

Artificial Intelligence for mission operations automation roadmap: the European Space Operations Centre updates and vision

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Abstract

In 2021, ESA’s European Space Operations Centre (ESOC) developed the Artificial Intelligence for Automation (A²I) Roadmap in collaboration with industry to leverage AI for automating mission operations. This roadmap provides a coherent direction and structured approach for future developments, marking a first within ESA and beyond. Over the past years, the use cases of the A²I Roadmap have been developed, operationalized, tested, validated, and scaled to benefit missions in both ESOC and non-ESOC environments. With advancements in AI, commercial interests, and European industry priorities the A²I Roadmap has evolved into the AI and Data Foundation Roadmap, where data has a more prominent role and acts as the key enabler of all AI solutions. This paper reports on updates, shares lessons learned, and discusses challenges that extend beyond technical aspects, offering an updated vision for the future of integrating AI into ground segment engineering, operations, and space safety.

Keywords: Artificial Intelligence (AI), automation, ground segment, space operations, data, impact

1. Introduction

The increasing complexity and volume of space missions necessitate innovative approaches to ground segment engineering, operations, and space safety. In 2021, ESA’s European Space Operations Centre (ESOC) initiated a strategic effort to integrate Artificial Intelligence (AI) into its operations, aiming to enhance efficiency, reduce workload, and enable the management of a growing number of missions [1]. The primary driver is to support the ambitious goal of operating twice as many missions by 2030 leveraging AI-driven automation. The Artificial Intelligence for Automation (A²I) Roadmap, developed by a team of over 70 specialists at ESOC with support from an industry consortium, laid the groundwork for this initiative, which has since expanded into the broader AI and Data Foundation Roadmap. This reflects a more holistic approach to integrating AI and managing the underlying data infrastructure. The paper details the journey that began with the initial A²I Roadmap at ESA’s ESOC and evolved into the comprehensive AI and Data Foundation Roadmap. It highlights the strategic approach, key achievements, and lessons learned. This initiative emphasizes user-centric development, agile methodologies, the importance of a strong data foundation, and strategic collaboration to maximize the effectiveness of AI integration in mission operations and foster the growth of the European Space Sector.

2. Summary of the A²I Roadmap

Mission operations encompass a wide range of tasks, including mission analysis, flight dynamics, operations preparation, simulator development, and satellite and ground station monitoring and planning. The A²I Roadmap was initially created in only 14 weeks despite the challenges of remote working caused by COVID-19. It involved stakeholders from both ESOC and industry covering both subject matter expertise in ground segment engineering, operations, space safety as well as in AI. The team conducted a thorough analysis starting from pain points to evaluate the potential impact of numerous AI use cases in mission operations and space safety, with activities at ESOC serving as a reference point. The analysis included an assessment of the data landscape, technological readiness, and feasibility of each identified use case. The findings indicated that AI can significantly enhance mission operations by streamlining processes, reducing workload, and automating repetitive tasks.

Based on expected impact and technical feasibility, the A²I Roadmap pinpointed 14 specific use cases across five priority mission operations domains (Operational Simulation and Operations Preparation, Systems Testing and Validation, Ground System Maintenance and Ground Operations, Satellite Health Monitoring and Data Processing, Flight Control Team and Ground Stations) for targeted AI application development. By capitalizing on synergies to facilitate cross-development, minimize deployment time, and enable scalability, the roadmap aimed to maximize the effectiveness of AI integration in mission operations.



Figure 1. Benefits of the A²I Roadmap.

The main objective of the A²I Roadmap was to cultivate the growth of the European Space Sector by leveraging applied AI in mission operations. Alongside this goal, the roadmap presents various supplementary advantages, illustrated in Fig. 1. Furthermore, it guarantees ESA’s continued prominence in both advancing and implementing AI for spacecraft mission operations, solidifying its role as a primary facilitator for the European industry, reinforcing ESA’s Agenda 2025 artificial intelligence aspirations and ESA ongoing transformation.

The A²I Roadmap also included a business case to quantify the benefits of bringing AI to automate mission operations, which was validated through the development and operationalisation of two prototypes, OCAI and ESTIM [2,3].

3. A²I Roadmap evolution

Since 2021, ESA and the European industry have developed AI solutions for 9 out of the 14 initial use cases. Five of these are under further development, while two more use cases have just started being implemented and last three should start later in 2025, pending funding approval.

From its inception, the A²I Roadmap was conceived as a living document that would adapt and evolve based on ESA and industry’s priorities, technology advancements, lessons learned. A major realisation during the execution of the Roadmap was the need to have a dedicated endeavour to tackle the data layer. We hypothesized that by developing each use case, we could evolve the data infrastructure. However, considering the contractual constraints we operated within while implementing the Roadmap, this turned out to be infeasible when scaling the solution to more and more missions, each presenting its own peculiarities. Moreover, evolving the data infrastructure and tackle governance aspects as well would bring benefits beyond AI, as summarised in the next section [10].

3.1 Data Foundation Target State and Execution Plan

ESOC and European Mission Operations Centres manage various diverse missions, each of which presents different needs in the daily generation, collection, storage and distribution of their data. The data is commonly processed and stored in separate, siloed systems.

While this current decentralised architecture has proven efficient for managing complex operations and ensuring reliable data delivery, it poses several challenges for data users, such as scientists, engineers, and AI systems. They often struggle to access, analyse and interpret the large volumes of structured and unstructured data due to difficulties in integrating data from various data sources, suboptimal access controls and the limitations of scaling on-prem systems. This fragmented nature of the data architecture and governance complicates advanced analytics including AI applications, as traditional systems are ill-suited to handle the volume, velocity, and variety of data generated in modern space operations.

ESOC aims to enhance the scalability of advanced analytics applications by implementing best practices for managing data and analytics products as valuable, reusable assets. This approach increases their value within the organisation and democratises data access, both internally and externally, thus also enabling industrial use cases. In the process of determining the most effective design of a common data layer, a comprehensive analysis of ESOC’s data and system landscape was conducted. This included exploring various approaches and architectures, such as various data platform architecture archetypes and cloud-native features. The investigation highlighted three key areas

of focus in order to streamline the systematic production of data products: data architecture, data governance and data management.

The architecture for the common data layer was then designed to accommodate a wide range of data types and formats, from structured data in databases to unstructured data in files and streams. The system includes tools for data ingestion, processing, storage and analytics, ensuring comprehensive data management. Additionally, data governance strategies were outlined to maintain data quality, consistency, and security.

3.2 AI and Data Foundation Roadmap

To reinforce the goal of developing effective AI solutions while addressing the data aspects identified, we decided to evolve the A²I Roadmap into the AI and Data Foundation Roadmap, which is composed of five capabilities:

1. *AI-enhanced decision recommendation and planning.* It focuses on leveraging AI to aid in complex decision-making processes and mission planning activities. This involves analysing past human behaviour and decisions based on past documents, log files, and reports through techniques like fuzzy logic, transfer learning, and neural networks to recommend optimal actions for anomaly handling, operations planning, manoeuvres, and maintenance schedules.
2. *Automated health monitoring and control.* It aims to automate the monitoring of spacecraft health and the execution of control actions, including AI-enhanced detection of anomalous conditions, diagnostics, prognostics, and automating processes with the monitoring and control of spacecraft and ground segment.
3. *AI-enhanced modelling and simulation.* It involves the use of AI to improve the accuracy and efficiency of modelling and simulation activities. This capability provides AI-enhanced simulation engines to be integrated into operational simulators and will enhance mission-critical analyses, simulations, situational awareness, and calibration synchronization of simulators.
4. *AI-automated content generation and AI-enhanced user interaction.* It explores the use of AI to automate the generation of reports and analyses, and to enhance how users interact with data through user-friendly and textual interfaces. This addresses the challenge of handling large volumes of structured and unstructured data by automating repetitive tasks like report generation, translating text into technical language, and data translation.
5. *Data handling, management, governance, assurance.* It addresses the critical aspects of data quality, security, and accessibility, ensuring a robust foundation for AI applications. This capability focuses on structuring data, improving user interfaces and data systems and architecture, and providing pipelines for governance and assurance.

This Roadmap is not a static plan but an evolving framework that adapts to technological advancements and operational needs. It encompasses activities across the Technology Readiness Level (TRL) spectrum, from research to operational deployment. By embracing a symbiotic relationship between low and high TRL activities, ESOC facilitates the rapid transition of research into operational capabilities and informs research directions with operational insights. This dynamic framework ensures that ESOC keeps supporting the European industry in the application of AI to mission operations, continually evolving to meet the challenges and opportunities of the future.

4. Implementation Phases and Progress

The implementation of the AI and Data Foundation Roadmap has been carried out in distinct phases, building upon the foundations laid by the initial A²I Roadmap:

- **2021:** A²I Roadmap creation. The initial phase focused on defining the overall strategy and identifying potential areas for AI application within ground segment operations. This involved a thorough analysis of pain points in mission operations and an assessment of the data landscape, technological readiness, and feasibility of various AI use cases.
- **2021 – 2022:** Business case and feasibility. This phase involved proving the business case for AI adoption and assessing the feasibility of proposed solutions through the development of OCAI and ESTIM, further refining the scope defined in the A²I Roadmap [2,3].
- **2022 – 2024:** First operational products and definition of the data layer. The successful delivery of the underlying MLOps-like platform AInabler [4] and of the first operational AI products [5-9], and as well as the definition of the target data layer marked a significant milestone [10], with validation extending beyond ESOC.
- **2024 – 2025:** Continued delivery. The ongoing phase focuses on the continuous delivery of operational products and further development of the AI and Data Foundation Roadmap activities [11-21].
- **2025+:** Adoption at scale. The future vision involves widespread adoption of AI solutions across ESA and the broader space community, with continuous evolution and innovation.

This phased approach has enabled ESA to systematically integrate AI, learn from each iteration, and build confidence in the technology’s capabilities. The plan foresees implementing the AI and Data Foundation Roadmap by 2026, with development currently on time and well underway.

5. Key Principles and Path to Success

Several key principles have guided the successful implementation of the AI and Data Foundation Roadmap, evolving from the initial principles of the A²I Roadmap:

- Solving Real Pain Points. AI solutions are developed to address specific challenges and inefficiencies in existing operational processes. The A²I Roadmap development began with a detailed analysis of these pain points, which continues to inform the AI and Data Foundation Roadmap.
- User-Centric Development. Solutions are designed with a strong focus on user needs and workflows, ensuring usability and adoption. This is achieved through a user-centric approach, focusing on user experience.
- Modular Architectures. A modular approach is employed to facilitate upgrades and integration with the latest AI technologies.
- Integration with Existing Tools. AI solutions are seamlessly integrated into existing operational tools to minimize disruption and ease the transition.
- Collaborative Development. Development and deployment are conducted in close collaboration with users to foster understanding and trust in AI. ESOC collaborates with European industry, research institutes, and national agencies.
- Comprehensive TRL Coverage. The development efforts span the entire TRL spectrum, from research to operational deployment.
- Agile Management. Agile methodologies are used to ensure flexibility and responsiveness throughout the development lifecycle. This involves cross-functional teams from ESA and industry working closely together, conducting daily check-ins and regular sprint reviews and planning sessions.
- CI/CD/CT and Code Management. Continuous Integration, Continuous Delivery, Continuous Testing (CI/CD/CT), and robust code management practices are followed. Inspired by MLOps principles, the AI-nabler platform is used to construct, train, and implement machine learning models for automating space operations [4].
- ESA Community License. Solutions are developed under the ESA Community License to promote wider adoption and collaboration [13].
- Technology Transfer. The initiative facilitates the transfer of AI technologies to industry, enhancing European competitiveness.
- Continuous Small Wins. The focus on delivering incremental value and achieving “small wins” builds momentum and demonstrates the tangible benefits of AI.

6. Achievements and Impact

The implementation of the AI and Data Foundation Roadmap has already yielded significant results, building upon the initial successes of the A²I Roadmap. Below is a list of the main achievements and impact.

- MLOps Platform (AI-nabler). A centralized Machine Learning Operations (MLOps) platform, “AI-nabler,” has been established to support the development, deployment, and management of AI applications. It is available on spacecodev. The platform is designed to be deployed in a Kubernetes cluster and is based on microservices to leverage scalability. It is being used both at ESA and at EUMETSAT.
- AI-Optimized Mission Planning. AI has been successfully applied to optimize mission planning for ESA’s XMM-Newton mission resulting in a 3-7x reduction in time spent on repetitive tasks [5].
- The Operations CompAnIon (OCAI). The development of the AI assistant OCAI [8] has automated the correlation and retrieval of information. OCAI enhances decision-making processes for flight control teams by providing advanced search and data correlation across diverse sources, supporting concise open language queries including mission operations specific terminology. It has achieved >50% adoption rate across ESOC missions.
- Health monitoring and control for satellite and ground stations. The Spacecraft health Monitoring AI-suite (SMAI) provides key functionalities related to anomaly detection, time series forecasting, and trend analysis [11-12]. The AI Investigation Assistant (AIIA) has been developed to assist with incident classification and maintenance tasks [11-12]. They have been deployed not only at ESOC but also at DLR’s GSOC [12] and are now operational as beta products.

- Data Foundation Layer [10]. Significant progress has been made in developing a robust Data Foundation Layer, including data qualification, validation, assurance, security, and cataloguing. This layer, a key component of the AI and Data Foundation Roadmap, is designed to accommodate a wide range of data types and formats, from structured data in databases to unstructured data in files and streams, with tools for data ingestion, processing, storage, and analytics.
- ESA Anomaly dataset [14-16]. The first large-scale, real-life satellite telemetry dataset with curated anomaly annotations originated from three ESA missions. It was released to the public on Zenodo in June 2024 to benchmark models and approaches on a common baseline as well as stimulate research and develop novel, computational-efficient approaches for anomaly detection in satellite telemetry data.

These achievements demonstrate the transformative potential of AI in enhancing the efficiency and effectiveness of space mission operations. Impact is measured for every application developed, and results so far indicate that the original business case was conservative, with benefits extending beyond initial metrics.

7. Lessons Learned

The journey of implementing the AI and Data Foundation Roadmap, which evolved from the initial A²I Roadmap, has provided valuable lessons. The importance of high-quality, well-prepared data cannot be overstated. Significant effort must be invested in data acquisition, cleaning, and validation to ensure the success of AI applications. Challenges often arise from difficulties in integrating data from various sources, suboptimal access controls, and limitations of scaling on-prem systems. ESOC aims to enhance scalability by implementing best practices for managing data and analytics products as reusable assets.

Adhering to software development best practices, including modular architecture, user experience (UX) expertise, and agile methodologies, is crucial for building robust and maintainable AI systems. A robust and scalable infrastructure is essential to support the development, deployment, and operation of AI applications.

Non-technical factors, such as identifying pain points, ensuring flexibility in execution, fostering user-centricity, and building fully-allocated teams, are equally important for successful AI adoption. The presence of key roles, such as product owners, translators (individuals who bridge the gap between technical and operational domains), and dedicated UX specialists, greatly facilitates the development and adoption process.

8. Conclusions and Future Directions

ESA’s AI and Data Foundation Roadmap, which grew out of the initial A²I Roadmap, has demonstrated the significant potential of AI to transform ground segment engineering and operations. The successful deployment of AI applications at ESOC and beyond highlights the maturity and applicability of these technologies. AI is proving to be a valuable tool for automating routine tasks, improving decision-making, and enabling the management of increasingly complex missions. This Roadmap not only cultivates the growth of the European Space Sector by leveraging applied AI in mission operations but also guarantees ESA’s continued prominence in advancing and implementing AI for spacecraft mission operations.

ESOC will continue to advance AI initiatives for the five key capabilities of the current AI and Data Foundation Roadmap and expand to new domains, namely AI for space safety and ground segment AI capability for cybersecurity. The ongoing commitment to research, development, and collaboration will ensure to remain at the forefront of AI innovation in the space domain, fostering future innovation, democratizing access to data, and enhancing efficiency.

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References

- [1] G. De Canio, J. Eggleston, J. Fauste, A. M. Palowski, M. Spada, Development of an actionable AI roadmap for automating mission operations, SpaceOps ID # 303, 17th International Conference on Space Operations, Dubai, United Arab Emirates, 6 - 10 March 2023
- [2] G. De Canio, J. Eggleston, A. M. Palowski, M. Schmidt, P. Collins, B. Sousa, D. Mesples, R. Santos, E. Ntagiou, OCAI: the Operations CompAnIon to support decision making of flight control teams, SpaceOps ID # 305, 17th International Conference on Space Operations, Dubai, United Arab Emirates, 6 - 10 March 2023

- [3] G. De Canio, J. Eggleston, A. M. Palowski, M. Unal, ESTIM: the ESTrack Investigation and Monitoring tool for analysis of ground station passes, SpaceOps ID # 307, 17th International Conference on Space Operations, Dubai, United Arab Emirates, 6 - 10 March 2023
- [4] P. Beltrami, N. Salor Moral, M. Hedegaard, J. Hansen, N. Policella, R. Santos, E. Ntagiou, F. Trifin, Enabling AI applications for space operations through a multi-missions DevOps platform, SpaceOps-2023, ID#277, 17th International Conference on Space Operations, Dubai, UAE, 2023, 6 – 10 March
- [5] N. Salor Moral, P. Pilgerstorfer, F. Marino, V. Sickling, M. G. F. Kirsch, A. McDonald, E. Ntagiou, G. De Canio, Automation of flight dynamics planning for ESA’s XMM-Newton, IAC-24,B6,2,6,x88657, 75th International Astronautical Congress, Milan, Italy, 2024, 14 – 18 October
- [6] A. Krstova, P. Fleith, J. Martinez-Heras, N. Salor Moral, A. Buccione, P. Pilgerstorfer, S. Foley, D. Mesples, J. Eggleston, G. De Canio, Intelligent root-cause investigation and AI-assisted handling tool for flight control teams, IAC-24,B6,IP,52,x88661, 75th International Astronautical Congress, Milan, Italy, 2024, 14 – 18 October.
- [7] A. Krstova, F. Hegwein, J. Hansen, P. Fleith, J. Martinez-Heras, J. Lerch, G. De Canio, Artificial Intelligence-based short-term satellite health forecasting, IAC-24,B6,IP,36,x88664, 75th International Astronautical Congress, Milan, Italy, 2024, 14 – 18 October
- [8] E. Ntagiou, T. Nogueira, Smart space operations: OCAI’s contribution to operational excellence, IAC-24,B6,2,2,x86830, 75th International Astronautical Congress, Milan, Italy, 2024, 14 – 18 October
- [9] G. De Canio, J. Eggleston, E. Ntagiou, M. Unal, H. Dreihahn, J. Lerch, M. G.F. Kirsch, S. Foley, N. Salor Moral, P. Pilgerstorfer, M. Szybowski, S. Napoletano, J. Martinez-Heras, A. Krstova, S. Krikorian, Artificial intelligence-based automation of mission post-launch operations processes, IAC-24,B6,1,1,x88670, 75th International Astronautical Congress, Milan, Italy, 2024, 14 – 18 October
- [10] E. V. Ntagiou, J. Eggleston, P. Collins, H. Dreihahn, F. Renk, K. Cichecka, DataX: a state-of-the-art data strategy for mission operations, IAC-24,B6,2,8,x89097, 75th International Astronautical Congress, Milan, Italy, 2024, 14 – 18 October
- [11] G. De Canio, R. Semola, V. De Caro, Advancing satellite health monitoring and control with AI through continual learning, SpaceOps ID # 334, 18th International Conference on Space Operations, Montreal, Canada, 26 - 30 May 2025
- [12] N. Policella, J. Martiinez, N. Salor Moral, S. Kotisis, K. Helmsauer, T. Goettfert, M. Cristoforetti, A. Gobbi, F. Hegweine, A. Riise, S. Mejri, V. D. Tran, I. Tanco, G. De Canio, Innovating Space Operations with AI: The AISHGO Project, SpaceOps ID # 49, 18th International Conference on Space Operations, Montreal, Canada, 26 - 30 May 2025
- [13] European Space Agency, European Space Agency Community License, <https://essr.esa.int/license/european-space-agency-community-license-v2-4-weak-copyleft-type-2> (accessed on 03/04/2025)
- [14] K. Kotowski, C. Haskamp, J. Andrzejewski, B. Ruszczak, J. Nalepa, D. Lakey, P. Collins, A. Kolmas, M. Bartesaghi, J. Martínez, G. De Canio, European Space Agency Benchmark for Anomaly Detection in Satellite Telemetry, arXiv, 2024
- [15] G. De Canio, K. Kotowski, C. Haskamp, ESA Anomaly Dataset (1.0), European Space Agency. <https://doi.org/10.5281/zenodo.12528696>, 2024
- [16] K. Kotowski, C. Haskamp, J. Andrzejewski, B. Ruszczak, J. Nalepa, D. Lakey, P. Collins, A. Kolmas, M. Bartesaghi, J. Martínez, G. De Canio, The Making of the European Space Agency Benchmark for Anomaly Detection in Satellite Telemetry, SpaceOps ID # 152, 18th International Conference on Space Operations, Montreal, Canada, 26 - 30 May 2025
- [17] F. Antonello, D. Segneri, V. Reggestad, Surrogate model-based calibration of a flying Earth observation satellite, Advances in Space Research, Volume 73, Issue 3, 2024, Pages 1925-1935, ISSN 0273-1177.
- [18] S. C. Gaiatto, F. Antonello, D. Segneri, B. Sousa, B. Abascal Palacios, A. Schiavo, M. Bartesaghi, J. Maass, A. Inojosa, A novel physics-based computational framework to model spacecraft solar array power under degradation: Application to European Space Agency (ESA) Cluster mission, Acta Astronautica, Volume 226, Part 1, 2025
- [19] F. Antonello, D. Segneri, J. Eggleston, A Bayesian framework for in-flight calibration and discrepancy reduction of spacecraft operational simulation models, Advances in Space Research, Volume 74, Issue 11, 2024
- [20] S. Madhogaria, M. Nidugala, E. Cocci, B. Werner, M. Taheran, E. V. Ntagiou, Bridging ESA Innovations with Commercial Space Operations: Integration of an Ops Companion for Satellite Decision Support, SpaceOps ID # 378, 18th International Conference on Space Operations, Montreal, Canada, 26 - 30 May 2025
- [21] E. Ntagiou, P. Choukroun, H. Hermanns, J. A. Fraire, P. Kubasta, G. Stock, R. J. B. Fabelo, Y. Al-Khazraji, S. Rahimian, S. P. Artati, J. Pierce-Mayer, E. Rapp, P. Houédé, F. Appaix, M. Spigai, Constellation Autonomy: AI Solutions for Adaptable and Efficient Operations, IAC-24,B6,5,5,x86874, 75th International Astronautical Congress, Milan, Italy, 2024, 14 – 18 October

