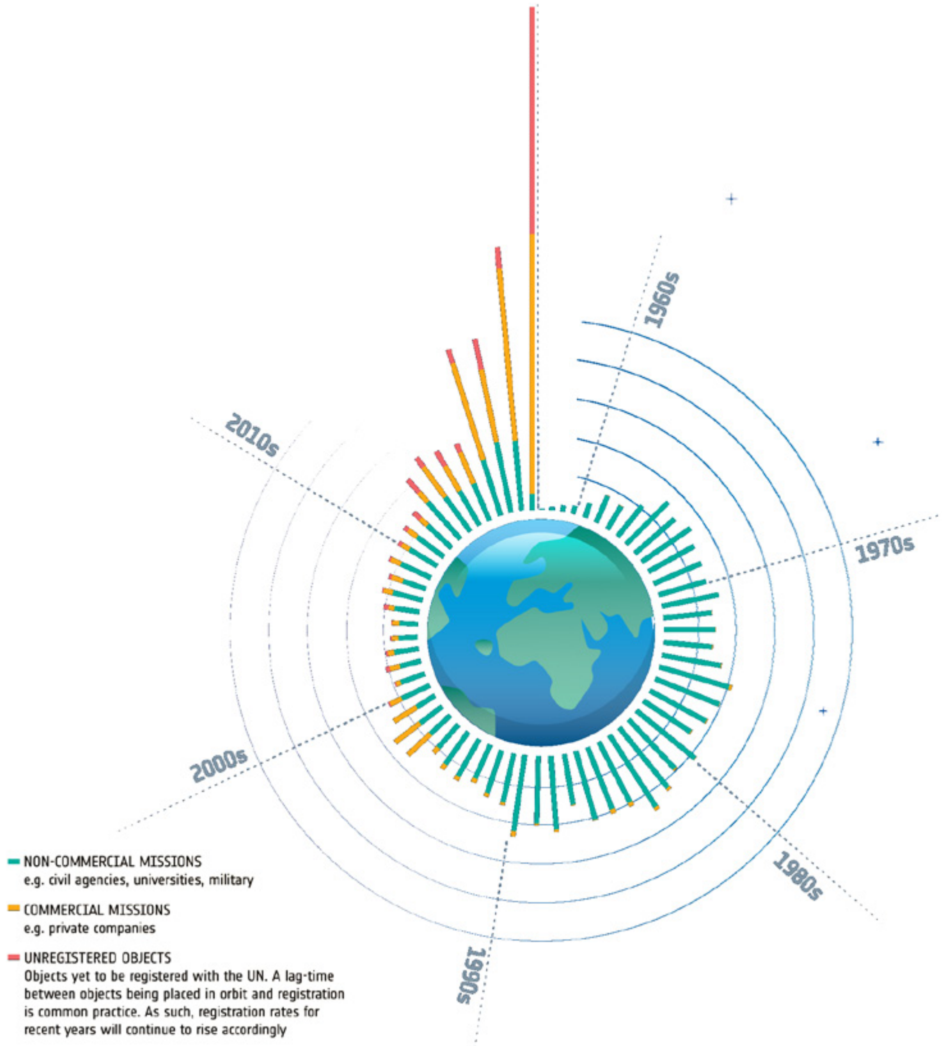


Figure 8 - Increasing number of space missions driven by commercial, and unregistered objects.

2.6 CYBERSECURITY TECHNOLOGY

The increased reliance of other sectors on space assets and services for their own success and competitiveness puts pressure on the incumbent need to address cybersecurity threats originating in space, which endanger critical assets in space and their supporting infrastructure on Earth. While space engineering has a long tradition of focussing on safety and reliability, given the harshness of the launch and space environment, cybersecurity introduces the dimension of intentional, human-made threats to the traditional threat sources coming from the natural environment, technical failures and unintentional human error.

Current developments worldwide have put an increased focus on safety and security aspects in general, and on cybersecurity in particular. The public sector is expected to be at the forefront of many of these activities with private entities involved as both users as well as investors.

An increasingly hostile and aggressive cyber environment in a time where connectivity is ubiquitous raises the importance of cybersecurity. The importance of defending space assets and activities from cyber-attacks will increase as space becomes more strongly integrated in other sectors – of both public as well as of private relevance.

These considerations are reflected in the introduction of space safety and security as one of the four pillars structuring the ESA long-term programmatic plan. These include the development of technology and infrastructure for the cybersecurity of ESA missions, for the layered cyber-secure systems aboard satellites, for cybersecurity operational services, and technology and processes to ensure the cybersecurity of data and transmission links.

ESA is addressing cybersecurity at various levels of innovation, specifically regarding technology and engineering:

- Cost effective implementation of individual security mechanisms through standardisation and validation of security protocols (e.g., the Consultative Committee for Space link Data Services' (CCSDS) space data link security protocol and its extensive procedures);
- Identification and implementation of reference architectures for space- and ground-based data processing system, which include flexibility and security by design, taking into account the rapidly changing nature of the cybersecurity threat;
- Integration of security into the ESA system engineering process;
- Compilation of cybersecurity compendia to drive GSTP R&D activities for cybersecurity for space missions to address the latest threats (e.g., quantum) and security needs;
- Development of ESA's Cyber Security Operational Centre for the security monitoring of ESA space missions; and
- Development of ESA's Security Centre of Excellence, for the security assessment and testing of space infrastructure, for the emulation of space missions, validation of security operation procedures, provision of cyber threat intelligence, security training and awareness.

2.7 QUANTUM TECHNOLOGIES

Quantum technology refers to technologies based on the principles of quantum physics.

The European Commission and many European countries have announced large investments towards the commercialisation of quantum technologies, primarily for communication and computing. The most publicised application of quantum technology is quantum computing. Agenda 2025 highlights quantum computing as key for translating big data into smart information and services.

Breakthroughs in quantum technologies will also enable a new generation of sensors and clocks of unprecedented accuracy and are estimated to significantly affect future space systems:

Figure 9 - Quantum gravimeter during an ESA airborne campaign over Iceland.

- Optical clocks are exceeding today's time standard and available atomic clocks with optical time and frequency links enabling long distance networks of clocks.
- Atom interferometers for precise gravity measurements are significantly improving the systems used for Earth observation, planetary science and fundamental physics.
- Quantum communication will enable new applications to connect quantum sensors or quantum computers.

Cyberattacks supported by hostile quantum computers will be countered by implementing a new generation of cryptographic algorithms (post quantum cryptography).

Quantum technologies and innovative concepts for quantum information processing have been subject of ESA research activities since 2005. These activities and their fast-evolving technical capabilities have prepared the ground for an ambitious new technology R&D initiative on quantum technologies with the main objectives to:

- Identify and support strategic interests of ESA Member States, industry and academia;
- Boost activities to raise TRL, IOV/IOD and applications for quantum technologies;
- Provide increased visibility on quantum activities at ESA through a dedicated technology roadmap; and
- Stimulate ESA internal and external collaborations.

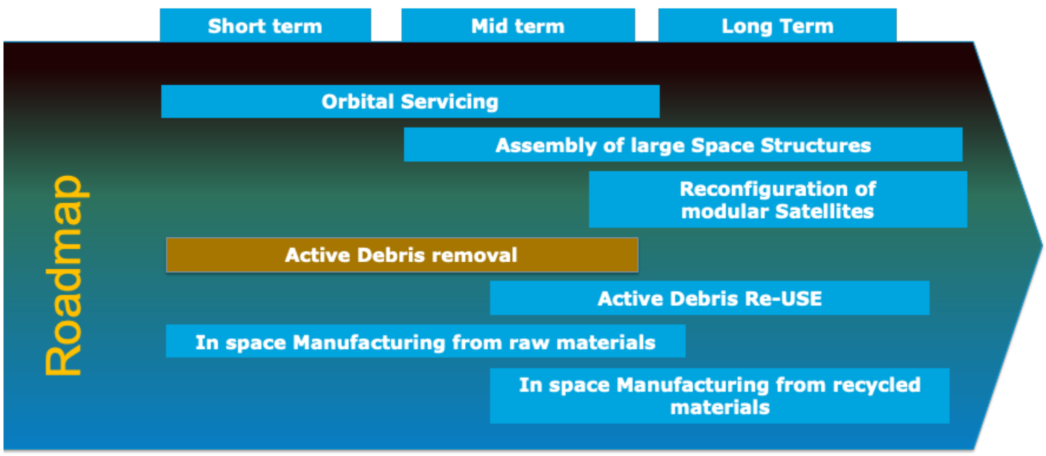
2.8 IN ORBIT SERVICING & CONSTRUCTION

ESA purchased through the ADRIOS in-orbit demonstration mission a unique service to demonstrate the first removal of an item of space debris from orbit.

Active space debris removal is one of several in-orbit services, considered as potential game changers, with the potential to impact the way space systems are designed, manufactured and operated. To increase Europe's ability to act sustainably in space and prepare for an emerging commercial market, Europe needs to further develop in-space servicing, manufacturing, construction and recycling capabilities.

In-space servicing includes satellite life extension, repair, upgrade, retrofit, repurpose and also de-orbit activities. In the medium term, in-space assembly is required to deploy any space infrastructure larger than a single launcher can accommodate, unlocking new applications in the process. In-orbit manufacturing from raw materials provides flexibility in meeting demands and optimisation of logistic and supply chains on orbit. It can be used for larger spacecraft structures and may in the long term allow the re-use of materials already available in-orbit to promote a circular economy in space.

ESA will therefore build upon several ongoing initiatives such as a range of Discovery element R&D activities proposed by industry through an open Off Earth Manufacturing call on OSIP and the Clean Space On-orbit Manufacturing, Assembly and Recycling activity to further advance European capabilities.



2.9 INNOVATIVE PROPULSION

Innovative propulsion spans from air-breathing rocket engines, to electric propulsion serving extremely low orbits, to green propellants. The emphasis is on new propulsion system for new applications which

- enable new, emerging applications;
- facilitate the creation of new markets; and
- enhance the reliability and competitiveness of European propulsion and flight vehicle products.

Agenda 2025 underlines the importance of propulsion for all space undertakings, and in particular to the Accelerators and Inspirators. Key technological challenges include delivering propulsion systems that run on non-toxic fuels, and utilising atmospheric air for airbreathing propulsion, either as an oxidant for launchers or as an ejection mass, such as for Low-Earth Orbit (LEO) station keeping (Section 6.7).

3 TECHNOLOGY DEVELOPMENT TARGETS

The four technology development targets were defined and set in 2018. If not specified, reference values are 2017/18 values. Their review and assessment are foreseen to take place in 2023.

3.1 30% IMPROVEMENT OF SPACECRAFT DEVELOPMENT TIME

We develop key technologies to allow ESA to reduce the time from Phase B2 to launch by 2023.

Specifically, ESA is developing & introducing:

- Technologies to fully digitise the workflow from early concept development, through manufacturing to integration and testing.
- Technologies needed to achieve increased flexibility, scalability and adaptability based on modular space system designs and standardisation.
- Processes to facilitate a fast introduction of new terrestrial technological progress into spacecraft.

Relevant actions are ongoing in all Competence Domains. Achieving the target critically depends on the speed of introduction of digital engineering and advanced analytics based on big sensory data, automation and artificial intelligence in processes driving schedule and cost, and on the availability of technology at the right maturity level at the start of Phase B2.

Following two years of supporting industry with dedicated additional work packages on MBSE, since mid 2021 all new phase A missions use MBSE as baseline. Furthermore, activities supporting achieving this target are ongoing within the Design-to-Produce and Advanced Manufacturing initiatives and via the development of technological building blocks in the application domains[13], which are considered essential to achieve the flexibility and modularity necessary to reduce development times.

3.2 ONE ORDER OF MAGNITUDE IMPROVEMENT OF COST EFFICIENCY WITH EVERY GENERATION

We develop key technologies to allow Europe to achieve one order of magnitude cost efficiency improvements with every space system generation.

Specifically, ESA is developing technology that will:

- Allow end-to-end cost efficiency improvement by one order of magnitude to the user when considering space as a service.
- Reduce the cost per useful bit transmitted by telecom satellite systems by one order of magnitude by 2023 compared to 2018.
- Allow the positioning, navigation and timing services of navigation systems to provide 100% service availability, reliability, extend accuracy by one order of magnitude for mass market and make the system resilient to spoofing attacks by 2025.
- Improve remote sensing mission performance in terms of resolution (4x), accuracy (4x), revisit time (10x), tasking and product delivery time and distribution (10x) overall by at least one order of magnitude cost ratio by 2023 compared to 2018; allow transformational science and increasing the science performance to cost ratio by one order of magnitude.

13. Examples include the development of the Advanced Data Processing Architecture (ADHA) and the Advanced Power Architecture (APA).

To achieve this goal, ESA is leveraging downstream commercial technological developments, the use of modular architectures for space systems, adapted standardisation, advanced manufacturing and lightweight structures, low cost propulsion concepts, and the smart use of commercial off-the-shelf devices and components. A dedicated Discovery element call on OSIP for industry proposed ideas has boosted the introduction of COTS components. The introduction of the ESA mission classification is essential to facilitate achieving this target.

Special attention is given to big data analytics technologies, end-to-end system design optimisation, on-board intelligence for smart processing to increase the value per pixel, miniaturization of instrument technologies and payloads, and technology advancements in the domain of optics and sensors.

3.3 30% FASTER DEVELOPMENT AND ADOPTION OF INNOVATIVE TECHNOLOGY

We develop processes, methods and technologies to allow Europe to take faster the full benefit from the early introduction of new technologies into space systems enabling new applications.

Specifically, ESA is

- Tripling the number of IOD missions, including in particular cubesats, flown in the 2020-2024 period compared to the 2015-2019 period;
- Reducing the time from TRL 4/5 to TRL 7/8 by 50% for technologies selected for in-orbit demonstration; and
- Increasing the use of COTS electronic components through a dedicated COTS strategy and a mission classification risk model.

To achieve this target, which is particularly underlined in the Agenda 2025, ESA focuses on technologies that enable new space-based capabilities and services, and offer fast and systematic qualification and in-orbit demonstration opportunities.

Key technologies currently identified in chapter 6 include quantum technologies, on-board artificial intelligence algorithms, advanced optics and detector technologies, in-orbit robotics, in- orbit manufacturing and assembly technologies, cybersecurity-related technologies as well as technology developments needed for COTS applications in space systems. ESA will develop, mature and qualify these technologies in close partnership with industry and research centres, investing in joint lab facilities for faster spin-in from terrestrial sectors into space. ESA has significantly increased number of opportunities for technology demonstration and verification payloads (IOD/IOV).

3.4 INVERTING EUROPE'S CONTRIBUTION TO SPACE DEBRIS BY 2030

We develop the technologies that allow us to leave the space environment to the next generation in a better state.

Specifically, ESA is

- Proposing a formal zero debris approach for ESA missions;
- Adding extra requirement for Copernicus expansion missions to prepare satellites to be removed by an external servicer in case of failures in orbit;
- Demonstrating active removal of space debris by 2025;
- Preparing steps to make all ESA missions environmentally neutral; and
- Developing the technology that allows all ESA missions to be risk neutral by 2030.

To achieve this target, ESA is developing technologies to eliminate the creation of new debris (such as Cleansat technologies, demisable components, end of life deorbiting technologies, retrieval interfaces), technologies for active space debris removal (such as advanced GNC for close proximity operations, in-space robotics), in-space servicing, space debris surveillance and characterisation technologies.

The investment into clean space technologies will also provide a competitive advantage in the future growth markets of in-space servicing.

These ambitious targets, first introduced in the 2018 version of the Technology Strategy remain valid. ESA foresees a thorough assessment of its effort, means and results in achieving these targets in the subsequent revision of this strategy.

4 TECHNOLOGY PORTFOLIO STRATEGY

4.1 EUROPEAN SPACE TECHNOLOGY R&D

ESA's technology strategy is conceived to implement the directions of the ESA Director General reflecting the dominant position of ESA's activities in overall European space technology developments. This update reflects the guidance for technology development provided by the ESA Director General in his 2021 published Agenda 2025, which specifically calls to "update the overall procurement approach and technology strategy to serve commercialisation and innovation targets", and to "shift the implementation focus of the Technology Strategy to achieve 30% faster development and adoption of innovative technologies". It furthermore specifies that by "adopting an open innovation approach, ESA will double its spending on game-changing technologies and enhance in-orbit demonstration and validation opportunities" and "to provide commercial actors with more pre-developed technologies, which they can readily use to create commercial applications, ESA will increase the industry-driven technology development share of its technology portfolio".

ESA's development activities are embedded into a wider European R&D landscape reflecting the maturation of the space sector, the resulting increases of private sector investments in some space technology areas and the substantial investments in space technologies at national level and via the European Union.

Over half of the public sector investment in space technology R&D in Europe is funded through ESA programmes. In 2020, that amounted to approximately €500 million, of the €860 million invested in public sector space technology R&D in Europe. This public support has been imperative to maintaining European industry's competitive edge considering the high costs and inherent risks, the comparatively low returns from commercial and institutional (including defence) markets when compared with the U.S., and the increasing support to the space sector granted by governments of emerging space players such as China and India.

With technology R&D investments distributed between programmes of ESA, the EU and national agencies, proper coordination is necessary to avoid unnecessary duplications, promote synergies and optimise use of the funding. The European Space Technology Harmonisation was established to achieve this, and has been operating for more than two decades, increasing its relevance and inclusiveness of stakeholders. It provides all actors of the European space sector (ESA Member States, European Commission and other stakeholders) with the framework to fill strategic gaps, minimise unwanted duplications and consolidate strategic capabilities, and with an input when preparing their respective technology R&D workplans.

4.2 TECHNOLOGY NON-DEPENDENCE

The security and sustainability of supply and industry's ability to export its products are impacted by Europe's high dependence on non-European critical technologies. Europe needs unrestricted access to those critical technologies which enable European space missions and allow the autonomy of European space systems and their operations.

A coordinated and coherent European institutional approach has been established between ESA, European Commission, and the European Defence Agency, targeting the development of critical space technologies and products for European strategic non-dependence.

Geopolitical instabilities, and the associated vulnerability of the supply chain, have heightened the need to take concrete actions to further reduce technology dependency. Furthermore, in technology domains for which Europe is dependent on a single source of supply and not developing own capacities, double sourcing via alternative international partners might be needed, together with a regular monitoring of the evolution of the associated risk of dependency. The technology development efforts reflected in Chapter 6, and dedicated initiatives such as the one targeting EEE sovereignty try to address some of these vulnerabilities.

4.3 ESA TECHNOLOGY PORTFOLIO MANAGEMENT

ESA's technology portfolio management includes all ESA technology research and development activities. It is an integral part of the European Space Technology Master Plan and the associated harmonisation process.

Structuring parameters: technological readiness and innovation type

The management of technology development activities is guided by two structuring parameters: technological readiness (TRL) and innovation (enabling, enhancing, game-changing). These determine the programmatic frame under which to conduct the activities, the appropriate risk levels, the funding levels and the relation to industry and academia. These parameters also allow the setting of high-level priorities according to strategic needs by allocating funding to certain types or classes of activities.

Based on its vocation as a comprehensive space agency and its dominance in the European public-sector space technology development domain (Section 1.4), ESA develops technology at all technology readiness levels and for all innovation types.

Technology at lower TRL is developed as part of ESA's Basic Activities, while higher, closer to application and market technologies are typically developed within optional programmes[14]. Similarly, enabling technology developments for selected ESA missions tend to be developed via dedicated project related R&D efforts while game-changing – and to a large extent also enhancing – technology developments are performed via generic technology development programmes such as those included in the Basic Activities and GSTP.

The spectrum and range of technology developed at lower TRLs is naturally substantially larger to allow the exploring of new concepts and preparing for parallel mission concepts in Phase A before down-selection by programmes. To make it possible that technology development results not selected for immediate mission implementation might be integrated in later missions, other concepts or outside of the space sector, ESA supports an efficient technology knowledge management infrastructure, promoting the further development and use of such technologies inside and outside of the space sector.

ESA's technology portfolio is balanced between the needs to ensure

- Coherence and effectiveness through coordination and cross-fertilisation between the different technology development programmes;
- Lean and fast implementation of technology development activities, which implies fast decision and selection processes;
- Transparency and accountability, to ESA Member States, space projects and industry; and
- Supporting critical core technology needs while investing sufficiently into technology that can substantially enhance mission performance or introduce game changing capabilities and services.

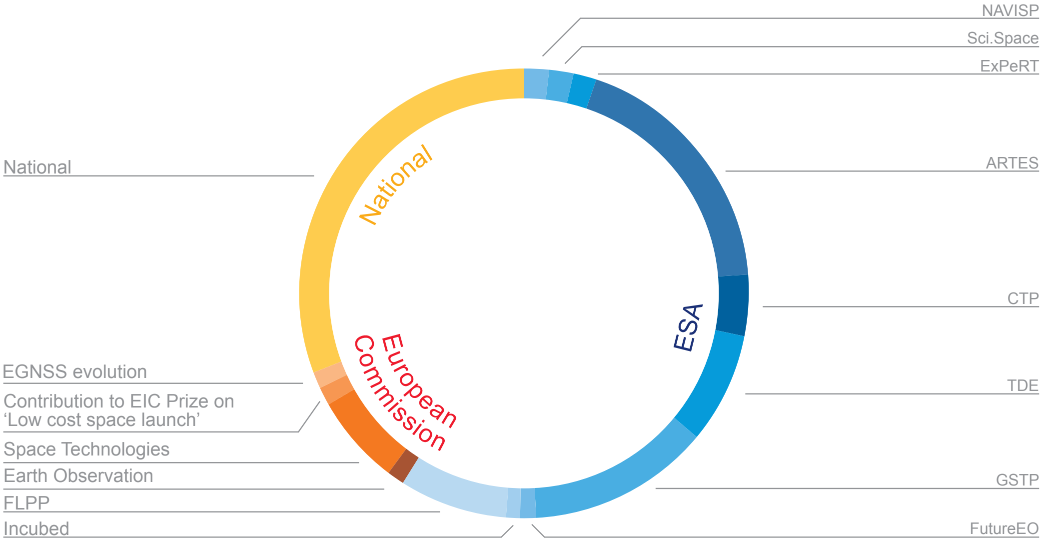
One of the core strategic decisions for technology development lies at the balance between investing in technology that sustains incremental innovation and technology that promises enhanced or potentially game changing solutions and disruptive innovation. This decision depends on the overall health of the space sector, the market situation and competition. Traditionally and except during severe crisis, the large majority of investment in technology is spent on enabling core technologies for identified space mission needs. Compared to the U.S., Europe has a strong mission focus in its technology portfolio, investing relatively little on enhancing and game changing technology development. In his Agenda 2025, the ESA Director General specifies that by "adopting an open innovation approach, ESA will double its spending on game-changing technologies and enhance in-orbit demonstration and validation opportunities".

Partnerships

ESA technology development activities are performed in partnership with industry and academia. Technologies at the very low readiness levels are developed mainly with research laboratories at

14. Mandatory budget funded ESA technology development include the Discovery, Preparation and Technology Development elements, and the Science Core Technology Programme. Optional ESA programmes with a strong technology development focus include General Support Technology Programme, Artes AT and CC, InCubed, Navisp, ExPeRT, SciSpace, FLPP.

academia and research centres, while for technology developments at higher readiness levels, ESA relies on industrial partners. Especially for the R&D programmes focussed on core competitiveness, ESA also partners with industry for their definition and orientation.



*Programme implemented by ESA through a delegation agreement

Figure 10 - Space Technology R&D via ESA, EU and nationally in ESA Member States, Cooperating and Associate States: estimated civil Institutional budget of 860 M€ for 2020 (source: 2021 European Space Technology Master Plan).

4.4 ENABLING CORE TECHNOLOGY FOR SPACE MISSION NEEDS

The development of enabling core technology represents the majority of ESA's technology investment. These activities ensure that ESA develops critical, enabling core technology for its planned missions on time. They are typically driven by clear deadlines integrated into the respective development plans and roadmaps.

Their development is time-critical and their availability conditions the readiness of space missions. Most enabling technology development at higher technology readiness level is conducted within space projects. Therefore, the development risk needs to be kept commensurate to the potential impact on the space missions they enable.

4.5 ENHANCING TECHNOLOGY

ESA invests in enhancing technology when these promise substantial performance increases for space applications. These activities are either performed directly within projects or via the General Support Technology Programme for higher technology readiness levels.

The development of these technologies allows taking higher risks, enables the use of different contractual approaches with incentives and hard go/no-go decision points and greater freedom to innovate for space industry.

4.6 GAME-CHANGING TECHNOLOGY

ESA investment into game-changing technology enables Europe and European industry to identify and assess technology developments that promise to introduce entirely new capabilities for applications and services early, and to avoid technological surprises.

Research and development activities for game-changing technology are typically high-risk, high-gain activities, which allow innovative partnership approaches with academia and industry. Such developments benefit most from fully open, geographically unconstrained competition and are thus performed via ESA's Basic Activities.

→ MISSION NEEDS AND TECHNOLOGY INNOVATION

5 MISSION NEEDS

5.1 SCIENCE AND EXPLORATION TECHNOLOGY NEEDS

5.1.1 Science

In general, ESA's Science missions - especially the large-class missions (currently JUICE, ATHENA, LISA) - require new, emerging and enabling technologies to be developed on the frontiers of what is technically and scientifically achievable. As payloads are provided by Member States, the related technology developments are to a large extent funded via national programmes. The following missions are currently in the early mission phases thus identifying and driving the associated technology development needs:

Mission: Athena

The Athena mission is a next-generation X-ray space observatory designed to study the million-degree-centigrade Universe (e.g., supermassive black holes, evolution of galaxies and large-scale structures and matter under extreme conditions). The observatory concept is based on novel telescope optics with the focal plane instrumentation consisting of a Wide Field Imager (WFI) and Cryogenic X-ray spectrometer – the X-ray Integral Field Unit (X-IFU). The envisaged launch date is during the later 2030s. The primary technology development focus is on novel silicon pore optics and on the cooling chain. ESA has developed mechanical coolers over many years, though the complete cooling chain for meeting the Athena mission requirements is a major challenge.

Mission: LISA

The LISA mission is a gravitational wave observatory measuring waves emitted by compact cosmic sources using laser interferometry and building on the successful in-orbit demonstration of LISA Pathfinder. The mission concept consists of three identical spacecraft in a quasi-equilateral triangular constellation and located on an Earth-trailing orbit. Each spacecraft carries two reference test masses in free fall and laser interferometry is used for measuring the distance variations between test masses on separate spacecraft. The mission launch is foreseen to be around 2035. Critical elements that require technology development are the laser system, the phase measurement system, the optical bench, the telescope and micro-propulsion. LISA is expected to produce large quantities of data, requiring the development of innovative data processing and analysis tools.

M-Mission: EnVision

EnVision will determine the level and nature of the geological activity and the sequence of events that generated the surface features of Venus. The proposed payload consists of an S-band synthetic aperture radar (SAR), subsurface sounder, IR mapper and an IR/UV spectrometer. The SAR is a complex instrument with heritage. However, to observe the surface of Venus, it requires S-band (or potentially lower) to sufficiently penetrate the atmosphere and extreme phase stability to allow (differential) interferometry to produce 3D terrain maps and measure surface deformation in the case of seismic events. The SAR instrument will require delta-qualification for the environment around Venus, and has a high data output, hence demanding high data rates and data volumes.

Mission	Member State Provision	ESA Provision
Athena (L2 mission)	Focal plane instrumentation: Wide field imager X-ray spectrometer (with JAXA and NASA contributions)	X-ray telescope (Silicon pore optics) Cryogenic cooling chain for X-ray spectrometer
LISA (L3 Mission)	Interferometric detection system, gravitational reference sensor, data and diagnostics system, optical performance GSE	Micro-propulsion system, HGA, high accuracy pointing mechanisms, Telescope (NASA), laser system (NASA),
EnVision (M5 mission)	Instruments are provided by ESA MS + NASA	VenSpec-H detector assembly with integrated cryocooler

Voyage 2050

The scientific community was consulted to establish a long-term plan to cover the period following Athena and LISA. Three large missions, which will encapsulate three scientific themes are proposed:

Moons of the giant planets: Exploring the issues of habitability of ocean worlds includes searching for biosignatures and studying the connection between the moon interiors, near-surface environments and the implications for the exchange of mass and energy in the overall moon-planet system.

From temperate exoplanets to the Milky Way: Our Milky Way contains hundreds of millions of stars and planets along with dark matter and interstellar matter but our understanding of this ecosystem, a stepping-stone for understanding the workings of galaxies in general, is limited. A mission specifically focusing on the characterisation of temperate exoplanets would be transformational in our understanding. However, if an informed down-selection of exoplanet candidates is not feasible then this priority can shift focus to the galactic ecosystem with astrometry in the near-infrared spectrum.

New physical probes of the early Universe: How did the Universe begin? How did the first cosmic structures and black holes form and evolve? These are some of the unanswered questions in fundamental physics and astrophysics. The recommendation is for a large mission deploying gravitational wave detectors or precision microwave spectrometers to explore the early Universe at large redshifts.

Long-term technological developments

Voyage 2050 identifies a number of technologies that could enable ambitious missions beyond the scope of Voyage 2050.

The first recommendation emphasises the high promise of cold atom techniques for space-based experiments. Feasibility of a mission in this field is driven by the maturity of payloads. Emphasis is put on cold atom interferometry, while atomic clocks are also considered an important application area.

A second recommendation deals with the possible development of interferometry in X-rays. Such techniques could enable extremely high spatial resolution with relatively small baselines and in turn enable novel science to be addressed with modest-sized spacecraft. Substantial development needs are required as, while highly promising (even on ground), this technique is still in a very early development stage.

In terms of developments for future planetary missions, an emphasis is placed on both, the need for better power sources to explore the outer Solar System and the benefits of sample return missions from planets and small bodies, in particular the return of cryogenic samples.

The final recommendation concerns the possible ways to reach high heliospheric latitudes enabling missions that could sample regions of the heliosphere and observe regions of the Sun, thus far impossible to reach. In this context, Voyage 2050 underlines the need for new propulsion technologies.

5.1.2 Exploration

Space exploration is expanding as never before, encompassing activities in low Earth orbit, cis-lunar space, the Moon's surface and on Mars. This includes both institutional and commercial initiatives that represent the first steps of a paradigm shift towards sustainable exploration missions. The aim of ESA's human and robotic exploration programme is to ensure that Europe is ready for these changes and will play a significant role commensurate with its stance as a political and economic power. While many exciting and rewarding opportunities exist, the key will be to focus and prepare for missions and roles with a primary interest to Europe.

ESA's current approach to Europe's role in global exploration endeavours is based on a balanced investment between the three ESA exploration destinations (LEO, Moon and Mars) and between human infrastructures, transportation and robotic missions. ESA's exploration strategy outlines the priorities for the next decade. (Terrae Novae 2030+ Strategy Roadmap[15])

15. ESA/C(2022)108.

The strategic framework consists of missions either led by Europe or to be implemented with international or commercial partners, as well as technology demonstrator missions and missions of opportunity.

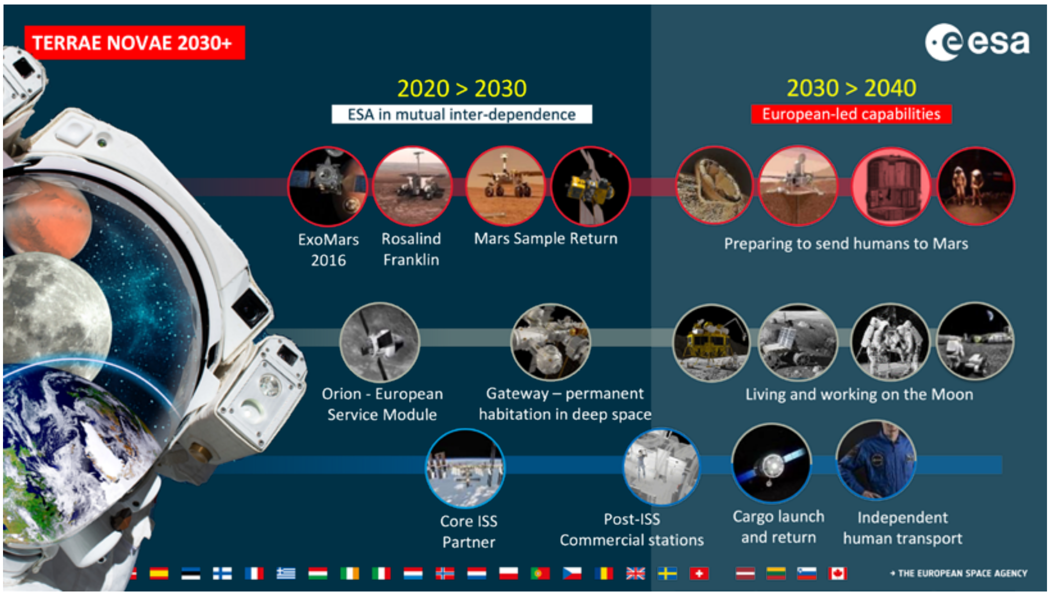


Figure 11 - Terrae Novae 2030+: ESA's long-term exploration strategy elements.

The activities started in the European Exploration Envelope Programme periods 1 (2016-2018) and 2 (2019-2022) will continue into the next period 3 and adapted following the indications at the ESA Council at ministerial level in November 2022. The main proposed elements are:

- Continued and sustainable human activities in LEO beyond 2024 (ISS and transitioning to post-ISS, e.g., SciHAB as European contribution to future LEO infrastructure) exploring the possibility offered by the commercialisation of services;
- Human-beyond-LEO exploration through European participation in the "Lunar Gateway" and ESM/Orion Missions;
- Starting at the end of this decade a sustainable Moon exploration phase centred around the European Large Logistic Lander (EL3), which will deploy either self-standing scientific payloads or infrastructure and logistic elements onto the Moon's surface, in support of international missions, to be followed in the next decade by contributions to the human exploration of Mars; and
- Robotic missions to Mars securing the launch of Exomars mission in this decade and an important European contribution to Mars Sample Return (MSR) as primary target.

The ExPeRT (Exploration Preparation, Research and Technology) element is part of the European Exploration Envelope Programme (E3P). It defines requirements, integrates activities, coordinates developments, and manages studies and technologies for future Exploration missions to low Earth orbit (LEO), Moon, and Mars destinations. ExPeRT oversees mission feasibility and system definition studies for all exploration activities. It is responsible for the definition and implementation of technology activities with the aim of reaching a technology readiness level of TRL 5-6 prior to the start of mission implementation.

To prepare for future exploration missions, investments in technology developments are required in enabling, enhancing, and game changing technologies. The following technology areas are considered key for exploration:

- Propulsion
- Novel Energy Systems
- Robotics and Mechanisms
- Artificial Intelligence Applications
- Advanced Life Support and Crew Health Management Systems
- In-Situ Manufacturing
- Space Resources/ISRU

- Radiation Protection and Environmental Effects
- Communication and Navigation
- Subsurface Sampling/Deep Drilling
- Avionics, Guidance, Navigation and Control
- (re-)Entry, Descent and Landing
- Thermal Control Systems
- Mission Operations Data Systems

The ExPeRT-defined technology requirements represent the technology needs in the Exploration application domain at ESA. These are technology-push and mission-pull requirements. Technology-push activity for exploration are expected to result in a step-change or breakthrough (disruptive, game-changing) that may facilitate exploration or considerably enhance the performance of current capabilities. Mission-pull activity responds to a specific identified exploration mission need. These requirements are derived from pre-phase A and phase A ESA mission concept and system studies.

The International Space Exploration Coordination Group (ISECG) is a forum where space agencies/offices work collectively in a non-binding, consensus-driven manner towards advancing the Global Exploration Strategy. The ISECG 2018 Global Exploration Roadmap (GER) with its addendum in 2020 and the outcome of the different ISECG Subworking groups capture the shared vision for international collaboration in space exploration based upon a common set of exploration goals, objectives, and identified benefits to humanity. It reflects an exploration strategy for the International Space Station (ISS), the Moon and its vicinity, asteroids, Mars and other destinations.

The ISECG Technology Working Group aims to facilitate leveraging investments in technology development efforts of individual space agencies, supporting implementation of the GER mission scenario and to advocate coordination and collaboration in technology development.

The following table highlights technologies identified by the ISECG as critical for future exploration missions.

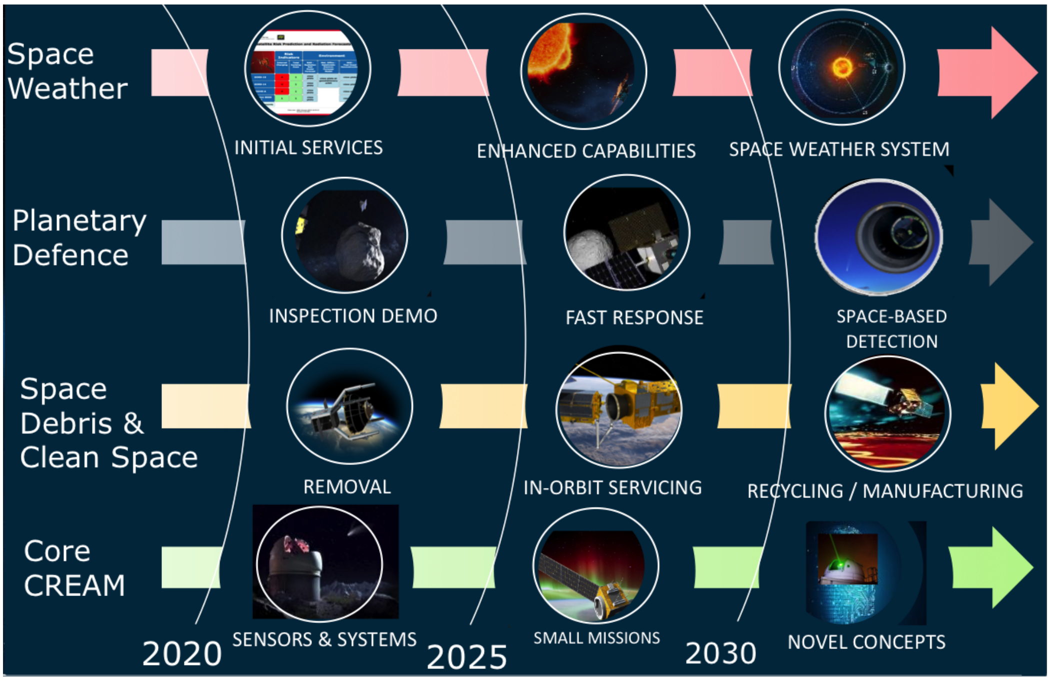
Global Exploration Roadmap Critical Technologies (Summary Table)	Today ISS & Spaceflight Heritage	Near-Future Moon Vicinity/Surface	Future Mars Vicinity/Surface
Propulsion, Landing, Return			
In-Space Cryogenic Acquisition & Propellant Storage	Spacecraft: CPST/eCryo demo	u-G vapor free liquid tank to propulsion transfer, Efficient low-power LOx H_2 storage>1Yr (Mars)	
Liquid Oxygen/Methane Cryogenic Propulsion		Throttleable Regen Cooled Engine for Landing (Lunar Scale)	Throttleable Regen Cooled Engine for Landing (Mars Scale)
Mars Entry, Descent, and Landing (EDL)	Spacecraft:MSL class (~900 kg)	Demonstration of advanced technology in deep space environment	Large Robotics>1000 kg; Human ~40,000 kg
Precision Landing & Hazard Avoidance	Spacecraft: Lunar & Mars Landers State-of-the-Art	~100 m accuracy, 10's cm hazard recognition, Support all lighting conditions	
Robust Ablative Heat Shield Thermal Protection	Spacecraft: Orion Heatshield test flight (EFT-1)	~1000 W/cm^2 under 1.0 atmospheric pressure	~2,500 W/cm^2 under 0.8 atmospheric pressure
Electric Propulsion & Power Processing	Spacecraft: 2.5 kW thruster (Dawn)	~ 10 kW per thruster, High Isp (2000 s) (for some mission options)	~ 30 - 50 kW per thruster(for some mission options)
Mid & High Class Solar Arrays	ISS: 7.5kW/Panel	High Strength/Stiffness Deployable, 10-100 kW Class (for some missions options)	Autonomously Deployable, 300+kW Class (for some missions options)
Autonomous Systems			
Autonomous Vehicle System Management	ISS:Limited On-Board Mgmt functions,<5 s comm delay	On-Board Systems Mgmt functions (handles > 5 s comm delay)	On-Board Systems Mgmt functions (handles > 40 min comm delay)
AR&D, Proximity Operations, Target Relative Navigation	ISS:Autonomus docking	High-reliability, All-lighting conditions, Loiter w/ zero relative velocity	
Beyond-LEO Crew Autonomy	ISS:Limited Autonomy	Automate 90% of nominal ops Tools for crew real-time off-nom decisions	
Life Support			
Enhance Reliability Life Support	ISS:MTBF<10 E-6, Monitored/ operated by GC	More robust & reliable components (eliminate dependence on Earth supply logistics) Increased systems autonomy, failure detection capabilities, and in-flight repairability	
Closed-Loop Life Support	ISS: 42% O_2 Recovery from CO_2 90% H_2O Recovery	Demosnstration of advanced technology in deep space environment	O_2/CO_2 Loop closure; H_2O Recovery further closure; Solid Waste, reduce volume/storages
In-Flight Environmental Monitoring	ISS: Samples to Earth	On-Board Analysis for Air, Water, Contaminants	
Crew Health & Performance			
Long-Duration Spaceflight Medical Care	ISS: First Aid+, return home	Demosnstration of advanced technology in deep space environment	Training (pre & in-flight for medical aspects) Continuous monitoring & decision support
Lond-Duration Behavioral Health & Habitability	ISS: Monitoring by Ground	Demosnstration of advanced technology in deep space environment	Cognitive performance monitoring Behavioral health indicators & sensory stim.
Microgravity Counter-Measures	ISS: Large treadmills, other exercise equipment	Demosnstration of advanced technology in deep space environment	Compact devices to assess/limit disorders Reduce weight/vol. aerobic & resistive eqpt.
Deep Space Mission Human Factors & Habitability	ISS: large crew volume, food & consumables regular resupply	Demosnstration of advanced technology in deep space environment	Assess human cognitive load, fatigue, health Optimized human systems factors/interfaces
Space Radiation Protection (GCR & SPE)	ISS: Partially protected by EarthApollo: (accepted risk)	Advanced detection & shielding New biomedical countermeasures	
Infrastructure & Support Systems			
High Data Rate (Forward & Retrurn Links)	Ground (DSN):256 kbs Forward, 10 Mbs Return Link	Demosnstration of advanced technology in deep space environment	Forward: 10's Mbps; Return: Optical> 1Gb/s
Adaptive, Internetworked Proximity Communications	ISS: Limited capabilities	Demosnstration of advanced technology in deep space environment	>10's of Mbps simultaneously between users Multiple Modes; Store, Forward & Relay
In-Space Timing & Navigation	ISS: Limited to GPS range Spacecraft: DSN Ranging	Demosnstration of advanced technology in deep space environment	Provide high-spec Absolute & Relative pos'n Space-Qualified clocks 10x-100x beyond SOA
Low Temperature & Long-Life Batteries	ISS: Lithium-ion (-156 C short duration), ~167 Wh/Kg	Luna night temperatures and duration	
Comprehensive Dust Mitigation	Apollo: limited 3 day crew opsRovers: limited mitigation	Multiple Active & Passive technologies required Significant advances in Life cycle	
Low-Temperature Mechatronics	ISS: +121 to - 157 C	Operations to -230 C (cryo compativle); multi-year life	
ISRU: Mars In-Situ Resources		Potential Test-Bed for Mars Forward, and enhance lunar missions	O_2/CH4 generation from atmosphere LOX/LH$_2$ generation from soil
Fission Power (Surface Missions)		Potential Test-Bed for Mars Forward, and enhance lunar missions	Fission Reactor (10's of kWe)
EVA/Mobility/Robotic			
Deep-Space Suit	ISS: EVA Ops at 0.3 Bar (4.3 Psid)	EVA Ops at 0.55 Bar (~8Psid), extended EVA lifecycle On-Back regen CO_2 &humidity control, High Specific-Energy Batteries	
Surface Suit (Moon & Mars)	Apollo: 3 day max (Lunar)	30 day min duration, improved lower torso mobility, dust tolernat	1 year+duration, thermal insulation (CO_2 atmosphere)
Next Generation Surface Mobility	Spacecraft: Lunar and Mars Rovers State-of-the-Art	Autonomous & Crewed capability, less Ground COntrol Extended range, speed, payload; navigate soft/steep varying soils	
Tele-robotic Control of Robotic Systems with Time Delay	ISS:<1-10 Sec delay for GC OpsSpacecraft: Lunar/Mars Rovers	Few seconds to 10's of seconds Dynamic environments w/variable delay & LOC	Up to 40 Minutes
Robots working side-by-side w/crew	ISS: Limited (Robotic support to EVA)	EVA control robots w/ no reliance on Ground Control International standard & protocols	

Figure 12 - Exploration Programme - Key technology development needs.

5.2 SPACE SAFETY TECHNOLOGY NEEDS

Space is a hazardous environment that threatens human safety and infrastructure, both in space and on the ground. Either in the form of naturally occurring threats, such as space weather or Near-Earth Objects (NEOs), or through manmade threats, such as space debris. The growing importance of space infrastructure puts additional focus on these hazards and the technologies needed to manage them.

While the dependency of society on functioning space assets and infrastructures is growing, the current vulnerability of this infrastructure is becoming an emerging concern. This is creating a significant pull on the technology required for the reliable protection of such assets.



The space safety programme contributes to the Agenda 2025 "to develop new standards through European technological and commercial leadership in the areas of space traffic management, debris mitigation and removal, space weather, planetary defence, space logistics and the goals of the PROTECT Accelerator through activities that protect our planet, humanity and assets in space and on Earth from dangers originating in space, specifically by addressing three segments: space weather, planetary defence and space debris".

The Space Safety Programme has defined high-level strategic goals[16] for Europe by 2030:

- For space weather: an operational space weather monitoring and tested early warning system providing timely, accurate and actionable information enabling prompt responses.
- For planetary defence: an early warning system for asteroids larger than 40 m in size about three weeks in advance, and deflect asteroids smaller than 0.5 km, if known more than ten years in advance.
- For space debris: technologies for sustainable European space traffic including monitoring, risk assessments, and debris avoidance and removal, including a zero-debris approach.

In this respect, the realisation of these long-term aims requires the Space Safety Programme to evolve, with the upcoming programmatic priorities and activities proposed.

16. ESA/PB-SSA(2022)4, rev.1.

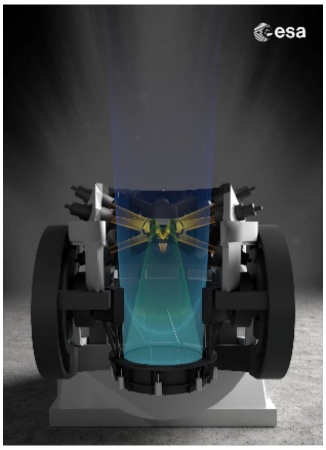


Figure 13 - The Izana Laser Test-Bed on Tenerife (left), the Fly-Eye NEO telescope prototype (right).

The related technology needs can be classified as those needed for:

1. forecasting, detection and analysis of threats and hazards;
2. prevention, protection and mitigation; and
3. response and recovery.

Enabling commercial and competitive products and services is another dimension of the technology strategy, strengthening the position of European industry in the emerging global market for space-safety related activities.

The focus of space weather activities is on protecting Europe's critical infrastructure from threats arising from solar activity, whether in space or on ground, by providing timely and accurate, actionable space weather status information, nowcasts and forecasts. Operational space weather services tailored to European user needs, including an early warning system allowing prompt response and a space weather monitoring system will contribute to a resilient society. In this respect, strategic technology requirements call for physics-based modelling techniques, machine learning technologies for space weather specification and forecasting and new tools for data visualisation for space weather forecasters.

In terms of space weather sensors in particular, an essential focus is on miniaturising instruments and improving radiation tolerance, especially in light of future operational smallsat and nanosatellite missions. Specific instrument developments include medium- and very- high- energy charged particle monitors, wide field of view imagers for UV and visible wavelength monitoring of the auroral oval, compact instruments for solar coronagraphy, magnetography, heliospheric imaging and EUV imaging. Low-cost technologies that enable the quick download of data from LEO missions, such as inter-satellite links, will be required for smallsat and nanosatellite constellations. Networking and coordinated development of space- and ground-based sensor systems will be another important aspect.

The focus of planetary defence activities is to enable Europe with the capabilities of providing early warnings for asteroids larger than 40m about three weeks in advance, to deflect asteroids smaller than 0.5 km if known more than ten years in advance and to be part of a global international effort to remove or mitigate the asteroid threat. To achieve these goals, technology emphasis is put on IR detection technologies in Europe. Telescope arrays and related software techniques to replace or complement monolithic telescopes will be worked out, including specific (curved) detectors. Finally, novel data collection and distribution techniques shall allow for a data hub for collection, processing and dissemination of planetary defence related information.

Overall, a focus on space debris and clean space activities will allow Europe to manage its space-related traffic and to develop autonomous systems capable of removing and avoiding debris. It is vital to develop end-of-life measures for the sustainable use of space and to evaluate environmental impacts of space missions to reduce the impact, including the implications of a zero-debris policy. European space traffic will become fully sustainable implementing space debris mitigation. Related technology goals to support debris neutrality and traffic management start with developing suitable sensor technologies and related data processing, including space-based optical observations (instruments/payloads and in-orbit demonstration). These are followed by data systems for space debris implications and cataloguing. Laser technologies for tracking and momentum transfer need to further strengthen the space debris tracking and mitigation capabilities. Risk modelling related to space debris will have to be based on collecting, processing and disseminating information on space debris, for which a community approach is envisaged. For collision risk estimation and automated mitigation (CREAM), technology needs will call for decision support systems including autonomous approaches, focusing also on data quality and consistency issues with respect to suitable and reliable decision criteria, the use of efficient commanding and coordination of operators.

5.3 APPLICATIONS TECHNOLOGY NEEDS

5.3.1 Telecom

ESA's first telecom satellite, OTS, was launched more than 40 years ago. It had a mass of 865kg, 600Watts of power and carried six Ku band transponders. The on-going deployment of constellations of low Earth orbit satellites, including OneWeb and SpaceX with more than 1200 commercial telecoms satellites launched (about 70 per cent of all satellites launched in 2021, with 43 out of 135 successful launches dedicated to putting telecom satellites into orbit) confirm telecom as the key customer of the commercial launch market.

The global satellite industry revenue has flattened as revenue growth in ground equipment has matched the fall in satellite TV revenue. Electronically steered flat panel antennas are considered a major enabler for future satcom systems, including for constellations of LEO satellites, since such antennas promise to substantially simplify and thus increase the use of ground terminals, especially for the fast-growing markets of connected cars, trucks, trains and planes. Satcom market needs and drivers follow the rapidly evolving consumer demands and habits, including an increasing demand for versatility, ubiquity and accessibility, for mobile connectivity, reduction of cost per bit, reduction of time to market, the provision of higher data rate broadband, low latency solutions and secure communication services.

Satcom services are a part of the much wider, mainly terrestrial, communications marketplace. Digital transformation and the green economy (incl. artificial intelligence, machine learning, cloud and virtualisation, digital twins, sustainable mobility), as well as 5G/6G and secure communications, significantly influence the positioning and the evolution of satcom services. Other influencers of the satcom market include the Internet of Things (IoT), machine-to-machine communication, industry 4.0, the evolving launcher landscape and initiatives and methodologies by new space companies. While recognising uncertainty in the evolving telecom market landscape, it is clear that flexible satellites, very low Earth orbit satellites, mass produced constellation satellites, low cost, global satcom mobile broadband services, satcom integration with 5G/6G, digital satcom ecosystems, will all be potential game changers that can open up of new markets. There is a growing demand also for federated infrastructure and sovereign and secure infrastructure within ESA member states, which requires advanced secure satcom systems and product solutions.

Technologies answering to the emerging opportunities and trends include millimetre wavelength communication (Q/V, W-band), digital processing (onboard transparent and regenerative processors, software defined radio, cloudification, miniaturisation), optical inter-satellite and feeder link communication and photonic components, smart antennas (e.g., low-profile self-scanning antenna) and disruptive platform sub-systems. In addition, there is a need for smart design and manufacturing (e.g., digital twins, augmented reality and AI supported design, automation in manufacturing and advanced manufacturing processes) and the sustainable use of space (e.g., technology for demisable satellites, debris avoidance, autonomous operation and reliable de-orbiting), especially regarding very large constellations.

The fast-changing market situation and growing initiatives by start-ups is putting considerable pressure on all satcom industries to innovate and develop game changing technologies to compete with terrestrial services.

Six pillars have been identified as the main technology needs for satcom for the near future and are further expanded in the table below.

Table 1 - Telecom technology needs

<table>
<tr><th>Area of application</th><th>mm Wavelength Communication</th><th>Digital Processing</th><th>Optical Communication</th><th>Smart Antenna</th><th>Disruptive Platform Subsystems</th><th>Smart Design, Manufacturing, Assembly and Testing</th></tr>
<tr><td>GEO flexible Ultra High Throughput satellite beyond terabit/s</td><td>Q/V, W-band devices, equipment, systems and techniques for ISL[17], feeder and user links[18]</td><td rowspan="6">High performance, low power digital signal processors (e.g., reconfigurable, hybrid transparent/ regenerative digital processors).
Integrated ground & space resource management.
Smart gateway and networking.
Beam forming, beam hopping.
System on Chips.
Software defined payloads/ networks and virtualisation.
5G/6G edge computing and IAB[19].</td><td rowspan="2">Techniques, components and equipment for ISL feeder and user links and signal processing (e.g., routing, multiplexing, frequency conversion).
HydRON network of optical ground stations</td><td rowspan="7">Low profile and electrical, optical steerable (stowable & deployable) multibeam, multiband antenna for Ground and Space Segment.
Large reflectors.</td><td rowspan="7">Flexible solar arrays
Deployable radiators
Compact, high capacity thermal management systems
Regenerative fuel cell systems
Solid state batteries
Multifunctional and inflatable structures
Efficient high voltage power supply units
Lightweight, multifunction harnesses
VLEO[20] platform (e.g., ramjet propulsion)

<u>Constellations:</u>
Uncoordinated CDMA[21] TT&C
AOCS[22] enabling autonomous flying and manoeuvring
Stackable spacecraft</td><td rowspan="7">Function tailored materials.
Machine learning supported development.
Use of COTS components.
Embedded sensors.
Virtual factory.</td></tr>
<tr><td>(V)LEO and MEO satellites and constellations offering IoT, broadband and FSS[23] services</td><td>Highly integrated, low power devices, equipment, systems and techniques for ISL feeder and user links</td></tr>
<tr><td>All IP, OTT[24] convergence and ultra HDTV broadcast</td><td>Ultra-wide band receivers, feeder links</td><td rowspan="2">Techniques and equipment for ISL pre-distortion and laser guide stars for feeder and user links.</td></tr>
<tr><td>Automated and connected multimodal mobility services</td><td>Q/V, W-band devices, equipment, systems and techniques</td></tr>
<tr><td>Ground as a service and cloudification</td><td>Air interfaces and handover techniques</td><td>Optical signal processing techniques</td></tr>
<tr><td>Satcom integration into 5G/6G, M2M[25] and IoT systems</td><td>eNodeB in the sky.
Very low power devices.
5G/6G hybrid terrestrial and satellite chipsets, modems etc</td><td>Integration of optical networks and 5G/6G systems (including backhauling, trunking)</td></tr>
<tr><td>Satcom systems for safety and security</td><td>Secure terminals, gateways, TT&C[26] and cloud solutions</td><td>Secure processor Efficient en/ decryption techniques
Secure operation and authentication</td><td>Quantum communication & quantum key distribution</td></tr>
<tr><td>Green, digital satcom ecosystem and satcom in-orbit servicing</td><td>Sustainable ground segment</td><td colspan="2">Power efficient signal processing</td><td>Antenna connecting to smart cities</td><td>Alternative propellants and propulsion systems
Demisable space assets
In-orbit serviceable platform</td><td>Lead free assemblies
Additive manufacturing
Augmented reality
Digital twin</td></tr>
<tr><td>Commoditisation, automation and miniaturisation</td><td colspan="6">Series production, low cost and short time to market making use of Artificial Intelligence where possible</td></tr>
</table>

17. Inter Satellite Link.
18. including aeronautical assets.
19. Integrated Access and Backhaul.
20. Very Low Earth Orbit (≈200km).
21. Code-Division Multiple Access.
22. Attitude & Orbit Control System.
23. Fixed Satellite Services.
24. Over-The-Top media services.
25. Machine to Machine.
26. Telemetry, Tracking and Command.

5.3.2 Earth Observation

ESA develops world-class Earth observation (EO) systems to address the scientific challenges identified in the Living Planet Programme (SP-1304) and other societal challenges, particularly with European (e.g., EU, EUMETSAT) and global partners. The key Living Planet Programme principle is that all missions, while relying on wide-ranging innovations, are user driven. These systems are centred on two broad activity lines:

- Research missions, of which the Earth Explorers (EE) are the main part. They are research driven and demonstrate new EO techniques. EEs are complemented with the new and much more budget-constrained Scout missions.
- Earth Watch (EW) missions, developed with and for partners, are typically driven by operational services, such as those in partnership with EUMETSAT for meteorology and with the EU for the Copernicus programme. EW also includes projects (e.g., Altius) and other activities driven by Member States or under the InCubed programme, the latter having the objective to support and develop commercial sectors based on EO products and services.

Overall, the two main technology thrusts for future EO missions are

- Higher performance (including spatial and temporal resolutions, accuracy), higher lifetime, and increased flexibility, especially for the institutional and scientific segment, also facilitating long-term continuity of data, and
- Miniaturisation, constellations (including convoys and formations), lower cost, fast-to-market ability, adaptability, and flexibility in particular for commercial EO.

EO technology needs are to be understood from an end-to-end system view, often in combination with external data sources (e.g., in-situ measurements for cross-calibration, or HAPS for very high resolution). The most demanding technological requirements from innovative and higher performance instruments need to be complemented by higher levels of standardisation and modularity at platform and associated ground segment to reduce recurring costs (Table 2).

Table 2 - Earth Observation technological drivers and challenges

Class	Driver	Instruments	System	Constellation enablers	Technology funding
EE-10, EE-11, Scout type	Science	Innovation (Optical/RF/ Digital)	Possible multi-sensor in multi-sat	For Scouts: Miniaturisation, Autonomy	DPTD + FutureEO + GSTP
Copernicus & Meteo Evolution	User Services	Improve performance & Data continuity	System of Systems (architecture, formation, Big Data)	Common Platform/GS (e.g., high-speed technology, autonomy) Constellation management	Copernicus + FutureEO + DPTD + GSTP
Commercial	Product/ Service Cost	Miniaturisation + OB processing	- CheapSats - Interaction with institutional	AI (Deep Learning) Autonomy	InCubed + GSTP +FutureEO + DPTD

Earth Explorers

Earth Explorer missions are part of the FutureEO Programme, which supports three types of user-driven research missions:

- EE core missions (e.g., EarthCARE, Biomass, EE-10, EE-11) are major missions that cover primary scientific objectives of the ESA Earth Science strategy using innovative EO techniques and undergo a first assessment step at Phase 0, prior to Phase A. These are identified from proposals received in response to a call for ideas. EE-10 (HARMONY) is in Phase A and the recent EE-11 call resulted in the selection in Q2-2021 of four mission concepts (STREAM, CAIRT, WIVERN and NITROSAT) for phase 0 studies.

- EE fast-track missions (e.g., FLEX as EE-8, FORUM as EE-9, both already in implementation phase) also follow a call for mission concepts process. They are smaller missions and with shorter development cycles (starting at Phase A) than core missions due to their higher initial technical and scientific maturity level (TRL/SRL typically 4) and have the objective to respond rapidly to evolving requirements.
- Missions of opportunity are responses to unsolicited proposals for cooperation with entities that are not under the jurisdiction of Participating States of FutureEO. Currently, only one such mission is in Phase A in collaboration with NASA: The Next-Generation Gravity Mission (NGGM) as part of the MAss change and Geoscience International Constellation (MAGIC) for sub-surface water and solid Earth dynamics. Further into the future for gravity measurements, cold-atom interferometric sensors (CAI) appear very promising.

Scouts

Scout missions are complementary to the EEs. They are characterised by an agile low-cost development process to prove new EO concepts and to add timely scientific value to current data through supplementary observations. A Scout mission consists of one or several small satellites for rapid prototyping and demonstration purposes of novel EO techniques in Earth science and related non-commercial applications. Small satellites (possibly in constellation) can be applied to demonstrate disruptive sensing techniques or incremental science, while retaining the potential to be subsequently scaled up in larger missions or implemented in future ESA EO programmes. Two scout missions (CubeMAP and HydroGNSS) are entering into implementation aiming to launch in 2024. Two more (NanoMagSat and TANGO) were also part of the early studies and risk retirement activities have been initiated for both.

Copernicus Evolution (Sentinel-NG , Next Generation)

In collaboration with the EU and driven by its high-level requirements, the Copernicus Space Component (CSC) evolution is expected to include, over a proper period of time, the following enhanced sensing capabilities:

- Microwave imaging over both land and (liquid, solid) water surfaces, based on a first specific mission family comprising highly complementary active and passive microwave sensors. These require the development of the following technologies:
    - C-band & L-band high-resolution wide-swath SAR; and
    - Bi-static or multi-static passive SAR on small platforms.
- Optical imaging over both land and water surfaces, with a second specific mission family of passive sensors covering virtually all spectral ranges. These require the development of the following elements:
    - super-spectral mission in VNIR & SWIR, + TIR imaging (Oceans);
    - hyper-spectral mission in the VNIR and SWIR (Land);
    - very high spatial resolution VNIR and SAR imagery (via data/service buy);
    - high spatio-temporal resolution thermal infrared (TIR); and
    - high-revisit observations from geosynchronous orbit.
- Highly accurate topographic measurement capabilities over water surfaces, including also ice and snow (i.e., water in solid state). These require the development of the following elements:
    - interferometric dual-band (Ku+Ka) SAR altimetry; and
    - constellation of miniaturised Ku- or Ka-band altimetry sensors.

- Spectroscopic imaging observations of the Earth's atmosphere. These require the development of the following elements:
  - o high-resolution imaging spectroscopy in NIR and SWIR.

A number of technologies (e.g., IR detectors, large scale antenna reflectors, digital beamforming) can be applied to more than one mission, thus generic developments are needed with improved modelling, better testing and characterisation techniques. Other technologies have a larger dependency on the frequencies under consideration and might be specific to one mission.

Meteorological missions

After the impact assessment of the Aeolus (EE-5) data by ECMWF, EUMETSAT recommended to initiate technical developments for a potential Aeolus-FO mission. The identified technology development needs are in the areas of lidar transmitters, receivers and end-to-end system.

Non-instrument specific needs for future EO missions

The EO needs are at end-to-end system level and therefore a technology evolution of EO platforms is required. With increasing maturity and operational integration into wider services, cost will play an increasing role. One option is to further exploit the commonalities between missions, with a limited set of variants envisaged to cover specific variations or configurations such as for optical or radar missions. There are major questions, challenges and hurdles that need to be addressed:

- Maximising the use of recurrent generic and standardised equipment;
- Reusability of the core avionics for any platform, independent from the system integrator;
- Standardisation of the space-to-ground interfaces;
- Increase of functionality and performance (e.g., speed, accuracy, stability, constellation synchronisation, reliability/lifetime, on-board re-programmability and flexibility);
- Reduction of development time, risk and mass/power/volume budgets of the platform; and
- Application of debris mitigation techniques, including standard design and techniques for deorbiting of satellites at the end of their mission.

These require the development of strategic platform technologies with:

- Higher data throughputs, both on-board with very high-speed serial links and routers configuring scalable networks, as well as space to/from ground interfaces in X-band for tele-commanding and K-band for sensor data with rates well above 1 Gb/s, complemented in some cases by inter-satellite links using RF and optical technologies.
- Constellation enabling technologies to allow better synchronisation, relative navigation between satellites and new metrology systems to determine highly accurate baselines between antennas, higher robustness, higher satellite autonomy, as well as higher attitude stabilisation and efficient electrical propulsion.

An improvement of the ground segment technologies is also required in the end-to-end approach, and in particular regarding:

- Deep automation for cost-reduction;
- Standardisation of space-to-ground interfaces, with higher data throughput and very good availability;
- Efficient constellation management and operational flexibility, enabling the optimisation of ground technical and financial resources for the operation of convoys, formations and constellations; and
- Advanced processing technologies on-ground (e.g., based on artificial intelligence including deep learning), especially for applications requiring big data analytics and multi-sensor data analysis.

Commercial EO

The institutional EO sector has focused on state-of-the-art EO instruments delivering very high quality calibrated data. This approach needs to continue, complemented by international EO collaborations and commercial initiatives, typically based on multiple dedicated small satellites (e.g., Cubesats or small satellites with multiple payload launches and a potential data-buy approach later on). The InCubed (Investing in Industrial Innovation) programme supports these types of developments and missions.

Φ-sat(s)

Φ-sat(s) are part of FutureEO as they can be used for fast in-orbit demonstration (IOD) of new EO techniques, enabled by potentially game changing technologies such as AI. The Φ-sat-1 experiment, part of the FFSCat mission, demonstrated accurate on-board cloud detection. The Φ-sat-2 mission, with a budget 10 times lower than a scout mission, is planned for launch in 2023 with several AI experiments on-board.

5.3.3 Navigation

Satellite navigation focuses on the mechanisms to determine position and time of a given user and its course from one place to another, using satellites. Position, navigation and timing (PNT) is a combination of three constituent capabilities:

- Positioning, the ability to determine locations and orientations accurately and precisely over two or three dimensions, whether continuous or duty-cycled (e.g., to reduce energy per fix),
- Navigation, the ability to determine current /desired position and trajectory and,
- Timing, the ability to acquire and maintain accurate and precise time from a standard timescale (e.g., Coordinated Universal Time).

The field covers several categories and verticals, such as land navigation (e.g., road, rail, agriculture), maritime navigation, aeronautic navigation, and space navigation (e.g., near Earth orbit, with GNSS on-board receivers, or Deep Space). The applications served by space-based PNT systems have become extremely diverse and about 10% of the world economic activity depends currently on such systems. It is therefore important for Global Navigation Satellite Systems (GNSS) and other space-based PNT systems to enable robust and trusted solutions, implementing integrity, authentication and resilience mechanisms, globally and in a wide range of environments.

Europe contributes actively to this fertile landscape with cutting edge technologies and expertise, and two operational space-based PNT systems: Galileo, which delivers first-in-class performances globally, and Egnos, which supports civil aviation users of Europe with integrity data and enables approach procedures at hundreds of airports and helipads.

The Galileo constellation is already the world's most precise satellite navigation system. It's Second Generation, with state-of-the-art satellites, will represent a major step forward and will incorporate numerous technology upgrades, developed through EU and ESA research and development programmes. Employing electric propulsion, and hosting an enhanced navigation antenna, their fully digital payloads are being designed to be easily reconfigured in orbit, enabling them to actively respond to the evolving needs of users with novel signals and services.

In parallel, Egnos NEXT aims to extend Egnos capabilities beyond DFMC for aeronautical users, and to introduce new capabilities for non-aeronautical safety-critical applications.

Trends by 2030

The success of space-based PNT solutions, combined with the growth of autonomous systems and global mobility, inspire more demanding needs and applications. By 2030, it is expected that PNT solutions will provide ubiquitous, reliable, secure and resilient, decimetre-level accurate positioning and ns-level timing (PNT-2030), calling for new technologies and concepts to be introduced in complement of existing and evolving ones.

Solutions enabled by GNSS are more and more assisted, complemented, augmented and/or hybridised with additional technologies. A system-of-systems PNT has therefore arisen over the years, recently devised into a multilayer PNT architecture, combining space systems in various orbits (e.g., GEO/IGSO/MEO/LEO), terrestrial systems (e.g., wide area or local hot spots such as 5G, WLAN) and Deep Space PNT technologies.

The R&D programmes implemented in the ESA Navigation Directorate, the EU funding part (H2020, Horizon Europe) and the Navisp ESA programmes, address short and mid-term needs for the evolutions of European PNT technologies:

- Under a delegation by the European Commission, ESA has undertaken the technical and management implementation of both the Horizon 2020 and the Horizon Europe Framework Programmes for Research and Innovation in Upstream Satellite Navigation domain (e.g., technologies, future system concepts and exploratory concepts for Galileo, Egnos and Multi-layer space-based PNT).
- Navisp supports short-term needs with the development of novel technologies and the competitiveness of European PNT industry, along the national strategic objectives of Participating States.

For the longer term, they are complemented with R&D aiming to incubate technologies with low TRL, high technological risks but with expected high impact, that will provide the technological nucleus for future concepts and developments in the Navigation programmes. These technology R&D needs can be broken down into PNT technologies with very low TRL and/or long term application perspectives for making best use of existing PNT systems (e.g., GNSS, 5G), and low TRL PNT technologies to enable future space-based PNT infrastructures, systems and concepts.

<u>Best use of existing PNT systems with game changing technologies</u>

Low TRL PNT technologies aiming to make best use of existing PNT systems contemplate existing PNT systems, in a system-of system architecture involving GNSS, cellular systems (among which 5G with both terrestrial and satellite components), and dead-reckoning sensors. The focus is on game-changing technologies, which would enable more demanding, safety-critical use cases in challenging environments (including space) with high-accuracy and reliability, more resilience and security (e.g., GNSS and non-GNSS such as 5G, signals from LEO), privacy of navigation-related data as well as on very low energy per fix.

<u>Systems concepts: preparation of future space-based PNT infrastructures and systems</u>

In this context, the mid-term focus (ca. 2030) for preparing future space-based PNT systems is on technologies for Lunar PNT and Planetary / Deep-space navigation, as well as for supporting geodesy, science and metrology for PNT.

For the long term (beyond 2030), the focus is on new technologies and/or paradigms that may

- provide optimised solutions for space and ground segments of future European space-based PNT infrastructures, systems and concepts (institutional and commercial): sustainability and competitiveness of European space-based PNT infrastructures in a multi-layer architecture involving several orbits (e.g., LEO/MEO/IGSO/GEO, 5G/6G positioning technologies from satellite networks), cost-effective and timely deployment of technologies and systems, and compliance to standards such as 3GPP, RTCM; and
- enable disruptive solutions in the space-based PNT landscape well beyond 2030 (e.g., non-conventional navigation concepts and associated technologies, navigation with pulsars, optical and quantum technologies, exploitation of artificial intelligence for PNT).

5.4 ENABLING AND SUPPORT TECHNOLOGY NEEDS

5.4.1 Space Transportation

European space transportation, at present based on Ariane 5 and Vega launch systems, guarantees access to space from Europe's spaceport. With the imminent launches of Ariane 6 and Vega C, the focus is on the stabilisation of their ramp-up and start of their exploitation.

Meanwhile, the space transportation sector worldwide is undergoing a transition towards more routine space transportation, with the increasing prominence of commercial activities and a growing diversification of the use of space. The uncertainty in the evolution of the launch services market is therefore greater than ever.

This overall external context poses challenges to all actors in the space transportation sector, both traditional and new entrants. Worldwide, the current trends are all aiming at improving competitiveness in terms of pricing for the commercial market, with agility and flexibility to adapt to an evolving demand for additional launch and space transportation services. It is crucial in this context that Europe is not left behind in seizing those opportunities in terms of services, economic growth and innovation.

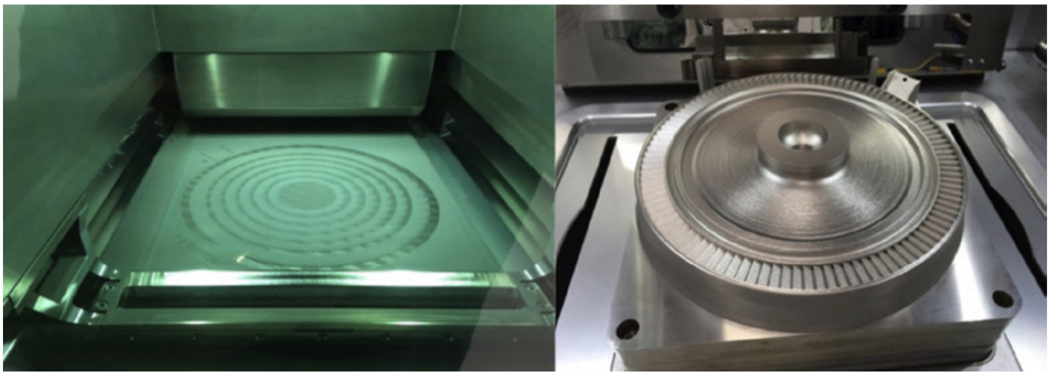


Figure 14 - ESA's Prometheus is the precursor of ultra-low-cost rocket propulsion that is flexible enough to fit a fleet of new launch vehicles for any mission and could be reusable. The mono-shaft turbo pump, built via additive layer-by-layer manufacturing (ALM) methods, is a key technology. It enables a radical simplification of the engine layout and slashes costs.

The consolidation of currently identified space transportation means, including Ariane 6 and Vega C, needs to be coupled with shaping and securing the future of evolving European space transportation solutions through:

- Accelerating the availability of a portfolio of space transportation services in Europe for accessing to, transporting in and returning from space;
- Positioning ESA's role in de-risking industry on both building blocks in development but equally in operations;
- Developing a concept for LEO logistics and beyond for European human exploration addressing related space transportation capabilities;
- Continued support to private economic operators in bringing new European commercial space transportation services into operations, equally supporting further evolutions and possibly acting as anchor customer of flight proven launch services for IOD/IOV missions up to 200 kg through competitive selection; and
- Definition of a concept for European ground infrastructure (spaceports, test centres) that serves public requirements and promotes private utilisation.

A rapid preparation of a new model is considered fundamental to paving the way in making any future European launch services sustainable, while still serving institutional needs. The following key improvements have been identified as necessary to recover competitiveness:

- Enlargement of the economies of scale (modularity, common elements re-use, higher production cadence);
- Optimisation of the industrial organisation selected on a competitive basis whenever possible (agile approach, digitalisation, model-based system engineering, automated production tests); and
- Increased value chain with mission extension modules (kick stages, in-orbit servicing modules, rideshares, experimentation and return to Earth).

ESA's space transportation technology strategy focuses on enabling technologies for increasing the competitiveness of future environmentally sustainable space transportation services, through cost reduction and value chain extension. The strategy for the new European model for space transportation relies on the following domains:

Launch System Reusability

Reusability is a major technological rupture for European launch systems. It requires the maturation of many enabling technologies (e.g., landing systems, precision landing, thermal protection, cost efficient maintenance and health monitoring) through ground or in-flight demonstration.

Launch Systems Increased Competitiveness through Modularity

The economic sustainability of future European space transportation services needs to be supported by modularity and commonality, as a key enabler to achieving crucial cost savings. Thanks to higher production rates and economy of scale, non-recurring costs can be optimised by investing in technology developments for multiple applications, while recurring costs can be saved through lower production per-unit costs.

Propulsion is a significant part of the overall cost of the launcher. New manufacturing techniques and processes (ALM, factory 4.0), extended performance domains through advanced engine control and monitoring, associated to reusability capability, will contribute to major cost reductions, through evolving current engines or defining new ones (Sections 2.3, 2.4 and 2.9).

Low-mass launch vehicles need leaner launcher designs, with a low structural index and yet high performance. These are key to achieving significant cost reductions at launch system level, with fewer components or even fewer stages (targeting two stages to orbit), using innovative vehicle architecture (e.g., smart pressurisation systems) or lightweight structures.

Smarter avionics with commonality across European launchers are enablers for lower launch costs and future reusable space transportation at vehicle level (e.g., COTS spin-in, harness with reduced complexity, smart sensor networks allowing for simpler system diagnosis), and at launch system level (e.g., next generation autonomous architecture, in-flight reconfiguration, recovery of safety violations).

Another objective is to reduce the costs associated with dedicated and expensive ground systems in spaceports, for operations (e.g., use of AI, remote controls, digitalisation of operations) and using space infrastructure assisted solutions (e.g., GNSS-based hybrid navigation and data relay services during launch).

Greener Launch Systems

European space transportation systems aim to achieve environmentally sustainable launch services. Enabling technologies are targeted to reduce the environmental impact of spaceports (greener production of propellant or energy) or future launchers (green propulsion), and to build new standards to include, from the very early stages of every development, life cycle analysis, to achieve carbon neutral space transportation (Section 2.5).

Value Chain Extension Beyond Launch Systems

Increasing the accessible market for European space transportation beyond launch services is a major focus to improve its competitiveness, while ensuring the robustness of the business model through flexibility and resilience to market evolutions.

Extend the range of launch services: This extension targets the technologies to efficiently launch a wide range of spacecraft, from micro to heavy, injected with the greatest precision and performance on multiple orbits, using for instance smart multiple payload adapters standardised missionisation.

Extend access to new markets in space transportation: With a growing diversification in how relevant actors use space, new space transportation markets are identified, for in-orbit services (e.g., in-orbit testing or manufacturing, spacecraft refuelling or decommissioning) or exploration needs, which require new technology and space transportation solutions (e.g., upper stage extended mission capabilities, kick-stages, space-tugs, re-entry modules).

Preparing for Future Human Space Transportation Systems

Preparing for future human space transportation is a significant step for Europe, requiring the maturation of technologies dedicated to human rated space transportation systems (e.g., launch abort strategies, re-entry, flight software with off-nominal manual modes, crew module propulsion).

5.4.2 Operations

With rapid commercialisation and the high demands of new missions (constellations, exploration, space safety), innovation in operating spacecraft and ground segment design is needed to enable flexible, efficient and high-performing operations concepts and, in particular, to further position Europe as a strong competitor on the world market.

The key strategic drivers in this area are to improve the commercial competitiveness of European operators. This includes harnessing new models of cooperation and partnerships, to focus strategic European ground operations assets on these evolving needs, especially the institutional tasks and to develop the ground segments and operations concepts and technologies needed for future human and robotic exploration missions, making use of novel technologies.

The resulting key technology needs for ground segments and operations are:

- Technologies and concepts to enable European industry to offer competitive operations services and products on the global market. This includes essential ground segment elements such as the EGS-CC, combined with a multi-mission concept, allowing for a faster time-to-market and reduced duplication while realising more complex missions and systems. Increased automation is a key enabler for efficiency, with the introduction of artificial intelligence, data analytics, and augmented/virtual reality providing opportunities to transform operation concepts.
- The rapid introduction of these technologies requires quick, efficient and recurring in-orbit demonstration as an essential element.
- Technologies that enhance today's cybersecurity capabilities in the operations domain, to stay ahead of future challenges, safeguard European assets, and ensure European independent access to space.
- Technologies for innovative concepts for ground segments and operations that allow access, utilisation and 'productisation' for all sorts of users similar to today's transparent internet access and services, such as through concepts like "ground segment as a service", or "network-centric" ground segments. These will be essential for the new models of cooperation and business to accommodate space ventures and actors in the rapidly evolving space environment, including private companies and ventures, public entities, NSAs, research organisations, but also, new business, start-ups and communities.
- Technologies for innovative ground stations, radar and laser-optical systems and data infrastructures are needed to evolve European ground assets for future space missions and services and specifically to fulfil institutional tasks. In particular, these include addressing issues of space safety, space debris, space weather, as well as operation concepts and technologies necessary to prepare Europe to contribute to future human and robotic exploration missions at international level such as distributed and shared operation schemes with international, national and private partners, hybrid human/robotic mission operations, deep space communications with innovative technologies (e.g., laser optics).

5.4.3 Space-based solar power

Space-based solar power, the concept of capturing solar energy in space and transmitting it wirelessly, could power exploration activities at the Moon and Mars at the small scale (kW-level), and, in the long term, at the very large scale (GW-level), potentially provide clean energy to terrestrial users.

The scale of its application for terrestrial energy needs in particular demands substantial advancements in a wide range of technological areas that might also be relevant for other space applications. Key technology development needs include the areas of:

- High mass-efficiency, low-cost solar to electric conversion technologies;
- High-efficiency radiofrequency generation and accurate beam forming technologies;
- High power management and distribution technologies;
- Technologies enabling the deployment and robotic assembly of very large structures, in-space manufacturing; and

- Technologies for very large, sufficiently rigid and light-weight structures integrating power generation, power conversion, RF generation, integrated antennas, their thermal management, attitude control (sensors, controllers, actuators) and in orbit maintenance, addressing clean space, debris, and security aspects.

5.5 EUROPEAN SPACE INDUSTRY TECHNOLOGY NEEDS

Eurospace, the main European space industry trade association, regularly produces research and development priorities on behalf of their members. These raise awareness on the key needs and expectations of the European space industry. *Eurospace* notes that the European space industry is competitive, despite less access to large governmental programmes than its U.S. and Chinese counterparts and valid concerns about the growing capacity gap and technology breakthroughs created by this imbalance. New business models are also shifting focus from state of the art, high performance systems to volume, series production and scalability, despite high risk, high reward schemes where the U.S. and Chinese competition are developing fast. In this context, *Eurospace* considers support to industry competitiveness and market access a core driver for technology policies for Europe sovereignty and economic growth.

The latest set of industry coordinated recommendations for key development actions was elaborated during the Space Technologies for Europe pilot project. The document puts a direct focus on developments supported by market opportunities and a wide range of generic technologies (such as power, propulsion, data handling) but does not cover critical developments or programmes driven by institutions (e.g., human space flights, Science, GNSS, Copernicus). The most significant proposals, applicable to the ESA technology strategy, are highlighted here, with the caveat that any strategy should also anticipate new, disruptive and enabling solutions.

For Earth observation, priority should be given to operational systems (also with the involvement of the EU and Eumetsat) and scientific developments. Main developments are driven by standard needs to improve satellite lifetimes, high reliability and robustness, while reducing cost. Technology developments should focus on new functionalities (e.g., night vision, infra red, hyperspectral, video), high speed and on board smart processing (including artificial intelligence) and increased autonomy (AI/ML, Cloud) on board and on ground.

For Telecommunication applications, smart and cost-effective satellite data management and processing solutions are needed for very large constellations with intersatellite links as well as solutions to protect these systems from increasingly sophisticated cyber-attacks. Technology developments should focus on antenna performance with increased number of beams, regenerative processing supporting UHTS supported by enabling technologies such as photonics and PICs and optical communication, data management from very low bandwidth to high data rates applications, end-user terminal affordability, performance, and mobility; seamless network integration; cyber-security and quantum communication (QCI/QKD) capability.

For ground operations, small satellites with shorter mission lifetimes and mega-constellations are putting new emphasis on cost management, despite an increased risk of space collisions and space debris. Requirements include data fusion, image intelligence with infrastructure security and an increasing demand on the SatCom market (with applications like autonomous vehicles, offshore communications, 5G networks).

On-orbit operation is seen as a game changer for space systems to globally reduce launch mass and life-cycle costs. Robotics, manipulation and vision/ranging technologies are key enablers (with interfaces as needed) for future life extension and active debris removal missions. Europe must also promote space sustainability (prevention/mitigation and remediation) and debris de-orbiting. Anticipating a trend for a more stringent international regulations, the readiness of these technologies will place the European industry in a prominent position.

For Exploration, key areas for development should consider rover mobility on the Moon (and Mars) ascent/descent stages or other systems like aerial vehicles and related autonomy, ISRU capabilities supporting critical mission functions (power, propellant, habitats and life support), energy solutions (radioisotope energy and power systems, fuels cells) and critical long distance high throughput data links and data relay solutions. Exploration involving humans will create further enhanced demands on technology like closed loop life support systems, radiation protection and regarding human health.

For navigation/GNSS, key drivers are to improve accuracy and service availability worldwide. Key areas for action should include clocks and signal generation and improving ground and space synergies (including robustness, anti-jamming/spoofing).

For science, the focus should be on state-of-the-art payloads including large telescopes, improved detection chains, infra-red/far infra-red, mm-wave technologies, low temperature/cryogenic temperature operations, radiation environment & very accurate time measurement. Structures for large & distributed instruments, wide field of view, large/deployable/ultra-stable structures and data handling for long distance communications, high data rate/high throughput, Ka/Ku/optical solutions are also priorities.

For digitalisation, digital twins will enable the full digital conception from manufacturing to advanced testing and automated inspection and control (and built-in testing), and fully secure data systems. An advanced statistical process control, and a connected advanced product quality planning will ensure customer satisfaction with new products or processes. Predictive maintenance will prevent asset failure by analysing production data to identify patterns and anticipate production stop.

For EEE components, power components need to fill a significant gap with respect to the current worldwide state-of-the-art. On the payload side, RF critical technologies (active and passive) need clear increases in performance, valid for active antenna (Radar, Telecom, Navigation). Photonics and PICS, even if at a rather low TRL today should be given more importance as they will enable many innovative and performant solutions in various type of payloads for applications in EO and satcoms.

Regarding avionics, implementing modularity is the key to re-use solutions for various type of missions. Increased integration of avionics design and development in the global digitalisation of and hardware/software codesign and optimisation (modelling, digital twins) through full system life cycle. Enabling functions such as MEMS/FPGAs and digitally driven modules for greater performance and miniaturisation, and on models and design/development tools for efficient HW/SW co-design (AI/ML based) to achieve an automated or tooled validation process.

For power subsystems, new exploration solutions like low-light intensity solar cells with higher power density (thin and flexible cells and radio isotopic power sources) may be needed as critical enablers for higher power missions.

Both electric and chemical propulsion systems are critical. As new manufacturing technologies and materials have to be implemented, the design has to be suited for production in large batches and in automated production lines.

For the protection of space assets, satellite robustness should be increased with the development of awareness and mitigation solutions. In particular, RF protection used against jamming needs to be available at lower cost. In addition, “in space” surveillance, tracking operations would be the next phase of securing space infrastructure, for which the development of specific technologies would be necessary in the wake of ESA’s Protect initiative. Security should be embedded in new software and ground sites, especially cloud-based ground systems.

Access to space: It is seen as mandatory for Europe to promptly start to test fundamental building blocks and technologies as well as to validate integrated flight demonstrators at a relevant scale including reusability and technologies for returning payloads as well as dedicated launch solutions for nano and micro satellites. Assuming end-to-end services, cost reduction for more competitive launcher operation and the enabling of new services are necessary for the European launcher ground infrastructure, e.g., through digitalisation or advanced data management.

6 TECHNOLOGY INNOVATION

CD1
EEE COMPONENTS, PHOTONICS, MEMS

CD2
STRUCTURES, MECHANISMS, MATERIALS, THERMAL

CD3
AVIONIC SYSTEMS

CD4
ELECTRIC ARCHITECTURE, POWER & ENERGY, EMC

CD5
RADIOFREQUENCY & OPTICAL SYSTEMS AND PRODUCTS

CD6
LIFE & PHYSICAL SCIENCE PAYLOADS, LIFE SUPPORT, ROBOTICS & AUTOMATION

CD7
PROPULSION, SPACE TRANSPORTATION & REENTRY VEHICLES

CD8
GROUND SYSTEMS & MISSION OPERATIONS

CD9
DIGITAL ENGINEERING

CD10
ASTRODYNAMICS, SPACE DEBRIS & SPACE ENVIRONMENT

6.1 ELECTRIC, ELECTRONIC, (MICRO-) ELECTRO-MECHANICAL AND PHOTONIC SYSTEMS

CD1

Most developments of electrical, electronic, electro-mechanical (EEE) and photonic components for space are adapting terrestrial applications by addressing space-related constraints (e.g., high reliability requirements or radiation hardness), addressing programme needs, national and industrial strategies, mainly targeting performance improvements, cost reduction and enabling new applications.

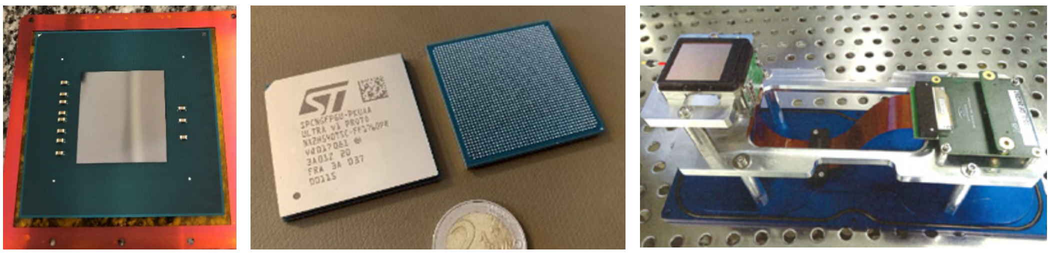


Figure 15 - NG-ULTRA FPGA - Large format Infrared Detector.

ESA follows a three-axis approach to provide innovative, cost effective and time-to-market solutions for EEE components, photonics devices and micro-electro mechanical systems (MEMS) strongly drawing from programme needs:

1. **Exploring game changing** technologies leaning on innovative ideas of European industrial and academic partners for Ultra Deep Submicron (UDSM) technologies, wide band gap devices for power distribution & RF system applications, enhanced and curved detectors, heterogeneous integration chiplets, system-in-package, photonic integrated circuits, supercapacitors graphene based and others.

2. **Enhancing performance** by exploiting mature technologies expanding their capabilities in line with programme strategies. ESA will strengthen these efforts by a more systematic continuous survey of terrestrial market for EEE Component technologies potentially suitable for space applications (e.g., press fit and solderless interconnections).
3. **Exploiting and enabling** the uptake by capitalising on established technologies supporting unrestricted access of European EEE Components for ESA missions. This is facilitated by a sustainable enlargement of the European EEE Component portfolio (all EEE Component families) aiming at high return of investment with time-to-market targets maximize their in-orbit utilization (e.g., European Power MOSFETS, FPGAs, Processors, Photonics, Passives).

These activities are supported by the development of a sovereign European supply chain, including specifically via a new EEE European Sovereignty initiative.

Harmonised at the European level, the strategic plan for the development of those components is divided into four main technology lines:

Semiconductor Technologies and Processes

Technological processes represent fundamental aspects of component technologies (e.g., Si process for microelectronics devices). Improvement of these processes can propagate and materialise as improvement of the final products (e.g., lower power/higher speed by reducing Si feature sizes). This technology line aims at improving processes maximising the number of benefitting applications.

The development of GaN processes needs to achieve frequency increases (up to Q/V/W bands), mass and volume reduction (e.g., replacing bulky traveling wave tube amplifiers by GaN solid-state power amplifiers), and performance improvements (power, gain, noise, efficiency/linearity).

UDSM FinFET (<7nm) and novel Gate All Around transistor structures are required to overcome the limitations of current on-board digital processing capabilities, enabling in space edge computing similar to terrestrial microelectronics capabilities.

Detector technologies and processes will need to achieve enhanced performance devices on SiGe, p-channel CCDs and novel technologies for deposition of antireflective coatings, backside thinning, flip-chip bonding hybridisation and 3-D stacking. Developments in photonics in the domain of digital payloads needs to include emerging technologies on micro-photonic links, novel fibre sensors and space-based laser-cooled atom interferometers, e.g., optical clocks, lasers, frequency combs and quantum technologies.

For MEMS, improvement in technologies and processes concentrates on the versatility of materials used and on the use of sealed cavities. In many applications, reliable hermetic cavities with a high vacuum level are necessary to increase the sensitivity of MEMS sensors. This is especially true for resonant devices or high frequency applications (RF - MEMS).

Design

The development and application of new design methodologies and IP Core reuse aims at an increase of functional densities, operational frequencies and range of power and signal bandwidth in Very Large Scale Integrated Circuits (VLSI) and in photonic devices. Specifically, developments to enable enhanced functionalities include high-speed serial links, VLSI devices such as microprocessors, ASICs, FPGAs, and moving from 65nm down to 6nm nodes, with a higher integration level (System on Chip) of the digital and analogue functions. Those devices, planned to be tested in space by 2025, are expected to reduce development time, improve cost efficiency and strengthen the European supply chain.

Several passive component technologies (e.g., capacitors with high capacitance densities, high density and high data rate connectors, flat cables with dedicated connectors, fast locking solutions, SMD RF passives for high frequencies) are needed to allow for better integration/ miniaturisation and increased performances (e.g., VLSI decoupling capacitors, high current low voltage transformers). Similar enhancements and increased performances are anticipated within the design of new photonics integrated circuits (PIC), that will provide multiple functionalities on the same chip (frequency generation, multiplexer, optics spectrometer) and the shift towards micro-photonics (e.g., improved frequency response, higher gain). In parallel, European non-dependence and obsolescence of critical parts (e.g., pump-lasers, optical modulators for ISL) will be addressed.

Packaging

Improvement achieved through design and process down-scaling will be accompanied by relevant developments at packaging level to benefit from technologies used in high volume semiconductor markets (e.g., flip-chip mounting, high pin count products, lead free solder, plastic parts) while mitigating issues on reliability (e.g., pure tin whiskers).

New applications have emerged that require higher frequencies and higher bandwidth levels and the combination of both analogue and digital with RF functions (Sections 5.1 and 5.3). Therefore, higher level of integration and the combination of different semiconductor technologies (e.g., Heterogeneous Integration, System in Package) will be required. The introduction of 2.xD packaging solutions and of new interposers/interconnection technologies (e.g., organic/silicon/glass substrates) can expand the possible solutions to overcome those challenges.

New technologies, such as non-hermetic packaging or enhanced plastic, will be assessed to overcome the known issue of current hermetic technologies (e.g., high cost, HPC limitation, power management) and to ensure compatibility with new photonics devices requiring large number of electrical connections (e.g., solderless mounting, Ball Grid Array). The evolution of Silicon photonics will also require developments in the field of packaging and test methods.

New methods of heat and power management will be assessed to identify further improvements beyond current solutions. Enhancements to performance are required to exploit modern higher power semiconductors, such as GaN and SiC. Whilst the encapsulation method has an effect, die mounting and substrate/heatsink technologies are the areas where most benefits can be gained.

Products

This technology line is addressing finished European products whenever improved performances are needed and lead-time and/or cost reduction are possible. Examples include infrared and CMOS visible detectors, new ADC or DAC devices, electro-optical transducers, more powerful microprocessors (adopting RISC-V for space) and re-programmable FPGAs. Ready-to-programme (inside FPGAs) or to-manufacture (inside ASICs) IP Cores remain key building blocks of multi-core and multi-function System-on-Chips.

For some applications, EEE parts designed for terrestrial applications such as automotive represent an alternative as they show high reliability levels when procured in massive quantities and properly controlled, and offer the benefit of reduced lead-time compared to qualified/mono-source solutions (e.g., PET capacitors).

Considerable effort has been put into the creation and maintenance of methodologies and standards to allow a more systematic usage of Commercial Off The Shelf (COTS) electronic components for space applications. Further work on reference designs, mitigations, alternative test methods and test data collection is needed.

Increased use of COTS for advanced devices with denser and more complex packaging (flip-chip, die stacking) of the state-of-the-art components requires high energy ions beams of larger penetration range (>1 mm) and associated difficulty of radiation hardness assurance/testing. Further support of radiation characterisation, evaluation and qualification of European space developed EEE components and of “low-hanging-fruit” type EEE Component technologies potentially suitable for space applications is needed.

Testing

The development and readily available, accessible infrastructure of testing facilities is considered critical. Activities include performing reliability assessment for COTS (e.g., life test to assess wear out behaviours), maintaining up-to-date radiation hardness assurance standards and test methods, supporting the development of component specific Radiation Hardness Assurance (RHA) related standards and developing new approaches to RHA in New Space type projects focusing on COTS.

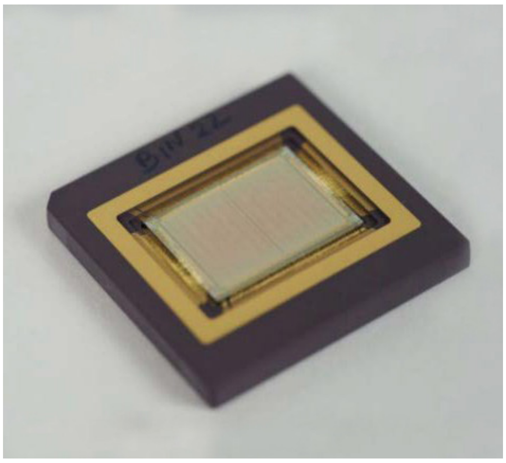


Figure 16 - Brave medium FPGA.

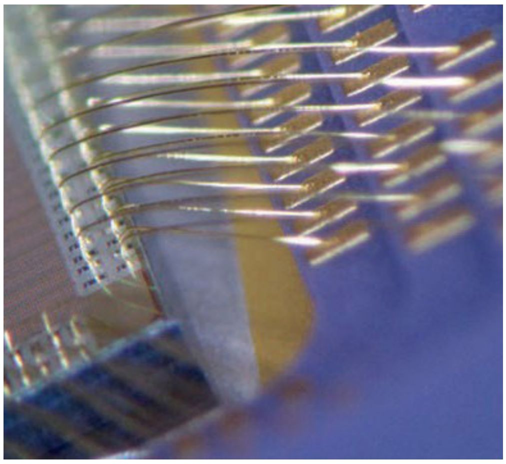


Figure 17 - HPDP bonding.

6.2 STRUCTURES, MECHANISMS, MATERIALS, THERMAL

CD2

The integration of structures, mechanisms, materials and thermal disciplines allows the development of innovative mechanical architectures and products for future space missions, serving the strategic targets of life-cycle costs and lead time reduction, as well as reduction of space debris. Some of the many key technology areas are deployable structures, stable and lightweight structures, mechanisms building blocks including tribology-free solutions, advanced manufacturing techniques, and coatings, cryogenics and advanced heat transport and rejection systems.

Figure 18 - 3D printed structures and mechanisms.

Space missions and products increasingly demand higher flexibility in adapting spacecraft late in the system design and development process to new requirements and to integrate late newly available advanced technologies (Sections 5.2 and 5.3).

This is driven by the need for agility of new space platforms to quickly react to market needs for competitiveness, enhancing versatility and low-cost production.

The full modelling of space products from the early design phases, based on trusted and authoritative data sources (shared among the complete supply chain) is enabling this flexibility (Section 2.4). This part of the digital transformation of the engineering and design process offers a particularly strong return of investment in the mechanical engineering realm.

For this reason, digital engineering is distinctly prominent in the Competence Domain for Structures, Mechanisms, Materials and Thermal: the already existing cross-fertilisation opportunities, fostered by the very nature of the represented disciplines, have been further extended by the digital transformation (Section 2.4).

The strategic action lines defined in the latest technology development cycle have shown an unprecedented level of implementation, and are expanding into the next step: to take full advantage of virtual engineering environments.

The already identified and pursued physical developments have achieved levels of maturation that consistently allowed their integration to flight missions, feeding back to the development path showing currently an even faster growth in the digital world.

Directly contributing to achieving the Technology Strategy targets 1 and 3, examples of the recent achievements obtained within the domain are the selection of the large deployable reflectors to be flown as key enabling European technologies on board of two Copernicus new generation flagship missions, as well as the first 2-phase Mechanically Pumped Loop in orbit with SES17. Building blocks for thermal control have been developed and are ready for use, e.g., deployable radiators to increase heat rejection capability.

ESA's early effort to push and mature additive manufacturing processes by systematically addressing all open technological challenges via development activities, have resulted in many ambitious mission applications in the space transportation, science, EO and telecommunication sectors. As an example for addressing the technology targets 3 and 4, ADEO, the Drag Augmentation De-Orbiting Sub-System has been launched in June 2021 for an in-flight demonstration of its capabilities in de-orbiting end-of-life satellites. This simple, non-invasive add-on system has the potential to become the backbone European technology for passive debris mitigation. It is selected for an IOD/IOV project to be launched in 2024, which will demonstrate increasing mass de-orbiting capabilities.

Addressing the 2nd technology strategy target, and the market pressure to reduce costs and lead-time, particularly for recurrent missions, mega-constellations and launchers, ESA has focus ed on to the development of European sources for COTS. The further focus will be to develop European COTS components for cryocoolers (spinning-in from terrestrial and tactical sectors), actuators, reaction wheels, position sensors, printed circuit boards and electronic assembly processes compatible with off-the-shelf automotive electronic components (Section 2.2).

REACH and RoHS regulations still represent substantial challenges on supply chains of products which span from coatings to lubricants, from electronics to large structural manufacturing. Following the progress already achieved, e.g., X-chromate-free conversion coating and black primer, green polyurethane, and with the overall aim to ensure the sustainability of high-end European space products, ESA will address specifically the led-free transition, going further than the compliance to regulations, addressing environmental sustainability and technological non-dependence. Greener and European solutions are pursued in a number of areas, from materials to manufacturing techniques, and demisability (Section 2.5).

"Digitalisation" will dominate until 2025, linking all engineering disciplines: From the manufacturing processes modelling, leading to accurate digital twins and to reliable performance predictions, to thermal and structural simulation enriched testing, to machine learning and artificial intelligence applied to all involved engineering processes (Section 2.4).

The Advanced Manufacturing Cross-Cutting Initiative (Section 2.3) will evolve integrating the virtual manufacturing and smart factory concepts, and taking the first major European step into off-Earth manufacturing and assembly, a domain expected to grow substantially and with potentially high return of investment opportunities in the commercial and New Space domain.

6.3 AVIONICS SYSTEMS

CD3

Avionics Embedded Systems (AES) are the brains of spacecraft. They include the on-board hardware and software required for the command & control of the spacecraft, its failure detection, isolation and recovery (FDIR) and all the mission and vehicle management functions including all functional chains. AES include on-board computers and data handling systems, on-board platform-payload data processing, microelectronics, TT&C transponders and payload data transmitters, Guidance Navigation Control - AOCS and Pointing systems, and finally on-board radio navigation receivers.

On-board software is executed on most of these elements to control their functions and allow their monitoring. AES represent between 30% and 70% of the platform non-recurrent development costs (50% in average for an ESA mission). Cost reduction of the AES is therefore essential to achieving the Technology Strategy Target 2. Adaptability and customisability are considered critical to remain competitive for constellation or convoy applications.

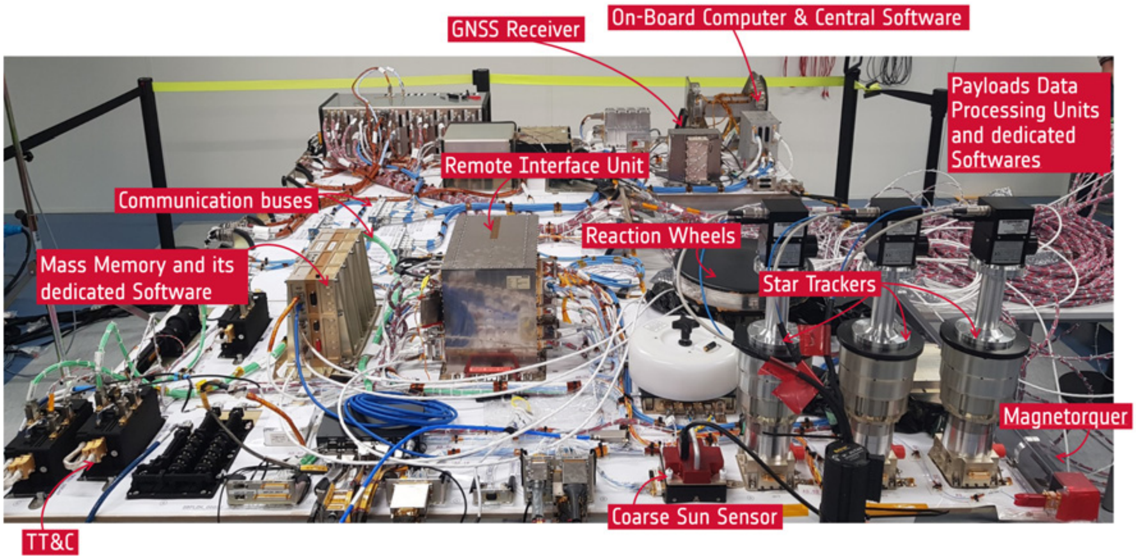


Figure 19 - Avionics elements on the MetOp-SG Flat Satellite at Airbus Defense and Space Toulouse (courtesy of Airbus Defense and Space).

To achieve these objectives, the R&D strategy for avionics aims to:

- Improve the process of definition, design and verification of AES, avoiding segmentation of the overall system approach, and linking seamlessly to the process at discipline level (co-engineering of control, software and data handling. This is achieved via Model Based System Engineering (MBSE), hardware and software modelling and simulation tools, the use of an avionics test bench, a dedicated Software Validation Facility (SVT), and a Functional Verification Bench (FVB);
- Promote the reuse of specification, design, tools and product lines between missions, avoid when possible new developments for non-recurring design, validation and qualification. This implies the standardisation and modularity of the main avionics functions and interfaces, and the development by industry of product lines that can help implement the reuse approach and the inter-products compatibility;
- Improve, define and develop on-board architectures and functionalities required to enable future missions like autonomy and FDIR, communication security, inter satellite links, artificial intelligence support; and
- Increase the pace of innovation by evaluating, testing and adopting state-of-the-art technologies developed outside the space sector.

On-board computers and data handling systems (OBCDHS), on-board platform/payload data processing and microelectronics (microprocessors, ASIC, FPGA)

Every satellite platform, instrument and launcher is equipped with an OBCDHS, which centralises, conditions, stores, and transfers all data (TM/TC and payload data) to other subsystems. To achieve the Technology Strategy targets 1 and 2, ESA is developing ADHA, a new Advanced Data Handling Architecture, which is flexible and scalable, and composed of standardised, interchangeable and inter-operable electronics modules based on the latest generation of microelectronics components and on-board data processing technologies. The module standardisation will allow lower cost and faster production, expecting to obtain in 4 to 5 years integrated and scalable units ready to fly. The activities aim at substantially reduced average cost, development and integration times per unit.

Regarding payload needs, more specific processing functions will require new high performance processing devices, modules and units for enhanced payload performance or increased mission performance/ autonomy (e.g., low latency or payload-in-the-loop applications). Data compression technologies as well as advanced data reduction techniques (possibly exploiting AI-based solutions) will be required.

High performance microelectronics technology and components are the key performance boost elements in all OBCDH. Multi-core digital and mixed-signal data processing and control System-on-Chips continue to increase their functional densities, operating speeds, exhibit lower power consumption, and bring more flexibility and reconfigurability for the OBCDHS addressing the mission needs expressed in Chapter 5. The strategy and new focus are on smaller and non-planar fabrication nodes (16-6 nm FinFET) for new ASIC platforms, heterogeneous multi-dice system-in-package solutions, consolidate and develop new European rad-hard FPGAs and microprocessors (introducing RISC-V open architecture after LEON/SPARC) and their tool ecosystems, and improving the ever more complex chip development methodology to save time and costs. At the same time, the strategy calls for the maintenance and ensuring access to existing European ASIC, FPGA, processor and reusable IP Cores capabilities, and the selective screening and adoption of COTS components.

On-Board Software

The inclusion of advanced software functions will enhance system flexibility and functionality, in particular autonomy. This includes fault management, planning and scheduling, intelligent control, on-board analysis of payload data, which will enable the envisaged challenging robotic, scientific and exploration missions, while remaining within the targeted schedule and cost (Section 5.1). Most of these can use recent advances in artificial intelligence, which however still represent challenges related to software engineering and performance.

Enhancements are required in productivity, complexity, reactivity, flexibility: Productivity will be enhanced through automation and a model-based approach, aligning system and software engineering. Complexity will be adequately managed via model-based engineering support, as well as early feasibility assessment and behaviour verification. The development of reference architectures, targeted to the functional domain, will enhance reactivity and flexibility.

Software development objectives will be based on model driven engineering and reference architecture engineering streamlining the software development from requirement engineering to validation through reuse and automation supported by a software factory approach, which will provide a seamless process for software generation and test. The introduction of new advanced software technologies will enable new functions for future system efficiency and flexibility. The generalisation of a hardware-software co-design approach and its integration into the software factory will make possible to get the best of new generation of System-on-Chips (Section 6.1).

TT&C Transponders and Payload Data Transmitters

TT&C is a mission critical function for all space missions. ESA's technology development in this domain aims for optimised functional and architectural partitioning, further miniaturised components (analogue, RF, and digital); to enable operations at weaker signal conditions in Deep Space, including at extremely low TC/TM data rates (Section 5.1.1); to cope adaptively with harsh environments; to enhance the TT&C subsystem to support (radio)science measurements and specific Deep Space functionalities; to increase maximum downlink data rates of PDT subsystem to 10Gbit/sec (EO missions Section 5.3), and to 100s Mbit/sec (Lunar/Libration point missions) using Adaptive Coding and Modulation (ACM); increasing Deep Space TM rates to 100Mbit/sec and beyond using GMSK modulation; to improve (European) Inter-Satellite and Proximity link technologies and functionalities (including SWaP); and the addition of security functions to TT&C links for robustness against cyber threats (Section 2.6).

GNC - AOCS and Pointing systems

Spacecraft, launchers, landers, and re-entry vehicles rely on GNC, AOCS, and pointing systems to estimate and correct their trajectory and attitude to provide safe and suitable conditions for the payload to be operated and collect mission data with the required quality, and for space transportation or exploration missions to be successfully accomplished (Section 5.1.2). New GNC, AOCS, and pointing systems are being developed for missions that require either enhanced performance, improved robustness, better competitiveness or a broader range of on-board functions. In the area of GNC systems for exploration and space-transportation (including reusable launchers, Section 5.4.1), robust and adaptable control techniques as well as techniques suitable to achieve real-time guidance capability like convex optimisation and model predictive control are being developed to enable safe precision landing capability on the Moon and planets as well as launcher stage recovery (Sections 5.1.2 and 5.4.1). Autonomous navigation through vision or assisted by GNSS is being implemented on a growing number of missions and further improvements and maturations are needed in this area, taking advantage of recent advances in data fusion, image processing and estimation. European capacity in AOCS and GNC sensors continue to expand, securing dual sourcing, investing in higher accuracy for attitude and rate sensors and enlarging product range for New Space type missions. Distributed command and control techniques as well as advanced guidance strategy allow growth of missions ranging from constellations up to distributed payload spacecraft formations. High pointing accuracy and stability missions are continuously enabled and enhanced through higher performance sensors as well as innovative, possibly disruptive, control architectures. For a sustainable space environment, effort will be continued on AOCS and GNC actuators demisability, as well as on de-orbiting strategy and providing GNC capacity for active debris removal (Section 5.2). Continuous progress on AOCS and GNC functional validation process and related test facilities, with use of model-based engineering, will reduce development cost and schedule as well as establish European AOCS and GNC subsystems as standalone products, especially for New Space economy applications. The integration and use of machine learning at several levels in the on-board control system architecture is potentially game changing but certainly enhancing the flexibility, autonomy, and adaptability of GNC, AOCS and pointing systems.

On-Board Radio Navigation Receivers

Almost every spacecraft in Low Earth and Goestationary orbits uses GNSS receivers for on-board autonomous operations and a posteriori precise orbit determination. GNSS receivers are also used in most launchers and re-entry vehicles. They can be of different types from low-cost COTS-based single frequency to high-end multi-frequency and multi-constellation based on class 1 components. In addition to the provision of orbit determination (position and velocity), this allows to synchronize on-board clocks with high accuracy (<50ns) to GPS or Galileo time.

It is expected that many missions will adopt real time on-board precise orbit determination that allows to compute orbits within 10cm 3D RMS, velocity within 1mm/s 3D RMS and timing accuracy below 1ns without ground intervention. This technology allows to increase the on-board autonomy with autonomous on-board manoeuvres in close loop with the on-board AOCS systems (guaranteed positioning and autonomous manœuvres) and to enable completely new mission concepts such as Low Earth Orbit positioning, navigation and timing and autonomous satellite formation. The use of GNSS has been proven to work also for cis-lunar space, thus following the demonstration expected in 2025 as part of the Lunar Pathfinder mission, the use of spaceborne GNSS receivers to compute orbit determination and provide time synchronisation in lunar orbit is expected to become the standard for future lunar missions by 2026-2027.

6.4 ELECTRIC ARCHITECTURE, POWER AND ENERGY, ELECTRO-MAGNETIC COMPATIBILITY

CD4

The technology development lines of action regarding electric architectures, power and energy and electro-magnetic compatibility are primarily linked to their nature as enabling European space ambitions.

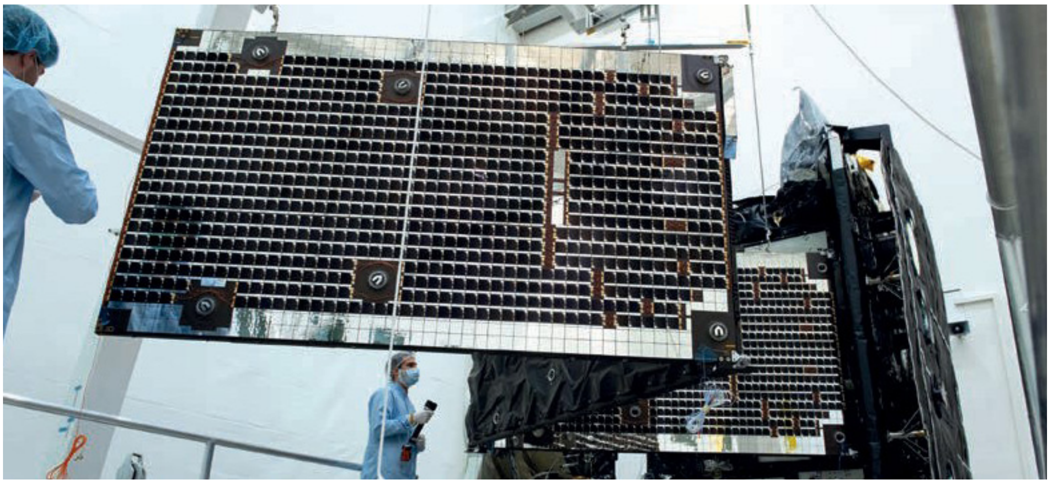


Figure 20 - A Solar-Orbiter Solar Array test.

Power Units

Power Units are evolving towards more modular and flexible ones. Standardising the technical and functional interfaces will be key to achieving the required modularity (Chapter 3 and Chapter 5). ESA has undertaken first steps for an advanced power architecture (APA) responding to the above trends. GaN power switches offering better performance and lower cost, combined with the use of Digital Control for power conversion will give place to smaller, more efficient power systems, with more complex embedded functionality.

Smaller FPGAs and microcontrollers with integrated ADC and integrated memory are the key component to make this technology cost effective. Thus, a European supply chain of advanced ASICS is a strategical asset in the power domain.

In the secondary power system, the enabler to achieve miniaturisation and increase the reliability of the units is to have high quality standard DC/DC converters with a high performance and high degree of integration. Given their high count number in a platform, a European line of standard converters is paramount.

High Voltage power electronics is also a key technology that enables more powerful electric propulsion systems and, in general, higher power satellites. High voltage GaN switches and SiC MOSFETS are the enablers for a new generation of high power electronics.

COTS components

Specific missions can benefit from COTS components for power system. Terrestrial Si solar cells, battery cells and commercial EEE components can, in some specific cases, reduce the size, the cost, the development time and improve the performance. If needed, the higher risk can be partially reduced by better understanding the performance of these components under space environments. This requires the definition of a reliable safety barrier allowing equipment of criticality classes Q2 and Q1 to be used in missions of all classes (Section 2.2).

Electromagnetic Compatibility (EMC)

Compatibility of electrical equipment with the electromagnetic environment, artificial or natural, is essential for its proper functioning and performance. Achieving compatibility by design is enabling for science, exploration and Earth observation, and fundamental for cost efficiency particular in telecom and navigation (Section 5.3). For astronauts, it ensures safety and enables sensor-based telemedicine.

The fast trend of electronics towards miniaturisation, higher frequencies, COTS, modularity, and reconfigurable components challenges EMC to face urgent needs:

- Enhance digital simulations to evaluate the interaction between equipment and environment in the earliest design phases, avoiding troubleshooting, additional testing and costly redesigns.
- Complement simulation with hardware testing as relevant design elements can be unintentional, parasitic, stochastic, or even non-linear. Advanced test facilities and methods are key for time and cost efficiency, enabling and enhancing testing for next generation of sensitive electronic equipment.
- Guarantee European non-dependence to optimise designs. Solutions such as filters, connectors, ferrite chokes need to be developed in Europe.

EMC is a prerequisite for mission success and depends more than ever on design. Thus, simulations need to be enhanced and accelerated, while test capabilities need to be matched to leverage synergies.

Electrochemical Energy Storage

The major needs for future batteries for space applications (satellites, launchers, landers, ISS) are:

- High power density (>50C) for future launchers due to electrification (Section 5.4.1);
- Ultra long life of 75,000 or more cycles for future satellite missions;
- High energy density (>200 Wh/kg) batteries to reduce the mass and relevant launch cost;
- Low temperature batteries for specific space applications including exploration missions (Section 5.1);
- Safe battery technologies, like solid state lithium batteries, to minimise the risk of thermal runaway and ensure smooth battery passivation at mission end of life; and
- Quicker innovation cycle to be able to implement state of the art battery technologies for future missions and manage the existing issue of battery materials obsolescence.

Fuel cells are an enabling technology especially for a human presence on the Moon and on Mars (Section 5.1.2). Regenerative Fuel Cell Systems (RFCS) can achieve much higher specific energy than conventional Li-Ion batteries. The main challenges identified are:

- Promote the current European leading position in stationary and mobile fuel cell and electrolyser technologies, water propulsion and life support systems to space applications;
- Develop balance of plant components to operate RFCS;
- Develop electrochemical pumping technologies of both hydrogen and oxygen; and
- Develop dry reduction of CO_2 coming from the Martian atmosphere for generating breathable oxygen for human Mars missions;

Power Generation: Solar Cells and Solar Arrays

Most spacecraft rely on the power generated by photovoltaic solar generators. This subsystem constitutes a significant part of the total satellite mass and costs. The availability of competitive solar cells and solar arrays – which today mainly means high efficiency, low stowage volume, low mass and appropriately priced - is important for scientific/Earth observation missions as well as for commercial programmes, where the European industry has to compete in a very challenging world market.

To maintain European non-dependence and competitiveness, in the coming years the related main challenges identified to be of key importance are:

- Cost reduction (W/€) on solar cell (including potential spin-in from terrestrial solar cells) and solar array level;
- Development of the technology building blocks for next generation solar cells to anticipate and react fast to new market trends; and
- Development of flexible/lightweight compact solar arrays, crucial to improve the figures of merit (W/kg, kW/m³), creating additional value to the platforms and allowing multiple satellite launches.

Addressing those challenges supports achieving the first three Technology Strategy targets (Chapter 3).

Power Generation: Nuclear

The ESA Human Spaceflight and Robotic Exploration mission roadmap defines requirements for lunar missions that require the use of nuclear technologies to provide heat and power during lunar night periods and within permanently shadowed regions in the lunar polar regions (Section 5.1.2). Future science missions to the outer planets and long-duration Mars surface missions will also require nuclear heat and/or power (Section 5.1.1 and Section 5.1.2).

The ESA nuclear power development strategy is to achieve a European capability in radioisotope power sources (both RHUs and electrical generators). Early-phase studies on nuclear fission reactor systems are also under preparation, focused to support the longer-term Moon/Mars exploration roadmap (Section 5.1.2).

6.5 RADIOFREQUENCY & OPTICAL SYSTEMS

CD5

Developments in the radio frequency and optical systems domain are driven by demands for performance and cost efficiency, covering space, ground and user segments (Chapter 5). The associated technology development strategy activities therefore cover all aspects related to the research, design, development and testing of telecommunication payloads and sub-systems, microwave, (sub)millimetre wave and optical remote sensing instruments, digital and optical on-board technologies, as well as quantum technologies. This includes the related hardware, algorithm development (coding, modulation, access, synchronisation, networking), and system performance tools.

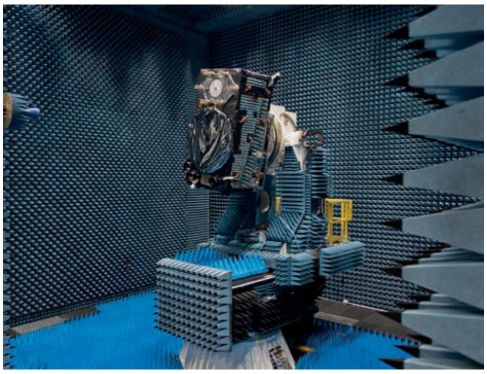


Figure 21 - Satellite testing inside ESTEC HERTZ facility.

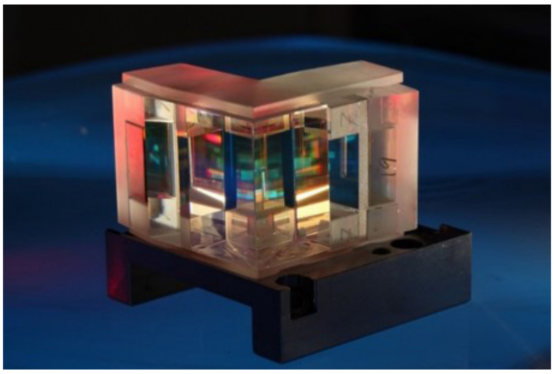


Figure 22 - Monolithic Spatial Heterodyne Spectrometer.

Antenna and Payload technologies

For telecom applications, the development of large (deployable) antennas and phased arrays, combined with high-efficiency solid state power amplifiers for distributed power amplification, compact analogue large size beam forming networks, wideband multi-beam digital processors for channelisation, switching and beam-forming exploiting photonic technologies, and very high-speed feeder and inter-satellite links will enable new payload architectures which support modularity and re-configurability. Payload re-configurability, large frequency reuse (small beam size) and dynamic beam allocation technologies allow efficiency gains for on-board resources to achieve flexibility at a competitive cost, by allowing to adapt to market uncertainties, short-term traffic variability and multi-mission capability (e.g., broadcast and broadband) and to reduce spacecraft development time. Those technologies are enabling for new types of very large throughput missions.

The advent of mega-constellations and 5G requires novel payload architectures with a special emphasis on commercial viability.

To enable complementary constellations operating in frequency bands different from the current Global Satellite Navigation Systems L-band (e.g., VHF, C-band) for higher navigation signal penetration and/or higher link margins, several enhancing and enabling technology developments are foreseen. To allow the payload to derive frequency and time reference from existing MEO GNSS constellations, and to enable payload technologies tailored to multi-layer PNT architectures, low-cost integrated medium power wideband amplifiers, frequency versatile passive output sections for GNSS satellites, versatile wideband antennas need to be developed as well as developments for low-cost, low-mass low-power, highly resilient and low-energy positioning solutions in existing (MEO) or alternative orbits (LEO) orbits with potentially LEO/MEO GNSS payloads. Penetrating signal technologies are considered potential game changers for global navigation satellite system applications.

The requirements for planned Earth observation instruments and astronomical missions go well beyond those of related RF and optical instruments developed outside ESA, resulting in the need for new antenna/telescope and payload configurations and for the refinement of existing configurations and technologies

Antenna and payload performance is a critical aspect in limb sounding and low frequency GPR, since it determines the measurement resolution and accuracy of the concentration profiles of atmospheric species and the depth or soil penetration. For pointed observatories, which seek to map point-like objects, the emphasis is on beam efficiency and the control of main beam shapes. For survey missions, the level of far side lobes becomes important.

The advent of small satellites as a realistic alternative to the traditionally large satellites requires new approaches to be adopted and extreme levels of integration with minimal resource demands.

Ground terminal technologies

The priority technologies for gateways aim at very high throughput support with high link availability, flexibility and optimum use of system resources, full integration with future terrestrial infrastructure, value-added services, and affordable ground segment for mega-constellations. The enabling technologies for the gateways for GEO applications are cost-effective Q/V and W-band and/or affordable optical feeder link solutions. For constellations, multi-satellite tracking active antennas operating at Ka/Q/V will enable reducing the number of tracking antennas per gateway location. Both radio frequency and optical technologies will require the intelligent reuse of spatial diversity to minimise the ground segment cost.

For optical feeders, link pre-correction techniques to compensate for atmospheric propagation effects and reduction of bandwidth expansion (i.e., RF over optical in free space) are considered enhancing technology developments.

Dynamic resource management algorithms based on machine learning will enhance the capabilities of flexible telecom payloads with a large number of beams in particular for telecom mega-constellations.

User terminal technologies

New SATCOM user terminal technologies enable lowering cost, increasing compactness and improving user friendliness, depending on application needs and markets: Low energy terminals for Internet of Things, high data rates and flexibility in spectrum usage for broadband services, and affordable low-profile user terminal antennas for aeronautical, land mobile, maritime applications. Enhancing technologies for user terminals are low-cost steerable antennas based on semiconductor technologies (GaAs, SiGe, Si), liquid crystal technology, or hybrid technology (Section 5.3).

The technology development for the navigation user segment will system-of-system PNT solutions, contemplating hybridisation and exploit the integration of the existing space backbone, signals from satcom and and terrestrial positioning services in a multi-layer PNT architectures (e.g., MEO GNSS, signals from LEO, 5G/6G including from non-terrestrial networks) in particular to cover challenging environments (e.g., urban canyon, indoor). Advanced positioning, navigation and timing (PNT) algorithms, including carrier phase processing and integrity, will enable the adoption in the most demanding safety of life applications (e.g., autonomous vehicles, railway signalling).

Improved interference monitoring and mitigation at user level, support for secure authentication algorithms, the integration of technologies complementing GNSS, will enhance the resilience of the PNT solutions in support of the demand for higher security. Such algorithms together with the development of chip-scale sensors, and MEMS and optical vision-based sensors are considered potentially game-changing technologies for inertial and position measurements (Section 5.3.3).

Radars

The developments of generic radar technologies will focus on power sources for Ka/Ku-band instruments, digital technology, novel antennas and RF front-end and improved models and algorithms. Millimetre-wave GaN technology, large deployable reflector antennas and reflect-arrays technology will enhance future Earth observation mission based on active antennas increasing the performance and operational flexibility.

The field of radar imagery from synthetic aperture radar (SAR) is undergoing a revolution in design resulting in greatly enhanced capabilities. Digital beamforming techniques enhance the provision of much wider swath products and thus greater coverage, whilst maintaining the same, or even improved spatial resolution.

Very high phase stability to produce 3D terrain maps and surface deformation in the case of seismic events will enable interferometric radars observing the surface of Venus. Frequencies like S-band or lower will allow all weather performance. The development of ultra-wide band stepped-frequency radars combining high resolution with low data rate will enable slow movement around asteroids.

The development of larger deployable antennas and multiple frequency systems will enhance future ground-penetrating radars to determine the subsurface structure of planets and asteroids by adding detail to the detected sub-surface structure.

Planetary landing radars fall into two main categories: pulsed (e.g., ExoMars) and frequency-modulated continuous-wave (e.g., Huygens). Technology developments to counteract variable attitude and locking of the signal onto false targets include the extension of their useful range, accuracy, and the development of multiple beams from ultra-lightweight antennas. These are enabled by moving to higher frequencies. The development of compact HF-VHF tubular deployable antennas will enable the ground penetrating radar of small planetary missions, together with associated verification and calibration techniques (Section 5.1.2).

Radiometers

The development of image reconstruction techniques with low side-lobe levels, advanced receivers and correlation with radio frequency interference mitigation capability, ASIC correlators, new deployment concepts and mechanisms for large array antennas of hexagonal shape will enable the microwave radiometers needed for SMOS follow-on missions. Constellations of instruments to synthesise a large aperture have also been proposed as game changing technology for a further future.

At (sub)millimetre wave frequencies, radiometers are expected to remain the workhorses of Earth Observation and Science in both limb and down-looking configurations. Radiometers based on (sub) millimetre wave synthetic aperture interferometers would enhance the high-resolution capability needed for certain applications (Section 5.1.1 and Section 5.3.2).

Strengthening the leading European position in technological areas such as RF-antenna modelling, submillimetre wave quasi-optics, frequency selective surfaces, and in HBV technology enhances the competitiveness of European industry and space systems.

The availability of certain reliable semiconductor technologies (Schottky, HBV) is considered critical. Two branches of technology development activities are being explored to address the lack of sufficient local oscillator power: a technology development focus on quantum cascade laser (QCL) and the development of novel THz multipliers using Schottky diodes. Radiometers installed on small and cubesat missions have attracted increasing attention. The development of solid state technologies such as SChottky or HBV will directly benefit the development of compact radiometers for such platform. However, a strong R&D effort is needed in this domain to fill gaps with technologies under development outside Europe.

The development of an interferometric dual-band (Ku+Ka) altimetry system will enhance topographic measurements over the oceans and polar ice caps for future missions targeting the cryosphere and oceans with either one or two satellites in polar (non-sun synchronous) orbit.

Optical Sensors

In the field of optical imaging, the constant demand towards increased optical performances (detection sensitivity, spatial and spectral resolutions in particular) has been driving the optical payload requirements and the need for enabling technologies for future missions (Section 5.3.2).

The development of hyper and multispectral imagers in the VNIR and SWIR domains has gathered momentum in both large flagship missions (e.g., CHIME in the frame of Copernicus Expansion) and smallsats with drastically reduced mass, size and cost but with limited compromise on the product quality (e.g., Hyperscouts) thanks to key enabling technologies (e.g., free-form surfaces manufacturing, free-form gratings, direct filter deposition on detectors, on-board image processing). This trend will continue, generating a constant need for technological innovations and improvements in the optical path.

To complement the spectral range, dedicated mid-to thermal infrared sensors are being developed, both imagers (e.g., LSTM in the frame of the Copernicus Expansion) or spectrometers (e.g., Earth Explorer FORUM) benefiting from developments in free-form surface manufacturing and metrology, Fourier Transform spectrometry, IR-specific materials and optomechanical techniques (e.g., bonding, mounting). In spite of robust technological improvements in this field in recent years, the increased New Space interest in thermal sensing imaging embarked on smallsats and the scientific demands of larger missions both keep driving its technological development towards state-of-the-art performances (detectors, highly efficient IR coatings and gratings, straylight-adverse optical designs) and/or cheaper and leaner payloads with faster development curves (e.g., replicated mirrors, direct Aluminium free-form polishing, transmissive gratings).

While keeping upgrading their performances for atmosphere research, and planetary altimetry, LIDAR systems technologies will extend their role to e.g., landing/docking, clean space, in-orbit services and deployments thanks to a push towards smaller form factors and potential integration as service to large payloads.

In parallel, fuelled by a science-based push for greater sensitivity and resolution from both Science and Earth Observation, studies on large space telescopes and their related technologies have garnered significant progress in recent years, both in terms of concepts (based on monolithic primary mirror such as GEOBS, sparse aperture approach, or deployable segmented primary mirrors) and technologies (active correction loops, large mirrors manufacturing, optomechanical concepts for segmented optics). However, these promising preliminary results need to be consolidated to reach a robust enough technological maturity status for adoption by missions, with a particular effort on metrology, mirror materials, active correction, high-accuracy actuation, and AIT of large optical systems.

Regarding optical telecommunications implementation at payload level, optical feeder links will keep their rapid rate of development to address the need for higher throughput, higher link availability, flexibility and optimal use of system resources, pushing for novel solutions (e.g., spatial and spectral optical filtering methods, detection strategies to enable the use of smaller laser terminals, adaptive optics).

Optical Path Technologies

To implement demanding trends in optical sensors, several key optical technologies need to keep their development pace. In particular, better straylight control is paramount to ensuring stringent radiometric accuracy. Better surface quality needs to be pursued through improved mirror and lens polishing techniques as well as better contamination control. Reliable straylight correction algorithms for image processing coupled with better characterisation (on-ground and most importantly in-flight) will constitute the next game changing technology in straylight control in the coming years.

Polarisation control is also becoming essential for many forthcoming payloads, either due to polarisation effects on radiometric accuracy or due to the growing scientific importance of polarisation as a measurement product. Regarding control, several polarisation scramblers have been developed in recent years, often at the expense of the instrument volume. An alternative would be improvement of coatings polarisation characteristics and knowledge, in particular for the UV and visible ranges. Diffraction-based technologies, such as nanostructured filters, allowing to shape both spectral and polarisation contents of the instrument signal, have the potential to act as game changing technologies both for polarisation control and sensing.

The strong market pull for optical payloads with reduced size, mass and cost demands, next to already existing enabling technologies (such as free-form surfaces) which need further enhancement, the exploration of potential game changing technologies, such as liquid crystal optics and meta-surfaces for planar optics, or active optics for compact payloads aiming at decreasing their thermo-mechanical and AIT complexity. Furthermore, the potential applications of the synergy between standard optics (e.g., front telescope) and photonics (e.g., instrument on a chip) need a thorough investigation as a disruptive approach for smaller payloads for both Earth Observation and Science applications (Section 5.1.1 and Section 5.3.2).

ESA's upcoming science missions will keep pushing the very boundaries of technology, with on-going developments such as the ultra-stable mounting technologies to achieve the picometer-level stability, distance measurement and pointing accuracy required by gravity wave detection (Section 5.1.1). Looking further, optical missions to be developed in the frame of ESA Voyage 2050 will trigger new developments in various payload technological fields (e.g., compact payloads for planetary exploration, space-based nulling interferometry for temperate exoplanet characterisation, cold atom interferometry, X-ray interferometry) that will need to be identified and mapped as early as possible.

In the mid-to long-term future, sustainability-driven approaches to space missions will put the emphasis on serviceability of optical payloads (e.g., in-orbit integration, repair) and designs compatible with demisability requirements (Section 2.5). For this, a significant change of paradigm in the traditional design of optical payloads will be need to take place and should be explored soon to tackle the related implementation challenges.

6.6 LIFE & PHYSICAL SCIENCE PAYLOADS, LIFE SUPPORT, ROBOTICS & AUTOMATION

CD6

The expansion of human activities in space requires the development of technologies in the fields of automation and robotics, autonomy, science instrumentation, environmental control and life support systems and in-situ resource utilisation. (Section 5.1.2)

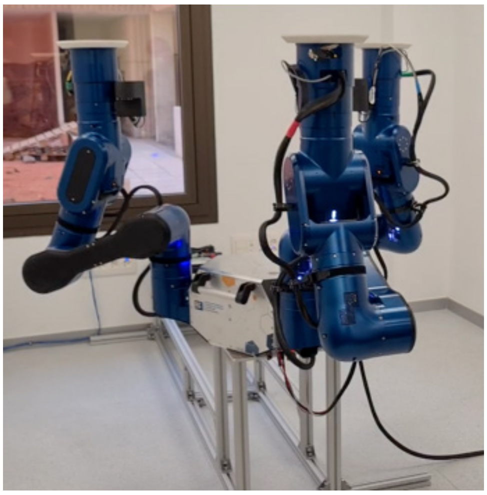


Figure 23 - 3-arm Installation Robot MIRROR.

Figure 24 - ESTEC Life&Physical Sciences Clean Room.

Automation and robotics technologies reduce operating cost, increase the performance and the flexibility of space infrastructure.

Autonomy related R&D enhance the scientific yield of missions, while technology developments of instrumentation for life and physical sciences enhance the availability of new high-performance instruments for human or robotic space missions. ISRU and advanced life support systems technologies are enabling long term presence of humans in space while improving the efficiency of resource usage and lowering the mass of consumables to be transported.

Technologies for environmental control and life support

Moving towards closed-loop systems entails the conception of regenerative systems based on waste/resource transformation processes, to provide consumables for humans. They include technologies for air processing, urine/water processing, food production, contamination monitoring and control, both for biological and airborne molecular contamination in a closed environment, and the protection and monitoring of environmental hazards.

The technology development for such systems has moved from a process view to a sub-system/ system view. Recent adoption of co-engineering practices, in small-scale industrial consortium setting, have proven to decrease the development time while limiting the technical risk. However, this concerns a limited number of developments and the approach would need to be repeated for full quantification and statistical relevance. Furthermore, to decrease the development time to a fully operational system, demonstrations of the scalability of subsystems in an operational environment (e.g., ISS) are essential before increasing complexity. Gradually adding and improving the capacity of the subsystem will demonstrate its robustness. In addition, synergies with related terrestrial applications R&D, specifically in the low TRL area, are catalysing the development of specific processes and technologies for LSS and reduce development time. These technologies will improve cost efficiency of orbital platforms by reducing the amount of critical supplies to be launched per year.

Robotics building blocks

The main purpose is the development of a set of standard and sufficiently generic robotic elements (physical or software) that can be used across space robotics missions and applications for exploration (Section 5.1.2), space transportation (Section 5.4.1) and telecommunication (Section 5.3.1) to reduce time, cost and increase cross-applications benefits. These building blocks in form of reliable, dependable and high-performance subsystems, components, and software will facilitate the integration of space robots into new space mission applications (e.g., for space safety applications) (Sections 5.2). The development of standard robotics building blocks will enhance the faster introduction of robotic applications into future missions and enable new services and missions, specifically in the fields of on-orbit servicing and on-orbit assembly.

Technologies for active space debris removal and reuse

Active Debris Removal controls the risk of defunct satellites fragmentation by deorbiting them. With the ADRIOS mission, ESA is addressing the demonstration of such space application. The collision risk on defunct satellites can also be controlled by attaching them to a system that can actively perform collision avoidance manoeuvres.

A large structure can be used to cluster a number of defunct satellites. The subject of spacecraft clustering technologies addresses the operations of collecting defunct satellites, tugging them to the structure, attaching them to it.

Clustering satellites is the way to transition from Active Debris Removal to Active Debris re-Use. Debris are at the moment a liability, but they can become in the future an asset as their components and materials can be reused for manufacturing other spacecraft in orbit. (Section 5.2 and Section 2.5).

These technologies are essential to achieving the technology strategy target aiming at inverting Europe's contribution to space debris by 2030, and instrumental in supporting European companies to benefit from the associated emerging and potentially large commercial market (Section 3.4).

In-orbit assembly and robotic modular space systems

Space applications increasingly demand operational flexibility of space infrastructure. Flexibility typically comes at the high cost of the complete replacement of space assets. Technologies that allow spacecraft to be reconfigurable in orbit offer an alternative to the reduction of lifetime to allow operators to be more responsive to changing markets (Section 2.8). The development of standardised modules and robotic technology (manipulation and interconnects) will enable the robotic replacement of payloads in orbit and reconfigurable space assets. It will therefore improve cost efficiency by allowing the replacement of just the elements of the spacecraft that are obsolete or no longer providing value.

Large sizes are of special interest for some satellite systems. In particular, the size of reflectors (radio or optical), solar arrays, radiators and shields/shrouds has increased substantially. The ever more complex mechanisms needed to deploy these appendages from packed launch configurations to their operational configuration reach levels that make space robotic systems more advantageous. The development of robotically operated interconnection systems and specialised manipulation and transportation robot systems will enable robotic in-orbit assembly of appendages made out of modules.

Finally, robotic assembly, population and maintenance of extremely large space structures, spanning hundreds of meters, are relevant to the development of Space based Solar Power Systems.

These systems which aim at providing power from space either in in form of microwave beams or reflected light or laser beams, require assembly of very large reticular structures, the installation of mirrors/solar panels/RF equipment/distributed RCS/harness and the continuous maintenance of all these. This can only be realised by robot crews which will probably be specialised (e.g., transport robots) as well as of general use (e.g., installation robots) and finally anthropomorphic (for highly dexterous ground-teleoperated work).

Instrumentation for health monitoring and countermeasures, telemedicine applications

The main technology objective in the field of instrumentation for medical instrumentation and countermeasures is to spin in terrestrial applications for human spaceflight. Medical diagnostic tools for astronaut health to enable routine monitoring and potential emergency response are required. Environmental monitoring technology (radiation, habitat atmosphere) will improve the cost efficiency of human missions by enabling longer human spaceflight with reduced ground personnel. Space-based telemedicine applications have demonstrated their value during the COVID pandemic[27], enabling resilient decentralised health care and fast crisis responses.

Instrumentation for life and physical sciences and for exploration

Miniaturisation and transfer of novel lab-based measurement technologies will enhance the understanding of gravity related phenomena via experiments on the ISS and the lunar gateway, prepared by cost-effective ground-based experiments using hypergravity and low gravity simulation.

The main technology development focus for instrumentation for exploration missions and in situ measurements for planetary exploration is to reduce their development cost while maintaining or increasing performance parameters (Section 5.1.2). This will be achieved mainly via the spin-in of novel technologies and their qualification for space applications.

Autonomy in Exploration

In the field of autonomy, the technology development focuses on next generation logically autonomous systems that will leverage on autonomous decision-making, cooperative exploration, and cooperative assembly and construction for exploration needs (Section 5.1.2). Autonomy improves cost efficiency by enhancing the science return for a given mission and by reducing the effort on ground control.

Technologies for in situ resource utilisation

The main focus is the development of new ISRU processes, the upscaling of known processes from laboratory and pilot projects to higher TRL, their implementation in relevant environment and robotic technologies for feed stock, consumables and product handling to enable and enhance exploration missions (Section 5.1.2). ISRU will improve cost efficiency of space exploration by reducing the amount of supply needed for future planetary missions.

27. “Space-enabled mobile bio-lab to test key workers for COVID-19”, 9 June 2020, www.esa.int/Applications.

6.7 PROPULSION, SPACE TRANSPORTATION AND RE-ENTRY VEHICLES

CD7

Propulsion, space transportation, and re-entry vehicle technologies jointly enable Europe's independent access to and use of space. Technology developments contribute to achieving the ESA technology strategy targets 1 and 3, decreasing the time to market and the faster adoption of cutting-edge technologies, via the demonstration of new technologies on complete platforms rather than in isolation. The development of state-of-the-art simulation and test facilities is essential to reaching these objectives, complemented by in-orbit demonstration where necessary. Integrated in the Agency's digital agenda, key technologies enable engine health monitoring, intelligent control technology (self-regulation) and vehicle testing through simulation. The following main technology areas implement this strategy.

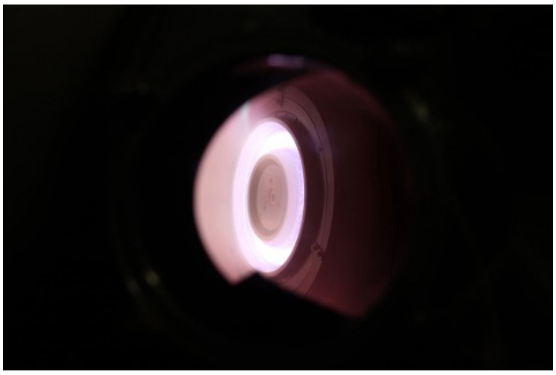


Figure 25 - Demonstrating the principle of air-breathing electric propulsion.

Figure 26 - ExoMars Parachute Inflation.

Propulsion Technologies

Technology developments in space propulsion enable the European access to space and the development of new space missions, covering chemical, electric and further advanced propulsion concepts. They are structured according to three strategic pillars:

1. Develop propulsion (sub-)systems to enable new, emerging applications and satisfy new requirements (non-toxic propulsion, retro-propulsion, throttle-ability, very high thrust), focussing on the reduction in development time and cost improvement.
2. Develop new re-usable propulsion technologies, components and systems (engine re-usability, re-fuelling of tanks) to enhance the creation of new markets in propulsion technology in Europe, focusing on the adoption of innovative new propulsion technologies and reducing space debris.
3. Develop propulsion technologies to enhance the reliability and competitiveness of European propulsion products and processes, contributing to all four of ESA's technology strategy targets.

The development of enhancing propulsion technologies will support the nascent European New Space industries by focusing on cost reduction and adopting a design to produce approach. Of particular importance are developments towards industrialisation of electrical propulsion, including high thrust and long-life systems, cost-reduction and production improvements for all propulsion systems, and thereby fostering and driving the development of propulsion for small satellite systems.

The development of simulation, testing, and diagnostic propulsion tools will enhance the capability for independent forecast and validation of the performances of European propulsion systems and components. They are also essential for innovative new technologies such air breathing engines for planetary orbiters.

Space Transportation Technologies

The technology developments in support of the European strategy for Space Transportation systems focus on enabling re-usability (including the development of intelligent hardware to increase reliability and autonomy), develop hypersonic sub-orbital, and orbital flight capabilities (for future advanced launchers and future point to point transportation, and their business cases), and enabling space servicing that includes tugging, payload exchange, re-fuelling and storage, in-orbit assembly, life extension, and active debris removal (Section 5.4.1).

These enabling developments contribute to the logistics framework for high-cargo routes in Low Earth orbit, transfer to the Moon, or other planetary bodies. This is complementary to supporting the existing markets already thriving in Earth orbit, by improving modularity and assembly, cost reductions, and re-using systems.

New multi-physics simulation, testing, and diagnostic tools, using of artificial intelligence to speed up computations, will enable the forecast and validation of performances of European systems and components, essential for de-risk, acceleration and cost reduction.

(Re-)Entry Technologies

Entry, together with descent and landing, technologies are enabling technologies for new services for return from space. They aim at non-destructive Earth and planetary (re-)entry, including advanced materials, precise guidance, navigation and control concepts, novel thermal subsystems, and structures. Applications of these technologies centre around increasing the capability of decelerator systems to enable high speed interplanetary entry for larger masses. In particular, the (Re-)Entry Technology developments will enable an operational capability to

1. Design, assess, and develop the performance of any (un)propelled flight vehicle along any trajectory or orbit (gaining one order of magnitude cost efficiency);

2. Assess life-time and endurance of any (un)propelled vehicle and its subsystems covering re-usability, expandability, and demise, and to maintain, evolve, and develop multi-disciplinary methodologies and transdisciplinary methods and techniques (cut 30% development time, one order of magnitude cost efficiency);

3. Allow near equilibrium glide efficient flight via new and revolutionary aerodynamics shapes (cut 30% development time, one order of magnitude cost efficiency);

4. Design and develop new thermodynamics systems providing efficient heat transfer (gain one order of magnitude cost efficiency, 30% faster development, inverting Europe's contribution to space debris);

5. Cover steady and transient flow related flight regimes in a wide range of speeds: from zero to hypersonic speeds, from incompressible liquids to highly compressible gasses and plasmas, from internal to external flows, from inert to chemically highly reactive (one order of magnitude cost efficiency); and

6. Deliver with high accuracy, performance, and safety all kind to payloads in a great variety of flight regimes (gain one order of magnitude cost efficiency, 30% faster development, inverting Europe's contribution to space debris).

The development of advanced GNC systems for (re-)entry will enable safe and precise (pin-point) landing capabilities through an enhancement of on-board autonomy (e.g., by means of real-time computation of trajectory guidance adjustments) and flying qualities (Section 6.3).

The in-orbit demonstration and maintenance of test beds and testing facilities for flight physics, aerodynamics, thermodynamics, decelerators, and fluid dynamics systems enhance the further reduction of system development time. Similarly, the development of new simulation, testing and diagnostic tools capable to support the forecast and validation of re-entry systems, enhance the reduction of development time and cost efficiency.

Planetary aircraft and submersibles

Technologies developed under the previous three areas in turn enable an area where all of them are integrated in vehicles used in the Earth and other planetary atmospheres and fluids. Enabling technologies in engine design and aerothermodynamics models lead to novel air breathing engines and open the door to planetary submersible and rotor designs.

6.8 GROUND SYSTEMS AND MISSION OPERATIONS

CD8

Mission operations represent typically between 3 to 9% of the total mission cost. The lower end is represented by standard and repetitive Earth observation missions, while the higher end is usually represented by complex interplanetary missions. The main focus for technology developments therefore targets new operational concepts and space communication techniques that reduce development time and cost, and allow faster adoption in mission operations.

Figure 27 - Ground Stations at New Norcia (AU) and Malargüe (AR).

The major drivers for technology developments are grouped into advanced operation concepts, tracking, telemetry and command technologies (radio and optical frequencies), space debris detection technologies, and mission operations data systems and their standardised interfaces.

Advanced operation concepts

Artificial intelligence, data analytics and the use of digital twin spacecraft will allow more effective, automated and economical operations. Large-scale international cooperative missions, e.g., robotics and/or human lunar and Mars exploration, will necessitate distributed and shared operations with associated innovative and cyber-secured data systems (Section 5.1.2 and Section 2.6). These require the initial demonstration in analogues on Earth before being deployed in space. The ESOC seamless response to the COVID pandemic has further confirmed the trend towards ubiquitous distributed operations. Modern human-machine interface methodologies like augmented and virtual reality (AR/VR) are introduced in support of future operational scenarios.

Tracking, Telemetry, Command Systems and Payload Data Transmission Systems in Radio Frequencies

Tracking, Telemetry, Command (TTC) Systems and Payload Data Transmission Systems (PDT) in Radio Frequency (RF) enable safe spacecraft communication, position, navigation, timing and high-rate transmissions. Enhancing technology development activities aim to maximise the exploitation of the scarce allocated RF spectrum by higher order modulations, variable/adaptive coding and modulation, efficient codes for deep space, arraying of ground antennas, disruption tolerant networking, high power uplink for spacecraft emergency, exploitation of new uplink frequency allocations in X-band for Earth Observation missions, and high rate K-band uplinks for lunar exploration missions. For spacecraft navigation, Ka-band Doppler and Delta-DOR measurements with associated atmospheric and solar calibration will enable a factor of ten improvement in orbit determination accuracy.

Enhancing technologies in the field of radio science include multi-frequency up- and downlinks for the elimination of frequency-dependent phenomena with associated radiometric calibrations of solar plasma, Earth atmosphere including wet and dry troposphere, and those to increase the antenna mechanical performance.

Payload Data Transmission Systems in Optical Frequencies

For payload data transmission systems in optical frequencies, the technology R&D focus is on direct-to-Earth communication for increased data return or substantially smaller on-board systems compared to RF, with the potential to becoming game-changing technologies, as the corresponding ground terminals are small (60-100cm) optical antennas for LEO up to Lunar distance communication with data rates of 1-10Gbps, and large ground terminals (2-12m) for deep space communication with normalised data rates of 100Mbps from 1AU distance or miniaturised on-board terminals at shorter distances, to be demonstrated in cooperation with NASA on the Psyche mission. Synergies with optical telecom feeder links and quantum key distribution ground terminals will allow to maximise the exploitation of the underlying optical and modem technology.

Enabling technologies are therefore cost-efficient large optical antennas for day and night operations with segmented optical mirrors made of aluminium, standard photon counting detectors, high photon efficiency modulation and coding, and high-power laser uplinks with associated safety systems.

Mission Operations Data Systems and Standardised Interfaces

The strategy for data systems aims at multi-mission software application building blocks that cover the full mission lifecycle from concept to operations (e.g., the European Ground System Common Core, EGS-CC). These multi-mission applications need to be extended to support future missions, thus enabling significant reduction of development time and cost. This Includes the provision of mission operations data systems “as-a-service” where required.

A main technological challenge is to keep the development pace with the fast-changing terrestrial IT sector (e.g., cloud/quantum computing, containers, DevSecOps, AR/VR, advanced MMI, AI, digital twins, model based system engineering, cybersecurity) and, at the same time, mediate with the often conservative on-board environment. Such technologies when not mission enabling tend to be discarded, translating in missed opportunities and limited innovation. ESA therefore actively supports in-orbit-demonstrators (e.g., OPS-SAT) to validate some of these technologies.

Responding to increasing mission requirements (e.g., rover/exploration missions, constellations, HAPS, CubeSats, space safety), technology developments are needed in the field of large data volumes, high-fidelity simulators, and distributed operations, always aiming to automatise and harmonise similar functionalities across domains.

The establishment of standard interfaces, in particular towards distributed, service oriented and net-centric communications and operations architectures will enhance cost and schedule reduction, and add flexibility. CCSDS based mission operations services, file-based operation and delay tolerant networks will be game changing technologies leading to a space-ground single system and to a re-usable standard on-board reference architecture.

6.9 DIGITAL ENGINEERING

CD9

Digital engineering for space missions is an integrated approach that uses authoritative sources of system data and models as a continuum across disciplines to support the end-to-end engineering process and all lifecycle activities. This ranges from concept through to mission disposal, and across both the space and ground segments. It also includes methods and tools to enable and maximise data exploitation.

As already taking place outside space in Industry 4.0, digital engineering covers all disciplines supporting the engineering, production and operations of systems. The introduction of digital engineering aims to reduce time-to-market and cost, and supports customisation and flexibility in the engineering and design of the systems. It also enables consistent management of the increased complexity of new systems. It is centred around a new way to approach the complete system lifecycle from requirements, to design, production, verification, assurance and in-flight operations, based on a digital representation of the system. Digital models and tools will be used to digitally represent the system of interest at all levels, from the overall system-of-systems, down to equipment and parts. It will include digital representations of the environment and of all engineering and management processes.

Following the emphasis given since 2018 (Section 2.4) and the resulting activities supported by the Discovery, Preparation and Technology Development elements of the Basic Activities, the transition to a digital model-based approach is well advanced. A large number of ESA missions are already implementing model-based engineering, including: EUCLID (Phase C/D), PLATO (Phase C/D), Galileo 2nd Generation (Phase B2), Ariane 6, Mars Sample Return ERO (Phase B2), ADRIOS, ARIEL, EL3, I-HAB, Envision, Truths, CHIME, EGNOS, LCNS and SAGA (all Phase A/B1).

This paradigm shift will allow the radical reduction of costs in industry and ESA by enabling the use of the native engineering models and tools as the basis of reviews and deliverables, instead of (or to supplement) traditional documents. This also requires adapting the procurement processes. Furthermore, the use of digital models allows the technical management team greater access to the system data itself. This will allow the use of tools working on the data for consistency, traceability, system optimisation, and cross-discipline consistency among others.

Digital engineering and data exploitation relies heavily on some technologies and disciplines, which have not previously been at the core of space system engineering. These include model-based techniques, big data analytics, artificial intelligence, virtual and augmented reality, advanced simulators, autonomy, and cybersecurity. The challenge is to efficiently spin-in these techniques, adapting the related processes and tools to enable their use and maximise the benefits in the space engineering context.

To allow the space sector to fully benefit from these developments, several ambitious steps are necessary. Beyond the applications of Model-Based Systems Engineering (MBSE) already in place, the development of further tools and refined processes is necessary. This will require Digital Continuity to extend and interconnect this model-based approach across all design disciplines, and other space project processes (e.g., procurement, manufacturing, qualification, verification).

Insights into the system via the model data and sensor data needs development through advanced data representation and analytics tools. These will extract information from heterogeneous, scattered and distributed data sources (space and non-space data) to build both data-driven and user-centric representations. Effective methods and tools for data sharing, inspection (e.g., visualisation), collaborative use, and dissemination need to be developed. The near-term focus is on AR/VR and advanced digital model interface techniques.

Digital engineering for spacecraft operations addresses the need for advanced onboard autonomy, for higher system robustness, for cost reduction related to the operational burden induced by an exponential increase in the numbers of satellites on-orbit. The OPS-SAT mission allows already novel autonomy technology demonstrations, such as autonomous scheduling, opportunistic science and autonomous decision-making.

Artificial intelligence will be harnessed further to allow designers, operators and autonomous spacecraft to make decisions during mission development and on-board navigation in challenging environments. An AI roadmap for operations has been developed, with a prototype for an AI-powered assistant to operations already receiving good feedback. Advanced cybersecurity concepts and technologies will improve the security and resilience of European space and ground assets.

Distributed Ledger Technologies (DLTs), quantum-based approaches and High-performance computing in space are considered potentially game changing digital engineering technologies, impacting the future competitiveness of the European space industry.

Fourth, effective concepts, mechanisms and architectures to protect space mission assets and products need to be developed. The systems' safety and dependability needs to be ensured through extensive use of data to support risk-informed decision making throughout the entire life cycle. This will also require efficient and effective means for regulating access to ensure authorised users have access to the right information at the right time to allow an uninterrupted flow of models and data within ESA but also between ESA and industry up to partners and end-users. It will enable access to the right version of the right information in the right form to the right person at the right time.

6.10 ASTRODYNAMICS, SPACE DEBRIS AND SPACE ENVIRONMENT

CD10

Measuring, modelling, understanding and mitigating risks induced by the natural and human-influenced space environment is of increasing importance to all space missions. This requires technologies for the monitoring of artificial objects, determination of their dynamics and precise orbit, for mission analysis and flight dynamics as well as monitoring and modelling for radiation, plasma, atmospheric and particulate space environments.

Figure 28 - ESA's Optical Ground Station.

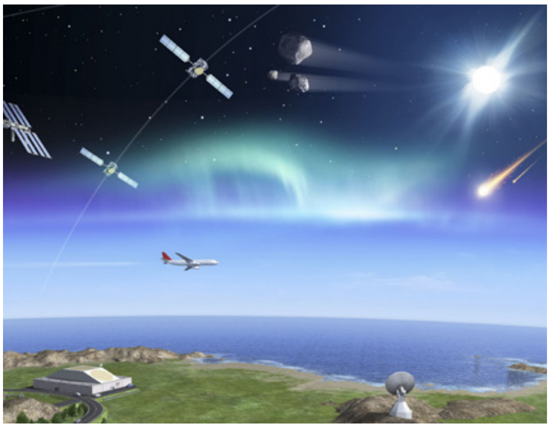


Figure 29 - CD 10 Perimeter.

Space Debris Technologies

ESA's forth technology target aims at inverting Europe's contribution to space debris by 2030 (Section 3.4). ESA's original focus on operational space event predictions, modelling, measurements, and protection allowed the identification of most debris generating sources, a quantification of their effects, improving our understanding of the effects of atmospheric re-entry for risk quantification on-ground and provided Europe with the means to understand and define the effect of mitigation measures. Further efforts to improve risk estimation and modelling of the environment and its evolution are needed to reflect the drastic changes in the use of space as a resource.

Monitoring and sampling the space debris environment needs ground-based and space-based radar or passive optical instrumentation. Further, active optical tracking using laser-ranging techniques even under daylight conditions is evolving and allows for a further evolution towards momentum transfer to induce small velocity changes to space debris. Addressing the current knowledge gap of mm and cm-sized space debris that can terminate missions requires space-based optical observations.

The safe and sustainable operation of space assets is deeply linked to space debris mitigation technologies and the progress towards automation. Technologies and models (such as Digital Twins of the environment and of spacecraft) are essential to enhance Europe's capabilities to predict and characterise space events and to establish a measurable logic (an index) for assessing the environmental criticality. Improved risk assessment methodologies and transparent assessment tools are needed. Europe's technical lead in the understanding of the space debris environment guarantees its authority in driving related regulations and policies.

Space Environments and Effects Technologies, Tools and Methods

The understanding and modelling of environments of concern to space system development and operation, and the capabilities for quantitative assessments of their effects enhances the reliability of space missions. These environments include radiation, plasma, atmospheric and particulate environments, which are described by statistical or physics-based models. Monitoring of the space environment feeds into modelling and enables post-event analysis of anomalies, the forecasting of radiation storms, build-up of differential potentials and hazardous discharges and mitigation of hypervelocity impact damage.

Development and adoption of innovative technologies has been accelerated through flight opportunities for in-orbit demonstration of environment monitoring units. This facilitates direct procurements for operational and science missions. It Is vital to complement these with opportunities for microparticle detectors and plasma instrumentation currently under development, including miniaturized environment monitors and charging mitigation devices .

Deeper space environment understanding, through more sophisticated modelling, allows for reduction of uncertainties, especially in poorly explored regions, leading to reduction in conservatism and spacecraft development costs. New modelling methods, using new extensive data sets and capable of capturing environmental variability, have been derived for the Earth's plasma, radiation and microparticle environments to mitigate storm risks through forecasting. To reduce spacecraft development time and costs, new data sets and modelling methods are being combined through digitised work flows, such as for internal charging and single event effect analyses.

Astrodynamics – Space Flight Dynamics Technologies

Mission Analysis and Flight Dynamics services are provided for all missions with a focus on the design of interplanetary tours, such as planetary and moon swing-by's, missions to the collinear and tri-angular Sun-Earth Libration points, multi-revolution solar electric propulsion transfers (to GTO, MEO and escape) and on cis-lunar locations for robotic and human exploration (Section 5.1.2). This typically includes the assessment of the navigation requirements for the missions as well as contingency scenario investigations and the provision of all trajectory related products for other sub-systems.

Specific technology developments now allow to fly disposal strategies that guarantee the adherence to the space debris mitigation standards at minimum propellant costs, to proof the compliance to planetary protection requirements or to nuclear safety requirement for exploration missions, even if extremely low probabilities need to be verified. Research activities for flight dynamics operations have enabled new operational concepts for multi-revolution solar electric propulsion transfers, optical/radiometric navigation around small bodies, formation flying and rendezvous. The transition from research to applications of artificial intelligence for flight dynamics allowed for improvements of environmental models and new environment modelling enabling substantial cost reduction.

GNSS Technologies

The drastically increasing number of satellite missions and the progressive movement towards commercialisation are significant key drivers for new and more standardised concepts in spacecraft navigation. In this respect, GNSS technologies are increasingly becoming a cornerstone for standardised navigation concepts, supporting autonomous navigation in a wide range of orbital regimes up to the Moon.

As demonstrated by the International Committee on GNSS (ICG) of the United Nations (UN), optimal performance in the Space Service Volume (above LEO) can be achieved by combining all the available observations from the different GNSS systems in the calculation process for satellite Precise Orbit Determination (POD). Another push, also underlining the importance of GNSS in future navigation concepts, is provided by the development of High Accuracy Services (HAS) for example the Galileo HAS. Next satellite missions ranging from LEO up to the Moon will require GNSS to achieve higher orbit accuracy and increasing on-board autonomy.