This technology strategy is intended to guide the planning, development and implementation of all technology development activities prepared, conducted and coordinated by ESA.

It has been developed involving of all internal technology development stakeholders and shareholders, and confirmed by the ESA DG following the consultation of the ESA Executive Board.
A CALL FOR ACTION ........................................................................................................... 5

Executive Summary ........................................................................................................... 7

Challenges, Opportunities and Targets ............................................................................ 7

TECHNOLOGY STRATEGY ............................................................................................... 9

1 The New Context for Space Technology Developments ............................................. 11
   1.1 Objective ................................................................................................................ 11
   1.2 Rationale ................................................................................................................ 11
   1.3 Methodology ......................................................................................................... 12
   1.4 Missions & Markets .............................................................................................. 12
       1.4.1 Trends ............................................................................................................ 12
       1.4.2 Space Economy ............................................................................................ 13
       1.4.3 Space Value Chain ....................................................................................... 13
       1.4.4 Space 4.0 - European Reliance on Commercial Markets ....................... 15
       1.4.5 Competitiveness of European Space Industry ............................................ 16
   1.5 Related Mega Trends ............................................................................................ 16
       1.5.1 Big Data .......................................................................................................... 16
       1.5.2 Digitalisation and ‘Industry 4.0’ .................................................................. 16
       1.5.3 Artificial Intelligence ..................................................................................... 17
       1.5.4 Cybersecurity ................................................................................................. 17
       1.5.5 Quantum technologies ................................................................................. 18

2 From Mission Needs and Technology Innovation to Technology Themes ................ 19
   2.1 Mission Needs and Technology Innovation ......................................................... 19
   2.2 Advanced Manufacturing .................................................................................... 21
   2.3 Digital Design-to- Produce .................................................................................. 22
   2.4 Cleanspace / Sustainability .................................................................................. 25
   2.5 Cybersecurity ....................................................................................................... 26

3 Technology Development Targets .............................................................................. 28
   3.1 30% improvement of spacecraft development time by 2023 .............................. 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 ................................... 30

4 Technology Portfolio Strategy ..................................................................................... 31
   4.1 European Space Technology R&D ................................................................. 31
   4.2 ESA Technology Portfolio Management ......................................................... 31
   4.3 Enabling Core Technology for Space Mission Needs ...................................... 33
   4.4 Enhancing Technology ....................................................................................... 34
   4.5 Game-Changing Technology ............................................................................ 34
MISSION NEEDS AND TECHNOLOGY INNOVATION

5 Mission Needs

5.1 Science and Exploration Technology Needs
5.1.1 Science
5.1.2 Exploration

5.2 Space Safety and Security Technology Needs

5.3 Applications Technology Needs
5.3.1 Telecom
5.3.2 Earth Observation
5.3.3 Navigation

5.4 Enabling and Support Technology Needs
5.4.1 Space Transportation
5.4.2 Operations
5.4.3 Generic Technology

5.5 European Space Industry Technology Needs

6 Technology Innovation

6.1 Electric, Electronic, (Micro-)Electro-Mechanical and Photonic Systems
6.2 Structures, Mechanisms, Materials, Thermal
6.3 Avionic Systems
6.4 Electric Architecture, Power and Energy, Electro-Magnetic Compatibility
6.5 Radiofrequency & Optical Systems
6.6 Life & Physical Science Payloads, Life Support, Robotics & Automation
6.7 Propulsion, Space Transportation and Re-entry Vehicles
6.8 Ground Systems and Mission Operations
6.9 Digital Engineering
6.10 Astrodynamics, Space Debris and Space Environment
A Call for Action
Executive Summary

Challenges, Opportunities and Targets

The successful implementation of this strategy will allow the European space sector to maximise its competitiveness and achieve its ambitious goals.

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 downstream services along with the emergence of 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 concrete and measurable ambitious targets:

1. 30% improvement of spacecraft development time by 2023
2. One order of magnitude improvement of cost efficiency with every generation
3. 30% faster development and adoption of innovative technology.

The development of technologies and concepts to enable the sustainable use of space such as debris mitigation and removal, and in-orbit spacecraft servicing will enable

4. Inverting Europe’s contribution to space debris by 2030, allowing future generations to continue making full use of space.

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.
Technology Strategy
1 The New Context for Space Technology Developments

1.1 Objective

ESA develops the technologies needed for European 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, and reduces the associated risk.

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

1.2 Rationale

ESA’s strategy is built upon the foundation of excellence in space science and technology.

![Figure 1-1: European Space Strategy](image)

This excellence enables Europe to fully integrate space into the European economy and society, to maintain a globally competitive European space sector and European autonomy in accessing and using space.

The technology strategy provides the guiding elements and technological topics and directions for ESA’s technology development activities. This strategy will therefore also allow ESA to provide the technical expertise needed by the European public sector (Member States, European Commission, Eumetsat) and private sectors (industry, new space sector) for their space activities.

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1 Draft ESA Long-term Plan 2019-2028 (ESA/C-M(2018)7);
The Director General’s Proposal – A United Europe in Space (ESA/C-M(2018)1)
1.3 Methodology

This strategy is based on the directions defined by the Director General related to technology as a result of his consultations with Member States, industry, the scientific and academic community and the general public, and on the diverse ESA Executive internal competence and expertise. The strategy development process has identified, discussed and distilled the short to mid-term needs for ESA programmes and projects (chapter 5) and the mid- to long-term technology innovation (chapter 6) performed via the 10 ESA competence domains. The analysis of user needs and technology innovation has led to recurrent common technology themes (chapter 2) and the development of concrete technology development targets (chapter 3) to be implemented via a technology portfolio strategy (chapter 4).

The present 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 process.

1.4 Missions & Markets

1.4.1 Trends

The maturation of the space sector and the integration of space products into modern economies implies the serving of new customers and the design of new space systems to support, take advantage and be integrated with user services, ground networks and ubiquitous smart devices.²

The maturing space sector is also characterised by the entrance of commercial space actors into domains previously supported only by space agencies. These new actors and commercial approaches to space activities contribute to the overall competitiveness of the European space sector, while also creating new international competitors.

Consequently, cost-effectiveness and time-to-market assume a central role in the development of space systems (including their ground segments), resulting in the need to reduce time and costs for satellite design, manufacturing, assembly, integration and test.

² This section is based on the analysis provided in ESA/C(2018)71 “The European Space sector in the global context, ESA Annual Analysis 2017-2018”, Paris, 7 June 2018.
1.4.2 Space Economy
The evolution of the space economy\(^3\) is forecasted to be driven by the following factors:
- **technological advances** creating expectations of more cost-effective (and therefore profitable) space activities;
- increased **private sector investment** by investors who are new to space;
- a global economy that is increasingly **data dependent** with diverse consequences on space capabilities and markets; and
- an increasingly widely-shared vision of space as transformative for humanity.

Space continues to attract attention from investor communities worldwide. Space ventures appeal to investors because new, lower-cost systems are envisioned to follow the path terrestrial technology has profitably travelled: falling system costs and massively increased user bases for new products, especially new data and telecom products. After a ten-fold increase in venture capital and seed investment in space start-ups from 2014 to 2015, such investment has remained relatively steady from 2015 to 2017, totalling between $2.5 and $3.0 billion annually, around 5% of governmental annual investment.

1.4.3 Space Value Chain
Worldwide, satellite services revenue is the largest space industry segment, powered by consumer satellite television broadcasting, satellite broadband and Earth observation services. Satellite ground equipment revenue represents the second largest segment dominated by satellite navigation equipment for both consumer and industrial customers. Satellite manufacturing revenue represents the much smaller, third largest segment, under increasing competitive pressure and facing reduction of the generally decreasing average size, mass and cost of spacecraft (with the increase in the number of cubesats and small satellites) and the reduction of the revenue share from communications satellites. Satellite launch services industry revenue, is the smallest revenue segment, with commercially procured launch revenues slightly larger than the ones for launching government satellites.

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\(^3\) As defined by the OECD, the Space Economy is 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.
The New Context for Space Technology Developments

Technology Strategy

The ESA technology development portfolio and its prioritisation need to take into account the nature of this evolving space market and its value chain, and the positioning of ESA in this, in supporting, structuring, enabling and directing roles. It needs to take into due consideration the fact that satellite manufacturing and launch services are only a small part of the value adding chain, and that growth is essentially driven by the attractiveness of space asset enabled services.
1.4.4 Space 4.0 - European Reliance on Commercial Markets

The overall European space market has grown substantially since 2002, despite and during the financial and economic crisis following 2008. European industry relied on commercial and export customers for 45% of its turnover in 2015, which provide the volumes key to enabling Europe’s institutional space ambitions. The growth of Europe’s still dominant institutional space sector has been close to that of the commercial space sector.

Against this background, with pressure from international competition benefitting from larger closed domestic institutional markets, it is unlikely that European commercial space profits will be sufficient to take over from governments the funding of basic space R&D infrastructure.

The Earth observation market is commonly expected to follow the same pattern of development as the commercial telecommunication space market, which resulted in strong European commercial leadership, while the space navigation market is mostly driven by institutional procurements. In the downstream, which represents a very large percentage of the overall business, European players have a limited role in the mass market, while playing a more substantial part in the professional user segment.

Since the European institutional satellite market represents only a fraction (15-20%) of the world market, the commercial and non-European institutional markets are fundamental for European industry. Similarly, satellites integrated outside of Europe are a source of activity for payload, equipment and component suppliers. Technology will be one of the deciding factor for future opportunities. Industrial needs for competitiveness therefore are an essential driver for ESA’s technology strategy.

Institutional and commercial markets operate on different time scales. Institutional projects for ESA, other European institutions and national programmes are mostly scientific or pioneering operational systems. Despite substantial time reductions in development due to increased efficiency and new working methods (expected to be improved further with digitalisation) institutional projects tend to have long development times from concept to implementation, allowing for significant risk-taking for the inclusion of new technologies to better achieve mission objectives.

Analog to the aeronautics sector, the market for spacecraft production is expected to remain driven by sales to institutional customers. A century after the invention of the aircraft and domination by commercial services, the institutional market drives and funds most technology development. In parallel
to the aeronautics market, space market technology might therefore be expected to remain driven by military and science-related hardware developments, focused primarily on performance rather than on price.

However, the increase in international competition and reduced profit margins require European industry to reduce the cost of commercial space systems. Therefore, ESA needs to support industry with technology that helps reduce production costs and increase production rates, while fostering novel technology that encourages unique capabilities.

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 fully in to account in the development of this strategy (section 5.5).

1.5 Related Mega Trends

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.

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

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4 ADS-Eurospace, Space RTD Priorities 2020, 2016, retrieved 7 May 2018
conceived, manufactured and qualified. They are at the heart of ‘Industry 4.0’ and the ‘smart factory’ approaches for 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 to Europe. They allow the transition 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 demanded by the Space 4.0 era.

1.5.3 Artificial Intelligence
Given the real-life benefits already seen by early adopters, artificial intelligence (AI) is considered to be at the core of the next wave of digital disruption, accelerating competition and speeding up digital transformations.

Worldwide public and private sector AI investment is 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 (particularly suited for health care), natural languages (education), 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. European space industry and services capitalise on previously academic-driven research, with first applications being demonstrated. The HyperScout imager for instance, tested in orbit aboard the Gomx-4B cubesat acquires and processes hyperspectral environmental imagery on an autonomous basis, deciding when surface changes such as flooding, drought or fire hazards require an alert to be sent to mission control.

1.5.4 Cybersecurity
Global annual cybercrime costs are estimated in terms of a trillion dollars, and 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 protect from damages, both private and public enterprises are increasing their information technology security spending.
Space systems, fast becoming more interwoven with critical terrestrial infrastructure, are not immune to cyberattacks. Cybersecurity therefore has become a critical requirement for next generation space systems.

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. The European Commission has created a Quantum Technology Flagship, foreseen to provide €1 Billion funding over 10 years.

The potential of quantum technologies has been reported on by several high-level ESA advisory bodies. These have resulted in recommendations regarding the high potential for future scientific activities and in R&D activities on the topic can improve the fields of telecommunications, science and optics. ESA has engaged in a range of state of the art quantum technology activities from cold atoms for atomic clocks to quantum encryption and quantum metrology, which might evolve into a new cross cutting technology theme.

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5 E.g. Gravitational Observatory Advisory Team (GOAT) to the SPC and the High-Level Science Advisory Committee to the ESA DG
2 From Mission Needs and Technology Innovation to Technology Themes

2.1 Mission Needs and Technology Innovation

The analysis of the different user needs (Chapter 5 Mission Needs) combined with the evaluation of the evolution of technology innovation and the resulting capabilities according to ESA’s 10 competence domains (Chapter 6 Technology Innovation) 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 represent an evolution of past analysis that has led to the introduction of cross-cutting initiatives at the ESA Council meeting at Ministerial level in 2012 in Naples and their revisions in 2014 and 2016. These 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 sector’s need for increased flexibility and reduced production costs (section 5.3.1), and for the miniaturisation and the increasing demand for faster standardisation for 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, European space industry has underlined the need for technological advances in new materials and manufacturing processes and methods for their competitiveness (Section 1.4.5). Many of these technologies and processes have been developed in and for other sectors. The European space industry needs to benefit from their fast spin-in.

Advanced Manufacturing (section 2.2) bundles and focuses these needs into actionable, concrete and coherent technology development roadmaps, ensuring cross-fertilisation between the different related technology development streams and application cases.

Similar to the transition from print/analogue to electronic/digital, the transition from documents to models enables another order of magnitude efficiency jump. This transition is the engineering part of the general digital transformation, described in ESA’s digital agenda for space. Practically all
space applications have expressed the need for more flexibility to adapt late in the space system design and development process to new requirements and the availability of new technologies. This flexibility is required for the agility of telecom applications to react quickly to market needs and infuse new technologies faster into space systems (section 5.3.1). Similarly, Earth observation (section 5.3.2) and future navigation systems (section 5.3.3) require more agility and speed, and the full modelisation of their products and services from the early design phases able to anticipate and react to changes in the larger terrestrial systems in which their services are integrated.

Future telecommunication systems furthermore require faster times-to-market and thus shorter development phases. The transition to a fully digital engineering workflow, extending the current digitalisation of the payload, promises to almost eliminate interface incompatibility delays and (section 5.3.1). It needs to be based on trusted, authoritative data sources shared among the full supply chain on a need to know basis. The full digitalisation and the transition to model based system engineering is also a key enabler to increase the opportunities for in orbit demonstration and verification, which will be more effective with a flexible spacecraft concept allowing late integration of new technologies, sensors and subsystems (section 5.4.3). The technology requirements from space transportation, dictated by needs for increased price competitiveness, and to be achieved via enhanced versatility and low-cost production, equally call for the full introduction of digital engineering in the transportation system engineering workflow (section 5.4.1).

**Digital Design-to-Produce** (section 2.3) addresses the spin-in and demonstration of the core technologies, which enable 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 the space system engineering, others will need some adaptations and adjustment. The key competence domains supporting this initiative and their technology drive are described in sections 6.1, 6.3, 6.4, 6.5, 6.6, 6.8, and 6.9.

**ESA** has been the global pioneer in introducing sustainability in space activities when it required a long-term vision and courage. The responsible, sustainable use of orbital and other resources has since become a prime concern for the economic viability of some telecommunication (especially mega-constellations) and earth observation businesses (sections 5.3.1 and 5.3.2), and the service reliability of navigation constellation (section 5.3.3). Sustainability and especially the issue of space debris have been highlighted as priority needs by European industry (section 5.5) and are one of the frequently voiced priorities of the public.
Cleanspace / Sustainability (section 2.4) integrates the associated technology development to allow leaving the space environment in an even better stage to future generation. It is addressed especially in the Space Safety and Security Technology Needs programmatic pillar (section 5.2).

The increasing integration of space systems to larger ground systems opens up a new vulnerability of the space system to cyber-attacks. Technologies and methods to enhance the cybersecurity level of space and ground systems have been identified as a new and increasingly important need for space transportation systems (section 5.4.1), for future telecom (section 5.3.1), EO (section 5.3.2) and navigation (section 5.3.3) missions, though generally of concern for practically all space missions. Cybersecurity requires a range of activities in 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.

With the proposed new Cybersecurity theme (section 2.5), ESA intends to group all cybersecurity related technology and engineering activities. These would include in addition to technologies for the above-mentioned activities also technology developments in the areas of cryptography (including quantum cryptography) and optical communication technologies.

Further technological themes will be added as certain technology development needs shared among different applications and programmes emerge and are mature to be pursued in targeted and feasible development processes (e.g. quantum technologies).

System Engineering and Quality Management
The 10 competence domains and their respective technology innovation plans (chapter 6) require thorough system engineering and quality control throughout 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 required to allow ESA to more systematically spin-in terrestrial technologies and offer a tailored risk management capability.

2.2 Advanced Manufacturing
With the Advanced Manufacturing initiative, ESA identifies new materials and processes, and spins-in disruptive materials and manufacturing processes

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6 A proposal for this initiative is planned for the ESA Ministerial Meeting in 2019.
already available in non-space industrial sectors. This allows benefiting from faster processes, shorter lead times for components increased design flexibility and associated cost benefits. Technologies include additive manufacturing, solid state joining, processing of advanced composites materials and forming technologies of large structures to create new high-performance space products without the limitations imposed by traditional manufacturing processing and concepts.

![Advanced Manufacturing](image)

Since some advanced manufacturing processes are readily available in the current European industrial landscape (section 6.2), part of the initiative consists in maturing them to a level suitable for use in space and placing the focus on the verification and qualification processes.

Europe is in a strong position in this field. Many of the advanced manufacturing leading industries have their headquarters in Europe and key space companies have started adopting advanced manufacturing as a standard manufacturing technique. However, the market is evolving very quickly with annual growth rates of up to 40%, which necessitates constant development for maintaining and expanding Europe’s position.

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

### 2.3 Digital Design-to- Produce

Digital technologies have radically changed businesses, industries and societies. Digital engineering is currently enabling a revolution of 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 lengthy document centric traditional design, build and then test process to a model centric analyse and build process more suitable to the new space environment. Using models and high-fidelity virtual environments to prototype, experiment and test options and concepts, means integrating new technologies with a faster pace.

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 willingness of programmes and projects to embrace this approach. In addition, ESA has to introduce a suitable standard for digital engineering, incorporating and harmonising all the relevant elements currently being developed (section 6.9).

In line with the ESA digital agenda for space⁷, with Digital Design-to- Produce, ESA develops techniques to improve the space system end-to-end development process with the aim to reduce engineering lead time and cost. At the heart of the initiative is the challenge to design space systems towards manufacturability, integration and verification and thus the need to feed relevant lessons learned from the manufacturing, assembly, integration and testing process back to the design process (sections 6.2, 6.3, 6.9). This requires a multidisciplinary approach, in-depth expertise and experience across all phases of a space system’s life-cycle.

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.

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 supporting space industry with setting up partnerships and pilot projects with specialised non-space actors for a rapid adoption of smart space factories modus operandi. The initiative will

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⁷ ESA Digital Agenda for Space; http://www.esa.int/About_Us/Digital_Agenda/The_ESA_Digital_Agenda_for_Space
substantially benefit 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.

These projects will prioritise activities aimed at reducing missions schedule and cost. They will cover the entire system lifecycle, from requirements management and design to innovative solutions for the shop floor and adopting adequate tools and methodologies along the following key lines of action:

**Digital engineering**
- Adopting digital model and digital engineering for end-to-end development across the entire supply chain

**Embedded sensors**
- Continuous improvement of design and product based on analysis of data from embedded sensors, both on-ground and aboard, plus streamlined assembly, integration and testing

**Latest generation techniques for the shop floor**
Application of augmented reality and automation techniques and methods supporting execution of assembly, integration and testing, to prevent anomalies and failures and reduce inefficiencies.
2.4 Cleanspace / 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, Cleansat, and Active Debris Removal.

![Image: Sustainability - Key lines of action](image)

**Eco-design**
Developing cleaner space missions requires the understanding of their environmental footprint from the design phase to their end of life. ESA has been pioneering the application of life cycle assessments to the space sector, from understanding the environmental impact of launch vehicles to the environmental footprint left by satellites and ground segments. This allows the identification of environmental hotspots and the development of innovative solutions to decrease the environmental impact. Furthermore, solutions are being developed to prevent potential disruptions to the space industry supply chain from environmental laws and regulations, most notably REACH, concerning the registration, evaluation, authorisation and restriction of chemicals.

**Cleansat**
With Cleansat, ESA aims at the maturation of the technologies necessary to achieve full compliance with space debris mitigation requirements. This is being carried out in a coordinated approach with system integrators and subsystem and equipment manufacturers. Space debris mitigation has been identified by all large European system integrators as the most impacting of
new requirements for future missions and as a high priority for the evolution of current platforms, both for the institutional and commercial markets. Platforms capable to carry out uncontrolled re-entry or controlled re-entry will be necessary and require very distinct technologies.

Building on the work achieved since 2012 for these technologies, Cleansat will bring these to TRL 7 for their systematic use in future missions. Consolidated requirements are necessary to satisfy the actual needs of the platform integrators. This, in turn, facilitates the integration of innovative technologies in the next generation of LEO platforms. Priority areas are power and propulsion passivation, design for demise and effective controlled re-entry.

Active Debris Removal
Satellites reaching their end-of-life need to be removed from protected regions, either to a graveyard orbit or to re-entry. Today, satellites are beginning to be designed to be removed or removable, but further technology developments are still needed to assure full application for all future spacecraft. On-orbit servicing is maturing and operations in space will need to be carried out in an updated and more sustainable manner. Achieving this will require advancements in several technology fields such as advance capturing, image processing and proximity guidance, navigation and control.

2.5 Cybersecurity
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 focussing on safety and reliability, given the harshness of the launch and space environment, cyber security introduces the dimension of intentional, man-made threats in addition 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 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 –both of public as well as of private relevance. For this reason, cybersecurity, which is already a concern, will continue to be an important field to address.
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 plans to address cyber security 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);
- 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 cyber security threat; and
- Integration of security into the ESA system engineering process.
3 Technology Development Targets

3.1 30% improvement of spacecraft development time by 2023

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

Specifically, ESA will:
- Develop technologies to fully digitise the workflow from early concept development, through manufacturing to integration and testing.
- Develop technologies needed to achieve increased flexibility, scalability and adaptability based on modular space system designs and standardization.
- Develop necessary processes to facilitate a fast introduction of new terrestrial technological progress into spacecraft.

Technology developments from all competence domains will be critical to achieving this goal. The success will largely depend on the success of the massive introduction of digital engineering and advanced analytics based on big sensory data, automation and artificial intelligence, especially in those processes driving schedule and cost. The Design-to- Produce and Advanced Manufacturing initiatives will be essential in developing relevant technology and processes. In the application domains, the development of technological building blocks will be essential to provide the flexibility and modularity that will 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 will develop 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 before 2023.
- 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;
- allow transformational science and increasing the science performance to cost ratio by one order of magnitude.

To achieve this goal, ESA will leverage 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 is envisaged.

Special attention will be 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 will
- Double the number of new space system technologies demonstrated at TRL [8/9] per year by 2021 and quadruple this number by 2024.
- Reduce the time from TRL 4/5 to TRL 7/8 by 50% for technologies selected for in-orbit demonstration.
- Double the use of COTS in ESA spacecraft by 2021 via a dedicated COTS strategy.

To achieve this goal, ESA will focus 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 seven 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 will introduce a significantly increased number of opportunities for technology demonstration and verification payloads (IOD/IOV), aiming at systematically adding to all ESA spacecraft launch opportunities for piggy-back cube/smallsats.

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 will
- Ensure that all ESA missions will be environmentally neutral by 2020, thus not producing debris larger than 1mm in orbit.
- Develop the technologies necessary for the successful active removal of space debris by 2024.
- Develop the technology that allows all ESA missions to be risk neutral by 2030.

To achieve this goal, ESA will develop 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 targets are ambitious but realistic and can be achieved by further increasing the management efficiency for these activities and a 20% funding increase of the dedicated technology development programmes.
4 Technology Portfolio Strategy

4.1 European Space Technology R&D

ESA’s technology strategy is conceived to implement the strategic directions of the ESA Director General in form of a coherent and consistent strategy that reflects the dominant position of ESA’s activities on the overall European space technology developments. ESA’s development activities are embedded into a wider European R&D landscape reflecting the maturation of the space sector, the resulting increasing private sector investments in some space technology areas and the substantial investments in space technologies at national level and via the European Union.\(^8\)

ESA leads a voluntary European-wide technology development planning and coordination process involving all major European stakeholders from the public and private sector to fill strategic gaps, minimise unwanted duplications, consolidate strategic capabilities, and enhance the complementary roles of the various European stakeholders.

About €400 million, over half of the approximately €740 million\(^9\) invested in 2016 in public sector space technology R&D in Europe, has been funded through ESA programmes. 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 US, and the increasing support to the space sector granted by governments of emerging space players such as China and India.

4.2 ESA Technology Portfolio Management

ESA’s technology portfolio 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 and innovation (enabling, enhancing, game-changing). These determine the programmatic frame under which to conduct the activities, the appropriate risk levels, the funding levels

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\(^8\) European Space Technology Master Plan 2017, ESA and European Commission.
\(^9\) Complemented by an additional approximate 200M€ per year of industry investment in technology development.
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 are developed as part of ESA’s basic activities, while higher, closer to application and market technologies are typically developed within optional programmes. 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 (e.g. basic activities, GSTP).

The spectrum and range of technology developed at lower TRL is naturally substantially larger to allow exploring new concepts and preparing for parallel mission concepts in Phase A before their selection by programmes. To allow that technology development results not selected for immediate mission implementation to be integrated in later mission, other concepts or outside of the space sector, ESA supports an efficient technology knowledge management, 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.

10 Mandatory budget funded ESA technology development is made as part of Discovery Preparation and Technology Development, and the Science Core Technology Programme. Optional ESA programmes with a strong technology development focus: General Support Technology Programme, Artes AT and CC, Incubed, Navisp, SciSpace, FLPP
One of the core strategic decisions for technology development is on the balance between investing in technology that sustains incremental innovation and technologies that promise 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 US, Europe has a strong mission-focus in its technology portfolio, investing relatively little on enhancing and game changing technology development.

**Partnerships**

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

**4.3 Enabling Core Technology for Space Mission Needs**

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

Their development is time-critical and their availability conditions the readiness of space missions. Most enabling technology 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.

4.4 Enhancing Technology

ESA invests in enhancing technology when these promise substantial performance increases for space applications provided from space. 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.

4.5 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.
Figure 4-2: Approximate relative budgets for enabling, enhancing and game-changing technology developments by ESA
Mission Needs and Technology Innovation
5 Mission Needs

5.1 Science and Exploration Technology Needs

5.1.1 Science
ESA’s Science missions in general, and especially the Large-class missions (currently JUICE, ATHENA, LISA) require the development of often emerging, enabling technologies on the frontiers of what is technically and scientifically achievable. Payloads are provided by member states. Related technology developments are funded under national programmes.

Mission: ATHENA
The Athena mission is a next-generation X-ray space observatory designed to study the hot, million-degree 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 2030. Primary technology focus is on the novel silicon pore optics and on the cooling chain. Mechanical coolers have been developed over many years by ESA. However, the complete cooling chain for meeting the mission requirements is a major challenge.

Mission: LISA
The LISA mission is gravitational wave observatory for observing gravity 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 in 2034. Critical elements that require technology development are the laser system, phase measurement system, optical bench, telescope and micro-propulsion. LISA is expected to produce large quantities of data. Therefore, development of innovative data processing and analysis tools is required.

Mission: ARIEL
ARIEL, the Atmospheric Remote-Sensing Infrared Exoplanet Large-survey, for determining the chemical composition and physical conditions of the atmosphere for a set of exoplanets in the wavelength 2-8μm. The mission
launch is foreseen in 2028 into a large amplitude Lissajous orbit at L2. Critical elements requiring technology development are the primary aluminium mirror and the cooling chain.

Table 5-1: Science missions - Key technology needs

<table>
<thead>
<tr>
<th>Mission</th>
<th>Member State Provision</th>
<th>ESA Provision</th>
</tr>
</thead>
<tbody>
<tr>
<td>Athena (L2 mission)</td>
<td>Focal plane instrumentation: Wide field imager X-ray spectrometer (with JAXA and NASA contributions)</td>
<td>X-ray telescope (Silicon pore optics) Cryogenic cooling chain for X-ray spectrometer</td>
</tr>
<tr>
<td>LISA (L3 Mission)</td>
<td>Optical bench, gravitational reference sensor, phasemeter</td>
<td>Telescope, laser system, micro-propulsion system</td>
</tr>
<tr>
<td>ARIEL (M4 mission)</td>
<td>Complete payload module including telescope and focal plane detectors</td>
<td>Cooling chain</td>
</tr>
</tbody>
</table>

The following medium-class mission candidates have been selected in 2018 for the target launch year 2032.

**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, in order 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 data rates and data volumes.

**SPICA**

SPICA is a mid and far-IR observatory, whose key science goals include the galaxy and black hole formation and evolution, resolution of the far-infrared polarisation of galactic filaments and understanding the formation and evolution of planetary systems. SPICA is proposed as a joint mission with JAXA, with payload elements funded by the Member States. The payload consists a 2.5m SiC Ritchey-Chretien telescope cooled to below 8K together with the shielded cryogenic payload module. The two instruments are a Far-IR high-resolution spectrometer (SAFARI) and a Mid-IR spectrometer/camera (SMI).
THESEUS
THESEUS is a mission dedicated to the observation of the high energy transient sky, in particular gamma ray bursts over a wide range of redshifts. The payload consists of a soft X-ray imager, a X-Gamma imaging spectrometer and an infrared telescope.

New Science Ideas
A call for new science ideas was issued in February 2016 to stimulate the emergence of innovative science ideas and future M or L class missions. The scientific peer review process of proposals has led to the selection of three themes:

Astrometry-based on NIR observations.
A weakness of the Gaia astrometry mission is that much of the Galactic centre and the spiral arm regions are obscured by interstellar dust. Traditionally, this problem is overcome by switching to infrared, however, this is not feasible with the current CCD technology. Options for the detector technologies for the NIR need to be investigated (NIR TDI detectors, APS detectors with different scanning/de-scanning methods), taking benefit of the knowledge gained by Gaia.

Small planetary platforms
A recurrent problem of planetary mission proposals is that they are difficult to fit within an M-Class budget envelope. The challenge is to provide a toolbox and building blocks for potential future proposals, rather than defining a very specific mission case. Novel concepts, such as a small platform delivering a set of cubesats for multipoint observations, can provide a fruitful path for future missions. Correspondingly, miniaturisation of optical systems (e.g. cameras and spectrometers) both for remote sensing and in-situ applications is required.

Need for advanced technologies
Optics technologies remain a very important base for future Science missions. Many innovative optics developments are expected to be required in the future, supporting and enabling cutting edge science. This includes cryo-optics for new IR and fundamental physics missions and special optics and systems for unusual environments (e.g. high radiation, high temperature, high g-loads, Venus atmosphere). Furthermore, scientific missions are usually pushing the technical feasibility in terms of stability and accuracy requirements.
Quantum technologies
Quantum technologies are a major enabler of potential future fundamental physics missions. The current lack of suitable space qualification and heritage of such technologies is proving to be an obstacle for innovative mission proposals. The focus is on the boundaries of and relationship between quantum and classical physics, in particular quantum de-coherence for massive particles.

5.1.2 Exploration
We are on the verge of an international drive to send robots and humans to the Moon and Mars, in which Europe wants to play an important role. While many exciting and rewarding opportunities exist, the key will be to focus on and prepare for those missions and roles of primary interest to Europe. Similarly, having gained the capability to live and work in Low Earth Orbit, it is necessary to give attention to the era beyond the ISS and consider the priorities and infrastructure solutions for the future of Europe’s involvement in exploiting LEO.

ESA’s 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. It is using a space exploration mission framework concept consisting of exploration cornerstone missions to be implemented with international or commercial partners, technology demonstrator missions, and missions of opportunity.

There are four possible exploration cornerstone missions planned for the period starting after the next ESA ministerial Council in December 2019:

1. Continued and sustainable human activities in LEO beyond 2024 (ISS and transitioning to post-ISS);
2. Human-beyond-LEO exploration through European participation in the “Lunar Orbital Platform-Gateway”;
3. Robotic sample return mission with European contributions to Mars Sample Return (MSR) as primary target and to other sample return missions (Phobos Sample Return; Lunar Polar Sample Return) as affordable backups; and

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4. Long-term lunar surface exploration, initiation with a robotic lunar surface precursor mission enabled by the “Lunar Orbital Platform-Gateway”.

To prepare for future sustainable exploration, investments in technology developments are required in each of the following technologies:

- Propulsion
- Life support
- Autonomy/navigation
- Energy
- In-situ Resource Utilization

The exploration technology roadmap shows the critical technologies with respect to the exploration cornerstones

Table 5-2: Exploration Programme - Key technology development needs

<table>
<thead>
<tr>
<th>Global Exploration Roadmap</th>
<th>Critical Technologies (Summary Table)</th>
<th>Today ISS</th>
<th>Near-Future Moon</th>
<th>Future Mars</th>
<th>Ventures</th>
</tr>
</thead>
<tbody>
<tr>
<td>Propulsion, Landing, Return</td>
<td>Spacecraft: Orion-type crew vehicle</td>
<td>Spacecraft: Orion-type crew vehicle</td>
<td>Spacecraft: Orion-type crew vehicle</td>
<td>Spacecraft: Orion-type crew vehicle</td>
<td>Spacecraft: Orion-type crew vehicle</td>
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<td>Life support: Orion-type crew vehicle</td>
<td>Life support: Orion-type crew vehicle</td>
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<td>Autonomy/navigation: Orion-type crew vehicle</td>
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<td>Energy: Orion-type crew vehicle</td>
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<td>In-situ Resource Utilization: Orion-type crew vehicle</td>
<td>In-situ Resource Utilization: Orion-type crew vehicle</td>
<td>In-situ Resource Utilization: Orion-type crew vehicle</td>
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<td></td>
<td>Closed-Loop Life Support</td>
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<td>In-Flight Environmental Monitoring</td>
<td>In-Flight Environmental Monitoring</td>
<td>In-Flight Environmental Monitoring</td>
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<td>In-Flight Environmental Monitoring</td>
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<td>Crew Health &amp; Performance</td>
<td>Long-Duration Spaceflight Medical Care</td>
<td>Long-Duration Spaceflight Medical Care</td>
<td>Long-Duration Spaceflight Medical Care</td>
<td>Long-Duration Spaceflight Medical Care</td>
<td>Long-Duration Spaceflight Medical Care</td>
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<tr>
<td></td>
<td>Long-Duration Behavioral Health &amp; Performance</td>
<td>Long-Duration Behavioral Health &amp; Performance</td>
<td>Long-Duration Behavioral Health &amp; Performance</td>
<td>Long-Duration Behavioral Health &amp; Performance</td>
<td>Long-Duration Behavioral Health &amp; Performance</td>
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<tr>
<td></td>
<td>Microgravity Counter-Measures</td>
<td>Microgravity Counter-Measures</td>
<td>Microgravity Counter-Measures</td>
<td>Microgravity Counter-Measures</td>
<td>Microgravity Counter-Measures</td>
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ESA unclassified – releasable to the public

43
5.2 Space Safety and Security Technology Needs

Space is a hazardous environment with threats to human safety and infrastructure both in space and on-ground, including naturally occurring threats from space weather or Near-Earth Objects (NEOs) as well as human-made threats such as space debris. The growing importance of space infrastructure puts additional focus on these risks and technologies to manage them.

The proposed space safety programme will contribute to ESA’s goal to “ensure European autonomy in accessing and using space in a safe and secure environment” by activities protecting our planet, humanity, and assets in space and on Earth from dangers originating in space and specifically by addressing three segments: Space weather; planetary defence; and space debris.

The focus of space weather activities is to enable Europe to protect its relevant space and ground infrastructure from space weather events. The focus of planetary defence activities is to enable Europe to have the capabilities to provide early warnings for asteroids larger than 40m in size about three weeks in advance, to deflect asteroids smaller than 1 km if known more than two years in advance; and to be part of a global international effort to address the asteroid threat. The focus of space debris activities is to enable Europe to manage its space-related traffic; to develop autonomous systems capable of removing and avoiding debris; and to develop end-of-life measures for sustainable use of space in an economically viable way.

The related technology needs can be classified into technologies for the detection and analysis of threats and hazards, technologies related to the.
prevention, protection and mitigation, and technologies for the respond and recover activities.

![Figure 5-1: Space Safety - Threat detection, protection and response](image)

It is proposed for Europe, that by 2030, the following should be achieved:

In Space Weather, a Europe able to protect its relevant space and ground infrastructure:
- Space weather services (quantity and quality, tailored to users and actionable information enabling a response);
- Prompt responses based on actionable information; and
- A resilient society (incl. infrastructure)

In Planetary Defence, a Europe with the capabilities to provide early warnings for asteroids larger than 40m in size about three weeks in advance; to be able to deflect asteroids smaller than 1km, if known more than two years in advance; and part of a global international effort:
- An early warning system with prompt mitigation measures based on actionable information; and
- An international planetary defence system based on technological solutions for removal/mitigation of threat

In Debris and Cleanspace, a Europe capable of safely managing its space-related traffic; equipped with (autonomous) systems free from causing damage: capable of removing and avoiding debris; capable of applying end-of-life measures for sustainable use of space in an economically viable way:
- Sustainable European space traffic management including damage and debris avoidance; and
- Capabilities for end-of-life activities.

**Future Capability needs**

Launch systems are putting strict limits in size and mass of its their cargo. Future space missions will require building and operating very large structures in space. In-orbit assembly and manufacturing is the only viable option for some of these structures. New technologies and market needs open up the possibility of servicing on-orbit spacecraft, to re-fuel, exchange payloads and to move into or remove from operational orbit.
The current largest ground-based telescopes use mirrors in the 10m diameter range, with future instruments designed to reach a mirror diameter of 25m or even 40m (European Extremely Large Telescope). Putting a 40m telescope into space would be a challenge, but there are several conceivable ways of creating a large telescope in space. The traditional way is to use a structure with finished mirror segments and then unfolded and aligned them. In orbit manufacturing or assembly could allow space-based telescope comparable in size to the next generation of terrestrial telescopes.

Experience has been gained through the assembly of the ISS, but to build on this experience, a real in-orbit manufacturing capability needs to be established.

### 5.3 Applications Technology Needs

#### 5.3.1 Telecom

ESA’s first telecom satellite, OTS, was launched 40 years ago. It had a mass of 865kg, 600Watts of power and carried six Ku band transponders. Fast-forward to 2017 and 25 out of 90 commercial launches were dedicated to putting 66 telecom satellites into orbit. Their mass, value and orbital positions all confirm telecom as the key customer of the commercial launch market.

The global satellite industry is still growing, but at a declining rate. Revenues are currently being driven by ground equipment sales. Electronically steered flat panel antennas are considered a major enabler for future satcom systems, including large constellations, 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 mobile connectivity, a 10-fold reduction of cost per bit, a 50% reduction of time to market, the provision of higher data rate broadband, low latency solutions and communication security.

Satcom services are a part of the much wider, mainly terrestrial, communications marketplace, which consequently has a significant influence on the positioning and the evolution of satcom services e.g. the emergence of 5G. Other influencers include the Internet of Things (IoT), Machine-to-Machine (M2M), ‘New Space’, ‘Industry 4.0’, and the evolving launcher landscape.
While recognising uncertainty in the continuously evolving telecom market landscape, it is clear that flexible ultra-high throughput satellites, all-IP satellites, mobile broadband, constellations, satcom integration into IoT/M2M, and secure communications will all be potential game changers, that can enable opening up of new markets.

The technology needs for the satcom sector include millimetre wavelength communications (Q/V, W-band) technology, digital processing as part of the full digitalisation of the payload providing operational flexibility, optical communications, and planar and smart antennas (e.g. low-profile beam steering, direct radiating arrays, multi-beam).

In addition, the more generic technology needs for the satcom sector are the spin-in from ‘industry 4.0’ in the form of smart manufacturing (e.g. the automation in manufacturing for series production and advanced manufacturing processes), and the sustainable use of space, especially regarding very large constellations.

The changing market situation and the acknowledgement that game changing technologies are required to compete with terrestrial services has led satellite operators to introduce and fly innovative technologies (Table 5-3).
Table 5-3: Telecom technology needs

<table>
<thead>
<tr>
<th>Area of Application</th>
<th>mm Wavelength Communication</th>
<th>Digital Processing</th>
<th>Optical Communication</th>
<th>Smart Antenna</th>
<th>Smart Manufacturing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flexible Ultra High Throughput Satellite beyond Tbps</td>
<td>Q/V, W band devices &amp; systems, techniques and equipment for ISL, feeder and user links, (incl. RPAS, HAPS)</td>
<td>Digital Signal Processor (e.g. reconfigurable, hybrid transparent / regenerative digital processors)</td>
<td>techniques &amp; equipment for ISL, processing techniques (e.g. routing, multiplexing, frequency conversion, backplanes), feeder &amp; user links, (incl. RPAS, HAPS)</td>
<td>Low profile and electrical / optical steerable multi-beam antenna for ground, radiating arrays, large apertures</td>
<td>Industry 4.0 technology and processes for space: Artificial Intelligence, Augmented Reality, machine learning, COTS, additive manufacturing, sensor network, virtual factory</td>
</tr>
<tr>
<td>All IP, over-the-top convergence &amp; Ultra-High Definition TV Broadcast</td>
<td>ultra-wide band receivers, feeder links</td>
<td>integrated ground / space resource management, smart gateway &amp; networking, beam forming, beam hopping, miniaturisation, chipsets,</td>
<td>feeder links</td>
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</tr>
<tr>
<td>Mobile Broadband</td>
<td>feeder &amp; user links for maritime, land &amp; aeronautical (incl. RPAS, HAPS)</td>
<td>software defined network and virtualisation</td>
<td>Processing techniques</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dynamic Resource Management &amp; Smart Ground Segment</td>
<td>multi-port amplifiers, direct radiating array</td>
<td>ISL, processing techniques, feeder links</td>
<td>low profile &amp; electrical / optical steerable multi-beam antenna for ground and space</td>
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<tr>
<td>Non-GEO systems &amp; constellations</td>
<td>techniques and equipment for ISL, feeder links</td>
<td>ISL, processing techniques, feeder links</td>
<td>low profile &amp; electrical / optical steerable multi-beam antenna for ground and space</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Satcom integration into 5G, Machine to Machine / Internet of Things systems</td>
<td>backhauling, trunking and user links</td>
<td>backhauling and trunking</td>
<td>low profile &amp; electrical / optical steerable multi-beam antenna for ground</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Secure Communication</td>
<td>Secure Processor</td>
<td>quantum communication &amp; quantum key distribution</td>
<td>directed radiating array, optical space &amp; ground terminals</td>
<td></td>
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<tr>
<td>Commoditisation &amp; Automation</td>
<td></td>
<td>serial production, low cost and time to market</td>
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</table>

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.

These systems are centred on two broad activity lines: Research missions, of which the Earth Explorers (EE) are the main part, and Earth Watch missions, which are developed with and for partners. The key Living Planet principle is that all missions, while relying on wide-ranging innovations, are user driven. EE are research driven and also demonstrate new EO techniques. Earth Watch missions are typically driven by operational services, such as those in partnership with EUMETSAT for meteorology and with the EU for the
Copernicus programme.

Overall, the two main technology thrusts for future Earth observation missions are
- Higher performance (including spatial and temporal resolutions), 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 ‘Space 4.0’.

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 high performance instruments need to be complemented by higher levels of standardisation and modularity at platform and associated ground segment (Table 5-4).

<table>
<thead>
<tr>
<th>Table 5-4: Earth Observation technological requirements</th>
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<td>EE10 (3 concepts)</td>
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<tr>
<td>Copernicus Evolution</td>
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<tr>
<td>Space 4.0</td>
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<td>Not-orbiting (incl. HAPS)</td>
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**Earth Explorers**
Earth Explorer missions are funded under the EO Envelope Programme, which supports three types of user-driven Research missions:
- EE Core missions (e.g. EarthCARE, Biomass, EE-10), as major missions to 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 among proposals in reply to call for ideas. The recent EE-10 call resulted three phase 0 activities at the end of 2018.
- EE Fast-Track Missions (e.g. FLEX, EE-9) follow a call for mission concepts process. They are smaller missions and with shorter (starting at Phase A) development cycles 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. The 2017 call
has led to two mission concepts for EE-9, currently under Phase A study: SKIM and FORUM.

• Missions of Opportunity responding to unsolicited proposals for cooperation with entities that are not under the jurisdiction of Participating States of the EOEP. Currently, only one such mission is under evaluation and being defined in detail: The Next-Generation Gravity Mission (NGGM) for sub-surface water and solid Earth dynamics. NGGM’s enabling technologies have been identified and are being developed. The determination of the gravity field is the only mean to probe far under the Earth surface from space and was revolutionised by the GOCE and GRACE Space missions. For further into the future gravity measurements, cold-atom quantum sensors appear promising.

Copernicus Evolution

In collaboration with the EU and driven by its high-level requirements, the Copernicus Space Component (CSC) evolution will 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.
  • 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 (data buy) high spatio-temporal resolution thermal infrared (TIR)
  • 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
  • constellation of miniaturised Ku- or Ka-band altimetry sensors
- **Spectroscopic Imaging Observations capabilities** of the Earth’s Atmosphere. These require the development of the following elements:
  • high-resolution imaging spectroscopy for CO2 Monitoring in NIR and SWIR

A number of technologies (e.g. IR detectors, large scale antenna reflectors,
digital beam forming) 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 just for one mission.

**Non-instrument specific needs for future EO missions**

The EO needs are at end-to-end system level and therefore 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 communalities between missions, with a limited envisaged set of variants to cover specific variations or configurations for e.g. optical or radar missions. There are major questions, challenges and hurdles that need to be addressed:

- Maximise the use of recurrent generic and standardized equipment;
- Reusability of the core avionics for any platform, independent from the system integrator; and
- 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.
- Application of debris mitigation techniques, including standard design and technique for de-orbiting 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:

- 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.
- 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.

**Space 4.0 in EO**
The traditional institutional EO sector has focused on state-of-the-art EO instruments delivering very high quality calibrated data. This approach needs to continue, but also be complemented by international EO collaborations (e.g. with a hosted payload approach) and commercial initiatives, typically based on multiple dedicated small satellites (e.g. cubesats with multiple payload launches and a data-buy approach).

### 5.3.3 Navigation

Satellite navigation focuses on the mechanisms to determine the position of a given user and its course from one place to another, using satellites. The field of navigation includes several categories such as land navigation (e.g. road, rail, agriculture), maritime navigation, aeronautic navigation, and space navigation.

Position, navigation and time (PNT) is a combination of three constituent capabilities:
- Positioning, the ability to accurately and precisely determine locations and orientations two or three dimensionally.
- Navigation, the ability to determine current and desired position (relative or absolute) and apply corrections to course, orientation, and speed to attain a desired position (sub-surface, surface, space).
- Timing, the ability to acquire and maintain accurate and precise time from a standard (Coordinated Universal Time), anywhere in the world and within user-defined timeliness parameters.

There are a wide diversity of market segments and applications enabled by Global Navigation Satellite Systems (GNSS), assisted, complemented, augmented and/or hybridised with additional technologies to provide high navigation accuracy globally and in wide range of environments. Additionally, GNSS can provide robustness and trust to its solutions implementing integrity, authentication and resilience mechanisms.

The applications and market segments addressed or served by space-based navigation systems have become extremely wide and diverse and currently about 10% of the world economic activity depends of such systems.
The required technology developments can be detailed and broken down into short-, mid- and long-term needs.

**Short-term technology needs**
In the short term, the focus is on the best use of current European GNSS in the existing PNT context, within a rapidly evolving landscape including the emergence of more demanding, safety-critical use cases in challenging environments, the introduction of future wireless terrestrial networks (e.g. 5G) which will stretch the scope of terrestrial PNT to address many other use cases (accuracy, availability, security) and the growing interests for more resilient alternative terrestrial and space-based PNT with already early operational capabilities available for commercial applications.

In this context, the following key technology areas have been identified:
- Precise positioning technologies for use cases such as vehicular, machinery, UAVs, railway.
- Low energy positioning technologies for Internet-of-Things (IoT) applications.
- Hybridisation of different positioning technologies including satellite, terrestrial and complementary sensors.
- Security-related technologies for trusted, assured and resilient PNT for safety-critical applications.
- Technologies for timing and synchronisation of networks (wireless cellular, grid).
- Technologies for the better exploitation of GNSS data for interference monitoring and scientific applications.

**Mid-term technology needs**
The mid-term needs are related to the evolution of European GNSS infrastructure to remain competitive ensuring service sustainability and offering new services and addressing new users (e.g. space users), improving performance and robustness, including flexibility for reducing the time-to-market and optimising operability. Many technology developments for the evolution of current EGNOS and Galileo are already being implemented, therefore the focus will be on new technologies or new paradigms that may provide optimised solutions for space and ground segments, for example in the areas of advanced RF equipment and atomic clocks, space and ground flexibility and re-configurability, improved robustness and reliability and enhanced security and resilience.
Long-term technology needs

The long-term focus is on non-conventional navigation concepts and associated technologies that can potentially deliver disruptive innovation and solutions to limitations of existing systems. Some examples already under consideration, include PNT solutions in alternative orbits (LEO, inclined-GSO) to complement existing systems for increased coverage in difficult environments, and increased resilience, the use of HAPS (High Altitude Pseudo-Satellites) for navigation, planetary navigation (GNSS space service volume beyond Earth, navigation with pulsars), the use of optical and quantum technologies (sensors, atomic clocks, quantum communications for PNT), non-conventional PNT in support of non-terrestrial applications (indoor, underwater positioning, etc), and the exploitation of artificial intelligence for PNT.

In addition to the commercial market needs, the evolution of PNT should also provide:
- Sustainability and independence of EU space-based PNT infrastructures
- Cost-effective, timely deployment of technologies and systems
- Privacy of navigation-related data
- Compliance with existing and recognised standards (3GPP, RTCM, etc.)
- Support to science and metrology with extremely high accuracy (on Earth and near-Earth orbits)

5.4 Enabling and Support Technology Needs

5.4.1 Space Transportation

ESA’s Space transportation programmes have the objective to guarantee independent, reliable, available and competitive launch services from European territory to European institutional missions, in particular for all missions fulfilling Europe’s sovereign needs, and to enable new in-Earth orbit and return from space transportation services.

The short-term priority for the European space transportation sector is the completion of the Ariane 6 and Vega C development, market introduction, and ramp-up to full operational capacity. This new generation of launch vehicles will further promote the introduction of additional new space transportation services targeting an even wider range of missions and logistics, and providing access to new markets.

For the timely introduction of such new space transportation systems and services the pre-development of enabling technologies and technological building blocks is a critical element in the implementation of the DG’s strategy for space transportation. It serves to continuously improve the competitive
advantage of European space transportation services on cost efficiency, flexibility, reliability and availability. The main drivers guiding technology development are:

- increase of competitiveness in terms of improvement of the service, cost reduction and return of investment;
- reduction of time to market of new operational services.

The following key industrialisation aspects are taken into account, when developing new technologies, processes, or building blocks:

- minimisation of manufacturing, integration and the recurring cost of operations;
- enhancement of industrialisation approaches, smart manufacturing (industry 4.0 approach);
- reinforcement of technology exchanges with other sectors/applications (spin-in/spin-off).

Technologies supporting the evolution of the Ariane 6 and Vega C launch systems

The main technical areas for the preparation of mid-term launch system incremental evolutions, include:

- Low-cost propulsion system enabling technologies: Lowering the cost of rocket propulsion systems is a key objective for the development of new technologies and processes, including low-cost manufacturing techniques, advanced engine control and monitoring, and engine reuse. Such technologies need to support the evolution of the Vulcain/Vinci engines, as well as the preparation of future LOX/Methane engine technology.

- Lightweight structures design: These require new technologies for mass reduction as an essential enabler for high-performing launch vehicles. New technologies are needed to support advanced stage architectures and structures design, increased use of composite materials and additive manufacturing, and allowing for cost efficient and automated manufacturing, integration and testing;

- Advanced avionics and electric architectures: Technology developments in avionics and electric architectures are needed with the objective to reducing harness complexity, using space infrastructure assisted solutions such as GNSS-based hybrid navigation and data relay services during launch, reusability supporting GNC algorithms and smart sensor networks allowing for simpler system diagnosis, FDIR and configuration.

- Exploring the economic viability of reusability: New technologies in the fields of reusable propulsion elements, re-entry technologies including hypersonic flight, thermal protection systems and landing techniques are needed to explore the economic viability of reusability of European space
transportation services through demonstration, experience, and qualification of reusable stages and/or engines.

Technologies for new space transportation services
New European space transportation services will be developed in addition to those offered by Ariane 6 and Vega C, opening new markets and responding to an evolving demand. In the short to medium-term, new services will be addressed in support of a wide range of applications, based on new key elements like the L3 initiative and the Space Rider system. The main objective of these new services is to offer:

- **Recurrent launch service solutions for light spacecraft.** These require new technologies for efficient and flexible light satellite deployment, standardised ‘missionisation’, and enabling technologies for micro launcher applications;

- **Orbital manoeuvrability, operations and return.** This requires enabling technologies for new in-orbit propulsion solutions, upper stage extended mission capabilities, kick-stages, space-tugs or orbital service and re-entry modules, as well as technologies for efficient orbital return and landing.

- **Transport solutions for exploration missions.** This requires new technologies for the realisation of exploration architectures and in-orbit cargo services including autonomous propulsion and docking modules, and landing capabilities on celestial bodies.

Technologies for Horizon 2030
To offer a perspective of enhancing the long-term robustness of the European space transportation sector, investments into technologies considered key for a significant competitive advantage towards 2030 are needed already now. The focus is on technologies enabling efficient reusability concepts, adapting innovative materials and advanced processes to space transportation requirements, exploring advanced aero-structures concepts, and preparing for next-generation autonomous and fault-tolerant GNC and avionics systems.

5.4.2 Operations
With rapid commercialisation and the high demands of new missions (constellations, exploration, space safety), innovation in operating spacecraft is needed to enable flexible, efficient and high-performant 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, allowing for a faster time-to-market and reduced duplication while realising more complex missions and systems, the introduction of artificial intelligence, data analytics, and augmented/virtual reality into operation concepts.

- The rapid introduction of these technologies requires quick, efficient and recurring in-orbit demonstration as an essential element.

- 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, e.g. 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 ‘Space 4.0’ environment, i.e. 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 needed for evolving the essential strategic European ground assets for future space missions and services and especially, to fulfil the 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 Technology, Engineering and Quality

In addition to the technology needs identified in the specific domains (section 5.3), science and exploration (section 5.1), and space safety and security (section 5.2) areas, the fast introduction of new technologies into future space system requires dedicated efforts to bring them to maturity either when they
are issued from space dedicated developments or when they are imported from non-space domain.

Operational space missions require technologies to be either already demonstrated in space or at high TRL. This reduces the risk of mission delays and cost overruns. It also leads to a conservative tendency of re-flying proven, yet no longer state-of-the-art, technology. This applies equally to newly developed technologies and concepts as to 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 in the Technology Readiness Level (TRL) ladder and to deliver products, techniques and technologies qualified on ground and validated in orbit. The pace of technological evolution and the competitive environment of the European space sector require special efforts to not only develop but also prove new technologies faster.

In IOD, new products and technologies are exercised in the operational environment and interfaces of user missions (or as close as possible to it), reducing risks and consequently raising further future buy-in. When space environment is hardly reproducible on ground, the IOD is of major importance.

There are two further, increasingly important drivers to perform IOD: First, 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, to showcase a precursor of the final system to alleviate risk and justify development budgets for the operational system.

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/IOV are therefore in all fields where innovation takes place:

- Technology and products
- Techniques: services, research, operations
- Mission architectures, system concepts

Additionally, it allows the introduction of newcomers in the space industry and facilitate evolution toward trends like New Space.
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 recently), 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 demonstrates entirely new concepts such as future missions based on cubesats or the massive utilisation of COTS.

Regular and accessible IOD opportunities are particularly important to newcomers to the space sector, allowing companies in new Member States to build experience, and new entrants to demonstrate new commercial ventures.

A main challenge for IOD as dedicated missions has been access to space, cost and opportunity. Today, with the increase of the space market using small missions, ESA is developing the offer with VEGA and A6 by providing ride-share opportunities to 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 not only onto launchers but also onto operational spacecraft. These technologies include a fully digital model-based engineering workflow of the “host” spacecraft, standardised power, communication and eventually thermal interfaces with new review and quality processes allowing for late accommodations and changes.

To optimise the IOD offer to industry, the different schemes such as the IOD element in the GSTP programme (“fly”), EC initiatives, specific programmes initiatives, it is necessary to develop standardised IOD payload interfaces and adopt similar processes through close coordination and cooperation between those hosting them. This will benefit especially new space missions in non-traditional domains such as servicing, debris removal and planetary defence.

**Evolution and usage of COTS**

Usage of COTS in space is the ultimate spin-in (e.g. direct use of an available item) and is gaining acceptance within the increasing pace of technology progress and innovation outside the space domain, the always higher performances required for space missions, the increasing pressure with cost and the new approach to mission qualification and risks in particular New Space. COTS in the wider sense not only include electronic components, but also complete elements and processes.

Therefore, increasing the penetration of COTS in space, as currently demanded by industry and operators, requires support from technology programmes to
evaluate their suitability for space and the identification of additional mitigation measures, e.g. coating or other environmental protection technologies and at space system level to adapt the system to COTS (e.g. lower or un-quantified reliability, lower availability and lower tolerances to space environment).

In the GSTP, 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 in space. Other technology programs, ARTES, EOPP include similar activities and together these are coordinated to cover all domains.

COTS acceptance is still in the making, and for the case of electronics components ESA, national agencies, industry and operators have set-up a framework to review all technical, programmatic and financial COTS aspects.

### 5.5 European Space Industry Technology Needs

Eurospace, the main European space industry trade association, regularly produces space technology research and development priorities of their industry members. These are intended “to raise awareness on key needs and expectations of the European space industry with regard to research development and technology” and to “supports the establishment of a consolidated consensual technology development roadmap supported by European space industry stakeholders.”\(^\text{12}\) These are aiming to “support the key objectives for ensuring European access to space to all missions and programmes, and maintaining an efficient, competitive and non-dependent industrial base.”

Eurospace considers that the growing competition from China, and the new space business models pioneered in the USA require specific attention, that the European space industry is competitive, but that support to industry competitiveness is a concern and a core driver for technology policies and strategies. Eurospace therefore promotes the setting up of a consistent and coordinated dialogue between institutions and industry. It considers that technology readiness for risk mitigation remains a core concern, whereas bringing technology to the appropriate maturity levels is a mandatory requirement, and programmes aiming at higher TRL, including in-orbit validation opportunities, are still very scarce.

The technology and development priorities of European industry according to Eurospace are the following\(^\text{13}\):
Earth Observation
- Improve resolution, timeliness, data processing, reactivity and system optimisation for observation systems competitiveness and efficiency - including readiness for constellation systems.
- Support short revisit time, accessibility, reactivity requirements and improved data update at system level.

Telecommunications
- Reducing the cost of available technologies and systems
- Pursuing performance increase to maintain competitiveness.

Navigation
- Improve life cycle costs
- Enhance clocks and signal stability
- Improve accuracy and service availability on all areas of the globe.

Ground systems
- Support increased data rate, flexibility, efficiency, ergonomics and the implementation of cloud-based solutions and data dissemination
- Support the development and take up of European design models and tools for system and architecture
- Development and optimisation via engineering, system virtualization, simulation, and modelling.

Protection of space assets
- Capabilities for independent assessment of the orbital environment (debris and objects tracking, and trajectory prediction) and support technological readiness for debris mitigation and prevention.

Science
- Improve system performance and payload capabilities
- Promote European readiness for state of the art instrument technologies, including large and very large structures (ultra-stable, deployable, thermal properties).

Human and robotic exploration
- Address long duration travel issues, increase readiness level for planetary activities
- Investigate and develop synergies between crew and robotics, improve European readiness level on habitats.

Launcher
- Improve launch service/system end-to-end competitiveness, from development and manufacturing aspects, to cost reduction strategies at all system and subsystems levels
- Support full life cycle cost assessment, minimise environmental impacts
- Develop re-usability aspects and modelling/engineering tools.
Materials and processes
- Continued investigation, assessment and development of materials, and advanced manufacturing techniques
- Develop new concepts, new designs, new processes, new tools to open new possibilities for space system design
- REACH, Cleanspace, dependence, eco-consciousness issues drive some developments.

(In-space) Propulsion
- Development of innovative, high performance electrical and chemical propulsion systems which are compliant to environmental regulations and address performance and versatility, test and tools, new systems
- It is critical to organise the synergies between the power roadmaps and the electric propulsion roadmaps.

Power and Avionic systems
- Innovative solutions for power generation, storage and distribution with a view of addressing the challenges of high power and high voltage as well as cost effective, competitive, solutions for lower power in the context of smaller spacecraft (and constellations)
- High stability associated to high, and very high-resolution systems, as well as the needs of high data rate in telecommunications, particularly with optical communications systems
- In all areas of avionics, Eurospace supports the SAVOIR initiative roadmaps and positions.

EEE components readiness
- Availability of critical EEE components and building blocks through sustainable European supply chains
- Readiness, maturity and evolution of the DSM functional chain
- Take up of COTS components in space programmes.
6 Technology Innovation

6.1 Electric, Electronic, (Micro-)Electro-Mechanical and Photonic Systems

Except for photonics devices, most development of EEE parts are based on terrestrial applications taking into account strong space-related constraints (e.g. high reliability requirements or radiation hardness).

A three-axis approach ensures innovative, cost effective and timely available solutions for electric, electronic and electro-mechanical (EEE) components, photonics devices and micro-electro mechanical systems (MEMS) to the current and future needs of the European space industry and institutional missions (chapter 5):

1. To explore the major trends from state-of-the-art (e.g. space qualified parts vs COTS), through latest innovation (22nm or smaller node Si technologies) till breakthrough technologies (ICs assembly technologies)
2. To enhance higher performances and uptake by capitalising on previous ESA R&D developments to push forward the technology (e.g. GaN microwave technology and processes), by enlarging ESA and national space agency sponsored product family (power MOSFETs) and improve and facilitate space usage of ESA qualified processes (capacitors for 65nm process and new power architectures)
3. To exploit previous R&D achievements to make them sustainable and start ensuring high return on investment (e.g. for example SpaceFibre products based on STm 65nm technology recently qualified for space).

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

**Design**

The development and application of new design methodologies and IP core reuse aims at an increase of functionalities integration in Very Large Scale Integrated Circuits (VLSI) and in photonics devices. Specifically, developments to enable enhanced functionalities include high-speed serial links, VSLI such as microprocessors, ASICs, FPGA, and moving from 65nm to 12nm, with a higher integration level (System on Chip) of the digital and analogue functions, including required reusable IPs core. Those developments are expected to reduce development time and cost and strengthen the European supply chain.
Similar advantages and increased performances are anticipated within the developments of 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). European non-dependence and obsolescence of critical parts (e.g. pump-lasers, optical modulators for ISL) will need to be addressed.

**Packaging**

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

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, GaN power management) and to ensure compatibility with new photonics devices requiring large number of electrical connections (e.g. MegArray connectors, Ball Grid Array).

**Technologies and Dies**

Technological progress is expected to meet the current and future missions needs such as frequency increase (up to Q/V/W bands), mass/volume reduction (e.g. replace bulky traveling wave tube amplifiers by GaN solid state power amplifiers), and performance improvements (power, gain, noise). The related technologies considered are:

- **Microwave technologies**:
  - Discrete and MMIC GaN HEMT processes up to V/W-bands
  - SiGe BiCMOS process for higher frequencies and/or RF output power
  - Metamorphic GaAs based process for low noise and high efficiency mm-wave and sub-mm-wave applications

- **Power Technologies**
  - GaN Monolithic Integrated Circuit (MIC) for DC/DC power conversion
  - SiC for power applications

- **VLSI Technologies**
  - 28nm FDSOI processes
  - High-k metal gate, planar technology (bulk substrate, not SOI)
  - 22nm FDSOI, planar technology and 12nm FDSOI, planar technology
  - 14nm and eventually 7nm FinFET (bulk substrate, not SOI)
- Photonics Technologies
  - New CIS CCD
  - MCT infrared detector to increase detectors size
  - Novel III-V materials for higher temperature
  - CDS and ADC to increase on-chip functionalities

**Products**

While the above strategic lines on design, packaging and technologies are dedicated to EEE parts, photonics devices and MEMS components, this line is addressing finished products whenever improved performances are needed, whenever lead time and/or cost reduction is possible.

A non-exhaustive list of high interest products includes:

- **EEE parts:**
  - High temperature capacitors for DC-DC converters
  - Smaller ferrite magnetics for electronic power systems
  - Substrate integrated waveguide circulator for integrated communication and radar systems
  - Improved radiation tolerance of SiC Schottky diodes and SiC MOSFET for high voltage application
  - Memory solutions for new FPGA products (e.g. Brave FPGA)
  - New ADC or DAC devices for EO, SCI, NAV and TEL payloads

- **Photonics products**
  - CIS performances enhancements for visible wavelength imaging and spectroscopy
  - Enhance CCD infrared detectors for imaging and spectroscopy
  - Multichannel low power transceivers with bandwidth above 12 GBps for telecom processors
  - Ka band photonic modulators for telecom payloads
  - Infrared Active Pixel Detectors (avalanche photodiode) arrays for low photon and high time resolution applications
  - Hybrid CCD/MCT arrays for true IR TDI, CMOS Image sensors and ROICs with on-board ADCs
  - Curved CCD detector arrays
  - Fibre optic transceivers for Space fibre standard (>10Gbps)

- **MOEMS**
  - Fast and light 2D MEMS micro-mirrors to be used for fine pointing of ISL LIDAR based rendezvous and docking
  - SiC or GaN MEMS pressure sensors for propulsion applications.
6.2 Structures, Mechanisms, Materials, Thermal

The integration of structures, mechanism, thermal and materials disciplines allows the development and use of innovative mechanical architectures and products for future spacecraft. The following key products have been identified together with main technologies to be developed to support needed improvements.

**Deployable Booms & Inflatable Structures**
To meet with increasing demand (e.g. high-performance antennae and solar array), new developments are needed to increase the lengths of deployable booms (up to 30m) and the tip masses (instruments to 1000kg, deployable reflectors to 100kg). Structures based on carbon nano-based composite or matrix/carbon nanotubes composites and associated joining technology will enable large deployable telescopes. Inflatable structures have a high potential for low-cost flight hardware, high mechanical packaging efficiency and low mass.

**Stable and light structures**
Novel ceramics and carbon nano-based composite materials, design methodologies, non-destructive inspection methods and joining technologies are becoming available for the development of stable structures. These are typically driven by institutional missions but also offer significant potential for satellite constellation deployments of commercial remote sensing and imaging missions, especially real-time imagining constellations for which manufacturing costs of optical payloads are important.

**Mechanisms’ building blocks availability**
The focus of technology development activities on the mechanisms’ building blocks (e.g. gear box, electrical motors and actuators, sensors, pyrotechnics and non-explosive actuators) is to improve their performances (e.g. high accuracy, shock level) while decreasing volume and cost, and complying with long duration storage, demisability and REACH legislation in a context of limited European market size, with difficulties to commercially sustain the products.

**Enhancing and game-changing tribology technology**
Tribology technologies require to improve lifetime performance, decrease friction levels and noise, to reduce sensitivity to environment (e.g. extreme temperatures) and improve the means to predict performance and the testing.
Tribology-free solutions can be a game changer that would overcome some drawbacks of tribology technologies and provide better performance (e.g. micro-vibration, accuracy, controllability) and improved lifetime capability. Solutions include magnetic bearings and gears, contactless sensors, compliant mechanisms, flex-pivot, guiding blades, and contactless signal and power transfer.

Welding and Joining
The capability to weld new or dissimilar materials supports specifically the development of propulsion sub-system as it is dominated by welding processes, specifically in the manufacturing of propellant tanks, flow control valves and pressure transducers. The development of integrated primary structures for launchers using a similar approach to aerospace and improved control during welding leading to zero defects for safety critical applications are promising. Improved feedback control during welding (benefitting of industry 4.0 and digital manufacturing opportunities) and new precise standards (new ECSS on welding and NDI) will reduce the risk of the often-observed underperformance and failures.

Additive Manufacturing
Additive manufacturing is a game changing technology one of the fastest rapidly emerging technologies having been developed in recent history. It is applicable to most materials (metals, polymers, ceramics) and a number of techniques have been developed which enable parts to be manufactured from a few millimetres to metres. The next challenge is to implement additive manufacturing processes into the supply chain across all space sectors. This will lead to a significant increase in design freedom, and a reduction in lead time and costs. The main areas include the qualification of primary and secondary AM parts across all space sectors, including ECSS standardisation. The technology developments cover on-Earth manufacturing as well as on-orbit and on-planet manufacturing.

Virtual Manufacturing
Virtual manufacturing is the use of computer models for the simulation of manufacturing processes before they are actually applied for production of hardware products. Virtual manufacturing provides the capability to not only design, but also model the full manufacturing process to ensure that activities such as design, planning and hardware manufacturing are implemented right-the-first-time, mitigating delays and cost increase, allowing also to develop new manufacturing process leading to shorter lead time, improved quality and cost reduction.
Electronic Assemblies and PCBs
New solder alloys allow coping with REACH regulation and ROHs. The use of more complex EEE devices with higher number of I/Os and increased power consumption are leading to higher temperatures at PCB level, impacting material selection and design, and reliability assurance processes. The need for higher performances (RF in telecommunication applications) requires the development and use of novel PCB finishes, such as NiPdAu. Novel assembly processes will enable science and exploration missions’ exposure to extremely low temperatures (i.e. -130°C or lower for lunar or Mars exploration). Printing technologies for electronics promise to further increase performance and production flexibility.

Composite Materials
Composite materials are of strategic interest for basically all missions, including polymer matrix composite materials, metal matrix composite materials and monolithic and composite ceramic materials. They also support in-orbit manufacturing applications. Key challenges are to reduce manufacturing costs through more automation and to improve in-situ process verification and validation (including health monitoring). At the same time, new developments are needed for a wide range of applications such as for cryogenic tanks or ‘demisability’ to fulfil re-entry requirements.

The improvement of polymer matrix composite materials performance will focus on RF properties, thermal envelope, conductivity, ‘demisability’, multifunctionality, and health monitoring. The implementation of in-line process monitoring and advanced NDI techniques allow reducing products cost and lead time.

The improvement of metal matrix composite materials will focus on the thermal domain, the mechanical resistance, the thermal stability or the friction behaviour. The development of more versatile processing technologies will further reduce production costs and expand the design possibilities by combining different MMCs and MMCs with metals.

The improvement of monolithic and ceramic composite materials will focus on processing techniques for improving design freedom, develop high Q factor ceramics for RF applications, spraying technologies for heat resistant and wear resistant coating, and low curing natural materials (Geo-polymers) for exploration.

Advanced coatings
The development of coatings is driven by the need to address REACH and to guarantee availability and qualified performances. Technology allows now to extend the performance of coatings to support longer operation time and handle more and more challenging requirements in terms of radiation
protection, temperature control, lubrication, ‘demisability’ and optical applications. Moreover, the tailoring of coatings allows accompanying the design freedom offered by additive manufacturing technologies or achieving multi-functional coatings combining for instance contamination or dust repellence. New technology promises achieving ultra-high temperature resistant coatings for propulsion applications.

Contamination
Developments in contamination are driven by increase in equipment sensitivity, lifetime, power requirements and new mission scenarios and environments that all impose more and more stringent requirements on contamination levels and control. New contamination sensors, better theoretical understanding, modelling and testing allows predicting with high reliability the evolution and the behaviour of contaminants during the lifetime of a spacecraft.

Adhesives
Technology developments for adhesive joints will enable high precision opto-mechanical applications (lenses, mirrors, detectors), enhance electrically/thermally conductive bonding, enable new cryogenic applications as well as new high temperature joints of heat shields for Earth re-entry/planetary entry missions. In addition, better life time predictions of adhesive joints over the entire life cycle (on ground, in-orbit, cruise and re-entry phases) will improve their reliability.

Cryogenics and focal plane cooling
Cooling of detector and optical elements is necessary for instruments for EO, science and surveillance missions. Demonstrating cryogenic cooling capabilities for science (cryo-chain or sub-KKelvin) gives Europe the capability to implement ambitious missions (e.g. ATHENA) and to participate in international cooperation (e.g. SPICA). Expanding the current family of coolers by providing post-MTG solutions allow to reduce their size, cost and make them less prone to vibrations for future EO missions.

Two-Phase Heat Transport Systems
Two-phase equipment is essential to cope with the increasing power dissipation of payloads on commercial programmes and to enable low/cryogenic temperature instruments for institutional missions. Embedded two-phase equipment at electronic unit level allow relieving some thermal management constraints.
Heat Rejection Systems / Radiators
Maximisation of heat rejection capabilities is required to accommodate high power payloads e.g. on telecom missions by optimising the use of the whole radiative area, to extend this area with deployable or inflatable radiators and to tune the heat rejection with self-regulating capabilities (e.g. variable thermo-optical properties coatings) to adapt to variations in heat load or environmental changes.

6.3 Avionic Systems
Avionics systems include all essential functional elements required to control the satellite platform and to manage the payloads. It covers several disciplines including data systems, software systems, control systems and the tracking, telemetry and tele-command end-to-end systems.

The general trend in the space market requires avionics systems to be cost-effective, easily tailored to institutional and commercial missions, and timely, adaptable and customisable to remain competitive. This implies a strong product orientation.

The avionics system must also fulfil the requirements of increasingly demanding missions, including a higher degree of autonomy (e.g. advanced autonomous functions required for planetary exploration), higher on-board data transfer and storage capabilities (e.g. big data applications) and higher performance control systems (e.g. improvement in pointing accuracy for science missions) to maintain European industry as a leader within this changing environment.

This requires the development and utilisation of advanced processors, more complex and flexible software, reliable networks, (smart) sensors, better performing downlink and uplink communication links, advanced control techniques and tools, high performance sensors and overall avionics architecture optimisation.

Data systems
New data systems have to provide higher performances (e.g. processing power in term of MIPS/MFLOPS) and through their global data handling architecture, provide more functionalities (on-board communications protocols, higher TM/TC data rate, multitask execution, autonomy, file-based operations, enhanced FDIR as fail operational/ fail safe) in less volume/mass; include
security mechanisms (to protect the spacecraft TM/TC link but also the payload data); support a large number of interfaces (mainly standardised); provide a high degree of modularity to facilitate the adaptation of the same unit on different missions; integrate hardware and software on a flawless basis; and take benefit from full access to non-space technology.  

In addition, obsolescence and the evolution of technologies, in particular for EEE components will require adapting the architecture to the available components. On board communication developments will benefit from spin-in from non-space domains (e.g. deterministic ethernet).

**On-board payload and data processing**

The payload data handling system has to cope with the increasing amount of data produced by the sensors. The development of high-performance payload data processors will allow to pre-process and compress the data on board to lead to a manageable data rate for the down link channel.

The intention is to provide the complete avionics processing functions for a spacecraft. This needs to address the SPARC or ARM processors, controllers, and reprogrammable FPGAs. A complete processing solution requires a complete solution combining software and operating systems for (multi-)core solutions, with demonstrators, engineering models and reference designs. The main issues are to consider the complete solution of hardware and software, to avoid delays in its effective use and improve the development time and consequent use on operational satellites.

The processor landscape is complex. Platform computer solutions currently exist within Europe and are ready for flight (monocore LEON3, multicore NGMP, soon SPARC or ARM based microcontrollers, and reprogrammable FPGAs of the BRAVE family). The ARM based DAHLIA is being developed for the longer term. The situation of payload computers is more complex as there are no European processors matching the performances of US products. Europe’s High-Performance Data Processor (HPDP) is for the moment the most advanced solution but it is still lacking software support.

**On-board software**

Advanced software functions will be developed to increase system flexibility and functionality, in particular autonomy: fault management, planning and scheduling, more intelligent control, on-board analysis of payload data (“big data” applications) which in turn will enable the envisaged challenging robotic and scientific missions, while remaining within the targeted schedule and cost.
Most of these can now use recent advances in Artificial Intelligence, which however are challenging in terms of software engineering and performance.

From an engineering point of view, further developments are also required in productivity, complexity, reactivity, flexibility:

- Productivity will be obtained (and increased) through automation and is supported by a model based approach. Model Based software engineering developments alongside model based avionics and model based system engineering are required and can be spun-in from the embedded software and system world.
- Increased complexity will be adequately managed relying on an appropriate process, requiring developments in early feasibility assessment, behaviour verification, etc.
- Reactivity and flexibility will be improved by further developing reference architecture targeted to the functional domain.

Technology objectives in software will be based on the following three elements:

- the model driven engineering and the reference architecture engineering which will streamline the software development from requirement engineering to validation through reuse and automation,
- the software factory which will provide a seamless process for software generation and test,
- the mastering of advanced software technologies (such as artificial intelligence techniques) to enable new functions for future system efficiency and flexibility.

Microelectronic
The development of deep sub-micron technologies in partnership with European foundries will allow Europe to ensure it has continued access to space ASICs, FPGAs, IP cores and IC design tools and methodologies which are either developed within European member states or readily accessible for use on European space platforms.
To accompany the development of more and more dense microelectronic components, specific avionics methods need to be developed, in particular:

- a proper process to ensure that the functions implemented in microelectronics have the same level of V&V as software has,
- new dependable methods to program the components, on ground and on-board, for patching or intended reprogramming foreseen by operational concepts (e.g. software radios)
advanced hardware-software co-design processes allowing to trade-off implementation of a complex function either in the software of a processor or in a FPGA, in the scope of a model-based approach.

Control systems
Advanced control systems for future scientific and commercial missions will require developments in several areas: sensors, system and engineering.

Sensors
European Star Tracker suppliers have captured worldwide a very large market. Using the AOCS sensors and actuators harmonisation exercise, established and emerging companies will further develop a complete sensor and actuator suite based on advanced technologies: a new generation of star trackers from medium to very high accuracy; fully European inertial measurement units based on highly competitive gyros and accelerometers; Optical navigation sensors and lidars; sun and Earth sensors, magnetometers and magnetic torquers; reaction wheels and control momentum gyros.

System
Innovative AOCS and GNC functional chains will be studied to pave the way for new and more demanding missions. These enabling activities will cover Very High Accuracy Pointing (including Line of Sight Stabilization within payloads), Ascent and Re-entry (including reusable launchers), Autonomous Rendezvous and Docking (for Exploration as well as in-orbit servicing and assembly), entry, descent and landing, drag free and formation flying, absolute and relative navigation techniques (in LEO and beyond).

Engineering
AOCS enhanced techniques and tools are necessary to satisfy more demanding missions while improving the efficiency of the design and verification process. ESA R/D activities will aim at solving the current lack of systematic derivation of key parameters and sizing cases and mitigating the need of accurate pre-flight knowledge of the satellite to be controlled.

Optical and RF metrology technologies
Formation flying radio frequency, optical metrology and combined orbit/attitude control represent a key technical challenge to deliver precise and reliable in-orbit servicing missions, starting with the twin Proba-3 precision formation flying satellites.
GNSS space-borne receivers
The success of terrestrial satellite navigation market has attracted companies with satellite navigation expertise to focus on the more profitable terrestrial-based applications. European industry can leverage on this by spin-in of technology and adapting it to the space environment requirements and dynamic conditions (signal acquisition and tracking).

TT&C transponders and Payload Data Transmitters
The trends are to strive continually for optimised functional and architectural partitioning, further miniaturised components, enabling operations at weaker signal conditions, cope adaptively with harsh environments, enhance the TT&C subsystem usability to support science measurements and further reduce the power required to receive each bit across far distances. Transponder and PDT technologies take inherent advantage of the spin-in from modern terrestrial concepts, design methodologies as well as digital and analogue technologies developed for non-space communication systems and applications.

6.4 Electric Architecture, Power and Energy, Electro-Magnetic Compatibility
The strategic technology development lines of action regarding electric architectures, power and energy and electro-magnetic compatibility are primarily linked to their nature as enabling technologies for European space ambitions and secondly to specific technologies needed for European missions.

Development of enabling technologies
Nuclear power solutions are required for deep space exploration to objects farther than Jupiter or for Moon habitats far from the poles. So far, Europe has been relying on US and Russian Pu-238 fuelled radioisotope power sources. Recently, ESA has developed a novel, much more cost-effective technology based on the extraction ofAmericium-241 from existing legacy nuclear materials both for radioisotope heater units and radioisotope electric generators. The development from the current laboratory prototype level requires substantial long-term investment and commitment to establish an operational fuel processing and heat source development manufacturing and testing capability for European devices, with a special focus on nuclear safety.

Similarly, fuel cells will enable the energy storage needs of human presence on Mars or Moon (section 5.1.2). The development of cost-effective, high-power
electronics and high-voltage high-power solar arrays will enable the electric propulsion requirements for future deep space exploration missions (section 5.1.2).

**Development of key and priority technologies**

Solar cells performances have a very high impact on satellite metrics (size, mass). Improving the solar cell absolute efficiency by 3% (every 1% increase on cell absolute efficiency means a 3% increase on solar array power) and reducing the thickness and mass of the cells by 30% (allowing their integration into lightweight panel structures under development), allows doubling the solar array power to mass ratio and reducing the in-orbit solar array costs by 30%. It is therefore necessary to continue improving the performance metrics of solar array technology and to maintain the European autonomy in the area of solar array technology up from the component level, through sub-assembly integration to solar array wing manufacturing. Solar cells and solar array technologies are enhancing technologies.

**Spin-in of non-space technology**

Development time and cost reduction requires increasing the spin-in of terrestrial technology and to develop new, “space-only” technologies only when and where necessary. Substantial resources can be saved by systematically monitoring and spinning-in terrestrial solutions. Specifically, this applies to

- Power management and distribution:
  - components (discrete power devices, control and ancillary functions contained in ASICs, capacitors and other passive devices);
  - control laws and communication protocols used in Power Conversion and Distribution Units (PCDUs) and in spacecraft electrical units in general, together with specific ICs used for the purpose;
- EMC methods and techniques; and
- Energy storage, for which we will develop the capability to identify and rapidly spin-in technology from terrestrial industries allowing access to benefits of emerging mature and much larger value chains and technologies. This enables to reduce qualification time, to lower validation costs, while still fulfilling specific space requirements.

**Increase integration levels of electric systems**

The increasing integration levels for electrical unit developments through better cross-domain concurrent engineering will overcome the classical space project split into separated technological compartments which is no longer
suitable to support the new and ambitious goals of integration and performance improvements (mass, size, cost) (chapter 5.3, 5.1 and 5.4). Only substantial concurrent engineering efforts can provide such results, with a flexible human interface structure adjusted on a case-by-case basis depending on the specific problem to solve.

Specifically, development of novel components with increased functionality and a new class of components (GaN and SiC) will allow to increase efficiency and to reduce dissipation and volume. The increasing use of digital components will enhance functionality and new packaging techniques will improve integration at module level and at unit level.

**Predictive technology for electric, electro-mechanic and electronic (EEE) reliability**

Modern tools and technologies allow improving knowledge on reliability and relevant methods for a better understanding of the failure mechanisms of EEE components, printed circuit boards (PCBs) and in general electrical and electronic assemblies, which in turn enables to apply more effectively redundancies and protections only where absolutely necessary and needed.

The evolution of reliability methods for terrestrial applications (e.g. automotive applications) might help to get away from a set of rules based on alleged failure mechanisms (currently the baseline for space failure mode effect analyses), to achieve substantial improvements and a more solid basis for better and more reliable space electrical equipment.

Similarly, the better production and manufacturing processes in the wider electrical and electronics components industry enhance predictability of the maximum components rating, which allows to substantially improve the utilisation factors of EEE components without compromising reliability: for many power components, including RF ones, the traditional derating rules established 50 years ago seem no longer justified. Large system advantages (size, mass) can be achieved just by allowing a slightly higher temperature on power devices and without resorting to complex equipment development or re-development.

**Introduce more COTS EEE components**

COTS EEE components offer performance improvement and cost reduction. Their integration would substantially help achieving cost, schedule and performance requirements but require testing and qualification processes. Enabling COTS technologies are discrete power devices, power, control and ancillary functions contained in ASICs, capacitors and other passive devices.
Streamline electrical architecture for recurrent platforms

Higher volumes and standardised spacecraft buses allow identifying and adopting recurrent electrical interfaces with industry (both Large System Integrators and equipment manufacturers) that offer major system advantages, ease integration, increase quality and reliability, and allow better control and understanding of products.

Similarly, technological advances allow establishing recurrent hardware and software failure detection, isolation and recovery (FDIR) systems, and affordable and feasible ways to introduce power line communication.

Another generic enhancing technology development focus is on the improvement of verification and testing methods adapting to future technologies and related requirements. Specifically, improved existing test and measurement methods will enable repeatable and reliable test results and reduce testing time. The development of new test and measurement methods will allow to verify new and highly demanding requirements such as extremely low AC magnetic emissions at low frequency as required by the JUICE mission, or extremely low, short term, main bus fluctuations required for thermal stability of some new scientific missions (chapter 5.1.1).

6.5 Radiofrequency & Optical Systems

Based on the needs identified in sections 5.3.1 and 5.3.3, the technology development focus for telecommunications and navigation applications is on microwave, digital and photonics technologies for payload and antenna equipment, on the improvement of radio and optical frequency front-end, modems, and networking techniques for the associated ground segment, on the development of advanced user terminals technologies (fully embracing the market evolution, section 1.4). These technologies will also serve the convergence of telecom, and navigation to deliver to customers ubiquitous connectivity and positioning as a commodity, business enabling big data and services for the Internet of Things. These technologies will also support the modelling and test techniques enabling high power operations, and reduce the overall cost of missions via re-configurability, production speed and infrastructure flexibility.14

14 Detailed information on the technology roadmaps to address these future needs are available in three dedicated R&D strategy documents: CD5 R&D Strategy for Space Telecom
The technology development focus for remote sensing instruments is on microwave, (sub) millimetre wave, digital and photonics technologies for payload and antenna equipment to answer to the needs of future Earth Observation and Science missions for improved data products to (scientific) end users. The most important enhancing technology developments are for radiometers, synthetic aperture radars, scatterometers, optical imaging, topographic measurements, thermal infrared sensing, landing and ground-penetrating radars. These need to be accompanied by the parallel pursuit of introducing terrestrial, potentially game changing technologies through dedicated spin-in efforts.

**Antenna and Payload technologies**

For telecom applications, the development of (large deployable) 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 channelization, 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 will be maximising the on-board resource exploitation to achieve flexibility at a competitive cost. These will allow in turn to also cope with market uncertainties, short-term traffic variability and multi-mission capability (e.g. broadcast and broadband).

To support complementary constellations operating in frequency bands different from current the 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, low-cost integrated medium power wideband amplifiers, frequency reconfigurable passive output sections for GNSS satellites, reconfigurable 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.

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Ground terminal technologies
The priority enabling satcom user terminal technologies are those that aim at lowering cost, compactness and improving user friendliness. They furthermore need to enable low energy terminals for Internet of Things, support of (mobile) high data rates, flexibility in spectrum usage, and affordable low-profile user terminal antennas for use in aeronautical, land mobile, maritime and mega-constellations. It has become clear that there is not a single winning solution and different technologies and products are required to meet different market segment requirements.

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 mega-constellation ground segment. 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 minimize 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.

Enhancing technologies for user terminals are low-cost steerable antennas based on semiconductor technologies (GaAs, SiGe, Si), liquid crystal technology, meta-surfaces and meta-materials or hybrid technology.

The technology development focus for the navigation user segment will focus on exploiting the existing space backbone infrastructure as well as terrestrial positioning technologies in particular to cover more difficult environments (e.g. urban canyon, indoor). Low-cost sensor stations and orbit determination and time subsystems will enable the mission and control segment efficient uplink and constellation control solutions.

Signal Processing and Algorithms
The development of advanced position navigation and timing (PNT) algorithms for carrier phase processing and integrity concepts will enable high performance, energy efficient time and frequency references. These will also enhance interference monitoring, support secure authentication algorithms, support the integration of technologies complementing GNSS, enabling low
cost, short time-to-market production and deployment strategy, and precise orbit determination resilience. Such algorithms together with the development of chip-scale sensors, and MEMS and optical/vision based sensors are considered potentially game-changing technologies for improved inertial and position measurements.

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

Radar
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. In addition, millimetre-wave GaN technology, large deployable reflector antennas, improved antenna testing technology, large reflect-arrays technology, precise orbit determination are envisaged.

For remote sensing 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.

The field of radar imagery from synthetic aperture radar (SAR) is undergoing a revolution in design resulting in greatly enhanced capabilities. Digital beamforming techniques will 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.

Planetary landing radars fall into two main categories: pulsed (as used for ExoMars) and frequency-modulated continuous-wave (as used for 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.

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 antenna of hexagonal shape will enable the microwave radiometers needed for SMOS follow-on missions. Constellations of instruments to synthesize 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 e.g. GeoSounder. The leading position of European companies and institutes in certain technological areas such as RF-antenna modelling, submillimetre wave quasi-optics, frequency selective surfaces, and in HBV technology allows European industry and space systems to successfully compete internationally. A specific objective is to maintain and strengthen the leading role of Europe in sub-millimetre wave reflectors and RF antenna testing.

The availability of certain reliable semiconductor technologies (Schottky, HBV) is considered critical. A technology development focus on quantum cascade laser (QCL) approaches has been chosen to address the lack of sufficient local oscillator power. Radiometers installed on small sats and cubesat missions have attracted increasing attention. A strong R&D effort would be needed in this domain to fill gaps with technologies under development in the US, China, and India.

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 technologies, the development of multi-spectral thermal infrared sensors at medium spatial resolution (50m or better) will enhance the spectro-radiometric quality to cater for both land surface and marine user needs.
The development of super-spectral sensors in the VNIR and SWIR spectral regions at both high and medium spatial resolutions, supplemented by TIR imaging payload at both medium and low spatial resolutions with large swath and (for marine applications) high radiometric accuracy and technologies will enable new hyper-spectral payloads for the observation of land surfaces, inland/coastal waters and atmospheric monitoring. Europe currently lacks the technologies for precise thermal infrared sensing to cover land and coastal zones, e.g. for agriculture and food security applications as well as for meteorology and climate studies.

**Optical Path Technologies**

The development of methods to improve the radiometric accuracy of the optical instruments will enhance the accuracy and fidelity of the data products. These include specifically technologies for a better control of stray light as well as improvements of the instrument characterisation on ground and in orbit. Stray-light control requires the enhancement of existing techniques or new technologies for a broad range of passive optical components, such as in the field of dispersive optical elements, lenses, mirrors, optical coatings and contamination control. On top of that, polarisation prediction tools and scrambling components will help to reduce polarisation related instrument errors. Novel optical designs and concepts based on, for example, free-form surfaces, will enable more compact and less massive instruments. In addition, the development of reliable and robust metrology and alignment methods will enable a faster and cheaper integration of optical instruments.

The upcoming L and M-class science missions such as Athena (L2), LISA (L3) and ARIEL (M4) require technologies that push the boundaries of science (section 5.1.1). New nano-materials and the latest generation of crystalline Silicon structures promise to produce high-performance high-energy optics enabling Athena. Ultra-stable mounting technologies will allow achieving the picometer-levels and pointing accuracy that is required for the advanced laser system and optical bench of LISA and further laser instruments missions (section 5.1.1).
6.6 Life & Physical Science Payloads, Life Support, Robotics & Automation

The expansion of human activities in space requires the development and maturation of technologies in the field of automation and robotics, autonomy, science instrumentation, environmental control and life support systems and in-situ resource utilisation. Automation and robotics technologies will reduce operating cost, increase the performance and the flexibility of space infrastructure.

The main aim for autonomy related R&D is to increase the scientific yield of missions, while the main goal for technology developments in the field of instrumentation for life and physical sciences is to improve the availability of new high-performance instruments for human or robotic space missions. The overarching goal for environmental control and life support technologies is to enable the prolonged permanence of a human presence in space while improving the efficiency of resource usage. The main aim for in situ resource utilisation related R&D is to lower the mass of consumables to be transported. ISRU and advanced life support systems are enabling technologies for long term presence of humans in space.

Technologies for environmental control, life support
These include the move from open-loop towards closed-loop systems, regenerative systems based on physio-chemical or biochemical processes to provide and retrieve consumables for humans, contamination monitoring and control, both for biological and airborne molecular contamination in a closed environment, food and nutritional challenges of human presence in space, and the protection and monitoring of environmental hazards.

The technology development for such systems is based on a step-wise, flexible and modular approach, first working on single elements of novel processes, demonstrating the operational capabilities first on ground and then in space, before linking the different building blocks first on ground and then on in-orbit demonstration missions.

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).

Technologies for active space debris removal and for orbital support services
The technological solution space for active debris removal concepts is still immature and diverse. Several of the key technologies to grab space debris need further developments. The ‘throw net’ system developed by ESA represents an attractive debris capture system for some space debris classes (e.g. objects that for dimensions, spin rate and access cannot be grasped) and could be used to capture multiple objects (sections 5.2).

The advent of massive satellite constellations (tens or more satellites sharing the same orbit) creates the possibility to provide common services to them, by means of a single service spacecraft that can move across the orbit to deploy satellites, refuel, add additional payload or de-orbit. This development line will increase the maturity of the robotic subsystems enabling serviceability of minimally-prepared satellites to be re-fuelled, updated and deorbited (sections 5.2). The advent of constellations with similar satellites sharing orbits/orbital spots and requiring regular replenishment allows the consideration of servicing vehicles that, by means of suitable interfaces, can solve the issue of satellite de-orbiting, replacement of early aging payload, and refuelling.

In-orbit assembly and robotic modular space systems
This technology development line is focused on technologies for in-space assembly and modular subsystems to increase flexibility.
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. To deploy these appendages from their packed launch configuration to their operational configuration, ever more complex mechanisms have been created, reaching 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.
Space applications increasingly demand operational flexibility of space infrastructure. At the moment, flexibility typically comes at the high cost of the complete replacement of a space asset. 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. The use of standard modules will allow the robotic replacement of payloads in orbit. The
development of robotics technology (manipulation and interconnects) will enable such reconfigurable space assets in orbit.

**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 (radiation, habitat atmosphere) forms part of this enabling technology. Telemedicine applications use space assets to enable decentralised health care and fast crisis response on Earth.

**Instrumentation for life and physical sciences and for exploration**
The research and development for instrumentation for life and physical sciences experiments under various levels of gravity is focused on miniaturisation and transfer of novel lab-based measurement technologies to the relevant experiment platforms, e.g. ISS for the observation of gravity related phenomena.

The main technology development focus for instrumentation for exploration missions and *in situ* measurements for planetary exploration is to minimise 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**
The technology development will focus on the next generation of logically autonomous systems that will leverage on autonomous decision-making, cooperative exploration, and cooperative assembly and construction for exploration needs (section 5.1.2).

**Technologies for in situ resource utilisation**
The main focus is the development of new processes for ISRU, the upscale of known processes from laboratory and pilot scales to higher TRL, their implementation in relevant environment and robotic technologies for feed stock handling to enable and enhance exploration missions (section 5.1.2).
6.7 Propulsion, Space Transportation and Re-entry Vehicles

Propulsion Technologies
Technology developments in space propulsion aim to enable the European guaranteed access to space, in-space operations, and new space missions, covering chemical, electric and hybrid/advanced concepts. They will be structured according to three strategic pillars: *Innovation for competitiveness and new services* (non-toxic propulsion, retro-propulsion, throttle-ability, re-usability, high efficiency orbital transfers, and re-fuelling), *time-to-market reduction and risk mitigation* for new services (development of new propulsion technologies and concepts to TRL compatible with a low risk adoption by projects and missions) and *non-dependence* (propulsion components).

In addition to the support to institutional space missions, the development of propulsion technology such as new chemical or electric thrusters for micro/cubesats, possibly fully integrated into spacecraft unit(s) and focussing on cost reduction will *enable* new propulsion systems for commercial applications and assist in the development of European “New Space” industry. New non-toxic propellant technology solutions will be identified, capable of maintaining comparable performances with current less-benign devices.

The development of simulation testing and diagnostic propulsion tools will support independent forecast and validation of the overall performances of European propulsion systems and components.

Space Transportation Technology
The technology developments in support of the European strategy for Space Transportation (section 5.4.1) focus on low-cost propulsion systems, advanced avionics, light-weight structures and re-usability. These technologies include multi-disciplinary vehicle design, multi-physics simulation and analysis tools, advanced and fault tolerant GNC systems for autonomous precision flight and precision landing.

(Re-)Entry Technology
Supporting new services for return from space, including non-destructive Earth and planetary (re-)entry, will include

- The development of the technological capability to design, assess, and develop the performance of any (un)propelled flight vehicle along any trajectory or orbit.
- Technologies to 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.
- New and revolutionary aerodynamics shapes that allow near equilibrium glide efficient flight.
- New thermodynamics systems providing efficient heat transfer.
- Tools capable to 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.
- New and efficient thermal protection systems to reduce mass while maintaining structural integrity protection.
- New reliable decelerators systems to deliver with high accuracy, performance, and safety all kind to payloads in a large variety of flight regimes.
- To develop and test advanced GNC systems for increased autonomy and enhanced flying qualities.
- To maintain test beds and testing facilities for flight physics, aerodynamics, thermodynamics, decelerators, and TPS systems.
- To maintain, procure or develop new simulation, testing and diagnostic tools capable to support in autonomy the forecast and validation of re-entry systems, including the outcome of virtual and augmented reality within on-ground and flying testing facilities.

6.8 Ground Systems and Mission Operations

Flight operations costs are the costs required to commission and operate satellites. These vary typically between 3 to 9% of the total mission cost. The lower end is represented by standard operational Earth observation missions, while the higher end is usually represented by interplanetary missions. It involves a number of technologies, related to the development, assembly, integration and test in pre-launch and maintenance phase and the development, assembly, integration and validation of all ground stations systems.
The major drivers for technology developments are:

**Tracking, Telemetry, Command (Systems and Payload Data Transmission Systems in Radio Frequency)**

Tracking, Telemetry, Command (TTC) Systems and Payload Data Transmission Systems (PDT) in Radio Frequency (RF) ensure safe spacecraft communication, navigation, timing and high rate transmissions. Priority technology development activities are to maximise the exploitation of the scarce allocated 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 uplinks for lunar exploration missions. For spacecraft navigation, Ka-band Doppler and Delta-DOR measurements with associated atmospheric and solar calibration will allow for a factor of ten improvement in orbit determination accuracy.

**Payload Data Transmission Systems in Optical**

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. The corresponding ground terminals fall into small (60-100cm) optical antennas for LEO up to Lunar distance communication with data rates of 1-10Gbps, and large ground terminals (4-12m) for deep space communication with normalised data rates of 100Mbps from 1AU distance or miniaturised on-board terminals at shorter distances.

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

**Space Debris Detection**

Space debris detection is performed with ground sensors using radar, passive and active optical tracking (laser ranging techniques). The technology development focus is on the cost efficiency of transmission, reception and synchronisation techniques of large-scale radars, and on the development of high-power lasers for space debris tracking with a potential evolution towards small debris (10cm) momentum transfer for just-in-time collision avoidance (sections 5.4.2 and 5.2).

**Radio Science**

Radio science covers 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 antenna mechanical performance.

**Frequency and Timing**
Frequency and Timing systems provide the stable underlying backbone in the deep space stations for Time Synchronization and Radiometric services (Ranging, Doppler, Delta-DOR) and for the provision of Universal Time Coordinated (UTC) in ESA as a basis for precise orbit determination.

**Ground Data Systems**
Efficient ground data systems aim at re-usable ground system software building blocks that cover the full mission lifecycle from concept to assembly, integration, test to operations. The main challenges to be addressed relate to keeping pace with the fast changing technology in the IT/software domain, to identify and benefit from spin-in opportunities from other areas, to respond to increasing mission requirements, including cybersecurity, to harmonise similar functionalities across domain, and to overcome missions’ reluctance to adopt new solutions that are not mission enablers. The ground data systems include mission control systems (e.g. European Ground Segment Common Core software, EGS-CC), mission planning systems, operational simulators, large data archives, data analysis/distribution/preservation systems, as well as other innovative data systems.

**Standardised Ground Interface Solutions**
Standardised Ground Interface Solutions covers the establishment of standard interfaces for the ground segment, in particular towards distributed, service oriented and net-centric architectures. The integration of technologies in future missions, such as mission operations services, file-based operation and delay tolerant network will be a game changer leading to a space-ground single system and to a standard on-board reference architecture.

Advanced operation concepts and enabling technologies will lead to further operations automation and autonomy by use of artificial intelligence and data analytics. In addition, large scale international cooperative missions, e.g. for robotic and human lunar and Mars exploration, require distributed shared operations with associated innovative data systems (section 5.1.2). These require an initial demonstration in mission analogues on ground and in-orbit. Modern human-machine interface methodologies like augmented and virtual reality need to be validated for their applicability in future operational scenarios.
6.9 Digital Engineering

Digital engineering for space missions is defined as an integrated digital 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 from concept through disposal, including also the methods and tools to enable and maximise data exploitation.

The digital revolution is significantly changing how engineers work. Digital models and tools are at the core of this work throughout the lifecycle of missions and projects. They digitally represent the system of interest at all levels, from the overall system of systems down to equipment and parts, including the environment and the engineering processes in a virtual representation. While models have always been used, the exchange of information has mostly been performed through documents. The paradigm change introduced and enabled by digital engineering is related to the persistent and consistent use of models, based on authoritative data, across disciplines and along the entire lifecycle of space systems. This paradigm shift allows to better address the challenges linked to complexity, flexibility, uncertainty, late changes, faster infusion of new technologies, and thus to improve efficiency, cost, schedule adherence and overall quality.

The paradigm shift from documents to models allows the radical reduction of costs in industry and ESA by allowing the use the engineering tools as basis of reviews and deliverables instead of documents. ESA would shift from accepting documents to accepting models, which will also require adapting the procurement processes.

Digital engineering and data exploitation relies heavily on some technologies and disciplines, which have not previously been at the core of space engineering but being developed outside the space domain: big data analytics, artificial intelligence, virtual and augmented reality, advanced computing, human-machine interfaces. The challenge here is to efficiently spin in those techniques, adapting our processes and tools to enable their use and maximise the benefits.

To allow the space sector to fully benefit from these developments, several ambitious steps are necessary. Building blocks in form of technologies and processes developed in and for other sectors need to be spun into space by
adapting them where necessary and demonstrating them for their applicability to space systems.

Figure 6-1: Current and future envisaged situation

To achieve a full implementation of digital engineering, several critical issues must be addressed.

First, the space system life cycle (development, procurement and operation) process needs adaptation to be centred around digital models, which are based on the seamless integration of authoritative data sources. This requires substantial changes from the current document centric processes to model centric processes. This also requires the formalisation of the development and use of models as an integral part of performing engineering activities. Such models need to be developed and used in a way that ensures that they are accurate, complete, trusted, and usable by and across different disciplines. This requires increased collaboration and sharing, and specifically the exchange of information between technical disciplines and different stakeholders (space system design, development, verification, operations, users) via model exchanges during and covering the entire project life-cycle. This will support the concurrent and fully collaborative design, verification, end to end testing and operation. It will further allow defining reference architectures and reference facilities for E2E testing.

Second, the insight 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) and to build both data-driven and user-centric representations. Effective methods and tools for data sharing, inspection (e.g. visualisation), (collaborative) use, dissemination need to be developed, compliant with IPR, access right and security requirements. This can
only be realised via the use of the capabilities of artificial intelligence, advanced analytics, high-performance computing, and advanced human-machine interaction tools leveraging the strength of both.

Third, these same data representation and analytics tools will support the exploitation of data phase, the response to complex queries and the visualisation of data relationships for practical use by projects and review teams.

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

Space debris
ESA’s main research on space debris has so far concentrated on operational space event predictions, modelling, measurements, and protection. This allowed the identification of most of debris generating sources and an initial quantification of their effects. It also strengthened understanding of the destructive effects of atmospheric re-entry for risk quantification on-ground and provided Europe with the means to understand the effect of mitigation measures and define them.

Debris smaller than 2cm are too small to be observed from the ground. However, debris larger than 1mm size have potentially mission terminating effect upon impact. Therefore, closing the 1mm gap through space based optical observations needs to be addressed as a priority. It might be possible to remove smaller debris by laser-based momentum transfer.

In the medium term, automated collision avoidance including autonomous decision and execution of collision avoidance manoeuvres is necessary to cope with the problems of debris and to reduce the associated operational costs. In addition, Europe’s capabilities to predict and characterise space events (like
conjunctions, re-entries, break-ups) and environment evolution models need to be improved and a measurable logic for the environmental criticality (a “Palermo Scale” for man-made objects) needs to be established. (section 5.2)

Tackling these major gaps for the coming five years and to deliver improved operational services for collision avoidance and re-entry will allow Europe to maintain a lead role in the related knowledge, tools and facilities. Emerging space nations may challenge Europe’s technical lead role in the understanding of the space debris environment, which today still guarantees its authority in driving related regulations and policies and avoiding a diversification of processes and tools in the ESA Member States.

Space Environments and Effects
The reliability of space missions depends on understanding and modelling of environments of concern to space system development and operation, and the establishment of capabilities for quantitative assessments of their effects. Environments include radiation, plasma, atmospheric and particulate environments, which are described by statistical or physics-based models, making use of data, and in-flight measurements. These rely on the development and flight of instruments for environment data capture and would benefit from adding low-resource space environment monitoring instruments on many platforms.

The analysis of these effects requires constant verification and refinement via ground-based testing. Such tools include simulators of high energy charged particle penetration of spacecraft and payloads, and the subsequent creation of radiation effects, and simulators of the interaction of plasmas with space systems, leading for example to high level electrostatic charging. Other issues related to atmospheres, dust and micro-particles are also simulated. Space based technology experiments are used to validate and improve effects simulation capabilities.

In the future, the effects of the space environment on space systems and humans will be increasingly problematic due to several important technological trends and aspirations in the space sector. Aspirations include missions of greater ambition and complexity (sensitive detectors, etc.) such as missions to hazardous locations (MEO, Jupiter, humans to Moon and Mars). Some of these regions are poorly understood. Reducing uncertainties will enable space missions to less well explored regions. Current technological trends include the orbital transfer by electric propulsion through the radiation belts and hot plasma environments, growth of on-board intelligence (in EO but also growth
of digital payloads on-board telecomm satellites), and drives to reduce costs (in particular mega-constellation and the use of COTS).

It is required to anticipate problems resulting from the above trends, ensure reliable and robust tools are available for quantitative evaluations, proactively monitor the environments and effects in orbit, and perform detailed ground-based and space-based campaigns of research and validation.

**Astrodynamics – Space Flight Dynamics and GNSS**

Astrodynamics covers the areas of precise orbit determination (POD) for Earth oriented satellites in low and medium Earth orbits, as well as satellites in high eccentric orbits, based on GNSS observations as prime source complemented by other types of observations like satellite laser ranging and delta-differential ranging.

The entire landscape of GNSS is currently undergoing significant evolutions. Fully operational systems like the US GPS and the Russian GLONASS are in a modernisation process. The European Galileo system is deployed and the Chinese BeiDou system is in deployment and new developments like the Indian Global Satellite Navigation System are underway. This requires the investigation, development and exploitation of these new GNSS capabilities (e.g. new frequencies, new signals and new services) to improve existing POD systems and develop new navigation and operations concepts for real-time and post processing to be operated either on-ground or on-board.

The R&D strategy focusses on the development of new satellite POD concepts for single satellites, satellite formation flying, and satellite constellations with a focus to exploit the full potential of the European GNSS elements.

To provide mission analysis and flight dynamics operations services to future space projects, R&D activities for mission analysis focus on the design of interplanetary tours, such as planetary and moon swing-by’s, of missions to the Earth-Sun Lagrangian points, of multi-revolution solar electric propulsion transfers (to GTO, MEO and escape) and on the exploitation of near lunar locations (NRO, DRO, LLO, EML1, EML2) for human exploration. The R&D activities for flight dynamics operations focus on operational concepts for future projects such as multi-revolution solar electric propulsion transfers, optical/radiometric navigation around small bodies, formation flying and rendezvous. The main technological goals for the evolution of flight dynamics systems are cost reduction, the introduction of new technologies such artificial intelligence for flight dynamics for the automation of flight dynamics product validation, image processing and environment modelling (e.g. Mars atmosphere during aero-braking) during operations.