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ESA AI STRATEGY PLAN

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1 INTRODUCTION

1.1 Scope of the document

With the unprecedented advancements in Artificial Intelligence (AI), it is imperative that ESA harnesses this transformative technology for all its missions and activities.

AI has the potential to revolutionize every aspect of ESA's work, from automating routine tasks to making breakthrough discoveries in all the domains of space. The integration of AI into our systems promises to enhance capabilities, enable new missions, streamline operations, and unlock new possibilities in the exploration of the universe.

This document presents the comprehensive ESA AI strategy and its objectives to serve as inputs to the preparation of AI related activities and roadmaps.

1.2 Where does Europe stand?

1.2.1 Position of Europe

Europe significantly lags behind North America and Asia in the adoption of applied AI and investments into AI R&D, despite its substantial academic and industrial potential.

AI adoption rates:

- Europe: In 2023, 30% of large businesses in the EU had adopted AI, only 7% of SMEs had done the same and Europe is hosting around 17% of activity in AI services[1].
- China and emerging economies: 57% of enterprises adopted at least one AI technology in 2021[2].
- In 2023, 61 notable AI models originated from U.S.-based institutions, far outpacing the European Union's 21 and China's 15. In the same year, the US saw AI investments reach $67.2 billion, nearly 8.7 times more than China, the next highest investor. While private AI investment in China and the European Union, including the United Kingdom, declined by 44.2% and 14.1%, respectively, since 2022, the United States experienced a notable increase of 22.1% in the same time frame[3].

[1] EU report "The Future of European Competitiveness" issued in September 2024

[2] McKinsey Analytics report "The state of AI in 2021" issued in December 2021

[3] Stanford Artificial Intelligence Index, https://aiindex.stanford.edu/ acc. 6 Sept. 2024 - https://aiindex.stanford.edu/

The US Government has integrated AI to enhance public services[4] across various departments:

- 27 Departments have published their AI use cases, including Healthcare, NASA, and Transport.
- 710 Use Cases have been documented, detailing:
- Description
- Development stage (e.g., initiation, operationalization)
- Techniques used (e.g., Machine Vision)
- Reference to source code (where publicly available)

NASA has published 33 use cases[5].

“The Future of European Competitiveness" report issued by EU in September 2024, clearly identifies AI as a major technology that needs to be integrated into European industries. The report outlines the importance of ïntegrating AI ‘vertically’ into European industry” and takes the automotive sector as an example where “AI-powered (generative) algorithms enhance vehicle design by optimising structures and components, improve performance and reduce material use, and optimise supply chains by predicting demand and streamlining logistics operations.”. This example can be transposed to the space domain.

[4] https://ai.gov/ai-in-gov/

[5] AI Inventory - NASA - https://www.nasa.gov/ai-inventory/

1.2.2 European initiatives

AI is transforming the aerospace and defence sector. European LSIs are developing AI strategies.

Thales has established a Digital Factory and cortAIx:

- Thales Digital Factory: The Thales Digital Factory aims to “propel Thales into the digital era” by:
  - Providing a cloud foundation for the development and operation of digital services
  - Driving business innovation within their ecosystems
  - Nurturing talent and fostering a culture of continuous learning
  - Over 230 experts are reported to be specializing in digital technologies, including cloud computing, the Internet of Things, big data, artificial intelligence, and cybersecurity, with proficiency in methodologies such as design thinking, lean start-up, and agile software development. It was opened in Paris in July 2017.
- cortAIx: Launched in 2024, cortAIx consolidates Thales's AI capabilities across research, sensors, and systems, with a team of over 600 AI experts. Its purpose is:
  - AI accelerator aimed at providing armed forces, aircraft manufacturers, and critical infrastructure operators with secure solutions for efficient data analysis and decision support.
  - Addresses specific constraints such as cybersecurity, embeddability, and frugality required in critical environments.

Airbus launched a company-wide GenAI working group in 2023, which aims to bring the power of generative AI, large language models and base models to Airbus. They have identified ~600 use cases in less than a year (e.g., engineering assistants, contract analysis, recruitment tools, cyber threat and risk analysis, and procurement optimization).

The European Commission is leading in AI regulation and promotion. Key initiatives include the AI Act, which establishes a comprehensive regulatory framework for AI, categorizing systems based on risk levels and imposing specific obligations on high-risk applications, and support for AI innovation through programs like the AI Innovation Package and Horizon 2020. The Commission also prioritizes ethical AI development, fostering collaboration through the European AI Alliance, and investing in AI research. Additionally, the establishment of the European AI Office ensures effective implementation and enforcement of AI regulations.

1.2.3 Role of ESA

Over the past years, we have observed three key trends in the space industry directly relevant to AI:

- A growing amount of available space data: ESA, as a naturally data-driven organization, owns and distributes hundreds of terabytes of data every day, with established standards and processes to ensure data quality.

- Increasing complexity of space systems: As mission ambitions grow, so does the complexity of the systems involved. Without advanced technologies, some missions may become unfeasible or highly inefficient.

- Game-changing technology advancements: AI algorithms and compute resources have reached unprecedented levels, specifically in the field of Generative AI. In 2024, supercomputing capabilities will become available at ESA, further propelling the entire European AI ecosystem forward.

ESA is already investing into AI to reshape space exploration, e.g., to analyse vast amounts of satellite data, enabling better understanding of Earth and other celestial bodies, powering autonomous spacecraft, optimizing satellite communication networks, and driving innovation through research partnerships and technology development. ESA's commitment to AI is crucial for maintaining Europe's leadership in space exploration and benefiting society through AI-driven applications. ESA indeed holds a distinctive role in championing innovative AI Space technology, accelerating performance, amplifying value from data, enhancing the European Space Economy, and protecting European sovereignty.

1.3 Key Objectives

The European Space Agency's AI strategy is crafted to position the Agency as a leader in the space sector's AI revolution. The objectives outlined below are pivotal to achieving this vision:

Championing Innovative AI Space Technology:

- Lead AI innovation: Position ESA as the vanguard of AI innovation within the European space sector, driving growth and technological breakthroughs.
- Foster a strong AI Community: Leverage ESA's expertise and collaborative spirit to cultivate a vibrant community dedicated to advancing AI in space exploration and innovation.
- Cultivate key relationships: Establish and maintain strategic relationships with essential stakeholders and actors to support the AI ecosystem within the space sector.

Advancing mission success, accelerating performance, amplifying value from data, increase operational efficiency:

- Enhance mission success: Utilize AI to significantly increase the number of ESA missions, and boost the efficiency of space operations.
- Expand mission capabilities: Utilize AI to redefine the technological limits of space missions, increase autonomy, reduce or eliminate ground control intervention, enable spacecraft with advanced decision-making abilities to reach more complex mission objectives, and increase responsiveness of space-infrastructures enabling near-real-time responses.
- Maximize data utilization: Expand the use, exploitation and comprehension of both space in combination with ground data to provide the public with high-quality insights and knowledge.
- Operational efficiency: Equip the organization with the tools to provide deeper insights, achieve higher operational efficiency and optimize resource allocation towards activities that add substantial value.

Enhancing European Space Economy, Protecting Sovereignty, EnsureCompliance:

- Promote industry leadership: Foster leadership of the European industry in the global space economy by encouraging the development of state-of-the-art AI solutions and applications and providing investment to fuel their growth and guarantee the European sovereignty.
- Lead in the legal, safe, secure and responsible use of AI to foster and maintain trust in ESA projects and programmes that use AI.

These objectives are designed to guide ESA's AI strategy.

2 AI VISION AND STRATEGY

The ESA AI vision is to be a trusted partner for Member States, driving the growth of the European AI ecosystem by supporting the development of innovative technologies fostering the expansion of the space economy, and amplifying value from space data while achieving resource efficiency.

The ESA AI strategy is supporting this vision through:

- The creation of an **operational model** defining the roles and unique value propositions of the different players driving the execution of a federated AI Strategy and related AI roadmaps.
- The creation of **partnerships** for investing into a European AI infrastructure and data-driven foundations for AI applications, through the funding of research and roadmaps aiming at achieving the operational deployment of AI technology, strengthening the European Sovereignty.
- The creation of an **AI Competence Centre** aiming at ensuring the definition of guidelines and policies regarding the use of AI, supporting ESA projects that create business, ecological and societal impact, fostering the use of AI, creating synergies and promoting the secure and ethical utilization of AI within ESA.
- The provisioning of a Data, AI and High-Performance Compute Foundation, which enables the development of Data and AI use cases.
- The establishment of a **Data & AI Academy** dedicated to enhancing the skills of all ESA's staff, specifically in data science and AI product management and use.
- The creation of an **ESA AI expert network** for sharing knowledge and experience on the numerous AI techniques and supporting the AI Competence Centre and Data & AI Academy.
- The development of an **effective communication framework** covering internal communication for knowledge sharing, technology promotion and data assetization, and external communication to position ESA as an innovative partner for industry, Member States, academia, and as an attractive employer.

The ESA AI strategy is in line with EU ambitions and with ESA's own strategy and vision, as expressed in Agenda 2025 and the ESA 2040 vision.

2.1 Key domains

The ESA strategy identifies four key domains, each domain being cross-sectorial involving the AI Competence Centre and all stakeholders, enabling a federated strategy that will grant autonomy to directorates while capitalizing on benefits from strong coordination:

- **AI for mission design and engineering** - Leverage AI technologies to enhance the design, and development of space missions.
- **AI for mission operations** - Use AI to improve the efficiency and effectiveness of operations, enabling autonomy.
- **AI for insights from mission data** - Apply AI to extract insights and knowledge from the vast amounts of data generated by space missions that otherwise would have been hard or impossible.
- **AI for Agency efficiency and effectiveness** - Leverage AI to provide assistance, automate processes, routine tasks, and facilitate collaboration and knowledge sharing across the organization.

The strategic roadmaps will be supported by technology and infrastructure capabilities, the ESA data strategy, risk management processes as well as guidelines for legal and ethical questions.

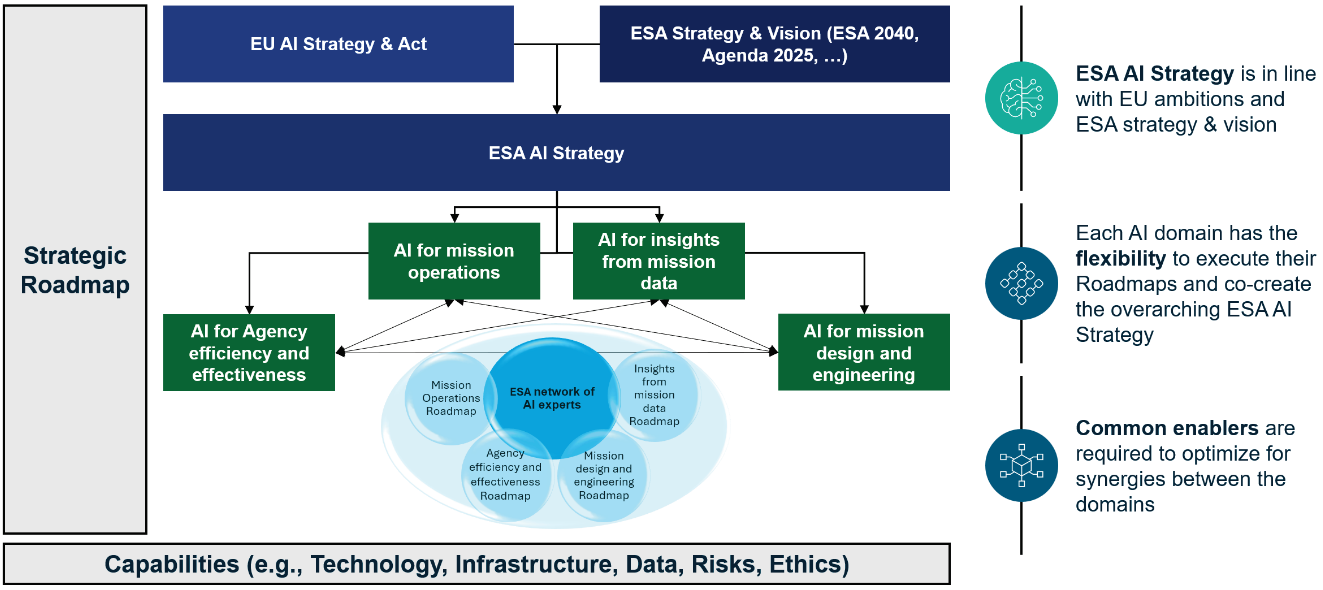


Figure 1: A federated AI Strategy enables exploiting synergies across ESA

2.2 Roles and responsibilities

All ESA Directorates have an active role in the implementation of the AI Strategy.

TEC

- Responsible for Technology roadmaps and engineering and quality standardisation.
- Acting as a competency centre for AI, including technical advisory services and support to projects, relying on an ESA-wide network of AI experts.
- Strategic roadmap leader for "AI for mission design and engineering", contributor to other roadmaps.

HIF

CDO team, with strategic guidance from the Digital Steering Committee

- Strategic roadmap leader for "AI for Agency efficiency and effectiveness".
- Demand Management for the Digital Transformation of the Agency, managing the business prioritisation of Digital & AI use cases in the Digital Steering Committee.
- Provisioning of Data & AI & High-Performance Compute Foundation at Agency level, which enables the development of Data & AI use cases.
- Data Management to secure the single source of truth, a solid data governance and data management standards.

IT Department

- Offering infrastructure and services that enable AI with reliable computing resources, safeguarding security and privacy, and maintaining compliance with evolving regulations (Accelerated Computing Resource Services, Security/ Privacy and Data Protection, Alignment with ESO, Review of PDP Framework).
- Providing Microsoft 365 Copilot Services: a powerful artificial intelligence assistant integrated within Microsoft 365 applications.

ESA Directorates

- Contribute to the strategic roadmap "AI for insights from mission data" and three other roadmaps, drive roadmap development and execution for respective domain.
- OPS, strategic roadmap leader for "AI for Intelligent systems for ground segment and mission operations".
- Participate to an ESA-wide network of AI experts.
- Enabling AI use cases through subject matter expertise: set up or strengthen directorate-specific teams of specialists that interact with central teams according to an hybrid-model for data teams.

- Develop Directorate-level Talent: ensure upskilling and retraining of current personnel in addition to defining career paths to provide conditions to attract and retain top-talent in the competitive markets of ML/AI.

2.3 AI for space applications

AI/ML needs data to be trained to create applications that process data to reach the goals identified by the stakeholders representing the different application domains.

Data and goals can be specific to an application domain or can apply to several domains or be generic. An example of specific goal and data is the detection of clouds in an image of the Earth. An example of multi-domain goal and data is the autonomous rendezvous that can apply to Human Exploration (docking to Lunar Gateway), Telecommunication (satellite servicing) and CleanSpace (debris removal), An example of generic data and goal is the support to project management.

The development of AI applications relies on a limited set of AI techniques that are evolving at very high pace. Hence, the interest of having one entity keeping track of these development and being able to support all stakeholders.

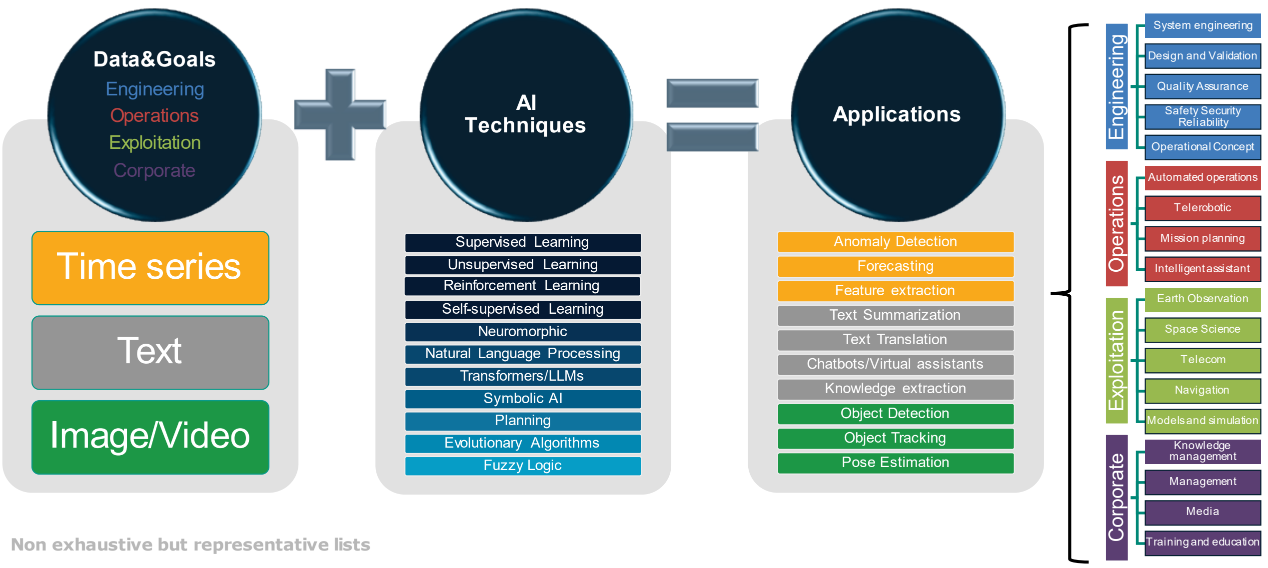


Figure 2: Directorates are stakeholders setting the goals and identifying data on which AI techniques are applied to create applications. A same AI technique can be used to develop different applications in different key domain areas for different stakeholder.

2.4 Organisational structure

The organisational structure of the AI strategy relies on three main bodies:

- The **stakeholders** who are part of the different Directorates are owners of the data and define the goals of applications (see section 4).
- The **AI Competence Centre** is supporting the stakeholders in the identification of the most appropriate AI techniques, consolidating and augmenting the data coming from other application domains. It coordinates all transversal activities related to AI technologies (see section 3).
- The **AI expert network** is supporting the AI Competence Centre in its different activities, providing specific expertise on the AI techniques and the development of the applications (see section 0). AI experts in various directorates may be organized in localized teams acting as points of contact interfacing with stakeholders (for use-case identification) and the competence centre (for support and reuse).

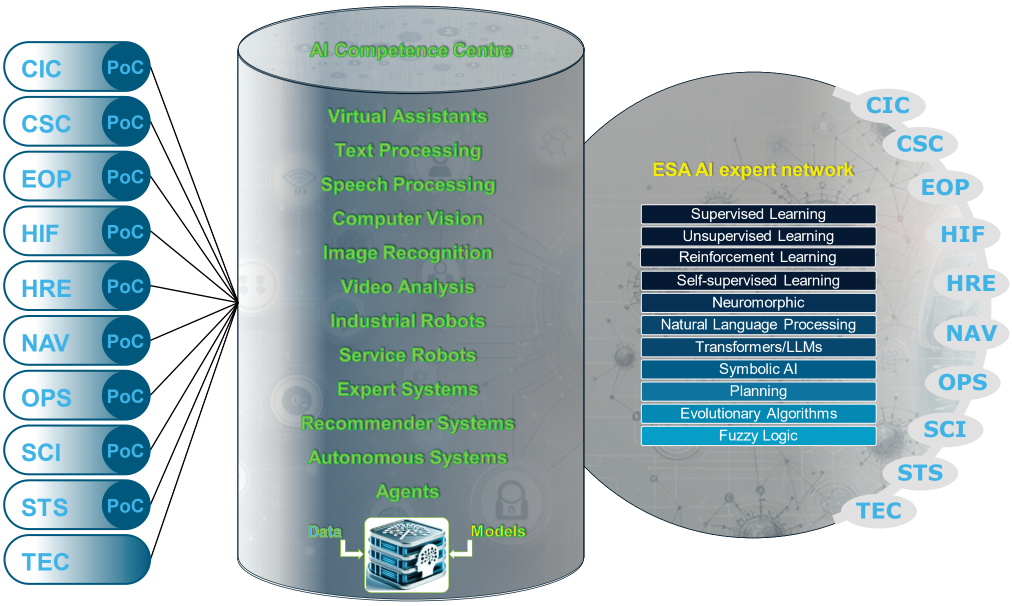


Figure 3: Organisational structure: the Directorates are stakeholders, possibly represented by a local point of contact (PoC), relying on the AI Competence Centre support, which involves the ESA AI experts.

3 AI COMPETENCE CENTRE

The AI competence centre is playing a key role in the implementation of the AI strategy. It is hosted in TEC and composed of a team of experts in Artificial Intelligence applied to the space domain. It is in direct contact with stakeholders and AI experts from all Directorates.

The main duties of the AI Competence Centre are to:

1. Maintain a network of AI experts within ESA

   Keeping up to date a list of competences in the various techniques of AI to easily identify best experts in each key domain area and AI technique. Members of the network will be invited to knowledge exchange and participate to the different activities of the AI Competence Centre.

2. Maintain a knowledge database

   Keeping up to date a knowledge database organizing and formalizing the domain to support the selection of techniques, reference libraries, toolchains, datasets, models and applications. The ESA Data Factory (EDAF) will be used to share datasets and support projects respecting data ownership.

3. Support the projects in the development or use of AI

   Act as business analyst and support engineers towards stakeholders for the development of applications with the backing of the network of AI experts.

4. Consolidate the vision of AI for ESA

   With the support of the network of AI experts and needs expressed by internal and external stakeholders, identify where and how AI can be beneficial, update the "AI for mission design and engineering" roadmap and participate to the update of the other AI roadmaps.

5. Consolidate needs related to the development of AI applications

   Collect needs from stakeholders and experts to ensure that data models and governance as well as the processing capabilities and development environments are adapted to the development of AI applications and provide them to HIF.

6. Consolidate on-board data handling and processing architectures and software environment for the execution of on-board AI applications

   To ensure that the onboard data handling and processing solutions are adapted to the execution of foreseen AI applications in coordination with existing harmonisation dossiers.

7. Create and maintain guidelines, standards and dossiers regarding the use of AI

   For supporting the development of core AI techniques used in the development of applications (e.g. Technology harmonisation dossier "Enabling artificial intelligence for space system applications") and sharing best practices while minimizing risks and promoting the secure and ethical utilization of AI within ESA. the execution support of AI techniques in space.

8. Support the organisation of a Data & AI Academy

   In close coordination with Directorates for enhancing the skills of all ESA's staffs, liaising with ESA Learning and Talent development section, set-up specific trainings prepared by ESA AI experts and identify external trainings for covering all aspects of developing, procuring and using AI applications.

9. Organise and coordinate events related to AI

   Facilitate the orchestration of all events organised by ESA that focus on Artificial Intelligence, enhance ESA's involvement in external events, and ensure broad dissemination of conference proceedings.

10. Organise and coordinate partnerships related to AI

    Establish and maintain strategic partnerships with AI vendors, research institutions, and other external entities to stay at the forefront of AI advancements, facilitate the exchange of knowledge and expertise and optimize resources. Identify, select and evaluate proposed solutions to ensure they meet ESA's standards and requirements. Foster collaboration with external partners to co-develop innovative AI solutions and share best practices.

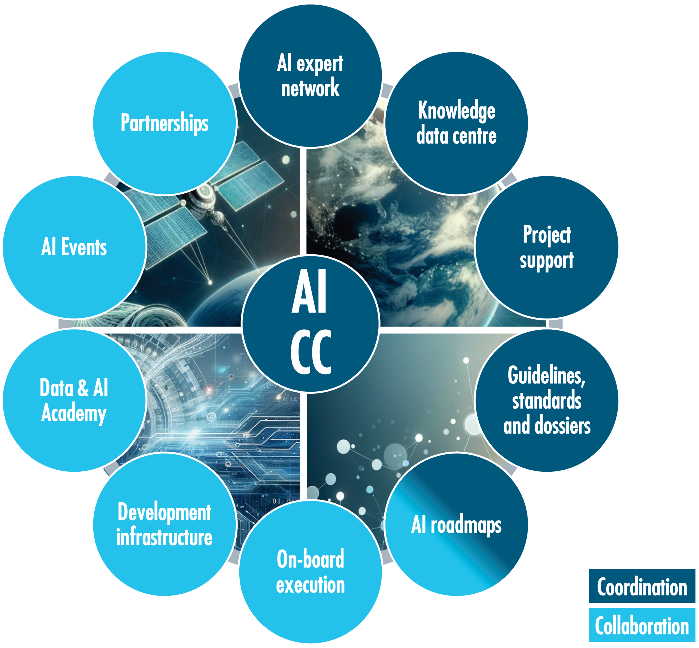


Figure 4: The multiple duties of the AI Competence Centre

The competence centre is envisioned as a centralised service provider and a knowledge hub for AI: The competence centre acts as a business analyst, a technology harmoniser, and a facilitator of cross-directorate collaboration and knowledge exchange. It will not take over AI application developments, but rather support the specific needs and applications of different stakeholders with the support of the AI expert network. It will support the identification and adaptation of AI technologies to make them at disposal of all stakeholders.

4 STAKEHOLDERS' STRATEGIC OBJECTIVES

This section outlines the strategic goals of ESA stakeholders concerning the adoption and application of artificial intelligence within their domains. These goals will be converted into concrete actions and activities, with the support of the AI Competence Centre and AI expert network.

4.1 CIC

The BASS (Business Applications Space Solutions) programme supports companies in developing sustainable services that leverage space technology and data. It has fostered the commercialisation of a wide range of AI applications with satellite data and technology, including machine learning algorithms for various purposes such as marine mammal surveys, flood mitigation, and distinguishing between organic and inorganic cotton fields. AI is instrumental in analysing large-scale datasets, leading to innovative commercial applications like advanced traffic monitoring, infrastructure integrity monitoring, and fleet management.

The rate of adoption of AI in the context of space-based applications is strongly sector dependant. This is due to differences in technology maturity, market readiness both at technology and service level, and specific space synergy potential. To respond to these challenges, BASS has implemented bespoke strategies to aid companies wishing to utilise AI integrated with space assets. This has resulted in dedicated initiatives (including thematic calls for proposals and competitive tenders) addressing commercial opportunities in key vertical markets such as Energy, Agriculture, Environment, Wildlife and Natural Resources, and Transport and Logistics through the use of innovative space-based services and applications relying on AI.

Commercial endeavours on the use of AI have also been supported through the ESA Business Incubation Centres (ESA BICs). ESA BICs focuses on creation of Economic Operators in an incubation environment, encouraging the creation of start-ups and fostering new business and venturing opportunities in all the upstream and downstream space sectors.

4.2 CSC

The directorate of Connectivity and Secure Communications (CSC) has been actively exploring the use of machine learning (ML)/AI techniques in the field of Telecom. Emphasis has been put into understanding how AI/ML could enhance performance in existing applications, or could introduce new capabilities to solve problems in new applications (e.g. 5G/6G spectrum management or mega constellations operations).

The strategic objectives identified are:

1. Flexible Payload Configuration

   Management and optimization of the payload, including carrier allocation, power transmission, beamforming and beam-hopping. On-board payload systems self-configuration can be possible thanks to cognitive radios/payloads driven by AI algorithms.

2. Spectrum management/ resource optimization

   Technologies like 5G and mega constellations will add enormous pressure to the already existing spectrum congestion issue. Since most of the allocated frequency bands are unused or underutilized, automation of frequency allocations supported by AI could allow exploitation of the underused available spectrum resources.

3. Interference detection, classification and mitigation

   At the present, although the communications payload may have features that support interference detection, classification and mitigation, human analysis and interaction is required to manage the interference environment and limit its negative impact on communication services. This is normally a time-consuming process that can sometimes lead to serious service outages before the problem can be solved. AI offers the promise of autonomous or semi-autonomous on-board interference detection, classification and mitigation methods which would translate into almost immediate communications link recovery.

4. Self-Organizing Networks (inter satellite-terrestrial networks)

   Self-Organizing Network (SON) functionalities, such as self-configuration, self-optimization, self-diagnosis and self-healing, aim to dynamically optimize the network performance for an improved user experience, while at the same time reducing the network operational cost. Several ML techniques applied to SON have been proposed for more than a decade, however a higher level of intelligence is still required to enable the targeted level of network autonomy.

5. Autonomous operations for mega constellations and autonomous rendezvous and docking for on-orbit servicing

   Constellations of 100s or 1000s of spacecraft require almost complete on-board autonomy to allow the operations to be run with minimum human control. ML and planning techniques are set to play a major role in enabling the autonomy necessary to operate such constellations and are required for in-orbit servicing operations.

6. Anomaly detection, classification and prediction

   Advancements on AI-based classification and prediction methods have improved, notably the capabilities of anomaly detection, classification and prediction. Some examples of the performance of such algorithms have been produced by OPS and their work can be used as heritage for future developments applied to SatCom.

7. Smart Manufacturing, Assembly, Integration and Testing

   Advancements in machine learning-based technologies have brought the opportunity to accelerate manufacturing processes and improving decision making. With the widespread deployment of sensors and Internet of Things, there is an increasing need of handling big manufacturing data characterized by high volume, high velocity, and high variety. Deep learning provides the necessary tools for processing and analysing big manufacturing data allowing companies to monitor manufacturing quality as well as optimizing operations.

8. Cloud-detection/ Weather monitoring for smart link allocation

   Cloud detection is not only an important preprocessing step for optical satellite imagery applications and earth-space optical communication links but can also be extremely useful for high frequency radio communications links (e.g. Ka-Band and above). By predicting the condition of the links, smart rerouting of satellite to ground station traffic (especially in megaconstellations) can translate into an increased overall system data throughput. Years of research and evolution in deep learning applied to feature detection and classification have significantly empowered the cloud-detection automation capabilities.

4.3 EOP

EOP's AI strategic objective is to harness the transformative potential of AI in converting EO raw data into actionable insights that generate value for end users and drive informed actions. AI can be applied at all levels of the EO value chain, including downstream applications, data analytics, digital twins, EO co-pilots, and data processing directly onboard satellites (i.e., edge computing), as well as coordinated and heterogeneous EO constellations (i.e., Cloud Computing in Space concept). The fields of application range from Earth science and weather prediction to commercial applications, green, sustainable and climate actions.

Since ESA Φ-lab's inception in early 2018, as the EOP innovation lab whose mission is to accelerate the future of Earth observation through disruptive innovation and commercialization actions, has been at the forefront of AI4EO. ESA Φ-lab has contributed to several AI research activities and initiatives in the field, such as foundation models, AI-based digital assistants, generative AI, AI-powered Quantum Computing for EO, edge computing (supporting more than 15 AI-powered satellite developments), and, in collaboration with the Advanced Concept Team, the futuristic concepts of Cognitive Cloud Computing in Space (3CS) and space-based data centres. These initiatives have highlighted significant commercial, scientific, and technical benefits of AI4EO.

Building on the results and expertise gained from AI4EO initiatives and anticipating the continued evolution of AI, EOP aims to further explore and leverage AI to:

- Extract value for end users from the vast availability of EO data
- Reduce barriers to the adoption of EO data
- Enable novel EO applications and mission paradigms
- Address current limitations of traditional modeling approaches in scientific sectors such as Earth science, remote sensing and weather prediction
- Strengthen European industrial competitiveness through disruptive innovation driven by AI applications
- Explore and capitalize on future developments in AI and the broader ICT revolution

EOP AI strategy is a user driven exploration and exploitation initiative based on 3 technological pillars as depicted in the following diagram.

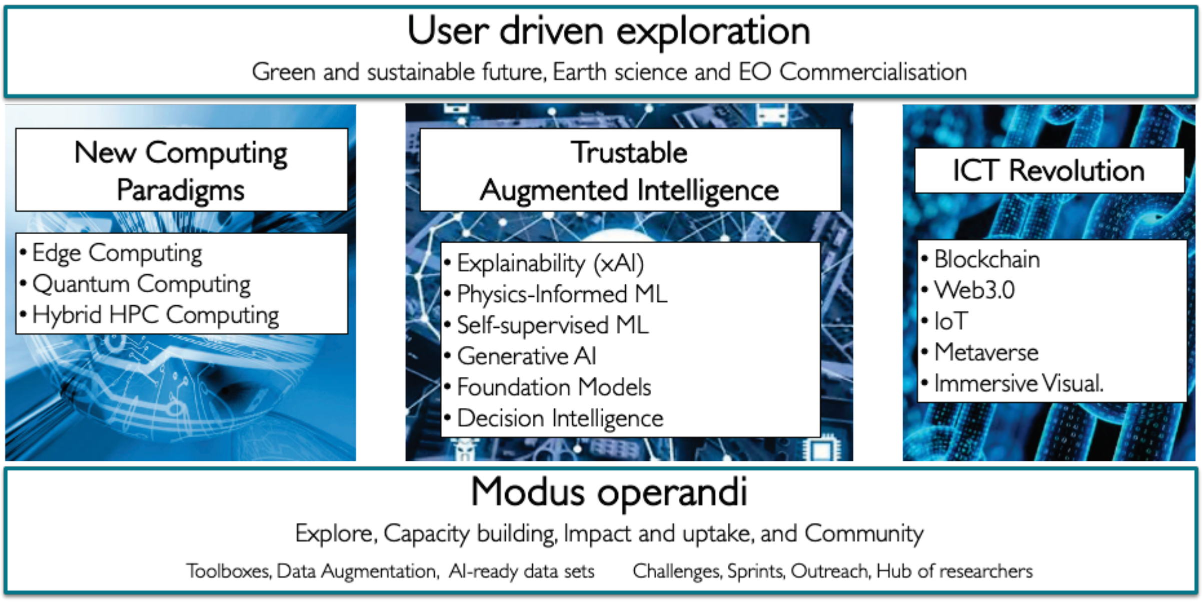


Figure 5. The EOP AI strategy

The EOP AI strategy is implemented pursuing the following key strategic objectives within a ten years timeframe:

1. Development of foundation models for EO analytics

   On the verge of Foundation models such as ChatGPT, EO foundations models are large AI models trained on a vast amount of data that can be tuned without use labelled data to specific use cases (also called downstream task). Expected benefits of foundation models include improved EO analytics integrating multiple satellite imagery (Copernicus, Earth Explorer) for various EO use cases. Foundation models could also enhance the ability to monitor environmental changes, predicting natural disasters, improving weather forecasting accuracy and reliability, taking informed decision and supporting sustainable development by providing precise and timely insights.

2. Cognitive Cloud Computing in Space (3CS)

   Exploration and implementation of a heterogeneous EO constellations of AI-powered satellites with sensing, cloud computing and communication capabilities to enable in-orbit experiments

   The 3CS constellation will be composed by minimum three small-sats equipped sensing, computing and communication capabilities implemented via onboard cloud computing nodes close to the payload data generation and Inter Satellite Links. The constellation will be heterogenous in sensing terms with a variegated set of payloads (e.g., multi-spectral, hyperspectral, Synthetic Aperture Radars) to enable exploring novel coordinated acquisition scenarios and approaches.

Examples of EO applications and mission paradigms potentially enabled by 3CS include: near-real-time payload data processing for latency-constrained use cases, novel acquisition strategies, enhanced satellite acquisition areas.

3. AI for climate science research and long time-series dataset generation in the context of the UNFCCC, the Paris Agreement and European institutional goals.

   This comprises the advancement of AI to support generation of long time-series Essential Climate Variable (ECV) datasets as a significant contribution to the UNFCCC 2nd Global Stocktake ending 2028, generation of ECV datasets beyond established spatial and time scales, data generated holistically across multiple ECVs as reflected in the latest GCOS objectives in support of the UNFCCC, facilitating ECV dataset usage widely across ESA projects, such as tailoring and simplifying ECV data access for AI usage, and providing benchmarking datasets.

4. Advancing AI for downstream climate science applications in the context of the UNFCCC, the Paris Agreement and European institutional goals.

   This includes the advancement of AI to support ECV datasets for planetary decision making such as through digital twins methods, usage of ECV datasets as a significant contribution to IPCC climate modelling goals and application of ECV datasets downstream from their generation for the purposes of supporting climate applications and venture building into other sectors.

5. Advancing AI for climate data training, education and outreach in the context of the UNFCCC, the Paris Agreement and European institutional goals.

   This includes the advancement of AI to support use of Large Language Models to enable and advance scalability and cost efficiencies in the public involvement in climate science, in support of Paris Agreement Article 12, such as through conversational public communications tools and code generation, provision of training and educational resources to support the next generation of scientists using ECV data, and inspiring climate action through storytelling and games.

6. AI for Destination Earth

   The Destination Earth (DestinE) is a flagship initiative of the European Commission (EC) to develop a highly accurate digital model of the Earth on a global scale. This model will monitor, simulate and predict the interaction between natural phenomena and human activities. The AI/ML contribution to DestinE cut across all domains, such as data dimensionally reduction to speed up transfer and reliability, operational benchmark training datasets for climate and atmospheric sciences, and traceability tools applied on academic/policy repositories and social media to detect and assess the usage of open-source assets.

7. AI for Digital Twin

   Digital Twins shall offer high-precision digital replicas of Earth system components, boosting our capacity to understand the past and monitor the present state of the planet, assess changes, and simulate the potential evolution under different (what-if) scenarios at scales compatible with decision making. Digital Twins can also assist in designing smarter cities by analysing data on traffic patterns, energy consumptions, infrastructure, natural disaster management to help predict occurrence and impact of natural disasters such as hurricanes, earthquakes and floods. Integration of AI with the Digital Twin enables more accurate predictions, better decision making and proactive measures to address global challenges.

8. AI4EO4Health

   AI techniques and EO products can support several public health applications, such as Epidemiological studies on the health effects of environmental hazards. In the last years, outbreak alert systems have improved after the addition of EO products and the integration of AI components into the forecasting models, reducing the prediction uncertainty.

9. AI-Powered QC4EO

   Quantum computing is an alternative computing paradigm based on quantum theory principles. When combined to quantum computing, machine learning solutions could provide further enhanced capabilities to extract actionable insight from intricated and large-scale EO data structure offering more efficient and rapid solutions for data analysis, image processing, and modeling applications. Additionally, quantum algorithms could optimize tasks such as satellite orbit scheduling and the extraction of valuable information from extensive datasets. They can also enhance the high-performance computing (HPC) and quantum computing workflows of climate adaptation digital twins.

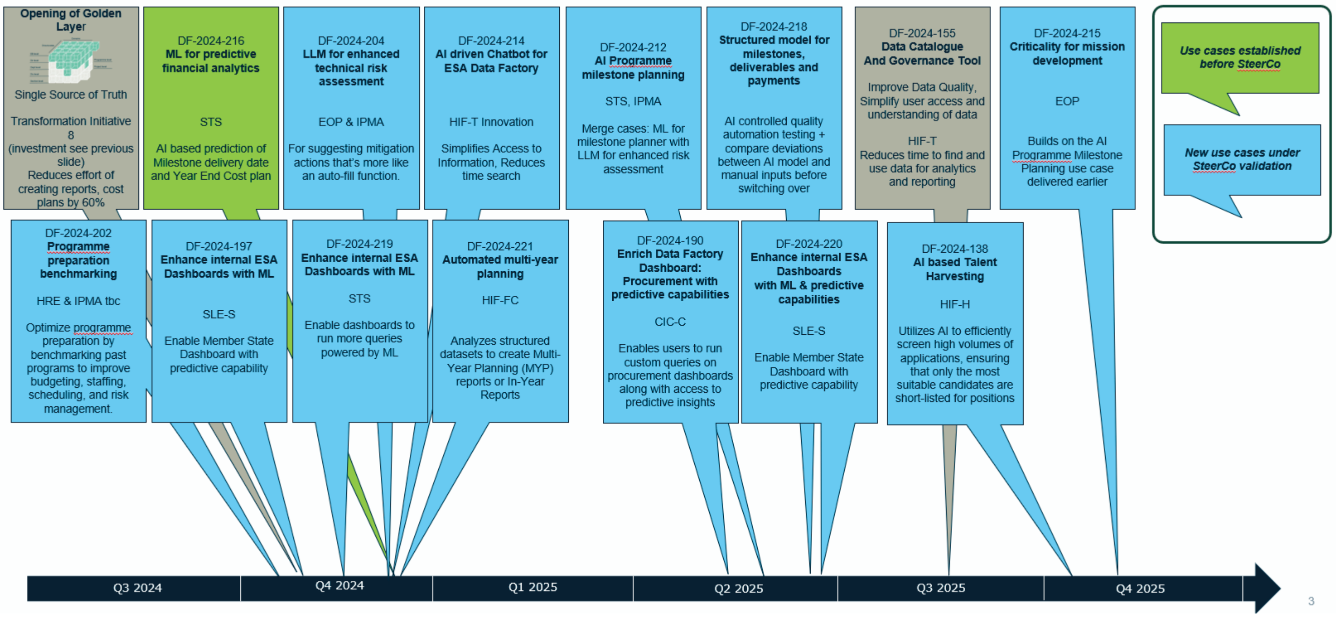
4.4 HIF

The Digital Transformation Office (HIF-T) has conducted an in-depth ESA-wide Data & AI Analysis by focusing on ways of working, process streamlining, automation, augmentation of human capabilities, and data-driven decision making. The outcome is a roadmap of 'AI for more efficiency and effectiveness in ESA's ways of working', with a staged implementation of individual AI use cases.

In a series of workshops between March and June 2024 the input and demands have been collected from all business stakeholders within the Corporate domain (HR, Finance, Procurement, Communication, Legal) as well as with the Agency's Senior Programme Managers, Senior Controllers, and with the ESA Project Manager Forum.

As result of the consolidation from the workshops and the impact and effort/investment assessments, the initial indicative AI roadmap is defined below, which has been submitted to the Digital Steering Committee for validation.

An ESA internal impact survey alongside this study has shown consensus that urgent and substantial acceleration is required to achieve a competitive edge in AI for the day-to-day operations of ESA.



AI use cases are only as good as the quality of data which they use, and models are only as good as the data they are trained on. Integration of quality data is a meticulous process critical to AI's success. Therefore, the Digital Transformation Office's task of defining and executing ESA's data strategy, data governance, and overall data architecture to establish and maintain the Agency's single source of truth, is key to success of the AI strategy.

4.5 HRE

The use of AI is key to delivering the European Exploration Programme. Focusing on Human and robotic exploration across several destinations from LEO, and the Moon to Mars and beyond involves the continuous use and supply of a myriad of mission data.

The use of mission data is key to the planning and development of new missions as well as to the operations of ongoing missions. The general applications that AI can bring to these use cases has already been detailed in previous chapters. Therefore, this chapter solely presents strategic objectives describing how AI will drive innovation and deliver new insights from mission data related to exploration use cases that are under development or planned:

1. Making accessible historical and real-time mission data

   In the context of operations, in particular for ISS and future LEO, Gateway, Moon and Mars missions, Generative AI and Large Language Models (LLMs) as well as general NLP capabilities, will allow for different formats and sources of data to be queried through a single interface, making operations-related processes faster and more efficient. Development of the Digital Twin Astronaut (DTA), a virtual model that emulates the behaviour of an astronaut entering the spaceflight environment. This digital representation is designed using systems engineering (SE) approaches and can incorporate real-time data to assess the state of the astronaut, simulate outcomes, and predict the effects of different scenarios or interventions. It's a powerful tool for mission planning and safety, allowing for the testing of various conditions and countermeasures without putting actual astronauts at risk while helping to enhance the performance of daily astronaut tasks. Moreover, design interfaces and protocols that facilitate effective collaboration between humans and AI agents, ensuring that astronauts can trust and understand the actions taken by AI.

2. Development of intelligent spacecraft companions and assistants

   Of interest for ISS and Gateway to monitor the health of the spacecraft as well as crew. AI will be required to provide cognitive assistance, communication and sharing of information, predictive modelling for maintenance and scheduling tasks, health monitoring of vital signs and possibly even emotional support.

3. Improvement of robotic systems

   To operate autonomously in environments where real-time interaction is no longer possible, e.g. on the Moon and Mars. Develop AI agents with advanced autonomy that can handle unexpected situations and make decisions without human intervention.

4. Swarm intelligence

   Development of systems that are using swarm intelligence and collaborative approaches to perform tasks and driving exploration.

5. Creation of digital twins based on historical and/or real-time mission data

   For enabling simulations and performance analysis. Digital Twins of Space Stations, Earth Analogues, Deep Space, Planetary Habitats, planetary surfaces, ISRU processes and Astronauts can enhance understanding, development of new technologies, aid problem resolution, and inform decision-making processes.

6. Creation of simulations in extended reality (XR) applications such as virtual and augmented reality solutions based on mission data

   Generative AI can fill gaps where data is missing and create artificial environments based on real inputs. XR applications are key to the planning and preparation of both crewed and robotic missions. This technology requires to crunch large datasets, it can be used to train AIs but is hungry for processing power.

7. Processing and making available of scientific data gathered through experiments aboard the International Space Station, Lunar Gateway, Moon and Mars and e.g. returned samples in the next decade.

   This can lead to potentially ground-breaking discoveries in our understanding of how life developed in the universe, but also lead to the development of new products for Earth and Space applications including in areas such as medicine, food, water supply, and many more areas. Science data from exploration missions is made publicly accessible in the HRE Data Archive (https://hreda.esac.esa.int/) and the Planetary Science Archive (https://psa.esa.int).

8. Investigation of AI-enabled quantum technology and in particular quantum computing

   To allow for the modelling of complex systems such as materials behaviour, accelerated model training to handle large-scale optimisation problems and improve predictive models.

4.6 NAV

The directorate of Navigation is running the Navigation Innovation Support Programme (NAVISP) and other FutureNAV Program initiatives to foster innovation and competitiveness in the Positioning, Navigation, and Timing (PNT) industry. The focus of these programs on AI/ML technology, systems, products and services will be considerable in the future.

PNT Applications, Products and Services

NAVISP has been an enabler programme for the advancement of PNT technologies in industry, especially in the areas of Artificial Intelligence (AI) and automation ensuring that industry stays ahead of technological innovation.

In the future, various areas could benefit from the latest AI developments, including KalmanNet, LSTM networks, Neural Positioning Systems, and set learning. These technologies are transforming navigation by making data aggregation independent of order and improving performance using techniques ranging from simple encoding to complex attention-based methods.

The following list presents some PNT applications that NAVISP has explored to enhance GNSS systems with AI:

- *Data fusion* from various sensors (GPS, inertial measurement units, LiDAR, cameras);
- Detect and counter *jamming and spoofing* attempts on PNT signal;
- Adapt to *challenging environments* (urban canyons, dense foliage) that degrade PNT signals;
- Predict and prevent PNT system failures;
- Secure PNT systems from cyberattacks;
- Improve pedestrian navigation accuracy using smartphone sensors and historical user data;
- Correct and update navigation maps in real-time using sensor data from multiple users;
- Optimize navigation routes;
- Develop indoor positioning systems using existing infrastructure and camera data;
- Generating realistic GNSS signals in degraded environments to maintain positioning continuity.

To further enhance PNT capabilities for applications, NAVISP will focus on the following objectives:

1. Enhance PNT System Performance
   - Utilize deep learning for advanced signal processing techniques, including modulation recognition, channel equalization, and interference suppression.
   - Employ AI agents to create self-organizing, decentralized PNT networks, optimizing sensor selection and fusion, and enabling collaborative PNT for improved accuracy and reliability in challenging environments.
   - Leverage multimodal AI to extract meaningful information from diverse sensor data, comprehend the environment, and detect anomalies for improved decision-making and threat detection.
2. Develop Innovative PNT Applications
   - Explore precision positioning for autonomous vehicles, drones, and maritime vessels.
   - Develop real-time location-based services, traffic management, public safety, and asset tracking solutions for smart cities.
   - Explore indoor navigation, immersive location-aware experiences through augmented and virtual reality.
   - Use Generative AI to generate realistic synthetic PNT data for AI model training, predict system failures for proactive maintenance, and create diverse PNT scenarios for enhanced system performance.
3. Strengthen PNT Security and Resilience
   - Develop deep neural networks for anomaly detection and prediction to enhance security.
   - Employ federated learning to train AI models collaboratively while preserving data privacy.
   - Create transparent and interpretable AI models (verifiable and explainable AI) for PNT systems.

To facilitate the integration of AI technologies into the European PNT sector, NAVISP Element 1 engages stakeholders through workshops and releases every year a new workplan (the 2025 workplan already integrates key PNT trends with AI, initiating strategic initiatives that align AI strategies across ESA). Element 1's comprehensive funding supports extensive innovation and development in the PNT sector, with consistent updates and communication to keep stakeholders informed about ongoing progress and upcoming endeavours, affirming its role as an adaptive and forward-thinking part of the NAVISP programme.

Element 2 is helping economic operators to reduce the risks of their more promising initiatives and Element 3 is supporting the strategic objectives of the Member States. These

Elements too will undoubtedly use funding to fulfil the needs of innovation in the AI technology needed for the respective PNT applications.

PNT System infrastructure

The PNT System Infrastructure market is a complex ecosystem reliant on precise and reliable systems. By exploring key drivers of change, such as the proliferation of satellite constellations, miniaturization of satellite technology, and increased launch vehicle reusability, we seek to inspire innovative solutions within the Directorate of Navigation.

To establish a strong and independent position in the PNT market, we must focus on technological leadership, market expansion, and robust cybersecurity. By leveraging AI and emerging technologies, we can create a resilient and adaptable PNT system capable of meeting future challenges.

The following strategic objectives have been identified for the Space Segment:

1. Enhance Satellite Autonomy and Intelligence

   By adopting agent-based AI into PNT Satellites, the aim is to transform satellite subsystems into intelligent entities capable of autonomous decision-making and adaptive behaviour. This approach will significantly enhance fault tolerance, system resilience, and overall satellite performance in complex space environments.

   Moreover, the trend towards satellite miniaturization presents both challenges and opportunities for PNT systems. Smaller satellites often necessitate trade-offs in payload capacity, power consumption, and thermal management, which can impact PNT-related ionospheric delay (IOD) modelling and signal generation. By optimizing component placement, refining IOD models, and enhancing power management, we can develop efficient and reliable PNT constellations that meet the demands of the future.

2. Optimize Satellite Constellation Design and Management

   Leveraging Generative Adversarial Networks (GANs) to generate optimal satellite constellation configurations based on various performance metrics (e.g., depth of coverage (DOC), dilution of precision (DOP), resilience). Develop advanced optimization algorithms to dynamically adjust satellite positions and resource allocation in response to changing conditions in near real-time.

3. Radio resource management

   Develop machine learning algorithms for adaptive beamforming and resource allocation to optimize the performance of internal data links. AI-powered cognitive radio techniques could allow dynamic spectrum and power allocation in challenging environments.

4. On-board navigation optimized with emerging technologies

   Utilize the computational power of machine learning to expedite complex processing of PNT satellite data, facilitating real-time data fusion, advanced signal processing, and optimal constellation management for improved PNT system performance. Quantum algorithms also promise breakthroughs in tackling computationally intensive tasks like image recognition and anomaly detection with unprecedented speed and accuracy. Integrating quantum technology with machine learning enables advanced computer vision techniques for autonomous satellite inspection and on-orbit maintenance, significantly enhancing satellite autonomy and operational efficiency.

5. Enhancing PNT Cybersecurity and Space Segment Resilience with AI

By analysing vast datasets of PNT system behaviour, AI can detect subtle anomalies indicative of cyberattacks, such as signal spoofing, jamming, or data manipulation. This proactive approach enables predictive maintenance of critical PNT components, optimizing satellite operations for enhanced resilience. Moreover, AI-driven autonomous decision-making empowers satellites to mitigate threats in real-time, while robust intrusion detection systems safeguard ground-based infrastructure. Key AI Applications in PNT Cybersecurity and Space Segment Resilience:

- Advanced Threat Detection: Utilizing AI to identify subtle patterns and anomalies indicative of cyberattacks.
- Autonomous Satellite Operations: Empowering satellites with AI-driven decision-making capabilities for enhanced efficiency and resilience.
- Clock performance parameter monitoring and anomaly prediction using advanced neural networks.
- Data-Driven Optimization: Leveraging AI to analyse satellite data for predictive maintenance, resource optimization, and improved operational performance.
- Intrusion Detection: Developing AI-powered intrusion detection systems to safeguard space assets from cyber threats.

The following strategic objectives have been identified for the Ground Segment:

1. Optimize Ground Segment Operations with AI-driven autonomy

The integration of advanced NLP, machine learning, and reinforcement learning technologies will enable the creation of a self-optimizing ground segment. By automating data extraction, analysis, and decision-making processes, the system will achieve real-time responses to anomalies, predictive maintenance, and dynamic resource allocation. The development of AI-powered digital navigation twins will facilitate the simulation and optimization of ground station operations, leading to reduced operational costs and increased system efficiency. Furthermore, the implementation of computer vision for equipment inspection and maintenance, combined with reinforcement learning for autonomous power management, antenna pointing, and tracking, will significantly enhance ground station performance and resilience.

2. Optimize Constellation Management

Transitioning from traditional constellation management paradigms, the system will leverage graph neural networks and advanced Kalman filtering techniques. The integration of quantum computing is envisioned to accelerate optimization processes and enhance orbit determination accuracy. A self-organizing constellation architecture capable of adapting to dynamic operational requirements and unforeseen events will be developed. Graph neural networks could be applied for modelling and optimizing satellite constellations, while advanced Kalman filtering techniques incorporating machine learning for process noise modelling can be employed to enhance orbit determination accuracy.

3. Ensure resilience with cyber security and data fusion

   Develop a comprehensive AI-driven cybersecurity framework utilizing multi-modal data fusion. Integrate intrusion detection, anomaly detection, and automated response mechanisms to safeguard PNT systems against evolving threats. Employ advanced machine learning techniques to correlate data from diverse sources, including satellite telemetry, ground station logs, and external intelligence, enhancing threat detection, response capabilities, and overall system resilience.

The following strategic objectives have been identified at System or User Segment:

1. AI-Enhanced SBAS

   Through advanced algorithms, SBAS can optimize various parameters, such as ground station network configuration, and ionospheric modelling, in real-time. Additionally, AI enables robust anomaly detection, identifying irregularities in satellite signals, ground station data, or user equipment, leading to faster issue resolution and improved service continuity.

2. LEO PNT with Integrated navigation/communication applications

   A system that combines the capabilities of providing accurate location information (PNT) with broadband communication services while orbiting closer to Earth's surface. Incorporating AI into this integrated system, satellites can autonomously manage and optimize their communication and navigation tasks. AI algorithms can analyse data in real-time to adjust frequencies, optimize signal paths, and enhance the accuracy of positioning information. This synergy between LEO PNT and integrated navigation/communication applications, supported by AI, aims to maximize the reliability and performance of satellite networks, making them more adaptable to dynamic environmental conditions and operational demands.

3. AI-driven Enhanced PPP

   Improving PPP accuracy through a set of ground-based reference stations. AI algorithms will optimize network design, data processing, and real-time calibration, significantly enhancing PPP accuracy and reliability, supporting high accuracy applications such as autonomous vehicles and geodesy.

4. AI-driven autonomous space vehicles

   Integrating PNT with AI for self-guided satellites and spacecraft. AI empowers autonomous space vehicles with enhanced navigation, real-time decision-making, resource optimization, fault detection, and mission adaptability.

5. PNT-enhanced augmented reality in the Solar System

   Creating immersive experiences with precise location-based information that could offer the benefit for astronauts and rovers to navigate complex terrains, identify potential hazards and optimize mission planning.

4.7 OPS

The Directorate of Operations is Europe’s centre of excellence for ground systems, mission operations and space safety; OPS is a pivotal player in the competitive space arena, shaping the future of space exploration and technology. It is the driving force behind Europe's most advanced, fully AI-enabled automated operations and collision avoidance manoeuvres. This is complemented by space safety to guarantee the protection of Europe’s critical space and ground infrastructure from hazards originating in space.

Given this strategic vision, OPS has identified AI as a key enabler to support its realization and has set a business objective of increasing systematic use of automation and AI, to introduce ever more efficiency gains and capabilities applied in the execution of complex space operations.

This began in 2021 when OPS defined the A^{2}I Roadmap for Mission Operations, by identifying 14 high potential use cases in across 5 OPS business domains. Work has been initiated to implement the necessary activities, with initial results confirming the expected impact of the use AI.

Specifically, the following strategic objectives have been identified.

1. Develop and evolve an OPS data science platform

   To make the most of operational AI, solutions require easy access to data, optimized and repeatable processes, and compute infrastructure, hence the need to clearly address aspects such as Data Access and Governance, Machine Learning Operations processes and Data Exploration.

   However, OPS traditional data architecture is highly distributed and heterogeneous, which poses problems for new stakeholders such as data scientists and especially AI and automation systems, who must deal with challenges of combining data from different sources, data access control, use of legacy systems, and the scaling on-premises systems, all of which increase the difficulty of implementing reliable automated solutions.

   The implementation of a consistent data architecture and management strategy a cornerstone for the implementation of complex analytics and automation. A mature Data Science platform capable of supporting data scientists and AI specialists in the initial exploration and generation of AI solutions, as well as the operational deployment, monitoring and eventual re-training of the AI components is needed. This platform will:

i. Access the heterogeneous data sources required for training and execution in a coherent and governed manner.

ii. Provide access to centralise IT resources necessary for development and testing purposes

iii. Meet operational requirements regarding availability, accuracy and security, requiring a validated and supported platform delivering MLOPS processes.

2. Complete the implementation of the AI for Automation (A2I) Roadmap for mission operations, and expand development and deployment of AI based mission operations capabilities.

OPS has identified the following technical capabilities which are under development now and will continue to mature over the next years, also to consider advancements in AI:

i. AI Automated Health Monitoring and Control

AI will be used for enhancing existing operation processes such as anomaly detection, root cause investigation and handling, short- and long-term prognostics.

Initially, it will provide operator alerts for unusual patterns, trend analysis, and assist in novel situations.

Future solutions could automate responses or processes, if qualified, and new monitoring features will be required for future AI-controlled spacecraft.

ii. AI Enhanced Decision Recommendation and Planning

AI will support analyses and enable the execution of what-if scenarios alongside ongoing operations, offering more comprehensive insights of on-board conditions and potential responses, ultimately supporting operators in their decisions and planning tasks, also including unexpected and unplanned events.

This capability will combine short- and long-term prognostics, AI predictive maintenance and intelligent planning and decision support.

iii. AI-Enhanced Modelling and Simulation for operations

AI will improve situational awareness through simulation, mission preparation and training, and identifying simulation failures. Spacecraft Digital Twins can integrate AI with physics-based simulations and onboard software to enhance these capabilities and contribute towards spacecraft and ground systems heath monitoring.

iv. AI-Automated Content Generation and AI-Enhanced Data Interaction

AI will assist in generating and analysing requirements and test cases, along with reporting. Also, multi-modal models will enhance data retrieval, questions and answering, and reasoning to help operators search and explore vast, diverse documentation repositories accumulated over time.

OPS also foresees additional activities beyond the content of the current A2I Roadmap. OPS will leverage AI to advance mission analysis and flight dynamics as well, including AI for model generation, e.g. digital elevation model of the Moon, data-driven physical models of the space environment.

3. Leverage AI for space safety

   With the goal of operating a carbon-neutral infrastructure and foster a circular economy in space through in-orbit production and recycling, AI will be used to support space weather and debris management with object detection, intelligent manoeuvre recommendations and visualisation, data catalogue enrichment and data fusion, data simulations and space weather forecasting. These capabilities will contribute towards leading the way in space debris mitigation, cis-lunar space traffic coordination technology, and active debris removal and in-orbit servicing.

4. Develop and evolve ground segment AI capability for cybersecurity

   Complete and evolve the development and deployment of AI solutions for threat detection, prevention, and response in the ground segment domain as well as vulnerability management. OPS is already driving AI technology development and application to this this domain for several concrete use cases, including the C-SOC for mission operations.

4.8 SCI

For the Directorate of Science, the focus of upcoming strategies related to advanced analytics, machine learning or artificial intelligence is to support the directorate in its mission to advance scientific progress. While this hinges on many of the aforementioned activities, so that SCI would benefit from efficiency improvements along established ESA processes for building and operating spacecraft, a unique aspect of SCI is the domain expertise related to gaining insights from the specific types of data generated by SCI missions and the complex relations to other institutions that work jointly with ESA towards the same goals (including academy, industry and space agencies). Due to the Directorates proximity to academic institutions leading in advances in AI, it has the responsibility of abstracting from overzealous implementation of trends and identifying opportunities with the potential of changing scientific knowledge production in current and future AI systems. This entails a focus on verifiable/explainable AI and mastering the fundamentals. Hence SCI is pursuing the following high-level objectives:

1. Unlocking inter-disciplinary AI use-cases with science platforms

   The data volume generated by our missions being to reach petabyte scale. To effectively explore and analyse this data, including with AI, we need data platforms that bring users and code to the data, instead of copying the data across. Such platforms have a tendency of requiring interoperation and federation capabilities to advance collaboration with SCI´s partners in academia and industry. This foundational component of the AI strategy will require close collaboration with ESA-internal stakeholders (e.g. HPC) as well as partnering agencies or institutions interested in joint use-cases (e.g. ground-based radio-astronomy communities, CSA, NASA). The main deliverable of this project will be federated access and processing of science data across organizations. The main return of this initiative will be dramatically improved collaboration opportunities and facilitating research on use-cases that are currently impossible to address.

2. AI-powered citizen science

   SCI is planning to increasingly utilize AI as part of an open science approach with emphasis on scientific engagement. Making space science data available to both scientific communities and citizen scientists allows the setup of innovative use-cases supported through science platforms. This objective requires advances in AI-related services offered to communities as well as building up related domain expertise in inter-disciplinary research. With these pre-requisites the main deliverables would be data products and benchmark datasets made easily available to scientific communities as well as training material and event support specific to scientific data exploitation. This approach yields multiple opportunities for collaboration: within ESA there are opportunities to team up with other directorates following similar approaches (e.g. EOP) and with central functions to support implementation. Other agencies are likely partners in respective projects, in particular agencies that frequently partner with ESA on space science missions. This approach opens a new return on science perspective for SCI and benefits overall engagement of Member States with our work.

3. Inter-agency foundational models for space science

   Building on the highly successful ESDC science archives recent experiments and discussions with partnering space agencies and institutions (in particular NASA, STScI and CSA) indicate a large potential of return on science achievable through the implementation of foundational AI models trained on science data. While this task is very ambitious, other agencies are succeeding in securing relevant funding. ESA would benefit from resource commitment that allow playing at least the role of a partner in such efforts. Respective activities would open collaboration opportunities with other ESA directorates and strongly increase ESA´s standing in the space science communities.

4. On-board AI for science mission studies and prototypes

   Leveraging experience from other directorates, in particular TEC, SCI needs to study the opportunities of AI system on board future missions to enhance autonomy (in particular for planetary science and asteroid-rendezvous missions) as well as on-board processing capability for observatories to enhance instrument functionality and improve efficiency of downstream bandwidth utilization. This activity yields synergies with plans to improve autonomous operations capability of future L4 mission that could benefit from advances to e.g. navigation and landing.

4.9 STS

The Space Transportation Directorate (D/STS) is committed to leveraging Artificial Intelligence to revolutionize the development and exploitation of European Launchers. Our strategy aims to foster innovation, increase competitiveness, and ensure independent European access to space through the implementation of AI technologies.

Our vision is to establish frequent optimisation as the new standard in space transportation, driving continuous improvement in manufacturing efficiency, quality and cost effectiveness

Key objectives & initiatives:

1. AI in Launcher Manufacturing, Assembly, Integration and Test

   We are implementing AI solutions to boost manufacturing efficiency, enhance quality inspection and streamline processes. Our initiatives include:

   - Advanced anomaly detection and management systems applying machine learning algorithms
   - Automated non-compliance management through machine learning
   - AI driven quality control and inspection processes
   - Real-time health monitoring of the flight component through MAIT processes

2. AI for Flight Analysis and Anomaly management

   We are developing AI-supported decision-making tools and digital twins to enhance launcher performance and adaptability

   - AI assisted parameter analysis for critical changes
   - Digital twins for critical components and the entire Launcher
   - Increased on-board autonomy and mission reconfigurability

3. AI in Ground Segment and Infrastructure

   The focus on smart infrastructure includes:

   - Deployment if advanced sensor technologies across production, test and launch facilities
   - Implementation of smart algorithms for performance analysis and improvement
   - Development of digital twins for critical assets and entire shop floors
   - Predictive and prescriptive maintenance systems
   - Real-time health monitoring of assets

4. AI supported Planning & schedule management

   - Optimizing spare parts management and safety protocols
   - Enhancing schedule planning and risk management with AI assistance

5. AI optimized supply chain and sustainability Management
    - End-to-end supply chain visibility
    - Carbon footprint analysis and reduction strategies
6. Augmented Reality and AI supported Training
    - Augmented reality for operational process enhancement
    - Smart glasses with AI-powered step-by-step instructions

Implementation process

Several pilot projects have already been initiated on these objectives, yielding excellent results with measurable cost savings and improved quality. For instance, our new Asset Management tool, Hexagon EAM forming the foundation for our AI infrastructure initiatives. The deployment of advanced sensors, measuring real-time health data of assets. Several pilot projects for predictive maintenance of critical assets at different manufacturing sites.

AI/ML is becoming an increasingly valuable tool in improving the European competitiveness of Space Transportation Vehicles (STV), e.g. Launch vehicles, Space-tugs, Orbital refuelling, etc. Already AI/ML techniques have shown the ability to reduce cross-lifecycle costs, improve technical performance of existing systems, develop new capabilities that tackle more complex transport missions and increase cross-lifecycle sustainability.

Efforts to spin-in AI technologies are primarily being deployed across three areas of the STV value chain:

- System Design Tools: New Modelling & Simulation tools that leverage the latest AI/ML techniques to accelerate design and prototyping of new systems (e.g. reusable launch vehicles).
- Fabrication of the System: New Manufacturing processes (i.e. Factory 4.0+) that leverage AI/ML in the manufacturing, assembly, integration and testing (MAIT) process.
- Operation of the System: New operational capabilities for both supporting Ground Infrastructure and the System itself.
- Ground Infrastructure: New Supply Chain Management tools, Maintenance, Repair, Operation (MRO) processes and Health Monitoring (HMS) solutions that aggregate disparate data sources and use AI/ML to generate actionable insights.
- Space Transportation Vehicle: New On-Board Decision Making (OBDM) that leverages improved embodiment (e.g. new sensors) and on-board AI/ML-derived intelligence (i.e. embodied intelligence) to improve, sub-system, system and ecosystem autonomy.

These novel AI/ML technologies are intended to be applied to both existing applications (e.g. Ariane 6, Vega-C, P120C, Space Rider) as well as emerging applications (e.g. Reusability, NewSpace Vehicles, Space-tugs, In-orbit Refuelling, etc.).

Therefore, AI/ML is regarded as a critical technology for STS to be developed through the pursuit of the following strategic objectives:

1. AI for System Design

   New engineering tools are leveraging the latest AI/ML techniques to accelerate the design and prototyping of new systems such as generative design, data-driven physics simulation, engineering co-pilots, automated product/lifecycle data analysis and smart requirements management software. Many of these developments can be tailored and leveraged to STS applications to improve the speed at which current and future systems can be built (e.g. Reusability, NewSpace Vehicles, Space-tugs, In-orbit Refuelling, etc.). For example, AI/ML techniques can be used in engine alloy selection, improving sim2real of launcher CFD, automated component design, design optimisation for additive manufacture.

2. AI for Smart Manufacturing

   AI/ML methods combined with a comprehensive Digital Engineering approach (including Digital Twins, MBSE, Virtual Testing, Physics-based numerical simulation etc.) can speed up tasks in identifying physical patterns and automating data extraction and property inference closing the gap between Flight model design and launcher operations. The idea is to automate laborious manufacturing processes, assembly and testing of spacecrafts, leading to substantial decrease in production cost and lead time. In the spacecraft life cycle (design, production, operations, decommissioning) the production is the driving cost element for recurring systems like launcher in terms of cost and for long running single element mission like scientific mission simulation and prediction of spacecraft manufacturing bear huge potential to minimize risk and reduce lead time to operations.

3. AI for Ground Infrastructure

   Digital Twins are high-precision digital representations of the Launcher and its Infrastructure delivery the functionality of monitoring, archiving and predicting events and performances of the overall launcher system. The utilisation of AI/ML methods should aim to create operational business value out of the plethora of data gathered by onboard sensors, IoT and Virtual sensors of the production and operations infrastructure, reducing the cost of launcher operations and stabilising the launcher cadence.

4. AI for Vehicle Sub-systems

   The many different sub-systems that comprise a STV such as a launcher (e.g. engines, GNC, thermal, power, structures, avionics, communications, etc.) are incrementally becoming more intelligent thanks to new AI/ML techniques. Increasingly AI/ML techniques are being deployed at this localised level to improve sub-system health monitoring, failure prediction and ultimately leverage online and adaptive control to improve sub-system performance.

5. AI for Space Transportation Vehicles

   At a higher system-level improving a vehicle's on-board autonomy and reconfigurability to changing missions' objectives, payloads and operational constraints is crucial to reducing cost, improving performance and ultimately tackling growing mission complexity. Incorporating new AI/ML-based On-board Decision Making (OBDM) approaches will be necessary in addressing the need to improve on-board autonomy and reconfigurability for STVs.

6. AI for Space Logistics

   With a growing market shift toward a space logistics 'ecosystem', where payloads are delivered via a system-of-systems in place of a dedicated launch vehicle, intra-system interactions will become crucial in facilitating low-cost, high availability space transportation services. To address the multi-agent interactions of a system-of-systems, AI/ML will be a core technology in maturing the multi-agent intelligence needed to build an automated space logistics network similar to the AI/ML-driven automation seen in terrestrial logistics.

4.10 TEC

The role of TEC Directorate is to support stakeholders in the development of their project and to support the development of technologies for the benefit of one or several stakeholders. The first role is covered by the AI Competence Centre. The strategic objectives defined in this section focuses on the second role.

1. Full development process supported by Artificial Intelligence

   Artificial Intelligence is transforming the field of space mission design and engineering. It is now possible to envisage a full development process of space missions from phase 0 to phase F supported by AI, including:

   i. Mission requirements and design definition, and cost estimation

      AI will be used to analyse not only past missions and their requirements, but also any data pertinent to space missions. Machine learning algorithms can identify patterns and trends that can help in defining precise and realistic mission requirements. AI will propose a specific tailoring of standards and a first top-level design that will be consolidated by system engineers. By analysing data from previous projects, AI will produce an accurate cost estimation of the project to support budget planning and allocation.

   ii. System and subsystem requirement definition, modelling and analyses

      AI will enhance System Engineering using Model-Based System Engineering[6] (MBSE) by automating the creation and validation of system models. AI algorithms can analyse these models to identify potential issues or improvements and support their simulation, leading to more efficient and reliable systems. Virtual assistants will increase the productivity of engineers while ensuring the consistency of the full system. This will cover at least, Mechanical, Thermal, Power, EMC, Radiation

[6] ESA/IPC/THAG(2024)9: Model-Based for System Engineering Technology Harmonisation Dossier

effects, Propulsion, Control, Data Handling, TT&C, RF payload, Optical payload, Software.

iii. System and subsystem verification, validation and qualification

AI to automate complex tasks, improving efficiency, and providing intelligent insights to enhance system performance and reliability while checking the compliance of the spacecraft design and operation with ECSS standards and assisting in the verification and validation processes by simulating different scenarios and measuring the spacecraft's performance.

This strategic objective consists in federating all the AI initiatives in the domain of Engineering in relation to the deployment of a fully integrated development process supported by AI and in its application to a concrete use case, leading to the first partially or fully developed AI spacecraft.

2. AI-powered platforms and payloads

One of the main challenges for AI-powered platforms and payloads is to ensure that the hardware components can withstand the harsh environment while providing the required level of performance and that a software stack supporting the execution of AI models is available for these hardware components. This strategic objective is coordinated with existing ESA technology roadmaps and programs to improve and ensure availability of European HW and SW building-blocks and the know-how that enable AI-powered onboard functions.

To fully enable the on-board execution of AI enabling all benefits, the following activities are proposed.

i. New disruptive edge processing accelerator for safety critical low power AI applications

Such as Neuromorphic hardware accelerator, which uses data and activation sparsity to save power, is recommended for space applications. This technology could reduce power consumption by 100x to 1000x, which is crucial for landers, rovers, and drones. The Neuromorphic hardware accelerator could also be used for in-orbit or High-Performance Computing if designed with versatility and scalability.

ii. Data Storage for AI applications

AI is a consumer and producer of huge amount of data that need to raise the capacity of existing space data storage at the next level for achieving the best performance / cost / radiation tolerance / energy efficiency ratio adequate for all the different use cases of onboard AI.

iii. Processing units for AI applications

Develop on-board processing hardware solutions with varying reliability levels to cater to different mission classes enabling the use of a mix of Radiation Tolerant

(RT), Radiation-Hardened by Design (RHDB), and Commercial Off-the-Shelf (COTS) components for AI processing.

iv. Software stack for AI applications

Develop or adapt existing software environments supporting the execution of AI models to the different hardware available for space applications considering their different criticality categories.

3. New in-space capabilities

AI can enable new in-orbit capabilities for the benefit of several stakeholders such as:

i. In-orbit servicing

Assure the maintenance or repair of satellites and other spacecraft while they are in orbit. This can extend the lifespan of valuable assets, reduce the risk of collisions or malfunctions, and create new business opportunities. In this context, AI can be used:

- to help automating rendezvous and docking procedures, ensuring safety and accuracy;
- to assist in performing delicate and complex servicing tasks, such as refuelling, replacing parts, or reconfiguring payloads with the help of robotic systems;
- to optimize the trajectories for servicing missions, for example passive safe trajectory to avoid the target, reducing fuel consumption and time for the servicing operations;
- to coordinate a fleet / swarm of servicing satellites optimizing their operations and ensuring efficient tasks distribution.

The successful completion of this project will enhance the reliability and sustainability of space missions, reducing the need for costly replacements and mitigating the problem of space debris. AI will be a key enabler in this process, providing intelligence and autonomy for in-orbit servicing operations.

ii. In-space Servicing and Manufacturing

In-Space Servicing and Manufacturing is already relying heavily on machine-learning and AI can be expected to drive innovation in this sector in the coming years, leading to a whole new range of possible applications. The development of such AI-enabled solutions is crucial to enabling and delivering successful long-duration exploration missions to LEO, the Moon, Mars and especially missions to deep space. Example use cases for technology development that will rely on AI include:

- The development of “smart” self-servicing space stations and other spacecraft with the aim to free crew time for other activities such as science and exploration, and to ensure continuity, maintenance and safety of spacecraft during absence of crew and upon their return. This applies also to for example rovers on the Moon and Mars who rely on self-service and repair to continue their journey.
- The on-demand production of spare parts, food, medicine and other products in space through on-board production capabilities with the aim to optimize usage of resources and ensure ad-hoc availability, especially in cases where re-supply missions would not be feasible and/or cost-inefficient.
- The prospecting, extraction, and processing of regolith by means of In-Situ Resources Utilisation (ISRU) enabling the production of oxygen, hydrogen, and metals which will enable in-space manufacturing and refuelling. ISRU will require the real-time fusion of a vast amount under conditions of the lunar surface which requires adequate HW. AI algorithms will be key to analyse and optimise mining and processing operations, identifying patterns, and making data-driven decisions to enhance efficiency and effectiveness.
- The in-space manufacturing and assembly of larger structures in space and on the surface, of e.g. the Moon and Mars, produced with recycled materials or sourced from planetary surfaces or asteroids.

iii. In-Orbit Assembly Technology for Large-Scale Space Structures

The primary objective is to develop and validate an AI-enabled in-orbit assembly technology that facilitates the construction of large-scale structures in space. These structures include large antennas for telecommunication spacecraft and solar arrays for in-orbit power generation and possibly large spacecraft. AI can be used:

- to analyse existing in-orbit assembly methods, understand their limitations, and explore potential improvements or new techniques.
- to help in optimizing the design process, predicting the performance of different designs, and selecting the most promising ones for further testing.
- to help in planning and executing complex assembly operations, ensuring precision and efficiency.

The successful completion of this project will revolutionize space construction, enabling the creation of larger and more complex structures in space. AI will be a key enabler in this process, paving the way for future advancements in space technology.

4. AI for Smart Manufacturing & MAIT

AI/ML methods combined with a comprehensive Digital Engineering approach (including Digital Twins, MBSE, Virtual Testing, Physics-based numerical simulation etc.) can speed up tasks in identifying physical patterns and automating data extraction and property inference closing the gap between Flight model design and launcher operations. The idea is to automate laborious manufacturing processes, assembly and testing of spacecrafts, leading to substantial decrease in production cost and lead time. In the spacecraft life cycle (design, production, operations, decommissioning) the production is the driving cost element for recurring systems like launcher in terms of cost and for long running single element mission like scientific mission simulation and prediction of spacecraft manufacturing bear huge potential to minimize risk and reduce lead time to operations. The following tasks reflect critical areas, which are similar in many ESA mission, and which can benefit from AI accelerated Smart Manufacturing.

i. AI/ML for automatic manufacturing/ joining of parts and assembly of components

Joining of different materials who then are exposed to space environment is a major source of failures, contributing to overall risk for a broad range of missions (e.g. I-HAB, European Service Module, Ariane 6, Vega-C etc.) AI/ML will contribute to accelerated behaviour/ property description arising from manufacturing and being made available during the spacecraft design phase. As well as enhance pattern recognition during physical inspections and testing before operational take-up.

ii. Automated in-situ process monitoring and predictive quality for the flight components

AI/ML techniques help assessing to quality of flight hardware during each production step, monitoring the progress and autonomously scrap components/ parts that don't suffice the performance requirements. This reduces time intensive human supervision and enables dynamic machine-/ data-driven production task scheduling, whereby parts don't run through costly production steps if the part is not fit for purpose.

iii. Material Accelerator Platforms for materials under tough environments

AI/ML will enable tailored materials discovery and selection driven by mission requirements. Including automated materials testing, production set-up and integration into spacecraft design (e.g. mechanical, thermal, electrical, fluidic properties etc.), assembly and integration. Through this methodology the time to market for new materials have been shorted by an order of magnitude and will lead to nigh intime integration into the spacecraft design process.

5. AI for end-to-end security

   AI can significantly enhance the security of systems during their development and operations.

   i. Threat Detection, Prevention and Response: AI can analyze vast amounts of data to identify patterns and anomalies that may indicate security threats and take action to mitigate potential security breaches in both Ground and Space segments. For example, AI systems can detect unusual network traffic or user behaviour that could signify a cyber-attack.

   ii. Vulnerability Management: AI can help identify and prioritize vulnerabilities in software and systems. By continuously scanning for weaknesses and assessing their potential impact,

   iii. Enhanced Encryption: AI can improve encryption methods, making it harder for attackers to decrypt sensitive information.

   iv. Security for AI Systems: Ensuring the security of AI systems themselves is crucial. This includes protecting AI models from adversarial attacks, ensuring data integrity, and implementing robust access controls.

6. AI spacecraft

   The objective is to exercise all the different techniques and tools resulting from the implementation of strategic objectives previously described to build a full small autonomous spacecraft. This includes:

   - AI-driven design, manufacturing and validation
   - AI based autonomous navigation and control systems
   - AI autonomous planning to realize the objectives of the mission and operate the spacecraft including predictive maintenance while optimizing the use of resources (power, propellant, data storage, etc.).
   - AI enhanced communication system and security

4.11 Resource overview

The following tables provide an overview of the resource allocation required for the implementation of the strategic objectives identified by ESA stakeholders.

It is important to note that:

- the total budget figures include past, present and future activities funded in the different ESA technology programmes that are supporting the achievement of the identified strategic objectives;
- the budgets need to be streamlined because some strategic objectives have common elements;
- the budgets do not cover data and HPC infrastructures as well as generic tools and services;
- the implementation of the objectives is foreseen to be distributed on 10 years.

Directorate	Total Budget (MEUR)
CIC	N/A*
CSC	60
EOP	190
HIF	20
HRE	80
NAV	140
OPS	90
SCI	85
STS	110
TEC	160
Total	**935**

*CIC activities are issued from propositions of industries, and it is not possible to identify which part of the budget will be dedicated to AI.

5 AI EXPERT NETWORK

The field of Artificial Intelligence is progressing swiftly, providing great advantages to numerous application domains. The AI expert network is key in the ESA AI strategy to capitalize on AI's possibilities and raise the global knowledge and awareness across ESA Directorates. The AI expert network comprises skilled professionals well-versed in one or several AI techniques and their use in one or several application areas.

AI Techniques
Supervised Learning
Unsupervised Learning
Reinforcement Learning
Self-supervised Learning
Neuromorphic
Natural Language Processing
Large Language Models
Planning
Symbolic AI
Evolutionary Algorithms
Fuzzy Logic

AI application areas
Virtual Assistants
Text Processing
Speech Processing
Computer Vision
Image Recognition
Video Analysis
Industrial Robots
Service Robots
Expert Systems
Recommender Systems
Autonomous Systems
Agents

The initial list of AI experts comprises 59 persons working in 8 different Directorates.

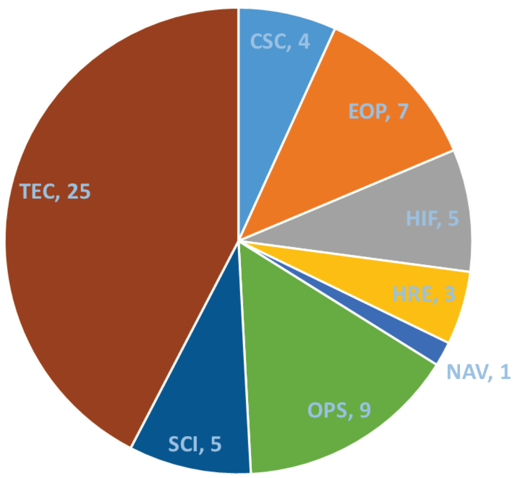


Figure 6: 59 AI experts from 8 different Directorates are part of the initial ESA AI expert network.

The AI Competence Centre (AI CC) will actively maintain the list of ESA AI experts. Each expert must be attentive to the demands of the AI CC and support it in its different duties. Experts have access to shared resources of the AI CC.

6 TECHNOLOGY AND INFRASTRUCTURE

6.1 Background

AI should be regarded as a pivotal technology. Analogous to the investment in a European space launch system, it is imperative that Europe commits to the development of AI technologies within its borders. The European Space Agency ought to serve as a role model in this pursue, taking inspiration from the European Commission's ambition to enhance Europe's autonomy in AI.

Due to the importance of foundational infrastructure components for enabling AI applications and the significant share of the value of such components of overall activities, ESA is well advised to continue a balanced strategy between utilization of efficient commercial-off-the-shelf solutions for general needs and programmatic investments into dedicated solutions that allow strengthening European industry in areas related to e.g. cloud computing.

6.2 CDO Office (HIF-T): Data, AI and High-Performance Compute Foundation

As part of the Digital Transformation, data strategy and framework of the Agency, the Digital Transformation Office has built up a **Data, AI and High-Performance Compute Foundation** over the past 2 years.

This foundation is the layer that enables the generation of business impact all across the agency's core business and supporting functions:

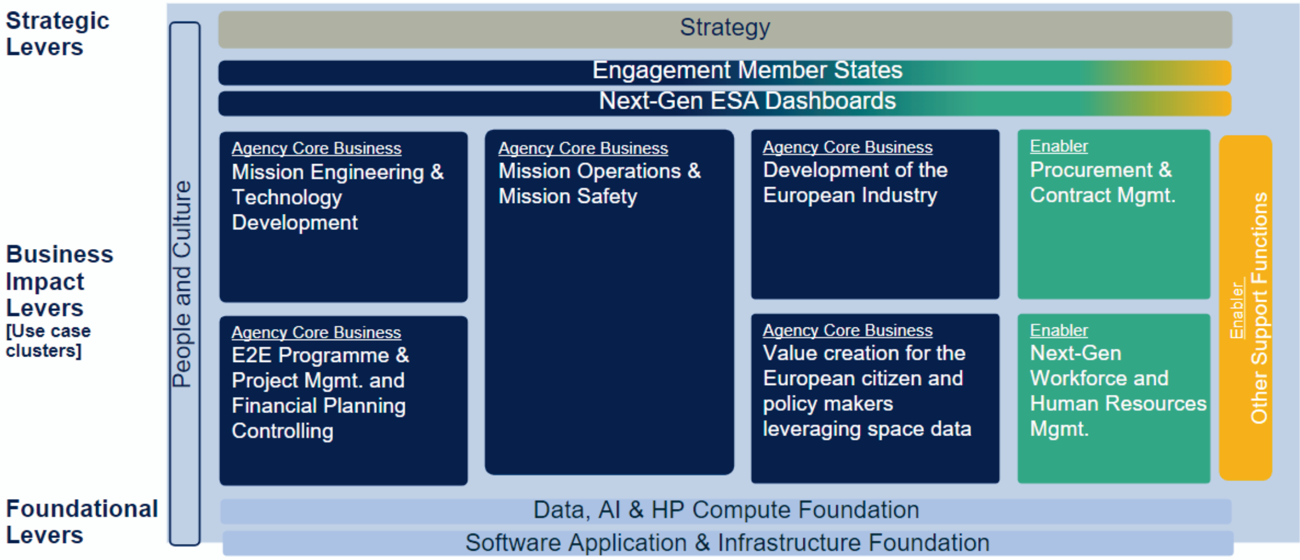


Figure 7: The ESA Digital Transformation Framework

Elements of this foundation are:

1. The ESA Data Factory
2. The Space High Performance Compute environment
3. The use case roadmaps including the AI for efficiency and effectiveness roadmap,

The strategic prioritisation and demand Funnel Management for Data & AI use cases

The ESA Data Factory [7]provides ESA's single source of truth. It consists of an infrastructural layer based on Microsoft architecture depicted in next figure.

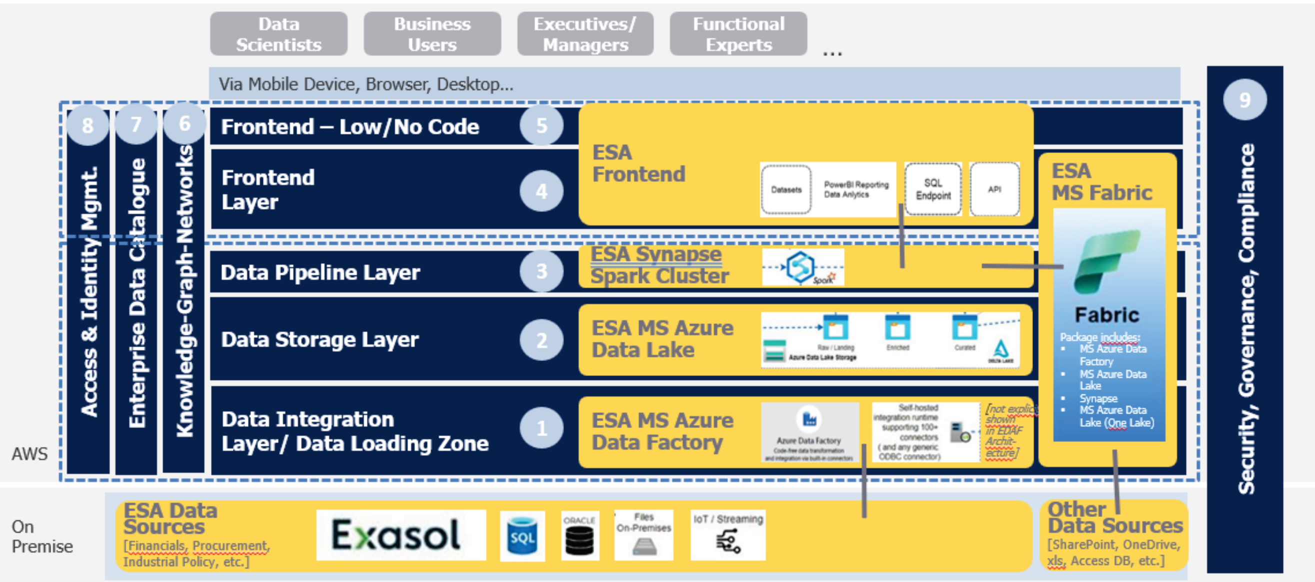


Figure 8: The ESA data factory

The ESA data factory (EDAF) provides the single source of truth with validated data across the Agency, role-based data access, and direct integration capability of data to execute business use cases. EDAF supports a series of use cases, many of which will evolve into AI-supported use cases:

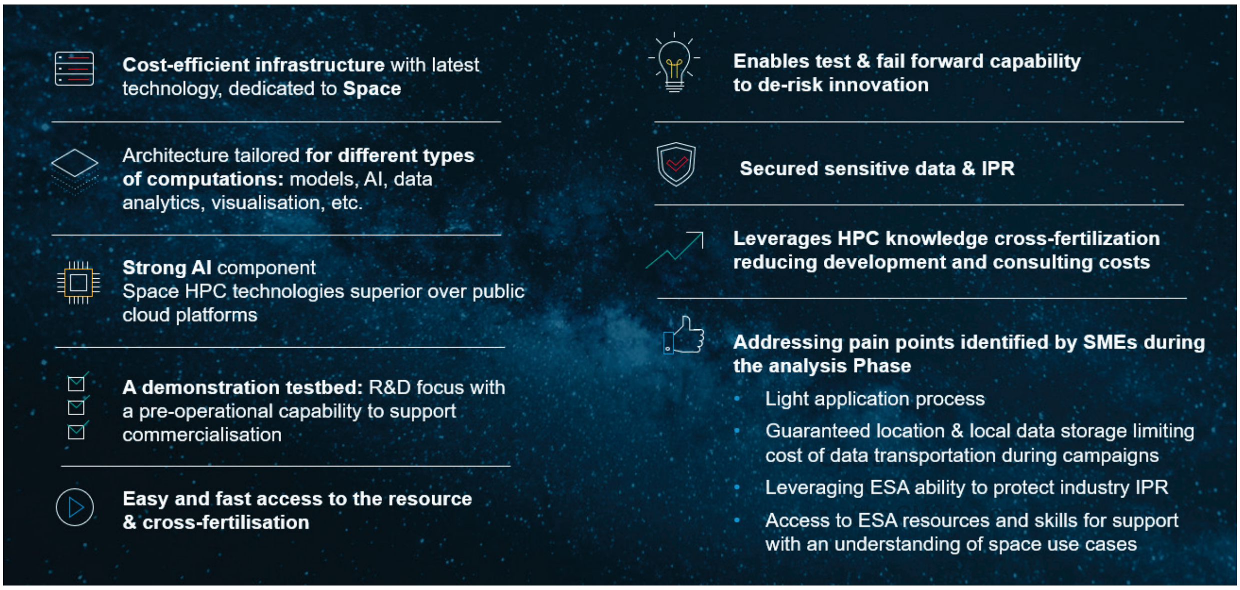
The High-Performance Computing (HPC) involves using extremely powerful computers to process vast amounts of data, e.g., collected from satellites, spacecraft, and telescopes. This technology enables complex simulations, trajectories, and scientific experiments and is essential for analysing data, making real-time decisions, and uncovering new scientific discoveries in the exploration and understanding of the universe. HPC systems split big problems into smaller parts and solve them simultaneously across many computers, speeding up calculations dramatically.

ESA has recently invested in a new High-Performance Computing infrastructure to support its scientific research and technological development activities, as well as to provide access to small and medium enterprises (SMEs) for fostering innovation and collaboration. This state-of-the-art HPC facility offers significant computational power, enabling large-scale

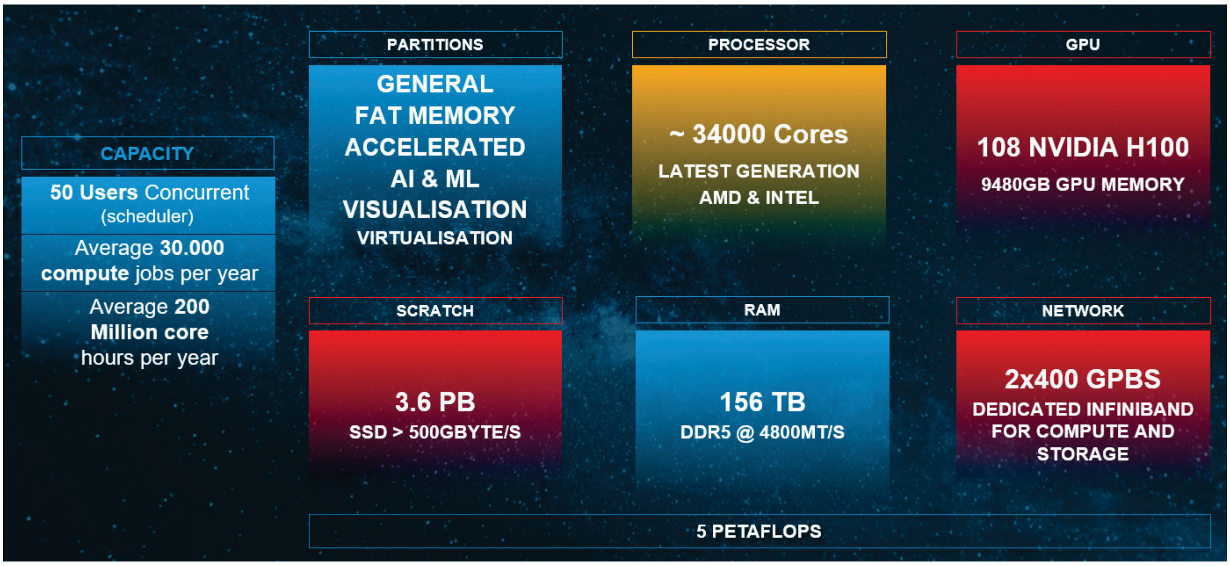
[7] ESA Data Factory Design and Roadmap, HIF-T-002-2024, Issue 1.2, 23/05/2024

simulations, data analysis, and model development in various domains related to space exploration, satellite operations, and Earth observation.

Main benefits expected are:



The technical architecture is shown below, with the main specifications being:



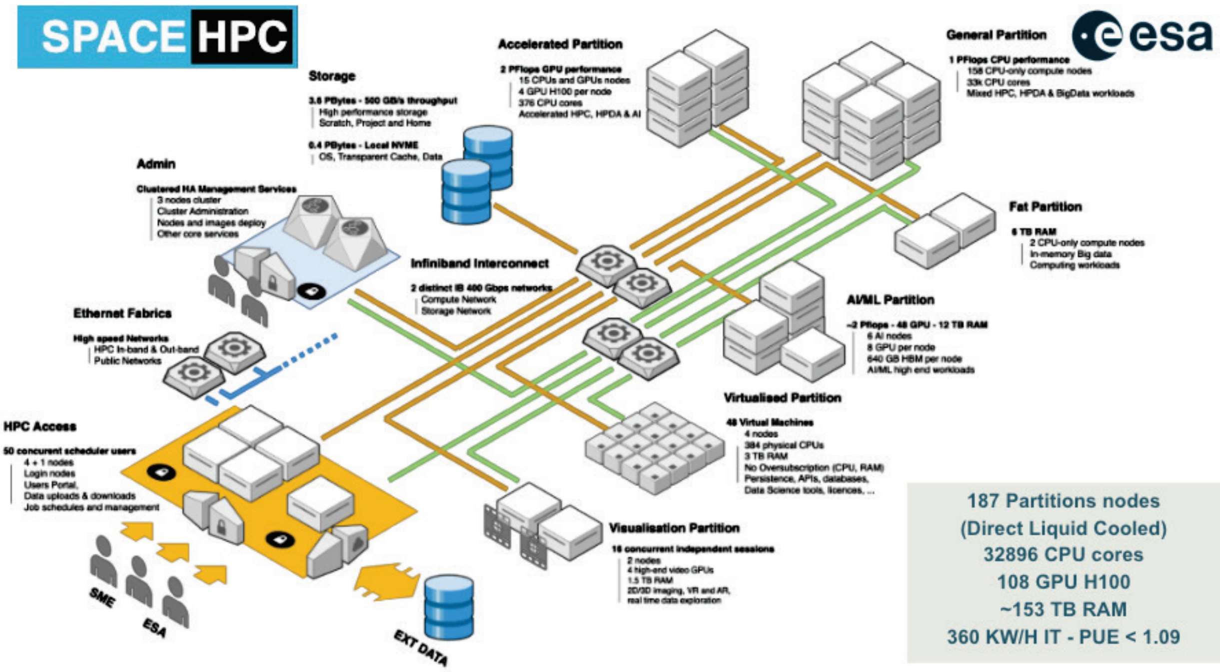


Figure 9: The Space High-Performance Computing infrastructure

HPC systems use advanced components like high-performance processors, Graphical/AI Processing Units, and fast storage to handle specific tasks more efficiently such as training AI models.

The Space HPC will support many use cases, many of them requiring an AI component:

Missions development & technology/missions preparation (upstream):

- Mission Analysis & Mission Data systems (TEC, OPS, programme Directorates)
- Mission testing & technology simulations (TEC, programme Directorates)
- Engineering tools (TEC, programme Directorates)
- Technology Research (TEC, programme Directorates)
- Integrated Computational Materials Engineering (ICME) for structures, Mechanisms and Manufacturing Processes (TEC)

Mission operations, safe operating environment & data operations:

- Space transportation simulations (STS)
- Data processing, data reprocessing (EOP, SCI, HRE)
- Mars weather and atmosphere modelling (HRE)
- Mars communication optimization, Mars communication network simulation (HRE)
- Multi-assets distributed simulations (HRE)
- Mission analysis and Flight dynamics/trajectories (OPS)
- Space weather including the Virtual Space Weather Modelling Centre (OPS)
- Mission planning and scheduling (OPS)
- Intelligent Mission Assistant Systems (OPS)
- Space Safety, Debris, Traffic and Security (OPS, Programme Directorates industry)

Data & Application development (downstream, data focus)

- Climate change analysis & simulations (EOP, NAV, TIA)
- Digital Twin Earth /Earth system modelling & simulations (EOP) including but not limited to, Hydrology, Polar science, Sold Earth, Geo-Magnetic field, solid organic Carbon, etc
- ScienceHub collaborative Project (EOP)
- Operational and pre-operational processing (EOP)
- Artificial Intelligence for Earth Observations (EOP)
- Digital twins of Mars and Moon Bases (HRE)
- Digital Elevation Maps of the Moon and Mars (HRE)
- Exploitation of Operational Simulator as a Digital Twin Spacecraft (OPS)
- Mission Data systems – Handlig of TT&C mission data (OPS)
- Universe modelling & simulations; data exploitation (SCI)
- Science Missions, data processing and Analysis of data and model output(SCI)
- GNSS Science support centre (NAV)
- Telecom, constellations and connectivity simulations (TIA)
- Signal Detection in IoT data streams (TIA)
- Civil Security from Space (TIA, EOP)

Commercialisation (upstream/downstream across above disciplines) (CIP) including cross-programme/thematic e.g. ML & AI, quantum preparation etc. (all)

6.3 AI Application Technologies and Tools

ESA should support existing and emerging open-source frameworks, in addition to existing commitments to COTS software, as this approach is more likely to strengthen its internal knowledge build-up, reduce vendor lock-in and corresponds to increasingly stringent national and European policy towards mandating that tax-funded software be openly available.

6.4 Data Management, Federation, Interoperability Strategy

The Agency's strategies for data management[8] as well as the results of the ESA Transformation Programme on the matter will be applicable to the AI domain as well.

The outcome of Transformation initiative 8 is summarized in document "Accelerate Digital Transformation and Streamlining of Processes"[9]. For what concerns ESA-internal applications of AI the Agency's digital roadmap[10] will apply.

Attention is drawn to the Agency's data assets which fall into 3 clusters and 28 categories[11]:

Cluster	Category	
Space-born & Ground Segments Datasets *held/owned & managed by ESA* (SGD)	SGD01- Payload Instrument datasets from ESA and/or 3rd party satellites in space	SGD06- Higher-level data processed from the SGD data types
	SGD02- Spacecraft housekeeping telemetry, auxiliary and ancillary data about satellites, instruments & vehicles	SGD07- Data produced during missions' study, development phases (MBSE data, test data, laboratories data at system level)
	SGD03- Humans – scientific clinical studies datasets	SGD08- Campaign data, calibration, simulation, experimental and validation data linked to the SGD data types (payload/system level)
	SGD04- Space weather and space debris datasets	SGD09- Software, Analysis tools and Data Services (e.g. Portals, …) related to the SGD data types
	SGD05- Ground Segment data	
Business & Management Data (BMD)	BMD01- Financials and Controlling data	BMD06- Estate Management metrics data
	BMD02- Procurement data (including suppliers, …)	BMD07- Sustainability metrics data (including Travel)
	BMD03- Industrial Policy data (including georeturn, …)	BMD08- Commercialization metrics data
	BMD04- Workforce and Personnel data	BMD09- Communication & outreach metrics data
	BMD05- Project and Programme Management data during all phases [1]	BMD10- Software and Analytics tools related to the BMD data types
ESA Documentation and Information (EDI)	EDI01- ESA Technical Reports, R&D reports, study results	EDI06- ESA Members States' and international cooperation documents
	EDI02- ESA SoWs, contracts, technical documents, plans & procedures	EDI07- ESA conferences, communication & outreach papers/documentation
	EDI03- ESA Projects and Programme documentation	EDI08- Patents and IPRs registered resulting from ESA contracts
	EDI04- ESA Official documents (Programme Boards, Tech Harm. Dossiers)	EDI09- Documentation Management Systems related to the EDI data types
	EDI05- ESA internal regulating, audit and legal documents	

1) including risks, schedule, quality, resources, …

Figure 10: ESA'S data

Each of the data categories is today treated or managed in a different way, by different internal communities and stakeholders, often also managed by different communities across one category (typically SGD01 space data are not managed in the same way across Directorates, while lose co-operation activities exist), and some categories exist without a clearly assigned data management responsibility or community.

[8] ESA DATA & INFORMATION MANAGEMENT IN THE DIGITAL AGE, ESA/ADMIN/IPOL-ITSW(2020)2)

[9] ESA TRANSFORMATION INITIATIVE 8 – ACCELERATE DIGITAL TRANSFORMATION AND STREAMLINING OF PROCESSES

[10] A NEW DIGITAL TRANSFORMATION FRAMEWORK FOR THE AGENCY

[11] ESA's data assets – first analysis

6.5 ESA IT infrastructure tools and services to support AI use cases

The following are the main features of esaIT's infrastructure and security services that enable AI, demonstrating the dedication to offering reliable computing resources, safeguarding security and privacy, and maintaining compliance with evolving regulations.

1. **Accelerated Computing Resource Services**

   esaIT provides accelerated computing resource services, offering both on-premises and public cloud infrastructure to support AI workloads. This includes the existing GPU infrastructure and the Space High-Performance Computing (HPC) initiative.

2. **Security, Privacy, and Data Protection**

   The security, privacy, and data protection (DP) aspects for esaIT-managed activities and technical resources are addressed through coordination with the AI Security working group. This ensures that all AI-related activities comply with the highest standards of security and privacy while interfacing with ESA security monitoring capabilities.

3. **Alignment with ESO**

   esaIT aligns with ESO to implement security risk assessments and security measures concerning AI tools and capabilities across the Agency. This collaborative approach ensures a unified security posture for AI applications.

4. **Review of PDP Framework**

   The Personal Data Protection (PDP) framework is under review considering the adoption of new EU regulations, with a particular focus on AI. This review aims to ensure that esaIT practices remain compliant and up to date with the latest legal requirements.

As indicated in chapter four and earlier, most goals related to AI applications require strong foundations related to infrastructure and platforms. Multiple directorates have built strong expertise in leveraging current technologies in this area to deal with increasing volumes of data.

The ESA IT Department has or will deploy several AI services:

- **esaIT Azure AI Toolkit and Factory Services:** Azure AI provides a comprehensive toolkit and factory services to support AI pilots with the necessary infrastructure and expertise. These services are available based on a review process driven by the Digital Steering Committee that aims to exploit the most relevant initiatives. Successful pilots are brought to sustainable operations and durability.

- **Microsoft 365 Copilot Services:** Microsoft 365 Copilot is a powerful artificial intelligence assistant integrated within Microsoft 365 applications. It operates alongside ESA users, combining Large Language Models with user data in Microsoft Graph. Copilot is now accessible to all ESA users and offers a broad spectrum of applications. It utilizes AI to streamline processes, simplify routine tasks, and enhance collaboration and knowledge exchange. It also aids in filtering, sorting, analysing, and visualizing data.

To support the implementation **and deployment of specific use cases:**

- **Cogito (Expert AI):** Cogito introduces a linguistic component to the Open Space Innovation Platform (OSIP), enhancing its capabilities.
- **Expert Identification Using AI Similarity Algorithms - Vectorization:** AI similarity algorithms are employed for expert identification through vectorization, improving the precision of connecting experts with relevant topics.
- **“ASK ESA” RAG (Pilot):** The “ASK ESA” RAG (Retrieval Augmented Generation) is a tool that employs Generative AI to improve novelty assessment, expert identification, and document search retrieval.
- **“TEC MATE” and Its Derivatives (Proof of concept of ASK-ESA):** TEC MATE and its derivatives utilize Retrieval Augmented Generation and Generative AI to enhance the efficiency and effectiveness of information retrieval and expert identification processes.

7 LEGAL AND ETHICAL CONSIDERATIONS

The ethical use of AI has already been addressed by an ESA-internal working group and a draft guideline developed[12].

Legal aspects of the use of AI will need to be addressed, elements of which are:

1. Privacy and Data Protection. Ensuring AI applications comply with laws regulating the collection, storage, and use of personal data in ESA and the EU.
2. Intellectual Property. Addressing issues related to the ownership of AI-generated works and the use of proprietary algorithms, such as copyrights for AI-created art, patents for AI technologies.
3. Liability. Determining who is responsible when AI systems cause harm or errors.
4. Bias and Fairness. Ensuring AI systems do not perpetuate or exacerbate biases, and promoting fairness and equality in AI decision-making, a typical example being discrimination in hiring algorithms.
5. Transparency and Explainability. Requiring AI systems to be understandable and interpretable to users and regulators, such as explainable AI in decision processes.
6. Safety and Security. Ensuring AI applications are safe to use and secure from malicious attacks, such as cybersecurity measures for AI, safety protocols in AI applications.
7. Regulatory Compliance. Adhering to industry-specific or ESA regulations and standards.
8. Managing the impact of AI on jobs within ESA.

[12] Review Draft - Principles for the Ethical Use of Artificial Intelligence at the European Space Agency

8 AI PARTNERSHIP AND COMMUNICATION

ESA will establish a coordinated interface with external stakeholders in industry, the European Commission, national research organisations and academia. This will also entail external communication to Member States and the public, e.g., by means of show cases. The main coordination and point of contact is the AI Competence Centre.

All Directorates will extend ESA´s ability to interact with relevant stakeholders with respective interface organization to communities and organizations in their proximity, such as respective scientific communities, industry, national and international entities (partnering space agencies). Directorates will liaise with the AI Competence Centre to identify synergies.

Working closely and coordinating efforts between the AI Competence Centre and the Directorates is crucial to maintain consistent engagements with external partners and to clearly execute ESA's AI strategy.

The AI Competence Centre engages with academic institutions, startups, SMEs and major industries and technology vendors to identify high-impact AI use cases that can benefit from partnerships and to internal stakeholders.

The AI Competence Centre encourages innovative AI solutions through collaborative projects and research initiatives and guide partners to the most appropriate R&D programme or incubation offer.

The AI Competence Centre oversees relationships with AI technology providers to ensure alignment with the needs in coordination with ESA IT.

The AI Competence Centre promotes sharing of knowledge and best practices with partners, e.g. by giving access to data sets and models, and by supporting them in accessing high-performance computing resources and AI development tools.

The AI Competence Centre initiates the creation of training programs with partners to upskill staffs in AI technologies.

The AI Competence Centre maintains transparent and continuous communication throughout the AI transformation process and keeps all ESA stakeholders and AI experts informed about progress and changes.

9 CHANGE MANAGEMENT

Change management is a critical component of successful AI transformation. To ensure the execution of ESA AI strategy in terms of coordination and to ensure its adoption, it is recommended that the following actions are addressed, some of which are already outlined in this document:

- Engage Stakeholders: Involve ESA workforce, industry, member states and international partners in the change process. This includes understanding their concerns, expectations, and the value AI brings to their roles. Their input and buy-in are essential for a smooth transition.
- Build Capabilities: Invest in training and development to equip ESA teams with the necessary skills for new technologies and processes. Work closely with HR/Training to bridge those gaps, ensuring the ESA workforce is prepared for AI integration.
- Upgrade Tools and Technology & follow up data governance.
- Create an AI Culture: Create a culture of innovation where ESA workforce feels inspired to participate in the AI transformation efforts. From early-adopter outreach to workforce skilling and engagement, promoting cooperation and knowledge sharing among ESA teams and departments, as well as external partners and stakeholders, to use AI best practices and solutions. Acknowledging and incentivizing ESA workforce who show initiative, innovation, and excellence in using AI to their work processes and outcomes.
- Effective Communication: Maintain transparent and continuous communication throughout the AI transformation process. Keep all ESA stakeholders informed about progress and changes.
- Monitor and Adapt: Regularly review the progress of the AI transformation and be prepared to adjust as needed. Focus on continuous improvement and be ready to adapt the AI strategy as technology and business needs evolve.
- Sustain Changes: It is crucial the ESA leadership & management is sponsorship and align with AI initiatives. This includes engaging ESA management building cross-functional teams to support AI integration. Moreover, it should be ensured that the changes made are embedded into the ESA organization’s culture and operations to prevent reverting to old habits.

10 RISK MANAGEMENT

This section identifies ten potential risks associated with the use of AI technologies and outlines strategies to mitigate these risks. It will be the task of the AI Competency Centre and the CDO office to manage these risks for ESA. ESA Directorates shall address AI risks within their roadmaps and activities.

1. Data Privacy, Confidentiality and Security
   - Risk: AI systems often require access to sensitive data or may generate such data from benign sources, which could be at risk of breaches or misuse. This risk is particularly important when personal data are used, mostly for corporate applications using personal data. For applications in technical domain, the risk is related to intellectual property rights and confidentiality.
   - Likelihood: Medium, Severity: High
   - Mitigation: Implement robust data governance policies and security measures, including encryption and anonymization techniques. Regularly conduct security audits and ensure compliance with data protection regulations. This mitigation is not restricted to the use of artificial intelligence and must be managed at corporate level (security assurance is already covered by the security certification and accreditation process mandated by the ESA Security Directives).
2. Bias and Fairness
   - Risk: AI models can inadvertently perpetuate or amplify existing biases in the data they are trained on. This risk is valid for all applications of AI.
   - Likelihood: Medium, Severity: Medium
   - Mitigation: Use diverse datasets for training and apply fairness metrics and bias correction techniques during model development.
3. Lack of Trust
   - Risk: AI models, particularly deep learning models, can be “black boxes,” making it difficult to understand how they make decisions and not selected.
   - Likelihood: Medium (High in few cases), Severity: Medium (High in few cases)
   - Mitigation: Invest in improving trustworthiness, e.g. through explainable AI techniques, uncertainty quantification and prioritize transparency in model design.

4. Regulatory Compliance
   - Risk: As AI technology evolves, so does the regulatory landscape, posing a risk of non-compliance. The main European regulations are the EU AI act and applicable ESA Regulations.
   - Likelihood: Medium, Severity: High
   - Mitigation: Stay updated with relevant laws and regulations and build compliance checks into AI development and deployment processes. Clearly define responsibilities related to this risk and ensure corresponding roles are well resourced.
5. Dependency on Vendors:
   - Risk: Relying heavily on external vendors for AI technology can lead to vendor lock-in and reduced control.
   - Likelihood: Medium, Severity: Medium
   - Mitigation: Accept risk. Use open-source tools.
6. Skills Gap:
   - Risk: Implementing AI may require skills that current staff may not poss. Selecting the AI applications to develop and using AI applications requires knowledge on the capabilities and limits of AI. This is particularly relevant for use of AI onboard space systems for critical applications.
   - Likelihood: Medium, Severity: Medium
   - Mitigation: Invest in training and upskilling of staff in line with their role and consider hiring new talents with the necessary skills.
7. Scalability Issues
   - Risk: AI systems that work well in a test environment may not scale effectively in a real-world setting.
   - Likelihood: Medium, Severity: High
   - Mitigation: Plan for scalability from the beginning, and conduct thorough testing under realistic conditions.
8. Misalignment with ESA AI Strategy
   - Risk: AI initiatives may not align with the organization’s strategic objectives, leading to wasted resources.
   - Likelihood: Medium, Severity: Medium
   - Mitigation: Ensure activities are aligned with ESA AI Strategy from the outset, and regularly review and adjust as necessary.

9. Lack of coordination
   - Risk: In a large organization with multiple organisational units, there can be a lack of coordination and communication. This can lead to siloed efforts, inconsistent AI applications, and duplication of work.
   - Likelihood: Medium, Severity: Medium
   - Mitigation: Clear operational model.
10. AI-organizational setup impeding progress.
    - Risk: The relation of the competence centre to points-of-contact and local teams in directorates needs to be well calibrated to avoid duplication of effort or organizational bottlenecks. In a fully centralized setup, the CC will become a bottleneck; in a fully de-centralized or badly coordinated setup local teams and CC have overlapping ambitions, staffing and tooling.
    - Likelihood: High, Severity: High
    - Mitigation: Encourage collaboration through matrix-policy: provide complement to CC and budget to directorates. Encourage frequent exchanges between CC and local efforts. Calibrate staffing of respective teams to create synergies.
11. Lack of computing resources
    - Risk: AI model development may require intensive computing and memory resources.
    - Likelihood: Medium, Severity: High
    - Mitigation: Powerful laptops, workstations, servers and ultimately HPC

The identified risks are summarised in the next table.

Risk	**Likelihood**	**Severity**
Data Privacy and Security	Medium	High
Bias and Fairness	Medium	Medium
Lack of Trust	Medium/High	Medium/High
Regulatory Compliance	Medium	High
Dependency on Vendors	Medium	Medium
Skills Gap	Medium	Medium
Scalability Issues	Medium	High
Misalignment with ESA AI Strategy	Medium	Medium
Lack of coordination	Medium	Medium
AI-organizational setup impeding progress	High	High
Lack of computing resources	Medium	High

11 TALENT AND SKILLS DEVELOPMENT PLAN

An ESA-internal talent and skills development plan will be developed together by the CDO Office, Human Resources, the AI Competence Centre and the ESA AI expert network.

From the assessment of the current skills and the identification of the required ones to achieve the implementation of the AI strategy, areas needing improvement or new skills to be acquired will be identified.

A list of learning resources will be identified considering internal training by AI expert network, online courses, university programs, and possibly professional certifications potentially supported by specific partnerships. A comprehensive list of books and papers will be created to serve as reference and for self-training.

Staffs will be encouraged to raise awareness and knowledge in the domain of artificial intelligence. AI experts will be encouraged to participate and organise events and conferences and to join AI communities for staying updated and for identifying potential partnerships.

Specific initiatives will be initiated such as challenges and hackathons to raise the practical experience while identifying optimal solutions for concrete use cases.

As the domain of AI is evolving at high pace, the talent and skills development plan must be revisited regularly.

Figure 11: Raising knowledge and expertise in AI of all ESA staffs is crucial for the success of the AI strategy plan

Raising knowledge and expertise in AI through a talent and skills development initiative is crucial to ensure a skilled workforce capable of innovating and implementing AI solutions effectively and understand the benefit, constraints and limits of the technology. This foundation of expertise is essential for driving the AI strategy plan forward, fostering technological advancements, and maintaining a competitive edge.

12 CONCLUSION

The ESA AI Strategy Plan sets a clear and elaborated path for consolidating the integration of Artificial Intelligence within the European Space Agency's missions and operations. By focusing on key domains such as mission design, mission operations, data insights, and agency efficiency, ESA aims to revolutionize its work and maintain Europe's leadership in space exploration. The plan defines ambitious strategic objectives for each key domain are defined with an estimation of the required budget.

In the proposed plan, the establishment of the AI Competence Centre is pivotal for ensuring a good collaboration and cooperation within ESA and with ESA Member State’s industries, making the best use of resources.

The emphasis on foundational infrastructure components, legal and ethical considerations, and risk management further strengthens the strategy's implementation. Additionally, the plan's focus on talent and skills development ensures that ESA staff are well-equipped to harness the power of AI. Through this comprehensive approach, ESA is ready to drive innovation, optimize operations, and deliver significant benefits to society through AI-driven applications.

13 APPENDICES

13.1 Glossary and acronyms

This document relies on terms, definition of terms and abbreviated terms defined in the ECSS Glossary of terms ECSS-S-ST-00-01C. For verification and validation terms, refer to ECSS Software standard ECSS-E-ST-40C when it applies to software domain.

Acronym	Definition
AWS	Amazon Web Services
BASS	Business Applications Space Solutions
CDO	Chief Digital Officer
CIC	Directorate of Commercialisation, Industrialisation & Competitiveness
CNN	Convolutional Neural Network
COTS	commercial off-the-shelf
CSC	Directorate of Connectivity and Secure Communications
DCR	Documentation Change Request
DTA	Differential Thermal Analysis
ECSS	European Cooperation for Space Standardization
EDAF	ESA Data Factory
EMC	ElectroMagnetic Compatibility
EOP	Directorate of Earth Observation Programmes
ESA	European Space Agency
ESO	ESA Security Office
FTE	Full-Time Equivalent
GNN	Generative Neural Network
GNSS	global navigation satellite system
GPS	global positioning system
GPU	Graphical Processing Unit
GSTP	general support technology program
HPC	High-Performance Computing
HRE	Directorate of Human and Robotic Exploration
ISL	Inter-Satellite Link
ISRU	In-Situ Resources Utilisation
ISS	International Space Station
LEO	Low Earth orbit
LLM	Large Language Model
LSI	Large Scale Integrator
MAIT	Manufacturing, Assembly, Integration and Test
MBSE	Model-Based System Engineering
MEUR	Million Euros
NASA	National Aeronautics and Space Administration
NAV	Directorate of Navigation
NAVISP	Navigation Innovation Support Programme

NLP	Natural Language Processing
ONNX	Open Neural Network eXchange
OPS	Directorate of Operations
OSIP	Open Space Innovation Platform
PDP	Personal Data Protection
PNT	Position Navigation Timing
RAG	Retrieval Augmented Generation
RAMS	Reliability, Availability, Maintainability and Safety
RHDB	Radiation-Hardened by Design
SAR	Synthetic-Aperture Radar
SCI	Directorate of Science
SON	Self-Organizing Network
STS	Directorate of Space Transportation
TBW	To Be Written
TEC	Directory of Technology, Engineering and Quality
TRL	technology readiness level