European Earth Observation Ecosystem Reference Architecture Blueprint

2025 edition

European Earth Observation Ecosystem Reference Architecture Blueprint: 2025

Prepared by	Earth Observation System Architecture Office
Document type	Technical Document
Reference	ESA-EOPFA-TN-2025-8
Issue/Revision	1.1
Date of Issue	14 March 2026
Status	Final

CHANGE LOG

Reason for change	Issue Nr	Revision Number	Date
Draft version 0.1 presented at DOSTAG ESA/PB-EO/DOSTAG/ROOMDOC(2024)41	0	1	04/11/2024
Updates based on contributions form EOP-G, EOP-P, EOP-S	0	2	05/07/2025
Consolidation and consideration of international collaboration aspects, EUMETSAT, CMIN25 and MFF28 discussions.	0	3	10/01/2026
Reformatted, corrected, consolidated and updated to final draft following extensive review.	0	4	17/01/2026
Final version	1	0	09/02/2026
Corrections	1	1	10/03/2026

CHANGE RECORD

Issue Number 1	Revision Number 0		
Reason for change	Date	Pages	Paragraph(s)
Updated Gravimetry section	10/03/2026		

TABLE OF CONTENTS

FOREWORD

Europe is entering a period of uncertainty marked by accelerating climate and environmental change, heightened geopolitical instability, rapid technological disruption, and growing pressure on public institutions and resources. In this context, Earth Observation has become a foundational public capability. It provides the trusted, objective evidence required to understand environmental change, anticipate and manage risk, verify and support policy outcomes, and protect citizens, infrastructure, and ecosystems. Europe's Earth Observation capabilities—built over decades through sustained investment, scientific excellence, and international cooperation—are among the most advanced in the world. Yet the scale, complexity, and pace of emerging demands can no longer be met through incremental, mission-by-mission evolution alone.

In 2025, the European Earth Observation Ecosystem is a rich but highly distributed system with numerous loosely federated components including Mereological programmes, Science missions, Copernicus Sentinel missions, and National as well as Commercial Missions. It brings together institutional and operational missions, national programmes, meteorological infrastructures, research assets, commercial actors, security-related capabilities, and an increasingly diverse user community. This ecosystem has evolved organically in response to scientific discovery, policy imperatives, and industrial opportunity, delivering globally recognised achievements. At the same time, growing interdependencies have introduced new forms of complexity and vulnerability—exposure to geopolitical disruption, spectrum congestion, space safety constraints, supply-chain fragility, skills shortages, and data and compute bottlenecks.

Europe is entering a period of uncertainty marked by accelerating climate and environmental change, heightened geopolitical instability, rapid technological disruption, and growing pressure on public institutions and resources. In this context, Earth Observation has become a foundational public capability. It provides the trusted, objective evidence across the world required to understand environmental change, anticipate and manage risk, verify policy outcomes, and protect citizens, infrastructure, and ecosystems. Europe's Earth Observation capabilities—built over decades through sustained investment, scientific excellence, and international cooperation—are among the most advanced in the world. Yet the scale, complexity, and pace of emerging demands can no longer be met through incremental, mission-by-mission evolution alone.

The European Earth Observation Reference Architecture Blueprint responds directly to these challenges. It provides a forward-looking architectural framework for the 2035–2050 timeframe that does not replace the real-world European EO Ecosystem, but offers a coherent, system-level perspective to guide its strategic evolution. The Blueprint is founded on the recognition that future EO value will be determined not only by the performance of individual missions, but by the effectiveness with which observations are integrated across domains, transformed into information and intelligence, and sustained over time with continuity and trust.

A central pillar of the Blueprint is the unique role of the European Space Agency as a neutral architect and long-term steward of Europe's EO capability. By providing architectural coherence, reference capabilities, and trusted coordination across institutional, national, and commercial actors, ESA enables Europe to preserve scientific credibility, policy relevance, and strategic autonomy in an increasingly complex and contested environment. The Reference Architecture Blueprint therefore offers policymakers and stakeholders a shared framework to align decisions, manage options and trade-offs, and ensure that investments made today accumulate into lasting European capability.

This first edition of the Reference Architecture Blueprint is conceived as a living framework. It will be updated and adjusted on an annual basis through iterative refinement informed by foresight analysis, technological progress, and evolving policy needs. In doing so, it aims to maintain a proactive, forward-looking perspective on the evolution of Europe's Earth Observation capabilities—supporting effective decision-making under conditions of persistent uncertainty and ensuring that European EO remains a trusted, resilient, and strategically relevant public asset for decades to come.

Simonetta Cheli, Director of Earth Observation Programmes

1. INTRODUCTION

Planet Earth is undergoing profound regime shifts driven by anthropogenic forcing of the dynamic equilibrium of the Earth system. Climate models predict a different Earth system with increasing extreme hydro-meteorological events in the coming decades with direct consequences on freshwater availability, food security, biodiversity integrity and change, human migration, social and economic equity, crossing earth system and social structure tipping points. Human-induced pressures are rapidly undermining the resilience of Earth systems that have long remained stable, propelling the Earth system and its societal fabric past a stable and equilibrium state capable of sustaining the world as we know it today.

Climate change is often thought about as a scientific problem with a technological solution although in reality, it is largely a social problem with a human solution. In this sense, Climate Action is an extremely important focus: the Earth system pays no respect to geopolitical and geographical borders. Likewise, European Earth Observation (EO) provides a unique data evidence resource that quantifies Earth system regime shift quasi-globally and synoptically, using a wide variety of scientific measurement techniques and advanced technologies. The free and open EO evidence base and knowledge extracted though applications and services available through user-friendly platforms underpin the credibility and ability of decisions made by scientists, engineers, government policymakers, authorities and public citizens to help navigate our changing world.

In this context ESA must maintain scientific curiosity driven approach that observe the most relevant parameters in the most robust manner using solutions that are technically innovative and affordable. These aspects are embodied in the European Space Agency (ESA) Earth Observation Science Strategy “Earth Science in Action for Tomorrow’s World (2024)” which notes that:

> *“A science-driven approach lies at the heart of the ESA’s Earth Observation Programme as it provides the basis to increase the collective understanding our evolving planet and the development of actionable information in tackling serious global environmental issues and the resulting challenges.* ***First-class science is absolutely essential for the promotion of European interests”***

In other words: a science-driven approach is central to ESA’s Earth Observation Programme. It strengthens our understanding of the changing planet and helps turn scientific insights into practical information to address major global environmental challenges.

Collectively diverse EO observations of the same Earth and societal system elements provide independent corroboration of human-made climate change and its impacts. In fact, EO now constitutes a primary scientific evidence base with a growing historical data set starting in ~1980 providing a long-term and consistent climate record archive of global change. It is a resource of knowledge that decision makers trust, delivered in a secure and dependable manner serving operational prediction systems, societal, and scientific applications for all domains. It enables society to define the policy thresholds, boundaries, and limits of human pressure on planetary systems.

Europe is entering a period of sustained uncertainty characterised by accelerating climate and environmental change, growing geopolitical instability, rapid technological disruption, and increasing pressure on public institutions and resources. In this context, Earth Observation (EO) has become a foundational public capability: it provides the trusted, objective evidence needed to understand change, verify policy outcomes, and protect citizens, the environment and anticipate risk (e.g. Figure 1-1).

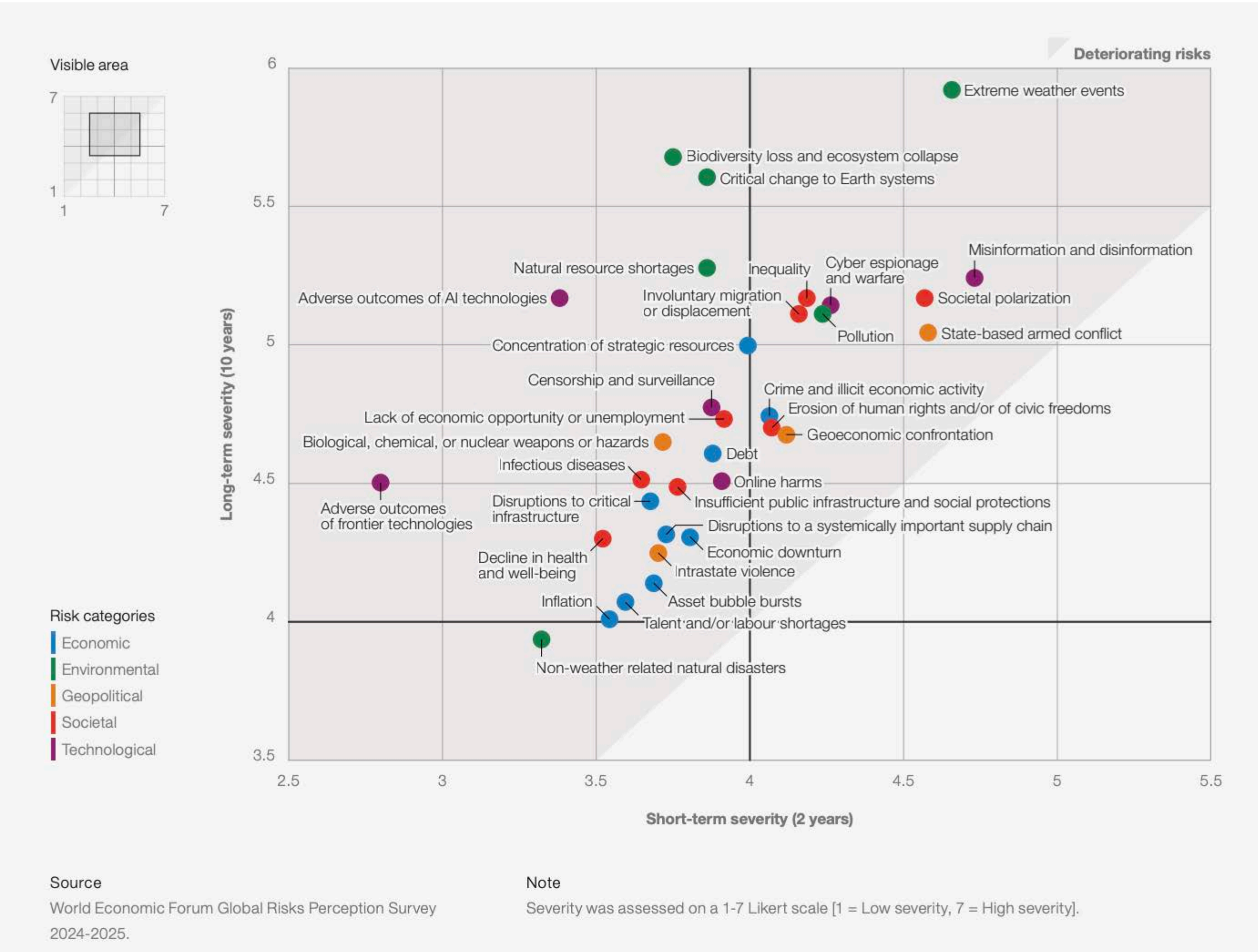


Figure 1-1. World Economic Forum (WEF) Global Risks Perception Survey 2024- 2025 (GRPS) relative severity of global risks over a 2- and 10-year period (WEF, 2025). While all 33 risks in the GRPS are expected to worsen in severity from the two-year to the 10-year time horizon, environmental risks present the most significant deterioration.

The European Earth Observation Ecosystem (EEOE) of today is a rich but highly distributed system-of-systems, comprising institutional missions, national programmes, operational meteorology, research infrastructures, commercial actors, security-related assets, and a diverse user community characterised by a broad suite of user needs and expertise. This ecosystem has evolved organically, driven by scientific excellence, policy needs, and industrial capability, resulting in globally recognised achievements. However, it's very success has increased interdependencies, complexity, and vulnerability to external shocks—ranging from geopolitical disruption and spectrum congestion to supply-chain fragility, skills constraints, and data overload. Europe's EO capabilities, built over decades through sustained investment and international cooperation, are among the most advanced in the world, but they now face a scale, complexity, and pace of demand that can no longer be addressed through incremental, mission-by-mission evolution alone.

The EEOE Reference Architecture (RA) Blueprint responds to this challenge. It provides a forward-looking (2035–2050) architectural framework that does not replace the real-world ecosystem, but instead offers a coherent, system-level perspective to guide its strategic evolution. The Blueprint enables Europe to move from reactive coordination toward proactive stewardship of EO capability—ensuring that investments made today accumulate into sustained, resilient, and policy-relevant capacity tomorrow.

At its core, the Blueprint recognises that future EO value will be determined not only by individual missions, but by how effectively observations are integrated across domains, translated into information, shared with the users, knowledge and intelligence, and sustained over time. It therefore places strong emphasis on foresight-driven scenario analysis, exploring how major drivers (e.g. climate impacts, security pressures, public–private convergence, artificial intelligence, geopolitical volatility, infrastructure complexity, and financial constraints) stress and shape the EEOE. These scenarios are used not as predictions, but as structured stress tests to reveal gaps, trade-offs, and strategic options.

A central pillar of the Blueprint is the unique role of the European Space Agency as a neutral architect and long-term steward of Europe's EO capability. ESA's position at the European interface of science, policy, technology, and industry enables it to maintain coherence across institutional boundaries, preserve continuity and trust, and sustain an innovation pipeline through programmes such as Earth Explorers. In close coordination with the European Union, Copernicus, EUMETSAT, Member States, and international partners, ESA provides the architectural logic that allows Europe's diverse contributions to function as a single, credible and sustainable system.

The Blueprint systematically analyses sustainability and gaps across the EO value chain—from ground segments and constellations to governance, commercial integration, spectrum, space safety, and emerging technologies such as quantum sensing. It further assesses capability gaps by mission family, ensuring that future investments are driven by observable needs and system performance rather than institutional silos. This approach supports informed prioritisation under constrained resources, while preserving strategic optionality in the face of uncertainty.

Ultimately, the Reference Architecture Blueprint positions European Earth Observation as a long-term public infrastructure for risk intelligence, planetary stewardship, and evidence-based governance. It provides policymakers and stakeholders with a shared framework to align decisions, manage trade-offs, and sustain Europe's leadership in Earth Observation—ensuring that EO remains a trusted, resilient, and strategically relevant capability in a rapidly changing world.

The analysis provided in this report sets out strategic elements and activities considered necessary to evolve and maintain a unified and sustainable European Earth Observation Ecosystem vision as a Reference Architecture Blueprint based on our knowledge in 2025. What missions do we need to fly in the next 20-30 years? What are the gaps in the existing EO system? What are the emerging and likely future user needs? What technologies need to be developed? How can we leverage federated system (ecosystem) synergies? What is the overall EO ecosystem we need? Against this background, the ***aim*** of the European Earth Observation Reference Architecture Blueprint is to:

> *Maintain a forward-looking view of Earth Observation activities that anticipate and prepare for emerging developments and potential disruptions to the evolution of the European Earth Observation Ecosystem.*

The Reference Architecture Blueprint identifies priority areas and proposes activities [RAB] for the evolution, maintenance and sustainability of the European Earth Observation Ecosystem.

1.1. The European Earth Observation Ecosystem (EEOE)

Europe has put in place interconnected EO enabled systems that strengthen understanding of complex, interacting risks—such as the links between climate tipping points, extreme events, and societal vulnerability—helping improve resilience to the growing impacts of climate change and other natural and human-induced hazards. In operational contexts, these systems support rapid crisis response, informed risk management, and evidence-based decision-making, contributing directly to the protection of citizens, critical infrastructure, and property.

The EEOE is the real-world (i.e. what exists or is planned today) constellation of organisations, missions (Figure 1.1-1), technologies, data systems, services, users, and policies that make up Europe's EO capabilities. It describes the full operational reality of Europe's EO domain that has taken an emergent, decentralised, approach as it has historically grown by responding largely on a mission-by-mission basis to scientific, commercial, and policy drivers. The EEOE includes many elements (for example):

- Space missions (Copernicus Sentinels, Earth Explorers, SCOUT, Φ-Sat, Earth Watch Missions, Stepping Stone Missions, national missions, commercial missions)
- Ground segments (e.g. ESA, EUMETSAT, national, commercial)
- Data infrastructures (e.g. CDSE/EOF, EUMETSAT, commercial)
- Copernicus Services (Marine, Atmosphere, Climate, Land, Emergency, Security)
- Users (policy, scientific, commercial, civil security, citizens)

- Calibration/Validation networks and Fiducial Reference Measurement networks
- Funding flows (e.g. ESA, EU, EUMETSAT, national budgets)
- Regulatory environment (e.g. Space Act, data policies)

Figure 1.1-1 Missions of the European Earth Observation Ecosystem (EEOE) as of 2025.

Recent geopolitical developments are driving new elements to assure European Resilience in Space (ERS) architectures and technologies that are set to further diversify the overall EEOE. In this edition of the Blueprint the defence sector is not explicitly included but current developments are painting a blurred picture which reveals some overlap between the civil and defence domains.

Certain aspects can be clearly attributed to defence applications such as ballistic early warning systems and are not addressed in the context of the Blueprint. Other elements of the EEOE serve a dual-use, responding to civil as well as to defence needs at the same time. The Blueprint will consider civil aspects in the dual-use context, excluding purely defence orientated ones.

The Governance of the EOEE has a *de facto* multi-actor, multi-level basis including ESA, EC, EUMETSAT, Member States and commercial operators that have historically driven implementation choices via political funding cycles, industrial capabilities and scientific push. A single unified architectural approach is not in place and consequently, system complexity emerges naturally leading to partial fragmentation, loss of focus, duplication and increased cost.

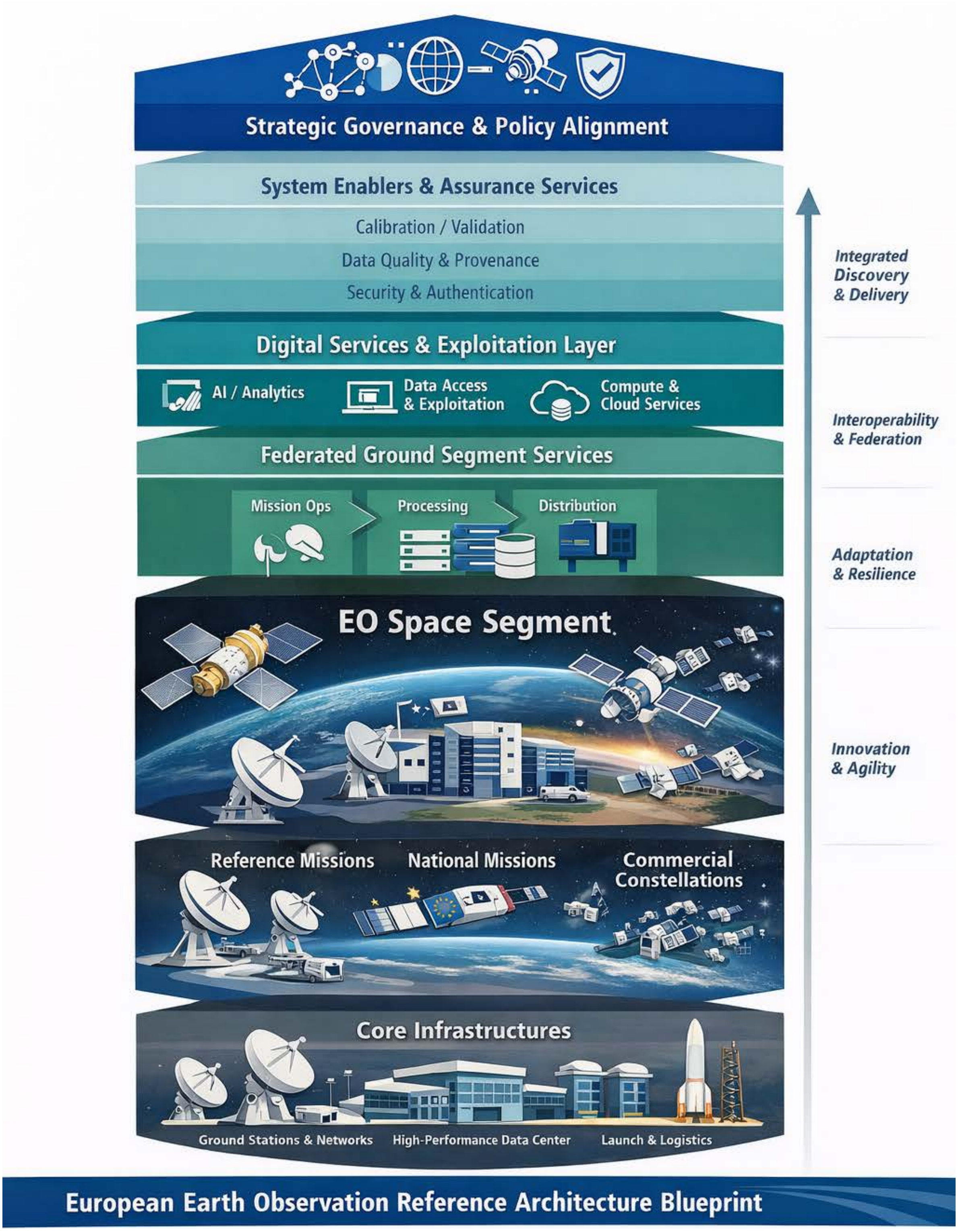


Figure 1.1-2 Schematic overview of generic Reference Architecture Blueprint elements.

Today the EEOE is the result of historical decisions and implementation programmes of different European contributions that collectively, constitute the Ecosystem. It is not fully optimised having distributed, partially overlapping and sometimes fragmented implementation in a continuously evolving paradigm in the ever-changing geopolitical world of today. As such, it becomes increasingly difficult to sustain and evolve in a prioritised manner.

1.2. The EEOE Reference Architecture (RA)

The EEOE Reference Architecture (RA) is a conceptual future-looking (~2035–2050) Architectural Blueprint with a designed structure, describing how the EEOE could be organised and evolve strategically as a coherent system-of-systems. It constitutes a guiding compass for a pan-European Earth Observation system as a single conceptual framework in which all actors align toward.

The RA does not replace the real-world EEOE; it guides its future evolution using a different view in the form of a target model for a coherent, efficient, integrated EO system. It considers how missions evolve, how user-driven capability gaps are closed, how new technologies (e.g. Artificial Intelligence/Machine Learning (AI/ML), hyperspectral, quantum sensing, new blue-sky mission concepts and technical capability) integrate and, importantly, how Europe becomes more resilient, sovereign, interoperable and autonomous. The mechanism employed to address these issues is by establishing logical, reasoned and traceable activities [RAB] that may be considered in strategic planning and decision making.

Reference architectures are commonly used to guide the design and implementation of complex systems. They provide a common language and framework for communication, collaboration, and decision-making among stakeholders involved in the development and operation the EO system-of-systems solution. They provide a standardized set of guidelines, best practices, and design principles to develop the future EEOE. A RA serves as a blueprint or template for future satellites within a living EO ecosystem. Key characteristics of the EO reference architecture blueprint include:

1. **Relevant:** the EO ecosystem remains relevant to user needs (user led) and can evolve as an ecosystem to continuously improve to meet user needs: *a living EO ecosystem for a living planet*.
2. **Layered:** A layered system design eases the partition of responsibilities and allows focus on elements deemed critical.
3. **Multi-scaled:** addressing local, regional and global user/stakeholder needs.
4. **Adaptive:** responds to continually changing user/Stakeholder needs and drivers on an annual basis.
5. **Standards:** It defines common standards, protocols, and interfaces to ensure consistency and interoperability across different components and implementations.
6. **Founded on Interface control:** the RA is considered a federated system building on the existing EEOE and common interfaces are a fundamental element that allows a seamless interaction between each.

7. **Authenticity:** certification that data are what they claim to be and are certified to a declared and traceable performance standard.
8. **Long-term knowledge and data preservation**: EO data are seen as cultural heritage – long-term records of our planet – and are thus securely saved (long-term archiving) and made easily accessible on the other side, e.g. as Analysis Ready Data (ARD) products.
9. **Best Practices:** It encapsulates proven methodologies, procedures, quality standards, design patterns, and architectural principles that are recommended for achieving desired outcomes efficiently and effectively.
10. **Modularity, Complementarity, and Scalability:** It promotes the use of modular and complementary components and scalable architectures to facilitate flexibility, adaptability, and growth as requirements evolve over time.
11. **Reusability:** It encourages the reuse of components, modules, and patterns to streamline development, reduce unnecessary redundancy, and improve overall throughput.
12. **Flexibility:** It allows for customization and adaptation to specific requirements, constraints and boundary conditions while maintaining alignment with the overarching architectural vision.
13. **Continuous evolution:** Systematic and continuous process of quality and efficiency improvement by evolution in a top-down and bottom-up collection and application of lessons learned.
14. **Interconnected:** components that can provide opportunities for all players to be part of the EO federated system.
15. **Co-operative:** the success of the EEOE and the RA Blueprint is predicated on co-operative relationships, sharing of knowledge and resources, open and transparent data and system element pipes between components, co-operative governance and shared aim and objectives.
16. **Cost effective:** the EEOE must be affordable.

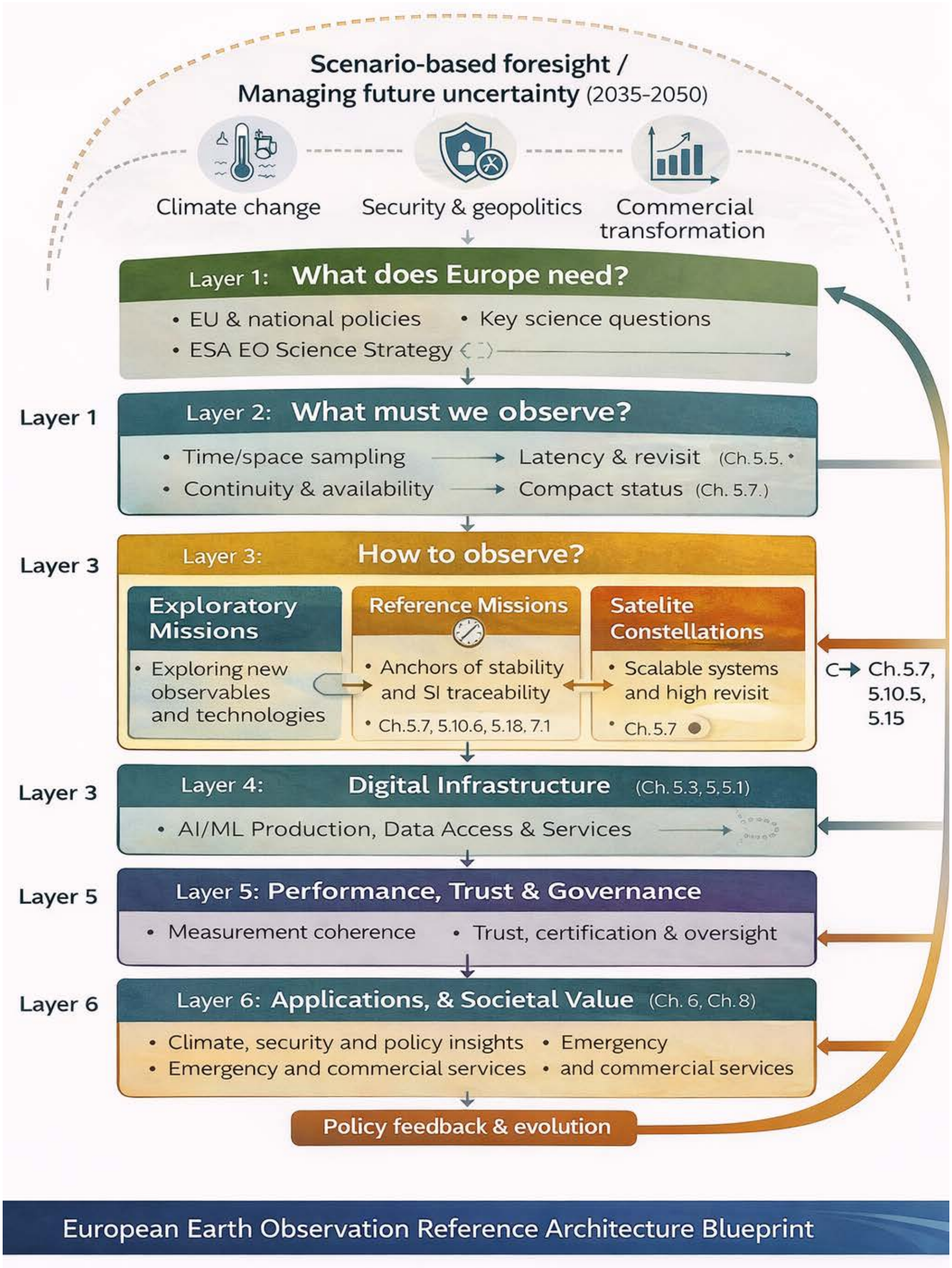


Figure 1.2-1. The European EO Reference Architecture Blueprint organises future Earth Observation as a layered system-of-systems, explicitly linking strategic drivers, mission design, digital infrastructure, governance, and societal value across the 2035–2050 timeframe.

The RA Blueprint is designed to highlight future opportunities and support strategic planning, EO portfolio optimisation, future mission design and implementation. It includes (for example):

- A focus on interfaces, roles, data flows, requirements, and governance principles - rather than a system attempting to controlling everything – is an approach well suited to the European hybrid institutional landscape.
- A layered system design eases the partition of responsibilities and allows focus on elements deemed critical.
- Includes standards-based traceability (e.g. policy driving mission requirements, data and end user services) to reliable sources articulating needs and technological innovation.
- Articulates a mission portfolio structure.
- Includes a ground/data segment functional model.
- Underlines the essential role and critical importance of performance and interoperability standards
- Includes governance and stakeholder roles.
- Proposes evolution pathways and scenarios for the 2035–2050 timeframe.
- Uses scenario analysis to inform architectural choices.

The RA Blueprint views the EEOE in a structured approach (Figure 1.2-1) to scope a future that is not completely limited by its current state. In this view, the RA Blueprint acts as the architectural framework through which governance alignment can occur since it defines: what are priority areas based on user/stakeholder needs, what elements are required and by when, how systems interconnect, and how responsibilities are shared amongst other aspects. Importantly, the RA Blueprint enables preparation and testing of different components before mission-scale investments are made using a future scenario-based approach.

1.3. Structure of the 2025 edition Reference Architecture Blueprint

The 2025 edition of the RA Blueprint is structured in the following way:

- Following this introduction section, components of the EEOE are discussed in Section 2.
- in Section 3 the unique role of ESA (on behalf of its Member States) is briefly discussed in the context of a living EO federated system ecosystem.
- Section 4 the Foresight analysis and RA Evolution is introduced together with relevant strategies, which can be seen as anchor points for the Blueprint.
- Section 5 considers the Reference Architecture Blueprint in terms of emerging trends, drivers and challenges that will impact the European EO ecosystem in the coming decades – providing both opportunities and challenges to be addressed.

- In Section 6, the fundamental sustainability of the European EO Ecosystem is then discussed in a dedicated section of the report - since this is considered a fundamental priority before any “new” elements are considered.
- Section 7 provides a detailed gap analysis and actions across the EO ecosystem.
- Section 8 concludes the report.

Throughout the document defined action areas [referred to as Reference Architecture Baseline, RAB] are included in a structured manner (strategic/programmatic, overarching technical aspects and mission family-specific aspects). These are defined to highlight options that could be pursued by different stakeholders within the EEOE based on reasoned foresight analysis.

2. COMPONENTS OF THE EUROPEAN EARTH OBSERVATION ECOSYSTEM (EEOE)

2.1. Historical Context

> *"Wise men say, and not without reason, that whoever wishes to foresee the future must consult the past" (Niccolò Machiavelli, 1532)*

The current European (ESA) Earth Observation (EO) System-of-Systems has developed and evolved uniquely over a period of more than three decades, driven by sustained user and stakeholder demand, scientific and technical innovation, and coordinated industrial, financial, and political investment across Europe (*Berger et al.,* 2020; *European Commission,* 2021). This evolution reflects ESA's long-term strategic role in orchestrating partnerships between European space industry, scientific institutions, and public authorities, while fostering human capital and expertise within the European EO community (*ESA,* 2015; *ESA,* 2023).

ESA's Earth Observation ambition is to leverage European industrial excellence and scientific leadership in parallel with systematic capacity-building and talent development, forming the backbone of Europe's global leadership in EO (*ESPI, 2024*; *OECD,* 2021). This has been a cumulative effort, built on both successes and lessons learned, with risk mitigation, reliability, and interoperability increasingly embedded through the European Cooperation for Space Standardization (ECSS) framework (*ECSS*, 2022). The result has been a resilient and innovative EO ecosystem, characterised by high-risk/high-return mission concepts, strong industrial engagement, and sustained scientific commitment (*Berger et al.,* 2020; ESA, 2023).

In 1977, ESA launched its first Earth observation satellite, Meteosat, the first of a series of geostationary satellites designed to meet the needs of weather forecasting services. Evident in Figure 2-1 are the European Remote Sensing, ERS-1, satellite developed in the 1980's and launched in 1991 and followed by ERS-2, in 1995. Building on the success of these missions, the multi-instrument ENVISAT satellite was developed and launched in 2002. The success of these pioneering missions added to the impetus to expand ESA's Earth Observation Programmes along a two-pronged strategy; (i) to develop technically innovative missions for research to yield scientific excellence, and (ii) to develop missions for operational applications based on the needs of identified user communities and organisations ready to exploit series of long-term data. In 1986 a new organisation was created – the European Organisation for the Exploitation of Meteorological Satellites, EUMETSAT, to manage operational European meteorological space components. Together with EUMETSAT, ESA has developed a series of Meteosat geostationary missions (currently MTG) and polar orbiting missions (currently MetOp-SG) missions dedicated to operational meteorology.

In the mid-1990s, ESA created its Earth Observation Envelope Programme (EOEP). It provided a framework for the systematic definition of all missions, for both research and for operational purposes. In 2019 the successful Envelope EOEP was restructured and renamed as FutureEO.

The technical and scientific experience gained by developing and using the ENVISAT mission was a notable reference point for ESA. ENVISAT played a fundamental role in the genesis of the European Union Copernicus system as we know it today: the Copernicus Sentinel-1 C-band SAR (ENVISAT ASAR heritage), Sentinel-3 SLSTR (ENVISAT AATSR heritage) and OLCI (ENVISAT MERIS heritage), Sentinel-4 and 5 (Sciamachy heritage). In addition, the ENVISAT ASAR instrument led to the MetOp series of ASCAT wind vector instruments and, soon to be launched, next generation SCA instrument aboard MetOp-SG.

It is fair to say that ENVISAT, while a major challenge, spawned a multi-branched family tree of highly successful satellite missions because of technical innovation, scientific curiosity in parallel with operational user needs and the continuous process of evolving and innovating European space technology.

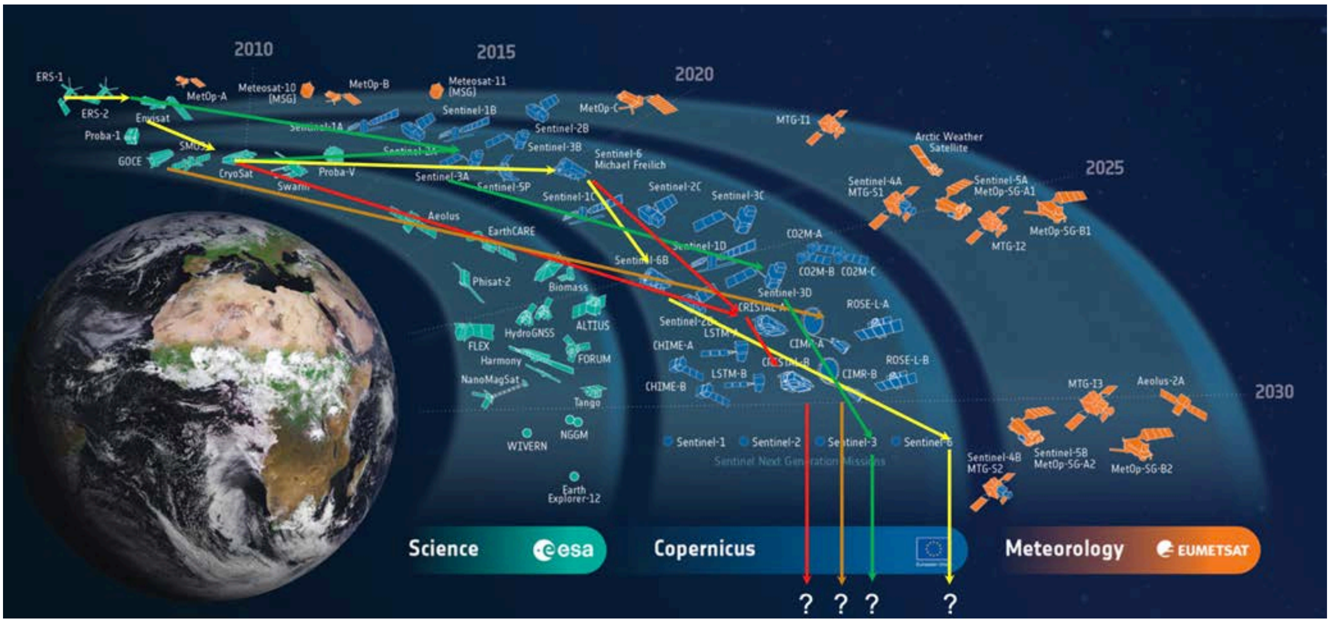


Figure 2-1 "Science, Copernicus and Meteorological" Mission collection drawn to emphasise programmatic families. Overlaid in Red is the evolution of ESA altimetry missions highlighting the importance of the CryoSat Earth Explorer mission cumulating in an ocean altimeter reference mission status of Sentinel-6 *Michael Freilich* and CRISTAL cryosphere operational mission (Green line). Yellow shows the evolution of reference infrared radiometry from (A)ATSR through to Sentinel-3 SLSTR reference sensor. In brown is the transition of Sea Surface Salinity from science (pioneered by SMOS microwave radiometer interferometry) to operations embodied in the conical scanning total-power CIMR radiometer.

Overplotted on Figure 2-1 are the evolutionary pathways of modern missions that can be traced back to show how they build on the flight-heritage of previous missions. For example, in ESA, altimetry missions and sensor technologies have evolved from ERS-1/2, through

ENVISAT to CryoSat at which point SAR technologies are introduced from which three operational missions evolved (Sentinel-3 SRAL, Sentinel-6 POS-4 and CRISTAL IRIS).

The challenges of ENVISAT in terms of technical, managerial, and political complexity and cost were large (e.g. *ESA,* 2012). The ESA Earth Explorer (EE) programme was convened to consider lower-cost more flexible satellite missions to explore new Earth Observation science concepts and to push new space technologies. The EE program has led to an enormous positive impact on the study of our planet Earth (*ESA,* 2025b; *ESSC,* 2025, Tassa et al. 2022). The preparatory in-depth scientific and technical studies undertaken by Explorer concepts, together with the hardware development and field experiments, is fundamental to their maturation and future potential for operational components of the Meteorological and Copernicus programmes (e.g. *Tassa et al,* 2022).

2.2. European Earth Observation Ecosystem Components

The European EO Ecosystem is a unique living system which is continually and rapidly evolving and improving. It provides opportunities to evolve the EO domain in different ways (e.g. in orbit demonstration, new technologies, applications, services etc) together with freely available high-quality and reliable data products. Earth Explorer, Copernicus, Meteorology, Scout, Earth Watch, Φ-Sat, Stepping Stone Missions and more recently, Commercial Space satellite missions constitute the programmatic basis for complementary satellite missions that can be grouped into **EO Mission Families** as follows:

- Active Microwave Imagery Family
- Passive Microwave Imagery Family
- Passive Microwave Sounding Family
- Altimetry Family (optical and active microwave)
- Optical Imagery Family (from UV – LWIR - FIR)
- Active Optical (LIDAR) Family
- Limb Sounder Family (passive and using active signal sources (RO))
- Atmospheric Spectroscopy Family
- Gravimetry Family
- Geomagnetic Family
- New Observatory Family
- High Altitude Platform Stations (HAPS), aircraft and drones

Considering the established missions that are either in orbit or planned today as a starting point[1], the existing EEOE includes the following satellite components:

- **ESA Earth Explorer missions** are typically designed to address specific scientific questions or challenges related to Earth science. Seven Explorer missions have been

[1] The Reference Architecture Blueprint is not a replacement for to be viewed as challenging established and agreed plans within specific programmatic context such as the Copernicus Long Term Scenario. Extrapolation of mission capability is to be interpreted as “Program Agnostic” in the sense that no formal agreements or plans are in place.

launched (GOCE, SMOS, CryoSat, Swarm, Aeolus, EarthCARE, Biomass), and with FLEX, FORUM, Harmony and WIVERN missions in preparation, and Cryorad, ECO, Hydroterra+ and Keystone as mission candidates for EE-12. They are all a world first of their kind and carry state-of-the-art payloads capable of measuring key Earth system parameters with high precision and accuracy pushing the technology and scientific boundaries. These missions contribute valuable data to global efforts to monitor and understand the Earth system and its responses to natural processes and human activities. They are usually pathfinder for the development of new families of observation techniques and instruments which advance the European EO capabilities. Earth Explorer missions characteristically demonstrate new technologies and approaches that have the potential to advance exploration of the Earth system and scientific understanding and are often pre-cursors to future operational systems (e.g. Figure 2-1), therefore they are the foundation for evolution of the EO systems of System.

- **Copernicus operational missions,** designed to provide long-term accurate, timely, and reliable EO information in an operational system to support the Copernicus Services as well as policy monitoring of the state of the Earth. They include Sentinel-1/2/3/4/5/5P/6 satellites, and an additional six Copernicus Expansion missions addressing new measurements beyond the original Sentinel-series (CO2M, LSTM, CHIME, CIMR, CRISTAL and ROSE-L). Next Generation enhanced continuity missions extending Sentinel-1/2/3 and 6 into the 2040+ horizon are in preparation. Sentinel-4 and Sentinel-5 NG discussions will take place in the framework of EUMETSAT operational missions. Copernicus provides the EEOE a sustained operational backbone of high-performance EO information.
- **Meteorological missions** providing accurate and timely data for operational weather forecasting, aviation, marine operations, agriculture, climate monitoring, and environmental research. These missions involve the deployment and operation of satellites in geostationary (MSG/MTG) and low Earth orbits (MetOp, MetOp-SG) equipped with various instruments to observe the Earth's atmosphere, oceans, and land surfaces. EUMETSAT typically manages user needs and cooperates closely with ESA and other international partners to develop and operate these missions. Additionally, the EPS-Sterna and EPS-Aeolus missions are in preparation, following the successful demonstration performed by the fourth Earth Explorer Aeolus and the ESA Arctic Weather Satellite (AWS). Meteorological missions provide the EEOE with a sustained backbone of geostationary orbit missions and missions tailored to operational weather forecasting.
- **ESA Scout missions** are small satellite solutions delivering value-added science, either by miniaturising existing space technologies or by demonstrating new observing techniques implemented within three years using a limited budget, from kick-off of the implementation phase to flight acceptance review. Scout missions pave the way to innovative science in a fast-agile fashion and, due to their relatively short preparation and development cycle, they can complement other EO missions or fill temporally

some observational gaps. The ESA HydroGNSS mission includes two small satellites with a GNSS reflectometry payload to determine soil moisture, inundation and wetlands, freeze–thaw over soil and permafrost, and above-ground biomass. ESA NanoMagSat aims to maintain Europe's leadership in monitoring Earth's magnetic field, and consists of a constellation of three 16U satellites, launched nine months apart. Each satellite will carry a miniaturised absolute magnetometer at the end of a boom and a high-frequency magnetometer half-way along the boom for magnetic measurements, a Langmuir probe to measure electron temperature and density, and two GNSS receivers. TANGO is a Cubesat satellite mission comprising two agile satellites: TANGO-Carbon and TANGO-Nitro flying on in close formation with a time difference of less than 1 minute. TANGO will estimate emissions of the greenhouse gases methane (CH_4) and carbon dioxide (CO_2) at the level of individual industrial facilities and power plants, complementing the CO2M Copernicus mission (where the CO2M mission provides a reference mission). Currently four candidate Scouts are being studied with a down-selection to two for implementation in mid 2026. These include HiBiDiS (Hyperspectral Biodiversity Scout Mission); NAIAD (Near-coast And Inland Aquatic impact Data mission); SIRIUS (Space Based Infrared Imager for Urban Sustainability mission), and SOVA-S (Satellite Observation of the Waves in the Atmosphere – Scout mission). Scout missions provide the EEOE with innovation as a flexible and rapid response to science challenges that can be achieved at low cost.

- **Φ-Sats:** are in-orbit demonstration missions of brand new and innovate technologies and/or remote sensing techniques for Earth Observation based on cube-sats. They provide a means to demonstrate new and radical EO ideas in a fast and incremental approach that could be reused for a more substantial mission concept. For example, FFSCat/Φ-Sat-1 demonstrated the use of on-board AI together with two small instruments in orbit; the UPC FMPL-2 and Hyperscout have been enhanced with AI capabilities (Φ-Sat-1). The upcoming Φ-Sat-2 aims to go further using a wider range of on-board AI applications. Future Φ-Sats will demonstrate in orbit other unique and innovative technologies and/or new remote sensing techniques. Φ-Sats inject low-cost, high-risk innovation into the EEOE and assist in the maturation of commercial companies in an incremental and sustainable manner.
- **Stepping Stone Missions (SpS)** complement and enhance existing institutional space infrastructure in response to current and foreseen needs for quality-certified data addressing European, National and Global environmental policy and regulations at relevant temporal and spatial scales. SpS Missions are (i) driven by active user's identified requirements addressing environmental regulations (ii), quality-certified as fit-for-purpose (iii) cost and schedule constrained (iv) scalable in terms of future constellation expansion and (v) developed as a service that will be owned and operated by private entities. SpS missions target new measurements to fill niche gaps in the EEOE.
- **European Resilience from Space (ERS) Missions**: ERS is a new application area that employs a systems-of-systems approach enabling Europe and its Member States

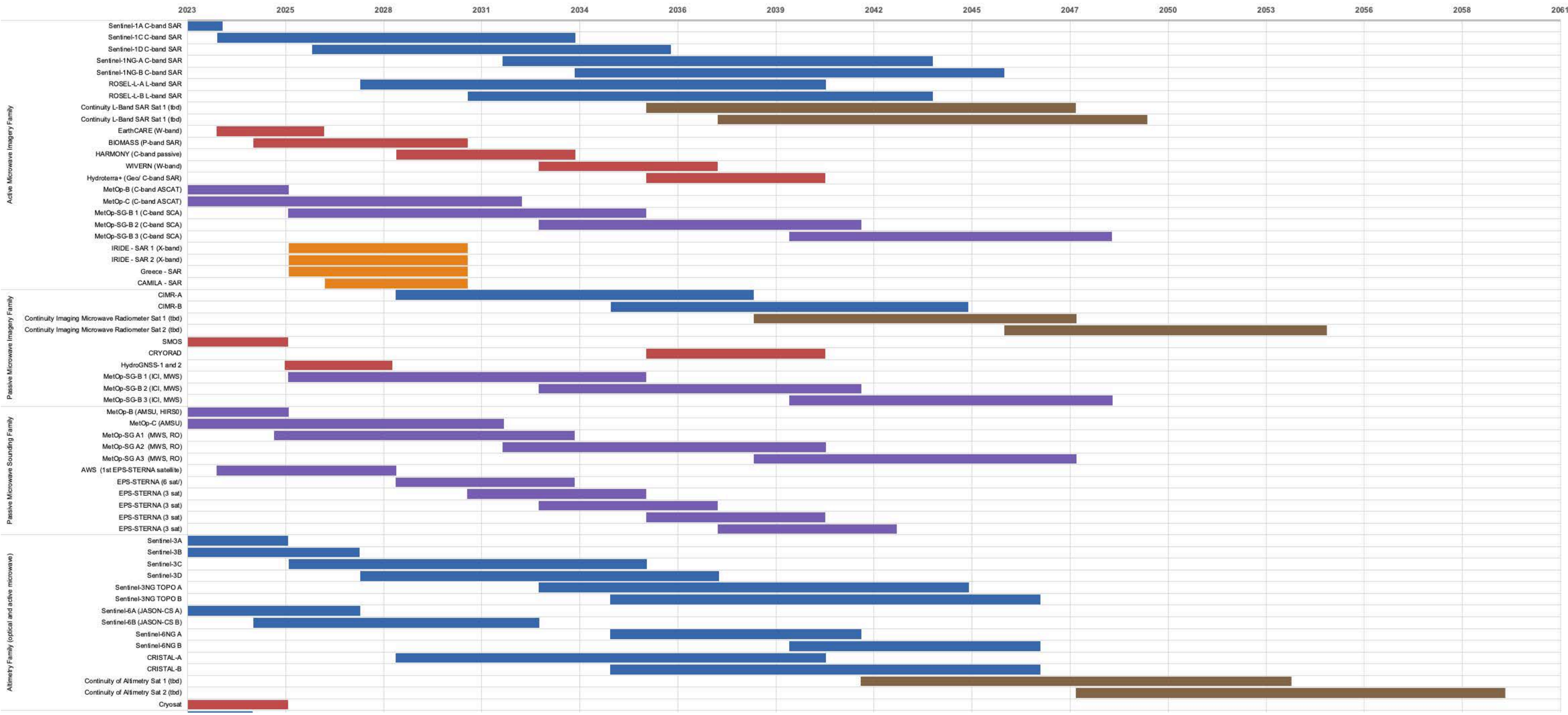
to rapidly and securely collect EO data necessary to protect citizens, institutions, and strategic interests. ERS is conceived from the onset as a dual-use system, serving civilian and defence needs. New ERS Missions may be required to fill highly specific gaps in EO, navigation, connectivity, and information services. The civilian element of ERS activities could provide rapid end-to-end (tasking to Level-1 delivery) data products that complement the existing EEOE capability for civil security and emergency applications (e.g. floods, fires, natural disasters etc).

- **Missions of Opportunity (MoO)** are cooperative EO research and demonstration missions developed through collaboration with Space Agencies outside ESA Member States and outside Associated and Cooperating States. They are characterised by arrangements without exchange of funds such as in-kind contributions by the Agencies at mission level (e.g. launch opportunities, hardware exchange or contributions to elements of a distributed space observation system), and by collaboration between the same Agencies during the mission exploitation phases. MoO can provide new measurements from space addressing observation gaps and enhanced science return (thereby paving the way to Reference Missions) and could enable access to technology not developed within ESA programmes, efficient use of launch opportunities and establishing international EO collaborations beyond the borders of ESA Member States. With MAGIC/NGGM the first Mission of Opportunity is now being implemented. MoO provide the EEOE a framework to inject new technologies and capability through international partnership.
- **ESA Earth Watch missions:** The Arctic Weather Satellite (AWS) launched in 2024 carries a cross-track scanning microwave radiometer designed to provide vertical profile measurements of atmospheric humidity and temperature. AWS was used to successfully demonstrate how the EPS-STERNA polar-orbiting constellation of satellites could provide data for very short-term weather forecasts and nowcasts in the Arctic, and around the world. The Atmospheric Limb Tracker for Investigation of the Upcoming Stratosphere (Altius) mission carries a high-resolution spectral imager and uses a limb-sounding technique to deliver profiles of ozone and other trace gases in the middle atmosphere to support services such as weather forecasting, and to monitor long-term trends. The Proba-V CubeSat Companion (PV-CC) embarks a spare Proba-V camera (development funded by ESA GSTP). The goal is to evaluate whether it is possible to mount the same sensor on a much smaller satellite and still have the same data quality. Earth watch missions inject missions into the EEOE that satisfy specific ESA Member State needs.
- **National Missions** are developed by Member States for national interests and industrial policy (typically within a timeline of political decision). As such, they are valuable complementary to the EEOE that is maintained by larger class reference missions. Examples include IRIDE that is a satellite “constellation of constellations” for Earth observation in LEO developed as an initiative of the Italian government, with the support of the resources of the Italian National Recovery and Resilience Plan (PNRR). IRIDE will be completed by 2026 managed by ESA with the support of the Italian

Space Agency (ASI). IRIDE includes a complete system approach (development, launch, operations, ground-segment and user led applications) based on satellites providing Synthetic Aperture Radar (SAR), high and medium resolution sensors including panchromatic, multispectral, hyperspectral to infrared capability. IRIDE will also provide analytical data for the development of commercial applications by start-ups, small and medium-sized enterprises, and industries in the sector. Programmatically similar concepts are currently under development or in planning including the Atlantic Constellation from Portugal and Spain. Other national programs have similar aspirations including Spain, Portugal, Poland, United Kingdom and Greece. National Missions to consider are also missions which are developed and implemented by the MS themselves examples are Germany – EnMAP or France – CFOSAT and SWOT (in partnership with USA and UK) (although not in the focus the Blueprint in 2025). National missions bring both scientific and operational independent yet complementary EO capability to the EEOE.

- **Commercial Missions** (not in the focus of the first blueprint): are developed by commercial companies providing EO data for a variety of users. The VHR imaging domain (optical and radar imaging) is well advanced as are services for GNSS-RO and AIS amongst others. This market is expected to grow in the future but poses challenges when combining data from multiple commercial providers that may not share a common calibration baseline which significantly complicates their use in synergy for some applications. Commercial missions are an essential component of the EEOE since they foster industrial European space business sector.
- **Continuity of capability Missions:** Missions that are considered necessary to mitigate future gaps in fundamental EO capability the 2040+ timeframe. Extrapolation of mission capability is to be interpreted as “Program Agnostic” in the sense that no formal agreements or plans are in place.

An indicative timeline of the EEOE Mission baseline is provided in Figure 2.2-1. Future versions may be expanded to include a full treatment of other international missions that participate in European EO federated system.


2023
2025
2028
2031
2034
2036
2039
2042
2045
2047
2050
2053
2056
2058
2061
Active Microwave Imagery Family
Sentinel-1A C-band SAR
Sentinel-1C C-band SAR
Sentinel-1D C-band SAR
Sentinel-1NG-A C-band SAR
Sentinel-1NG-B C-band SAR
ROSEL-L-A L-band SAR
ROSEL-L-B L-band SAR
Continuity L-Band SAR Sat 1 (tbd)
Continuity L-Band SAR Sat 1 (tbd)
EarthCARE (W-band)
BIOMASS (P-band SAR)
HARMONY (C-band passive)
WIVERN (W-band)
Hydroterra+ (Geo/ C-band SAR)
MetOp-B (C-band ASCAT)
MetOp-C (C-band ASCAT)
MetOp-SG-B 1 (C-band SCA)
MetOp-SG-B 2 (C-band SCA)
MetOp-SG-B 3 (C-band SCA)
IRIDE - SAR 1 (X-band)
IRIDE - SAR 2 (X-band)
Greece - SAR
CAMILA - SAR
Passive Microwave Imagery Family
CIMR-A
CIMR-B
Continuity Imaging Microwave Radiometer Sat 1 (tbd)
Continuity Imaging Microwave Radiometer Sat 2 (tbd)
SMOS
CRYORAD
HydroGNSS-1 and 2
MetOp-SG-B 1 (ICI, MWS)
MetOp-SG-B 2 (ICI, MWS)
MetOp-SG-B 3 (ICI, MWS)
Passive Microwave Sounding Family
MetOp-B (AMSU, HIRS0)
MetOp-C (AMSU)
MetOp-SG A1 (MWS, RO)
MetOp-SG A2 (MWS, RO)
MetOp-SG A3 (MWS, RO)
AWS (1st EPS-STERNA satellite)
EPS-STERNA (6 sat/)
EPS-STERNA (3 sat)
EPS-STERNA (3 sat)
EPS-STERNA (3 sat)
EPS-STERNA (3 sat)
Altimetry Family (optical and active microwave)
Sentinel-3A
Sentinel-3B
Sentinel-3C
Sentinel-3D
Sentinel-3NG TOPO A
Sentinel-3NG TOPO B
Sentinel-6A (JASON-CS A)
Sentinel-6B (JASON-CS B)
Sentinel-6NG A
Sentinel-6NG B
CRISTAL-A
CRISTAL-B
Continuity of Altimetry Sat 1 (tbd)
Continuity of Altimetry Sat 2 (tbd)
Cryosat

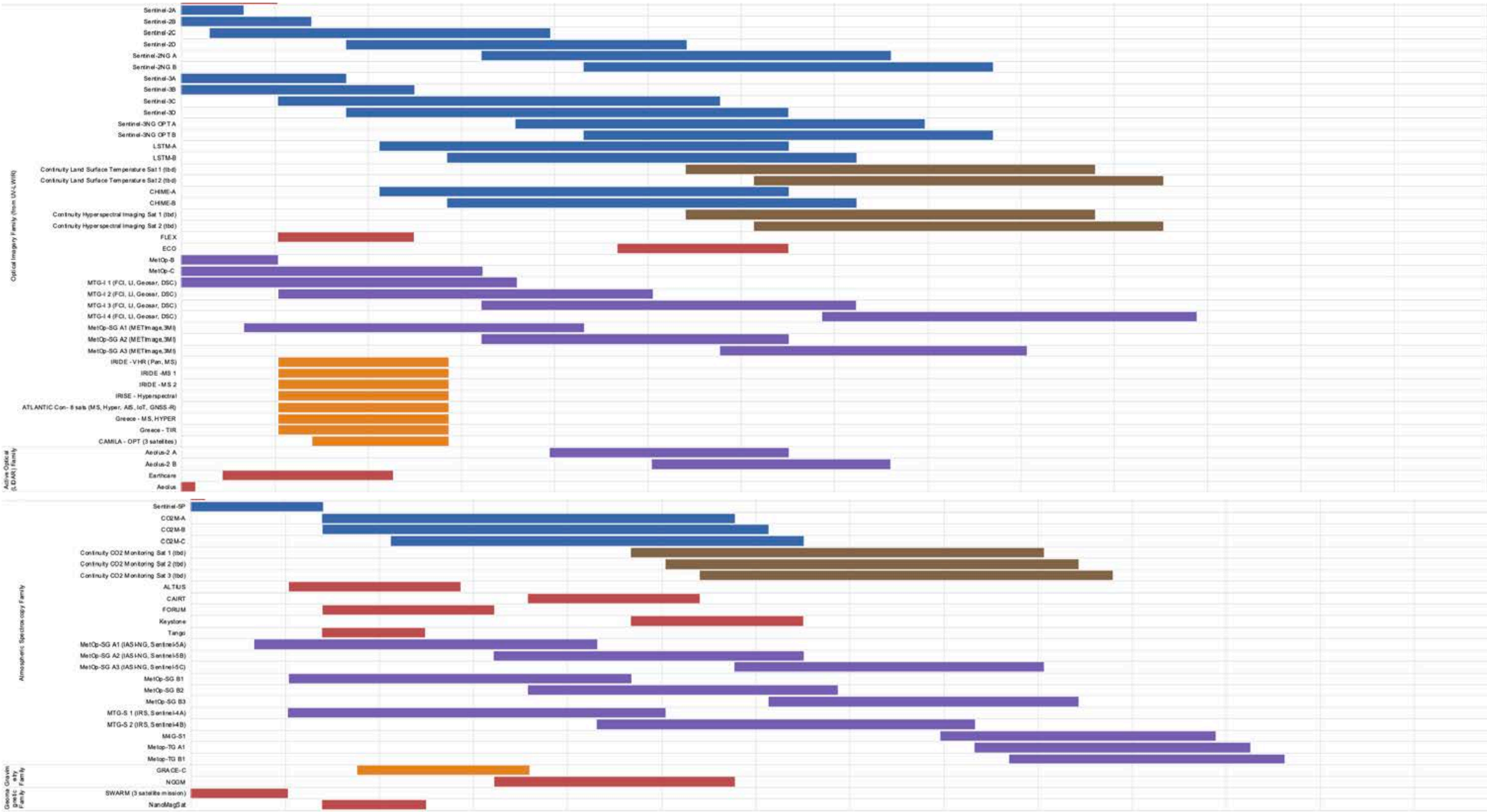


Figure 2.2-1 Illustration of the ESA EO Federated system Reference Architecture ecosystem timeline for 2020-2060. (Colour-coding: Copernicus Missions: BLUE; Meteo Missions: PURPLE: Copernicus Missions not yet approved: BROWN; ESA Research Missions: RED: ESA National Programme Missions: ORANGE)

The EEOE is in continuous evolution and improvement in a full mission-life cycle (Figure. 2.2-2) view which is similar to that of individual satellite missions except that multi mission synergies between mission families are leveraged.

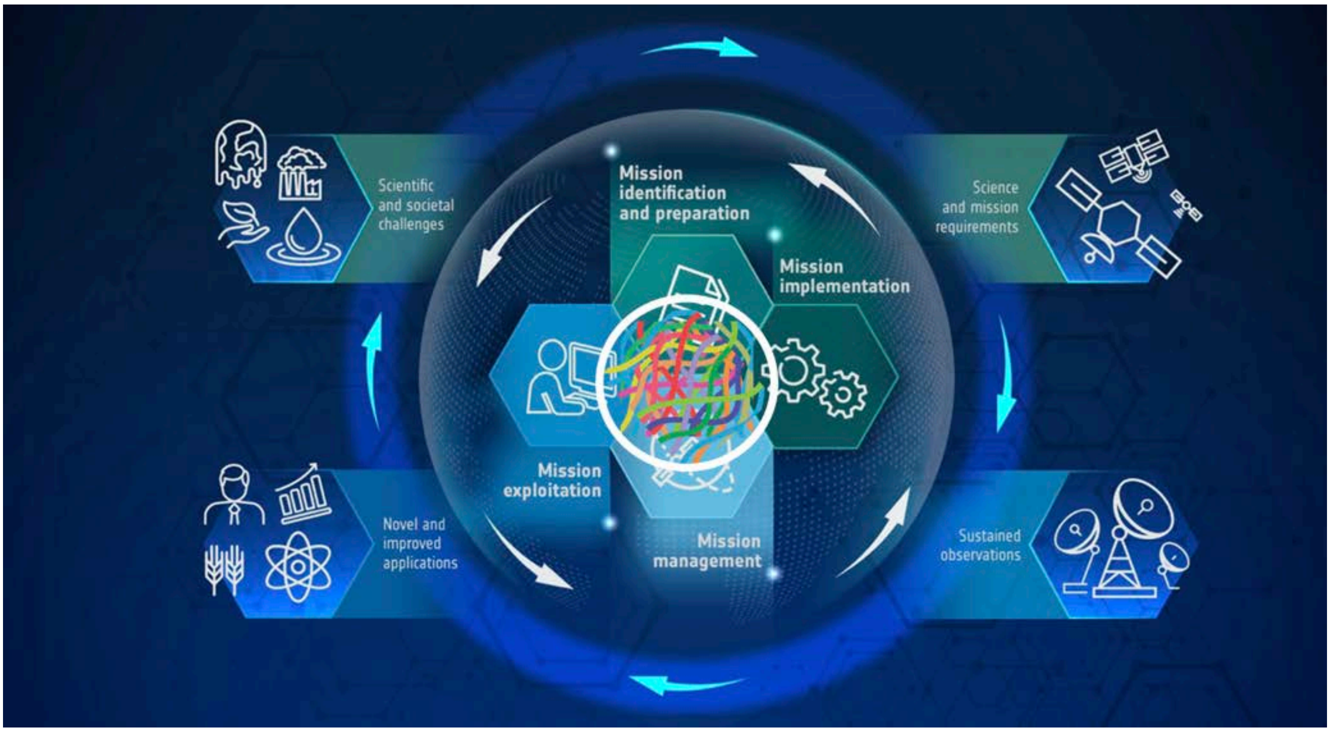


Figure 2.2-2. Illustration of European full-mission life cycle (continuous improvement) including primary feedback loops. Synergies between missions within the European EO Ecosystem are fundamental and are central to the effective design, development, implementation and operation of the federated system (centre graphic) via horizon scanning and forward looking.

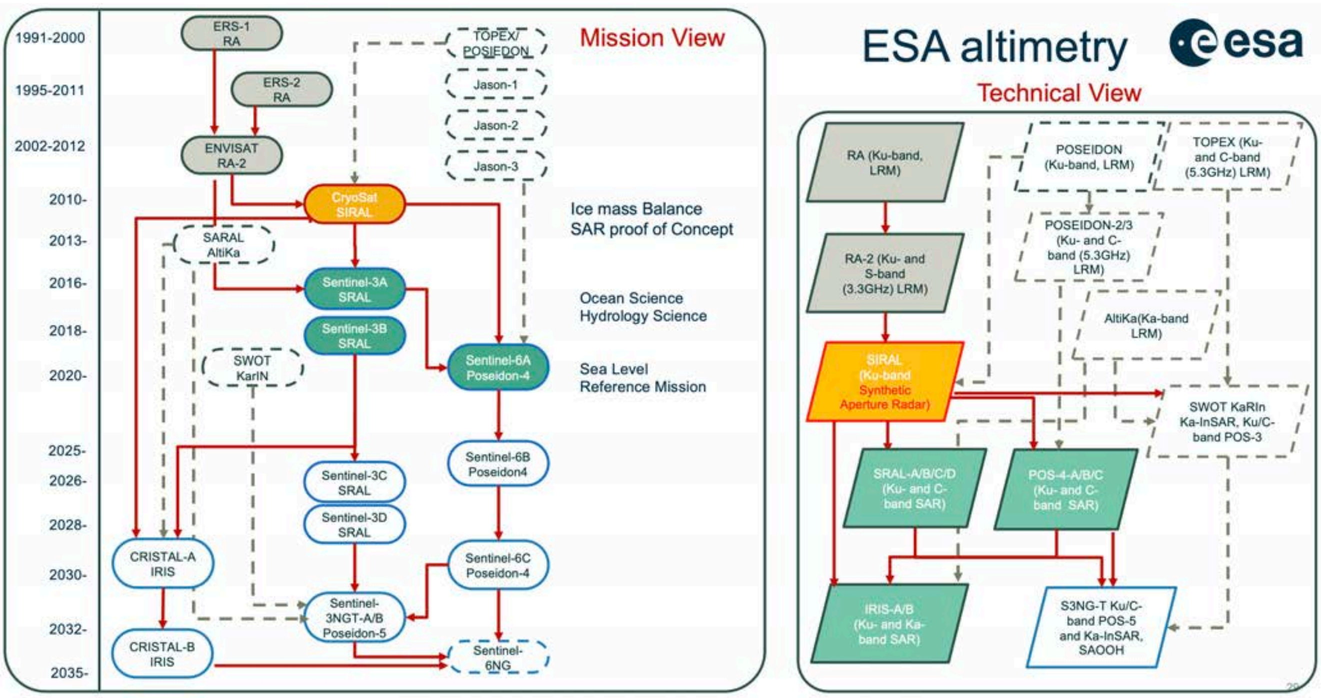
2.3. Documenting the European Earth Observation Ecosystem

Figure 2.1 is intended to highlight the European programmatically driven mission families for Science, Copernicus, and Meteorological domains. While such mission family-based groupings are useful in certain contexts, they obscure the interconnected programmatic foundation of the EEOE. Although frontier science missions are clearly identifiable, the figure does not readily convey how the system as a whole enables coordinated action or exploits synergies to address user needs. This is particularly evident in the dual, and increasingly blurred, role of Copernicus missions: they underpin operational Copernicus services (Marine, Land, Atmosphere, Climate, Emergency, and Security) while simultaneously serving as core inputs to ongoing scientific research and development.

In practice, the distinction between what is considered “operational” and what is considered “science” is far from clear: all of these missions depend on the scientific performance of the observations they provide. Moreover, interactions with commercial providers are not represented, nor is the extensive preparatory work for missions that are ultimately financed and implemented in the national and commercial domains.

Within the EEOE, transitions from science to operations is not at all guaranteed nor are not always driven purely by direct technology transfer. For example, while SMOS pioneered L-band microwave radiometer interferometric techniques, operational user and stakeholder requirements called for a multi-frequency capability that is more effectively delivered by a total-power, conically scanning radiometer, as embodied in the Copernicus CIMR mission. Similar evolutionary pathways can be observed for other instruments, such as the progressive enhancement of C-band Synthetic Aperture Radar (SAR) capabilities across the Sentinel-1 series, Altimetry, visible and infrared missions.

Figure 2.3-1 shows a more detailed “Family Tree” view of how ESA developed altimeter missions and thermal infrared imaging capability relates to modern Copernicus missions. This view provides a technical evolution assessment including the role of external partnerships and collaborations (in light grey) from both a mission and technology perspective.



→ THE EUROPEAN SPACE AGENCY

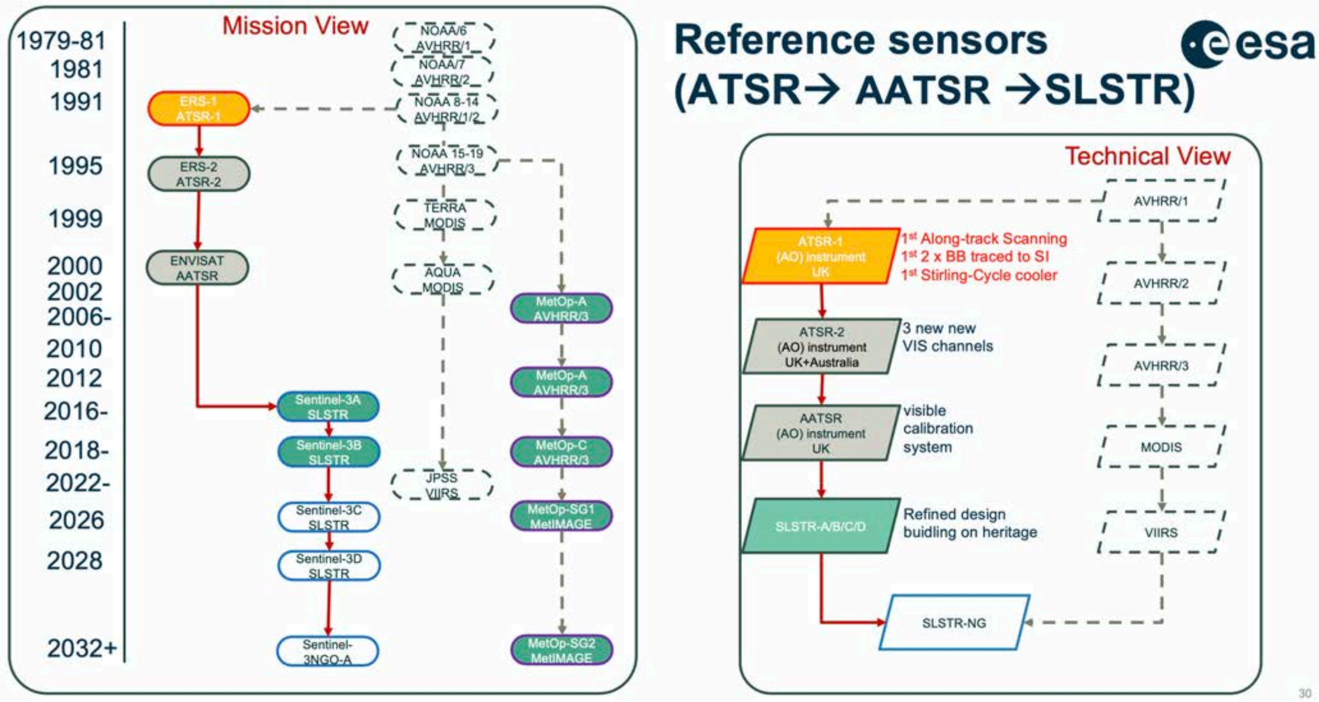


Figure 2.3-1 (Upper) Evolution of ESA altimetry missions and ESA altimetry instruments. Grey boxes and lines indicate international partnership/collaboration elements. Blue lines indicate future missions/technologies. The importance of the ESA CryoSat Earth Explorer mission within the ESA mission development, is highlighted. (Lower) Evolution of ESA thermal infrared reference sensor highlighting the long heritage of (A)ATSR and SLSTR sensors.

The structured visualisation of mission family heritage helps to illustrate how instrument technologies and remote sensing techniques often form the foundation for future missions. In some cases, entirely new capabilities emerge with little or no heritage, such as the ESA FLEX Earth Explorer, which will provide the first spaceborne measurements of photosynthetic activity. In other cases, the lineage is clearer, demonstrating how early exploratory investments shape long-term capability development.

The importance of the ESA Earth Explorer programme’s “daring vision” is well illustrated by the CryoSat altimeter mission. The SAR altimetry techniques proven by CryoSat became a major springboard for subsequent altimetry missions, with ESA’s investment leading to a fundamental improvement in the performance of all later ESA altimeters (complemented by national investment by other Agencies). Ultimately, the Sentinel-3 altimeter was able to fully capitalise on the experience of CryoSat in terms of payload engineering, mission operations concept and scientific output. The Sentinel-3 altimeter, while capable of SAR operations, was only foreseen to use SAR in coastal zones – CryoSat was used to build confidence that SAR “everywhere” was a logical mode for all ocean surfaces – which then became the primary operational mode for the mission.

A second example, representative of many others, is the transition of the ERS-1/2 and ENVISAT Advanced Along Track Scanning Radiometer ((A)ATSR) instrument heritage to the operational Copernicus Sentinel-3 Sea and Land Surface Temperature Radiometer (SLSTR).

In this case, the foundation approaches of the instrument (i.e. along-track scanning, cooled detectors, dual view of the same Earth target scene and two-point reference radiance cavity calibration) were pulled through from the original instrument design: the ERS-1/2 ATSR instruments established a new remote sensing approach that evolved into the Advanced ATSR (AATSR) and is now embodied in the operational Sentinel-3 SLSTR. Through continuous evolution, this instrument family has retained its status as a CEOS reference for thermal infrared radiometer missions for more than two decades. Although this evolution followed a more incremental, step-by-step path, it was the instrument technology and remote sensing approach pioneered within ESA that ultimately resulted in an internationally recognised reference mission capability. It is notable that the EUMETSAT MetOp payload developed independently of the (A)ATSR/SLSTR heritage, instead drawing more strongly on the NOAA AVHRR lineage, reflecting a less risky but also less performant operational mission design choice.

In contrast, the ESA Arctic Weather Satellite (AWS) represents a markedly different development pathway, progressing from conception to launch in just four years and now transitioning to operational implementation by EUMETSAT within the EPS-STERNA programme, which will comprise around 20 satellites.

Developing mission family heritage diagrams across different mission classes (including Earth Explorer concepts that were not selected for implementation) and across technologies provides valuable input to the Reference Architecture Blueprint. However, these are predicated on the existence of a database containing technical details of missions and instruments at fine granularity.

The OSCAR (Observing Systems Capability Analysis and Review)[2] database, maintained by the World Meteorological Organization (WMO), is a comprehensive, operational tool used to document, assess, and coordinate the global EO observing system. It consolidates international information on satellite missions, instruments, surface networks, and observing platforms, describing their technical characteristics, coverage, performance, and data availability. OSCAR directly links observing capabilities to user requirements defined by WMO programmes (e.g. weather forecasting, climate monitoring, hydrology, oceanography), enabling systematic gap analysis, impact assessment, and prioritisation of future observing investments. For policymakers and system architects, OSCAR provides a shared, evidence-based view of the global observing landscape, supporting coordination among agencies, avoidance of unnecessary duplication, identification of critical dependencies, and planning for continuity and resilience of essential Earth observations.

The complementary Mission, Instruments and Measurements (MIM) Database, maintained by the Committee on Earth Observation Satellites (CEOS)[3], is a comprehensive reference catalogue of current, planned, and historical civil Earth Observation satellite missions worldwide. It documents mission objectives, instrument payloads, measured variables, orbit characteristics, and operational status, offering a consistent, up-to-date overview of global

[2] WMO OSCAR | Observing Systems Capability Analysis and Review Tool - Home

[3] CEOS | Committee on Earth Observation Satellites

EO capabilities. The MIM database supports international coordination by enabling agencies to identify complementarities, overlaps, and gaps across observing systems, and is widely used for gap analysis, continuity planning, calibration and validation coordination, and alignment with global frameworks such as GCOS and GEO.

For system architects and policymakers, the WMO OSCAR and CEOS MIM databases provide a factual foundation for strategic planning, helping ensure that national and regional EO investments collectively contribute to a coherent and resilient global observing system.

However, at the mission level, the technical granularity of OSCAR and CEOS MIM is insufficient for the purpose of the Reference Architecture blueprint analysis and constitutes a gap in the EEOE.

[RAB-1]: Establish and maintain, as an integral component of the Reference Architecture Blueprint, a pan-European technical heritage database that extends beyond existing mission-level catalogues (e.g. CEOS and WMO) capturing fine-grained architectural detail for all European Earth Observation missions and mission concepts.

This database will be used to document complete heritage “family trees” for ESA EO missions, instruments, measurement techniques, processing chains, and enabling technologies preserving institutional knowledge and enabling traceable lineage analysis. By providing mission-, instrument-, and technique-level continuity views, the database will support gap analysis, option assessment, technology reuse, and strategic investment decisions, ensuring that the Blueprint is grounded in a comprehensive understanding of Europe’s EO evolution and future option space.

3. THE UNIQUE ROLE OF ESA

Since its establishment in 1975, the European Space Agency has played a central role in advancing global space science, technology, and exploration. The sustained trust and commitment of its Member States have enabled ESA to deliver world-class achievements, from pioneering scientific missions and technological breakthroughs to unique space infrastructures and secure access to space, that are translated into tangible benefits for Europe's economy, security, and the daily life of citizens. This success has been reinforced through long-standing international partnerships, ensuring Europe's credibility and influence on the global stage. The importance and success of ESA Earth Observation was underpinned by the success at the ESA Ministerial Council in 2025. However, the scale and complexity of today's space ecosystem and its sustainability by individual programmes or missions alone is an increasing challenge.

Earth Observation from space empowers ESA Member States to implement evidence-based policy making, adopt a standards-based enforcement of regulations, manage national resources, take climate action and fuel a thriving commercial space economy based on a plethora of world-class applications that are in continuous evolution. The ecosystem of ESA EO services and knowledge across an international operational, scientific, institutional and commercial user base has grown massively over the last 30 years: the EEOE of today stands today as testament of European cooperation and vision embodied in the ESA convention.

It is important to recognise that European policy (e.g. *EC,* 2021; *EEA*, 2022) definition, enactment, monitoring, and assessment using EO data and EO-intelligence takes many years (decades) to complete thus long-term provision of stable EO data are required (e.g. *Anderson et al*, 2017; *ESPI,* 2024, 2025a). Copernicus is an infrastructure explicitly designed to match long policy timelines rather than short technology cycles (e.g. *Berger at al*. 2020). Furthermore, scientific development and understanding of the Earth system (e.g. *Trenberth et al.* 2014) also requires sustained observations (e.g. the ESA Climate Change Initiative data sets e.g. *Hollman et al*, 2013; *Merchant et al,* 2013; *WMO,* 2022) to avoid data gaps (e.g. cessation impacts of SSM/I descope, *EUMETSAT,* 2025) and commitment apply the historical and contemporary resources for expanding user applications and services. Dependencies on the application of EEOE data is growing (600 000+ registered users on the Copernicus Sentinel and Copernicus Data Space platforms[4])) although the actual number of researchers, service providers, industry users, policy agencies, and third-party apps relying on Copernicus data is likely much larger, since many access EO data via third-party APIs, value-added products, and federated infrastructures not captured by a single registration count.

[RAB-2]: **Ensure the long-term continuity and evolution of the European Earth Observation Ecosystem through sustained architectural**

[4] Copernicus Data Space Ecosystem | Europe's eyes on Earth

stewardship that balances policy-grade observational stability with systematic innovation. This includes protecting critical climate and environmental time series, coordinating investment across institutional, national, commercial, and international actors, and coherently integrating new technologies, data sources, and services to align long scientific and policy timescales with rapidly evolving societal and strategic needs.

The space domain is evolving at unprecedented speed. Space has become a strategic asset for resilience, technological sovereignty, and economic growth; public investment is rising globally; commercial actors are reshaping innovation cycles; and the boundaries between civil, security, defence, and digital domains are increasingly blurred. In this environment, maintaining European leadership requires not only ambition and investment, but also coherence, coordination, and long-term architectural thinking. Space technologies are no longer solely instruments of exploration—they are foundational infrastructures underpinning competitiveness, scientific authority, security, and societal resilience. This reality demands a shared framework to guide choices, manage trade-offs, and recognise and act on strategic opportunities in an uncertain future.

3.1. ESA as the Neutral Architect for the EEOE

The effectiveness of the European Earth Observation Reference Architecture Blueprint ultimately depends on ESA's unique ability to act as Europe's neutral system architect and long-term steward of Earth Observation capability.

At the centre of the Reference Architecture Blueprint, ESA occupies a role that no other European or international actor can fulfil. ESA operates at the intersection of science, policy, technology, and industry, with a mandate and governance structure that allow it to take a long-term, system-of-systems perspective beyond individual missions, programmes, or political cycles. Within the Blueprint, ESA provides the architectural discipline needed to translate diverse and sometimes competing requirements into a coherent strategic direction. Through foresight, scenario analysis, expert knowledge and structured trade-off assessment, ESA ensures that emerging science priorities, policy needs, technological opportunities and programmatic constraints are systematically reflected in the evolution of the EEOE. This includes preserving measurement continuity and trust, managing interfaces between institutional and commercial actors, and preventing premature technological or organisational lock-in that could constrain Europe's future options. Importantly, ESA's stewardship of exploratory programmes such as FutureEO at allows high-risk, high-return innovation to be deliberately injected into the Reference Architecture, de-risking future operational and service capabilities.

This position enables ESA to design, maintain, and evolve architectural coherence across Europe's highly distributed EO landscape, ensuring that national, EU, operational, scientific, commercial, and security-driven contributions accumulate into sustained capability rather than fragmented success. By moving from mission-by-mission optimisation to system-of-systems stewardship, the Blueprint translates Europe's collective ambition into an executable, evolvable architecture. In doing so, it underpins ESA Strategy 2040 and marks a decisive step toward ensuring that Europe's space sector remains a trusted, competitive, and enduring driver of progress and prosperity in an increasingly strategic and contested environment.

[RAB-3]: **Maintain ESA in its role as the neutral architect of the European Earth Observation Ecosystem, providing anticipatory governance and uncertainty (risk) assessment through the Reference Architecture Blueprint to ensure that Europe's EO system evolves coherently, remains resilient to emerging pressures, and stays strategically aligned in a rapidly changing global environment.**

3.1.1. ESA as a long-term steward

ESA also plays a central role in sustaining Europe's credibility and autonomy in an increasingly contested geopolitical environment. As the custodian of long-term calibration, validation, and data stewardship, ESA underpins the scientific integrity and international trustworthiness of European EO data—qualities that are essential for climate monitoring, security, legal defensibility, and global cooperation.

At the same time, ESA's ability to federate partnerships with the European Union, EUMETSAT, Member States, and international partners ensures that Europe remains both strategically autonomous and globally engaged. In this way, the Reference Architecture Blueprint positions ESA not simply as a mission implementer or service-enabler, but as the enabling architect that aligns Europe's EO investments with long-term societal resilience, policy relevance, and global leadership.

3.1.2. ESA fosters de-risk options between science, technology, operations, industry and policy.

Unlike any single operational, commercial, or national actor, the ESA operates at the intersection of science, policy, technology, and industry, with a mandate and time horizon that allow it to design and evolve the EEOE as a true system-of-systems. ESA goes beyond mission implementation; it curates the architectural logic that connects exploratory science (e.g. Earth Explorers and Scout), operational services (e.g. Copernicus and meteorology), emerging commercial capabilities, and future policy needs into a coherent whole.

This architectural role is critical for managing future uncertainty (i.e. risks) including interface definition and stability, avoiding premature lock-in, preserving calibration and data continuity, and maintaining a credible innovation pipeline that feeds operational systems over decades.

Strategically, through instruments such as the Reference Architecture Blueprint and the Copernicus Long-Term Scenario, ESA provides Europe with a trusted, evidence-based framework for trade-off analysis, scenario testing, and coordinated investment—ensuring that diverse national and institutional contributions accumulate into sustained capability, resilience, and global leadership in Earth Observation rather than a collection of optimised but disconnected parts.

3.1.3. Continuous horizon scanning and early architectural response

Establishing a permanent, structured horizon-scanning and assessment function, led by ESA in coordination with European and international partners, users, stakeholders, policymakers and scientists is an essential element within the EEOE Reference Architecture framework. This function must systematically monitor emerging trends, drivers, and challenges—spanning science, policy, geopolitics, technology, commercial markets, regulation, and user demand—and translate them into early identification of architectural gaps, risks, and opportunities across the European EO Ecosystem. By linking foresight directly to gap analysis, scenario stress-testing, and option development, ESA and its partners can elaborate timely mitigation or leverage strategies (e.g. technology insertion, partnership formation, governance adaptation, or mission re-prioritisation) before pressures materialise into capability shortfalls.

[RAB-4]: **Systematically monitor and assess emerging trends, drivers, and challenges to identify gaps and future needs in the European Earth Observation Ecosystem at the earliest possible stage, and to develop timely response options that exploit opportunities and mitigate risks to system performance, resilience, and strategic coherence.**

3.2. ESA FutureEO: the Reference Architecture Innovation Engine

The ESA FutureEO programme[5] is the forward-looking research, end-to-end programme, covering mission conception, implementation and operation as well as user applications, interfaces and respective service development. FutureEO is designed to anticipate and address tomorrow's scientific, societal, and technological challenges through pioneering satellite missions and innovative EO concepts. It builds on ESA's long heritage in Earth science and systemic observation to maintain Europe's leadership in understanding planetary processes and informing action on environmental, climate, and sustainability priorities. At its

[5] ESA - FutureEO https://www.esa.int/Applications/Observing_the_Earth/FutureEO

core, FutureEO ensures that new ideas, sensing technologies, and observation strategies are nurtured from early concept through to readiness, enabling science excellence to flourish and feed into future operational capabilities. FutureEO is guided by the former and current ESA Earth Observation Science Strategy.

FutureEO fosters a range of mission classes—including flagship Earth Explorer science missions, agile “Scout” missions, and small satellite Φ-sats—enabling rapid innovation while continuing to push the boundaries of measurement science. In 2025, a new class of future potential missions called Stepping Stone Missions will be prepared (up to Preliminary Requirements Review) that are directly linked to new user-policy needs. The programme also supports development of innovative space technologies and new observation techniques that can be injected into future operational missions, ensuring continuity with evolving user needs and societal demands. Importantly, FutureEO plays a key role in boosting resilience, policy relevance, and socio-economic impact by enabling Europe to observe critical Earth processes such as atmospheric dynamics, cryosphere change, the carbon and water cycles, and environmental hazards in greater depth and with enhanced precision.

FutureEO’s agility and innovation focus allow it to adapt to emerging opportunities and challenges, including competitive pressures from international space actors, the growth of commercial EO, and convergence with digital technologies such as data analytics and artificial intelligence. By bridging upstream scientific discovery with downstream application and service development, Future EO forms a strategic foundation for Europe’s next generation of Earth observation missions and information systems, reinforcing capability continuity, scientific credibility, and long-term value delivery for both science and society.

3.2.1. The importance of Earth Explorer, Scout and Φ-Sat Missions

The ESA FutureEO Earth Explorer (EE) mission concept (complemented by ESA Scout and Φ-Sats) is fundamental to the future Reference Architecture Blueprint because it is a primary mechanism for injecting combined scientific disruption, technological innovation, and long-term capability renewal into Earth Observation (Table 3.2.1-1 and Figure 3.2-1).

Table 3.2.1-1 Summary of ESA Earth Explorer Missions studied at Phase 0 and above (See Annnex-1 for further information).

Call for Proposals	Year	Selected Earth Explorer Candidates/Missions			
		Assessment (Ph 0)	**Feasibility Phase (Ph A)**	**UCM**	**Selected Mission(s)**
1st Call for Opportunity Missions (COM-1)	1998	ACE CryoSat SMOS Swarm SWIFT	CryoSat SMOS	No UCM - PB-EO #78 May 1999	**CryoSat** (Earth Explorer 1) **SMOS** (Earth Explorer 2)

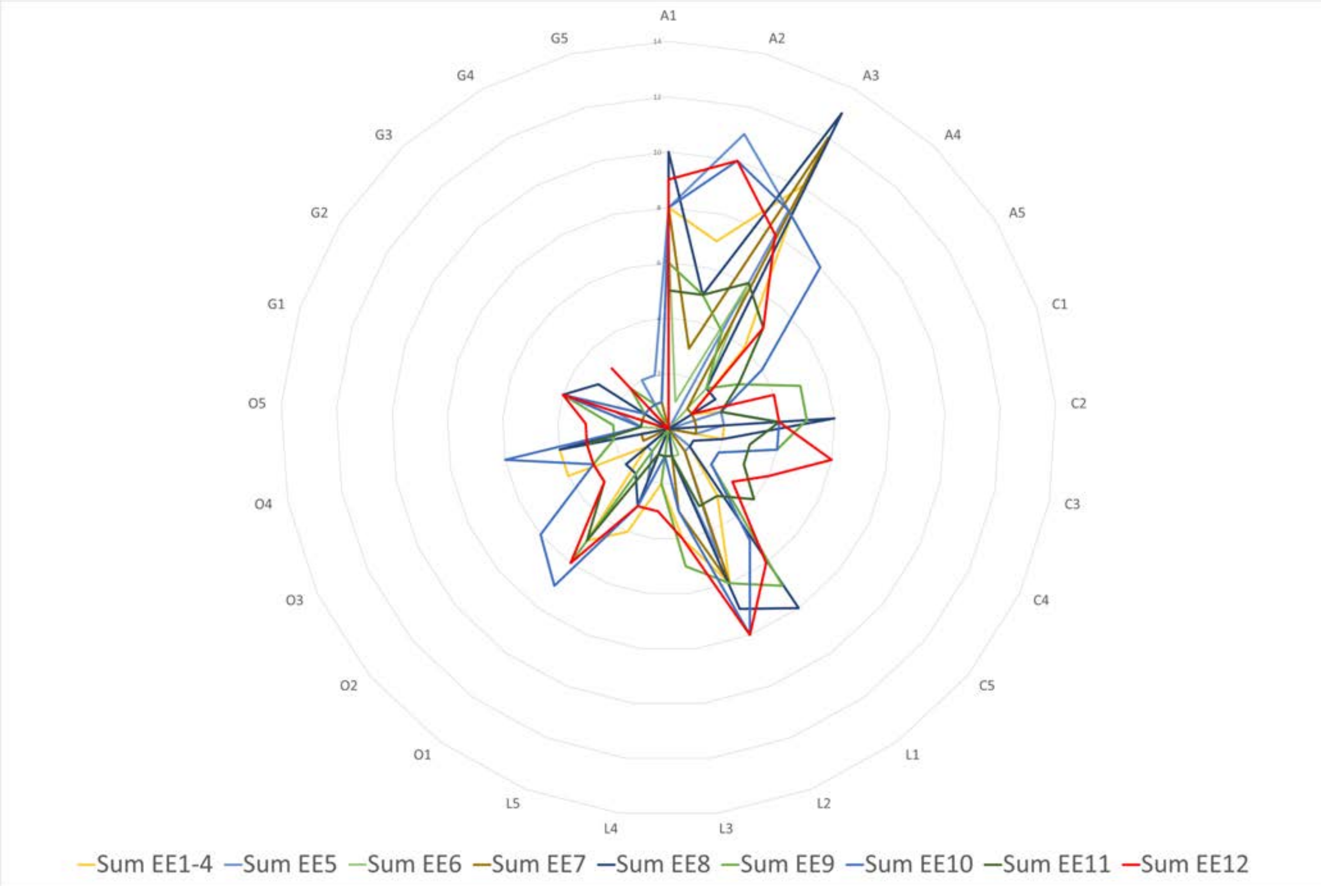
Ideas selected at an ESTEC User Consultation Meeting (UCM)	1994	Gravity Field Land Surface Processes Earth Radiation Atmos. Dynamics Magnetometry Atmos. Chemistry Atmos. Profiling Precipitation Topography	ADM-Aeolus ERM GOCE LSPIM	Granada Oct. 1999	**GOCE** (Earth Explorer 3) **ADM-Aeolus** (Earth Explorer 4)
2nd Call for Opportunity Missions (COM-2)	2001	ACE+ Carbosat EGPM Swarm Swimsat TROC	ACE+ EGPM Swarm	ESRIN Apr. 2004	**Swarm** (Earth Explorer 5)
1st Call for Core Missions (CCM-1)	2000	ACEChem EarthCARE SPECTRA WALES WATS	EarthCARE SPECTRA WALES		**EarthCARE** (Earth Explorer 6)
2nd Call for Core Missions (CCM-2)	2005	ASCOPE Biomass CoreH2O FLEX PREMIER TRAQ	Biomass CoreH2O PREMIER	Graz March 2013	**Biomass** (Earth Explorer 7)
3rd Call for Opportunity Missions (COM-3)	2009	- N/A -	CarbonSat FLEX	Krakow Sept. 2015	**FLEX** (Earth Explorer 8)
Revised Call for Earth Explorer 9 'Fast Track' Mission Proposals	2016	- N/A -	FORUM SKIM	Cambridge July 2019	**FORUM** (Earth Explorer 9)

Call for Earth Explorer 10 Mission Ideas	2017	STEREOID (Harmony) Daedalus G-Class (Hydroterra)	Harmony	ESTEC July 2022	**Harmony** (Earth Explorer 10)
Call for Earth Explorer 11 Mission Ideas	2020	CAIRT Nitrosat SeaStar WIVERN	CAIRT WIVERN	Prague July 2025	**WIVERN** (Earth Explorer 11)
Call for Earth Explorer 12 Mission Ideas	2023	CryoRad ECO Hydroterra+ Keystone	Not yet started		Earth Explorer 12 To be selected

While the approach of ESA to select and develop EO missions is evolving (e.g. European Resilience in Space), generating and providing feedback on mission implementation selection and applying lessons learned to inform future mission calls and selection should be structured and timely. Such feedback is important for the evolution of the Reference Architecture Blueprint.

[RAB-5]: **Feedback on the outcome of mission selection/proposals should be provided in a structured and timely way (ESA/PB-EO(2025)13,REV.1) and fed into lessons learned processes for future mission calls and selections.**

The ESA mission portfolio has expanded in recent years which has led to a well -balanced approach to propose and exploit new ideas. The Earth Explorer element of the Programme (as a bottom-up science-driven Programme) is its core and is extremely well-regarded by other space agencies. It is a unique process and a fundamental opportunity for scientists to submit ideas covering a broad range of Earth Observation scientific options. ESA Earth Explorer, Scout, and Φ-sat missions act as the upstream 'ESA EO innovation engine', testing new measurement techniques and mission concepts well before they are ready for operational use. They focus deliberately on high-risk, high-return science priorities from the ESA Earth Observation Science Strategy, exploring new variables and processes that cannot yet be observed at scale. This approach safeguards future mission options. It is a fundamental approach to secure future mission options. Even when concepts do not reach flight, the EE process generates validated technologies, algorithms, calibration strategies, and expert communities that later may migrate into operational systems (e.g. Copernicus, meteorological, security, or commercial services), effectively de-risking future investments



	A1	A2	A3	A4	A5	C1	C2	C3	C4	C5	L1	L2	L3	L4	L5	O1	O2	O3	O4	O5	G1	G2	G3	G4	G5
Sum EE1-4	8	7	10	4	1	2	2	2	0	1	3	6	4	2	4	5	1	4	4	1	2	0	1	1	1
Sum EE5	8	11	9	0	0	2	2	1	0	1	1	5	1	0	2	1	1	0	3	1	2	0	0	2	2
Sum EE6	7	1	6	2	0	0	0	0	0	0	0	1	1	0	0	0	1	0	0	1	0	1	0	0	0
Sum EE7	8	3	12	1	1	1	1	1	0	0	1	6	3	0	2	0	0	1	1	0	1	1	0	0	1
Sum EE8	10	5	13	2	2	0	6	2	1	1	8	7	1	0	3	2	2	0	4	1	4	3	0	1	0
Sum EE9	6	5	4	2	3	5	5	4	2	2	7	6	5	2	0	6	3	3	2	2	4	1	2	1	0
Sum EE10	8	10	9	8	4	2	4	4	2	2	5	8	3	1	3	7	6	3	6	1	4	1	1	1	1
Sum EE11	5	5	6	5	3	2	4	3	3	4	3	3	1	1	1	5	3	3	3	1	1	0	1	0	0
Sum EE12	9	10	8	5	1	4	4	6	4	3	6	8	4	3	3	6	3	3	3	3	4	0	3	0	0
	11%	9%	12%	5%	2%	3%	4%	4%	2%	2%	5%	8%	4%	1%	3%	5%	3%	3%	4%	2%	3%	1%	1%	1%	1%
			39%					15%					21%					17%					8%		

Figure 3.2-1. Earth Explorer 1-12 proposals linked to the scientific challenges (originating from the ESA EO Science strategy 2015) (ESA's Living Planet Programme: Scientific Achievements and Future Challenges - Scientific Context of the Earth Observation Science Strategy for ESA) in the Atmosphere (A), Cryosphere (C), Land (L), Ocean (O) and Solid Earth (G) illustrating the variety of scientific topics addressed via the Earth Explorer calls. Most of the proposals addressed several scientific challenges.

The following examples highlight the fundamental importance of the EE *process and outcomes* (i.e. not just the missions selected for implementation):

- Radio occultation (RO) based on the refraction of GPS/Galileo signals by the atmosphere was a technique proposed for the Atmospheric Profiling Mission Earth

Explorer concept and again for the Atmosphere and Climate Earth Explorer concept – both of which were thoroughly prepared, but ultimately not selected for implementation. Nevertheless, the preparatory work led to include the Global Navigation Satellite System Receiver for Atmospheric Sounding (GRAS) instruments on the MetOp series of satellites, which will be continued with the radio occultation instruments on MetOp Second Generation.

- The Copernicus Sentinel-4 mission now monitoring air quality is closely related to the Geostationary Scanning Imaging Absorption spectrometer (GEOSCIA) Earth Explorer proposal. Sentinel-4 is embarked on the geostationary MTG-S sounder satellites and is complemented by the Sentinel-5 imaging absorption spectrometer embarked on MetOp-SG.
- The Copernicus Carbon Dioxide Monitoring mission, CO2M, is derived from the CarbonSat Earth Explorer candidate that concluded studies that demonstrated the capability of carbon dioxide and methane point-source detection to estimate anthropogenic emissions.
- The Copernicus Hyperspectral Imaging Mission for the Environment, CHIME, which is scientifically and technologically closely related to two Earth Explorer concepts: the Land Surface Processes and Interactions Mission (LSPIM) and the Surface Processes and Ecosystem Changes Through Response Analysis (SPECTRA). Both Earth Explorer candidates completed Phase-A studies but were not selected for implementation.

Lessons learned and experience gained from previous missions is a key element to evolving future mission design. Unquestionably, the EE process (i.e. the preparation of missions that under EE did and did *not* fly) has benefitted both Copernicus and EUMETSAT operational satellite development and in-flight services available today. Successful EE missions are all unique. Before launch several scientific questions remain to be answered and often, technical concepts proven for the first time in space. Yet the impact of GOCE, Swarm, Aeolus, SMOS, CryoSat has been immense. EE GOCE is being followed up by NGGM/MAGIC, EE Aeolus in the EUMETSAT EPS-Aeolus programme with Aeolus-2A and 2B), L-band radiometry pioneered by EE SMOS has transitioned to the Copernicus Imaging Microwave Radiometer (CIMR) mission, EE CryoSat has revolutionised the use of SAR altimetry in Sentinel-3 and Sentinel-6 and, in the near future, the Copernicus Polar Ice and Snow Topography Altimeter. To be launched in the coming years, EE FLEX will pioneer measurements of photosynthetic processes from space flying in formation with Sentinel-3, FORUM will pioneer space measurements in the Far-Infrared spectrum to study the Earth Radiation Imbalance, HARMONY will pioneer innovative bistatic formation flying with Sentinel-1 to study ocean, cryosphere and tectonic dynamics amongst others. Wivern will provide the first measurements of wind within clouds together with information on the internal structure of clouds, filling a significant gap in the global satellite observing system. EarthCare is now in orbit and provides critical insights of the atmospheric interactions between aerosols, clouds, and radiation. In 2025 Biomass also joined the Earth Explorer fleet in space, demonstrating the use of P-band SAR and tomography measurements to study forestry and potentially discovering the unknown underneath the surface as former riverbeds and archaeological features. All these missions bring enormous potential to innovate new missions for operational sustainability via Copernicus and Meteorology programmes but also to uniquely advance European Earth System Science. The investment in the Earth Explorer programme is a fundamental aspect of how and why ESA maintains global Leadership in Earth Observation today.

There are numerous additional examples within the extensive portfolio of Earth Explorer (EE) mission concept proposals and studies (see Annex-1 and Fig. 3.1-1) that did not ultimately progress to flight. Although the preparation of a mission concept requires substantial scientific, technical, and industrial effort, not all user-driven proposals can be implemented as Earth Explorers—most often due to programme timing, budgetary constraints etc, rather than any deficit in scientific ambition or technological merit. Importantly, this effort is not lost: several non-selected concepts have directly contributed to the development of valuable operational capabilities, while the process itself consolidates multidisciplinary scientific and industrial teams into focused communities that act as a highly effective training ground for future missions. Many Earth Explorer concepts therefore remain “on the shelf” as a reservoir of unrealised potential and should be regarded as a strategic pool of future opportunities.

[RAB-6]: **Reassess unstudied Earth Explorer concepts and identify those that may be strategically attractive due to advances in technology and mission implementation approaches.**

Strategically, the Blueprint depends on the Earth Explorer programme to sustain Europe’s scientific EO innovation ensuring that the long-term architecture remains adaptive, scientifically credible, and resilient to emerging risks and policy needs, rather than converging prematurely on incremental extensions of existing capabilities.

As a result, the FutureEO programme underpins the Blueprint by keeping Europe’s EO architecture adaptive, scientifically credible, and resilient to emerging risks and policy needs, rather than limited to incremental evolution of existing capabilities.

[RAB-7]: **Sustain and strengthen the FutureEO programme as a core pillar of the Reference Architecture Blueprint, ensuring continuous injection of high-risk, high-return scientific innovation into the European EO system-of-systems. This includes protecting its exploratory mandate, maintaining a robust pipeline of mission concepts and studies, and systematically linking Earth Explorer, Scout, Φ-sat and potentially Stepping Stone Mission outcomes—whether flown or not—to future operational, commercial, and security capabilities, so that Europe’s long-term EO architecture remains adaptive, scientifically authoritative, and resilient to emerging risks and policy demands rather than constrained to incremental evolution.**

The Commended Mission status afforded to some mission concepts by the Advisory Council for Earth Observation (ACEO) acknowledged that specific mission concepts, while not selected for implementation, have recognised potential to address scientifically relevant challenges and should be 'commended for further [pre-]development by ESA'. However, a systematic work programme for commended missions is still to be fully developed.

[RAB-8]: **Establish a structured, time-bounded "Commended Missions Development Track" within the ESA Earth Observation Programme to systematically mature high-potential, non-selected Earth Explorer concepts.**

This activity would formalise the status of ACEO-commended missions by moving them from an honorary recognition into a managed portfolio with clear objectives, governance, and resources. While clearly not pre-empting any implementation opportunities the track should include (i) defined technical and scientific maturation milestones (e.g. TRL advancement, algorithm and calibration concept development, mission architecture updates), (ii) modest but sustained pre-Phase-A funding, (iii) periodic re-assessment against evolving policy needs, technology readiness, and Reference Architecture gaps, and (iv) explicit interfaces to Copernicus, EUMETSAT, security, and commercial pathways. By doing so, ESA would preserve strategic options in a "pool" of mission concepts that have been assessed, avoid loss of prior investment and expertise, and ensure that commended missions actively inform the Reference Architecture Blueprint as credible future building blocks rather than remaining dormant concepts.

3.2.2. ESA InCubed and Φ-lab

ESA InCubed is an architectural enabler, accelerating the integration of commercial innovation into Europe's Earth Observation system while preserving trust, coherence, and strategic alignment.

Within the Reference Architecture Blueprint, the InCubed programme plays a key role in strengthening the commercial pillar of the European Earth Observation Ecosystem by de-risking innovative services, data sources, and business models that complement institutional capabilities. InCubed enables rapid development, market validation, and early user uptake of novel EO solutions, helping Europe respond more flexibly to emerging needs, surge demands, and evolving policy priorities. Architecturally, InCubed provides a structured pathway for integrating commercial EO into the system-of-systems—ensuring interoperability, data quality assurance, and alignment with long-term public objectives—while avoiding fragmentation or erosion of trust.

[RAB-9]: **Maintain InCubed as an interface between commercial innovation and the Reference Architecture, enabling scalable uptake of trusted commercial EO capabilities that enhance responsiveness, resilience, and cost-effectiveness of the European EO Ecosystem without compromising continuity, governance, or scientific integrity.**

The ESA Φ-lab plays a critical role in ensuring that the Reference Architecture remains adaptive, innovative, and future-ready in the face of rapid technological and market evolution. Φ-lab provides ESA with a structured mechanism to explore, de-risk, and accelerate disruptive technologies—particularly in artificial intelligence, advanced onboard processing, quantum computing, and novel sensing concepts—that cannot be matured efficiently within traditional mission development cycles alone. Through its close coupling with the InCubed programme, Φ-lab bridges early-stage innovation and downstream exploitation by supporting startups, SMEs, and LSI, as well as research teams in developing EO technologies and services that respond directly to emerging user and market needs. Within the context of the Reference Architecture Blueprint, Φ-lab is therefore not an auxiliary activity but a strategic innovation engine: it allows new architectural patterns (e.g. AI-native missions, service-centric ground segments, hybrid institutional–commercial constellations, rapid demonstrators, and one-off training satellites) to be explored, tested, and validated before they are institutionalised. By systematically feeding proven concepts from Φ-lab and InCubed into pre-Phase-0 activities, Earth Explorers, and operational programmes, ESA ensures that the Reference Architecture evolves through evidence-based innovation rather than reactive adaptation, preserving European leadership while keeping critical architectural options open.

[RAB-10]: **Embed ESA Φ-lab and InCubed outputs into the Reference Architecture lifecycle by establishing a formal transition path from Φ-lab experimentation to pre-Phase-0 mission preparation and ground-segment evolution.**

[RAB-11]: **Ensuring that ESA Φ-lab outputs (e.g. validated AI, digital, and service-centric innovation) are assessed early as architectural building blocks for future institutional–commercial missions and systems while deliberately keeping high-risk, high-value options open until evidence justifies consolidation.**

4. FORESIGHT ANALYSIS AND REFERENCE ARCHITECTURE EVOLUTION

Earth-observing missions are conceived, implemented, and funded through multiple independent programme cycles that are frequently misaligned in time, scope, and governance. This fragmentation introduces a structural risk of measurement gaps and discontinuities that threaten the long-term integrity and usability of essential Earth observation data records. When considered as a system-of-systems, the European EO architecture must reconcile heterogeneous objectives, constraints, institutional roles, and governance models, such that unified optimisation and sustained long-term coordination inherently challenging. How these interacting factors will evolve toward the 2050 timeframe remains uncertain. In an increasingly globalised and interconnected world—where environmental change, societal dynamics, and geopolitical conditions evolve at accelerating rates—systematic, futures-oriented thinking becomes a critical enabler for effective decision-making within the Reference Architecture (RA) Blueprint. Foresight activities, including scenario development, identification of key trends and core drivers of change, identification of first-order consequences, second-order impacts and third-order effects, quantitative modelling, and scenario-guided design of policies and programmes, provide essential tools for exploring response options to complex socio-economic and environmental challenges across multiple sectors and decision-making levels (e.g. Wiebe et al., 2018).

The rapid growth and diversification of the EO user community demonstrates that sustained Earth observation constitutes a strategic global public good that requires long-term coordination and collective stewardship (e.g. OECD, 2025; GEO, 2025). Nevertheless, current EO achievements and the global leadership position Europe has established (ESPI, 2024) remain vulnerable. Without sustained strategic ambition and commensurate long-term planning, continuity of capability and innovation can be eroded rapidly. Recent reconvergence trends within the European space and defence industrial landscape—driven by geopolitical shifts and increasing reliance on emerging technologies for space system implementation—illustrate how external pressures can reshape priorities and investment patterns (e.g. ESPI, 2025b). Addressing these dynamics requires deliberate recognition and action, supported by systematic strategic trend assessment of the European EO ecosystem (EOEE), to preserve continuity while sustaining innovation (e.g. JRC, 2025; WEF, 2025).

Strategic foresight analysis provides a structured approach for understanding potential futures and translating future-oriented insights into organisational strategy and decision-making (e.g. Iden et al., 2017; OECD, 2025). It serves a dual purpose: first, to observe, perceive, and capture signals, trends, and drivers that may induce future change; and second, to analyse the implications of these changes—particularly those that challenge existing systems, assumptions, and governance arrangements—and to articulate appropriate organisational responses, including preparation for less favourable or disruptive futures. Foundation analysis and the systematic identification of trends and core drivers of change are used to construct hypothetical but well-reasoned world-evolution scenarios that extend beyond simple extrapolation of the current status quo. These scenarios provide a long-term strategic context for decision-makers, enabling exploration of potential trajectories, scientific and technological opportunities, and the societal and strategic implications for the EEOE as a whole.

4.1. Scenario based foresight

The RA Blueprint employs a systems-based foresight-scenario approach as the framework for analysis. It is important to distinguish between the EEOE *ecosystem*, *reference architecture*, and *scenarios:*

- The EEOE describes what EO capability exists today,
- Scenarios explore what *might* happen in the future and what the Reference Architecture requires for a future version of the EEOE, based on defined assumptions and descriptive future world narratives,
- The Reference Architecture describes what EO capability Europe should align and build toward.

As noted by Ivanko et al. (2024), when assessing potential gaps across multiple spaceborne missions addressing similar scientific parameters, a shift away from traditional objective- and criteria-based assessment approaches towards a scenario-based methodology is warranted. Rather than relying on a prioritised set of common objectives, the scenario-based approach evaluates how alternative decisions propagate through the system-of-systems, characterising a range of plausible future system states. This method provides inherent flexibility, allowing assumptions to be adjusted, inputs updated, and supporting models refined as new information becomes available. It also enables the early identification of emerging challenges, sensitivities, and critical decision points at a stage where mitigation options remain open. As time progresses and real-world developments unfold, scenarios evolve accordingly, with their underlying assumptions either proving robust or revealing weaknesses and inconsistencies.

This perspective aligns closely with the growing emphasis on strategic foresight within ESA. As stated by the ESA Director General (ESA, 2024):

> *"In an era characterised by rapid change and complexity, the necessity for strategic foresight has never been more crucial… to help ESA anticipate and prepare for emerging developments and potential disruptions. Strategic foresight helps us explore the potential trajectories of change, providing essential resources to enhance our strategic planning and ensure we are prepared to respond as events unfold."*

4.1.1. Foresight foundation sources

There are several well-founded studies that document plausible scenarios for how the socio-techno-economic future might play out based on informed assumptions (e.g., DCDC, 2024, ESA 2024). Relevant strategic foresight and mission-architecture documents are those that explicitly address systems-of-systems design, continuity, governance, resilience, and long-term evolution of EO capabilities in Europe. These documents contribute to architectural foresight in EO by:

- Anchoring mission architecture in policy drivers (climate, resilience, sustainability).
- Encouraging data-centric architectures that support flexible uses, policy integration and multi-stakeholder access.
- Setting strategic priorities that define what missions should measure and why.
- Informing capability roadmaps that determine how mission systems should evolve (e.g., constellations, service layers, interoperable standards).
- Fostering international cooperation and common standards, shaping systems-of-systems design.

The following Foresight foundation sources are used in the 2025 Reference Architecture Blueprint.

- **ESA Strategy 2040 (ESA, 2025c)** sets out how European Space Agency intends to position Europe's space activities over the next two decades in response to accelerating geopolitical, environmental, technological and economic change. At its core, the strategy reframes ESA from a programme-centric space agency into a system architect and enabler for a much broader European space ecosystem. It emphasises strategic autonomy (reducing critical dependencies), resilience (space systems that can withstand shocks, disruption and competition), and societal value (space delivering tangible benefits for climate action, security, sustainability and the economy). The strategy highlights four mutually reinforcing roles for ESA: (1) shaping long-term European space objectives and architectures; (2) driving breakthrough technologies and innovation; (3) strengthening European industrial competitiveness, including New Space actors; and (4) acting as a trusted partner for EU institutions, Member States and international allies. For Earth Observation in particular, ESA Strategy 2040 implies a shift toward system-of-systems thinking, with stronger integration between ESA science missions, Copernicus, meteorological systems, national missions and commercial data sources. It stresses continuity of critical measurements, architectural flexibility, and data-to-decision pipelines, recognising that climate change and security pressures will demand persistent, reliable and policy-ready EO capabilities well beyond traditional mission lifetimes. The ESA Strategy 2040 is less a fixed roadmap and more a strategic framework: it acknowledges deep uncertainty about the future operating environment and therefore prioritises adaptability, partnerships, and long-term architectural coherence across Europe's space activities to mid-century.

- **ESA Earth Observation Science Strategy** (ESA, 2025a) – sets the scientific and architectural direction for Europe's Earth Observation activities over the coming years, framing how missions should be designed and evolved to address major Earth-system challenges. Led by European Space Agency, the strategy emphasises EO as a cornerstone of understanding and responding to climate change, environmental degradation, extremes and hazards, while maintaining Europe's leadership in Earth system science. At its core, the strategy identifies key science drivers - including the water, energy and carbon cycles; cryosphere change; ocean–atmosphere interactions; ecosystems and biodiversity; and Earth system feedbacks -and translates them into observation requirements that guide future mission concepts. Architecturally, it moves beyond single-mission thinking toward coherent mission families and constellations, combining passive and active sensors, multi-scale observations, and long-term data continuity. The strategy explicitly recognises the need to sustain climate data records over decades while also enabling innovation through exploratory missions (e.g. Earth Explorers and Scouts) that de-risk future operational systems such as Copernicus. Importantly, the strategy acknowledges growing uncertainty in the operating environment and therefore promotes flexibility, modularity and international cooperation in mission design. It also highlights tighter coupling between science missions, operational services and modelling, ensuring that observations are not only scientifically robust but also policy-relevant and societally impactful. In the context of European EO foresight to 2050, the ESA EO Science Strategy acts as a scientific anchor, ensuring that evolving architectures remain driven by fundamental Earth-system questions while adapting to technological, political and environmental change.

- **The Copernicus Strategic Research and Innovation Agenda (SRIA)** (EC, 2024), is the European Union's long-term framework for steering how the Copernicus Programme evolves scientifically, technically and operationally over the coming decades, with a strong emphasis on mission architecture foresight, continuity and adaptability. It translates EU policy needs (climate action, environmental regulation, security, resilience and economic competitiveness) into research priorities, technology roadmaps and architectural choices for Copernicus space, in-situ and service components. At its core, the SRIA moves Copernicus away from a static, mission-by-mission paradigm toward a dynamic system-of-systems architecture. It stresses the need for measurement continuity of essential climate variables, while simultaneously enabling innovation through new sensors, constellations, small satellites and complementary commercial data. Architecturally, this implies hybrid fleets (Sentinels + contributing missions + commercial sources), increased use of constellations for temporal resolution, and tighter coupling between space segment, in-situ observations, models and downstream services. The SRIA also foregrounds data-centric architecture: cloud-based processing, analysis-ready data, AI/ML integration, and interoperability across European and global EO systems. From a foresight perspective to ~2050, the SRIA explicitly recognises uncertainty in technology evolution, policy demand and operating conditions. As a result, it promotes modularity, scalability and resilience as design principles, reducing dependency on single missions or rigid replacement cycles. It also aligns Copernicus evolution with broader EU strategic foresight (climate neutrality, digital transition, strategic autonomy), positioning Copernicus as critical European infrastructure rather than a collection of satellites. In the European EO ecosystem, the SRIA therefore acts as the bridge between policy foresight and concrete mission architecture, ensuring that Copernicus can evolve coherently while absorbing disruption and innovation.

- **EUMETSAT Strategy: Destination 2030** (EUMETSAT, 2021) - defines how EUMETSAT intends to evolve Europe's operational meteorological and climate-monitoring satellite systems beyond 2030, with a strong focus on continuity, resilience, and service reliability in an increasingly uncertain and demanding operating environment. At its core, the strategy prioritises uninterrupted delivery of operational data for weather forecasting, climate monitoring and environmental services, recognising these as mission-critical societal infrastructures. Architecturally, this translates into robust system-of-systems design, combining next-generation polar and geostationary satellites (e.g. post-MTG and post-EPS-SG eras), ground-segment modernisation, and tighter integration with in-situ observations and numerical weather prediction models. The strategy also anticipates growing user demand for higher temporal resolution, improved accuracy, and near-real-time availability, driving increased use of constellations, redundancy, and cross-programme interoperability. Looking toward the 2040–2050 timeframe, EUMETSAT Strategy 2030+ explicitly acknowledges rising risks from climate change, cyber threats, congestion in space, and geopolitical uncertainty. As a result, it places strong emphasis on resilience and risk diversification, including technology refresh, multi-partner cooperation (with ESA, the EU and international meteorological agencies), and preparation for future observing concepts such as smaller satellites, hosted payloads, and greater exploitation of commercial capabilities where appropriate. Within the wider European EO ecosystem, the strategy positions EUMETSAT as the operational anchor, ensuring long-term measurement continuity and reliability while enabling architectural evolution in step with ESA science missions and Copernicus services.

- **Global Strategic Trends (GST 7)** (DCDC, 2024) is the UK Ministry of Defence's flagship long-term strategic foresight assessment, looking out to 2055, and is widely used across Europe as a reference frame for stress-testing assumptions in defence, security, technology and space planning. GST 7 does not set policy or prescribe actions. Instead, it identifies structural drivers of change, explores how they may interact over decades, and highlights areas of deep uncertainty where today's assumptions are most likely to fail. Its central value lies in challenging continuity-based thinking and encouraging scenario-based planning rather than linear forecasting. GST 7 identifies six interacting global drivers—global power competition, demographic change, climate and environmental stress, technological transformation, economic and energy system change, and pressures on governance and inequality. A key insight is that these drivers act simultaneously and often contradict one another, producing futures characterised by both cooperation and fragmentation, resilience and fragility. Climate change is treated explicitly as a systemic disruptor, not a sectoral issue, with cascading impacts across economies, governance, security and infrastructure. For the EEOE, GST 7 is particularly relevant as a boundary-condition document. It implicitly challenges a common assumption in EO mission planning: that while the Earth system may change radically, institutional, economic and regulatory frameworks will remain broadly stable. GST 7 suggests this assumption is weak. From a mission-architecture perspective, this strengthens the case for resilient, adaptive, and diversified EO systems-of-systems, rather than tightly coupled, single-line replacement programmes. It supports architectural principles such as redundancy, modularity, international partnership diversification, and the ability to absorb geopolitical, economic or governance shocks without catastrophic loss of capability or data continuity. In foresight terms, GST 7 complements ESA, Copernicus and EUMETSAT strategies by forcing explicit consideration of non-technical disruption—including political fragmentation, economic stress and institutional change—when designing EO architectures intended to operate reliably out to 2050 and beyond.

- **The UNU-INWEH report Global Water Bankruptcy: Living Beyond Our Hydrological Means in the Post-Crisis Era** (*Madani,* 2026a,b), argues that the world has entered a new phase in which an increasing number of river basins and aquifers are no longer able to return to their historical "normal." Droughts, shortages, and pollution events that were once treated as temporary shocks are becoming chronic features of many regions, signalling a post-crisis condition the report describes as water bankruptcy. The report calls for a fundamental shift in the global water agenda—from repeatedly reacting to emergencies toward active bankruptcy management. This implies confronting long-standing overshoot through transparent water accounting, enforceable limits, and the protection of water-related natural capital that generates and stores water, including aquifers, wetlands, soils, rivers, and glaciers, while ensuring that transitions are explicitly equity-oriented and safeguard vulnerable communities and livelihoods. The report frames water not only as a growing source of systemic risk, but also as a strategic opportunity in an increasingly fragmented world. It argues that serious, coordinated investment in water can unlock progress across climate action, biodiversity protection, land stewardship, food security, and public health, while offering a practical platform for cooperation within and between societies. Acting early—before stress hardens into irreversible loss—can reduce shared risks, strengthen resilience, and rebuild trust through tangible, measurable outcomes. A key action is to Develop a Global Water Bankruptcy monitoring framework. relies on extensive Earth Observation data sets and calls for action to track total water storage, groundwater depletion, wetland and glacier loss, water quality degradation and key markers of irreversibility and claim–capacity mismatch, using advances in Earth observation, satellite technologies, AI, and integrated modelling.

- **The GEO Post-2025 Strategy – Earth Intelligence for All** (*GEO*, 2025), - sets the global strategic direction for Earth Observation beyond traditional data provision, reframing EO as a means of delivering actionable "Earth intelligence" to support decision-making on climate, sustainability, resilience and development. Led by the Group on Earth Observations, the strategy shifts emphasis from individual missions or datasets toward an integrated, user-driven system-of-systems, in which satellite, in-situ, modelled and socio-economic data are combined to produce insights that are timely, trusted and usable. From a mission-architecture foresight perspective, the strategy is significant because it explicitly decouples value from any single space mission. Instead, it promotes interoperability, open standards, cloud-based infrastructures, and service layers that allow diverse observing systems—including Copernicus, national missions, EUMETSAT systems and commercial data sources—to function as a coherent whole. This implies future EO architectures that are data-centric rather than satellite-centric, prioritising continuity of information services even as individual sensors, platforms or providers change over time. Looking toward 2040–2050, the GEO Post-2025 Strategy also embeds equity, resilience and global partnership as architectural principles. It assumes growing disruption from climate change and geopolitical fragmentation, and therefore favours distributed, federated architectures that reduce single-point dependencies and enable participation from a wide range of actors. For the European EO ecosystem, the strategy acts as an external alignment framework, reinforcing trends already visible in ESA, Copernicus and EUMETSAT planning: flexible system-of-systems design, integration of public and commercial capabilities, and a strong focus on translating observations into sustained societal value rather than merely maintaining satellites in orbit.

- **World Economic Forum (WEF) Global Risks Report 2025, 20th Edition Insight report** (*WEF,* 2025) is based on a Global Risks Perception Survey (GRPS) that has been used as a methodology by WEF for two decades. The GRPS collates leading insights on the evolving global risks landscape from over 900 experts across academia, business, government, international organizations and civil society. “Global risk” is defined as the possibility of the occurrence of an event or condition that, if it occurs, would negatively impact a significant proportion of global GDP, population or natural resources. WEF (2025) emphasises that today’s dominant risks—climate extremes, environmental degradation, geopolitical fragmentation, infrastructure fragility, and erosion of trust through misinformation—are systemic and interconnected, which maps directly onto the Blueprint’s rationale for a federated, resilient EO system-of-systems rather than isolated missions or programmes. This elevates the importance of Blueprint elements such as long-term data continuity, cross-institutional coordination (ESA–EU–EUMETSAT–national–commercial), trusted calibration and traceability, and transparent governance frameworks that support policy, legal, and societal decision-making under uncertainty. Strategically, the WEF report implies a risk-oriented public EO infrastructure, designed to support early warning, stress-testing, and scenario analysis across critical domains (climate, food, energy, security). The WEF report reframes the EO Blueprint not as a technical optimisation exercise, but as a foundational component of global risk governance and societal resilience, strengthening the case for sustained political commitment, open data, and internationally trusted European leadership in Earth Observation.

- **The Organisation for Economic Co-operation and Development Strategic Foresight Toolkit for Resilient Systems** (OECD, 2025) provides a methodological framework for governments to design policies and infrastructures that remain effective under deep uncertainty, systemic shocks and long-term disruption. Developed by the OECD, the toolkit is not sector-specific, but it is highly influential for domains like Earth Observation (EO) that underpin critical public decision-making over multi-decadal timescales. From a mission-architecture foresight perspective, the toolkit is important because it explicitly challenges continuity assumptions. It argues that future systems must be robust not only to gradual trends (e.g. climate change, digitalisation) but also to non-linear shocks such as geopolitical fragmentation, economic crises, governance failure, or compound hazards. It promotes the use of multiple futures, stress-testing, horizon scanning and weak-signal detection to expose hidden vulnerabilities in long-lived infrastructures—an approach directly applicable to EO systems designed to operate to 2040–2050 and beyond. Applied to the European EO ecosystem, the toolkit reinforces the case for adaptive, modular and diversified system-of-systems architectures rather than tightly optimised, single-path replacement programmes. It supports architectural principles such as redundancy across institutional actors (ESA, EU, EUMETSAT, national and commercial), flexible technology insertion, and governance models that can evolve as policy priorities and societal conditions change. In this sense, the OECD toolkit acts as a cross-cutting foresight enabler, complementing ESA, Copernicus, EUMETSAT and GEO strategies by providing the analytical tools needed to ensure that EO architectures remain resilient under futures where today's economic, regulatory and institutional frameworks cannot be assumed to persist.

Scenarios provide an assumed narrative from which challenges in that landscape can be identified allowing an architectural approach to be defined. In this process, essential components can be assessed using defined foresight assumptions and conclusions (likely outcomes) drawn. Elements include:

- **User-stakeholder components:** User and stakeholder needs and requirement management to drive the specification of the EO,
- **Operational satellite components** (Meteorology, Copernicus) serving user communities directly linked to everyday socio-economic challenges e.g. weather and ocean forecasting with defined delivery timeliness and availability metrics,
- **Scientific satellite components**: Each satellite mission carries a precision payload instrument that delivers scientific measurements – how that information is managed and delivered separates operational from scientific Earth Explorer missions that are designed to pioneer new measurement approaches (that may evolve into future operational missions such as AEOLUS). They serve user communities invested in the advancement of Earth system knowledge and space technologies,
- **Emergency response satellite components** (operational resources as well as ad-hoc activations and dual-use elements) serving user communities to respond fast and in an informed manner to emergency situations as natural or man-made disasters,
- **Civil security response satellite components** (operational resources as well as ad-hoc activations and dual-use elements) serving user communities to respond to needs emerging from the need to protect the civil society, which includes inter-alia support to police operations,

- **Dual-use satellite components** (operational resources as well as ad-hoc activations of dual-use elements) serving European strategic autonomy, to preserve global situational awareness.
- **Reference mission components**: missions to which other missions are referenced e.g. Sentinel-6 reference altimeter, Sentinel-3 SLSTR reference infrared radiometer, Sentinel-2 the quasi-reference land mission – with full international recognition. Future reference missions include CO2M and MAGIC/NGGM, while other scientific or operational missions may also become future reference missions,
- **Commercial components:** commercial space and ground segment service providers across the European EO landscape are complementary to large class science and operational reference missions.
- **Small satellite components**: flexible, low-cost missions either delivering value-added science and technology innovations (i.e. Scouts) or in-orbit demonstration of brand new and innovative technologies and/or remote sensing techniques for Earth Observation (i.e. Φ-Sats),
- **Mid-sized satellite components:** filling the gap between science-driven and operationally driven missions, between large and small satellite systems and between agency-driven and commercially driven missions (i.e. Stepping Stones) addressing environmental needs,
- **Data and Operations Management components**: federated data management services and user services from near real-time to climate data records, scientific, experimental, and operational applications,
- **Ground Segment components:** continuously evolving ground segment ecosystem leveraging new technologies and approaches to apply EO resources to satisfy user needs,
- **Technical/industrial components**: advancing innovative space technologies necessary to maintain and evolve the ESA SoS ecosystem including the technical coordination role of ESA and as a source and repository of knowledge from which create new industrial capabilities or develop new capabilities across the European EO landscape,
- **Predictive modelling and decision-support components**: Digital Twin Earth/Destination Earth modelling and analysis systems to leverage synergy across all Earth Observation assets,
- **Partnership components:** complementing the European EO Ecosystem by strengthening and evolving international partnerships beyond Europe,
- **Verification and certification components:** services to guarantee the authenticity of data, and services to certify EO measurement performance.
- **Access to space components**: Ariane, Vega, small launchers (e.g. Isar Aerospace, Orbex, PLD Space and Rocket Factory Augsburg), European National launch services and international launch services, potential future in-space refuelling facilities or direct capture space components.

[RAB-12]: Develop, maintain, and agree a structured set of future scenarios for the European Earth Observation (EO) Ecosystem, spanning different strategic drivers, uncertainties, and time horizons. These scenarios shall provide coherent, assumption-based narratives against which challenges, dependencies, and trade-offs within the EO system-of-systems can be systematically identified, assessed, and addressed through an architectural approach.

4.2. Reference Architecture Blueprint Scenario built on the ESA Earth Observation Science Strategy

Scenario framing narrative (2030–2050): From Observations to Stewardship: Europe's Earth Observation System-of-Systems in a Discontinuous World

By mid-century, Europe's Earth Observation (EO) ecosystem operates in a fundamentally altered global context. Climate change has transitioned from a long-term risk to a continuous operational reality, characterised by accelerating extremes, compound hazards, and non-linear Earth-system responses. The planetary freshwater boundary has been transgressed. Water bankruptcy (droughts, shortages, and pollution events) are chronic features of many regions and millions of people are living with chronic water insecurity. Societal demand for authoritative, timely, and legally robust environmental intelligence has increased sharply, driven by climate adaptation, biodiversity protection, infrastructure resilience, security, and economic risk management. These developments unfold against persistent geopolitical tension, intensified competition in space, increasing congestion of the orbital environment, and growing pressure on radio-frequency spectrum. The ESA Earth Observation Science Strategy identifies this period as one in which integrated Earth-system science, predictive capability, and science-to-policy translation become inseparable requirements for EO systems

The challenge landscape: In this scenario, the Reference Architecture Blueprint becomes a central instrument enabling Europe to respond coherently to these converging pressures. Between 2030 and 2050, four structural challenges dominate:

1. **Earth-system non-linearity and tipping dynamics**. Observations increasingly reveal regime shifts in the water, carbon, energy, and ecosystem systems, consistent with the Science Strategy's emphasis on water bankruptcy coupled Earth-system processes and tipping points. Traditional mission-by-mission approaches prove insufficient to capture these dynamics, as continuity, cross-sensor coherence, and long time-series become critical scientific and policy assets.
2. **From monitoring to prediction and decision support**. Policy and operational actors require EO not only to describe change, but to anticipate impacts and evaluate response options. The rise of Digital Twin Earth components, AI-enabled assimilation,

and scenario simulation shifts EO architecture requirements from data provision towards persistent analytical capability, spanning observation, modelling, and decision support.

3. **Trust, admissibility, and accountability**. EO data underpin regulatory compliance, climate accountability mechanisms, financial risk assessments, and legal proceedings. Trust in EO-derived information—through calibration, validation, traceability, and uncertainty characterisation—emerges as a systemic requirement rather than a mission-level attribute.
4. **Resilience under constraint**. Orbital debris, stricter de-orbit requirements, spectrum congestion, supply-chain fragility, and geopolitical fragmentation increasingly constrain feasible architectures. Ensuring continuity of critical observations becomes an architectural problem, not a programmatic afterthought.
5.

Architectural response: In this scenario, the Reference Architecture Blueprint evolves into a living architectural control framework that guides Europe's EO system-of-systems through successive adaptation cycles.

1. **The Blueprint anchors the system around a persistent reference backbone of reference-class missions and ground-segment capabilities.** These assets ensure continuity of climate data records, cross-calibration across institutional and commercial systems, and long-term measurement stability—directly supporting the Science Strategy's emphasis on filling critical observation gaps and sustaining long-heritage datasets. For example, stakeholders choose to prioritise a Global Water Bankruptcy monitoring framework to track total water storage, groundwater depletion, wetland and glacier loss, water quality degradation and key markers of irreversibility and claim–capacity mismatch, using advances in EO technologies, AI, and integrated modelling (Madani K., 2026a,b)
2. **Architecture-led stewardship replaces mission-centric optimisation.** User needs—articulated through science questions, policy requirements, and societal benefit pathways—drive requirements that are assessed at system level. Trade-offs between performance, cost, resilience, and autonomy are made explicit and revisited through scenario stress-testing, consistent with the Science Strategy's call for decadal foresight in mission and technology preparation
3. **A federated digital layer integrates observations, models, and AI.** Rather than centralising data, the architecture institutionalises interoperability, provenance, and explainability across distributed infrastructures, enabling scalable Digital Twin Earth components while preserving scientific credibility and legal robustness.
4. **Innovation remains structurally protected.** Earth Explorers, Scouts, Φ-sat missions, Stepping Stone Missions, and pre-Phase-0 activities continue to explore novel measurements and techniques, while the Blueprint defines explicit transition pathways into operational and service-oriented systems. This avoids both premature lock-in and perpetual experimentation, reflecting the

Science Strategy’s balance between frontier science and societal benefit delivery.

Role of ESA in the 2050 architecture. By 2050, ESA’s distinctive value lies not in ownership of all system elements, but in architectural stewardship. ESA maintains the end-to-end system perspective across the mission lifecycle and across institutional, national, and commercial actors. It acts as:

- ESA responds directly to user/stakeholder priorities.
- custodian of reference-class measurement performance in a user/stakeholder led context,
- integrator of science-driven requirements into architectural options,
- broker between research, operations, and policy domains,
- and guardian of long-term continuity trust and credibility.

This role directly reflects the Science Strategy’s positioning of ESA as the actor capable of linking frontier science, operational systems, and policy-relevant outcomes across decades.

Optimal Outcome in 2050. Europe operates the world’s most coherent and trusted Earth Observation system-of-systems. The value of the EEOE is not defined by any single mission or constellation, but by the integration, resilience, and credibility of the whole architecture. EO data and information are routinely used to inform climate adaptation, monitor ecosystem health, evaluate policy effectiveness, and manage risk—supported by traceable, explainable, and scientifically robust evidence. A Global Water Bankruptcy monitoring framework has been implemented serving international policy needs for water management and societal protection. The Reference Architecture Blueprint proves decisive in enabling this outcome through fore-sighting and preparation. By making architectural choices explicit, preserving optionality where uncertainty dominates, and anchoring continuity where trust is non-negotiable, it allows Europe to navigate a discontinuous future while retaining leadership, autonomy, and societal relevance in Earth Observation.

4.3. Reference Architecture Blueprint Scenario to explore the evolution of operational numerical weather prediction.

Scenario framing narrative (2030–2050): From Numerical Weather Prediction to Intelligent Earth System Prediction

By 2050, operational meteorology has undergone a profound transformation. Traditional numerical weather prediction (NWP), long anchored in physically based models and variational data assimilation, has evolved into a hybrid intelligent Earth system prediction capability, combining physics-based modelling with artificial intelligence and machine learning (AI/ML) at scale (*Dueben and Baur*, 2018; *Dueben et al.* 2021; *Ben Bouallègue et al.* 2024; *Chantry and Dueben*, 2025). This transition has not displaced physical understanding; rather, it has elevated the importance of Earth Observation (EO) as the authoritative, trusted, and continuous source of information required to train, constrain, validate, and govern AI-enabled prediction systems.

The challenge landscape: In this scenario, the Earth Observation Reference Architecture Blueprint provides the long-term coherence mechanism that enables Europe to sustain operational meteorology through this transition, ensuring forecast skill, trust, resilience, and sovereignty under accelerating environmental and technological change. Interacting challenges shape the evolution of operational meteorology and prediction systems over the coming decades:

1. **Non-stationarity of the Earth system**. Climate change, land-use transformation, cryosphere loss, and changing aerosol and moisture regimes introduce persistent non-stationarity into the atmosphere–ocean–land system. Statistical relationships embedded in historical datasets become less reliable, creating a fundamental challenge for purely data-driven AI models. Continuous, high-quality EO observations are therefore required to detect regime shifts, refresh training datasets, and anchor prediction systems to physical reality.
2. **Explosion of data volume and dimensionality**. The proliferation of multi-sensor satellites, constellations, and high-resolution observations generates data volumes far exceeding the capacity of traditional assimilation pipelines. AI-based encoders, emulators, and surrogate models increasingly replace or augment classical operators. This shifts the architectural emphasis from raw data throughput to information integrity, representativeness, and uncertainty characterisation.
3. **Compute Power and Data Bottlenecks.** By 2050, operational meteorology relies on hybrid physics–AI prediction systems operating across global to sub-kilometre-scale resolutions and sub-hourly refresh cycles**.** While observation volumes continue to grow, the dominant constraint shifts to the ability to process, move, and learn from data in near-real time**.** Training foundation models, running ensemble predictions, and continuously re-baselining AI systems against non-stationary climate conditions impose computational demands that scale faster than sensor growth.
4. **Operational dependence on AI/ML systems**. By mid-century, AI-enabled nowcasting, sub-seasonal to seasonal prediction, and coupled Earth-system forecasting are embedded in operational services. Ensemble probabilistic systems are used as standard tools rather than specialised systems. Forecast centres rely on ML systems not only for speed and resolution, but also for pattern recognition of extremes and compound hazards. This dependence raises new requirements for explainability, auditability, and robustness, particularly where forecasts inform safety-critical decisions.
5. **Trust, liability, and governance**. As AI-driven forecasts increasingly underpin aviation, energy systems, civil protection, defence, and climate services, the provenance and traceability of both observations and models become legally and politically significant. Trust in operational meteorology becomes an architectural

property of the EO–model–AI ecosystem, not a by-product of individual missions or algorithms.

Architectural response: Under this scenario, the Reference Architecture Blueprint evolves to explicitly support AI-enabled operational numerical prediction as core architectural principles.

1. **EO becomes the reference truth for AI-enabled prediction.** Operational AI/ML systems require long, stable, and well-characterised training datasets. The Blueprint therefore prioritises continuity of reference-class meteorological observations—temperature, humidity, winds, clouds, precipitation, surface fluxes, and radiative balance—ensuring cross-generation consistency and calibration. These reference observations – together with an optimized in-situ data infrastructure act as anchors against which AI models are trained, validated, and periodically re-baselined.
2. **Observation requirements are redefined in information space, not sensor space.** Rather than optimising missions solely for traditional retrieval performance, the Blueprint frames observation requirements in terms of information content for learning systems: sensitivity to boundary-layer processes, extremes, moisture transport, and coupled air–sea–land interactions. This leads to architectures that emphasise temporal refresh, multi-angle and multi-frequency sensing, and synergistic use of active and passive instruments from space-based infrastructures, in-situ networks, drones/HAPS to constrain AI models in regimes where physical understanding is weakest.
3. **Compute Power and Data Bottlenecks. Data movement and locality bottlenecks:** Traditional EO architectures assume that data are downlinked, archived centrally, and then distributed for processing. In an AI-enabled operational context, this paradigm becomes untenable:
    - Moving petabyte-scale EO datasets to central HPC facilities introduces latency incompatible with nowcasting and rapid-update cycles.
    - Energy and cost associated with data transport exceed those of computation itself.
    - Centralised pipelines become fragile under surge demand during extreme events and easy locations for cyberattacks

    The Blueprint shifts toward **compute-to-data** paradigms:

    - On-board and near-sensor pre-processing and feature extraction
    - Regional and federated data centres with major observation streams
    - Training and inference pipelines designed around data locality rather than global aggregation
    - Data authentication and verification stamps to prove data authenticity and protect against cyberattacks.
4. **Compute scalability and energy constraints:** By mid-century, AI-driven meteorology competes for compute with defence, climate modelling, digital twins, and commercial AI systems. Even with exascale and post-exascale HPC, unrestricted scaling is neither economically nor energetically sustainable. Key tensions emerge:

- Training large AI models vs. running operational ensembles
- Physics-based model resolution vs. AI surrogate fidelity
- Peak compute demand during extreme events vs. baseline operational loads

The Blueprint embeds compute efficiency as a design requirement, including:

- Hybrid workflows where AI emulates expensive physical components
- Event-driven compute escalation rather than constant peak operation
- Prioritisation of information gain per joule, not raw FLOPS
- Long-term planning for heterogeneous compute (HPC, GPU, neuromorphic, quantum accelerators)

5. **Training data bottlenecks and model brittleness:** AI-enabled prediction systems require continuous retraining to remain valid under changing climate regimes. However:
   - High-quality, well-labelled training data become scarce for extremes and rare events
   - Historical EO datasets embed biases linked to sensor evolution and mission changes
   - Re-training cycles can exceed available compute windows

   The Blueprint treats reference EO continuity as a strategic asset for AI:

   - Stable, cross-calibrated EO records reduce retraining frequency
   - Synthetic data generation via Digital Twin Earth components supplements real observations
   - Validation architectures prioritise representativeness over volume
6. **EO, modelling, and AI are architected as a single prediction system.** The Blueprint explicitly couples EO systems with federated digital infrastructures, AI training environments, and Earth system models. Data assimilation evolves into a broader concept of learning-informed constraint, where observations continuously correct, guide, and explain AI predictions. Digital Twin Earth components become operational assets, used to stress-test AI behaviour under extreme or unseen conditions.
7. **Resilience and adaptability are designed in.** Given rapid technological change, the Blueprint avoids hard-coding specific AI methods. Instead, it defines stable interfaces, standards, and governance mechanisms that allow AI architectures to evolve while preserving continuity of EO inputs and operational services. This modularity ensures that Europe can adapt to disruptive advances in AI, computing (including quantum and neuromorphic systems), and observation technologies without loss of forecast capability.
8. **Trust and explainability are elevated to system-level requirements.** To support operational decision-making, AI-enabled forecasts must be interpretable and auditable. The Blueprint therefore embeds uncertainty propagation, explainable-AI diagnostics, and traceability from observation to forecast product as architectural

functions. Reference EO observations play a central role in identifying bias drift, data leakage, and failure modes in learning systems.

Role of ESA in the 2050 architecture. By 2050, operational meteorology in Europe is delivered through a tightly coupled ESA–EUMETSAT–ECMWF ecosystem, with national services and commercial actors integrated through common architectural standards. In this context:

- **ESA** acts as the steward of long-term observational integrity, innovation, and architectural coherence, ensuring that EO capabilities evolve in step with AI-driven prediction needs. ESA also acts as an overall EEOE architect highlighting innovation opportunities, gaps and, mitigation solutions in the overall system (e.g. in-situ networks).
- **EUMETSAT** ensures continuity, reliability, and operational availability of meteorological observations and services from increasingly diverse user requirements across the European meteorological community.
- **ECMWF and national centres** operate hybrid physics–AI prediction systems, leveraging EO as a foundational asset.
- **Commercial actors** contribute complementary data and AI capabilities within a framework that preserves trust, transparency, and interoperability.
- The **Reference Architecture Blueprint** provides the shared long-term reference that aligns these roles across decades.

Optimal Outcome in 2050. In this foresight scenario, Europe operates one of the world's most advanced and trusted meteorological prediction systems. Forecast skill has improved not only through higher resolution and faster computation, but through deeper integration of observations, physical understanding, and AI. Early warning of extremes, compound hazards, and climate-driven regime shifts has become more reliable, supporting societal resilience and economic stability. Importantly, this outcome is enabled by the Earth Observation Reference Architecture Blueprint. By anticipating the architectural consequences of AI-driven operational meteorology, and by safeguarding continuity, trust, and adaptability, the Blueprint ensures that Earth Observation remains the authoritative foundation for intelligent prediction systems through 2050 and beyond.

4.4. Reference Architecture Blueprint Scenario to explore Planetary Stewardship

Scenario framing narrative (2030–2050): Earth Observation as Infrastructure for Planetary Stewardship

By 2050, the global policy discourse has converged on Planetary Stewardship as an organising principle for governing human–Earth system interactions. Rather than treating climate, biodiversity, water, food, and energy as separable policy domains, governments and institutions increasingly operate within a planetary boundaries framework, recognising that societal stability depends on maintaining the Earth system within a safe and just operating space. This shift fundamentally changes the role of Earth Observation (EO): from a supporting data source to a core public infrastructure for stewardship, accountability, and anticipatory governance.

The challenge landscape: In this scenario, the European Earth Observation Reference Architecture Blueprint becomes a central enabling instrument, translating stewardship principles into an operational, resilient, and trusted observation system-of-systems. Between now and mid-century, five interlinked challenges dominate the stewardship agenda:

1. **Boundary proximity and overshoot risk**. Multiple planetary boundaries—climate, biosphere integrity, freshwater use, biogeochemical cycles, ocean acidification, stratospheric ozone—are approached or exceeded at regional or global scales. Stewardship requires not only global averages, but spatially resolved, temporally continuous monitoring of pressures, states, and responses.
2. **From monitoring change to governing transitions**. Policy focus shifts from describing environmental degradation to actively managing transitions in land use, energy systems, food production, and urban development. EO must therefore support decision cycles, including scenario testing, early warning, and evaluation of intervention effectiveness at different timescales as well as for regional to global scales.
3. **Accountability in a polycentric governance system**. Stewardship operates across international agreements, EU policy, national regulation, corporate disclosure, and local action. EO evidence underpins compliance, reporting, and verification across this fragmented governance landscape, increasing demand for traceability, consistency, and legal robustness.
4. **Compound risks and cascading impacts**. Earth-system interactions generate cascading effects—e.g. climate extremes triggering ecosystem collapse, infrastructure failure, and socio-economic instability. EO architectures must capture coupled processes, not isolated variables.
5. **Equity, legitimacy, and trust**. Stewardship requires legitimacy. Observations informing decisions that affect livelihoods and development pathways must be transparent, explainable, and perceived as fair and scientifically credible.

The global commons framework is the closest existing approach to governing the biophysical systems on which humanity collectively depends. Building on this, the proposed planetary commons framework (*Rockström et al.*, 2024) introduces a new paradigm of Earth System Stewardship, recognising that human well-being depends on effective governance of shared planetary systems, including Earth System Tipping Points (ESTPs), planetary boundaries, and other critical biophysical processes.

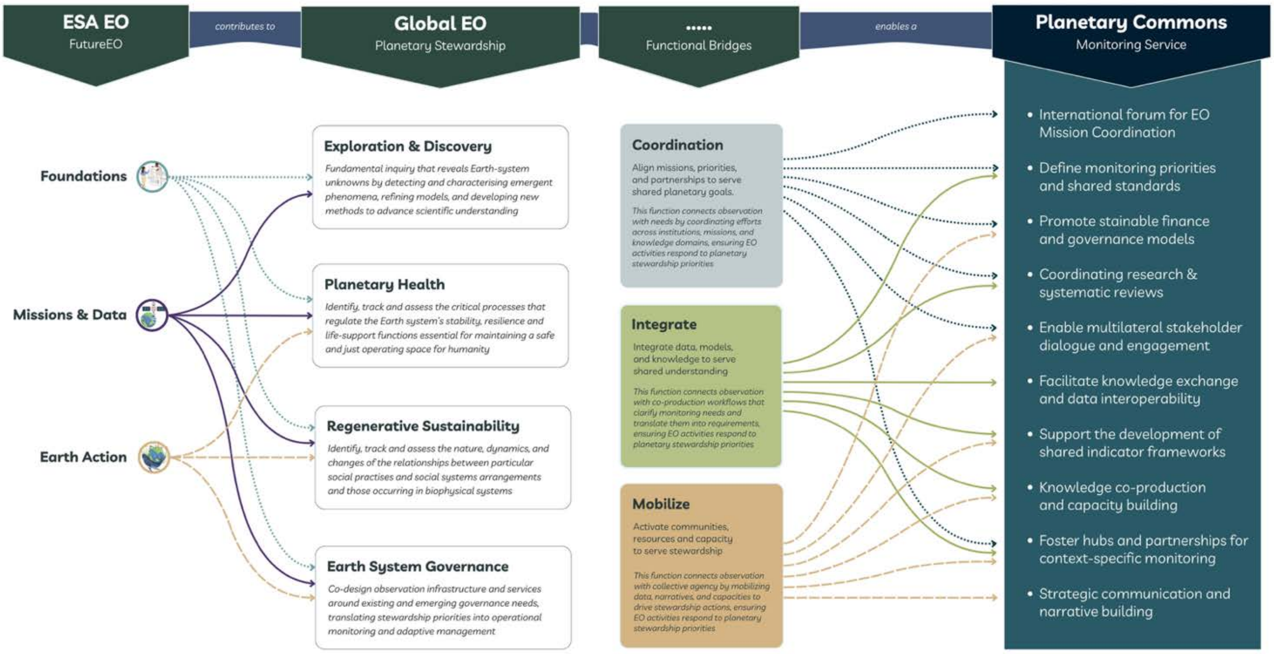


Figure 4.4-1 Overview of a potential planetary commons monitoring service scenario.

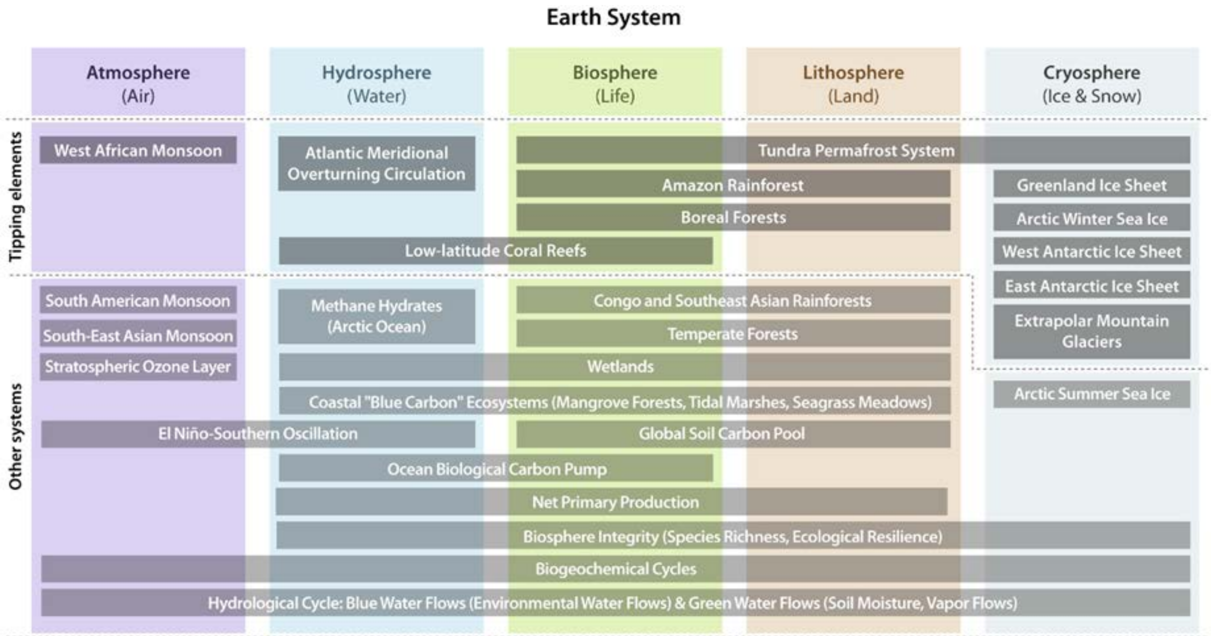


Figure 4.4-2 Categories of planetary commons. The Earth system, represented by the outer grey frame, constitutes the ultimate overarching planetary common, given its interconnected self- regulating characteristics. The Earth system is configured by planetary commons "spheres" (atmos- , hydro- , bio- , litho- , and cryosphere) and other subsystems within and across these spheres, namely the tipping elements (in bold font) and other biophysical systems that may not exhibit tipping behaviour but play a vital role in regulating the viability of Earth to sustain life. (from Rockström et al (2024))

Architectural response: Under a Planetary Stewardship paradigm, EO architecture requirements evolve in fundamental ways.

1. **Reference-quality continuity becomes non-negotiable**. Long-term, stable, and internationally trusted observations of climate variables, ecosystem state, water and carbon cycles form the evidentiary backbone of stewardship. The Reference Architecture Blueprint therefore prioritises a persistent set of reference-class missions, cross-calibrated across generations and platforms, ensuring continuity of records that define proximity to—and recovery from—planetary boundary thresholds.
2. **EO systems are designed around Earth-system coupling, not thematic silos.** The Blueprint shifts architectural emphasis from single-variable optimisation to integrated, multi-sensor system design, explicitly addressing interfaces between atmosphere, ocean, land, cryosphere, and biosphere. This enables observation strategies aligned with Earth-system feedbacks, tipping elements, and compound risks central to stewardship thinking.
3. **Observation is inseparable from analysis and foresight.** Planetary Stewardship requires anticipating trajectories, not just observing states. The Blueprint therefore embeds EO within a federated digital architecture combining observations, Earth-system models, AI-enabled pattern detection, and Digital Twin Earth components. This transforms EO from a passive monitoring function into a persistent stewardship intelligence capability.
4. **Governance, trust, and accountability.** By 2050, EO data routinely inform international stocktakes, EU environmental regulation, biodiversity frameworks, and climate finance mechanisms. In this context, trust becomes an architectural property. EO-based information becomes a trusted and reliable legal information source.

Architectural response: In this scenario, the Reference Architecture Blueprint responds by institutionalising:

- calibration, validation, and uncertainty characterisation as system-level functions;
- traceability from raw observations to derived indicators used in policy;
- new approaches to use EO information in a legal context;
- certification pathways for integrating commercial and national missions into stewardship-relevant products.

Role of ESA in the 2050 architecture. ESA's role in this scenario is that of architectural steward: safeguarding measurement integrity, maintaining the reference backbone, and ensuring coherence across institutional, national, and commercial contributions—consistent with its mandate to enable collective European outcomes that exceed national capability. ESA will also manage innovation under stewardship constraints. Planetary Stewardship does not reduce the need for innovation; it increases it. Novel measurements are required to observe ecosystem resilience, feedback strength, human–environment interactions, and emerging risks. Exploratory pathways are required to monitor planetary boundaries: Copernicus and Meteorological missions provide a backbone operational capability and Earth Explorers, Scouts, Φ-sat, activities are developed to secure relevant observations to monitor Planetary Stewardship. This avoids two systemic risks identified in the scenario:

- premature lock-in of immature indicators that could misguide policy,
- over-reliance on fragmented, non-validated data streams that erode trust.

Optimal Outcome in 2050. In this foresight scenario, Europe operates an Earth Observation system explicitly recognised as critical infrastructure for Planetary Stewardship. Its value is not measured by the number of satellites, but by its ability to:

- detect early warning signals of boundary transgression,
- support adaptive governance under uncertainty,
- evaluate the effectiveness of societal transitions,
- and provide trusted, equitable evidence for collective decision-making.

The Earth Observation Reference Architecture Blueprint proves essential in achieving this outcome. By aligning EO system design with stewardship principles—continuity, integration, resilience, trust, and foresight—it enables Europe to act not only as an observer of planetary change, but as a responsible steward of the Earth system through 2050 and beyond.

5. REFERENCE ARCHITECTURE BLUEPRINT: DRIVERS OF CHANGE AND ARCHITECTURAL DESIGN CHALLENGES

There are numerous emerging Earth Observation–related trends, challenges, and drivers of change that must be explicitly considered within the Reference Architecture Blueprint. These shape both the demands placed on the EEOE and the conditions under which it must operate, and how it evolves in the Reference Architecture as they change rapidly in scale, pace, and interdependence. Examples of key drivers[6] with direct relevance to the Blueprint include

- **User and stakeholder expectations** are changing based on the application of outputs from the existing EEOE revealing technical challenges to address (e.g. coherent calibration across the ecosystem, sampling in both time and space) and political changes in priorities.
- **Accelerating climate impacts** and the pursuit of adaptation and mitigation strategies, including increasing frequency of extremes, compound events, and long-term environmental change requiring sustained EO evidence.
- **Escalation of defence, security, and resilience agendas**, with growing reliance on EO across civil, security, and dual-use domains.
- **Increasingly blurred and fractured boundaries between public, private, and institutional EO domains**, driven by rapid growth of commercial EO capabilities and new service models.
- **Rapid advances in artificial intelligence** and data exploitation technologies, transforming EO processing, fusion, automation, and decision support, while introducing new governance and trust challenges.
- **Fragile and volatile geopolitical dynamics**, affecting international cooperation, supply chains, data access, and strategic autonomy.
- **Transformation of European demographics**, societal expectations, and the social contract[7], increasing demand for transparency, accountability, and evidence-based policy.
- **Catalytic convergence of technologies**, including EO, digital infrastructure, cloud/HPC, AI/ML, communications, autonomy, and emerging sensing paradigms.
- **Escalating pressure on European institutions**, driven by expanding mandates, cross-sector dependencies, and rising expectations under constrained capacity.
- **Rising infrastructure complexity**, interdependencies, and systemic vulnerabilities, across space, ground, data, and digital segments, increasing exposure to cascading failures.

---

[6] 20251512 Global Trends Report - GN RevJB-92_GO

[7] The implicit agreement between society and governing institutions that defines mutual rights, responsibilities, and expectations—particularly around protection, fairness, and the provision of public goods.

- **Growing pressure on financial resource prioritisation**, requiring architectural trade-offs, efficiency gains, and maximised return on long-term public investment.

The following paragraphs present a non-exhaustive set of high-importance trends and challenges (as of 2025) that have strategic implications for the Reference Architecture. While many of these trends are driven by multiple underlying factors and are strongly interconnected, each is introduced only once for clarity and readability. Together, they provide a structured context for stress-testing the architecture, identifying emerging gaps, and guiding coherent, forward-looking evolution of the European Earth Observation Ecosystem.

5.1. Architectural principles guiding the Reference Architecture Blueprint

The Reference Architecture Blueprint is founded on a set of architectural principles that guide how the EEOE should evolve as a Reference Architecture in response to accelerating scientific, societal, technological, and geopolitical change. These principles provide a stable decision framework for managing trade-offs, prioritising investments, and preserving long-term value under future-world uncertainty. They are not tied to individual missions or programmes. Instead, they define a logical approach for system-of-systems design, governance and sustainability.

1. **Continuity of essential observations is a fundamental requirement**. The architecture shall prioritise the long-term continuity, stability, and traceability of critical Earth system measurements that underpin European services, climate science, policy implementation, and environmental governance. Protection against data gaps, degradation of calibration, or loss of reference standards is treated as a systemic requirement rather than a programme-specific concern.
2. **Federation by design.** The European EO Ecosystem is inherently distributed across institutional, national, commercial, and international actors. The architecture therefore adopts federation as a core principle, enabling diverse contributions to interoperate through common standards, interfaces, and governance mechanisms, while avoiding centralised dependency or uncontrolled fragmentation.
3. **Trust, traceability, and uncertainty as architectural properties.** Scientific credibility, policy legitimacy, and legal defensibility depend on trusted data. The architecture embeds calibration, validation, authenticity, provenance, and uncertainty characterisation as intrinsic properties of the system, extending across space, ground, processing, and service layers, including hybrid public–commercial constellations and AI-enabled analytics.
4. **Preserve flexibility and trade-spaces to avoid premature lock-in.** Given long policy and scientific timescales and rapidly evolving technology cycles, the reference architecture must preserve future options. Exploratory missions, enhanced pre-development activities, and modular system design are essential to prevent premature convergence on suboptimal solutions and to enable adaptive evolution as new user/stakeholder needs and opportunities emerge.

5. **Resilience through diversity, redundancy, and graceful degradation**. The architecture must be designed to withstand disruption arising from technical failure, geopolitical instability, market volatility, or environmental stress. Resilience is achieved through diversified sensing approaches, complementary mission families, redundant pathways, and the ability to degrade gracefully while maintaining core functions.
6. **Integration of innovation with stewardship.** Innovation and continuity are treated as complementary, not competing, objectives. The architecture ensures that high-risk, high-return scientific and technological innovation is systematically connected to long-term operational EO capability, enabling smooth transitions from research to sustain operational service without compromising stability.
7. **Proportionality, efficiency, and prioritisation.** Under increasing financial and institutional pressure, the Reference Architecture promotes proportional responses to user needs, efficient use of shared infrastructure, and informed prioritisation of investments based on system-wide benefit rather than local optimisation.
8. **Human capital and institutional memory are critical assets.** The reference architecture recognises scientific expertise, engineering skills, and institutional knowledge as core enablers of system performance. Sustaining and renewing these capabilities is essential to maintain long-term credibility, innovation capacity, and stewardship of Europe's EO assets.

Together, these architectural principles provide the foundation for the drivers, challenges, and design choices explored in the subsequent sections of Chapter 5. They ensure that the Reference Architecture Blueprint remains a living, coherent, and resilient framework for guiding the evolution of the European Earth Observation Ecosystem toward 2035–2050 and beyond.

5.2. System failure modes and resilience thinking.

The Blueprint explicitly recognises that the EEOE system-of-systems will operate in an environment where failure is not an exception but a design condition. Increasing system complexity, tighter interdependencies, geopolitical volatility, and reliance on digital infrastructure mean that future EO performance will be shaped as much by the ability to withstand disruption as by nominal mission success. Resilience design and thinking is therefore a core architectural concern, ensuring that essential EO functions can be sustained under stress, degraded conditions, or partial system loss.

Key system failure modes identified for the European EO Ecosystem include:

- **Loss or degradation of measurement continuity**, arising from mission failure, delayed replacement, mission cancellation, launch disruption, or funding discontinuity, particularly for climate-critical and reference observations (e.g. Sentinel-6C).
- **Calibration and traceability failure**, where loss of fiducial reference measurements, in-situ networks, EO measurement link to SI traceability or expertise undermines long-term data integrity and trust.

- **Digital infrastructure failure**, including outages or obsolescence in ground segments, cloud/HPC platforms, data hubs, or algorithm pipelines, leading to loss of access or service disruption.
- **Spectrum and orbit denial, caused by congestion, interference, regulatory constraints, or space debris events** that reduce observing capability or data quality.
- **Geopolitical and supply-chain disruption**, affecting collaboration, access to launch services, components, international data exchange, or cooperative missions amongst others.
- **Market and commercial dependency failure**, where reliance on commercial EO providers introduces vulnerability to business model changes, consolidation, or market exit.
- **Human capital erosion, including loss of specialised expertise** with potential impact at any point in the architectural design.
- **Deliberate data manipulation** with the potential to jeopardise the trustworthiness of the system and its reliability.

To address these risks, the Reference Architecture adopts resilience-by-design rather than resilience-by-recovery. This includes architectural measures such as diversity of sensing techniques and mission families, redundancy across institutional and commercial sources, modular system design, and federation rather than single-point dependency. Continuity of critical observables is supported by explicit contingency planning, overlap strategies, and international coordination.

Resilience also requires the ability to degrade gracefully. The architecture must ensure that, under partial failure, core functions—such as climate monitoring, hazard response, or policy verification—remain operational at reduced performance rather than collapsing entirely. This is particularly important for hybrid constellations, AI-enabled processing chains, and multi-actor data infrastructures, where cascading failures can propagate rapidly if not architecturally constrained.

Resilience thinking extends beyond technology to governance, stewardship and security related aspects. Long-term architectural oversight, led by the ESA in coordination with European and international partners, is essential to anticipate failure modes, stress-test scenarios, and maintain institutional memory. By embedding failure awareness and resilience requirements into the Reference Architecture Blueprint, Europe ensures that its EO system remains robust, trusted, and strategically reliable in an increasingly uncertain operating environment.

5.3. Metrics to quantify success of the Reference Architecture Blueprint

The Reference Architecture Blueprint requires clear, observable metrics to assess whether it is delivering its intended strategic outcomes over time. These metrics are not designed to optimise individual missions or programmes; rather, they evaluate the performance, coherence, resilience, and adaptability of the EEOE system-of-systems as a whole.

Together, they provide policymakers, programme managers, and system architects with evidence-based signals to guide adjustment, prioritisation, and long-term stewardship.

RA-KPI 1. **User/Stakeholder satisfaction.** Measure the degree to which the European Earth Observation Ecosystem meets user and stakeholder needs (fitness for purpose) by tracking the proportion of policy, scientific, operational, and commercial users reporting that EO data and services are fit for purpose in terms of availability, continuity, quality, accessibility, and timeliness. Periodic structured surveys and trend analysis can be used to inform architectural prioritisation, identify systemic gaps, and monitor trust and satisfaction across the ecosystem over time.

RA-KPI 2. **Continuity and stability of essential observations.** A primary measure of success is the sustained availability of priority observables critical to climate science, environmental monitoring, and policy implementation. Metrics include the absence (or minimisation) of data gaps, stability of long-term time series, maintenance of calibration and traceability standards, and successful overlap between successive missions. Persistent continuity across decades indicates that the architecture is functioning as intended.

RA-KPI 3. **System resilience and robustness under stress.** The architecture should demonstrate the ability to withstand disruption without catastrophic loss of capability. Success metrics include the system’s performance during mission failures, launch delays, geopolitical disruptions, digital infrastructure outages, or market shocks. Evidence of graceful degradation, redundancy utilisation, and rapid recovery are key indicators of architectural resilience.

RA-KPI 4. **Integration and interoperability across the ecosystem.** A successful architecture enables diverse institutional, national, commercial, and international contributions to function coherently. Metrics include the level of interoperability between data sources and platforms, adoption of common standards, effectiveness of federated ground segments, and reduction of duplication or fragmentation across programmes.

RA-KPI 5. **Innovation throughput and transition effectiveness.** The Blueprint should sustain a healthy pipeline from exploratory research to operational capability. Indicators include the rate at which Earth Explorer concepts, technologies, algorithms, or methodologies are matured and transitioned into operational, commercial, or service-oriented use, as well as the preservation of option space through non-selected mission concepts and pre-development activities.

RA-KPI 6. **Trust, traceability, and policy usability.** The architecture’s success is reflected in the degree to which EO outputs are trusted and used for policy, regulatory enforcement, and international reporting. Metrics include availability of documented uncertainty, provenance, and validation; uptake of EO products in policy processes; and acceptance of European EO data in international frameworks and legal or regulatory contexts.

RA-KPI 7. Responsiveness and timeliness. As demand shifts toward rapid decision support, success can be measured by latency from observation to usable information, scalability of processing during crisis situations, and the ability to support near-real-time applications alongside long-term reanalysis.

RA-KPI 8. Efficiency and value for investment. Under increasing financial constraints, the Blueprint must demonstrate efficient use of public resources. Metrics include reuse of infrastructure, cost avoidance through federation and coordination, reduction in redundant developments, and demonstrable socio-economic value generated across science, policy, security, and commercial domains.

RA-KPI 9. Sustainability of human and institutional capacity. Long-term success depends on maintaining expertise and institutional memory. Indicators include continuity of key skills (e.g. mission design, mission implementation, mission operations and management, ground-segment management and evolution, calibration and validation, system architecture, long-term data stewardship amongst others), effectiveness of training and community development, and the ability of the system to absorb generational change without loss of capability.

RA-KPI 10. Enabling user-driven Earth Action. The overall system is driven by user needs and continues to deliver benefit for humanity. It is the impact of the system on Earth that matters and not the feature “Space” driving the system. Therefore, the satisfaction of the users is an essential parameter of success.

Taken together, these metrics provide a balanced scorecard for the Reference Architecture Blueprint. They allow the ESA and its partners to assess not only whether Europe’s EO system is delivering today, but whether it remains fit for purpose, trusted, and resilient in the face of evolving scientific, societal, and geopolitical demands toward 2035–2050 and beyond.

5.4. Mapping drivers of change to Reference Architecture layers and functions

The Blueprint explicitly links external drivers of change to architectural consequences across the layers and core functions of the EEOE system-of-systems. This mapping ensures that the drivers introduced throughout Chapter 5 are not treated as isolated themes, they are systematically translated into concrete design pressures that recur across user needs, data and processing chains, observing systems, governance, and infrastructure. In this way, the Blueprint provides clear traceability between the strategic context established in Sections 5.1–5.15 and the architectural responses required to address it.

At the user and policy layer (Sections 5.5–5.8), drivers such as rising climate and environmental pressures (Section 5.7), security and societal resilience needs (Section 5.8), and evolving user expectations place increasing emphasis on decision-grade information. For example, climate adaptation and mitigation drivers affect latency requirements for hazard products, long-term continuity of climate variables, and explicit uncertainty budgets to support monitoring, reporting, and verification. Similarly, security and resilience drivers translate into requirements for rapid access, reliability, and trusted provenance during crisis and contingency situations.

At the data and information layer (Sections 5.9 and 5.14), public–private convergence, regulatory evolution, and growing user dependency introduce new architectural demands. For instance, commercial uptake of EO and blurred public–private boundaries affect data harmonisation, quality indicators, licensing, and provenance, while AI as an architectural enabler (Section 5.11) directly impacts data pipelines, requiring analysis-ready data, consistent metadata, and embedded uncertainty characterisation to support automated exploitation and foundation models.

At the processing and digital infrastructure layer (Sections 5.11 and 5.14), accelerating advances in AI and rapid growth in data volumes place strong pressure on scalability and resilience. As examples, AI and machine learning affect processing architectures, validation workflows, and governance of automated outputs, while infrastructure complexity and interdependencies require redundancy, portability, and graceful degradation of cloud and HPC platforms to prevent cascading system failures. An innovation push might potentially arise from quantum computing and the ability to further optimise tasks and solve even more complex processing requests. In the foreseeable future, quantum computing will allow us to solve certain computationally intensive tasks exponentially faster than classical computers. This opens up many new possible solutions e.g. for processing demanding and highly complex radar signals and evaluating radar data.

At the modelling, analytics, and intelligence layer (Sections 5.7, 5.10, and 5.11), multiple drivers converge. For example, increasing Earth-system complexity drives tighter coupling between EO observations and Earth-system models, while AI foundation models introduce new requirements for explainability, validation, and trust in derived intelligence products, particularly where outputs inform policy, regulatory, or security decisions.

At the mission and observing system layer (Sections 5.7, 5.10, 5.12, and 5.13), drivers translate into concrete design constraints for future observing capabilities. For instance, climate stewardship pressures affect mission continuity strategies, overlap planning, and calibration stability; technology convergence and small-satellite complementarity → affect constellation design and measurement densification; and geopolitical volatility and autonomy considerations (Section 5.12) affect launch access, supply chains, and international mission partnerships, reinforcing the need for architectural resilience and diversification.

Finally, at the governance, partnership, and stewardship layer (Sections 5.8, 5.12, and 5.15), cross-cutting drivers shape how the system is coordinated, prioritised, and sustained. For example, geopolitical dynamics affect partnership stability and data-sharing arrangements; institutional and financial stress affects coordination mechanisms and long-term continuity; and resource constraints drive the need for system-level trade-off analysis rather than programme-level optimisation. These pressures underpin the requirement for continuous architectural oversight and stewardship by the European Space Agency.

By explicitly mapping drivers of change to Reference Architecture layers and functions using consistent examples drawn from across Chapter 5, the Blueprint ensures internal coherence and analytical traceability. This structured approach enables early identification of emerging gaps, supports informed trade-off analysis, and provides a robust foundation for the gap assessment and strategic actions developed in subsequent chapters. The drivers and trends within EO can also be coupled with the overall drivers and trends within the Space sector (ESA, 2024).

5.5. User, community and knowledge foundations

5.5.1. Evolving and increasingly sophisticated user needs.

According to Euroconsult[5], the entire global space economy was worth US$464 billion in 2022, and while the Earth observation portion is only around 4% of that figure, the sector is undergoing significant growth. Looking at the trend over time, the space economy as a whole has seen annual growth of 7% since 2017, and this is broadly expected to continue up to 2031. The Earth observation data and service market are anticipated to increase from US$4.6 billion in 2022 to US$8 billion by 2032. These are impressive numbers that highlight the increasing user and stakeholder dependency on EO capability.

As users gain more experience with EO data and thus rely more on EO-based services, more exotic applications are emerging – particularly in financial markets and business beyond Earth system science. This places more emphasis on a living federated system model for EO architecture – one that can adapt and evolve in harmony with user demands. Digital Twin Earth or the EU DestinE is an example of this in practice.

[RAB-13]: **Continuously monitor and periodically assess the evolution of scientific, operational, and commercial user needs in order to identify emerging gaps and inform the timely development and prioritisation of future Earth Observation components.**

[RAB-14]: **Continuously monitor and periodically assess evolving socio-economic and policy priorities and identify corresponding Earth Observation applications and services that can support evidence-based decision-making.**

5.5.2. Stakeholder and user co-design

User and stakeholder co-design is a fundamental foundation for the EEOE and Reference Architecture Blueprint. ESA takes great care to actively involve the scientific community in devising and implementing the EO program at all stages. This allows a steady feed of scientific activities that help to define gaps and trends in user needs that allow strategic planning of future missions and system capability across all aspects of the Ecosystem in short- and long-term timescales. Regular calls for user engagement through technical and scientific mission concept studies, application studies, new mission ideas and scientific community coordination should be continued. For example, the EO Science for Society open call (https://eo4society.esa.int/) has provided a flexible route to initialise innovative research to enhance the societal benefits of the EO program.

[RAB-15]: **Strengthen the process of soliciting open research topics, enabling high-impact scientific studies with relatively rapid implementation as a flexible mechanism to initiate innovative research that enhances the societal value of the EO programme**

5.5.3. Strategic partnerships and international cooperation

Strategic partnerships are increasingly essential to address emerging data gaps and to understand their implications across current and future Reference Architecture scenarios, particularly as the global Earth Observation landscape evolves in scale, diversity, and pace. Sustained collaboration with national agencies and programmes, international partner space agencies (e.g. AfSA , NASA, JAXA, ISRO, CNSA…), and other spacefaring nations is critical to extend Europe's collective observing capacity, reinforce measurement continuity, and jointly address priority science and societal challenges. Such cooperation enables Europe to engage more effectively in Earth action science while strengthening the resilience and global relevance of its EO capabilities.

[RAB-16]: **Sustain, deepen, and strategically expand (international) partnerships and cooperative frameworks across the European EO Ecosystem, recognising growing interdependencies and ensuring coordinated access to complementary capabilities, data, and expertise.**

5.5.4. Open and free data as a structural enabler.

A European open and free data policy is currently in place that maximises the societal and economic value of Earth Observation data generated by institutional missions within the EEOE. This policy promotes open and transparent innovation and supports a balanced use of EO data across scientific research, public-interest applications, and commercial services. Crucially, it maximises return on public investment by providing a level playing field on which industry and service providers can develop and scale innovative application solutions.

[RAB-17]: **Maintain a free and open data access and use policy for the European Earth Observation Ecosystem institutional satellite data.**

Looking ahead, commercial satellite system providers are expected to play an increasingly prominent role in the EO landscape. The EEOE must be prepared to accommodate a wider range of data provision business models and asset ownership arrangements, as these will influence how effectively the ecosystem can evolve and shape the Reference Architecture. Already today, several missions involve shared or distributed ownership, such as Sentinel-6, where the microwave radiometer is a NASA-provided contribution and the associated data are owned and processed by NASA. Commercial missions, developed using Public-Private Partnership business models, are emerging. Greater clarity and consistency in addressing such arrangements will be required within a robust architectural and governance framework to ensure affordability, performance, and coherence of the future European EO Ecosystem.

[RAB-18]: **Establish and maintain a clear, harmonised architectural and governance framework for data provision, asset ownership, and shared mission responsibilities, including institutional, international, and commercial contributions, to ensure affordability, performance, interoperability, and long-term coherence of the future European Earth Observation Ecosystem.**

5.6. Human capital, skills and institutional memory

The effectiveness and long-term viability of the Reference Architecture depend fundamentally on the availability, continuity, and renewal of human capital. Space and ground infrastructures, data systems, and digital platforms only deliver sustained value when supported by specialised expertise that is developed and maintained over decades. Human capital is therefore treated in the Reference Architecture Blueprint as a core architectural dependency, on a par with missions, data continuity, and governance.

The EEOE relies on a set of critical skill domains that are both scarce and slow to regenerate. These include technical engineering and mission development at all stages, scientific expertise, IT-expertise, long-term calibration and validation expertise, essential for maintaining trusted climate records and measurement traceability; algorithm stewardship, required to ensure continuity, reproducibility, and transparency of processing chains as methods and software evolve; system architects, capable of maintaining coherence across a distributed, multi-actor system-of-systems; and policy–science translators, who bridge scientific outputs and policy, regulatory, and operational decision-making. Loss or fragmentation of any of these competencies represents a structural risk to the credibility, usability, and resilience of the EO system.

The Blueprint recognises that many of these skills are tightly coupled to institutional memory—knowledge accumulated through mission development, calibration campaigns, non-selected mission concepts, and long-term data stewardship. Such expertise cannot be rapidly replaced and is vulnerable to erosion through short programme cycles, discontinuous funding, or excessive reliance on transient project structures. Preserving this knowledge base is therefore a strategic requirement, particularly as the EO system becomes more complex and increasingly dependent on hybrid public–commercial architectures and AI-enabled processing.

At the same time, skills sustainability requires active renewal and adaptation. Emerging drivers described in Chapter 5—including artificial intelligence, public–private convergence, and growing policy reliance on EO—demand new hybrid competencies that combine EO science and engineering with data science, AI governance, cybersecurity, and regulatory awareness. Preparing new generations of scientists, engineers, and system architects through pre-development activities, exploratory missions, and early involvement in operational systems is a deliberate architectural function, not a peripheral benefit.

Section 5.10.5 presents a series of activities to strengthen technical, scientific and joint technical-scientific communities to develop and build human capital, skills and institutional memory.

Within the Reference Architecture Blueprint, ESA plays a unique and central role as the institutional memory holder and steward of expertise across the European EO Ecosystem. By providing long-term continuity across missions, programmes, and partnerships, ESA ensures that critical skills are preserved, transferred, and evolved over time. This stewardship underpins the ability of the Reference Architecture to remain adaptive, credible, and resilient to ensure that Europe’s EO capability is sustained not only through technology and infrastructure, but through the people and knowledge that give the system its enduring value.

[RAB-19]: **Enhance sustained mechanisms to recruit, develop, retain, and transfer critical human capital competencies to safeguard EO institutional memory necessary to evolve the EEOE.**

ESA offers a variety of information on opportunities through its websites. However, the wealth of information and its sources may sometimes be overwhelming for those less familiar with the ESA system. This is particularly true for early career scientists and engineers. The Living Planet Fellowships are especially well suited to target the next generation of EO scientists but have been offered only sporadically and the conditions of the award have been challenging for some potential hosts.

[RAB-20]: **Improve the connection of young scientists and engineers and between the entry point of the ESA Web Portals, especially between mission description/status and scientific exploitation including finding calls for funding and recruitment opportunities (including well-advertised, regular and reliable call frequency of the Living Planet Fellowships and flexibility on required hosting institute contributions) (ESA/PB-EO(2025)13,REV.1).**

5.7. Climate, Environment, and Planetary Stewardship Pressures

5.7.1. Earth system governance and stewardship

The Earth System has already demonstrated regime change: ESA EO must choose wisely the future direction for EO success and Earth Action in a manner that is capable of understanding Earth System dynamics, feedback loops and the implications of regime change (e.g. Earth system tipping points). The EEOE does not have at this stage all of the necessary measurements to monitor such changes and the EEOE should aim to gather a complete picture of them. A new paradigm of Earth System Stewardship (e.g. *Rockström et al,* 2024) is taking shape that calls for the radical reassessment of how we understand and structure our economic, political, technological and social systems, with the understanding that people and nature are entwined within socio-ecological systems (e.g. . It underscores a shared reality—that our collective well-being relies on the governance of our planetary commons (i.e., Earth System Tipping Points (ESTPs), Planetary Boundaries, and other biophysical systems) that maintain the stability, resilience, and life-support functions of the Earth system. In addition, *Raworth (*2017) calls for an interdisciplinary and whole-earth approach: at its core, it aims to create a balanced space where humanity thrives without compromising environmental and social boundaries. This model challenges our traditional definition of economic success, advocating for policies that prioritize both human well-being and ecological preservation. It stresses the need for redistributive measures, including progressive taxation and robust social safety nets, to counteract growing inequalities. Businesses are encouraged to adopt a more sustainable and long-term perspective, considering not just profits, but their broader impact on society and the planet. By fostering sustainable practices and moving away from a disposable consumerist culture, doughnut economics champions a circular economy model, which values reuse and minimal waste. The doughnut economics model integrates earth system science with the UN Sustainable Development Goals to provide a navigational tool for the Anthropocene and 21st century

Strategic consideration of these aspects responds to the immediate governance challenge of preventing the transgression of tipping thresholds, with the long-term vision of fostering necessary remote sensing infrastructure (i.e., Acquisition, Dissemination and Intelligence) for the monitoring of our planetary commons. In this manner, appropriate satellite solutions and priorities can be pioneered to establish the measurement evidence base that underpin effective governance and policy decisions essential to protect Earth's complex and self-regulating systems that have maintained the stable conditions of the Holocene. Furthermore, this new paradigm offers new opportunities for studying institutional and structural dynamics, relationships and functional behaviour within the proposed polycentric and decentralised governance architecture—which is particularly significant considering ESAs strategic and unique global position. The inclusion of this new paradigm invites an interdisciplinary and whole-earth approach, forming part of a broader vision to nurture community, awareness, momentum, and support for effective Earth System Governance and Stewardship.

[RAB-21]: Assess the application of Earth System Governance and Stewardship as a scenario framework for the evolution of the EEOE and reference architecture.

5.7.2. Implement the ESA Science Foundation Study methodology

The ESA Earth Observation Science Foundation Study was conducted using a structured, evidence-based and participatory methodology designed to establish a robust scientific and strategic basis for long-term Earth Observation planning. The study combined an extensive horizon-scanning exercise with systematic review of existing international science strategies, policy frameworks, and observational capabilities, complemented by wide-ranging consultation with the European and international EO science community.

An initial longlist of candidate science questions was developed through expert elicitation and literature review, then iteratively refined through dedicated user workshops, Advisory Committee on Earth Observation engagement, and open community feedback. Science questions were subsequently assessed against explicit criteria, including scientific relevance, knowledge gaps, observation maturity, feasibility, timescale of impact, and relevance to societal and policy needs. Traceability was established between science questions, required geophysical observables, measurement specifications, existing and planned missions, and links to international treaties and policy domains. This structured, transparent approach ensured that the resulting priorities reflect both frontier scientific ambition and policy-relevant societal demand and provided a defensible foundation for the development of an EEOE reference architecture guiding ESA activities over decadal timescales.

5.7.2.1. Example Application of the ESA EO Science Foundation Study Methodology to Ocean Carbon Fluxes

Applying the ESA EO Science Foundation Study methodology to the challenge of understanding and monitoring the ocean carbon cycle reveals a critical gap between current observational capability and policy-relevant requirements. Using the Science Foundation Study approach, the analysis begins with the identification of the core science question—quantifying air–sea CO_2 fluxes and their drivers—and proceeds through a structured assessment of existing observations, knowledge gaps, and future capability needs. Existing space-based observations of ocean colour and key geophysical variables such as sea-surface temperature and winds provide valuable qualitative insight into the relative roles of biological processes and ocean dynamics in regulating the ocean carbon sink. However, when assessed against the measurement specifications required to resolve net CO_{22} fluxes across the air–sea interface, these observations are shown to provide only weak quantitative constraint. In situ ship-based pCO_2 measurements, while accurate, are identified through the methodology as fundamentally insufficient in spatial and temporal coverage to support sub-basin-scale flux estimates on policy-relevant timescales.

Extending this assessment to the 2040+ horizon, the continuation of currently planned missions is not yet assured and highlights a potential erosion of capability. This is driven both by the absence of suitable spaceborne instruments optimised for ocean CO_2 flux estimation and by the lack of planned continuity beyond the nominal lifetime of the CO2M mission. Within the methodology, this constitutes a clear critical observation gap: no sustained EO capability is foreseen to address the ocean CO_2 flux science question at the required accuracy, resolution, and temporal persistence.

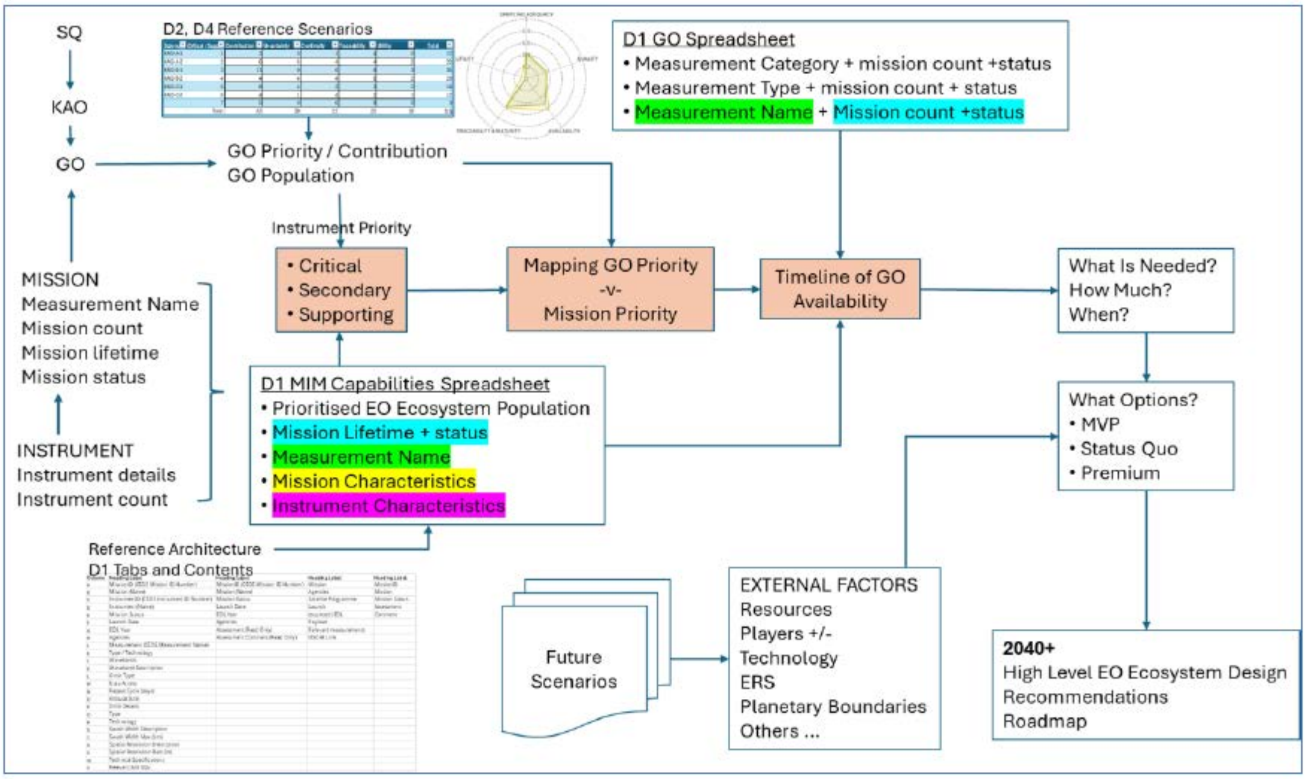


Figure 5.7.2-1. Schematic workflow and link between the EO Science Strategy and how the RA Blueprint and underlying database can be used to build and evaluate future scenarios.

The methodology also explicitly evaluates validation and verification pathways. At present, no direct method exists to validate space-based CO_2 flux estimates at spatial scales of approximately 1°–10°. Indirect validation approaches, comparing a posteriori CO_2 fields from flux inversion systems with near-surface vertical CO_2 profiles obtained from aircraft and balloon platforms, are identified as the only available mechanism. While these approaches have demonstrated value over land and in selected ocean regions, the Science Foundation Study framework assessment activities identify a lack of systematic, ocean-focused airborne validation campaigns as a limiting factor for scaling and robust evaluation of EO-derived ocean fluxes.

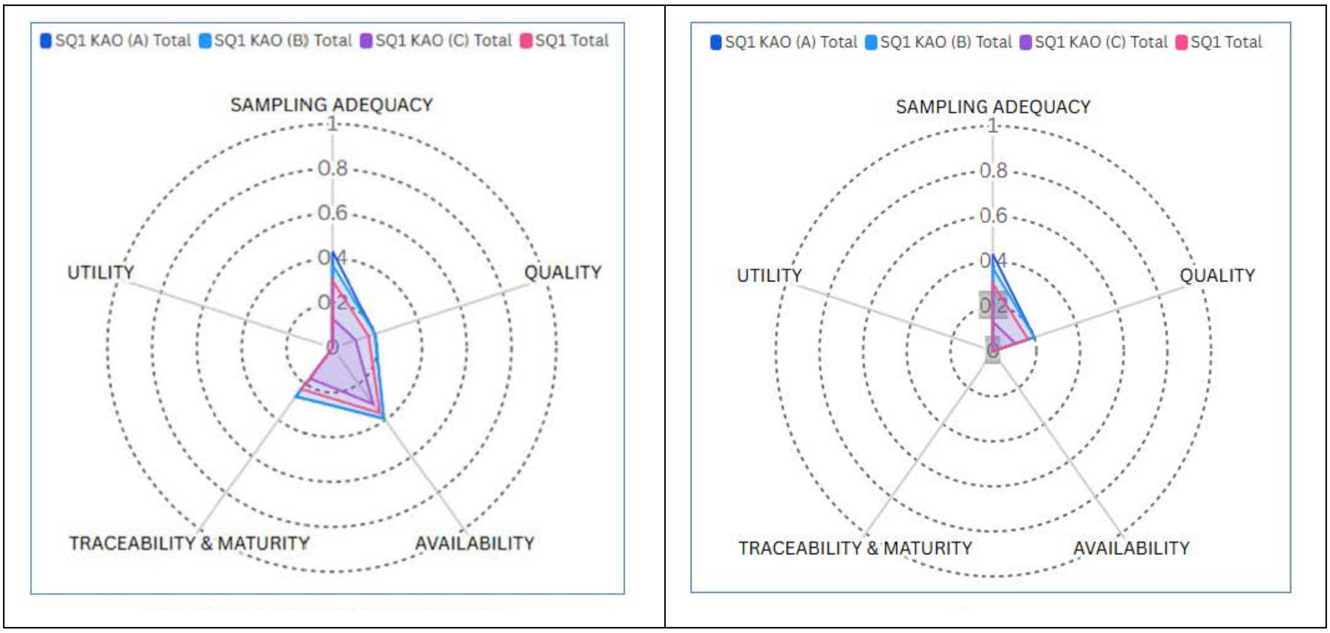


Figure 5.7.2-1. Left (2030) and on the Right (2040) how well the EO Ecosystem can support the monitoring and understanding of the underlying process governing the Ocean Carbon Cycle .

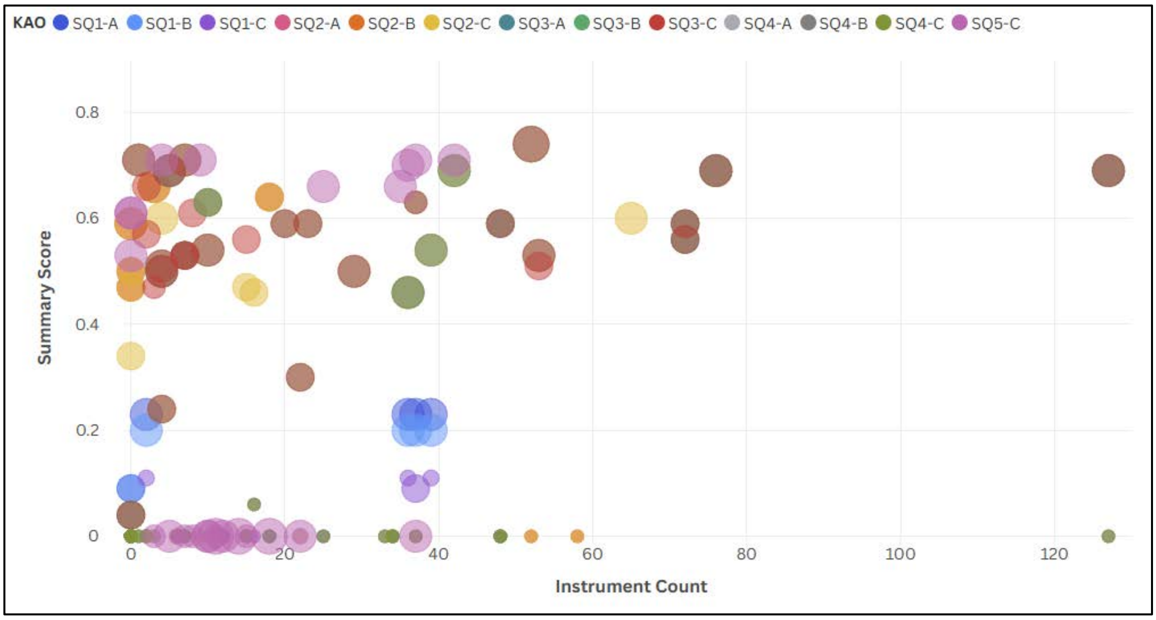


Figure 5.7.2-1. The number of missions in the 2040 horizon assuming continuation of current plans. (SQ1: Ocean CO_2 fluxes SQ2: Ice mass balance, SQ3: Ecosystems in transition, SQ4: Coastal processes and SQ5: Energy Balance).

From this structured assessment, the methodology leads to clear architectural implications. In principle, space-based XCO_2 observations could provide the spatial and temporal coverage needed to complement in-situ pCO_2 measurements and reduce uncertainty in ocean carbon flux estimates. However, when evaluated against the required accuracy and bias stability, existing XCO_2 sensors have not yet demonstrated suitability for constraining the weak, spatially extensive fluxes over the open ocean. The SoS Needs Assessment Study therefore points to the need for purpose-designed spaceborne ocean CO_2 measurement systems, coupled with enhanced, fit-for-purpose validation architectures integrating surface-based and airborne observations.

Viewed through a system-of-systems lens, this example application of the Science Foundation Study methodology demonstrates that reducing uncertainty in ocean carbon fluxes is not solely a sensor development challenge, but an architectural one. Addressing this gap is essential to ensure the robustness of global carbon budget assessments and to maintain the scientific credibility of EO inputs to international climate policy mechanisms, including the IPCC assessments and the Global Stocktake.

[RAB-22]: Implement the ESA Science Foundation Study methodology for assessing current and future user needs and prioritisation as part of the Reference Architecture development, maintenance and evolution process.

5.7.2.2. Example use case of linking the ESA EO Science Strategy to identify future EO constellation needs addressing environmental policies

Applying the ESA EO Science strategy as a compass for future activities the different policy domains can be used as a framework to identify user needs and thus map those against the current EEOE to identify future potential for new EO constellations and potential for commercialisation. The methodology developed will support the Stepping Stone Missions and help to cluster users’ needs to those of policy makers and policy implementers.

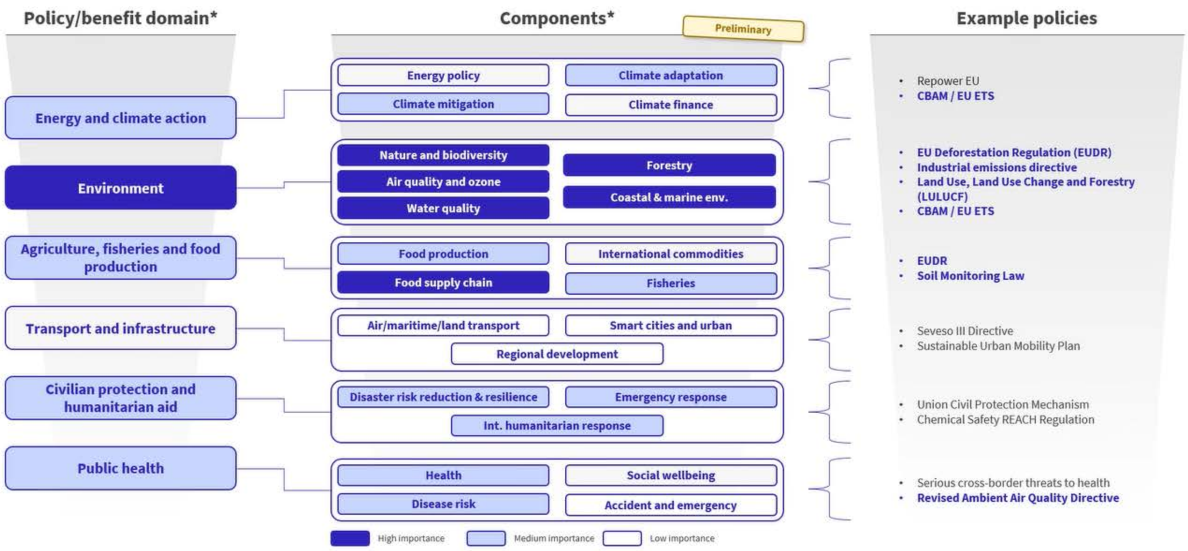


Figure 5.7.2-2. Example of linking the policy domains identified in the EO Science Strategy to concreate policy examples, this will support the later identification of gaps in the EO Ecosystem and thus potential for future constellations.

5.7.3. Performance, continuity, and uncertainty challenges

Some Earth Observation measurements are expected to become more challenging as environmental policies are implemented and begin to take effect. As components of the Earth system recover or stabilise in response to regulation—for example, the decline of ozone-depleting substances following the Montreal Protocol—the signal-to-noise (SNR) ratio of certain variables decreases, making detection and attribution increasingly demanding for future mission concepts. A similar challenge is anticipated for greenhouse gas monitoring: as policies drive emission reductions, atmospheric concentrations and gradients are expected to diminish, requiring more sensitive retrieval approaches and higher-performance sensors than those currently available to reliably detect changes and verify policy impact.

[RAB-23]: **Anticipate and define future Earth Observation sensor performance requirements for policy-relevant variables whose signal-to-noise ratios (SNR) are expected to decrease under successful climate and environmental policy implementation, ensuring that next-generation EO capabilities remain able to monitor, attribute, and verify policy impacts with sufficient accuracy and confidence.**

5.8. Security, Defence, and Societal Resilience

5.8.1. European resilience and security dependencies

The European Resilience from Space (ERS) initiative has recently emerged as a strategic effort to deliver critical capabilities in Earth Observation, Navigation, Connectivity, and Information Services, enabling Europe and its Member States to protect citizens, institutions, and strategic interests. ERS is conceived as a federated system designed to strengthen independent and resilient European space-based capabilities. It complements existing EU programmes such as EGNOS, GALILEO, future LEO-PNT, IRIS², and Copernicus, potentially relying on these core system functionalities. The ERS federated system is designed to leverage and federate European infrastructure, including governmental, commercial, and national capabilities, such as IRIDE, Pleiades, SAR-Lupe, ICEYE, COSMO SkyMed. This federated model is based on pooling and sharing to: reduce duplication by sharing infrastructural elements (such as space assets, ground stations, control segments, and data dissemination networks); enables joint procurement and supply chain optimization, fostering European economies of scale and industrial serialization; supports dual-use operations, ensuring continuity of services in both civilian and governmental crisis scenarios; guarantee European strategic autonomy and resilience. This approach ensures that Europe maintains autonomy in providing both critical and commercial space-based services while benefiting from collaborative efficiencies.

5.8.2. Rise of dual-use technologies/programmes.

Civil security is an application domain in Europe that is making increasing and effective use of Earth Observation. However, the spatial and temporal density of observations required to support many civil security and emergency management use cases is not yet sufficient to fully meet user needs. Addressing these requirements necessitates greater reliance on satellite constellations and a system-of-systems approach, enabling rapid tasking, higher revisit rates, and improved responsiveness.

In this context, dual-use satellite architectures—designed to serve both civil (scientific, environmental, commercial) and defence or security applications from shared platforms and payloads—offer a compelling pathway. Such approaches enable cost sharing, maximise return on investment, and promote interoperability across sectors. By combining flexible tasking capabilities, appropriate data access controls, and layered service architectures, dual-use systems can support diverse user communities without compromising performance, security, or governance requirements. ERS leverages components of the EEOE although in a restricted high-security implementation framework that is discussed in detail elsewhere. However, the civilian element of ERS activities operating in “dual-use” could provide rapid end-to-end (tasking to Level-1 delivery) data products to complement the existing EEOE for civil security and emergency applications (e.g. floods, fires, natural disasters etc). the exact role and capability of ERS will emerge in the coming years.

[RAB-24]: **Continuously monitor the evolution of space defence and dual-use satellite architectures and assess how their capabilities can be leveraged within an open European Earth Observation Ecosystem to enhance civil security and emergency response applications requiring rapid tasking and timely data delivery.**

5.9. Public–Private Convergence and Market Transformation

5.9.1. Potential European space act and other legal frameworks

The UNOOSA Outer Space Treaty (UNOOSA,1966, formally the Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies) is the foundation of international space law. It is ratified by over 115 nations as of 2024, and bans weapons of mass destruction in orbit, restricts celestial bodies to peaceful use, and declares space a free, non-appropriable, "common benefit" for humanity. The Liability Convention (UNOOSA, 1971) expands Article 7 and provides that a launching State shall be absolutely liable to pay compensation for damage caused by its space objects on the surface of the Earth or to aircraft, and liable for damage due to its faults in space. The Convention also provides for procedures for the settlement of claims for damages. In addition, the Convention on Registration of Objects Launched into Outer Space (UNOOSA, 1976) calls for a register objects launched into space with full and open access to the information provided by States and international intergovernmental organizations.

The European Commission published a proposal for a new EU Space Act on June 25, 2025 – which is currently still in the debate, aiming to establish a harmonized, legally binding framework for space activities, replacing fragmented national rules. The regulation focuses on safety, resilience, and sustainability, including mandatory requirements for space traffic management and a "European space label". Key aspects of the currently proposed EU Space Act initiative include:

The proposal is structured around three key pillars:

- **Safety:** The Act introduces robust rules for tracking space objects and mitigating space debris, preserving Europe’s secure and uninterrupted access to space.
- **Resilience:** Tailored cybersecurity requirements will strengthen protection of European space infrastructure and ensure business continuity.
- **Sustainability:** Operators will need to assess and reduce the environmental impact of their space activities, while benefiting from support for innovation in emerging technologies like in-orbit servicing and debris removal.

[RAB-25]: Assess the opportunities and implications presented in the emerging EU Space Act for the future reference architecture Blueprint.

5.9.2. EU Policy drivers

EU policy priorities are a primary driver shaping the evolution of the EEOE and are a central rationale for the Reference Architecture Blueprint. Policies related to climate action, environmental protection, security, resilience, and economic competitiveness increasingly depend on long-term, trusted, and policy-grade EO evidence. As EU legislation is defined, implemented, monitored, and revised over multi-decadal timescales, EO systems must be designed not only to deliver data today, but to sustain continuity, traceability, and credibility well into the future. Examples include:

- The EU Green Deal transition implements policy initiatives designed implement a successful EU-wide green transition to achieve climate neutrality by 2050. It supports the transformation of the EU into a fair and prosperous society with a modern and competitive economy. Carbon-zero by 2050 brings investments toward in situ observing systems, the Green Deal focusses on societal change to address the climate crisis, new initiatives toward sustainability – leverage EO for these aspects.
- EU ocean policy is evolving into a more unified, strategic, and legally grounded framework that combines ocean health, climate resilience, blue economy competitiveness, security, and international governance. For the Reference Architecture Blueprint, these policies create clear drivers for long-term, policy-grade Earth Observation across marine domains—requiring continuity, high accuracy, trusted data, integrated analytics, and sustained monitoring capacity to support implementation, compliance, and impact assessment.

Such key EU initiatives (including, climate neutrality targets, biodiversity strategies, disaster risk reduction frameworks, and security and resilience agendas amongst others) place explicit requirements on EO for monitoring, reporting, and verification. These policy drivers translate directly into architectural needs: stable time series, quantified uncertainty, calibration traceability, rapid access during crises, and the ability to integrate EO data with models and indicators used in regulatory and policy processes. In this context, programmes such as Copernicus rely on the Copernicus Long-term Scenario and the Reference Architecture Blueprint to ensure that evolving policy demands can be met coherently, without fragmentation or loss of trust.

The Blueprint provides the mechanism to anticipate policy-driven requirements rather than reacting to them mission by mission. By mapping EU policy drivers onto architecture layers—users, data, processing, missions, and governance—it enables early identification of capability gaps, performance limits, and emerging risks (e.g. declining signal-to-noise as policies succeed). It also supports coordination across institutional, national, and commercial actors, ensuring that EO investments align with EU priorities while preserving scientific integrity and long-term flexibility.

Strategically, the Reference Architecture Blueprint ensures that Europe's EO capabilities evolve in step with policy needs, for example via the Copernicus missions or in the future via the Stepping Stone Missions enabling evidence-based governance, regulatory enforcement, and societal trust—while safeguarding continuity, affordability, and strategic autonomy in an increasingly complex and contested global environment.

[RAB-26]: **Anticipate future EU policy needs, translating them into measurable EO requirements, and ensure that the Reference Architecture Blueprint evolves proactively to support long-term policy implementation, monitoring, and impact assessment in a coherent, resilient, and cost-effective manner.**

[RAB-27]: **Systematically integrate evolving EU and Member State policy requirements that rely on the EEOE into the Reference Architecture Blueprint, using them to guide foresight, capability development, and architectural trade-offs.**

5.9.3. Commercial uptake and user dependency

The world-wide Earth Observation market reached ~ 4.6 B$ in 2022 and is expected to grow to 8B$ until 2032. The actual growth will thereby largely depend on the ability of the market players to expend their customer base especially within the sector of high-resolution information or higher-value products. In the European market context, the increasing importance for European space sovereignty – space as a critical infrastructure also needs to be considered.

The European EO market is evolving at pace. Not all application opportunities are realised and there is still significant market uncertainty due to a lack of robust business cases. The EO commercial opportunity awareness and difficulties in realising applications among non-space companies is limiting EO solution adoption. Where there is awareness, price is perceived as a barrier for some business cases. The quality, availability, reliability, and user-friendliness/user-readiness of EO products must improve, giving a long-term perspective, if robust business cases are to be realised.

Commercial space in-orbit capability transition: A commercial New Space industry is rapidly emerging posing institutional challenges to the role of ESA in this domain in terms of technical support, venture capitalist, anchor customer, partnership, co-founder, standardisation, data security and deep fake data sets, performance certification amongst others. The European EO industry is dominated by Small to Medium Enterprise (SMEs) almost exclusively active in downstream activities. A more favourable mix of industrial maturity, together with a higher concentration of start-ups and Large System Integrators (LSI) and larger average company sizes is an emerging trend. ESA EO is providing strategic support to European commercial EO via creation and nurturing of start-ups and mechanisms to scale these up. Access to the unique ESA technical capability, experience and excellence across the European continent is a particularly relevant strategic support direction for commercial expansion.

[RAB-28]: Nurture a more resilient and diverse European EO industrial base by accelerating the creation, scaling, and integration of start-ups, SMEs, and larger system integrators, thereby supporting the transition toward greater industrial maturity and long-term competitiveness within the European EO Ecosystem.

Commercialisation of EO and "data buy" models in the RA remains a challenge. Data buy must be justified on the basis of proven user's needs, validation of the data quality, and the respective value in the context of the EO Ecosystem. Simply purchasing, for example, VHR data without due thought to how that data would be used (i.e. bringing added value with respect to the other missions in the EEOE) will lead to significant challenges and financial investments necessary to account for technical, performance and political disparities between each mission. The notion of "gluing" data together in pan-European mosaic maps is significantly underestimated in terms of the homogenisation of each data set to provide a meaningful output. The "*Grandmas patchwork quilt*" syndrome (see section 7.1.2) is to be avoided because it becomes extremely challenging (if not impossible) to generate a coherent and homogenised data set, such as a reflectance map of Europe, from a diverse set of satellite payloads managed by many operators with non-standard calibration sub-systems and performances. It remains a difficult task for the best EO scientists and one that will take considerable resources to achieve success (e.g. the ESA Climate Change Initiative has dedicated considerable work to addressing satellite cross-calibration issues (e.g. *Merchant et al.* 2019; *Sathyendranath et al.,* 2019; *Madelon et al.,* 2021). However, ESA could have a significant role in this process by ensuring reference satellite missions and performance certification systems are available to commercial small-satellite EO constellation operators.

[RAB-29]: Apply a disciplined, architecture-led approach to EO commercialisation and data-buy strategies by requiring demonstrated user need, validated data quality, and clear system-level value before procurement.

[RAB-30]: Establish ESA-led reference missions, calibration standards, and performance certification frameworks to enable coherent integration of commercial data into the European EO Ecosystem,

avoiding fragmented "patchwork" datasets and ensuring interoperability, scientific credibility, and cost-effective long-term use.

5.9.4. Major Trends in European Commercial Earth Observation data and Implications for the Reference Architecture

The European commercial EO sector is undergoing rapid structural change, characterised by faster innovation cycles, new business models, and increasing strategic relevance for public policy, security, and economic resilience.

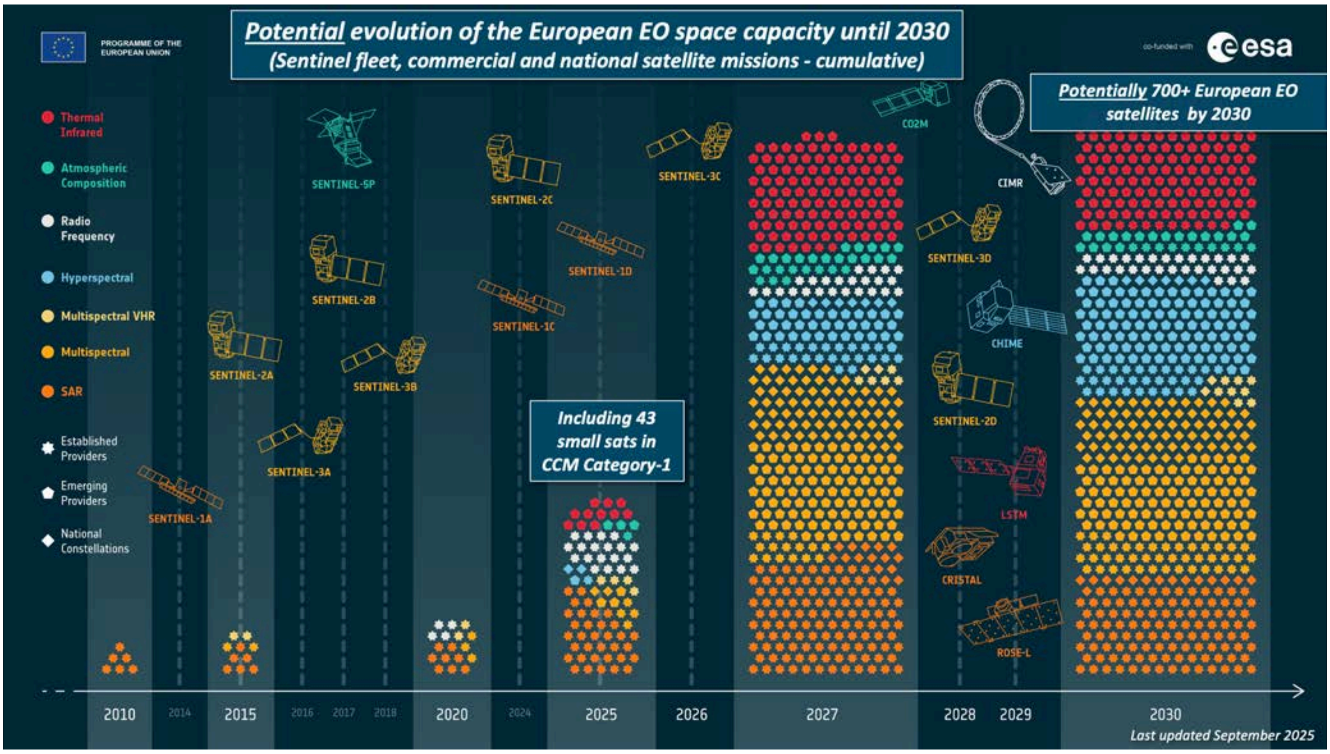


Figure 5.9.4-1. Potential evolution of the European EO space capacity until 2030.

The Reference Architecture Blueprint must explicitly recognise these trends - not to mirror the commercial market, but to stay ahead of it, ensuring coherence, trust, and long-term European advantage. These include:

1. **Proliferation of commercial constellations and rapid revisit models**. European companies are deploying constellations optimised for high temporal resolution, low latency, and responsive tasking rather than single-mission longevity. Examples include ICEYE (X-band SAR), Satellogic (optical), and

Spire Global (RO, weather and maritime signals). These systems deliver operationally valuable data streams, particularly for security, insurance, maritime awareness, and disaster response. However, they often prioritise speed and coverage over long-term calibration stability and inter-mission consistency.

2. **Shift toward data-as-a-service and "data buy" procurement models.** Commercial EO is increasingly delivered as subscription-based services or analytics rather than traditional data products. This lowers barriers for users but risks architectural fragmentation if data quality, uncertainty characterisation, and provenance are inconsistent across providers. Without reference benchmarks, public authorities may become locked into opaque service chains that are difficult to audit or compare.
3. **Growing dual-use relevance and security entanglement.** Commercial EO systems are now routinely used for civil security, defence support, and geopolitical monitoring. This raises new requirements for assured continuity, trust, legal robustness, and resilience to market or ownership shocks. The Reference Architecture must therefore account for commercial assets as system dependencies, not just optional supplements.
4. **Miniaturisation and vertically integrated industrial models.** European commercial players increasingly rely on miniaturised payloads, serial production, and vertically integrated stacks (space, ground, analytics). While this improves affordability and agility, it can also narrow design diversity and reduce transparency unless balanced by open standards and independent performance verification.
5. **Increasing demand for certification, authenticity, and legal defensibility.** As EO data is used for regulation enforcement, climate compliance, insurance claims, and litigation, commercial providers face growing pressure to demonstrate data authenticity, quantified uncertainty, and traceability. Many lack the incentive or capability to do this independently, creating a clear role for institutional reference functions.

[RAB-31]: **Position the Reference Architecture to stay ahead of European commercial EO evolution by anchoring commercial constellations and services to ESA-led reference missions, SI-traceable calibration frameworks, and independent performance and authenticity certification, ensuring that commercial innovation strengthens—rather than fragments—the European EO System-of-Systems while preserving trust, interoperability, and strategic autonomy.**

This enables Europe to benefit fully from commercial speed and innovation, while safeguarding the long-term credibility, resilience, and policy value of its Earth Observation capabilities.

5.9.5. Rapid industrial transformation

Worldwide access to space has fundamentally changed which in turn, changes the overall EO landscape including that of ESA. As a consequence, the industrial landscape has also changed – now driven by the expanding marketplace for small satellites, the new space paradigm and the evolution of the EO capabilities and operational systems developed by the Agency during the last 20 years. In the EO operations and data management context, the Copernicus Ground Segment (GS) transformation - from individual EO image delivery to platform as a service offers - has been a game changer in this respect - the approach has become standard practice in the commercial context. Keeping a sustainable and competitive landscape between large system integrators and medium and small companies, while containing the cost, will be instrumental to the stability and evolution of the European federated system ecosystem.

However, Project Bromo (e.g. *AIRBUS*, 2025) is a proposed consolidation of satellite manufacturing and services activities of Airbus, Leonardo, and Thales that would fundamentally reshape Europe’s space industrial base. The primary positive impact would be scale and integration: a unified entity could compete more effectively with vertically integrated global rivals such as SpaceX, particularly in cost, production cadence, constellation delivery, and service bundling. For Europe, this could strengthen strategic autonomy, stabilise critical supply chains, and improve the ability to execute large, recurring programmes (e.g. EO, secure connectivity, defence). However, the consolidation also introduces systemic risks. Reduced competition at prime level could weaken price pressure, slow innovation, and marginalise SMEs unless strong governance and procurement safeguards are applied. For public programmes (ESA, Copernicus, EUMETSAT), there is a risk of over-dependence on a single industrial actor, increasing vulnerability to industrial, political, or programme shocks. The impact on innovation is finely balanced: while Bromo could accelerate technology maturation and industrialisation, it may also reduce the diversity of design approaches that historically underpinned Europe’s scientific and technical leadership.

Strategically, Project Bromo would push Europe toward a US-style “national champion” model in space and could significantly strengthen Europe’s global position in space. However, deliberate policy measures to preserve innovation, resilience, and plurality within the European space ecosystem may remain a significant challenge for scientific missions.

[RAB-32]: **Actively steer the evolving European EO industrial landscape through architecture-led procurement and governance, ensuring a**

balanced ecosystem in which large system integrators, SMEs, and start-ups can coexist competitively.

[RAB-33]: **Maintaining long-term innovation capacity, affordability, and strategic autonomy of the EEOE by safeguard industrial competitivity to promote diversity of design and innovation pathways, prevents over-dependence on single industrial actors**

[RAB-34]: **Support industrial EO consolidation where it can deliver cost-effective scaling and maintain performance and resilience.**

5.10. Innovation Transfer and Capability Evolution

5.10.1. From exploratory blue-sky research to sustained capability

Exploratory research is a critical engine of long-term innovation within the EEOE, but its strategic value is fully realised when it is translated into sustained, operational capability. The Reference Architecture Blueprint therefore treats the transition from exploratory research to enduring capability as an explicit strategic architectural function rather than an ad hoc outcome of individual projects or missions. It is noted that new AI/ML numerical prediction paradigms may challenge this approach in the Reference Architecture (see Section 4.2 and 5.11).

Within the European EO context, exploratory / blue-sky research—most prominently embodied in Earth Explorer, Scout, and Φ-sat missions, as well as technology and algorithm pre-development—serves to test novel observing concepts, measurement techniques, processing methods, and scientific hypotheses under real-world conditions. These activities deliberately operate at higher risk and uncertainty, addressing variables, processes, or couplings that are not yet observable or exploitable at scale. Even when such initiatives do not result in immediate operational missions, they generate lasting assets, including validated technologies, algorithms, calibration strategies, data handling approaches, and expert communities.

The Reference Architecture emphasises the need for structured transition pathways that connect exploratory outcomes to downstream operational, commercial, or service-oriented systems. This includes early identification of operational relevance, alignment of exploratory activities with emerging user and policy needs, and systematic assessment of maturity in terms of performance, robustness, scalability, and trust. Architectural mechanisms such as pre-Phase-0 studies, sustained technology maturation, and coordinated involvement of operational actors ensure that promising innovations are not lost, delayed, or prematurely discarded.

However, the transition from research to sustained capability is not solely a technological process. It also involves governance alignment, funding continuity, institutional commitment, and human capital retention. For example, the evolution of novel measurement techniques into policy-grade capabilities requires long-term calibration and validation strategies, stable data stewardship, and clear ownership across institutional boundaries. The Reference Architecture therefore integrates innovation transfer with stewardship, ensuring that continuity and credibility are preserved as capabilities evolve.

By formalising the pathway from exploratory research to sustained capability, the Blueprint preserves Europe's options while reducing long-term risk. It ensures that high-risk, high-return research feeds coherently into the EEOE, enabling adaptive evolution without compromising stability. In doing so, the Reference Architecture safeguards Europe's ability to respond to emerging scientific questions, societal needs, and policy demands with mature, trusted, and enduring EO capabilities.

[RAB-35]: **Continue to strengthen innovation by supporting timely implementation of innovative research mission concepts and explore specific technological solutions to strengthen further industry competitiveness. This will facilitate technology maturation and consolidating technological leadership. (ESA/PB-EO(2025)13,REV.1)**

[RAB-36]: **Continue agile implementation of research missions to maintain attractiveness to industry in all pre- and post-launch activities. (ESA/PB-EO(2025)13,REV.1)**

5.10.2. Blurred boundaries between science and operations

The capability and technology gap between Earth Explorer and Copernicus missions is narrowing, while funding levels for Explorers increasingly limit the ability to pursue more ambitious, higher-risk concepts. At the same time, from a data-centric perspective, user uptake of operational missions for scientific applications is growing rapidly, particularly through the combined use of multiple mission datasets. As a result, the traditional distinction between "science" and "operational" missions is becoming increasingly blurred.

This shift is strongly influenced by industrial and programmatic factors. Changes in Cost at Completion (CaC) expectations have made multi-satellite operational series more attractive to industry than single, higher-risk Explorer missions, altering the European industrial landscape. There is a growing perception that Explorers should act primarily as precursors to operational series. While some Earth Explorer measurements have successfully transitioned to operations after demonstrating clear value, many Explorer missions were never conceived with operational use in mind and only revealed their importance through exploration.

Designing Explorers from the outset as proto-operational missions risks suppressing scientific discovery and prematurely constraining innovation.

The Earth Explorer approach has proven its long-term value: over more than two decades, many of today's mission families and observing concepts originated from Explorer calls. This success argues for adaptation, not dilution, of the Explorer paradigm in response to the changing environment.

[RAB-37]: **Preserve and strengthen the exploratory mandate of the Earth Explorer programme by protecting its high-risk, high-return character, while adapting programmatic and industrial mechanisms to the evolving data-centric and industrial landscape. Ensure that Earth Explorers continue to explore fundamentally new observations and techniques, with transition to operations driven by demonstrated value rather than predefined operational intent.**

5.10.3. Exploration of novel remote sensing techniques

Scientific user communities must explore new remote sensing techniques in a cost effective yet convincing manner. This is a fundamental part of the scientific conception for new EO missions. Developing new remote sensing techniques using experimental ground-based instruments is essential for the long-term advancement of Earth Observation because it provides a low-risk, high-learning pathway for physics-based remote sensing innovation.

ESA has an excellent history of developing innovative airborne demonstrators for a variety of missions (most recently CIMR-AIR and CRISTAL-AIR – airborne demonstrators for each named mission) that allow large areas to be covered and synergies between future missions to be studied in detail prior to launch. Ground-based experiments allow new measurement principles, retrieval algorithms, and calibration concepts to be tested, iterated, and validated under controlled and repeatable conditions and often form the basis for future satellite techniques. Furthermore, ground/aircraft-based measurements enable direct comparison with in-situ reference measurements, improve physical understanding of geophysical signals and uncertainties, and help identify practical limitations early in the technology lifecycle. This process accelerates technology maturation, reduces mission risk, and ensures that future satellite instruments are based on proven, well-characterised techniques, thereby strengthening scientific return, operational reliability, and long-term measurement continuity.

[RAB-38]: **Continue support the implementation of new airborne/ground-based demonstration instruments to facilitate a low-risk, high-learning pathway for physics-based remote sensing innovation. (ESA/PB-EO(2025)13,REV.1)**

Experimental campaigns are vital to scientific user/community development because they improve our understanding of Earth processes, trigger the generation of new ideas through observation, and to demonstrate new technologies. Ambitious campaigns are needed, capable of bringing together different scientific and technological expertise and looking in exploratory directions.

[RAB-39]: Continue supporting ambitious experimental campaigns that bring together different scientific and technological expertise to address both new scientific findings and technological demonstrations. (ESA/PB-EO(2025)13,REV.1)

5.10.4. Earth Observation Ground Segments

Present and future EO Ground Segments face several challenges in the Reference Architecture:

Security and Supply Chain Vulnerabilities: EO ground segments increasingly face cyber threats, especially as they integrate diverse vendors and open-source components. Legacy infrastructure exacerbates risk. Expanding to cloud-native and Ground Segment as a Service (GSaaS) models increases the attack surface, requiring robust encryption, authentication, access control, and clear delineation of responsibility between providers and users.

Complexity and Legacy Infrastructure: Ground systems are evolving from vertically integrated mission-specific setups to modular, federated architectures. This transition introduces complexity, requiring standard interfaces and decoupled services. Legacy components—antennas, converters—must integrate with virtualized environments, demanding interoperability and digital-to-digital conversion capabilities. [innovation...etwork.com].

Cloud Integration Challenges: The shift to cloud-enabled, software-defined ground control (e.g., AWS Ground Station, Azure Orbital) promises scalability and agility but introduces challenges:

- Regulatory concerns (data sovereignty, export controls)
- Cybersecurity in shared hosting
- Technical complexity in digital IF and ground station virtualization.

Data Volume and Processing Bottlenecks: EO data volumes are skyrocketing—petabytes daily from constellations like Sentinel and Landsat. This scale stresses storage, archiving, transmission, and initial processing systems. Traditional workflows buckle under the pressure in terms of ingestion speed, annotation, latency, and quality assurance.

Latency, Throughput and RF Spectrum Constraints: To meet near-real-time demands, ground systems rely on multi-station configurations for continuous downlinks. Balancing latency, throughput, and interference management is a challenge. RF signal noise, jamming, regional constraints, and hardware heterogeneity all complicate consistent operations.

Diversity of Standardization: Global initiatives have advanced harmonization in ground segment interfaces, but fragmentation persists. Diverse protocols, data formats, and mission-specific systems hinder interoperability across agencies and providers.

Federation and Coordination: As ground segments scale across multiple operators and nations, federation becomes essential. However, coordinating workflows, tasking, data sharing, and service levels across distributed infrastructures remains complex. Achieving consistent performance and availability across federated nodes relies on strict coordination and API-based interoperability.

Data discoverability: how easily users can find, identify, and access EO datasets that meet their needs. It's about making data visible, searchable, and understandable across platforms and communities. In practical terms, it means:

- Users can locate relevant EO data quickly through catalogues, portals, or APIs.
- Metadata is rich and standardized, describing what the data is, where and when it was collected, its quality, and how it can be used.
- Interoperability: Data can be discovered across different systems thanks to common standards (e.g., ISO, OGC).
- Persistent identifiers (like DOIs) ensure datasets remain findable over time.
- Search and filtering capabilities allow users to query by spatial extent, time range, sensor type, or thematic category.
- Accessibility and openness: Clear licensing and machine-readable formats make data usable once discovered.

Discoverability is the first step in the FAIR principles (Findable, Accessible, Interoperable, Reusable), which are widely adopted in EO data management. However, the challenge remains how to prepare for the future and adjust to different ways of data use in the era of AI.

[RAB-40]: Prepare ESA Ground Segments for the future addressing aspects as cyber-threats, increasing data volumes and complexity and potential RF-constraints.

5.10.5. Pre-development and mission incubation: large research mission development

Europe's Earth Observation leadership is entering a decisive decade. Policy ambitions are rising, geopolitical uncertainty is increasing, and technological change is accelerating—yet the cost, complexity, and irreversibility of space missions continue to grow. Decisions taken before missions formally begin increasingly determining whether Europe remains a global reference or becomes a follower.

Strengthening pre-Phase-0 activities is essential because this is the only stage where Europe can still shape ambition without locking in cost and risk, explore genuinely new observing capabilities, and align science, policy, security, and industrial priorities before irreversible commitments are made. Without this upstream investment, the system naturally drifts toward incremental missions, reduced scientific return, and over-dependence on heritage solutions.

Acting now protects Europe's ability to deliver world-leading flagship missions, sustain Copernicus and meteorological evolution, and provide trusted, policy-relevant evidence over decades. It is a relatively small investment with outsized impact: preserving architectural freedom today is the most cost-effective way to secure European autonomy, resilience, and credibility in Earth Observation tomorrow.

[RAB-41]: Strengthen and institutionalise pre-Phase-0 activities as leading architectural instruments, enabling early science–technology–industry co-design, preserving mission ambition, reducing systemic proposal burden, and maintaining architectural flexibility across the European EO System-of-Systems.

This addresses the following:

1. **Pre-Phase-0 is where architectural freedom still exists.** Pre-Phase-0 is point in the mission lifecycle where core architectural choices remain genuinely reversible. At this stage, Europe can still explore alternative measurement principles (not merely instrument implementations), observing geometries and orbital regimes, constellation versus monolithic concepts, coupling to ground segments and AI-enabled processing chains, and alignment with policy, operational, and commercial users. Once a mission enters Phase-0 proper, these degrees of freedom collapse rapidly under cost caps, schedule pressure, and industrial optimisation. Strengthening pre-Phase-0 therefore acts as an explicit architectural safeguard against premature lock-in—one of the central risks identified in the Blueprint.
2. **Pro-actively manage cost realism and ambition.** A recurring issue across recent Earth Explorer calls is that ambition is filtered out too early, as feasibility and cost arguments are applied before concepts have benefited from structured technical maturation. Reinforced pre-Phase-0 activities enable early science–technology co-design rather than sequential hand-offs, credible first-order cost and risk envelopes without forcing conservative architectures, and clear identification of dominant cost drivers—whether arising from instrument physics, calibration requirements, orbit selection, or operational concepts. This preserves Europe's ability to pursue large or complex flagship missions without transferring unrealistic burdens onto proposing teams.
3. **Reducing systemic proposal burden and bias**. The current expectation that proposers deliver near Phase-A maturity at selection stage creates structural distortions. It disproportionately penalises small scientific teams and SMEs, favours concepts with existing industrial heritage, and diverts effort from innovation toward proposal survival. A strengthened pre-Phase-0 framework—building on mechanisms such as NEOMI—redistributes effort upstream, where

ESA can absorb part of the system-engineering burden and ensure that selection is driven by scientific merit and strategic value, rather than by proposal-writing capacity.

4. **Protecting the Reference Architecture innovation pipeline.** The Blueprint recognises Earth Explorers as the primary innovation engine of the European EO system-of-systems. Stronger pre-Phase-0 activities ensure that non-selected concepts continue to mature rather than disappear, that mission ideas can feed multiple downstream pathways (Copernicus, meteorology, national missions, Missions of Opportunity), and that exploratory science is not forced prematurely into an operational framing. This avoids the "throwing the baby out with the bathwater" effect, where scientifically essential concepts are lost simply because they are not yet operationally mature.
5. **Integrating industry earlier with scientific leadership.** Future missions involving quantum sensing, advanced LIDARs, formation flying, hyperspectral sounding, gravimetry, or geomagnetism cannot be matured by science teams alone. Strengthened pre-Phase-0 enables early industrial input on feasibility, interfaces, manufacturability, and supply-chain risk, while supporting realistic assessments of technology readiness and cost evolution. Crucially, this integration occurs before procurement logic dominates design choices, preserving scientific leadership while aligning ambition with Europe's evolving industrial base.
6. **Enable system-of-systems thinking by design.** The Reference Architecture Blueprint shifts Europe from mission-by-mission optimisation to deliberate system-of-systems stewardship. Pre-Phase-0 is the only stage where this perspective can be embedded by design: assessing how a concept complements existing missions, whether it fills a genuine gap or duplicates capability, and how it interacts with calibration references, AI pipelines, DestinE, and policy use cases. Without a strengthened pre-Phase-0-layer, system-level optimisation is unattainable, and decision-making inevitably collapses back to programme-level optimisation alone.

To take full advantage if these aspects, the Blueprint calls to strengthen and expand preparatory programme elements building on the success of the New Earth Observation Mission Ideas (NEOMI) approach. Such activities should address not only scientific readiness but also technological maturity, enabling closer collaboration between scientists and engineers at the earliest stages of mission definition. This early integration can reduce proposal preparation burden, better manage technical and cost risks, improve feasibility assessments, and preserve scientific ambition in future Earth Explorer and exploratory mission concepts.

The Reference Architecture Blueprint proposes four pre-Phase-0 mission concept definition study types to address this issue:

Table 5.10.3-1. Scope of proposed new study types to enhance pre-development activities (pre-Phase-0) and reduce cost and risk through early mission definition activities.

Name	NEOMI	AURION	ASCEND	GENESIS
Aim	New Mission Idea investigation and SRL uplift.	New Mission Idea investigation SRL and TRL uplift	Mission/instrument concept exploration and TRL uplift	Mission/instrument concept definition
SRL and TRL Entry point	SRL 1-2 TRL 1-3 Mission idea never studied	SRL 2-3 TRL1-2 Mission idea never studied	SRL 3 TRL1-2 Mission idea formulated	SRL 3 TRL 3-4 Mission concept never assessed
Work to be performed	New mission ideas focussed on SRL building up to SRL 3 including training a diversity of new lead investigators and teams. Progression on the definition of the mission idea	New mission ideas focussed on SRL and TRL building up including training a diversity of new lead investigators and teams. Progression on SRL up to SRL 3 Progression from TRL 1 to 2 or from TRL 2 to 3 on critical technology Progression on the definition of the mission idea.	Progression on TRL to TRL 3 Mission Concept exploration New mission/instrument concept exploration focussed on exploring possible mission or instruments concepts and uplift of TRL on the critical technology to TRL 3	Assessment at high level of potential mission concepts Investigation of potential mission concepts that could have the capability to meet certain defined requirements including limited iteration of requirements Full preparation for Phase-0
Duration	18 months	18 months	18-24 Months	18-24 months

The relationships between pre-Phase-0 mission concept definition study types outlined in Table 5.10.3-1 is shown in Figure 5.10.3-1.

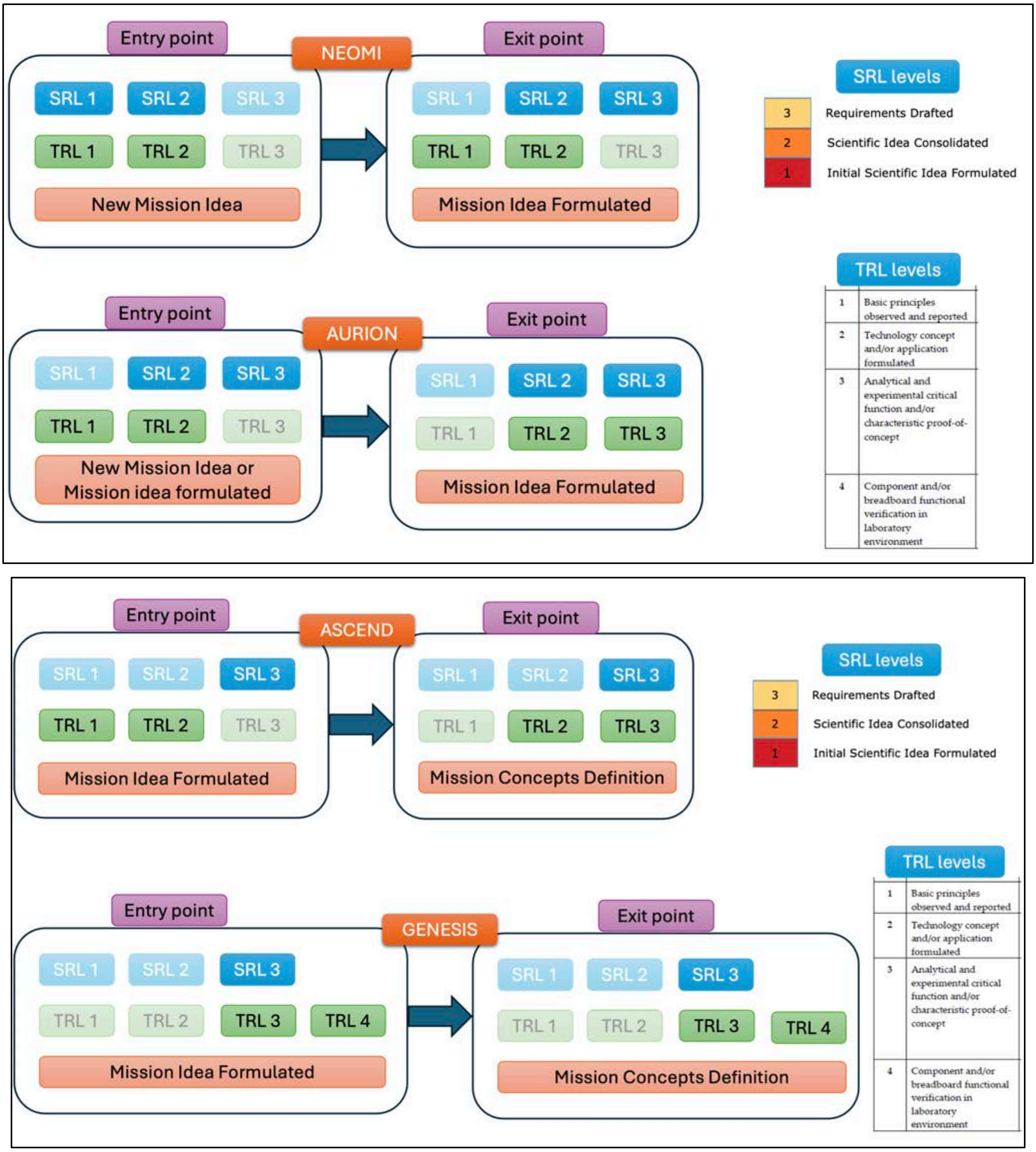


Figure 5.10.2-1. Family of pre-phase-0 "early mission definition" study types and logical progression to enhance and protect preparatory programme elements facilitating scientists and engineers to work together to address both scientific and technological maturity. (responding to ESA/PB-EO(2025)13,REV.1).

The pre-development activities proposed here allow ESA to remain abreast of critical technological developments supporting science challenges. The desired outcome is a “pool of new ideas” for potential future missions by increasing the number of technological and scientific pre-phase 0 activities and strengthening the fundamental and detailed relationship between science teams and Industrial teams proposing new mission ideas.

[RAB-42]: **Enhance and protect preparatory programme elements using NEOMI studies (focussed on scientific developments to SRL-3 and training future mission lead investigators) for the study of new missions and/or new instruments, by facilitating scientists and engineers to work together to address both scientific and technological maturity. (ESA/PB-EO(2025)13,REV.1).**

[RAB-43]: **Enhance and protect preparatory programme elements using new ASCEND studies (focussed on new mission concepts not studied before) consolidating scientific activities to SRL3 and building up to TRL2 to mature promising innovative concepts. (ESA/PB-EO(2025)13,REV.1).**

[RAB-44]: **Enhance and protect preparatory programme elements using new AURION studies (focussed new science-led technology ideas) consolidating scientific activities to SRL2/3 and building essential technologies up to TRL3 to mature promising innovative concepts.(ESA/PB-EO(2025)13,REV.1).**

[RAB-45]: **Enhance and protect preparatory programme elements using new GENESIS studies (focussed on maturing promising and innovative new mission concepts not studied before) consolidating scientific and technologies for mature promising innovative concepts in preparation for Phase-0 activities. (ESA/PB-EO(2025)13,REV.1).**

5.10.6. Flagship Research Missions

Although ESA Earth Explorer missions are themselves scientific flagships, the development of the next generation of truly breakthrough (XL) flagship missions, which discover the unknow by leveraging cutting-edge technology, requires a deliberate evolution of the preparatory framework. Such missions demand an explicit and sustained balance between scientific ambition and feasibility of implementation from the very outset, with this balance progressively strengthened throughout the preparatory phases. Continuity of technology development and design maturation from Phase 0, Phase A and through Phases B2/C/D is essential for selected mission-specific development pathways. A more strategic and systematic technology preparation framework is required to nurture novel measurement concepts and architectures in earlier phases in a coherent manner, so that they can credibly support large, the creation of high-impact missions.

Strengthening preparatory activities (with a cadence that is linked to programmatic key decision points e.g. CMIN) is therefore a critical enabler for future flagship mission development. Calls for ideas must be structured to explicitly address both key scientific challenges and their associated technological risks, allowing concepts with exceptional blue-sky scientific value to enter Phase 0 even if they do not yet satisfy all programmatic constraints. Where such concepts are not selected for implementation but address clear and persistent observational gaps, alternative defined mechanisms must exist (e.g. Missions of Opportunity or targeted technology maturation activities) to ensure continued maturity through alternative pathways, rather than losing these concepts entirely.

Breakthrough (XL) flagship missions also require early and systematic involvement of scientific leadership and industry. Industrial teams provide essential insight into measurement feasibility, system architecture, manufacturability, supply-chain risk, and cost drivers—inputs that are indispensable when mission scale, complexity, and risk increase. Preparatory activities should therefore be adapted to explicitly include industrial participation alongside scientific teams, before procurement and contractual optimisation dominate design choices. These preparatory and heritage-building efforts do not serve Earth Explorers alone; they directly feed the evolution of Copernicus, future meteorological missions or future constellations, strengthening the entire European EO system-of-systems.

Maintaining sustained awareness and long-term continuity of critical technological developments that underpin emerging scientific challenges is equally essential. Early advancement of key technologies and components enhances European competitiveness, preserves technological autonomy, and reduces downstream implementation risk. Expanding the pool of scientific and technological preparatory activities deepens collaboration between science and industry, improves realism in cost and risk assessment, and ultimately lowers uncertainty and cost escalation during mission implementation.

At the same time, while well-defined proposals are necessary for ESA to assess feasibility within a given cost envelope, the effort currently required to reach near-Phase-A maturity has become disproportionately high. This affects industrial partners but also scientific teams evaluating novel concepts and technologies at an early stage. Over time, this dynamic discourages ambitious or unconventional flagship ideas and introduces an unintended bias toward lower-risk, incremental science. Enhanced pre-development is therefore not an administrative convenience, but a structural prerequisite for sustaining ambition.

In this context, strengthened preparatory investment is a direct enabler for realising a future scientific ambitious Earth Explorer mission - an objective that has proven increasingly difficult in recent calls, where many concepts were judged technically immature relative to available cost caps and preparation time despite their scientific significance.

[RAB-46]: **The Earth Explorer element of the programme budget allocation should be commensurate with, and enable the development of, breakthrough (XL) research missions with major scientific and technical objectives (ESA/PB-EO(2025)13, Rev.1).**

[RAB-47]: **Elaborate a long-term (nine-year) plan for FutureEO by defining clear objectives for Period 2 (2029 – 2038), cadence, scale of missions, and preparatory investment for larger "flagship" research missions, including larger developments for key enabling technologies and scientific preparation (ESA/PB-EO(2025)13, Rev.1).**

5.10.7. Avoiding premature lock-in while enabling transition

The Reference Architecture Blueprint recognises that long-term effectiveness of the European Earth Observation (EO) system depends on its ability to evolve without becoming constrained by early design choices, institutional inertia, or short-term optimisation. Avoiding premature lock-in—while still enabling timely transition of mature capabilities into sustained use—is therefore a central architectural challenge.

Premature lock-in can arise from several sources: early standardisation around immature technologies, over-commitment to single mission concepts or observing techniques, rigid governance or procurement models, and tight coupling between research, operations, and specific implementations. In an environment where policy timelines and mission development span decades but technologies evolve rapidly, such lock-in risks limiting scientific discovery, reducing adaptability to emerging needs, and increasing long-term costs.

To address this, the Reference Architecture promotes options as a core design principle. This includes maintaining parallel exploratory pathways, encouraging diversity of sensing approaches, and supporting modular and interoperable system designs that allow components to be upgraded, replaced, or complemented over time. Exploratory missions, in-orbit technology demonstrators, and pre-development activities are explicitly valued not only for their immediate outputs, but for the strategic flexibility they provide to future architecture evolution.

At the same time, the Blueprint recognises that excessive hesitation can delay the uptake of proven capabilities and undermine user confidence. Enabling transition therefore requires clear, transparent criteria for moving from exploration to sustained capability, based on demonstrated performance, robustness, scalability, and trustworthiness. Architectural mechanisms such as staged maturation, overlap periods, and hybrid configurations allow new capabilities to be introduced alongside existing systems, reducing risk while building confidence.

Importantly, avoiding lock-in is not solely a technical issue. Governance, funding continuity, and institutional coordination play a decisive role in maintaining flexibility. The Reference Architecture therefore emphasises foresight-driven decision-making, regular reassessment of assumptions, and scenario-based stress testing to ensure that transitions are informed by evolving scientific, societal, and geopolitical contexts.

By balancing flexibility with decisiveness, the Reference Architecture enables Europe to transition innovative EO capabilities into long-term use without constraining future options. This approach ensures that the European EO system remains adaptive, resilient, and scientifically credible—capable of responding to emerging challenges while sustaining continuity and trust over the long term.

[RAB-48]: Preserve architectural flexibility by preventing premature lock-in through modular, interoperable, and option-preserving design, while defining clear, evidence-based transition criteria that enable timely uptake of mature EO capabilities into sustained operations without constraining future scientific, technological, or policy options.

5.10.8. In-Orbit Demonstrators within the Reference Architecture Blueprint

In-orbit demonstrators (IOD) provide a critical bridge between EO architecture intent and operational reality. While ground testing, simulation and airborne demonstrators remain essential, they cannot fully reproduce the coupled effects of the space environment, system interactions, and real geophysical signals that ultimately determine mission performance. Demonstrators allow key architectural assumptions (e.g. remote sensing technique, sensor physics, calibration strategies, onboard processing, autonomy, and data latency etc.) to be validated at system level. For the Reference Architecture Blueprint, this is extremely important since the focus timeline spans multiple decades, multiple stakeholders, and multiple technology generations, where early design errors or untested assumptions propagate into long-term cost, risk, and capability gaps.

From a systems-engineering perspective, IOD act as focal point to de-risk technical approaches within the architecture lifecycle. Likewise, they act as a focal point to build new science/application communities that may act as champions for future evolution of IOD activities. They enable rapid learning on technologies with low heritage (e.g. new microwave techniques, optical links, AI-enabled onboard processing, formation flying, hosted payloads), provide quantitative evidence to raise TRL and SRL using in-orbit configurations, and de-risk potential future industrial scale-up activities.

Strategically, IOD strengthen European autonomy and agility. They shorten the innovation cycle, lower entry barriers for new actors (including SMEs and commercial providers), and create a controlled environment for international cooperation without committing core operational services. The ESA InCubed program directly supports, co-funds, and enables in-orbit demonstrators (IOD) for Earth Observation (EO) technologies and services. The program focuses on taking innovative, commercial EO products from development to a minimum viable product (MVP) or flight demonstration stage (e.g. https://incubed.esa.int/activity-portfolio/).

Within the Blueprint logic, demonstrators are therefore not “precursor missions” in isolation, but integral architectural elements: they feed evidence directly into roadmap updates, gap analyses, and scenario stress-tests, ensuring that Europe’s future Earth-observation system evolves through measured, data-driven steps rather than irreversible leaps.

[RAB-49]: Enhance the use of focal point in orbit demonstrators to strengthen European autonomy and agility to de-risk technical and scientific approaches within the architecture lifecycle

5.10.9. Quantum sensing

Quantum sensing is one of several emerging technology families relevant to future Earth observation. Its distinguishing feature is the ability to realise measurement references and observables in new ways (for example absolute field references, improved low-frequency stability, or calibration traceability), which becomes relevant when classical approaches reach structural limits.

In an EO architecture context, quantum sensing should be treated as an option space rather than a single technology line. It covers distinct sensing approaches targeting different physical quantities, each with different implications for spacecraft design, operations, and maturity timelines. At low maturity, scientific relevance and technical feasibility evolve through iteration rather than linear progression. A study may start from technologies with comparatively high TRL but uncertain scientific value and conclude with clearer scientific relevance while redefining and thus reducing maturity of the technical implementation. Consequently, exploratory concept, prototyping and end-to-end performance studies should focus on observable-driven architectural investigations that primarily reduce uncertainty about measurement value and mission feasibility, informing subsequent SRL and TRL maturation rather than constituting SRL or TRL progression studies themselves.

Such studies have also already clarified boundaries. For example, direct active sensing with quantum light is fundamentally constrained by link budgets, yielding too few correlated photons returning for EO measurements.

The most relevant threads to track today are cold atom inertial sensing, atomic and defect-based magnetometry for geomagnetism and external field science, and Rydberg-based electric-field sensing as a potential calibration approach and niche RF capability.

5.10.9.1. Cold Atom Inertial Sensing

Cold atom inertial sensing and specifically cold atom accelerometery sparked interest for use in future gravimetry missions based on the potential for lower drift and higher accuracy acceleration measurements. ESA's QSG4EMT study showed that retrieval improvements could be realized if background model errors were reduced by a large extend. However, the experts stated that “such a large improvement in background models is not considered realistic”. Other Earth observation concepts relying on highly accurate acceleration measurements might still benefit from the technology.

5.10.9.2. Atomic and Defect-Based Magnetometry

Atomic magnetometry based on helium and alkali vapor magnetometers is established for space-based magnetometry missions due to their recognized function as long-term stable reference instruments. New generations of magnetometers leveraging Nitrogen-Vacancies in diamond or MEMS alkali vapor cells open new avenues towards integrated functionality (vector capability, high accuracy, high sensitivity and high bandwidth) in a single, compact device.

5.10.9.3. Rydberg-Based Electric-Field Sensing

Electric field sensing with Rydberg atoms experiences growing interest as demonstrated sensitivities keep getting better and functionalities beyond SI-traceable electric field amplitude measurement are explored. As of today, research and development focuses on identifying ways of integrating the sensing element into remote sensing instrument concepts to assess via modelling and prototyping how such Rydberg-enabled instruments can complement and fill capability gaps.

[RAB-50]: **Use targeted exploratory study and technology activities to establish a shared European direction on quantum sensing in Earth Observation, focusing on observables where added value is plausible. Progress should be recognised primarily through reduction of scientific and mission-feasibility uncertainty, providing a sound basis for subsequent SRL and TRL maturation.**

5.11. Artificial Intelligence as an Architectural Enabler.

5.11.1. Earth Intelligence paradigms

Earth Intelligence (e.g. GEO, 2025) comprises integrated Earth and social science derived knowledge and insights that inform strategic decisions, build capacities and empower society to address environmental, societal, and economic challenges. Its design is based on user needs at all scales and across sectors and integrates Earth observation data, socio-economic data, research and science, citizen observations, indigenous knowledge and other sources of information and combines this with modelling, prediction and scenario analysis. Several tools and approaches are in place already (e.g. Digital Twins, Destination Earth, Copernicus etc.) and as these mature in concert with AI/ML tools the impact and importance of Earth Intelligence is set to grow dramatically.

5.11.2. Big data exploitation

EO produces an enormous amount of data that is not fully exploited in synergy to generate new knowledge products. The modern ground-segment capability must be enabled to maximise cross-mission synergy to leverage the full benefit of EO data sources using modern AI and related big-data technologies – including socio-economic data. This is particularly important in the context of AI/ML systems used in numerical prediction systems where the bottleneck to advance future capability is accessing vast amounts of data with low latency.

5.11.3. Computing infrastructure maturity

AI offers approaches to modelling of Earth system components that are data driven, 10,000 times faster than full physics-based approaches – yet outperform those models (e.g. Wang et al. (2024) although such systems are often trained on the output of physics-based model systems in the first place).

5.11.4. AI/Machine Learning (ML) paradigm shift

The application of artificial intelligence directly onboard spacecraft represents a significant shift in how EO missions are designed and operated. The ESA Φ-sat programme provides a demonstration of how AI can be safely and effectively embedded in space systems. Φ-sat missions have pioneered the use of onboard machine learning to perform tasks such as real-time image classification, cloud detection, and data filtering, enabling satellites to downlink only the most valuable data. This reduces bandwidth demands, lowers latency, and increases mission efficiency—particularly important as data volumes grow and constellations expand.

From a Reference Architecture perspective, Φ-sat illustrates how AI can act as an architectural enabler across the EO system-of-systems. Onboard AI shifts part of the processing chain from ground to space, altering data flows, ground segment design, and operational concepts. At the same time, Φ-sat highlights key architectural requirements: robust validation and verification of AI models, clear governance of algorithm updates, traceability of AI-derived products, and resilience against unintended behaviour. The lessons learned from Φ-sat therefore inform how future EO architectures can integrate AI at scale—balancing autonomy and efficiency with trust, transparency, and long-term sustainability.

[RAB-51]: **Systematically integrate in-space-based AI capabilities into the Reference Architecture by building on the Φ-sat experience, ensuring that future EO missions incorporate validated, governable, and updateable AI components that optimise data flows and latency while preserving trust, traceability, and long-term system resilience.**

In the RA blueprint timeframe, EO becomes predictive, not simply observational. AI mediates between raw measurements and policy decisions. in Numerical Weather and Ocean Forecasting (NWP/NOP) systems, climate prediction and science are embracing AI/ML at pace (e.g. *Dueben and Baur*, 2018; *Dueben et al.* 2021; *Ben Bouallègue et al.* 2024; *Chantry and Dueben*, 2025). Physics-based model solutions with ML hybrid models/ensembles ("physics-informed ML") are running operationally. Multi-sensor and cross-domain data fusion at scale is now possible. New approaches (e.g. McNally et al. 2024) train a neural network to predict future weather purely from historical observations with no dependence on reanalyses. Raw observations are used to initialise a model of the atmosphere (in observation space) learned directly from the observations themselves. Such an approach, by staying purely in observation space, avoids many of the challenges of traditional data assimilation, can exploit a wider range of observations and is readily expanded to simultaneous forecasting of the full Earth system.

However, AI introduces new governance challenges for public EO systems in terms of legal admissibility of AI-derived products and data knowledge transparency for policy decisions (we have an incomplete view of how most AI/ML work compared to a traditional physics-based approach).

[RAB-52]: **Systematically assess and anticipate the evolving requirements of operational AI/ML-based numerical prediction systems, and define the Earth Observation architectures—across sensing, data, processing, and governance layers—needed to support their reliable, scalable, and trustworthy integration within the future European EO Ecosystem.**

To gain a full understanding of EO data using AI/ML approaches, particular attention is required to guarantee that AI products are explainable and that the necessary information (e.g. in terms of training/validation/testing data) is provided to enable the possibility of independent assessment and comparison against other methodologies.

[RAB-53]: **Consider AI explainability an irreplaceable component in EO. Ensure that AI products are provided along with the necessary information to enable independent and objective assessment of the results. (ESA/PB-EO(2025)13,REV.1).**

5.11.5. Foundation models

Foundation models are trained in a self-supervised manner on Europe's long, calibrated, multi-mission EO archives and enable cross-sensor generalisation, rapid downstream adaptation, and resilience to mission evolution or data loss *(Zhu et al.,* 2026). This shifts the architectural design from mission-specific processors to a multi-mission persistent analytical capability. They directly support Blueprint objectives on continuity, efficiency, and impact by lowering the barrier between Level 1 observations and knowledge-based outputs to support decision makers while importantly, preserving scientific traceability when coupled with uncertainty quantification and provenance tracking. Europe should act to institutionalise AI foundation models as shared EO infrastructure, stewarded at system level tightly coupled to data access, compute, and standards. AI foundation models are a pre-requisite to ensure robust and full AI/ML exploitation and architectural evolution of EO in the context of socio-economic of policy and stakeholder needs.

[RAB-54]: Coordinated investment in reference EO foundation models, pan-European training datasets and computing facilities, together with a governance framework is required to enforces openness, validation, and long-term coordination of AI foundation models.

5.11.6. Specific Missions for AI/ML prediction system training evolution

Short-duration, one-off satellite missions operating for periods of around one year play a critical and often under-appreciated role in advancing AI-based weather and climate prediction systems. Their value lies not in long-term continuity, but in informational diversity. AI and machine-learning models improve predictive skill by being exposed to variations in observing geometry, frequency, resolution, noise characteristics, and sampling strategies that are absent from stable, operational missions optimised for consistency and longevity.

In this context, long-term continuity is not a prerequisite. AI training relies on statistically rich, well-characterised examples rather than uninterrupted time series. Short-lived missions can be deliberately designed to explore novel measurement regimes—new frequencies, angular views, vertical sensitivities, or synergistic payload combinations—and flown in temporal overlap with trusted reference missions. This overlap provides the calibration anchor required to label the data correctly, quantify biases, and translate observations into a common physical space, after which the mission can be safely retired without loss of value.

Such missions act as controlled perturbations of the observing system, injecting new degrees of freedom into training datasets while avoiding long-term commitments in cost, operations, or infrastructure. They enable AI models to learn cross-sensor relationships, improve generalisation beyond single-instrument families, and become more robust to changes in observing systems over time. In effect, these missions train AI models to adapt—an increasingly critical capability as the EO ecosystem itself becomes more dynamic and heterogeneous.

The Reference Architecture Blueprint therefore recognises short-duration experimental missions as a strategic enabler for AI-driven prediction systems. By prioritising measurement diversity over continuity, and by anchoring these missions to reference observations during their operational lifetime, Europe can accelerate AI capability development without compromising the stability or integrity of its long-term EO records.

[RAB-55]: Explore the need and impact of specific short-duration experimental EO missions to provide diverse, well-characterised training data for AI-based weather and climate prediction systems, flown in calibrated overlap with reference missions, prioritising informational diversity and cross-sensor learning over long-term continuity to accelerate model robustness and adaptability.

5.11.7. Implications of AI/ML for the Reference Architecture evolution

The established EEOE has a solid basis with stakeholder user needs that is to a large extent founded on a need for continuity of observations serving dedicated applications and services. AI/ML is complementary and currently not as a replacement for existing systems.

There is a clear need to investigate new EO architectures that serve numerical prediction systems that may have specific and quite different needs to the established EOEE.

[RAB-56]: Maintain a leading role for the development of new approaches to the architectural evolution of the European Earth Observation Ecosystem and Reference Architecture in the context of AI/ML evolution.

5.12. Geopolitics, Autonomy, and System Resilience

5.12.1. European Space Sovereignty and Independence

Technical independence is a strategic prerequisite for the credibility, resilience, and long-term viability of Europe’s Earth Observation (EO) Reference Architecture. As EO missions become more complex, longer lived, and more tightly coupled to policy, security, and economic decision-making, reliance on externally controlled or non-sovereign critical technologies increasingly translates into architectural risk. Two recent examples illustrate this clearly. The CIMR deployable mesh reflector is not simply an antenna development: it represents Europe’s ability to realise large-aperture, high-performance microwave systems without dependence on non-European industrial supply chains, export-controlled components, or externally governed qualification paths. Without such autonomy, continuity of key measurements would be exposed to geopolitical disruption, procurement constraints, or strategic misalignment beyond European control. Similarly, Canada's long-term investment in high-power klystron and RF amplifier technology demonstrates how sustained national competence in a narrowly defined but critical subsystem can underpin decades of scientific and operational capability, enable system-level optimisation, and preserve freedom of architectural choice. For Europe, the lesson is clear: technical independence is not about duplicating everything domestically, but about deliberately protecting and sustaining a small set of mission-critical technologies—antennas, clocks, RF sources, lasers, detectors, calibration references, onboard processing—without which flagship missions, constellations, and reference measurements cannot be assured. The Reference Architecture Blueprint therefore treats technical independence as an architectural design constraint, ensuring that Europe retains the capacity to design, build, calibrate, operate, and evolve its EO systems on its own terms, even as it continues to cooperate internationally from a position of strength rather than dependency.

[RAB-57]: **Identify, protect, and sustain a limited set of mission-critical Earth Observation technologies (e.g. large deployable antennas, RF power sources, precision timing, lasers, detectors, calibration subsystems, and onboard processing) as European sovereign capabilities, ensuring that future flagship missions, constellations, and reference measurements can be designed, implemented, and evolved without unacceptable external dependency.**

The ability of Europe to design, build, launch, operate, protect, and evolve space systems that are essential to public policy, security, science, and economic resilience without unacceptable external dependency or loss of control is a foundation for the future reference architecture. Reliance on non-European supply chains, external digital platforms and data infrastructures, single-supplier industrial bottlenecks, and regulatory or geopolitical exposure beyond European control must be avoided in the future. These dependencies can translate into loss of strategic choice, reduced resilience to shocks, and vulnerability to coercion or disruption—especially in long-lived infrastructures like energy, space, digital, and defence. The core risk is not global cooperation itself, but asymmetric dependence**,** where Europe cannot sustain, adapt, or protect essential capabilities on its own terms when geopolitical conditions change.

[RAB-58]: **Safeguard European strategic autonomy within the Reference Architecture by identifying and reducing asymmetric dependencies across supply chains, digital infrastructures, industrial capacities, and regulatory exposures, while ensuring that Europe retains the ability to design, operate, protect, and evolve essential EO capabilities under changing geopolitical conditions.**

5.13. Earth Observation Constellations

Earth Observation constellations are becoming a foundational element of the future European Earth Observation Ecosystem (EEOE), driven by the need for higher temporal resolution, improved resilience, reduced latency, and scalable coverage of dynamic Earth system processes. Within the Reference Architecture Blueprint, constellations are not treated simply as collections of satellites, but as architectural instruments that enable new observing strategies, service models, and system-level performance that cannot be achieved by single missions alone.

A critical enabler of this evolution is the miniaturisation of technologies, which allows high-performance sensing, processing, and communications capabilities to be distributed across multiple platforms. Advances in compact payloads, low-power electronics, deployable antennas, digital beamforming, onboard processing, and optical and RF communications now make it feasible to implement constellation architectures without proportionally increasing cost or operational complexity. Miniaturisation is therefore not a cost-driven compromise, but a strategic architectural lever that enables observation densification, redundancy, and adaptability while maintaining measurement ambition.

From a measurement and application perspective, constellations enabled by compact, high-performance payloads allow observations at time–space scales aligned with increasingly demanding user needs—particularly for fast-evolving phenomena such as extreme weather, ocean dynamics, land-use change, cryosphere processes, and security or emergency response. By distributing sensing across multiple platforms, constellations improve revisit frequency, reduce latency, and enhance robustness against single-point failures, which are essential capabilities for near-real-time services and evidence-based decision-making.

From a resilience and sustainability perspective, miniaturised constellation elements enable architectural redundancy and graceful degradation. They allow incremental replenishment, phased deployment, and technology refresh without disrupting continuity of service—an essential requirement for long-lived policy, climate, and environmental monitoring. Constellations also enable flexible combinations of platform classes, where smaller satellites complement larger reference missions, allowing performance, cost, and risk to be balanced dynamically within a coherent observing system.

From an industrial and innovation perspective, miniaturisation aligns with evolving European industrial models, including serial production, modular payload design, and shorter development cycles. It lowers barriers to entry for SMEs, supports innovation transfer from exploratory missions to sustained capability, and enables more predictable procurement. However, these benefits can only be realised if miniaturised systems are embedded within a standards-based architectural framework that preserves interoperability, calibration traceability, and long-term data trust.

Miniaturisation also introduces new architectural risks. Without coordination, compact constellation elements can lead to fragmentation, inconsistent calibration, degraded data quality, and increased burden on ground segments and users. The Reference Architecture therefore emphasises that miniaturisation must be paired with reference missions, cross-constellation calibration, performance certification, and harmonised data standards, ensuring that distributed sensing does not undermine scientific credibility or policy usability.

In this context, the Reference Architecture Blueprint defines the European EO constellation as follows:

"The European Earth Observation Ecosystem satellite constellation combines different satellite systems—ranging from reference-class missions to miniaturised constellation elements—in different ways to strategically leverage the strengths of each through synergy in a Systems-of-Systems architecture, providing authenticated products and services with certified performance to meet user and stakeholder needs."

Within this framework, miniaturised technologies enable a set of strategic opportunities:

- Observation densification at policy- and process-relevant time–space scales without reliance on single, monolithic missions.
- Hybrid constellations, where compact satellites complement reference missions rather than replace them.
- Faster innovation cycles, allowing new sensing concepts to be demonstrated, refined, and integrated into the architecture.
- Improved resilience, through distributed capability and reduced single-point failure risk.
- Cost containment, by enabling serial production and incremental deployment rather than infrequent large procurements.

The Blueprint makes clear that miniaturisation must not come at the expense of measurement integrity and performance. Compact payloads and platforms must be designed within an architecture that ensures SI-traceable calibration, uncertainty characterisation, and performance certification, anchored by European reference missions. This is essential to maintain trust, enable multi-mission synergy, and support regulatory and policy applications.

Miniaturisation alone is insufficient. For many EO applications—particularly those supporting climate monitoring, policy verification, and long-term environmental records—measurement quality, stability, and traceability are as important as sampling density. Compact sensors, payload electronics, clocks, timing systems, and onboard processing units must therefore be designed from the outset to preserve calibration fidelity, long-term stability, and traceability to SI units. Without this, constellations risk delivering large data volumes that cannot be reliably combined, compared, or sustained over time.

The Reference Architecture Blueprint emphasises the need to co-develop compact technologies and metrology concepts. This includes embedding calibration capabilities within miniaturised payloads, developing scalable onboard reference sources, ensuring consistent inter-satellite calibration strategies, and maintaining links to external reference missions that provide absolute performance anchors. Reference-class missions remain essential in this context, not as competitors to constellations, but as the calibration and validation backbone that enables constellation data to be trusted and exploited coherently.

From an architectural perspective, compact technologies must also support interoperability across mixed fleets comprising institutional, national, and commercial satellites. This places additional requirements on standardised interfaces, harmonised calibration approaches, and transparent performance characterisation. The challenge for Europe is therefore not only to enable compact and affordable constellation elements, but to do so in a way that preserves scientific credibility, policy relevance, and long-term continuity.

By explicitly linking constellation development to SI-traceable performance standards, the Reference Architecture ensures that increased sampling density strengthens—rather than dilutes—the value of the European EO system-of-systems. This approach enables Europe to benefit from the agility and scalability of constellations while maintaining the high-quality, trustworthy measurements that underpin climate science, operational services, and evidence-based policy.

[RAB-59]: **Strategically develop and qualify compact Earth Observation technologies that enable constellation deployment while preserving measurement integrity, performance, long-term stability, and traceability to SI standards, ensuring that increased sampling density strengthens—rather than degrades—the scientific credibility, policy relevance, and interoperability of the European EO System-of-Systems.**

In summary, miniaturised technologies that preserve measurement integrity, performance, long-term stability, and traceability to SI standards are not an alternative to flagship missions, but instead, a force multiplier within the Reference Architecture. When combined with reference-class missions, robust calibration frameworks, and coherent governance, they enable Europe to move decisively from mission-centric optimisation to capability-centric stewardship enhancing temporal resolution, resilience, affordability, and adaptability while preserving Europe’s scientific authority, policy relevance, and long-term sustainability in Earth Observation.

5.14. Technology Convergence and New Measurement Acceleration

5.14.1. Data volume growth

The rapid growth in EO data volumes represents one of the most pervasive and systemic challenges for the Blueprint. This growth is driven by higher spatial, temporal, and spectral resolution sensors; the proliferation of satellite constellations; increasing use of hyperspectral, SAR, and multi-frequency instruments; and the expansion of downstream analytics, including AI- and model-based data fusion. While increased data volume enables richer information and new applications, it also fundamentally reshapes the architecture of the European EO system-of-systems.

At mission level, rising data volumes place pressure on onboard storage, downlink capacity, spectrum availability, and mission design trade-offs. Without architectural intervention, data growth risks forcing inefficient compromises between coverage, revisit, and data quality. The emergence of onboard processing and AI-based filtering (e.g. Φ-sat-type approaches) partially mitigates this pressure but introduces new requirements for validation, governance, and updateability.

At the ground segment and digital infrastructure level, data volume growth challenges the scalability, sustainability, and resilience of storage, processing, and distribution systems. Continuous reprocessing, long-term archiving of climate records, and user-driven analytics significantly amplify computational and energy demands. Dependence on large-scale cloud and HPC infrastructures introduces cost, sovereignty, and environmental considerations that must be managed at architectural level rather than project by project. The evolution of the ESA ground segment is a notable positive development here.

At the user and application level, data volume growth does not automatically translate into value. Users increasingly require analysis-ready data, derived products, and decision-relevant information rather than raw data access. Without coherent architectural design, there is a risk of overwhelming users, duplicating processing across the ecosystem, and fragmenting value creation across incompatible platforms and services.

From a governance and sustainability perspective, unchecked data growth directly impacts affordability, long-term stewardship, and environmental footprint. Decisions on what data to downlink, store, reprocess, retain long term, or discard become strategic choices with implications for scientific reproducibility, policy verification, and trust. These choices cannot be left to individual missions or services but must be guided by shared architectural principles and system-level optimisation.

The Reference Architecture therefore treats data volume growth not as a purely technical scaling issue, but as a cross-cutting architectural design challenge that affects missions, ground segments, digital infrastructure, user engagement, and long-term sustainability. Addressing it requires coordinated decisions for more onboard intelligence, data prioritisation, federated processing, reuse of shared infrastructure, and clear alignment between data provision and user value.

[RAB-60]: **Proactively manage EO data volume growth through an architecture-led approach that integrates onboard processing, scalable and sovereign digital infrastructure, data prioritisation and lifecycle management, and analysis-ready product strategies—ensuring that increasing data volumes translate into sustained scientific, policy, and societal value without compromising affordability, resilience, or long-term stewardship of the European EO Ecosystem.**

5.14.2. Measurement densification in time and space

A key element of the Reference Architecture is to address the need for observations at spatial and temporal scales that are truly compatible with evidence-based decision-making.

Despite the sophistication of today's European EO system, many key variables remain chronically under-sampled in time and space relative to their primary scientific, operational, or policy applications.

While increasing observation density represents a comparatively accessible opportunity to improve utility (e.g. through the development of satellite constellation), it does not in itself constitute a major technological breakthrough and should not be pursued at the expense of advancing flagship or reference-quality capabilities. Small satellite capacity in terms of constellations or in-orbit demonstrations can be complementary to larger class satellites – but they are not a replacement. Medium and large-class satellite missions with excellent measurement performance, revisit and resolution are a pre-requisite to enabling a hybrid constellation in which smaller satellites depend on the reference mission capability provided by ESA reference class missions.

From a scientific perspective, any densification of observations must be driven by a clear understanding the underlying physical, biological, or socio-environmental processes, and must respect fundamental sampling requirements, including adherence to Nyquist criteria, to ensure that additional measurements translate into meaningful information rather than redundant data.

[RAB-61]: **Align future EO mission designs with decision-relevant spatial and temporal scales by systematically assessing under-sampling relative to user needs and process dynamics and implementing observation densification only where it is scientifically justified, adds demonstrable value, and is consistent with fundamental sampling theory—while preserving investment focus on high-impact, reference-quality capabilities.**

Intelligent, autonomous EO sampling architectures are essential to support precision formation flying and advanced measurement concepts—such as large-aperture synthesis foreseen in proposed Earth Explorer STRATUS and SALIN-type missions. These will help to realise a fully interconnected European EO system-of-systems for next-generation flagship missions.

[RAB-62]: **Develop and invest in intelligent, autonomous EO sampling architectures based on satellite-to-satellite and satellite-to-ground-to-satellite communication links, enabling adaptive tip-and-cue operations and embedded autonomy within future constellations.**

[RAB-63]: **Intelligent, autonomous EO sampling architectures must support dynamic reconfiguration of processing chains, including secure update and replacement of onboard software, and exploit emerging communication infrastructures—such as IRIS²—as potential EO data relay and hosting opportunities.**

5.14.3. Small-Spacecraft Formation Flying for Synthetic Apertures and Novel Observations

The development of small-spacecraft formation flying is a key enabler for next-generation EO concepts that cannot be realised with single platforms. Precisely controlled formations allow distributed or synthetic apertures in radar, radiometry, lidar, and optical systems; enable bi-static and multi-static measurements; and support adaptive observing strategies such as tip-and-cue sampling. These approaches open new measurement regimes—including very large effective apertures, enhanced sensitivity, improved vertical or angular resolution, and observation geometries tailored to specific Earth system processes—while retaining the flexibility and resilience of small satellites.

Realising these concepts introduces significant technical and operational challenges. Hardware constraints include high-precision relative navigation and timing, inter-satellite ranging and metrology, ultra-stable clocks, low-latency cross-links, propulsion systems capable of fine control with minimal contamination, and payload designs tolerant to relative motion. In-flight risks must be actively mitigated: collision avoidance and safe-mode behaviour, formation acquisition and reconfiguration, differential drag and perturbation management, failure containment within a formation, and robust calibration transfer across platforms. Autonomy and onboard decision-making become essential to manage latency, reduce ground-operations burden, and ensure safety.

Despite these challenges, the payoff is substantial. Formation flying with small spacecraft enables Europe to pursue flagship-class performance through distributed systems, complementing reference missions and enabling scalable, upgradable architectures. Within the Reference Architecture Blueprint, formation flying is therefore treated not as a niche technology, but as a strategic capability that underpins future synthetic aperture missions, hybrid constellations, and resilient system-of-systems designs—while preserving European technical independence and innovation leadership.

[RAB-64]: **Develop, demonstrate, and de-risk small-spacecraft formation-flying capabilities—including precision navigation, timing, inter-satellite links, autonomous control, and safety mechanisms—to enable distributed and synthetic aperture EO missions as a core element of Europe's future Reference Architecture.**

5.15. Space Environment, Spectrum, and Measurement Integrity

5.15.1. Orbit congestion and debris

Orbit congestion and space debris are emerging as critical constraints for the design, deployment, and long-term sustainability of new Earth Observation missions (e.g. ESA Space Debris Office, 2025, see Figure 5.15-1). The rapid growth of large constellations across multiple domains—including Earth observation, telecommunications, and global navigation satellite systems—is leading to unprecedented levels of traffic in key orbital regimes. Some orbits are already under significant operational stress: for example, within a six-month period, SpaceX's Starlink constellation reportedly executed more than 25,000 collision-avoidance manoeuvres in 2021, increasing to around 50,000 manoeuvres in 2024 (*Pultarova,* 2024). Such figures illustrate both the scale of the challenge and the growing burden placed on satellite operators and space traffic coordination mechanisms.

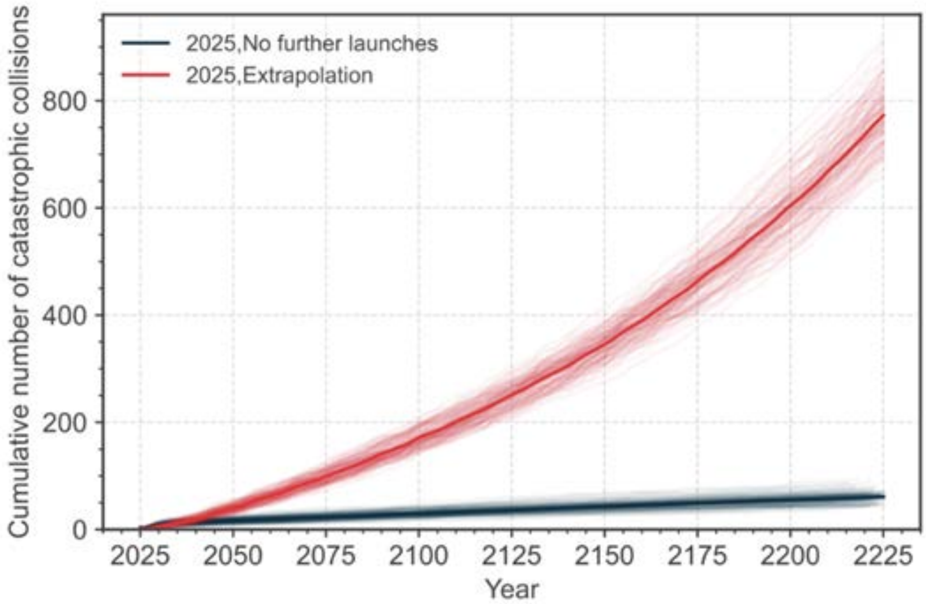


Figure 5.15-1. Number of cumulative collisions in LEO for simulated scenarios of long-term evolution of the environment (ESA Space Debris Office, 2025)

Addressing this challenge requires internationally accepted and consistently applied space debris mitigation measures. These include limiting debris released during nominal operations, reducing the risk of on-orbit break-ups, ensuring reliable end-of-mission disposal, and preventing collisions through effective space situational awareness and traffic management. Beyond mitigation, active remediation is increasingly necessary. ClearSpace-1 represents ESA's first Active Debris Removal (ADR) mission and will demonstrate the end-to-end capability to rendezvous with, capture, and safely deorbit a defunct object for controlled atmospheric re-entry. Together, such measures highlight that orbit congestion and debris are no longer peripheral concerns, but fundamental architectural constraints that must be explicitly addressed within the Reference Architecture Blueprint to ensure the safe, resilient, and sustainable operation of Europe's future EO system-of-systems.

[RAB-65]: Integrate orbit congestion and space debris constraints as first-order design drivers within the Reference Architecture Blueprint by

enforcing debris-mitigation and end-of-life standards, supporting space situational awareness and traffic management, and enabling active debris removal capabilities, thereby ensuring the long-term safety, resilience, and sustainability of Europe's Earth Observation system-of-systems.

By 2030–2050, access to specific low-Earth-orbit (LEO) planes becomes a strategic bottleneck, not just a collision-avoidance nuisance. Large commercial constellations now occupy (and actively manoeuvre within) the same altitude–inclination "real estate" that EEOE missions depend on. Starlink alone operates ~9,400 active satellites (e.g. https://satellitemap.space/constellation/starlink) and has regulatory approvals (https://docs.fcc.gov/public/attachments/DOC-417881A1.pdf) to expand further, with planned altitude adjustments that change conjunction dynamics across commonly used orbit shells. In January 2026, SpaceX announced (*SpaceX*, 2026) that its Starlink service

> "…*is beginning a significant reconfiguration of its satellite constellation focused on increasing space safety. We are lowering all Starlink satellites orbiting at ~550 km to ~480 km (~4400 satellites) over the course of 2026. The shell lowering is being tightly coordinated with other operators, regulators, and USSPACECOM. Lowering the satellites results in condensing Starlink orbits and will increase space safety in several ways. As solar minimum approaches, atmospheric density decreases which means the ballistic decay time at any given altitude increases - lowering will mean a >80% reduction in ballistic decay time in solar minimum, or 4+ years reduced to a few months. Correspondingly, the number of debris objects and planned satellite constellations is significantly lower below 500 km, reducing the aggregate likelihood of collision. Starlink satellites have extremely high reliability, with only 2 dead satellites in its fleet of over 9000 operational satellites. Nevertheless, if a satellite does fail on orbit, we want it to deorbit as quickly as possible. These actions will further improve the safety of the constellation, particularly with difficult to control risks such as uncoordinated manoeuvres and launches by other satellite operators.*"

In parallel, multiple LEO constellations already exceed 30 spacecraft and collectively drive sustained congestion and manoeuvre coupling across orbit planes: Eutelsat OneWeb (~648) (European secure connectivity), Planet (200+ smallsats for high-revisit optical), Spire (100+ LEMUR-class satellites supporting weather/maritime/aviation data services), Iridium (66 LEO cross-linked sats), and Globalstar (~48), among others.

For the Reference Architecture Blueprint, the implication is clear: some of the orbit planes the EEOE historically assumed available will no longer be feasible or will be available only at the cost of significant anti-collision demanding higher propellant reserves, increased operational burden, and degraded mission performance. This directly threatens missions that must use carefully chosen low-drag, low-altitude well-separated orbit planes to achieve their science objectives. Time time-variable gravity missions such as MAGIC/NGGM rely on precisely maintained formation geometry and low altitude to maximise gravity signal sensitivity and spatial resolution. It also affects high-resolution visible/hyperspectral imaging missions that depend on stable sun-synchronous orbit geometry (LTAN control) measurement performance and cross-calibration with reference sensors. Increased manoeuvring and forced orbit compromises erode continuity, comparability, and uncertainty budgets.

Orbit planes cannot be reserved or claimed and international coordination remains difficult. However, the reference architecture must protect institutional orbit access and use within the EEOE. Elements to achieve this include:

- Convene an agreed international approach to manage the of orbit planes similar to that used to manage the radio spectrum via ITU.
- Consider “protected mission orbital regimes” (altitude–inclination–LTAN bands) for critical public-good capabilities (e.g., gravimetry, reference imagers, key climate ECV continuity) and treat them as strategic infrastructure in European planning and procurement.
- Embed orbit-access risk as a primary design driver in early phases including propellant margin policies, autonomous collision avoidance requirements, operations staffing, and end-to-end performance impacts (latency, continuity, uncertainty).
- Strengthen European Space Traffic Management (STM) and SSA coupling including mandatory high-quality ephemeris sharing for licensed operators, harmonised conjunction thresholds, coordinated manoeuvre protocols, and auditability (who manoeuvred, why, with what residual risk).
- Procure “orbit assurance” as part of mission architecture: e.g., resilient formation flying acquisition strategies, multi-plane fallback modes, and launch/orbit insertion flexibility to maintain the ability to reach/keep required planes.
- Use regulatory leverage and public procurement: if a constellation benefits from European markets/public contracts, require compliance with European STM rules, debris mitigation, and operational transparency sufficient to protect public missions.

[RAB-66]: **Establish and maintain a set of protected orbital regimes for key public-good capabilities (including MAGIC/NGGM-class gravimetry and reference-class high-resolution optical imaging) and implement European STM/SSA-based governance that mandates conjunction data sharing, coordinated manoeuvre practices, and licensing/procurement conditions to preserve safe, predictable access to these regimes through 2030–2050.**

5.15.2. Implications of space environment cleanliness regulations.

Independent access to space is a fundamental strategic European pre-requisite to a competitive European space industry. It is essential to Europe. As the space environment becomes increasingly populated the potential for in-orbit collision becomes more likely.

Furthermore, space debris on re-entry is becoming more prevalent posing risks to populations around the world.

Consequently, new satellite missions are now subject to very stringent de-orbit requirements that are designed to maintain a clean space environment while mitigating as much as possible negative impacts of space debris and potential impacts on the Earth atmosphere. This means that new missions must now carefully consider their fundamental design for de-orbit within 5 years of decommissioning, guarantee a high reliability at the end of life to re-entry, demonstrate that under un-controlled re-entry condition the casualty risk is less than 10-4 and that while de-orbiting the cumulative probability of collision with debris of more than 1 cm of diameter is below certain threshold. The implication of all these requirements is significant, and in particular:

a) Controlled re-entry will be required in the Earth Explorer and Copernicus and in a class of satellites above certain dimensions and mass,
b) Satellites placed in LEO orbits at a certain altitude will require fuel expensive manoeuvres to decrease the orbit perigee to comply with the 5 years de-orbit. This would increase the fuel required or the use of Electric Propulsion.
c) Certain altitude orbits will not be achievable using existing low-cost medium class platforms because of the need to increase embarked fuel, implementation of alternative electric propulsion, the need to perform control re-entry or, the need to increase the platform reliability and avionics functionality. This may create a gap in terms of more affordable medium class platforms and increase the cost and size of small satellites. Because of the new regulation, any objective toward the use of reduced reliability, low-cost medium class platforms may not be realistic since the overall cost of such satellites will increase.
d) The longer the lifetime of a satellite, the harder it will be to meet the reliability requirements for re-entry, increasing the cost of the satellites or reducing their lifetime, with the subsequent reduction of the science and societal return of the investment. Extension of operations of very successful satellites such as CryoSat and SMOS may not be possible in the future.
e) While controlled de-orbit of satellites not designed with this functionality has been successful (e.g. Aeolus-1), this is not a reliable strategy to follow.

In summary, adoption of the new space regulation will generally increase the cost of the missions and may create a gap in terms of affordable medium and small size class satellites.

To address these aspects and bearing in mind the international effort to use small low-cost spacecraft as part of constellations, a concerted effort should be made to design and develop miniaturised high-performance payloads. This will not completely solve the issue because not all missions can be miniaturised. In addition, the need of development high functional, reliable, and affordable avionics (as attempted for the PROBA platforms) for medium size platforms and their standardisation following the CubeSat philosophy would be required.

The increasing demands of deorbiting and clean-space regulations creates a structural risk for future missions unless addressed proactively.

[RAB-67]: **The benefit and urgent need for ESA Clean Space and deorbit regulations must be communicated clearly and transparently. This will foster a realistic expectation from user communities at the end of a satellite life rather than advocacy to prolong dying missions with a risk that deorbit may not be feasible.**

[RAB-68]: **Prioritise the design and development of miniaturised, high-performance payloads that enable mission capability while reducing mass, volume, and orbital lifetime, explicitly supporting de-orbiting compliance and a clean space environment.**

[RAB-69]: **Develop high-functionality, reliable, and cost-effective avionics for medium-class satellite platforms, and promote platform standardisation following a CubeSat-inspired philosophy, in order to mitigate potential capability gaps arising from evolving space-debris and de-orbiting regulations.**

[RAB-70]: **Systematically advance satellite platforms, subsystems, and enabling technologies with de-orbiting and clean-space requirements embedded by design, including end-of-life disposal, passivation, and minimisation of long-lived orbital and atmospheric impacts.**

The controlled de-orbiting and atmospheric re-entry of satellites introduces emerging and still poorly quantified perturbations to the upper atmosphere. During re-entry, spacecraft materials ablate and vaporise, releasing metal particulates and chemical species into the mesosphere and lower thermosphere. Recent studies suggest that a fraction of these materials may persist, be transported downward, and only interact with the stratosphere and ozone layer after significant time delays—potentially on decadal timescales.

These delayed pathways imply that the environmental consequences of satellite re-entry may manifest long after the operational lifetime of individual missions, complicating attribution and risk assessment. The cumulative nature of re-entry events, combined with rapidly increasing launch and de-orbit rates, raises concerns about non-linear effects on stratospheric chemistry, aerosol formation, radiative balance, and ozone depletion processes. At present, the underlying mechanisms, residence times, transport pathways, and thresholds for systemic impact remain insufficiently understood, introducing long-term uncertainties into space sustainability and environmental protection frameworks. To support environmentally responsible de-orbiting practices and to inform future international regulatory and mitigation frameworks for sustainable space operations, there is a need to quantify timescales, sensitivities, and systemic risks of de-orbiting satellites on the upper atmosphere.

[RAB-71]: **Urgently strengthen the scientific understanding of the atmospheric impacts of satellite re-entry, with particular emphasis on the production, transport, and long-term fate of metal particulates and ablation by-products released during de-orbiting. This includes targeted laboratory studies, in-situ and remote atmospheric observations, modelling of multi-decadal transport and chemical interaction processes, and assessment of cumulative effects under high-traffic space scenarios.**

5.15.3. Space situational awareness and satellite traffic management

Space Situational Awareness (SSA) is the capability to detect, track, characterise, and predict the behaviour of objects and hazards in space, including:

- active satellites
- debris (tracked and untracked)
- fragmentation events
- space weather effects (drag, radiation, charging)

Satellite Traffic Management (STM) builds on SSA and adds decision-making, coordination, and governance, covering:

- conjunction assessment and collision avoidance
- manoeuvre coordination between operators
- norms, rules, and eventually binding procedures for space traffic

By the 2030–2050 timeframe, SSA and STM become enabling infrastructure, not optional support functions. Without them, dense EO constellations, AI-driven operations, and long-term sustainability of key orbits (LEO, MEO, GEO) are not achievable.

The European EO ecosystem is moving toward an ecosystem including large LEO constellations originating in specific programmatic and governance frameworks that leads to higher orbital congestion, especially 500–800 km. Autonomous and AI-assisted operations are also emerging. Collision risk scales non-linearly with the number of satellites and the risk of collisions with loss of long-term data continuity and dispersion of satellite collision debris (augmenting the collision problem) is of serious and growing concern.

Satellite Traffic Management (STM) is the most challenging strategic problem to address because it requires both technical and political coordination. From the technical perspective, automated conjunction screening at constellation scale, standardised manoeuvre coordination protocols, data-sharing frameworks between civil, defence, and commercial operators, and rules of priority and right-of-way are all fundamental. However, these functions are not always clear from an international perspective.

Given the growing number of European satellites either on-orbit or planned, Europe cannot rely indefinitely on non-European SSA data sources since EO mission architecture increasingly depends on trusted SSA services – especially since future scenarios highlight that STM will influence orbit selection, constellation design, and end-of-life strategy. SSA/STM therefore becomes a design driver for EO missions, not an external service.

The architectural consequences of SSA/STM for EO missions up to 2050 implies (e.g. ESA, 2023):

- “SSA-aware” spacecraft design
- propulsion margins for frequent small manoeuvres
- precise navigation and timing
- Constellation-level autonomy
- AI-assisted collision avoidance
- coordinated fleet responses
- Integrated end-of-life disposal
- guaranteed deorbit compliance
- STM-aware passivation strategies

If these elements are not addressed correctly the EEOE risks include:

- Escalating collision probability in key EO orbits
- Loss of climate data continuity due to avoidable incidents
- Regulatory fragmentation, disadvantaging European operators
- Forced orbital exclusions reducing EO system performance

Recent policy signals from the United States indicate a shift away from the long-standing practice of providing free Space Situational Awareness (SSA) and space traffic safety services to civil and commercial satellite operators. As articulated in the Space News opinion article “No more free rides: it’s time to pay for space safety” (*Space News*, 2026), this marks a transition toward cost-recovery or user-pays models for conjunction assessment, debris tracking, and space safety services. This shift poses a strategic risk to European space systems if not addressed proactively. European space infrastructures—particularly Copernicus, Galileo, EGNOS, GOVSATCOM and emerging commercial constellations—depend on timely, high-quality SSA data to manage collision risk, protect continuity of service, and comply with debris mitigation obligations (*EUSPA*, 2024). Historically, Europe has benefited from open access to U.S.-provided SSA data and services, especially the publicly shared orbital catalogue and conjunction warnings. The erosion of this model creates systemic exposure for European operators:

1. **Strategic dependency and loss of assured SSA access.** If SSA services become fee-based, restricted, or prioritised for national users, Europe risks reduced or delayed access to critical safety data. This undermines Europe’s ability to independently protect its space assets and conflicts with objectives of strategic autonomy.
2. **Operational and financial burden on European operators.** A commercialised SSA environment introduces recurring operational costs, disproportionately affecting

publicly funded missions and small or emerging European companies. This may reduce manoeuvre responsiveness, increase residual collision risk, or divert funding from mission performance.

3. **Fragmentation of global space traffic management.** A patchwork of national or commercial SSA providers risks inconsistent conjunction assessments, conflicting manoeuvre advice, and coordination failures—particularly dangerous for dense LEO orbits heavily used by Earth Observation systems (e.g. EUSPA, 2024).
4. **Threat to long-term data continuity.** European EO systems rely on multi-decadal continuity (e.g. climate data records). The loss of even a small number of key satellites due to avoidable collisions would have irreversible scientific and policy consequences.

The operational and policy implications of these issues are significant. In terms of collision risk management, a free or subsidised SSA supports everyday conjunction assessments and avoidance manoeuvres. A transition to fee-based access could degrade real-time responsiveness and increase residual collision risk. In terms of space traffic coordination, Europe's critical position on space traffic management as orbital traffic grows must consider how to fund, operate and govern STM in a landscape where access to U.S. services is no longer guaranteed. This includes possible user contributions or cost-share frameworks for European STM services to ensure continuity and fairness. In terms of EEOE global interoperability, the EOEE SSA strategy must balance openness with sustainable cost recovery mechanisms to avoid unilateral dependencies. The end of "free" SSA services is not simply a budgetary issue—it is a strategic warning. Without decisive action, Europe risks increased collision exposure, higher operational costs, and loss of control over the safety of its space infrastructure. Proactive investment in European SSA and STM as sovereign, trusted capabilities is essential to safeguard the EOEE to 2050 and beyond.

[RAB-72]: **Accelerate European autonomous SSA/STM capability. Expand sensor coverage (radar, optical, and space-based) across LEO, MEO, and GEO and improve update frequency and orbit determination accuracy to operational levels required by large constellations.**

[RAB-73]: **Establish a sustainable European funding model to develop a public-good–first model for European SSA, including cost-sharing where appropriate. Avoid replicating a purely commercial model that could disadvantage public-interest missions.**

[RAB-74]: **Integrate SSA/STM into mission design and regulation. Make "SSA-aware" design (propulsion margins, autonomy, manoeuvre coordination) a standard requirement for European missions. Europe could consider aligning STM policy with licensing, debris mitigation, and end-of-life regulations.**

[RAB-75]: Strengthen international governance and interoperability. Use Europe's diplomatic and regulatory influence to promote transparent, interoperable, and rules-based STM, resisting fragmentation into competing national or commercial silos.

These issues have been recognised with an urgency for Europe to accelerate its own SSA/STM capabilities under the EU Space Programme (EC, 2025). The EU Space Surveillance and Tracking service (https://www.eusst.eu/) is part of the SSA component of the EU Space Programme, adopted by the European Union (EC, 2021; 2023). 15 EU Member States (Austria, Czech Republic, Denmark, Finland, France, Germany, Greece, Italy, Latvia, the Netherlands, Poland, Portugal, Romania, Spain and Sweden) work together with EUSPA acting as the EU Space Surveillance and Tracking Front Desk form the SST Cooperation. A comprehensive explanation of the criteria used for collision avoidance service (EUSPA, 2024) is available at https://portal.eusst.eu. The EU SST services are available free of charge to all registered users.

The Partnership's Member States have networked their assets to provide, through the SST Service Provision Portal operated by EUSPA, a set of SST services which assess the risk of in-orbit collisions and uncontrolled re-entry of space debris into the Earth's atmosphere and detect and characterise in-orbit fragmentations. EU Space Surveillance and Tracking aim at having full coverage of the GEO and MEO regions for objects larger than 35 cm by 2023. For the LEO region, EU Space Surveillance and Tracking aims at covering almost 100% of objects larger than 50 cm and approximately 20% of the objects larger than 7 cm. EU SST seeks to increase its autonomy at all orbital regimes. To this end, its sensors network is under continuous upgrade and expansion, which improves the EU Space Surveillance and Tracking coverage and orbital information accuracy and timeliness. The EU SST Database is a data-sharing platform that connects all national operations centres (OCs) of EU SST. Each OC can upload and download data and information. Apart from storing measurement and orbit data, the Database offers the capability to provide an overview of the network of sensors contributing to EU Space Surveillance and Tracking (including information on availability, maintenance, operational status, and sensor parameters) and support the operational daily work regarding tasking requests, where an OC can ask for additional data on specific events such as conjunctions, re-entries or fragmentations.

5.15.4. Frequency Management: Implications of 5G/6G terrestrial telecommunications systems.

The rapid deployment of 5G and emerging 6G telecommunications systems is creating significant new pressures on Earth Observation sensors that operate in shared or adjacent radio-frequency bands. As terrestrial and spaceborne communications expand, the risk of radio-frequency interference (RFI) affecting EO measurements is increasing, with direct implications for data quality, continuity, and long-term climate records. These challenges must be addressed within the Reference Architecture Blueprint as first-order design constraints rather than as mission-specific mitigation issues.

From an architectural perspective, this evolution has multiple consequences. Enhanced onboard processing and filtering capabilities may be required to detect, characterise, and mitigate RFI in real time, complementing existing mitigation techniques applied within ground processing chains. In parallel, systematic research into alternative or less congested frequency bands is needed to preserve measurement capability for future EO missions, recognising that spectrum access is governed internationally. In this context, coordination with the International Telecommunication Union (ITU) is critical to protect passive sensing allocations, influence future spectrum regulations, and ensure that EO requirements are adequately represented in global frequency management processes.

At the same time, the increasing presence of anthropogenic RF signals also presents potential opportunities. As demonstrated by GNSS-Reflectometry (GNSS-R) and GNSS Radio Occultation (GNSS-RO), signals not originally designed for Earth observation can be exploited as novel sources of environmental information. A similar question now arises for 5G/6G and other anthropogenic RF emissions: whether, under controlled and well-understood conditions, they could be harnessed for new EO measurement concepts, rather than being treated solely as interference.

[RAB-76]: **Proactively address the impact of 5G/6G spectrum expansion within the Reference Architecture Blueprint by strengthening coordination with the ITU, advancing onboard and ground-segment RFI mitigation capabilities, safeguarding passive sensing frequency allocations, and systematically assessing the potential dual role of anthropogenic RF signals both as a risk to measurement integrity and as a possible new source of EO information.**

As the mobile telephone industry embarks on a vigorous development of 5G/6G terrestrial telecommunication networks, frequency space used by EO that was shared with original allocations to telecommunication systems is becoming unviable for EO applications. Furthermore, the character of 6G means that signals are encrypted and appear as noise without any structured signal that can be exploited by RFI detection and mitigation approaches.

Future missions must take these developments into consideration in two ways:

1. Explore the full exploitation of the ITU frequency spectrum allocated to EO and in particular, ensure that the geophysical sensitivity of each allocation is fully characterised and understood (e.g. the allocation to EO of 100MHz bands at 4GHz and 8GHz *should* allow the retrieval of surface temperature from space but little evidence exists today to build confidence that such allocations are feasible bearing in mind the typically high performance requirements of EO missions). Many primary passive and active frequency allocations remain underutilised today.

2. Invest in enhanced development of RFI detection and mitigation systems, both in-orbit and on-ground, to limit the damage of RFI on EO measurements (e.g. Sentinel-1 C-band SAR, SMOS and CIMR radiometers).
3. Continue and strengthen ESA EO reporting of ITU regulation infringement impacting EO data sets and monitor the evolution of RFI across the frequency spectrum in a coordinated manner.

[RAB-77]: **Ensure that new Earth Observation missions systematically assess and, where feasible, exploit underutilised portions of the International Telecommunication Union (ITU) frequency spectrum allocated to EO, in order to expand measurement capability and reduce congestion in heavily used bands.**

[RAB-78]: **Advance the incorporation of advanced radio-frequency interference (RFI) detection, characterisation, and mitigation techniques in both spacecraft payload design and ground-segment processing chains, to protect data quality throughout the mission lifecycle.**

[RAB-79]: **Strengthen ESA's coordinated monitoring and reporting of ITU regulation infringements that impact Earth Observation data sets and implement systematic surveillance of RFI evolution across the frequency spectrum to safeguard EO spectrum allocations and long-term data continuity.**

[RAB-80]: **Investigate and monitor the implications of emerging 5G and 6G terrestrial communication systems for EO frequency management, including both the risks of increased interference and the potential exploitation of these signals as opportunistic sources for Earth Observation measurements.**

The increasing density, diversity, and global coverage of anthropogenic radio frequency (RF) emissions from terrestrial communication and navigation systems represent a growing, yet largely untapped, observational resource for Earth Observation. Beyond their traditional role as sources of interference, these signals offer opportunities for passive and bistatic sensing techniques that can complement dedicated EO payloads, increase temporal sampling, and enable new classes of measurements at comparatively low marginal cost.

[RAB-81]: **Systematically investigate the use of anthropogenic RF signals—beyond Global Navigation Satellite System (GNSS) transmissions—as opportunistic sources for Earth Observation, while continuing**

and expanding the exploitation of GNSS-based techniques. The aim is to broaden the range of EO applications, improve observational coverage and revisit, and assess the technical, regulatory, and architectural implications of integrating opportunistic RF sensing within the European EO ecosystem.

5.15.5. Satellite refuelling and servicing

Satellite refuelling and in-orbit servicing are expected to become technically and operationally viable by around 2040, first as a routine capability in geostationary orbit—where replacement costs are extremely high—and potentially later for selected critical low Earth orbit missions. These capabilities are increasingly linked to sustainability and regulatory pressures, as life extension, controlled end-of-life disposal, and debris mitigation become integral to responsible space operations. In-orbit servicing can reduce the need for full satellite replacement, improve mission resilience, and lower long-term system costs, while also supporting compliance with emerging space environment regulations.

In this context, the ESA-supported RISE mission represents an important milestone. RISE is a commercial in-orbit servicing demonstration that will validate safe rendezvous and docking with a geostationary client satellite, enabling life-extension services for GEO assets. Beyond refuelling, such missions pave the way for refurbishment, modular upgrades, and potentially in-orbit assembly, marking a transition toward a more circular and sustainable space economy. From a Reference Architecture perspective, these capabilities introduce new design degrees of freedom—affecting mission lifetime assumptions, redundancy strategies, resilience planning, and the economics of long-lived EO infrastructure.

[RAB-82]: **Integrate in-orbit servicing, refuelling, and life-extension capabilities into the Reference Architecture Blueprint as emerging enablers of resilience and sustainability, by anticipating their impact on mission design, lifetime management, end-of-life disposal, and cost models, and by ensuring that future European EO missions are compatible—where appropriate—with servicing and debris-mitigation architectures.**

5.15.6. International Terrestrial Reference System (ITRF)

The Earth undergoes continual changes in shape, which are observed through the motion of its crust. To accurately interpret this motion, a Terrestrial Reference Frame (TRF) is required as a reference providing coordinates for points on the Earth's surface. The TRF frame serves various purposes including representing the Earth's rotation in space relative to celestial objects. Established in 1988, the International Earth Rotation and Reference Systems Service (IERS) oversees the creation and maintenance of both the Celestial Reference

Frame (ICRF) and the Terrestrial Reference Frame (ITRF), which are interconnected through Earth Orientation Parameters (EOPs). These reference frames offer a common basis for comparing observations and results across different locations.

Geodetic techniques such as GNSS, Very Long Baseline Interferometry (VLBI), Satellite Laser Ranging (SLR), Lunar LASer Ranging (LRR) and DORIS (Détermination d'Orbite et Radiopositionnement Intégré par Satellite) are employed to compute precise coordinates, with the ITRF continuously updated to accommodate improvements in tracking networks and data availability.

The ITRF is used in satellite orbit prediction as the fundamental, high-accuracy, Earth-fixed coordinate system (the realisation of the international reference frame service, ITRS) that provides precise positions and velocities for ground-based tracking stations and satellites. By defining a consistent, geocentric coordinate system (originating at the Earth's centre of mass), ITRF allows for the accurate modelling of ground-to-satellite observations (i.e. SLR, GNSS, DORIS) to determine current orbits and extrapolate them into the future.

The ITRF serves as the cornerstone for determining positions both on Earth and in space, providing a reliable framework for accurately measuring the impacts of geodynamic processes and ongoing climate change. By maintaining and improving a consistent reference system, the ITRF, present and future challenges across a spectrum of location-based applications, including navigation, traffic management, transport logistics, and the control of industrial and agricultural machinery, as well as emerging technologies such as autonomous driving can be addressed. Furthermore, a globally uniform reference frame is essential for comprehending the dynamics of our planet, monitoring climate change phenomena, and deploying early-warning systems to mitigate natural hazards.

The International Terrestrial Reference Frame (ITRF) underpins all precise positioning on Earth and in space and is a foundational enabler of Earth Observation, navigation, geodesy, and climate monitoring. Accurate detection of geodynamic processes, sea-level change, ice-mass loss, and long-term climate signals depends critically on the stability, continuity, and accuracy of the ITRF. A healthy and continuously improved IRTF is fundamental to the future of the EEOE in the Blueprint.

[RAB-83]: Actively sustain, evolve, and strengthen Europe’s contribution to the ITRF—across spaceborne and ground-based systems—as a core public infrastructure and a non-negotiable building block of the European Earth Observation Ecosystem.

5.15.7. Advanced on-board technologies that maintain SI traceable calibration

Advanced on-board calibration technologies are a cornerstone of the Reference Architecture Blueprint because they enable Earth Observation (EO) measurements that are not only precise at launch, but remain traceable, comparable, and defensible over decades. As missions increasingly rely on constellations, autonomous processing, and hybrid institutional–

commercial data streams, maintaining SI-traceable calibration in orbit becomes an architectural necessity rather than a mission-specific enhancement. Techniques such as phase-change thermometry cells (e.g. Pearce et al. 2019) provide absolute temperature reference points that are inherently stable over time; on-board reference radiance blackbodies and microwave active cold loads (e.g. *Thomas et al.* 2025) anchor radiometric calibration for infrared and microwave instruments; optical diffusers and solar diffusers enable stable reflectance calibration for imaging spectrometers; and high-stability timing and frequency references (including space-qualified atomic clocks) ensure phase, coherence, and geolocation accuracy across distributed systems.

Together with in-orbit cross-calibration and reference missions, these technologies form a self-consistent calibration framework that preserves measurement integrity despite instrument ageing, radiation damage, and evolving operational modes. The Blueprint therefore treats advanced on-board calibration subsystems not as optional payload features, but as core architectural elements required to sustain Europe's ability to deliver trusted climate records, policy-grade evidence, and interoperable multi-mission products across the full European EO System-of-Systems.

[RAB-84]: **Establish advanced on-board calibration subsystems as mandatory architectural elements for European EO missions—deploying SI-traceable references such as phase-change thermometry cells, radiance blackbodies, optical diffusers, active cold loads, and high-stability timing clocks—to ensure long-term measurement accuracy, cross-mission interoperability, and policy-grade data trust across institutional and commercial constellations.**

Maintaining compact, low-mass, and low-power calibration devices is essential to ensure that SI-traceable performance remains compatible with modern EO mission architectures, particularly constellations and miniaturised platforms. If calibration subsystems scale disproportionately in size, mass, or power, they become the first elements to be removed under cost or platform constraints: this directly undermines data quality, interoperability, and long-term trust. Compact phase-change cells, miniaturised blackbodies, solid-state diffusers, low-power active cold loads, and chip-scale timing references allow rigorous calibration to be embedded across a wide range of platforms without sacrificing payload capability or constellation viability. In the Reference Architecture Blueprint, miniaturisation of calibration technology is therefore a strategic enabler: it preserves SI traceability while allowing high-performance measurements to be distributed across resilient, scalable, and affordable EO systems.

[RAB-85]: **Prioritise the miniaturisation and space qualification of SI-traceable on-board calibration and timing devices ensuring that high-performance calibration devices can be embedded across constellation and small-satellite platforms without compromising measurement integrity, interoperability, or long-term data trust.**

5.15.8. Spaceborne automatic identification system (AIS)

Since 2004, the International Maritime Organization (IMO) has required Automatic Identification System (AIS) transponders to be aboard ships at sea via the Safety of Life at Sea (SOLAS) Convention, Chapter V: "All ships of 300 gross tonnage and upwards engaged on international voyages and cargo ships of 500 gross tonnage and upwards not engaged on international voyages and passenger ships irrespective of size shall be fitted with an automatic identification system (AIS)." AIS transponders broadcast vessel transit information (course, speed etc) every few seconds allowing other ships to chart their progress using electronic navigation charts to avoid collision at sea.

More than 60,000 ships worldwide have installed AIS transponders making AIS one of the most successful maritime technology deployments of all time. Equipment that uses AIS technology is increasingly being deployed in smaller vessels, as well as radio/AIS-enabled aids to navigation (AtoNs), and it is also being installed on search and rescue (SAR) vessels and aircraft.

AIS signals can be tracked from space and Spire Inc. provides advanced commercial AIS tracking services in real time that exploit many properties of the AIS signal (e.g. Doppler signal characteristics) to international customers. Scientific activities have led to the development of commercial systems that provide estimates of total ocean surface current (e.g. e-odyn.com). The Copernicus Sentinel-1 C and D satellites include AIS as part of their design allowing the simultaneous acquisition of SAR imagery and space-based AIS data to simplify data fusion and analysis of acquired data. AIS data will be collected during Sentinel-1 SAR acquisitions to receive the AIS signal transmitted from AIS ship mobile stations on the same access area of the radar instrument facilitating the required time and position correlation for further analysis.

The implementation of AIS systems as hosted payload will increase the coverage and may be used in a variety of security and commercial applications.

[RAB-86]: **Building on the Sentinel-1 heritage, encourage the systematic deployment of reference-grade Automatic Identification System (AIS) payloads on ESA satellites. These payloads should support maritime security applications, enable the derivation of ocean surface current information, and provide a stable reference framework that complements and underpins commercial European AIS constellation approaches.**

5.15.9. Fiducial Reference Measurement (FRM) capability gap

The character of satellite data is such that it provides an overwhelming number of measurements compared to the *in situ* system. Consequently, small bias errors have profound impact on our understanding of the Earth system – particularly for global scale budgeting purposes (e.g. Water Cycle, Carbon Cycle, sea level rise budget closure). In some cases, in situ observations form part of the payload observing system transition form Level-1 to Level-2 products (e.g. vicarious calibration gain adjustment of ocean colour spectro-radiometers). Despite nearly a decade of activity, it is startling to realise that Europe still has no operational FRM capability to implement and manage vicarious gain calibration of Sentinel-3 OLCI instruments. This is further compounded by fractures in the US MOBY vicarious calibration in situ reference system that is impacting the recently launched NASA PACE mission. Further action is required in Europe to address this type of situation, which is not limited to ocean colour instruments. In terms of a full understanding of EO data, validation of EO data through agreed FRM protocols is vital to Earth science, where products of different technologies and methods need to be understood and compared in the most objective way. For this, the introduction of a general Fiducial Reference Measurement (FRM) framework transversal to all established missions and products has marked a significant step forward. It is not only necessary within activities by ESA and collaborating space agencies, but even more in today's global context, where products are generated by privately owned constellations, to ensure users correctly understand and can utilise EO products.

[RAB-87]: **Support the Fiducial Reference Measurement (FRM) framework and foster activities to assess objectively EO products generated by established ESA programmes and communicate the quality and uncertainty quantification of ESA EO data to final users. (ESA/PB-EO(2025)13,REV.1)**

5.16. Institutional and Financial Stress on the Reference Architecture

5.16.1. Governance

The Reference Architecture implementation approach provides a governance framework in terms of accountability (Authenticity, Certification), leadership (Reference Architecture design and implementation together with European Partners), integrity (reference missions used together with commercial and other missions to assure quality), stewardship (long term sustainability and innovation), transparency (open inclusive framework where uncertainties provided) and data precision (free and open data access and use policy). Governance of each individual mission within the ecosystem is clear but overall governance of the European EO ecosystem as envisaged in the Reference Architecture Blueprint requires further elaboration.

[RAB-88]: **Clarify governance of the European EO ecosystem (federated system) through articulation and analysis of different governance models.**

5.16.2. Stability, continuity and sustainability

Reference Architecture Blueprint recognises that institutional and financial pressures are now among the dominant constraints shaping the long-term performance of the EEOE system-of-systems. As EO becomes increasingly embedded in policy implementation, security, economic decision-making, and societal resilience, expectations of continuity and reliability rise - often faster than the growth of available resources. Stability and sustainability must be treated as architectural properties, not as emergent outcomes of individual programmes.

Institutional stress arises from expanding mandates, overlapping responsibilities across European and national actors, and growing interdependence between civil, security, scientific, and commercial domains. At the same time, EO infrastructures are inherently long-lived, requiring commitments over decades to maintain climate records, calibration traceability, and operational services. Discontinuities driven by short-term budget cycles, programme fragmentation, or shifting political priorities risk undermining data trust, policy credibility, and return on investment.

Financial stress compounds these challenges. Rising mission complexity, increasing system interdependencies, growing data volumes, and stricter sustainability requirements place upward pressure on costs across space, ground, and digital segments. Without architectural coordination, these pressures can lead to reactive prioritisation, erosion of continuity, or premature termination of capabilities that are essential for long-term science and policy objectives. Conversely, over-constraining innovation in response to cost pressure risks locking the system into suboptimal solutions that reduce adaptability and long-term value.

The Reference Architecture therefore emphasises stability through coherence: aligning institutional roles, investment horizons, and capability evolution within a shared architectural framework. Continuity of essential observations, preservation of reference measurements, and sustained operation of critical ground and data infrastructures are treated as system-level obligations rather than discretionary programme choices. Sustainability is addressed not only in financial terms, but also through efficient reuse of infrastructure, federation across actors, and integration of innovation pathways that reduce long-term risk and cost.

In this context, the Blueprint provides a mechanism for anticipatory governance, enabling the European Space Agency and its partners to balance ambition with affordability, and innovation with continuity. By explicitly accounting for institutional and financial stressors, the Reference Architecture supports informed trade-offs that protect Europe's long-term EO capabilities, ensuring that the system remains stable, credible, and sustainable in the face of evolving demands and constrained resources.

[RAB-89]: **Treat stability, continuity, and sustainability as explicit system-level architectural objectives of the European Earth Observation Ecosystem. The Blueprint provides an anticipatory mechanism to balance innovation with continuity and ambition with affordability,**

ensuring long-term credibility and resilience under constrained resources.

5.16.3. Mission complexity and cost escalation

Mission complexity and cost escalation have become structural challenges for the future evolution of the EEOE system-of-systems. As the existing EO landscape matures, many of the lower-risk, lower-complexity mission concepts have already been implemented. Future missions are therefore increasingly characterised by higher technical ambition, tighter performance requirements, more demanding calibration and validation needs, greater interdependencies across system elements, and stronger expectations for continuity, resilience, and policy relevance. These factors collectively drive upward pressure on development cost, schedule risk, and operational burden.

Complexity growth is not confined to the space segment. Ground systems, data infrastructures, processing chains, and governance arrangements have expanded significantly, particularly with the rise of multi-mission synergies, continuous reprocessing, AI-enabled analytics, and near-real-time service demands. While these capabilities increase system value, they also introduce hidden coupling between components, reduce flexibility, and amplify the cost of change. Without architectural discipline, incremental requirements accumulated across missions and services can lead to disproportionate increases in Cost at Completion, reduced industrial competition, and longer development timelines.

Cost escalation is further influenced by industrial and programmatic dynamics. High-risk, one-off missions are increasingly unattractive to industry compared to recurring production lines and constellation-based systems, shifting incentives toward standardisation and series builds. While this trend supports affordability and schedule predictability, it also risks narrowing the design space and constraining innovation if not balanced by dedicated exploratory pathways. In addition, stricter sustainability, debris mitigation, cybersecurity, and regulatory compliance requirements, while essential, add further cost drivers that must be managed at system level rather than absorbed mission by mission.

The Reference Architecture Blueprint therefore treats complexity and cost escalation as system-level issue that requires anticipatory management. Architectural principles such as modularity, reuse, interoperability, staged capability maturation, and explicit separation of exploratory and operational pathways are essential to containing complexity while preserving ambition. Equally important is early, architecture-led trade-off analysis that makes the cost implications of performance, continuity, latency, and resilience requirements transparent before they become embedded in programme commitments.

In practical terms, the management of mission and architectural complexity and cost escalation is achieved through a coherent and linked set of preparatory activities from pre-phase 0 to the end of a mission on orbit. Sustained and early investment in key technologies and scientific preparation is particularly important (i.e. increasing SRL, TRL and mission concept maturity to 5 at the end of Phase-A). In terms of architectural coherence in a federated system, many system-to-system interface aspects are important in terms of standardisation (e.g. ECSS) and care must be taken to include future architectural aspects when tailoring. Likewise, design choices to enhance interoperability (e.g. reuse or redesign philosophies) must be balanced against the need for continued innovation and evolution of the EEOE.

[RAB-90]: Actively manage mission complexity and cost escalation through architecture-led design and governance by enforcing modularity, reuse, and interoperability; applying early system-level trade-off analysis; and maintaining distinct exploratory and operational development pathways—ensuring that future EO missions remain affordable, competitive, and ambitious without accumulating unsustainable complexity across the European EO Ecosystem.

5.16.4. External geopolitical and international funding dependencies

Under the current U.S. administration, evolving trends in funding allocation and policy priorities for science and related domains may significantly affect the continuity, volume, and accessibility of Earth Observation (EO) data streams provided by NOAA and NASA, which are extensively used by the global Earth science community. NOAA has already articulated a commercial engagement policy for the future provision of weather-related data, signalling a potential shift in how key observational capabilities are sustained and accessed. At the same time, pressures arising from budget reductions, staffing constraints, political interference, and the ageing of critical satellite and observational infrastructure introduce additional uncertainty regarding the long-term stability of U.S. EO data provision.

Concerns are particularly acute for NASA's science portfolio. Ongoing pressure to reduce NASA science programmes has reportedly led to mission teams being asked to prepare accelerated "closeout" plans during 2025, raising the prospect of a substantial reduction in the Congressionally approved science budget for fiscal year 2026 (FY26) although not realised in practice. While the full implications for NASA's Earth science fleet remain uncertain, early signals suggest that reductions in mission scope, data continuity, or archive maintenance may occur. What is known is that a large number of NASA and NOAA employees with direct involvement of EO activities have been laid off, significantly impacting the corporate memory of Earth Observation in both institutions.

These developments underscore the growing risk of external dependencies for long-term EO data records and highlight the need for the European EO Reference Architecture to anticipate and mitigate potential impacts arising from shifts in international funding and policy environments.

6. SUSTAINABILITY OF THE EUROPEAN EO FEDERATED SYSTEM ECOSYSTEM

The Reference Architecture Blueprint adopts a fundamental shift in perspective: from sustaining individual programmes to sustaining capability over decades. This encompasses continuity of key observables, institutional and governance sustainability, preservation of critical skills and industrial capacity, and the long-term maintenance of trust, legitimacy, and scientific credibility. These dimensions align directly with ESA's unique stewardship role as the long-term architect and custodian of Europe's Earth Observation (EO) capability.

While many elements of this capability already exist, a new paradigm is required to maintain, apply, and evolve the mono-mission EO profiles developed over the past 40 years. The future European EO system must function as a coherent, evolving system-of-systems, integrating modern space technologies with established assets. It must support Earth Action and near-real-time strategic applications, embed traceable security and authenticity mechanisms, respond to emerging European and global geopolitical dynamics, and fully embrace Artificial Intelligence and other enabling technologies—while maintaining continuity with proven methodologies.

The Reference Architecture must enable coherent constellation-level calibration and traceability, support the participation of national and commercial space providers, and integrate enhanced in situ reference measurement systems traceable to SI standards. It must also rely on agile, industrialised ground segment architectures that empower users through advanced multi-mission processing, long-term data preservation, and scalable service provision. In this context, the shift toward service-based, industrial data and operations architectures is essential to remain effective in a rapidly evolving digital environment.

Such an architecture must be dynamic yet traceable, capable of responding to evolving user needs while maintaining long-term consistency. It must explicitly support the definition, monitoring, and verification of policy-mandated thresholds, Earth system tipping points, and planetary boundaries—enabling informed governance of the Earth system and societal sustainability objectives, including those embodied in the EU Green Deal. At the same time, it must preserve technical and scientific innovation, fostering the development of new knowledge, technologies, and applications that underpin Europe's global leadership in Earth Observation.

In this way, the Reference Architecture Blueprint provides a cooperative framework for Europe's—and increasingly the global—capacity to understand the Earth system and its interaction with the biosphere, while delivering tangible societal benefit in a rapidly changing climate system.

Sustaining Earth system knowledge and policy-relevant evidence responds directly to escalating climate impacts, Earth system instability, and rising policy dependence on EO. It ensures continuity of trusted observations and predictive capability despite institutional and geopolitical uncertainty, reinforcing EO as critical public infrastructure rather than discretionary science.

[RAB-91]: **Maintain European leadership in holistic Earth system understanding by delivering observational and predictive, evidence-based solutions that support the definition, implementation, and monitoring of policies addressing climate change, Earth system stability, and societal security. This requires sustaining and evolving the satellite system-of-systems while retaining a strong appetite for scientific and technological risk—particularly through innovative Earth Explorer missions and the preparation of future operational capabilities.**

This responds to Blueprint drivers discussed in sections:

- 5.7 Climate, Environment, and Planetary Stewardship Pressures
- 5.8 Security, Defence, and Societal Resilience
- 5.15 Institutional and Financial Stress

Flagship reference missions and metrology leadership addresses the sustained need for trusted reference standards in an increasingly commercial and hybrid EO ecosystem. This mitigates fragmentation, data authenticity risks, and loss of scientific authority through internationally recognised calibration leadership. ESA can achieve such missions through the common effort of all its Member States.

[RAB-92]: **Ensure the presence and promotion of the world's most ambitious EO "flagship" missions by leading the design and implementation of reference satellite capabilities that adhere to international metrology and calibration standards. Such missions anchor Europe's scientific authority, enable capabilities only achievable through collective European effort, and provide essential calibration references for commercial and institutional EO constellations.**

This responds to Blueprint drivers discussed in sections:

- 5.13 Space Environment, Spectrum, and Measurement Integrity
- 5.10 Innovation Transfer and Capability Evolution
- 5.9 Public–Private Convergence and Market Transformation

A systematic, constant and predictable flow of mission selection and implementation is inextricably linked to ESA CMIN and EC MFF funding approval cycles. Predictable mission cadence and system-level optimisation though a stable mission flow reduces institutional and funding volatility, sustains industrial and skills bases, and allows long-term system optimisation rather than reactive programme decisions—directly addressing governance and sustainability pressures. To mitigate overcommitment within the European industrial, scientific and institutional landscape, planning should integrate interleaved preparation cycles in a harmonised manner as a “full picture view” across Explorer, Scout, Φ-Sat, Earthwatch, Copernicus, and Meteorological missions.

[RAB-93]: **Maintain a predictable and transparent flow of mission selection and implementation aligned with Ministerial Conference and EU funding cycles. A stable cadence across Explorers, Scouts, Φ-sat, Earth Watch, Copernicus, and meteorological missions enable long-term planning for industry and user communities, supports investment confidence, and optimises the European EO system-of-systems through coordinated evolution rather than isolated programme decisions.**

This responds to Blueprint drivers discussed in sections:

- 5.15 Institutional and Financial Stress
- 5.9 Public–Private Convergence and Market Transformation
- 5.6 Human Capital, Skills, and Institutional Memory

Earth system stewardship and planetary boundaries embed Earth system governance concepts (tipping points, planetary boundaries) into EO architecture, aligning observation strategy with long-term societal resilience and global sustainability frameworks.

[RAB-94]: **Embed Earth system stewardship and systems thinking at the core of the EO system-of-systems by aligning observation capabilities, technologies, data, and applications with the governance of planetary commons, including Earth system tipping points and planetary boundaries. This positions Europe as a global leader in shaping EO for the Anthropocene and catalysing international cooperation for sustainable futures.**

This responds to Blueprint drivers discussed in sections:

- 5.7 Climate, Environment, and Planetary Stewardship Pressures
- 5.8 Security, Defence, and Societal Resilience
- 5.4 Mapping drivers to architectural functions (cross-cutting)

Observation densification and process-scale relevance address chronic under-sampling relative to policy and process time–space scales, responding to rising expectations for decision-grade EO while respecting scientific sampling theory and avoiding naïve densification.

[RAB-95]: **Systematically document and address limitations of the current European EO ecosystem through sustained dialogue with scientific**

and operational users, particularly regarding observation densification at policy- and process-relevant time and space scales. Explore solutions including GEO and highly elliptical orbits, advanced constellations, formation flying, novel calibration approaches, HAPS, and integrated in situ networks.

This responds to Blueprint drivers discussed in sections:

- 5.7 Climate and Environmental Pressures
- 5.12 Technology Convergence and Measurement Acceleration
- 5.13 Measurement Integrity and Performance

An inclusive and federated EO ecosystem design responds to increasing ecosystem fragmentation by enabling federation without loss of coherence, ensuring resilience while accommodating new national, commercial, and non-space actors

[RAB-96]: **Ensure an inclusive and federated EO ecosystem by promoting open, collaborative partnerships across institutional, national, commercial, in situ, and HAPS-based systems, enabling complementary contributions while maintaining architectural coherence.**

This responds to Blueprint drivers discussed in sections:

- 5.9 Public–Private Convergence and Market Transformation
- 5.6 Human Capital and Institutional Memory
- 5.12 Geopolitics, Autonomy, and System Resilience

Observe the unobserved to address structural observation gaps critical to future climate, water, carbon, and cryosphere governance, reinforcing the need for daring exploration beyond incremental extensions of existing systems.

[RAB-97]: **Advance the observation of currently unobserved or poorly observed components of the Earth system, including subsurface oceans, land processes, atmospheric transition regions, and coupled biogeochemical cycles. Initiate coordinated scientific and industrial efforts to explore novel measurement techniques and spectral domains, assessing feasibility and impact for future missions.**

This responds to Blueprint drivers discussed in sections:

- 5.7 Climate and Earth System Pressures

- 5.12 Technology Convergence
- 5.10 Innovation Transfer

AI/ML-enabled system-of-systems exploitation addresses exponential data growth and AI adoption by repositioning the ground segment as a system-level “value engine,” ensuring that EO scales into policy, economic, and societal decision frameworks with traceability and trust.

[RAB-98]: **Exploit system-of-systems synergies through AI and modern computing paradigms, evolving the ground segment into a high-performance, multi-mission analytics environment capable of generating integrated, policy-relevant products. Ensure traceability, authentication, and certification of inputs and outputs to support trusted decision-making across scientific, societal, and economic domains.**

This responds to Blueprint drivers discussed in sections:

- 5.11 Artificial Intelligence as an Architectural Enabler
- 5.9 Public–Private Convergence
- 5.3 Metrics of Architectural Success

Intelligent autonomous EO sampling addresses the limits of static observing strategies under congestion, data volume growth, and formation-flying ambition—enabling adaptive, efficient sensing in future flagship architectures.

[RAB-99]: **Strategically develop intelligent, autonomous EO sampling capabilities using satellite-to-satellite and satellite–ground–satellite links to enable tip-and-cue operations, adaptive observing strategies, and precision formation flying. These capabilities are essential for next-generation flagship missions and a fully interconnected EO system-of-systems.**

This responds to Blueprint drivers discussed in sections:

- 5.11 Artificial Intelligence
- 5.12 Technology Convergence
- 5.13 Space Environment and Measurement Integrity

Near-real-time data relay and processing addresses rising demand for sub-hour latency products in crisis, defence, and forecasting contexts, while reducing dependency on external infrastructure through secure relay and processing pathways.

[RAB-100]: Enable efficient, secure near-real-time relay of EO data for time-critical applications by investing in inter-satellite communication, dedicated processing hubs, and reconfigurable onboard processing. Explore synergies with emerging communication constellations, including opportunities to host EO payloads.

This responds to Blueprint drivers discussed in sections:

- 5.8 Security and Societal Resilience
- 5.11 AI and Digital Infrastructure
- 5.12 Geopolitics and Autonomy

Destination Earth (DestinE) is a flagship European Commission initiative to develop a high-fidelity Digital Twin of Earth capable of monitoring and simulating natural processes, hazards, and human activities to support adaptation and mitigation strategies. DestinE is built on three core pillars: the DestinE Platform developed by European Space Agency, the Data Lake implemented by EUMETSAT, and the Digital Twin Engine led by European Centre for Medium-Range Weather Forecasts. In 2025, the platform hosts over 4,300 registered users, 27 services, and two operational Digital Twins: Climate and Extremes.

The DestinE Platform provides a cloud-based access point to the DestinE ecosystem, enabling users to access data, models, and services across the system. It manages data access from the Data Lake, supports traceability and harmonisation, and offers basic analytics tools, catalogues, and 2D/3D visualisation, with scalable infrastructure to serve scientific, policy, industrial, and public users.

The Data Lake enables near-data processing and seamless access to large, distributed datasets via APIs and graphical interfaces, while the Digital Twin Engine provides the modelling infrastructure to operate DestinE's Digital Twins. The Climate and Extremes Digital Twins deliver kilometre-scale global simulations on EuroHPC systems, supporting short-term extreme-event prediction and multi-decadal climate scenario analysis. DestinE enables AI-based methods to complement physics-based models, significantly advancing Earth system forecasting and decision support.

[RAB-101]: Further invest in transformative digital infrastructures—including space data platforms and Digital Twins—as structural enablers across the geospatial ecosystem. Fully exploit multi-mission synergies, AI-based analytics, and federated access models to maximise user uptake, policy impact, and commercial value across institutional and market domains.

This responds to Blueprint drivers discussed in sections:

- 5.11 Artificial Intelligence
- 5.7 Climate and Planetary Stewardship
- 5.15 Institutional and Financial Stress

7. EUROPEAN EO ECOSYSTEM GAP ANALYSIS 2030-2050

This section provides a succinct analysis of gaps in the ESA EO ecosystem that are considered priorities to address in the 2030-2050 timescale. Gaps in the Reference Architecture Blueprint can be classified as:

- **Capability gaps:** Gaps where the European EO Ecosystem lacks the ability to observe, process, or deliver information at the spatial, temporal, spectral, or accuracy levels required by scientific, operational, or policy needs. These include missing observables, insufficient measurement performance, inadequate revisit or latency, lack of continuity, or absence of mature methods to translate observations into decision-grade products. Both "mission-specific" gaps (technological gaps) and scientific gaps must be considered.
- **Enabling infrastructure gaps:** Gaps in the supporting space, ground, digital, and in situ infrastructures that limit the effective exploitation of EO capabilities. This includes shortcomings in launch access, satellite communication and data relay, ground segment scalability, calibration and validation networks, computing and storage capacity, interoperability of platforms, and resilience of digital infrastructures.
- **Governance and policy gaps:** Gaps arising from unclear, fragmented, or misaligned institutional roles, policies, funding mechanisms, standards, or coordination processes. These gaps affect decision-making efficiency, long-term continuity, data access and sharing, performance certification, commercial engagement, and the ability to manage system-level trade-offs across the EO ecosystem.
- **External constraint gaps** (spectrum, SSA, regulation): Gaps driven by constraints largely outside the direct control of EO programme design, including radio-frequency spectrum availability and protection, space situational awareness and traffic management, space debris and sustainability regulations, export controls, and evolving international legal and geopolitical frameworks. These constraints can limit feasible mission designs, observing strategies, and long-term system resilience if not anticipated architecturally.

The following elements of the EOEE are discussed:

- Elements not fitting a federated system family
- Active Microwave Imagery Family
- Passive Microwave Imagery Family
- Passive Microwave Sounding Family
- Altimetry Family (optical and active microwave)
- Optical Imagery Family (from UV – LWIR - FIR)
- Active Optical (LIDAR) Family
- Limb Sounder Family (passive and using active signal sources (RO))
- Atmospheric Spectroscopy Family
- Gravimetry Family
- Geomagnetic Family

Other families could include In-situ Family (e.g. electron density measurements in a geomagnetic Family), New Observatory Function Family, High Altitude Platform Stations (HAPS).

7.1. Performance within the European EO Ecosystem

7.1.1. Measurement authenticity and trust

Today, EO data is applied by almost every major industry with increasing demands as new applications across scientific, institutional, government, social, business, and financial/insurance risk markets mature. EO data is increasingly applied for diverse purposes, particularly in finance for risk analysis, cash flow forecasting models and credit scoring tools. Insurance companies use EO to identify disaster-prone areas, ensuring cost-effective coverage policies for policyholders while remaining profitable. Financial awards to offset damaging practices (e.g. deforestation, urbanisation etc.) rely on EO data for verification. New satellite systems such as CO2M will enable to identify and quantify sources of CO_2 and CH_4 allowing to support policymakers and a potential for enabling enforcement. The applicability of subsidies granted within the Common Agriculture Policy (CAP) regarding specific agricultural practices can be verified in a fully automatic way using remote sensing data. There are many examples where EO data may be used today or in the future as evidence in a court of law.

For a successful application in a court of law, EO data must demonstrate authenticity in a world of increasing “deep fake” systems. Authenticity regarding the satellite platform and instrument, acquisition time, geographic area of coverage, scientific content and measurement performance, a guarantee that no alterations to the original data are present, legitimate ownership and intellectual property rights are amongst the attributes requiring authenticity. In addition, data confidentiality is of growing concern for sensitive financial and political aspects. To address these issues, new technologies must be further consolidated (e.g. blockchain) to guarantee authenticity of EO data.

[RAB-102]: Design, develop, implement, and operate tools and procedures to certify EO data authenticity.

New technologies must be further consolidated (e.g. blockchain) to guarantee authenticity of ESA EO data. While, such technologies exist today, and it is mostly a matter of applying them to Level-1 and Level-2 products produced *within* the European EO Ecosystem. For higher-order products (e.g. amalgamating different data using synergy/AI processors for specific user applications), authenticity certification rests with the product producer or regulatory authority.

7.1.2. Measurement performance certification

EO data are now embedded across almost every major industrial sector, with rapidly increasing demand as applications mature in scientific, institutional, governmental, social, commercial, and financial domains. In particular, the finance and insurance sectors are becoming major consumers of EO-derived information, using it for risk analysis, asset exposure assessment, cash-flow forecasting, and credit-scoring models. Insurance providers increasingly rely on EO to identify hazard-prone regions, price risk appropriately, and design cost-effective yet profitable coverage policies. Similarly, the verification of financial mechanisms intended to incentivise or penalise environmental practices—such as payments linked to deforestation, land-use change, or urban development—depends critically on trusted EO evidence.

A specific aspect of EO data certification is the scientific content of EO data and the performance uncertainty of the measurements provided to the user community. For a successful application in a court of law, EO data must demonstrate that the measurement data are indeed an accurate representation of the phenomenon in question (e.g. field boundary and crop type, carbon dioxide or methane concentration in a plume etc). To withstand detailed scrutiny, measurement data must have certified scientific performance uncertainty that is documented, traceable to SI standards and recognised as authentic. This is particularly relevant in the context of climate data records and future Earth Action where climate mitigation and adaptation policies may have significant societal implications – raising the prospect of legal challenges.

Today, many commercial satellite companies propose “New Space” constellations that are tailored to specific applications and markets. Yet, little information is available reporting the performance uncertainty of the EO solutions (either measurement data or analysed service products). Given the limited duty-cycle (often a few minutes per orbit), typical of most small satellites operating in such constellations that are tailored to specific geographic regions, end users may need to rely on several providers to mosaic multiple data streams together to attain the coverage necessary or the time evolution of the target observation for a given application. Furthermore, the small satellite solutions increasingly proposed and deployed by commercial satellite operators have limited capacity to implement robust traceable calibration sub-systems necessitating the use of larger “reference class” satellite missions (typically operated by ESA and other institutional providers) to maintain calibration and calibration stability by transferring the calibration from the reference mission.

If calibration aspects are not adequately managed and controlled against International Measurement Standards (SI) across the European EO Ecosystem, deriving homogeneous data products from multiple inputs becomes a financial and technical challenge – a condition referred to as “Grandmas Patchwork Quilt” (GPQ) -see Figure 7.1.2.1. It becomes extremely challenging (if not impossible) to generate a coherent and homogenised data set, such as a reflectance map of Europe, form a diverse set of satellite payloads managed by many operators with non-standard calibration sub-systems and performances. It remains a difficult task for the best EO scientists and one that will take considerable resources to achieve success (e.g. the ESA Climate Change Initiative has dedicated much of its work to addressing different satellite calibration issues). Commercial missions do not always provide detailed documentation to understand payload characteristics and retrieval algorithms and changes may be implemented by the provider without any notification to the user base or public documentation – often tied to the implementation of restrictive licensing policies. In this scenario, even with the availability of satellite reference quality missions, the level of effort to understand and compensate/mitigate calibration differences is extremely high: the level of investment to "fix the calibration problem" later in a satellite mission implementation timeline may be considerably higher than to design a robust SI traceable on-board calibration system in the first place.

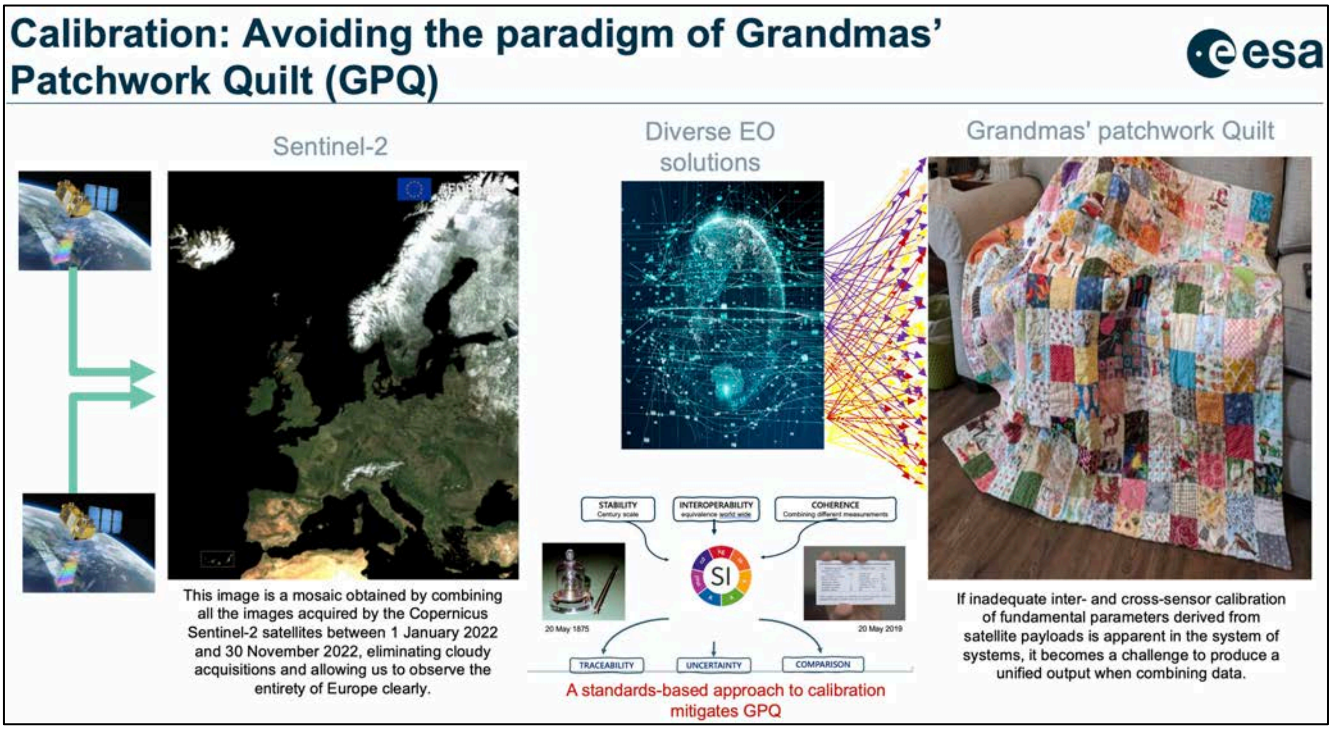


Figure 7.1.2-1. The paradigm of "Grandmas Patchwork Quilt" (GPQ). The figure illustrates that without adequate calibration control deriving homogeneous data products from multiple inputs becomes a financial and technical challenge. This is because the level of effort to understand and compensate and or mitigate calibration differences is extremely high. As an example, the ESA Climate Change Initiative has invested considerably in such work to derive a stable time series of global variables. In an operational context, recent examples from NOAA using commercial Radio Occultation (RO) data find a similar conclusion.

It is implicitly assumed that a reference class mission has a calibration that is robust, stable, and traceable to SI standards. To support future applications of EO data for climate adaptation and mitigation policy, challenges in a court of law and to facilitate and enable new commercial space" constellations and systems, future ESA developed missions must strive to certify scientific performance uncertainty with well documented traceability to SI standards to be recognised as authentic measurements. In addition, Commercial Space providers must be strongly encouraged to develop openness and transparency on mission calibration aspects to facilitate their full inclusion in the European EO ecosystem in a cost-effective manner.

As EO data moves further into regulatory, legal, and financial decision-making, data authenticity, provenance, and trustworthiness become central architectural requirements. Technologies capable of ensuring data integrity and traceability—such as cryptographic signing, distributed ledgers, and secure provenance frameworks—already exist and can be applied systematically to institutional EO products. In particular, authenticity guarantees can be embedded at the level of ESA-produced Level-1 and Level-2 products, providing a trusted foundation for downstream use. For higher-order products generated through data fusion, AI-based analytics, or multi-source synergies, responsibility for authenticity and certification necessarily rests with the product or service provider, requiring clear standards and governance frameworks across the ecosystem.

[RAB-103]: **As a strategic investment, design, develop, implement, and operate a European EO Authentication and Measurement Performance Certification Service that can guarantee certification of EO measurement performance uncertainty with well documented traceability to SI standards to be recognised as authentic measurements.**

[RAB-104]: **As a strategic investment, develop sustained reference class reference satellite missions and supporting ground system services that form the backbone of the European EO Authentication and Measurement Performance Certification Service.**

[RAB-105]: **As a strategic investment, design, develop, implement all future mission on-board payload calibration sub-systems adhering to the European EO Authentication and Measurement Performance Certification Service requirements for subsequent operations within the EO data and operations framework.**

[RAB-106]: **Commercial Space providers must be strongly encouraged to develop openness and transparency on mission calibration aspects to facilitate their full inclusion in the European EO ecosystem in a cost-effective manner.**

Challenges remain since there is an implicit assumption that cross-calibration of commercial/national missions using institutional missions is generally feasible. However, most commercial/national missions are not designed to address requirements that ensure cross-calibration. Often, they are driven by high revisit user needs but are based on inherently difficult (if not impossible) technology in terms of a performant calibration sub-system (e.g. application of microbolometers for TIR, high-ambiguity small SAR systems, webcam-style cameras with poor spectral response). Feasibility of cross-calibration is not granted *a priori,* and effort is required to ensure that appropriate in-flight calibration is improved for all EO missions if they are to be used in synergy. Considering several decades of EO evolution at ESA, traceability to SI standards is highlighted as a solid baseline to move forwards. However, at this moment in time, it is an expensive and time-consuming scientific endeavour to harmonise and homogenise EO data with poorly implemented and documented calibration sub-systems – as exemplified by the considerable investment committed to the ESA Climate Change Initiative (CCI). The starting point for Climate Action using EO data is trust in EO measurements which is directly related to the stability and performance of the calibration approach implemented.

[RAB-107]: Ensure a fully functional and high-performance cross-calibration system within the ground system, to allow for an efficient cross-mission data exploitation and to ensure the long-term relative data quality between different missions.

7.2. National missions from ESA Member States (agency-driven)

Earth Observation Missions from ESA Member States and Associated states (ESA has 22 Member States: Austria, Belgium, the Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Luxembourg, the Netherlands, Norway, Poland, Portugal, Romania, Spain, Sweden, Switzerland and the United Kingdom. Latvia, Lithuania, Slovakia and Slovenia are Associate Members.) which are concretely planned, currently in implementation or already in-orbit are another element to consider for the gap assessment. The ESA MS missions can be Core Missions, Reference Missions, R&D Missions or any other element of the European Earth Observation Ecosystem.

The following tables provide an indicative list of missions that could be considered based on missions driven by ESA MS agencies. Not included at this time are the ESA National Third-Party Programme Missions.

Table 7.2-1. Example National missions within the Active Microwave Imagery Family.

Mission	Instrument	Agency	Timing	Technical Specifications
CSG-2	CSG SAR	ASI / MoD	2022 - 2028	**Imaging radar (SAR)** to monitor: Sea-ice cover, Sea-ice type, Snow cover, Snow water equivalent, Glacier cover, Glacier motion, Soil moisture at the surface, Land cover, Soil type, Land surface imagery, Land surface topography, Oil spill cover Resolution: [range x azimuth] Spotlight: 0.5x0.35 or 0.63x0.63 m (Single/Dual pol),

				Stripmap: 3x3 m (Single/Dual/Quad pol), ScanSAR: 4x20 or 6x40 m (Single/Dual pol) [Best: 0.35 m] Swath width: Dual polarisation modes: Spotlight [range x azimuth]: 7.3x3.1 or 10x10 km, Stripmap: 40 km, ScanSAR: 100 or 200 km. Quad polarisation mode: 15 km. [Max: 200 km] Wavebands: X-Band [Microwave: X-band (9.6 GHz) single-, dual- and quad- polarization]
CSG-3	CSG SAR	ASI / MoD	2024 - 2031	**Imaging microwave radars / Imaging radar (SAR)** to monitor: Sea-ice cover, Sea-ice type, Snow cover, Snow water equivalent, Glacier cover, Glacier motion, Soil moisture at the surface, Land cover, Soil type, Land surface imagery, Land surface topography, Oil spill cover Resolution: [range x azimuth] Spotlight: 0.5x0.35 or 0.63x0.63 m (Single/Dual pol), Stripmap: 3x3 m (Single/Dual/Quad pol), ScanSAR: 4x20 or 6x40 m (Single/Dual pol) [Best: 0.35 m] Swath width: Dual polarisation modes: Spotlight [range x azimuth]: 7.3x3.1 or 10x10 km, Stripmap: 40 km, ScanSAR: 100 or 200 km. Quad polarisation mode: 15 km. [Max: 200 km] Wavebands: X-Band [Microwave: X-band (9.6 GHz) single-, dual- and quad- polarization]
CSG-4	CSG SAR	ASI / MoD	2025-2032	**Imaging microwave radars / Imaging radar (SAR)** to monitor: Sea-ice cover, Sea-ice type, Snow cover, Snow water equivalent, Glacier cover, Glacier motion, Soil moisture at the surface, Land cover, Soil type, Land surface imagery, Land surface topography, Oil spill cover Resolution: [range x azimuth] Spotlight: 0.5x0.35 or 0.63x0.63 m (Single/Dual pol), Stripmap: 3x3 m (Single/Dual/Quad pol), ScanSAR: 4x20 or 6x40 m (Single/Dual pol) [Best: 0.35 m] Swath width: Dual polarisation modes: Spotlight [range x azimuth]: 7.3x3.1 or 10x10 km, Stripmap: 40 km, ScanSAR: 100 or 200 km.

				Quad polarisation mode: 15 km. [Max: 200 km] Wavebands: X-Band [Microwave: X-band (9.6 GHz) single-, dual- and quad- polarization]
PLT-1	PLATiNO X-SAR	ASI / SITAEL	2023-2029	**Imaging radar (SAR)** Resolution: 2.85 m [Best: 2.85 m] Swath width: RX-1 Stripmap Rx at 619 km altitude: 40.8 km; ST-1 Stripmap Tx-Rx at 410 km altitude: 15.3 km [Max: 40 km] Wavebands: X-Band [X-band]
PLT-1	PLT SAR	ASI / SITAEL	2023-2029	**Imaging radar (SAR)** Resolution: 1 m, 3 m [Best: 1 m] Swath width: 40 km [Max: 40 km] Wavebands: X-Band [Microwave: X-band, 9.6 GHz]
TanDEM-X	TOR	DLR	2010 - 2026	**Imaging radar (SAR)** Resolution: Spotlight, Stripmap and ScanSAR each having a resolution of 1.2m x 1m- 4m, 3m x 3m-6m, and 16m x 16m, respectively. Swath widths of 10km (Spotlight), 30km (Stripmap) and 100km (ScanSAR). The HRTE-3 (High-Resolution Terrain Elevation, level-3) model provides the spacecraft with a relative vertical accuracy of 2m where a slope is ≤ 20% and 4m where a slope is ≥20%.

Table 7.2-2. Example National missions within the Passive Microwave Imagery Family

Mission	Instrument	Agency	Timing	Technical Specifications
AOS-Storm	SAPHIR-NG	JAXA/ CNES / NASA	2029-2031	**Imaging multi-spectral radiometers (passive microwave) / Multi-purpose imaging MW radiometer** Resolution: 10 km (89 GHz), 5 km (183 GHz), 3 km (325 GHz) Swath width: ~750 km Wavebands: MW [89 GHz, 183 GHz (6 channels), 325 GHz (3 channels)]

AOS-PMM	SAPHIR-NG	JAXA/ CNES / NASA	2029-2034	**Imaging multi-spectral radiometers (passive microwave) / Multi-purpose imaging MW radiometer** Resolution: 10 km (89 GHz), 5 km (183 GHz), 3 km (325 GHz) Swath width: ~750 km Wavebands: MW [89 GHz, 183 GHz (6 channels), 325 GHz (3 channels)]

Table 7.2-3. Example National missions within the Altimetry Family (optical and active microwave)

Mission	Instrument	Agency	Timing	Technical Specifications
SWOT	POSEIDON-3C Altimeter	NASA/ UKSA / CNES / CSA	2022-2025	**Radar Altimeter**, Ku-Band, C-Band to measure: Wind speed over sea surface (horizontal), Significant wave height, Sea level.
JASON-3	POSEIDON-3B Altimeter	CNES/ NASA/ NOAA/ EUM	2016-	**Radar Altimeter**, Ku-Band, C-Band to measure: Wind speed over sea surface (horizontal), Significant wave height, Sea level.

Table 7.2-4. Example National missions within the Optical Imagery Family (from UV – LWIR - FIR)

Mission	Instrument	Agency	Timing	Technical Specifications
SBG-TIR	SBG TIR Instrument	NASA / ASI	2028 - 2031	**High-resolution nadir-scanning IR spectrometer** to monitor Land Surface Temperature Resolution: TBD Swath width: TBD [Max: 935 km] Wavebands: MWIR, TIR [TIR bands (8 bands up to ~12 μm)]
TRISHNA	SWIR	CNES / ISRO	2026 - 2031	**Imaging multi-spectral radiometers (vis/IR) / Medium-resolution IR spectrometer** to monitor: Snow cover, Glacier cover, Earth surface albedo and to do cloud masking Resolution: 57m Swath width: 1060 km Wavebands: SWIR [2 bands (1.3 and 1.6 μm)]

HAWCSat	SHOW	CSA / NASA / ECCC / USask / UQAM	2031 - 2036	**High resolution optical imager** Resolution: 0.13 km vertical resolution Swath width: 63 km swath Wavebands: SWIR [1362.00 – 1368.32 nm wavelength range]
TRISHNA	TIR	CNES / ISRO	2026 - 2031	**Medium-resolution IR spectrometer** to monitor: Land Surface Temperature, Fire Temperature Resolution: 57m Wavebands: TIR [2 bands (8.5 and 11.6 μm)]
PLT-2	PLATinO TIR	ASI / SITAEL	2024 - 2029	**Narrow-band channel IR radiometer** to monitor: Glacier cover, Land surface temperature, Vegetation type, Vegetation Cover, Glacier Area, Lake Surface Temperature, Surface Water Extent Resolution: 40m cross track, 60m along track [Best: 40 m] Swath width: 170 km strip length [Max: 170 km] Wavebands: TIR [TIR: 8.6 - 9.1 - 10.3 - 11.5 μm]
PRISMA2 GEN	PAN Camera	ASI	2027 - 2034	**High resolution optical imager** to monitor the Land cover Resolution: 5 m [Best: 5 m] Swath width: 30 km [Max: 30 km] Wavebands: VIS [VIS: 400 - 700 nm]
SBG-TIR	VNIR Camera (SBG-TIR)	NASA / ASI	2028 - 2031	**Multi-purpose imaging Vis/IR radiometer** for Land Surface Monitoring Wavebands: VIS, NIR [Operates at the 0.665 micron and 0.835 micron wavelengths.]
CO3D	Optical Instrument (CO3D)	CNES	2023 -2031	**High resolution optical imager** for Land surface imagery, Land surface topography Resolution: 50cm Wavebands: VIS, NIR [Red, green, blue and VNIR bands with 50 cm GSD]
WildFireSat	CWFMS	CSA / NRCAN / ECCC	2028 - 2032	**Multi-purpose imaging Vis/IR radiometer** to monitor CH_4 Mole Fraction, CO_2 Mole Fraction, CO Mole Fraction, Cloud imagery, Upward long-wave irradiance at TOA, Downward long-wave irradiance at Earth surface, Long-wave Earth surface emissivity, Air temperature (near

				surface), Sea surface temperature, Sea-ice surface temperature, Normalized Differential Vegetation Index (NDVI), Leaf Area Index (LAI), Vegetation type, Fire fractional cover, Fire temperature, Land cover, Land surface imagery, Aerosol absorption optical depth (column/profile), Cloud mask, Vegetation Cover, Active Fire Detection, Upwelling (Outgoing) Short-wave Radiation at the Earth Surface, Sea surface heat flux, Lake Surface Temperature Resolution: 400 m (TIR, MWIR), and 200 m (NIR, VIS) at the geodetic sub-satellite point. [Best: 400 m] Swath width: 400 km [Max: 1200 km] Wavebands: VIS, NIR, MWIR, TIR [VIS: 0.6 – 0.7 µm (red) (possibly also VIS 0.4 - 0.6 µm); NIR: 0.8 – 0.9 µm; MWIR: 3.4 - 4.2 µm wavelength; TIR: 10.4 µm – 12.3 µm;]
EnMAP	HSI	DLR	2022 - 2026	**Hyperspectral imagers / High resolution optical imager** to monitor: CH_4 Mole Fraction, CO_2 Mole Fraction, Vegetation type, Land surface imagery, Volcanic ash, Earth surface albedo Resolution: GSD 30 m [Best: 30 m] Swath width: 30 km [Max: 30 km] Wavebands: VIS, NIR, SWIR [420 - 2450 nm]
TRISHNA	VNIR	CNES / ISRO	2026 - 2031	**Medium-resolution IR spectrometer** to monitor Vegetation type, Land cover, Vegetation cover Resolution: 57m Swath width: 1060 km Wavebands: VIS, NIR, SWIR [4 bands (0.48 - 0.86 µm)]
AOS-Storm	SAPHIR-NG	JAXA/ CNES / NASA	2029-2031	**Imaging multi-spectral radiometers (passive microwave) / Multi-purpose imaging MW radiometer** Resolution: 10 km (89 GHz), 5 km (183 GHz), 3 km (325 GHz) Swath width: ~750 km Wavebands: MW [89 GHz, 183 GHz (6 channels), 325 GHz (3 channels)]
AOS-PMM	SAPHIR-NG	JAXA/ CNES / NASA	2029-2034	**Imaging multi-spectral radiometers (passive microwave) / Multi-purpose imaging MW radiometer**

				Resolution: 10 km (89 GHz), 5 km (183 GHz), 3 km (325 GHz) Swath width: ~750 km Wavebands: MW [89 GHz, 183 GHz (6 channels), 325 GHz (3 channels)]
PRISMA2 GEN	HYC2	ASI	2027 - 2034	**Hyperspectral imagers / Medium-resolution IR spectrometer** to monitor: Vegetation type, Land surface imagery, Volcanic ash, Earth surface albedo Resolution: 30 m STRIP, 10 m SPOT [Best: 10 m] Swath width: 30 km [Max: 30 km] Wavebands: VIS, NIR, SWIR [VNIR: 400 - 1010 nm, SWIR: 920 - 2500 nm]
HAWCSat	ALI	CSA / NASA / ECCC / USask / UQAM	2031 - 2036	**High resolution optical imager** Resolution: 0.25 km vertical resolution Swath width: 200 km swath Wavebands: VIS, NIR, SWIR [10 bands in the 610 - 1560 nm wavelength range]

Table 7.2-5. Example National missions within the Active Optical (LIDAR) Family

Mission	Instrument	Agency	Timing	Technical Specifications
Merlin	IPDA Lidar	CNES / DLR	2028 - 2031	**Atmospheric Lidar** to monitor the CH_4 Mole Fraction Resolution: 50 km x 0.15 km [Best: 150 m] Swath width: 0.15 km Wavebands: SWIR [Two laser wavelengths, mean wavelength 1645 μm]
AOS-Storm	ALICAT	NASA / JAXA / CNES	2029 - 2031	**Atmospheric lidar** Resolution: 100 m horizontal, 30 m vertical Swath width: Nadir only Wavebands: VIS, NIR [532 nm (polarization-sensitive), 1064 nm (polarization sensitive), VIS - NIR]

Table 7.2-6. Example National missions within the Limb Sounder Family (passive and using active signal sources (RO))

Mission	Instrument	Agency	Timing	Technical Specifications
SWOT	DGXX-S	NASA/ UKSA / CNES / CSA	2022-2025	Radiopositioning system

Table 7.2-7 Example National missions within the Atmospheric Spectroscopy Family

Mission	Instrument	Agency	Timing	Technical Specifications
MicroCarb	MicroCarb	CNES / UKSA	2025-2027	High-resolution nadir-scanning SW spectrometer to monitor Atmospheric chemistry in concreate the CO_2 Mole Fraction Resolution: 3 FOV size 4,5 km (ACT) x 8.9 km (ALT) simultaneously acquired [Best: 4500 m] Swath width: 13km with 3 contiguous pixels of 4.5x8.9km, up to > 25km in Glint mode [Max: 13 km] Wavebands: SWIR [B1 (O_2): 763.5 nm BW : 10.5nm; B2 (CO_2): 1608 nm BW : 22.2nm; B3 (O_2): 2037 nm BW: 28.1 nm; B4(O_2): 1273.4 nm BW: 17.6 nm]
PLT-2	MAIA	ASI / SITAEL	**2024 - 2029**	**Multi-purpose imaging Vis/IR radiometer** to monitor Aerosol optical depths (column and profile) Resolution: 0.5 km - 1 km [Best: 500 m] Swath width: 300 km [Max: 300 km] Wavebands: VIS, NIR, SWIR [VSWIR imager with polarimetric bands]

Table 7.2-8. Example National missions within the Gravimetry Family

Mission	Instrument	Agency	Timing	Technical Specifications
SWOT	LRA	NASA/ UKSA / CNES / CSA	2022-2025	Precision orbit / Laser retroreflector to measure: Sea level, Gravity field, Ocean dynamic topography
LARES-2	LCCRA (LARES-2)	ASI	2022 - 2026	**Precision orbit / Laser retroreflector** to monitor: Gravity field, Gravity gradients, Crustal plates positioning, Crustal Motion Wavebands: VIS [VIS: 400 - 750 nm]
GRACE-FO		DLR / NASA	2018 - XXX	**Laser-ranging interferometry**

GRACE-C		DLR / NASA	2029 - XXX	**Laser-ranging interferometry**

Table 7.2-9. Example National missions within 'Other' aspects such as in-situ networks, reference frames, quantum technologies, opportunistic signals (e.g. GNSS, signal), HAPS.

Mission	Instrument	Agency	Timing	Technical Specifications
SWOT	GPSP	NASA/ UKSA / CNES / CSA	2022-2025	Precision orbit / GNSS receiver to measure: Sea level, Gravity field, Ocean dynamic topography L-Band (L1/L2/L5)

[RAB-108]: Explore options to allow the full participation of National space missions in an intercalibrated European Earth Observation Ecosystem.

7.3. Gaps in the European EO Ecosystem Mission Family capability

7.3.1. Mission Families in the Reference Architecture: Problems, Roles, and Complementarities

The Reference Architecture Blueprint organises Earth Observation (EO) capabilities into mission families to ensure that Europe's EO system-of-systems addresses societal, scientific, and policy needs in a coherent, resilient, and evolvable manner. Each family responds to a distinct class of observation problems, contributes a specific architectural function within the system-of-systems, and interacts with other families through complementarities or, in some cases, partial substitution. Explicitly articulating these relationships is essential to avoid duplication, manage trade-offs, and optimise long-term capability evolution.

7.3.1.1. Elements not part of a System-of-Systems Family

Some EO missions and concepts address highly specific scientific questions, demonstrate novel technologies, or explore emerging domains that do not yet justify a sustained mission family. They are targeted to exploration of new scientific domains, pathfinding new remote sensing techniques, and rapid response to emerging knowledge gaps. Within the Blueprint, they act as innovation injectors and boundary expanders that keep the architecture adaptive and prevent premature convergence. They are often complementary to other established Mission families and may evolve into a new family once maturity, demand, and continuity requirements are demonstrated.

7.3.1.2. Active Microwave Imagery Family

This family addresses the need for robust surface imaging independent of illumination and weather conditions. They monitor surface structure, deformation, motion, and roughness under all-weather, day–night conditions. They provide a resilience backbone for land, ocean, cryosphere, security, and disaster-response applications and are complementary to optical imagery (structure vs reflectance) and passive microwave imagery with limited substitution by optical systems in cloud-free conditions only.

7.3.1.3. Passive Microwave Imagery Family

This family focuses on observing surface thermodynamic and dielectric properties at typically low (>5 km) spatial resolution. These missions focus on retrieval of soil moisture, sea ice concentration, snow properties, and ocean surface parameters under most atmospheric conditions. They are capable of climate monitoring continuity and provide a hydrological monitoring anchor and a are particularly valuable for long-term records (since 1980’s). Missions in this family are complementary to active microwave imagery (emissivity vs structure) and optical systems with limited substitution possible through data fusion but not replacement.

7.3.1.4. Passive Microwave Sounding Family

This mission family underpins global atmospheric profiling. They provide a vertical profiling of atmospheric temperature, humidity, and precipitation for weather and climate and act as a foundational input to numerical weather prediction, reanalysis, and climate services. This family is complementary to infrared sounders and radio occultation with a partial substitution possible in some atmospheric layers.

7.3.1.5. Altimetry Family (Optical and Active Microwave)

Altimetry provides precise height measurements of Earth’s surfaces above a reference datum along the satellite nadir point. The NASA SWOT mission and future Sentinel-3Next-Generation Topography mission provide informetric swath based capability at high spatial resolution. This family of missions is designed to monitor sea level rise, ocean circulation, ice sheet dynamics, inland waters, and topography. Some altimeters (e.g. Sentinel-6) provide a reference capability for climate change indicators and mass balance assessments. Optical and radar altimetry are complementary (precision vs coverage) with limited substitution by LIDAR for specific applications (e.g. ice sheet and sea ice monitoring).

7.3.1.6. Optical Imagery Family (UV–LWIR–FIR)

This family provides reflectance- and radiance-based observations across a wide spectral range and high spatial resolution. They provide a fundamental capability to map land cover, ecosystems, urbanisation, coastal zones, and atmospheric–surface interactions amongst many other applications. This mission family is often the primary interface between EO and broad user communities, enabling high uptake across science, policy, and commercial domains. Missions in this family are complementary to radar and LIDAR.

7.3.1.7. Active Optical (LiDAR) Family

LiDAR systems provide direct vertical structure measurements at high resolution along the satellite nadir point. This advanced mission family is capable of resolving vertical distributions of aerosols, clouds, vegetation, ice elevation, and atmospheric constituents. Missions provide process-level data and act as a calibration/validation reference for other families. Missions in this family are strongly complementary to passive optical and microwave systems but are not substitutable for wide-area coverage missions.

7.3.1.8. Limb Sounder Family (Passive and Active, including Radio Occultation)

This family targets high-vertical-resolution atmospheric observations by observing the atmospheric limb. Missions in this family are used to characterise atmospheric composition, temperature, and dynamics across altitude regimes. Missions provide a stability anchor for long-term atmospheric trend detection and model constraint. They are complementary to nadir sounders although radio occultation offers high stability but limited horizontal resolution.

7.3.1.9. Atmospheric Spectroscopy Family

This family measures atmospheric trace gases and pollutants and form the backbone missions to monitor air quality, greenhouse gases, and chemically active species relevant to climate and health policy. Missions provide the evidence backbone for regulatory compliance, emissions verification, and international reporting and are complementary across spectral ranges (UV, VIS, IR).

7.3.1.10. Gravimetry Family

Gravimetry observes mass redistribution within the Earth system by detecting changes in ice mass, groundwater, ocean mass, and solid Earth processes. Missions in this family provide a unique constraint on Earth system budgets that cannot be obtained by other observation types. Mision in this family are highly complementary to altimetry and in situ data.

7.3.1.11. Geomagnetic Family

Geomagnetic missions monitor Earth’s magnetic field. They are designed to understand the Earth’s interior, space weather coupling, and impacts on navigation and infrastructure. This mission family is a specialised but essential component supporting both science and operational services and are complementary to space weather monitoring and navigation systems. No practical substitution exists for these missions.

7.3.2. Gap analysis approach

Gaps in the European EO ecosystem have been analysed in the 2030-2050 time frame. This includes European institutional missions that have been developed (on-orbit) or those under preparation with theoretical “continuity of service” missions extending out to 2060. Table 7.4.2-1 summarises missions that are already agreed and constitute the current baseline for the EEOE.

Across all families, the Reference Architecture emphasises complementarity over substitution. Redundancy is pursued only where it increases resilience or continuity, not where it erodes diversity of measurement approaches. By explicitly structuring EO capabilities into mission families, the Blueprint ensures that Europe’s EO system-of-systems remains scientifically credible, operationally robust, and adaptable to future societal, environmental, and geopolitical challenges.

Each mission family within the ecosystem is then reviewed to highlight aspects to address in the future evolution of the system and provide a “blueprint” for the future ecosystem. Future versions of this document will revise and refine the content based on decisions to implement missions within the programmatic and financial constraints of the ecosystem.

Table 7.4.2-1. Summary of European institutionally developed or under preparation satellite missions (December 2025).

Family	Core Operational Missions	Reference Missions	R&D Missions
Active Microwave Imagery Family	**CSC S1 A/B./C/D (C-band SAR)** **MetOp-B (ASCAT)** **MetOp-C (ASCAT)** **CSC ROSE-L A/B (L-band SAR)** **CSC S1NG (C-band SAR)** **MetOp-SG-B 1/2/3 (SCA)**		**EE7 BIOMASS (P-band SAR)** **EE10 HARMONY (C-band bistatic)** **EE6 EarthCARE** **EE11 WIVERN (W-band, PhA)** **EE12 Hydroterra+ (Geo C-and SAR, Ph0)**
Passive Microwave Imagery Family	**CSC CIMR A/B (5 Ch 1.4-36.5GHz)** **MetOp-SG-B 1/2/3 (ICI, MWS)**	**CIMR (TBC)**	**EE1 SMOS (L-band)** **EE12 CryoRad (L-band Ph0)** **SC1 HydroGNSS**[8]
Passive Microwave Sounding Family	**MetOp-B (AMSU, HIRS)** **MetOp-C (AMSU)** **AWS (19 Ch. 50-325GHz)** **MetOp-SG-A 1/2/3 (IASI-NG, MWS, RO)**		
Altimetry Family (optical and active microwave)	**CSC Sentinel-3 A/B/C/D (SRAL, C, SAR Ku)** **CSC CRISTAL A/B (IRIS, SAR Ku, SAR Ka)** **CSC Sentinel3-NG topo (C, SAR , Ka-SAR interferometer)**	**CSC Sentinel-6 A/B (POS4,C, SAR Ku)** **CSC Sentinel-6NG (C, SAR , SAR Ka (TBC)**	**EE1 Cryosat (SIRAL, SAR Ku)**

[8] HydroGNSS is not strictly an imaging mission.

Optical Imagery Family (from UV – LWIR)	**CSC Sentinel-3 A/B/C/D OLCI** **MetOp-B/C AVHRR/3** **MTG-I 1 (Geo. FCI, LI)** **CSC LSTM A/B** **CSC CHIME A/B** **MetOp-SG-A 1/2/3 (METImage, 3MI)** **MTG-I 2/3/4 (Geo. FSI, LI)** **CSC Sentinel-2NG MSI** **CSC Sentinel-3NG OLCI** **CSC Sentinel-3NG SLSTR**	**CSC Sentinel-3 A/B/C/D SLSTR** **CSC Sentinel-2 A/B/C/D MSI**	**EE8 FLEX** **EE9 FORUM** **EE12 ECO (Ph0)**
Active Optical (LIDAR) Family	**Aeolus-2 A** **Aeolus 2 B**		**EE4 Aeolus-1** **Earthcare/ATLID**
Atmospheric Spectroscopy Family	**CSC Sentinel-5P A** **MetOp-SG-A + CSC Sentinel-5 A** **MTG-S 1/2 (Geo. IRS)** **CO2M A/B/C** **ALTIUS**	**CO2M**	**EE9 FORUM** **EE11 CAIRT (PhA)** **EE12 Keystone (Ph0)** **SC3 Tango**
Gravimetry Family	**NGGM (Ph B1)**	**MAGIC (Ph, B1)**	**EE1 GOCE**
Geomagnetic Family			**EE5 Swarm** **SC2 NanoMagSat**
Limb Sounder Family	**MetOp GRAS** **MetOp-SG RO**		**EE12 Keystone (Ph0)**

Click or tap here to enter text.

7.4. Active Microwave Imagery Family

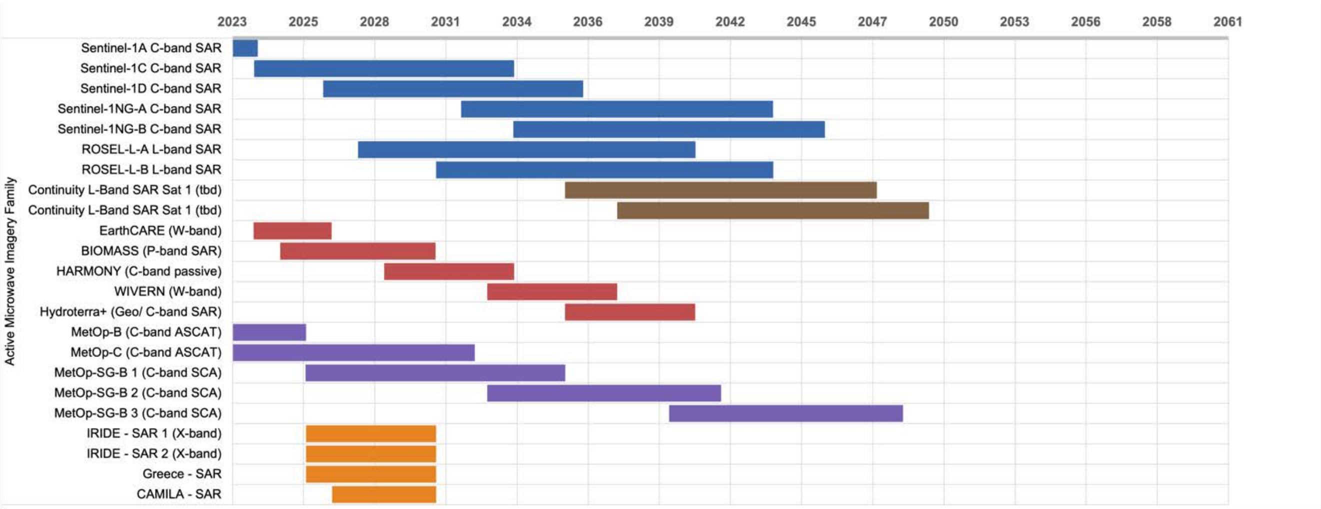


Figure 7.5-1. Illustration of the ESA EO Reference Architecture ecosystem timeline for Active Microwave Imagery Family for 2020-2060. (Colour-coding: Copernicus Missions: BLUE; Meteo Missions: PURPLE: Copernicus Missions not yet approved: BROWN; ESA Research Missions: RED: ESA National Programme Missions: ORANGE)

ESA has a very long heritage of C-band SAR imagers (ERS-1/ERS-2/ENVISAT) on which the Sentinel-1 C-band SAR builds. Sentinel-1NG is now in preparation and will likely fulfil most user needs in the 2030-2045 timeframe. Further enhancement is required to develop enhanced capability to exploit Doppler signals over the ocean (and access elements of the ocean total surface current velocity, TSCV which, surprisingly, remains undetermined from space) and provide improved 2D directional wave spectra over the ocean surface.

[RAB-109]: The Doppler measurement capability intrinsic to SAR instruments must be better exploited in the design of future C-band SAR instruments to provide access to elements of the TSCV (as available on ENVISAT).

In terms of radar scatterometer the MetOp ASCAT and MetOp-SG SCA scatterometers (derived from experience with ERS1/ERS2/ENVISAT C-band SAR) operate at C-band and will serve most user needs in the 2030-2050 timeframe. However, there is a Doppler enabled Wind scatterometer gap. This is important since, to improve the surface wind vectors over the ocean surface derived from scatterometry, the impact of TSCV must be included in the Level-2 retrieval. This can be done, to first order, using Doppler parameters that could be provided from the scatterometer system itself – although care is required to use the most appropriate geophysical space scales since the active geophysical processes influencing the retrieval are complex and highly dynamic. This has been a long-standing issue that will ultimately restrict the performance of scatterometry.

[RAB-110]: Doppler capability must be studied in the design of future scatterometer instruments to enable corrections for the impact of

total ocean surface current velocity on the wind vector retrieval that regionally limits the performance of such instruments.

The Joint ESA/JAXA EarthCARE Earth Explorer mission is the first space-borne W-band cloud profiling radar (CPR) with Doppler capability (developed by JAXA). It provides vertical profiles measurements of clouds and have the capability to observe vertical velocities of cloud particles using Doppler measurements. EarthCARE is now on orbit and informing ESA on how to proceed with future W-band CPR.

[RAB-111]: **Based on the impact of EarthCARE mission, a CPR capability could potentially translate from a science mission to an operational mission following a similar route as AEOLUS. In that case, a follow-on mission would already need to be considered in the 2025 timeframe.**

The BIOMASS Earth Explorer mission will uniquely explore the potential of P-band SAR including SAR Polarimetry (PolSAR), Interferometric SAR polarimetry Pol-InSAR), and SAR tomography (TomoSAR) furthering knowledge on the state of forest stock, how they are changing, and their role in the carbon cycle. While restriction on the geographic area is in place, the mission will also explore the application of P-band SAR over deserts, ice surfaces and oceans. The results from BIOMASS will inform ESA on how to proceed with PolSAR, PolInSAR and TomoSAR at P-band.

[RAB-112]: **It is noted that SAR imaging polarimetry remains a notable gap in the EO ecosystem architecture. It could be lucrative to consider flying bistatic passive P-band satellites together with BIOMASS to explore imaging with multiple baselines or as a close formation to synthesise a very large antenna.**

The HARMONY Earth Explorer mission will leverage Sentinel-1/NG and demonstrate bi/multi-static C-band imaging with multiple baseline configurations. HARMONY will inform ESA on options for the future of bistatic systems. It will provide new measurements for ocean, atmosphere, solid earth and cryosphere surfaces including experimental relative Total Surface Current Velocity retrievals at kilometre scale over its 5+ mission lifetime.

[RAB-113]: **Assuming success of EE-10 Harmony, the future Copernicus L- and C-band SAR fleet could be complemented with passive SAR companions to provide a larger baseline dispersion and allow derivation of single-pass Digital Elevation Models (DEM) and other structural/volume information through single-pass tomography.**

The Copernicus ROSE-L mission will provide L-band SAR imaging flying together with Sentinel-1 C-band SAR providing a powerful combination allowing access to a variety of user products over land, ice and ocean surfaces. The formation flight plan of Sentinel-1 and ROSE-L is highly relevant to ice surfaces since each SAR provides different measurements of the same target within a few minutes significantly advancing the classification of sea ice for maritime operations.

[RAB-114]: The continuity of ROSE-L capability must be addressed. A launch of a first continuity mission would be required by 2035 at which point the ROSE-L A satellite is expected to reach end of life (assuming a launch of ROSE-L A in 2029 and a design mission lifetime of 7.5 years).

The WIVERN Earth Explorer mission is a dual polarisation conically scanning W-band (94 GHz) Doppler radar with an 800 km swath. It will provide the first measurements of wind within clouds and precipitation systems. It also delivers profiles of rain, snow and ice water. WIVERN is strategically important for Europe because it addresses one of the most critical and least observed processes in the Earth system: the dynamics of clouds and precipitation. While Europe already operates world-class meteorological and climate missions that observe atmospheric state variables, surface impacts, and long-term trends, the vertical motions inside clouds that control rainfall intensity, persistence, and extremes remain largely unmeasured. WIVERN fills this gap by providing global Doppler radar observations of vertical winds in clouds and precipitation systems, directly constraining how storms grow, intensify, and dissipate. This capability is essential for reducing uncertainty in climate sensitivity, improving prediction of floods and droughts, and governing extreme-weather risks (e.g. Water bankruptcy) that drive economic loss and societal disruption.

In the 2030–2050 timeframe, as operational meteorology evolves toward hybrid physics–AI Earth-system prediction and Europe adopts a planetary stewardship approach to climate and water security, WIVERN becomes not just a scientific mission but a core public infrastructure asset, ensuring that AI-enabled forecasts remain physically grounded, explainable, and trusted, and that European policy decisions on climate adaptation, disaster risk reduction, and water security are based on authoritative process-level evidence rather than inference alone.

[RAB-115]: A launch of WIVERN is expected in the 2035-2040 timeframe and, based on the impact of the mission could potentially transition from a science mission to an operational mission following a similar route as AEOLUS. In that case, a follow-on mission would need to be considered in the 2040 timeframe.

The Hydroterra+ Earth Explorer mission is now in a Phase-0 study. It proposes a C-band SAR in geosynchronous orbit. The first geo-synchronous SAR satellite (Ludi Tance-4 operating at L-band) was launched by China in summer 2023 although no details of that mission are readily available at this time. Hydroterra+ would provide a unique and potentially game changing mission with coverage up to 60-70deg N and S and near instantaneous access to measurements serving many applications of high societal relevance (e.g. disaster response over land following earthquake, floods, agricultural resilience, ocean wave spectrum and other ocean parameters amongst others). It would be a complement to the global repeat coverage measurements of Sentinel-1, rather than a replacement due to the regional sampling and reduction in performance at higher latitudes.

[RAB-116]: **Hydroterra+ would be the first the Earth Explorer mission to open geostationary orbits and the first European Geosynchronous SAR mission. In this sense it is of high strategic importance.**

Despite the outstanding success of the CNES CFOSAT wave scatterometer at Ku-band, a follow-on mission providing precise 2D wave spectral information is currently absent in Europe. While a proposal is in place for a joint NASA/CNES wind scatterometer with some wave sensitivity (ODYSSEA mission) it must be remarked that current funding challenges at NASA may have a negative impact on the selection of this mission for implementation (or even its maturation should it be selected). While C-band SAR provides some capability, the nature of Sentinel-1 means that wave spectra derived from that sensor have a long-wave cut-off and are unable to access a complete wave spectrum. Given that the exchange of all heat, gas (CO_2 and other GHGs), mass and momentum between the ocean and atmosphere are governed by the ocean wave field, the lack of a follow-on mission has profound implications for the ability of climate models (and coupled ocean-atmosphere NWP) to progress. Furthermore, one of the few successful markets for ocean parameters is a wave forecast that is required for marine operations.

[RAB-117]: **Building on the success of CNES CFOSAT, a European wave scatterometer is an obvious gap to be filled by the operational Copernicus or Meteorological programmes.**

Over the last decade several mission concepts have been proposed to measure the TSCV (e.g. ESA WaveMill, ESA OCM, EE9 SKIM, EE11 STREAM, EE12 SEASTAR) although none have yet found success. EE10 Harmony will demonstrate some capability in a bistatic configuration together with Sentinel-1. Part of the issue rests in the incorrect assumption that satellite radar altimeters provide the TSCV whereas in practice, only the theoretical geostrophic current can be derived from measurements of sea surface height (which breaks down completely in the equatorial regions effectively blinding EO in that region with important implications for our knowledge of El Niño and equatorial upwelling, precipitation, and the water cycle amongst other issues). Given that the exchange of all heat, gas (CO_2 and other GHGs), mass and momentum between the ocean and atmosphere are governed by the ocean wave field, despite 40 years of EO, the fact that the community cannot measure TSCV from space has profound implications for the ability of climate models (and coupled ocean-atmosphere NWP) to progress.

[RAB-118]: **Logically, an Earth Explorer mission is required to demonstrate TSCV capability with global mapping capability at <15 km spatial resolution – which is not likely to emerge from a commercial provider since the mission would be a medium to large class solution. The Harmony mission provides one approach to achieve this.**

The SAR cartwheel approach is a formation-flying observation concept in which multiple synthetic aperture radar (SAR) satellites are arranged along the same orbital track with controlled along-track and cross-track separations, effectively forming a rotating “cartwheel” geometry around a reference orbit. This configuration enables the satellites to observe the same target area from slightly different viewing angles and time offsets within a short interval, dramatically enhancing temporal sampling and enabling multi-baseline SAR measurements. Architecturally, the cartwheel approach allows the separation of functions that are traditionally combined in a single platform—such as revisit rate, interferometric baseline, and radiometric performance—across several coordinated satellites. This enables advanced capabilities including improved soil moisture retrieval, vegetation and snow characterisation, deformation monitoring, and reduction of ambiguities caused by surface roughness or vegetation structure. Within a system-of-systems perspective, SAR cartwheel constellations provide a scalable pathway to densified observations without relying on ever-larger single satellites, while introducing new requirements for precise orbit control, inter-satellite synchronisation, calibration consistency, and low-latency coordination across the constellation.

[RAB-119]: The concept of a SAR “cartwheel” measurement approach remains absent from the European EO fleet. All SAR missions today are effectively zero-baseline missions except BIOMASS. There is a need to reconsider cartwheel multi-static interferometer SAR systems to access bio-/geo-physical structures and volume parameter retrievals.

There is a gap for a high-performance Ka-band imaging SAR particularly over the ocean and for atmospheric precipitation. Interferometric SAR over cryosphere measuring the static and dynamic topography (e.g. EE11 and EE12 SKADI mission concept) also presents a gap. Sentinel-3NGT is unlikely to provide the performance required for many applications due to a narrow swath (2 x 100 km) and near-nadir incidence angle geometry. The JAXA Ka-band GPM mission is now nearing the end of life and no replacement is evident.

[RAB-120]: There is a gap for a mission having a high spatial resolution of ~0.5 km and vertical resolution of ~250m ideally with a multifrequency capability of Ka-band (36GHz), W-band (94 GHz) and G-band (frequencies between 110 and 300 GHz) This would provide unprecedented access to imagery of precipitation, water vapour and cloud parameters – especially if it adopted a wide swath conically scanning approach similar to WIVERN. Note that a G-band radar is currently under study at ESA.

Multi-frequency, multi-angle SAR imaging is highly attractive for the Reference Architecture Blueprint because it directly addresses some of the most persistent limitations of single-frequency, single-geometry radar observations. Different radar frequencies interact with the Earth’s surface and vegetation in fundamentally different ways—longer wavelengths penetrate deeper into vegetation, snow, or dry soil, while shorter wavelengths are more sensitive to surface roughness and fine structural features. When combined with observations acquired from multiple viewing angles, these measurements enable the separation of surface, volume, and subsurface scattering contributions, significantly improving the physical interpretability of SAR products.

From an architectural perspective, such capability strengthens the retrieval of key variables central to climate, hydrology, cryosphere, and biosphere monitoring—such as soil moisture, biomass, snow water equivalent, and surface deformation—while reducing reliance on empirical assumptions. In a system-of-systems context, multi-frequency, multi-angle SAR also enhances resilience and adaptability by allowing complementary mission elements or constellations to be combined into a coherent observing system, providing richer information content without over-optimising any single mission design and supporting the Blueprint's emphasis on flexibility, scalability, and scientifically robust Earth system observation.

[RAB-121]: There is a gap in multi-frequency multi-angle SAR imaging capability which could be an asset for many geophysical parameters. This could be studied further to determine optimal mission characteristics using aircraft campaigns.

High-resolution X-band synthetic aperture radar (SAR) provides unique sub-meter imaging capability that is critical for applications requiring fine spatial detail, including infrastructure monitoring, urban dynamics, maritime surveillance, ice and hazard mapping, and rapid crisis response.

At present, this capability is largely delivered by commercial operators such as ICEYE, complemented institutionally by activities led by DLR. While this mixed public–private provision has enabled rapid innovation and user uptake, it remains structurally fragile from a Reference Architecture perspective, as continuity, access conditions, calibration consistency, and long-term availability are not assured at ecosystem level. Given the growing dependency of European users on very-high-resolution SAR data, the Blueprint identifies the need to assess options for a sustained baseline X-band SAR capability—whether through reinforced institutional anchoring, hybrid public–private arrangements, or explicit performance certification and continuity mechanisms—to avoid future gaps in service and ensure that this strategically important measurement class remains reliably available within the European Earth Observation Ecosystem.

[RAB-122]: Assess and define a sustained baseline for high-resolution X-band SAR capability within the European EO Ecosystem, recognising its critical sub-meter imaging value and the current reliance on a fragile mix of commercial and institutional provision. Explore architectural and governance options to ensure continuity, accessibility, and long-term resilience of this capability, thereby avoiding potential gaps in service.

The VHF frequency range is valuable for active microwave sensing of sub-surface and sub-ice features because its long wavelengths (approximately 6–7.5 m) allow electromagnetic energy to penetrate far deeper into natural media than higher-frequency radar systems. At these frequencies, attenuation and volume scattering are reduced in dry soil, sand, rock, and ice, enabling interaction with buried interfaces such as soil horizons, bedrock structures, permafrost layers, internal ice stratigraphy, basal ice conditions, and sub-ice hydrological features. In glaciated and polar regions, VHF radar is uniquely sensitive to internal ice layering and ice–bed interfaces, providing critical insight into ice thickness, basal conditions, and processes controlling ice dynamics that are largely inaccessible to C-, X-, or even L-band systems.

From a system-of-systems perspective, VHF sensing complements higher-frequency SAR by adding access to otherwise unobservable components of the Earth system, particularly within the cryosphere and sub-surface domains. Although challenges remain—such as large antenna requirements, ionospheric effects, and radio-frequency interference—the potential scientific return is high, especially when VHF observations are combined with multi-frequency radar architectures to separate surface, volume, and sub-surface scattering in a physically robust manner.

Previous Earth Explorer proposals in EE-10, EE-11, and EE-12 and notably the STRATUS distributed SAR concept for ice-sheet structure demonstrated both scientific relevance and architectural feasibility. The Reference Architecture should reassess and mature this opportunity to determine pathways toward implementation and integration within the European EO system-of-systems.

The International Telecommunication Union (ITU) recently updated the Radio Regulations following the World Radiocommunication Conference 2023 (WRC-23) to include a formal recognition of the 40–50 MHz frequency band for Earth Exploration-Satellite Service (active) use specifically for spaceborne radar sounders, subject to technical and geographic conditions defined in Resolution 677 of WRC-23. This represents a targeted allocation for spaceborne radar systems operating in the 40–50 MHz range, enabling active sub-surface and sub-ice sounding from orbit. Systems operating in this band must comply with conditions designed to prevent harmful interference with incumbent services, including limitations on power flux density and coordination outside defined regions, but the allocation itself establishes a regulatory basis for future spaceborne VHF radar missions that were previously precluded by spectrum constraints.

[RAB-123]: Address the current gap in active microwave sensing in the VHF frequency range, which is uniquely suited to sub-surface and sub-ice observation. A recent ITU frequency allocation has opened a timely opportunity to pursue such a capability.

7.5. Passive Microwave Imagery Family

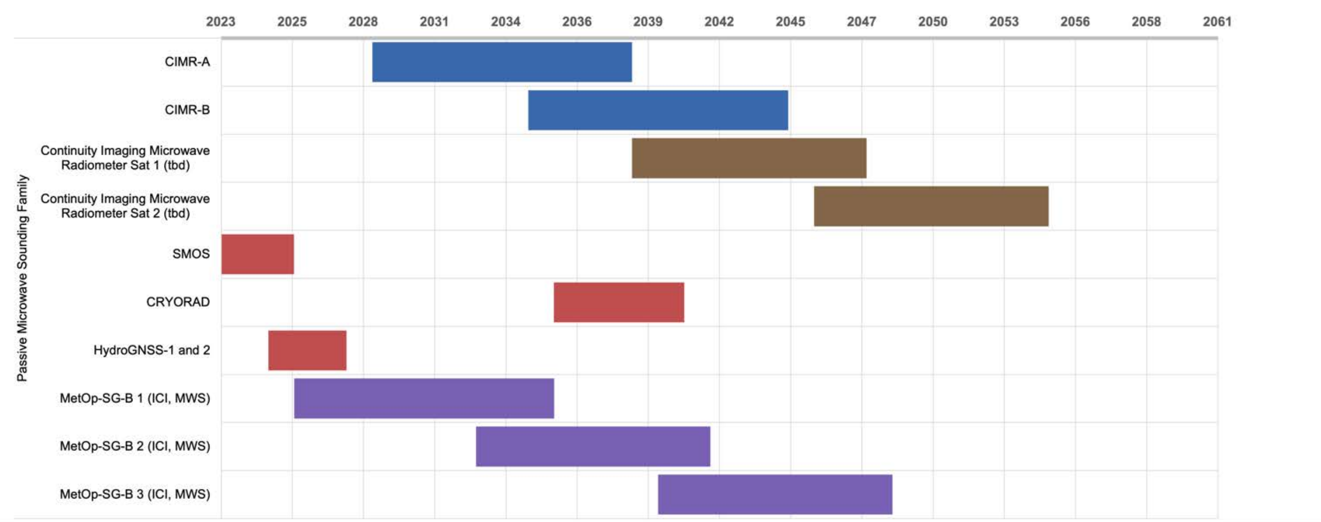


Figure 7.6-1. Illustration of the ESA EO Reference Architecture ecosystem timeline for Passive Microwave Imagery Family for 2020-2060. (Colour-coding: Copernicus Missions: BLUE; Meteo Missions: PURPLE: Copernicus Missions not yet approved: BROWN; ESA Research Missions: RED: ESA National Programme Missions: ORANGE)

Passive microwave imagery has historically not been a primary focus of the European Earth Observation portfolio, largely because global needs were effectively met by highly successful non-European missions such as the USA DMSP SSM/I–SSMI/S series, JAXA's AMSR/AMSR-E/AMSR2/AMSR3 instruments, and the TRMM TMI and GPM constellation. Within Europe, passive microwave capabilities were instead delivered through MetOp missions, primarily optimised for atmospheric sounding rather than high-resolution surface imaging and through SMOS, which pioneered L-band interferometric radiometry for soil moisture and ocean salinity but with spatial resolutions not tailored to many operational imaging needs.

This situation is now evolving. Growing strategic dependence on external systems, combined with increasing demands for higher-resolution, multi-frequency passive microwave imagery for polar, ocean, and climate applications, has driven a renewed European focus on this capability. New initiatives—most notably the Copernicus Imaging Microwave Radiometer (CIMR)—represent a deliberate shift toward establishing a sovereign, high-performance European passive microwave imaging capability. Together with the heritage of MetOp and SMOS, these missions reposition passive microwave imagery as a core component of the future European EO Reference Architecture, ensuring continuity, resilience, and enhanced performance while reducing long-term reliance on non-European data sources.

MetOp-SG-B (1, 2, and 3) Microwave Imager (MWI) is a conically scanning total power radiometer that measures aspects such as precipitation, temperature, cloud, water vapour, sea ice and snow cover. MWI provides multifrequency microwave radiometer measurements from 18-183GHz at a resolution of 30-50 km at frequencies <53GHz and 10km for higher frequencies over a 1700km swath (global coverage in ~1.5 days) in support of weather forecast providing precipitation over the ocean, total column water vapour, cloud liquid water, and other surface parameters.

MWI will serve operational meteorology, climate applications, oceanography, and sea ice, snow, and land surface observations. When used in combination with the Microwave Sounding Instrument and the Ice Cloud Imager, data from MWI will contribute towards improving precipitation estimates, particularly in short range forecasts. MWI features 26 channels, and its broad spectrum of high-resolution observations will enable the creation of cloud and precipitation products supporting numerical weather predictions and nowcasting. Datasets will also contribute to observations of sea surface wind speeds, land surface analysis, and climate records, providing continuity to instruments on current missions operated by EUMETSAT and partner organisations.

MetOp-SG B (1,2, and 3) Ice Cloud Imager (ICI) is a conically scanning radiometer that will help to fill in gaps in microwave observations and enrich global observations of ice clouds, such as cirriform clouds. It operates at frequencies from ~183 to 664 GHz with a spatial resolution of ~15 km at nadir, degrading toward the swath edge (~20–30 km depending on frequency). It has a swath width of ~1,500 km, enabling near-global coverage with high revisit at high latitudes. ICI will enable specialists to gain a more comprehensive understanding of critical properties for validating and representing ice clouds in climate and numerical weather prediction models. Observations will be highly complementary to other microwave sounding instruments on MetOp Second Generation satellites, with combined datasets also set to contribute to more accurate and frequent precipitation estimates for hydrology applications.

The Earth Explorer SMOS mission piloted radiometric interferometry at L-band to measure Soil Moisture, ocean salinity and vegetation parameters over a wide swath with great success. In parallel, the NASA SMAP mission uses a total power dual polarised conically scanning L-band radiometer providing fixed spatial resolution measurements at ~40 km over a swath of ~1000km. The user communities for L-band radiometry have grown enormously but developing cost-effective mission designs to provide a multi-frequency capability using radiometer interferometer techniques has been challenging. For SMOS, the spatial resolution varies across the swath with a minimum at the antenna boresight of ~40 km growing to > 80 km towards the alias free swath edge. Furthermore, NEdT remains a challenge with negative impact in the higher latitudes where cold waters reduce the L-band sensitivity to ocean salinity.

The Copernicus Imaging Microwave Radiometer (CIMR) mission builds on the previous conically scanning radiometer missions (that have provided decades of ocean surface temperature, wind speed and sea ice concentration measurements). Based on Copernicus user needs and leveraging the experience of the NASA SMAP Large Deployable Reflector (5m diameter), CIMR uses a conical scanning total power multifrequency microwave radiometer. It provides continuity to SMOS L-band measurements but complements these with unique high (≤15 km) spatial resolution (for this class of mission) dual polarisation capability at C, X-, K- and Ka-band and improved NEdT targeting ocean salinity and SST using L-band and C-band respectively. In addition, CIMR flies advanced RFI detection and mitigation processors aboard the satellite to minimise the impact of RFI. CIMR flies in coordination with MetOp-SG B1 MWI to ensure measurements from both missions are available within +/-10 minutes over the Arctic regions above 55°N. Two satellites are in development to be launched in succession (CIMR-A in 2029/30 and CIMR-B in 2038) providing 15-20 years of service. At this time, no continuity mission is planned to replace CIMR.

[RAB-124]: Recognising the Copernicus Imaging Microwave Radiometer (CIMR) mission as a transformative capability for cryosphere and ocean observation, and to ensure its long-term continuity within the Reference Architecture, planning for a follow-on mission should target a launch no later than 2045, aligned with the expected end of life of the CIMR B satellite (assuming a 2038 launch and a 7.5-year design lifetime), to avoid gaps in this critical observational record.

The EE12 CRYORAD concept (now in Phase-0) will study the development of a spectroradiometer covering P- to L-band (0.4 – 2.0 GHz) using a deployable mesh antenna similar to CIMR (although non-rotating) that would allow study of subsurface structure within ice sheets and sea ice, optimise L-band retrievals and mitigate RFI aspects at these frequencies.

RFI in C-band is expected to further increase in the next years. This is likely to be driven by two factors:

1. Countries are adopting the 5.925-7.125 GHz band for future WiFi systems (https://www.wi-fi.org/regulations-enabling-6-ghz-wi-fi),
2. The last World Radiocommunication Conference, WRC-23, has identified the bands 6.425-7.025 GHz and 7.025-7.125 GHz to be used for future mobile networks in several administrations[9]

Theoretical studies done before WRC-23 concluded that both WiFi and 5G networks in these frequencies would cause significant interference to satellite microwave radiometers[10]. Future RFI that is expected near 7 GHz directly impacts the sustainability of the 40-year of satellite measurements in C-band that provide a unique record. To alleviate this situation and, building on the AMSR2 “dual-band” brute force approach to RFI detection and mitigation, the ITU WRC-23 decided to consider protection for two new potential bands for satellite microwave radiometers [AD2]:

- 4.2-4.4 GHz (Low-C-band, LCB)

[9] See footnotes 5.457D, 5.457E and 5.457F of the Radio Regulations.

[10] See Annex 16 to the Working Party 7C Chair’s Report (document 7C/236), accessible with an ITU TIES account.

- 8.4-8.5 GHz (Low-X-band, LXB)

These two bands would be used in addition to the traditional microwave radiometer channel centred near 7 GHz. This approach is believed to be beneficial for scientific geophysical retrievals because:

- The 4.2-4.4 GHz frequency space offers maximum sensitivity to SST for cold waters (see Figure 1)
- The 8.4-8.5 GHz frequency space offers better sensitivity to SST than conventional X-band channels at 10.6-10.7GHz.
- Both channels, if used together with existing channels, could be used to improve RFI detection.

However, SST retrievals in the 4.2-4.4 and 8.4-8.5 GHz frequency space are new and remain largely untested in the field. The focus of this study is to collect an in-situ data set to demonstrate the viability and usefulness of the proposed new channels (Low-C-band and Low-X-band). Notably, the results from this study could be used to contribute to the ITU discussions demonstrating to ITU administrations that there is a deep and fundamental interest in the science community to use the two potential new bands that could lead to other services avoiding their use.

[RAB-125]: The potential of new protected frequency bands at C- and X-band (under discussion by ITU) to mitigate 5G/6G telecommunications systems should be studied to confirm their utility for future missions.

The continuity and evolution of CIMR mission capability will need to address this issue which could take the form of a spectrometer approach like that proposed by CRYORAD allowing optimisation in the face of growing frequency allocation restrictions. In terms of continuity and evolution of the MWI in the 50-183Ghz imaging domain, a similar spectrometer approach could also be envisaged.

[RAB-126]: To avoid potential gaps in capability due to the rise of 5G/6G telecommunications systems, the use of different frequency allocations must be explored to ensure geophysical measurement continuity with high performance.

[RAB-127]: New microwave spectroradiometer solutions should be investigated to mitigate the impact of RFI and expand the observation performance of microwave radiometers. The EE-12 Cryorad concept now under study provides one approach to achieve this.

Recent EE12 proposals suggest a user need for L-band resolution of <10km. Improvement in microwave radiometry instruments with respect to high spatial resolution should also be considered for future microwave imaging capability maintaining the ESA leadership in “low frequency – high resolution” missions.

[RAB-128]: Improvement in microwave radiometry instruments with respect to high spatial resolution should also be considered for the post CIMR era maintaining the European leadership in “low frequency – high resolution.”

GNSS reflectometry (GNSS-R) is a passive remote sensing technique that exploits navigation satellite signals reflected from water, ice, and land surfaces. By analysing the properties of the reflected signals, key geophysical variables can be derived, including surface roughness, soil moisture, inundation extent, freeze–thaw state, and—in specific contexts—altimetric information. GNSS-R observations can support both numerical weather prediction and climate research by providing frequent, all-weather measurements relevant to the Earth system.

HydroGNSS will deliver measurements of essential hydrological climate variables, including soil moisture, freeze–thaw state over permafrost, inland water and wetland extent, and aspects of above-ground biomass sensitivity, using GNSS-R observations from Galileo and GPS signals. HydroGNSS will complement established missions such as SMOS, BIOMASS, Sentinel-1, and SMAP by providing high-temporal-resolution, passive observations that enhance hydrological process understanding and data synergy.

HydroGNSS, launched in December 2025, is one of the new Scout missions within ESA’s Earth Observation FutureEO programme. Two satellites are in development that will be phased 180° apart when in flight (see https://www.hydrognss.org/about/mission-information/). Pending success, the in-orbit demonstration of GNSS-R should be followed with a coordinated approach to more widespread deployment aboard other missions given the small payload footprint, mass and power requirements to enhance the spatial and temporal resolution of measurements.

[RAB-129]: Build on the HydroGNSS approach by encouraging the systematic inclusion of reference GNSS-R payloads on ESA large missions, providing calibrated, trusted measurements that support Earth Observation applications while enabling and de-risking the integration of European commercial GNSS-R and AIS constellation capabilities within the EO ecosystem.

7.6. Passive Microwave Sounding Family

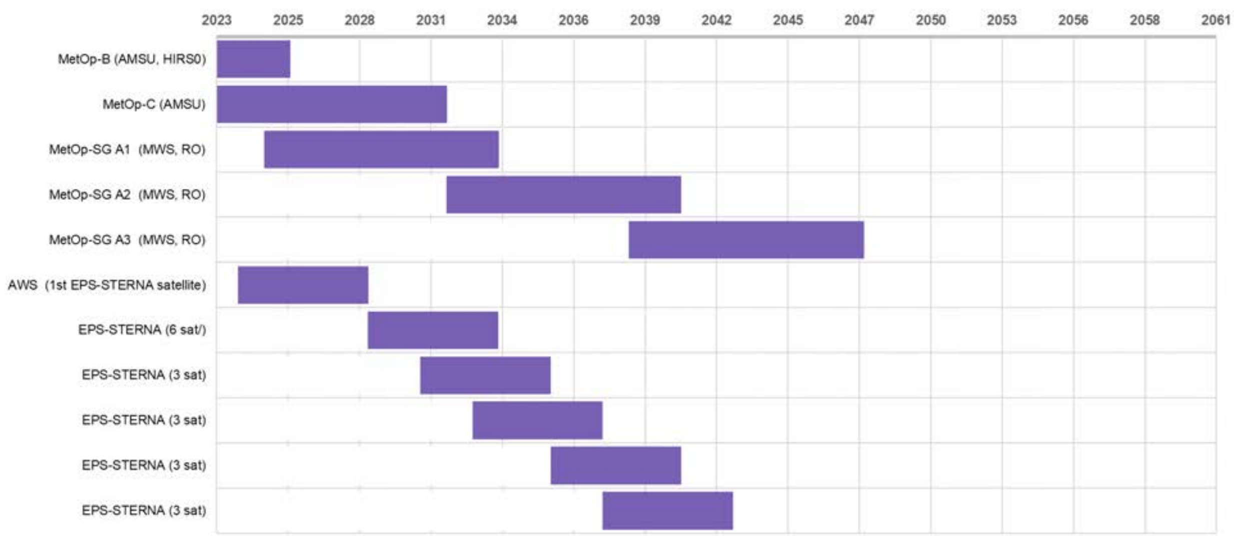


Figure 7.8.3.1. Illustration of the ESA EO Reference Architecture ecosystem timeline for Passive Microwave Sounding Family for 2020-2060. (Colour-coding: Copernicus Missions: BLUE; Meteo Missions: PURPLE: Copernicus Missions not yet approved: BROWN; ESA Research Missions: RED: ESA National Programme Missions: ORANGE)

Atmospheric sounding is a fundamental application of satellite measurements in meteorology, entailing the extraction of vertical temperature and humidity profiles and trace gas measurements used to support NWP. This process relies on observations at wavelengths where atmospheric attenuation is significant. Passive microwave sounding provides information on the vertical structure of the atmospheric temperature and humidity in an unprecedented accuracy and constitutes a core capability.

The MetOp Microwave Humidity Sounder (MHS) is designed to collect information on various aspects of the Earth's atmosphere and surface, in particular, atmospheric ice, cloud cover and precipitation. It can also determine the temperature at the Earth's surface. The MHS is a self-calibrating, cross-track scanning, five-channel microwave, full-power radiometer, operating in the 89 to 190gHz region. It scans the surface of the Earth three times every eight seconds, taking 90 pixels across the Earth view each scan.

The Microwave Sounder (MWS) will be flown on MetOp-SG-A series (1/2 and 3) and is a total power radiometer that will deliver calibrated and geolocated atmospheric temperature and water vapour sounding data at various altitudes and in all weather conditions. MWS will also provide observations of cloud, snow, sea ice, and surface phenomena. MWS has heritage from sounding microwave instruments on board current MetOp series and NOAA satellites and will also feature new channels that will enhance observations of the lower troposphere and of ice clouds.

The Arctic Weather Satellite (AWS) mission (recently launched) provides frequent coverage of Earth for improved atmospheric profiles for nowcasting and numerical weather prediction. AWS is conceived as a prototype satellite for a future operational constellation of passive, microwave sounders to complement the MetOp-SG and JPSS satellites (constellation now called EPS-Sterna). AWS is based on a “new space” development and implementation approach with a short development cycle allowing for an affordable follow-on constellation. AWS carries a cross-track scanning microwave radiometer, consisting of a rotating antenna focusing the incoming radiation onto four feedhorns (one for each group of channels) and four receivers, providing 19 channels in the frequency range 50–325 GHz. Currently, one AWS prototype will launch in 2024. For EPS-Sterna, the plan is to have 3 orbital planes with 2 satellites in each orbital plane, and to replenish this twice (i.e. 3 sets), to give a total of 3 x 2 x 3 = 18 satellites, plus 2 additional flight spares. This gives a total of 20 (+ the PFM) satellites.

During the last decade the satellite-based GNSS Radio Occultation (GNSS-RO) technique was established as a standard method for sounding of the global Earth's atmosphere. Using GNSS-RO globally distributed and very precise vertical profiles of atmospheric parameters, as temperature, water vapor and also electron density in the ionosphere can be derived. Specific advantages of the method are all-weather, long-term stability, global availability and high accuracy combined with high vertical resolution. GNSS-RO based on the refraction of GPS/Galileo signals has been included on the MetOp series of satellites, which will be continued with the radio occultation instruments on MetOp Second Generation, by embarking the Global Navigation Satellite System Receiver for Atmospheric Sounding (GRAS) instruments. Sentinel-6 also includes a GNSS-RO payload in support of NWP. Airborne RO platforms can provide much higher spatial and temporal sampling of ROs around regional weather events and are of interest in the context of HAPS. GeoOptics Inc. and Spire Global Inc. both offer commercial GNSS-RO from CubeSats with similar quality as those from other previous validated RO missions (e.g. Ho et al. 2023). This technology and data product service is well on the way to commercialisation (exemplified by the InCubed ROOC activity in this domain).

Systematically embarking radio occultation (RO) payloads—either as hosted instruments on large satellites or through dedicated constellations of small satellites—would generate a sustained, high-volume flow of vertically resolved atmospheric observations. Such measurements are among the most impactful inputs to numerical weather prediction (NWP), providing highly stable, calibration-independent temperature and humidity profiles that strengthen forecast skill and long-term climate consistency.

[RAB-130]: **Encourage the systematic inclusion of reference-quality RO payloads on ESA large missions to anchor and de-risk the evolution of commercial RO constellations, ensuring long-term continuity, performance certification, and trusted integration of RO observations within the European EO and meteorological ecosystem.**

GNSS-RO is currently covered on MetOp by the GRAS instrument and will be present also as part of the next generation (MetOp-SG A and B series) by the RO instrument due to its significant impact on the forecast skill of NWP systems with regards to temperature and water vapor profiling capabilities. A pilot with EUMETSAT regarding the use of commercially procured RO data is currently in implementation.

In summary, passive microwave sounding is generally well covered in the European EO ecosystem. However, some gaps do exist:

[RAB-131]: **There is a gap Microwave sounding at high spectral resolution 50 GHz and above (up to 183GHz). Spectroradiometer techniques considered by the Earth Explorer 12 CRYORAD concept could be promising in this domain.**

A persistent and well-recognised gap in the current EEOE is the ability to measure temperature and humidity in the atmospheric boundary layer, particularly over the oceans, with sufficient vertical resolution and accuracy to constrain air–sea exchanges of heat, moisture, gases, and momentum. These fluxes are fundamental to weather systems, climate variability, and the global energy and carbon cycles, yet they remain poorly observed from space because the lowest few kilometres of the atmosphere are difficult to sense remotely. Conventional passive microwave and infrared sounders provide strong constraints above the boundary layer but suffer from reduced sensitivity near the surface, especially under cloudy conditions, while radio occultation offers high vertical stability but limited resolution in the lowest atmosphere. As a result, key processes controlling ocean–atmosphere coupling—such as surface fluxes driving storms, marine boundary-layer structure, and feedbacks affecting climate sensitivity—remain weakly constrained by EO, representing a long-standing challenge that continues to motivate the development of new observing techniques and mission concepts within the Reference Architecture.

[RAB-132]: **There is a gap to measure boundary layer temperature and humidity for studies of ocean-atmosphere fluxes of heat, gas and momentum exchange. This has remained a stubborn challenge to address by EO.**

The BARometric pressure from Oceanic Doppler And Radar (BARODAR) mission concept was proposed within ESA's Earth Explorer 12 call to address a long-standing observational gap: direct, global measurement of atmospheric surface pressure from space, particularly over the oceans.

BARODAR aimed to retrieve surface pressure indirectly by exploiting the Doppler shift of microwave backscatter from the ocean surface, measured with a highly stable radar system. The core idea is that near-surface wind fields and wave motions—modulated by atmospheric pressure gradients—imprint a measurable Doppler signature on radar echoes. By combining precise Doppler radar observations with auxiliary information (e.g. surface winds, wave state, and numerical models), BARODAR sought to infer surface pressure with accuracy sufficient to impact NWP and climate analysis. This approach would have provided a fundamentally new spaceborne constraint on mass fields, complementing existing wind, temperature, and humidity observations.

From a system-of-systems perspective, BARODAR was particularly attractive because surface pressure is one of the most influential but poorly observed variables in the global observing system. Over oceans and polar regions—where in situ measurements are sparse—direct pressure information would significantly improve weather forecasts, storm intensity prediction, and air–sea flux estimates. Although BARODAR was not selected for implementation, it remains a reference example of a high-risk, high-return Explorer concept, and its scientific rationale continues to motivate interest in novel observing techniques for surface pressure within the Reference Architecture Blueprint.

[RAB-133]: There is a persistent gap in global atmospheric surface pressure measurement. New remote sensing techniques could potentially close this gap and should be assessed to identify viable pathways for future surface pressure observation.

Polarimetric observations offer a powerful yet under-exploited means of closing several long-standing retrieval gaps in Earth Observation by introducing independent physical constraints on scattering processes. Over land, polarimetry can significantly improve aerosol retrievals by separating atmospheric signals from highly variable surface reflectance, enabling better discrimination of aerosol type, absorption, and radiative forcing. In clouds, polarimetric sensitivity to particle shape and orientation allows more robust determination of cloud phase, droplet size, and ice habit, directly addressing key uncertainties in cloud–aerosol interactions and climate feedbacks. Over snow and ice, polarimetry provides enhanced sensitivity to grain size, surface roughness, and melt state, improving estimates of albedo and energy exchange and strengthening observations of cryosphere–atmosphere coupling in polar regions. For vegetation and land surfaces, polarimetric information helps disentangle canopy structure, moisture, and soil contributions, supporting improved biomass estimates and land–atmosphere flux studies. Over the oceans, polarimetry enhances retrievals of surface roughness, foam fraction, and wind stress, benefiting air–sea interaction studies and numerical weather prediction. Across all these domains, the principal architectural value of polarimetry lies in its ability to reduce ambiguity where intensity-only measurements reach fundamental limits, particularly when combined with multi-angle, multi-frequency observations and integrated into next-generation retrieval and AI-based processing frameworks within the Reference Architecture Blueprint.

Polarimetric observations introduce independent physical constraints on scattering processes, offering significant but under-exploited potential to separate atmospheric and surface contributions; nevertheless, their systematic use in atmospheric sounding architectures remains limited.

Polarimetric observations can be explicitly linked to priority use cases including, but not limited to: improved aerosol characterisation for air-quality regulation and climate forcing assessments; enhanced cloud microphysical retrievals to reduce uncertainty in climate sensitivity and weather prediction; accurate surface albedo and bidirectional reflectance measurements to support climate mitigation and land-use policy; improved ocean-colour and surface roughness characterisation for marine environmental protection and maritime applications; and advanced land biophysical parameter retrievals supporting agriculture, biodiversity monitoring, and ecosystem management. Targeted studies, technology maturation activities, and in-orbit demonstration missions, with the objective of establishing polarimetry as a core, traceable observational capability within the Reference Architecture Blueprint should be pursued.

[RAB-134]: Systematically advance and prioritise the development, assessment, and integration of polarised measurement capabilities to characterise atmospheric and surface properties and address policy-critical Earth Observation needs.

7.6.1. Altimetry Family (optical and active microwave)

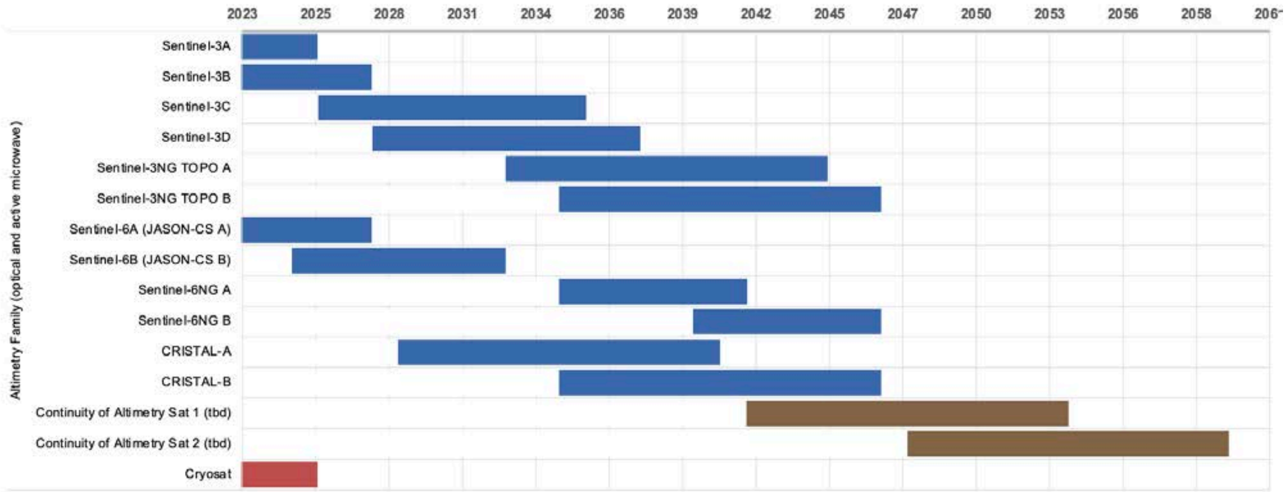


Figure 7.8.4.1. Illustration of the ESA EO Reference Architecture ecosystem timeline for Altimetry Family (optical and active microwave) for 2020-2060. (Colour-coding: Copernicus Missions: BLUE; Meteo Missions: PURPLE: Copernicus Missions not yet approved: BROWN; ESA Research Missions: RED: ESA National Programme Missions: ORANGE)

Europe has a strong heritage in nadir pointing Ku-band altimeter instruments and missions including ERS-1/2 RA, ENVISAT RA2, Earth Explorer CryoSat (the first SAR enabled radar altimeter), and a successful transition from science to operational missions in the form of Copernicus Sentinel-3 A/B/C/D SRAL SAR altimeter supported by a dual channel nadir pointing microwave radiometer (MWR). Copernicus Sentinel-6, a joint mission between

ESA/NASA/NOAA/EUMETSAT and the support of CNES, pioneered Sentinel-6 Poseidon-4 instrument with advanced digital electronics and an open burst chronogram bringing a significant improvement in performance – particularly in terms of measurement stability. This is supported by a NASA AMR-C 3-channel nadir pointing microwave radiometer with enhanced external calibration to achieve challenging calibration stability requirements. Sentinel-6 maintains the status of CEOS reference altimeter.

The Copernicus Sentinel-3 C/D units are still to be launched and will carry Ku-band SAR closed burst nadir altimetry into the 2035 timeframe together with the dual-channel MWR. The Sentinel-3NG mission foresees a continuity of Ku-band nadir altimetry from 2030+ as a two-satellite constellation that, in addition, includes a Ka-band SAR interferometer capability over a 100 km swath each side of the nadir point – building on the success of the NASA/CNES SWOT mission. Assuming a mission lifetime of 7.5 years, Sentinel-3NG will secure basic altimeter measurements into the 2042-45 timeframe at which point a follow on-mission will be required.

The Copernicus Sentinel-6 mission provides reference-quality radar altimetry for sea level, ocean dynamics, and climate monitoring. The mission is implemented through a US-Europe partnership (NASA/NOAA, ESA, EUMETSAT, EC, CNES) and designed to provide altimetry data into the 2030s. The payload complement includes a precision radar altimeter (Poseidon-4), a climate quality multi-channel microwave radiometer (provided by NASA) and associated Precision Orbit Determination instruments to measure global sea surface height, wave height, and inland water levels with climate-quality accuracy.

Each satellite has a reduced lifetime due to radiation impacts at the higher 1300km orbit. Sentinel-6B is due for launch in the 2025/26 timeframe and was foreseen to be replaced by Sentinel-6C in the 2030+ timeframe. On 17 December 2025 the Copernicus Procurement board cancelled Sentinel-6C. The following impacts on the EEOE are noted:

Data Continuity and Reference Time Series

High Risk of Data Gaps: The Reference Architecture Blueprint stresses that a first launch of Sentinel-6NG (next generation) is required by 2035 to replace Sentinel-6C: descoping Sentinel-6C creates a serious risk of a discontinuity in the reference global mean sea level (GMSL) time series, which is a critical data set for many high profile applications underpinning climate monitoring, operational oceanography, and policy support.

EO Ecosystem Reference Altimeter Stability: The stability of the Sentinel-6 reference mission time series is essential for maintaining the credibility and scientific value of long-term sea level records. Any gap or change in orbit/technology without overlap could compromise the ability to detect trends and anomalies reliably. A break in the time series jeopardises GMSL trend continuity and increases trend uncertainty (by ~20% on global mean sea level trend and ~40% estimates of global mean for sea level rise acceleration) due to instrument-to-instrument drift.

Operational and Scientific Consequences

Operational Services: Sentinel-6 supports a range of operational services, including weather forecasting, marine safety, and disaster response. A gap in data would impact these services, especially those relying on near-real-time sea level and ocean state information.

Climate Policy and Research: The mission is central to climate change monitoring and reporting, including commitments under the Paris Agreement and EU Green Deal, Copernicus GCOS, amongst others. Discontinuity would undermine Europe's ability to provide authoritative, policy-relevant climate data. Descoping S6C would likely create a 3–5 year reference gap (post-S6B until first S6NG launch), with high risk to the stability and legal defence of the most iconic climate time-series from space and for cross-calibration/stabilisation of Copernicus and partner altimeter missions.

Technical and Programmatic Risks

Orbit and Lifetime Constraints: The Reference Architecture Blueprint notes that Sentinel-6 operates at a higher orbit (~1300 km), which reduces satellite lifetime due to higher levels of radiation exposure. To address this, options to lower the orbit to ~820km as a long cost saving element (longer lifetime of ~8-12 years) is being considered although this transition must be managed carefully to maintain data consistency. Descoping Sentinel-6C would increase the risk of an unplanned gap during this transition. Importantly, without Sentinel-6C, it is unlikely that sufficient overlap between S6B and S6NG could be guaranteed, *de facto*, forcing S6NG to remain in the higher (~1330km) limited lifetime (5-years) orbit altitude.

Calibration and Cross-Validation: Overlapping missions (e.g., A/B/C) are mandatory for inter-mission cross-calibration, ensuring measurement consistency and climate-quality stability. Without Sentinel-6C, it is unlikely that sufficient overlap between S6B and S6NG could be guaranteed, increasing the risk of calibration drift or bias and destabilisation of the reference altimeter time series stability performance. This will bring into question the need for Sentinel-6NG continuity.

Strategic and International Implications

European Leadership: The Reference Architecture Blueprint repeatedly emphasises the importance of Europe maintaining leadership in reference-class missions. Losing Sentinel-6C would weaken Europe's position as a provider of one of the most recognised satellite-derived global reference data sets or sea level and climate. The sustainability and operational nature of the Copernicus programme will be challenged.

International Collaboration: Sentinel-6 is a joint mission with NASA, NOAA, EUMETSAT and CNES. Removing Sentinel-6C could affect international partnerships and Europe's reputation for reliability in global Earth observation.

[RAB-135]: Assess alternative routes and positioning/support to implement Sentinel-6C within the international partnership of ESA, EUMETSAT,

CNES and EC. Explore new options for additional partnership agreements.

[RAB-136]: **Urgently assess the impact of an interruption in the altimeter reference mission time series on climate services, international climate policy (e.g. IPCC), operational services and scientific research.**

[RAB-137]: **Prepare the Sentinel-6 user community for a potential data gap in the altimetry time series. e.g. develop a formal updated covariance model for the post-6B era allowing downstream services to propagate uncertainties correctly rather than assuming continuity.**

[RAB-138]: **Urgently assess the technical feasibility of extending Sentinel-6B to overlap with Sentinel-6NG to mitigate loss of GMSL stability.**

A Sentinel-6NG mission is about to commence a Phase-0 study in 2024 with a first assumed launch to replace Sentinel-6C by 2035 but with a lower obit (~800km) to address clean space requirements and attain better mission longevity (7-10 years instead of 5 years) and improved mission performance.

[RAB-139]: **It remains critical to find a satisfactory approach to maintain the stability of the Sentinel-6 reference mission time series while considering alternative orbit configurations to mitigate de-orbit constraints on the system and affordability (the subject of related Phase-0 Science Studies).**

An acceleration of Sentinel-6NG preparation would be a significant mitigation action for the descoping of Sentinel-6C. This should be further analysed in detail in terms of mission scope, schedule, planning and cost). In the ideal scenario, a launch of Sentinel-6NG would be required in the ~2030-33 timeframe although this will depend on an analysis of how long extended operations for Sentinel-6B could reasonably be expected.

However, it remains critical to find a satisfactory approach to maintain the stability of the Sentinel-6 time series when moving to the new orbit (the subject of related Phase-0 Science Studies). This emphasises the blurred boundary between science and operation, potentially putting data continuity at risk.

[RAB-140]: **Assuming Sentinel-6B remains operational for an additional 2 years, a first launch of Sentinel-6NG is required by ~2032 to replace Sentinel-6B to avoid gaps in service.**

Building on the success of the Earth Explorer CryoSat mission and user needs expressed by the Copernicus programme, **the Copernicus CRISTAL mission** will extend Ku-band nadir pointing interferometer altimetry measurements to include Ka-band. The CRISTAL IRIS radar altimeter will fly, for the first time, both a Ka-band and a Ku-band SAR altimeter allowing access to snow surface height that has been a major source of uncertainty in CryoSat and Sentinel-3 sea ice thickness retrievals. CRISTAL anticipates a first launch in 2028 with a second replacement satellite ~7 years later meaning that a replacement mission would be required in the early 2040 period. Given the enticing performance of the NASA/CNES SWOT mission over sea ice where both the sea ice and ocean surface can be uniquely obtained from SAR interferometry techniques, it can be reasonably expected that the CRISTAL-NG mission would build on the heritage of SWOT and Sentinel-3NG topography missions. This is an interesting example for the role of ESA to build on national initiatives to implement a European operational mission.

[RAB-141]: **CRISTAL anticipates a first launch in 2028 with a second replacement satellite ~7 years later meaning that a continuity mission would be required in the early 2040 period to avoid gaps in service.**

[RAB-142]: **Given the enticing performance of the NASA/CNES SWOT mission over sea ice, where both the sea ice and ocean surface can be uniquely obtained from SAR interferometry techniques, it can be reasonably anticipated that a continuity to the CRISTAL mission would build on the heritage of SWOT and Sentinel-3NG topography missions. Further work should explore the application of SWOT data in this respect.**

Cross- and co-polarised altimeter techniques are under study as part of an ESA NEOMI study. Even in nadir-looking geometries, polarimetric radar observations provide valuable physical information over snow and ice surfaces that cannot be obtained from intensity-only measurements. Real cryosphere surfaces are neither smooth nor isotropic: radar signals penetrate into snow and firn, interact with layered density contrasts, ice lenses, and anisotropic grain structures, and undergo multiple scattering events that modify their polarisation state. These interactions generate measurable cross-polarised returns and co-polar phase differences, even at nadir incidence. When combined with frequency diversity (e.g. Ku- and Ka-band), polarimetry enables partial separation of scattering contributions from the surface, near-surface, and subsurface horizons, addressing a long-standing ambiguity in radar altimetry over ice sheets and sea ice. Within the Reference Architecture Blueprint, this capability highlights the potential of polarimetric nadir radar to improve elevation, freeboard, and mass-balance retrievals, and to enhance the scientific credibility of long-term cryosphere observations in support of climate monitoring and policy-relevant assessments.

Extensive field measurements using Ku-band and Ka-band radar reveal that cross- and co-polar measurements have potential to differentiate different scattering horizons in the snow-ice surface which has remained an elusive and troublesome issue for Ku-band radar altimeter missions. Pending a successful outcome of this work, further development could be anticipated.

[RAB-143]: Systematically assess and mature the use of polarimetric nadir-looking radar techniques, in combination with multi-frequency operation, to discriminate surface and subsurface scattering horizons over snow and ice. This capability should be evaluated through targeted simulation studies, field campaigns, and mission concept activities to reduce penetration-related ambiguities in radar altimetry, improve elevation and freeboard retrievals, and strengthen the long-term credibility of cryosphere measurements within the European Earth Observation Reference Architecture.

In general, the outlook for nadir altimetry in an operational capacity is very good to the mid 2040s. However, given the very narrow measurement regime of a nadir altimeter (2-~20 km depending in sea state) and even a swath altimeter (which is significantly restricted by near nadir incidence angles), the altimetry system remains severely under sampled. This is a significant gap that could be addressed using a combination of swath altimeters and a constellation of ~10 nadir pointing altimeters. Currently, four swath altimeters are required to meet full performance in the Sentinel-3NG constellation (although only two are currently foreseen). Densification of measurements is particularly important to properly capture ocean mesoscale dynamics and extreme events over river and lake targets that cannot be captured by the current constellation. The CNES SMASH mission concept may address this aspect for inland waters in the future, but under sampling of ocean altimetry is set to remain a gap for the foreseeable future without additional capability.

[RAB-144]: There is a European gap in sampling of altimetry at the appropriate time- and space scales required by users and policy makers in the hydrology domain.

Some experimental potential exists within the HARMONY Earth Explorer mission to consider interferometry techniques over a much wider swath than Sentinel-3NG although the performance of this approach will need to be demonstrated. Clearly, new sea surface height measurement techniques should be explored based on wide swath imaging approaches and/or smaller satellite constellations.

[RAB-145]: Effort should be given to investigate the potential of bistatic satellite SAR systems to determine sea surface height over swath widths of 500+ km.

7.7. Optical Imagery Family (from UV – LWIR)

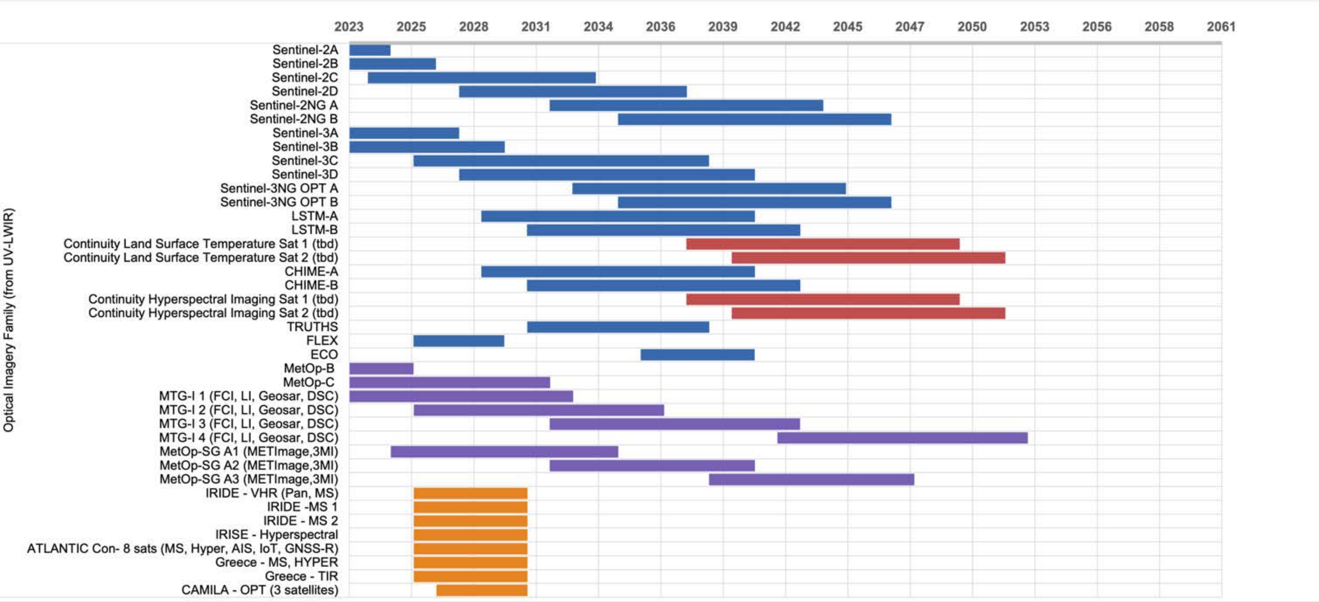


Figure 7.8-1. Illustration of the ESA EO Reference Architecture ecosystem timeline for Optical Imagery Family (from UV – LWIR) for 2020-2060. (Colour-coding: Copernicus Missions: BLUE; Meteo Missions: PURPLE: Copernicus Missions not yet approved: BROWN; ESA Research Missions: RED: ESA National Programme Missions: ORANGE)

Currently and for the foreseeable future, there are many missions in the European fleet. Optical imagery data is one of the most widely used kind of observations since it supports many applications with a long-lasting tradition in governmental and patrimonial services as land and recourses management. The commercial entry barrier of using that kind of data for certain applications is rather low.

The European institutional optical imager family includes workhorse Sentinel-2 A/B MSI and Sentinel-3 A\B OLCI instruments, where Sentinel-2 serves the medium to high resolution applications (10-30 m) with appropriate radiometric performance and Sentinel-3 OLCI the respective coarse resolution (300 m) applications with demanding SNR (i.e. ocean colour imaging). It is expected that Sentinel-3 NGO AOLCI will move from a multi spectral to a hyperspectral sensor extending the wavelength range to about 350 nm at a spatial resolution of about 150 m. SLSTR of Sentinel-3 serves as the global reference sensor for Earth's surface temperature and observations will be prolonged by SLSTR NG onboard Sentinel-3 NGO building on a solid dual view conical scanning heritage, cooled detectors and dual SI traceable calibration blackbody sources inherited from (A)ATSR and SLSTR (gen. 1).

The next generation of Sentinel-2 is aiming at the provision of 5 m data in a number of spectral bands (10 m for most of the rest). In the timeframe of Sentinel-2 NG, it is expected that commercial data providers will widely cover metric and sub-metric resolution imaging, still necessitating a mission targeting excellent radiometry following a systematic acquisition approach.

Sun-glitter observations offer a largely under-exploited optical pathway to characterise ocean surface waves and surface currents by converting reflected solar radiance into physically meaningful information on surface slope statistics and roughness. Accidental but well-documented overlaps of Sentinel-2 MSI imagery under favourable sun–sensor geometries have demonstrated the ability to retrieve wave spectra, dominant wave direction, surface roughness gradients, and even the velocity of large moving targets through pattern displacement and Doppler-like effects in the glitter field. These results indicate that high-resolution, multi-angle optical imagery can complement traditional SAR and altimeter approaches, particularly in coastal and marginal seas where spatial scales are small and dynamics are complex. The STREAM Earth Explorer 11 concept explicitly targeted this observation space, highlighting that sun-glitter measurements—if systematically designed rather than opportunistic—could provide valuable constraints on air–sea interaction, wave–total surface current coupling, and upper-ocean dynamics within the European EO system.

[RAB-146]: **Undertake dedicated studies and pre-development activities to systematically exploit sun-glitter observations for ocean surface wave and current retrievals. This should assess optimal viewing geometries, multi-angle and constellation approaches, algorithm maturity, and synergy with SAR and altimetry, with the aim of defining a viable future mission or payload option within the Reference Architecture to address coastal and upper-ocean dynamics.**

The Copernicus Land Surface Temperature Monitoring (LSTM) mission is a Copernicus Sentinel expansion spacecraft designed to provide high-spatial- and high-temporal-resolution land surface temperature observations that advance beyond existing global products. Equipped with thermal infrared, visible, near-infrared, and shortwave infrared radiometers, LSTM will deliver ~50 m land surface temperature and evapotranspiration measurements every 1–3 days, enabling field-scale agricultural water-use monitoring, drought and heat-stress assessment, coastal management, and improved understanding of land-climate interactions. The mission consists of two satellites—LSTM-A, planned to launch in 2028, and LSTM-B, planned for ~2030–2031—operating in a sun-synchronous orbit with a combined revisit that meets critical policy and scientific requirements for sustainable resource management and climate adaptation. However, no mission if continuity is foreseen beyond ~2040.

[RAB-147]: **Ensure the long-term continuation of the data streams expected to be provided by Copernicus LSTM by 2040.**

The Copernicus Hyperspectral Imaging Mission for the Environment (CHIME) is a planned expansion mission in the EU–ESA Copernicus Earth Observation programme that will provide routine, high-fidelity visible to shortwave infrared hyperspectral imagery across hundreds of contiguous spectral bands. CHIME’s imaging spectrometer will enable detailed characterisation of land surface materials, vegetation health, soil properties, coastal and inland waters, and raw materials—supporting sustainable agriculture, biodiversity management, natural resource monitoring, and related EU policies that are currently unmet by existing missions. Two identical satellites—CHIME-A and CHIME-B—are being developed to ensure high revisit and continuity; CHIME-A is scheduled to launch in 2028, with CHIME-B targeted for launch in 2030–2031 and both designed for long operational lifetimes to deliver consistent hyperspectral data for global land and environmental applications. However, no mission if continuity is foreseen beyond ~2040.

[RAB-148]: Ensure the long-term continuation of the data streams expected to be provided by Copernicus CHIME by 2040.

The ESA Earth Explorer FLEX (Fluorescence Explorer) mission is pivotal because it provides the first global measurements of sun-induced chlorophyll fluorescence (SIF), a direct and quantitative proxy for photosynthetic activity. By observing how efficiently vegetation converts absorbed sunlight into chemical energy, FLEX delivers unique insight into plant functioning, stress, and productivity that cannot be inferred from reflectance alone. Flying in close formation with Sentinel-3, FLEX explicitly couples physiological information with biophysical context such as surface temperature, land cover, and reflectance, enabling robust separation of climate-driven stress from land-use and management effects. This synergy substantially improves estimates of gross primary production and terrestrial carbon uptake, reduces uncertainties in carbon-cycle and ecosystem models, and strengthens attribution of droughts, heatwaves, and ecosystem degradation. From a system-of-systems perspective, FLEX marks a step change for the European EO ecosystem, extending Copernicus capabilities from observing what the land looks like to understanding how the biosphere functions, with direct relevance for EU climate mitigation, biodiversity policy, food security, and ecosystem resilience.

[RAB-149]: Ensure continuity of fluorescence spectrometry and vegetation functional measurements beyond FLEX by assessing follow-on mission options, alternative implementation pathways, and integration with Copernicus and commercial capabilities. Without a planned continuation, the European EO ecosystem risks losing a unique and policy-critical capability for monitoring vegetation dynamics, carbon uptake, and ecosystem health.

[RAB-150]: Establish and sustain an independent, systematic, and high-quality European backbone of multi- and hyperspectral imaging observations across complementary spatial and temporal scales, anchored by globally recognised reference sensors that provide traceable calibration, long-term stability, and interoperability for scientific, operational, and commercial Earth Observation applications.

The Flexible Combined Imager (FCI) on the MTG-Imager satellites provides state-of-the-art observations of Europe and Africa for forecasting severe weather, and for near-real-time monitoring of our changing atmosphere, land surfaces and oceans. The FCI will continue the very successful operation of the Spinning Enhanced Visible and Infrared Imager (SEVIRI) instrument on Meteosat Second Generation satellites. FCI will scan the full Earth disc every 10 minutes and the upper quarter of the disc, that is, Europe, every 2½ minutes. The FCI measures in 16 channels in the visible and infrared spectrum. The FCI is essential for monitoring and forecasting severe weather events, such as storms. It will also provide more precise information about fog, volcanic ash, air mass characteristics, clouds and aerosols and will assist the detection and monitoring of fires.

For the first time over Europe and Africa, MTG's Lightning Imager provides data on the location and intensity of lightning flashes. The Lightning Imager continuously detects the light pulses produced by lightning flashes. The instrument has four cameras covering Europe, Africa, the Middle East and parts of South America. The fields of view of the Lightning Imager's four cameras cover 84%of the Earth disc. The cameras can capture 1,000 images per second, 24 hours a day, and can detect even a single lightning flash faster than the blink of an eye. The data is processed on board the MTG-I satellite. The cameras will continuously observe lightning activity from space and EUMETSAT will disseminate the data to weather services in its member states and beyond. Crucially, EUMETSAT will deliver the data to weather services in Africa and other regions where lightning detection capability with ground-based observations is limited.

The MTG Infrared Sounder will provide hyperspectral soundings of the atmosphere from geostationary orbit. It is set to revolutionise weather forecasting by tracking the three-dimensional structure of atmospheric water vapour and temperature. The Infrared Sounder instrument will detect instability in the atmosphere before clouds have formed. The Infrared Sounder acquires a number of spectral soundings simultaneously over an area using a two-dimensional detector array. It uses a "step-and-stare" mechanism to probe the Earth´s atmosphere. The soundings will be produced every 30 minutes and transmitted to the ground as interferograms and transformed to spectral channels as part of the ground processing, before dissemination to the end users of the data.

Despite the strong demand for persistent, high-signal-to-noise-ratio (SNR) imaging for Ocean Colour applications, no geostationary Earth Observation mission addressing this need is currently in the European development pipeline. Nevertheless, relevant on-orbit precedents exist, most notably the Geostationary Ocean Colour Imager (GOCI), developed by ASTRIUM SAS to observe the Korean Peninsula. In addition, the OCAPI mission concept, proposed within the Earth Explorer framework, has demonstrated the technical feasibility of a geostationary ocean-colour imager. The European EO community has expressed a clear need for an equivalent capability providing sustained coverage over the European domain.

Beyond ocean applications, further potential exists for geostationary imaging at moderate spatial resolution focused on land surfaces, supporting applications such as land monitoring and environmental management. As an initial step, a combined mission concept addressing both ocean-colour and land-imaging applications within a single geostationary platform should be considered to maximise synergy and cost effectiveness.

[RAB-151]: **Explore the potential of persistent, high-resolution (< 0.3 km) imaging from geostationary orbit across multiple application domains and initiate preparatory activities—including feasibility studies and technology maturation—to enable future implementation.**

[RAB-152]: **Explore the potential of geostationary multi- and hyperspectral ocean-colour measurements to support persistent water-quality monitoring and management, with particular emphasis on high-SNR observations tailored to European coastal and regional seas.**

In the context of the Earth explorers a hyperspectral imager, focusing on inland waters and coastal areas was proposed to provide higher spatial resolution data as currently available or planned to allow monitoring these sensible areas at higher level of granularity. The GALENE mission concept was proposed at EE12 for this purpose.

Imaging terrestrial lights at night from space provides a unique and increasingly policy-relevant observational capability for monitoring human activity, infrastructure, and socio-economic dynamics at regional to global scales. Night-time light emissions serve as a well-established proxy for population distribution, urbanisation, economic activity, energy access, infrastructure resilience, and post-disaster recovery, complementing traditional daytime Earth Observation data.

Within the ESA Earth Explorer programme, dedicated “night-lights” imaging concepts have previously been proposed, notably to EE11 (N8) and EE12 (EULE), where night-time light detection was explicitly considered as a proxy for socio-economic studies. These proposals demonstrated both the scientific relevance and the technical feasibility of systematically observing artificial lighting from space.

From an architectural perspective, night-lights observations do not necessarily require a standalone mission. To a significant extent, this application can be addressed through the accommodation of a dedicated night-band sensor as an additional payload on missions with suitable orbit characteristics, radiometric performance, and mission profiles. Key requirements include high radiometric sensitivity, stable calibration, appropriate spatial resolution to resolve urban and infrastructure patterns, and temporal sampling sufficient to capture diurnal, weekly, and seasonal variability, as well as rapid changes following extreme events.

When integrated into the broader EEOE, night-time light imaging provides strong synergies with land, energy, climate, disaster risk reduction, and development policy domains. It offers a complementary perspective to conventional EO variables, enabling cross-analysis with population, land-use, atmospheric composition, and climate datasets, and supporting evidence-based policymaking at European and international levels.

[RAB-153]: Systematically integrate night-time light observation capabilities into the EEOE Reference Architecture by promoting the inclusion of dedicated night-band imaging payloads on suitable future missions. This capability shall be developed to support socio-economic monitoring, urbanisation and infrastructure assessment, energy access analysis, and disaster impact and recovery evaluation, and shall be implemented in synergy with existing and planned Earth Observation missions rather than as isolated standalone systems.

The domain of VHR imaging is currently served by commercial data in the context of Copernicus via the Copernicus Contribution Missions (CCM) scheme. It is expected that the domain of VHR imagery is maturing in the commercial market which is expected to grow and offers limited potential for ESA missions. Nevertheless, this raises issues and challenges of maintaining a credible system that can provide coherent well calibrated outputs when data are aggregated (hence the need for a European EO Authentication and Measurement Performance Certification Service).

The VHR domain in Europe is currently dominated by commercial operators and mastered from the metric down to 30 – 20 cm spatial resolution domain. In other areas, such as hyperspectral and thermal infrared, the first commercial actors now start to enter the market. The performance of the latter still has to be demonstrated, but they might provide a valuable contribution mostly in the area of specific targeted acquisitions to support local to regional applications. Besides the obvious defence applications, the possible rapid response is also a key element for emergency and disaster management.

[RAB-154]: Explore an optimal approach to integrate commercial data into the overall federated system architecture of imaging missions cross all domains covering aspects of cross-calibration, gap filling, densification as well as reactiveness.

The current and immediate future portfolio of optical imager missions under the responsibility of ESA is expected to provide now and in the foreseeable future the operational backbone for application and services relying on a secure high quality and long-term data stream. The nature of the data will allow commercial providers to link their data and products to those references adding significant value and confidence.

Considering a long-term perspective, it remains to be seen if there is potential to streamline the ESA mission portfolio. Currently, each single mission is addressing a specific spectral, spatial and temporal domain making them complementary and technically challenging to integrate as a single mission solution. The role of commercial providers in the landscape (except for VHR where it is already established) needs to be monitored and the domains of no interest for them (e.g. benchmark sea surface temperature) identified for optimised projection of the mission line-up for the future.

[RAB-155]: Assess potential streamlining approaches for the operational backbone missions of the European EO Ecosystem.

A growing number of Earth Observation imaging applications are directly used to monitor and verify policy implementation, which places stringent requirements on data authenticity, traceability, and quantified uncertainty. To be fit for purpose, EO data—whether originating from institutional or commercial missions—must be demonstrably original, tamper-free, and accompanied by well-defined performance and uncertainty bounds. ESA is uniquely positioned to address this challenge in a holistic manner, given its long-standing stewardship of reference missions, deep expertise in calibration and validation, and comprehensive understanding of EO measurements across spectral, spatial, and temporal domains. Establishing and maintaining such certification frameworks will represent a significant technical and institutional burden; however, this is precisely an area where the commercial sector would benefit from outsourcing to a trusted, internationally recognised authority rather than duplicating effort.

[RAB-156]: Create a European EO Ecosystem architecture that enables ESA to act as a trusted international authority for optical Earth Observation data integrity, authenticity, and quality certification—not only for ESA and Copernicus missions, but also, where appropriate, as an entrusted certifying entity for commercial EO data and service providers.

Missions addressing the Earth's radiation budget and its imbalance are typically not conceived as classical imaging missions, yet they play a foundational role in climate science by providing absolute, traceable measurements of the energy flows that govern the Earth system. The Earth Explorer 12 (EE-12) ECO concept was specifically proposed to deliver such observations, targeting the measurement of outgoing shortwave and longwave radiation with the accuracy required to close the global energy budget and quantify small but climatically decisive imbalances. These measurements would act as a "gold-standard" climate reference, underpinning attribution of climate change, evaluation of model feedbacks, and long-term trend detection. In parallel, the FORUM mission focuses on the far-infrared / long-wave infrared (LWIR, ~50 µm) spectral region, a poorly observed but critical part of the radiation spectrum that carries a large fraction of the Earth's thermal emission, particularly under cold and dry atmospheric conditions. Together, ECO-type broadband radiation budget missions and FORUM's spectrally resolved LWIR observations illustrate how non-imaging missions can provide indispensable climate constraints and complement meteorological and imaging systems within the Reference Architecture.

[RAB-157]: Explore and define new mission synergy concepts that combine radiation budget and spectrally resolved thermal observations to address advanced meteorological and climate user needs beyond the capabilities of MTG, MetOp-SG, and STERNA, ensuring

traceability and integration within the European EO system-of-systems.

[RAB-158]: **Systematically explore and mature new observational approaches to monitor the Earth's radiation imbalance, building on Earth Explorer concepts such as ECO and FORUM, with the objective of establishing long-term, SI-traceable reference measurements that can anchor climate monitoring, model evaluation, and policy-relevant climate assessments.**

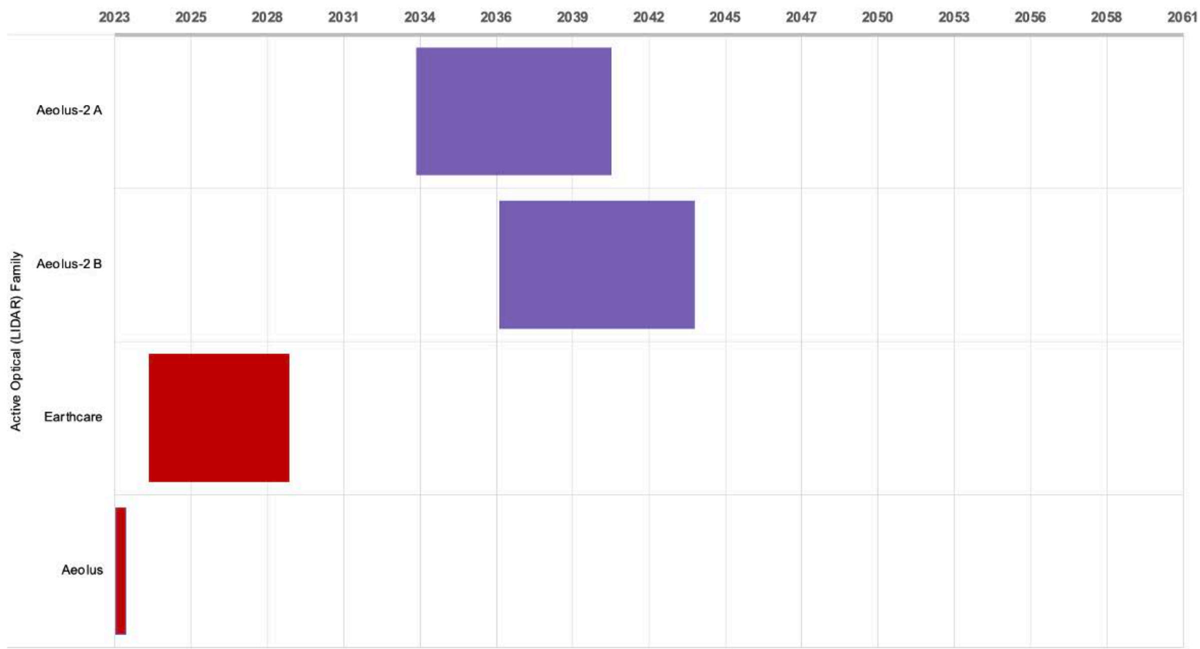
One of the persistent technical challenges in exploiting multi-mission optical datasets in synergy remains atmospheric correction, particularly for applications that rely on high-precision radiometry such as biophysical parameter retrievals, climate trend analysis, and policy-grade monitoring. Differences in spectral response, viewing geometry, calibration accuracy, and temporal sampling across missions—both institutional and commercial—compound uncertainties and limit the full value of combined datasets. Addressing this challenge requires moving beyond mission-specific processing toward advanced multi-mission algorithms that explicitly integrate auxiliary information from models, in situ data, and complementary EO missions, while accounting for spectral diversity and calibration traceability. Such approaches are essential to unlock consistent, interoperable products across the European EO ecosystem and to maximise return on investment from an increasingly heterogeneous observing landscape.

[RAB-159]: **Advance multi-mission algorithm development to maximise the scientific, operational, and commercial value of optical EO data from both institutional and commercial missions, with particular emphasis on atmospheric correction, spectral harmonisation, and explicit treatment of calibration traceability to SI standards.**

A critical enabler for this vision was the TRUTHS mission concept, conceived as a hyperspectral reference sensor designed to provide SI-traceable on-orbit calibration and to serve as a cross-calibration anchor for a wide range of optical missions, including non-ESA, national, and commercial systems. The cancellation of TRUTHS in October 2025 leaves a significant gap in the European Earth Observation Ecosystem, removing a cornerstone capability for systematic, independent validation of radiometric accuracy and long-term stability across missions. Without such a reference, ensuring consistency and trustworthiness of multi-mission optical products becomes increasingly complex and resource-intensive.

[RAB-160]: **Explore and mature alternative approaches for SI-traceable optical cross-calibration and define a robust reference calibration architecture for the European EO ecosystem that can support both institutional and commercial missions, ensuring long-term radiometric consistency, interoperability, and confidence in multi-mission optical products.**

7.8. Active Optical (LIDAR) Family



7.8.6.1 Illustration of the ESA EO Reference Architecture ecosystem timeline for the Active Optical (LIDAR) Family for 2020-2060. (Colour-coding: Copernicus Missions: BLUE; Meteo Missions: PURPLE: Copernicus Missions not yet approved: BROWN; ESA Research Missions: RED: ESA National Programme Missions: ORANGE)

Spaceborne LIDAR (Light Detection and Ranging) missions represent a strategically distinctive European capability within the Earth Observation (EO) system, providing active, vertically resolved, and calibration-stable measurements that cannot be achieved by passive sensors alone. European LIDAR missions have consistently targeted high-impact, high-uncertainty variables—winds, clouds and aerosols, greenhouse gases, and vegetation structure—where vertical information and absolute measurement traceability are essential. Within the Reference Architecture Blueprint, LIDAR missions play a dual role: they act as process-resolving science pathfinders and as reference standards that anchor multi-mission and multi-sensor retrievals.

Europe has established global leadership in atmospheric LIDAR through Aeolus, the first mission to demonstrate direct global wind profile measurements using Doppler LIDAR. Aeolus fundamentally transformed numerical weather prediction and atmospheric dynamics research, while also proving the technical feasibility of complex spaceborne laser systems. Building on this heritage, EarthCARE carries the ATLID ultraviolet atmospheric LIDAR, providing high-resolution vertical profiles of clouds and aerosols in synergy with radar and radiometers to quantify cloud–aerosol–radiation interactions. Together, Aeolus and EarthCARE illustrate the role of LIDAR as a cornerstone for atmospheric process understanding, model evaluation, and data assimilation.

In the greenhouse gas domain, Europe has pioneered active optical sensing through MERLIN, a joint French–German mission employing differential absorption LIDAR (DIAL) to measure atmospheric methane columns with high accuracy and reduced sensitivity to surface reflectance and cloud contamination. MERLIN represents an important step toward policy-relevant, measurement-based verification of greenhouse gas emissions, complementing passive spectroscopic missions and strengthening the credibility of emission inventories.

Looking ahead, LIDAR technology remains central to several future European EO ambitions. Advanced concepts under consideration include multi-wavelength atmospheric LIDARs, spaceborne vegetation structure and biomass LIDARs, and next-generation wind and trace-gas LIDARs with improved efficiency, lifetime, and constellation compatibility. These developments are enabled by progress in laser sources, detectors, power systems, and on-board processing, much of it driven by heritage from Aeolus, EarthCARE, and MERLIN. Within the Reference Architecture, future LIDAR missions are envisaged not as isolated assets, but as reference-capability providers that calibrate, validate, and de-risk passive and commercial observations across the EO ecosystem.

From an architectural perspective, European LIDAR missions are essential to:

- provide vertically resolved reference measurements for atmosphere, biosphere, and climate studies,
- reduce structural uncertainties in models and derived products,
- enable science-to-operations transitions for variables such as winds, clouds, aerosols, and greenhouse gases, and
- maintain European leadership in complex, high-precision EO technologies that few actors worldwide can deliver.

Accordingly, the Reference Architecture Blueprint treats LIDAR missions as strategic anchors within the European EO system-of-systems—capabilities that must be preserved, evolved, and periodically renewed to ensure long-term scientific credibility, policy relevance, and global trust in European Earth Observation.

The Earth Explorer Aeolus mission for wind measurements has been a fundamental success, and the global acquisition of wind profiles became possible with the development of the ALADIN instrument. The EUMETSAT EPS-Aeolus program is a partnership with ESA to provide operational, high-resolution global wind profiles, featuring two satellites launched sequentially (starting with Aeolus-2) to ensure over 10 years of continuity. The mission includes Doppler wind lidar (ALADIN instrument) for vertical wind profiles and planned GNSS radio occultation for temperature/humidity (launch of the A unit in the 2032 timeframe with a B unit in the 2039 timeframe) within the operational context of EUMETSAT EPS-Aeolus.

In the past, CO_2 Differential Absorption LIDAR (DIAL) concepts have been proposed within the Earth Explorer programme as a means to obtain highly accurate, low-bias measurements of atmospheric CO_2. While the achievable horizontal spatial resolution is inherently limited—because multiple along-track backscatter signals must be averaged to reach the required signal-to-noise ratio—the differential measurement principle offers a decisive advantage: it is largely insensitive to surface reflectance, aerosols, and thin clouds, enabling retrievals with minimal systematic bias. This makes CO_2 LIDAR particularly attractive for applications where absolute accuracy and long-term stability are more critical than fine spatial detail, such as climate trend detection, carbon-cycle attribution, and policy verification. In the methane domain, this approach is already being realised through the MEthane Remote sensing LIdar missioN (MERLIN), a joint French-German satellite mission, scheduled for launch around 2029, designed to map atmospheric methane (CH_4) with high precision. This will demonstrate spaceborne DIAL measurements of CH_4 with unprecedented accuracy and robustness. The MERLIN experience provides an essential technological and algorithmic stepping stone for reassessing the feasibility and value of a future CO_2 LIDAR capability within the European EO system.

[RAB-161]: Systematically assess the scientific value, technical feasibility, and architectural role of a CO_2 DIAL mission to deliver ultra-low-bias vertical and column CO_2 measurements, building on MERLIN heritage, with the objective of strengthening Europe's capability for long-term carbon-cycle monitoring, climate attribution, and policy-relevant greenhouse gas verification.

Other proposed LIDARs addressed e.g. biomass estimates and surface properties by analysing the backscatter signal. Depending on the frequency used, there is also some potential regarding bathymetry in coastal regions. Future potential topography LIDARS have the potential to deliver not only 3D surface elevation maps (but also potentially city scale topography), but also information regarding the foliage and vegetation density.

[RAB-162]: Assess the potential of a topography Lidar including aspects of foliage characterisation, snow cover and bathymetry.

In situ and airborne lidar systems have a long-standing heritage in aquatic and oceanographic applications, and more recently, satellite-based lidar measurements have demonstrated the potential to retrieve ocean surface and near-surface properties. Within ESA, studies conducted under the AEOLUS+ innovation framework have explored the feasibility of exploiting the ALADIN Doppler wind lidar for deriving ocean-colour bio-optical and biogeochemical parameters. These investigations have shown, however, that robust retrievals from ALADIN are extremely challenging due to its low signal-to-noise ratio for ocean returns, coarse vertical sampling, strong atmospheric contributions, and dominant surface backscatter, as well as its design optimisation for atmospheric rather than oceanic measurements.

Despite the broad applicability of lidar to ocean science, active optical remote sensing has historically received limited attention within the ocean-colour community. Key limiting factors include the complexity, cost, and size of spaceborne lidar payloads, restricted sampling swath widths, the limited number of usable laser wavelengths, and the absence—until recently—of dedicated demonstrations of spaceborne ocean-profiling lidar capability. Nevertheless, interest in lidar-based ocean observations has re-emerged strongly in recent years, driven by advances in laser technology, detectors, power efficiency, and the growing demand for independent, vertically resolved ocean observations.

The ability to provide global, active, and independent measurements of ocean properties using blue/green lidar represents a uniquely valuable capability. Such observations would enable robust validation of passive ocean-colour products, many of which underpin operational services well beyond research, including climate monitoring, ecosystem assessment, and policy reporting. Looking forward, advances in blue/green laser technology may make constellations of spaceborne ocean lidars feasible, opening new opportunities to observe upper-ocean dynamics, phytoplankton physiology, particle distributions, mixed-layer depth, photochemical processes, and potentially even shallow-water or clear-water subsurface communication and sensing. These capabilities would significantly advance understanding of ocean processes and their role in the Earth system.

[RAB-163]: **Systematically assess the scientific value, technical feasibility, and architectural role of a multi-frequency blue/green spaceborne lidar for ocean bio-optical and biogeochemical applications, including its potential to provide vertically resolved reference measurements and to complement and validate passive ocean-colour missions within the European Earth Observation system-of-systems.**

The Earth Explorer 12 QLEO proposal put forward a novel spaceborne LIDAR concept designed to measure atmospheric specific humidity with high vertical resolution and excellent precision. Specific humidity remains a critically under-sampled variable in the global observing system due to its strong spatial and temporal variability, particularly in the lower troposphere. Improved humidity profiling is expected to deliver a substantial positive impact on Numerical Weather Prediction (NWP) by constraining moisture-driven processes such as convection, cloud formation, and precipitation. While radio occultation (RO) observations contribute valuable information on atmospheric moisture, they provide only indirect constraints and are inherently ambiguous without independent temperature information, placing a significant burden on data assimilation systems. In this context, a direct humidity-sensing LIDAR would represent a step change in atmospheric thermodynamic observations.

Among the most technically ambitious Earth Explorer concepts are Raman LIDAR systems, which exploit inelastic scattering to retrieve water vapour and temperature profiles simultaneously. Such instruments offer the potential to deliver multiple thermodynamic quantities with unprecedented vertical resolution, particularly in the boundary layer and free troposphere, where current EO capabilities remain limited. Despite their promise, no spaceborne Raman LIDAR mission has yet been implemented within the European EO ecosystem.

[RAB-164]: **Further investigate the scientific value, technical feasibility, and operational impact of implementing a QLEO-type humidity LIDAR mission, including assessment of alternative active optical approaches such as Raman LIDAR capable of delivering vertically resolved water vapour and temperature profiles, and their integration into future NWP and climate architectures.**

Active optical techniques also offer important opportunities in the cryosphere domain. By combining LIDAR altimetry with radar altimeter measurements, the snow depth over sea ice can be directly estimated—an essential parameter for accurate sea-ice thickness retrieval. At present, no European LIDAR altimeter mission is planned for this purpose. Instead, Europe has pursued Ku-/Ka-band SAR radar altimetry, with the working assumption that Ka-band returns originate near the snow surface. However, radar techniques suffer from penetration and scattering ambiguities, while the small (metre-scale) footprint of LIDAR altimeters offers a clear advantage in resolving snow–ice interfaces and reducing interpretation uncertainty.

[RAB-165]: **Address the European capability gap in LIDAR altimetry for snow-on-ice measurements by assessing mission concepts that can directly detect snow freeboard, ensuring complementarity with CRISTAL Ka/Ku-band interferometric radar altimetry.**

LIDAR missions are inherently complex and high-risk due to demanding requirements on laser stability, lifetime, power, and calibration. Nevertheless, Europe has built substantial expertise through missions such as Aeolus, planned follow-on developments (Aeolus-2), national initiatives such as MERLIN, and advanced airborne demonstrators. Given their technical complexity and strategic importance, future active optical missions are well suited to institutional flagship implementation, where risk, cost, and long-term stewardship can be shared across ESA Member States rather than borne by individual national programmes.

[RAB-166]: **Define the characteristics and architectural role of a future European reference mission in the active optical domain, such as a Raman LIDAR, and assess credible routes to implementation as an ESA-led flagship capability.**

High-vertical-resolution profiles of water vapour and temperature are fundamental to understanding and predicting atmospheric processes that control weather, climate, and extremes, yet they remain among the most weakly constrained variables in the current EEOE. Passive satellite sensors provide broad coverage but suffer from limited vertical resolution and reduced sensitivity in the lower troposphere, while radio occultation delivers highly stable thermodynamic information but cannot independently resolve humidity without ancillary temperature constraints, placing a heavy burden on data assimilation systems.

Active LIDAR techniques—particularly Raman and differential absorption approaches—offer a unique capability to directly and simultaneously retrieve water vapour and temperature with fine vertical resolution and low bias, especially in the planetary boundary layer and free troposphere where forecast errors are most sensitive.

Despite Europe's demonstrated leadership in complex spaceborne LIDAR missions (e.g. Aeolus and EarthCARE), no active optical mission currently exists or is planned to provide these core thermodynamic profiles. Recognising and addressing this gap through targeted studies, technology maturation, and mission pre-development is therefore essential to strengthen European leadership in atmospheric observation, improve numerical weather prediction and climate reanalyses, and ensure the Reference Architecture remains capable of supporting future scientific and operational demands.

[RAB-167]: Recognise and address the absence of active LIDAR missions capable of delivering high-vertical-resolution water vapour and temperature profiles within the current European EO ecosystem and prioritise exploratory and preparatory activities to close this gap.

7.9. Atmospheric Spectroscopy Family

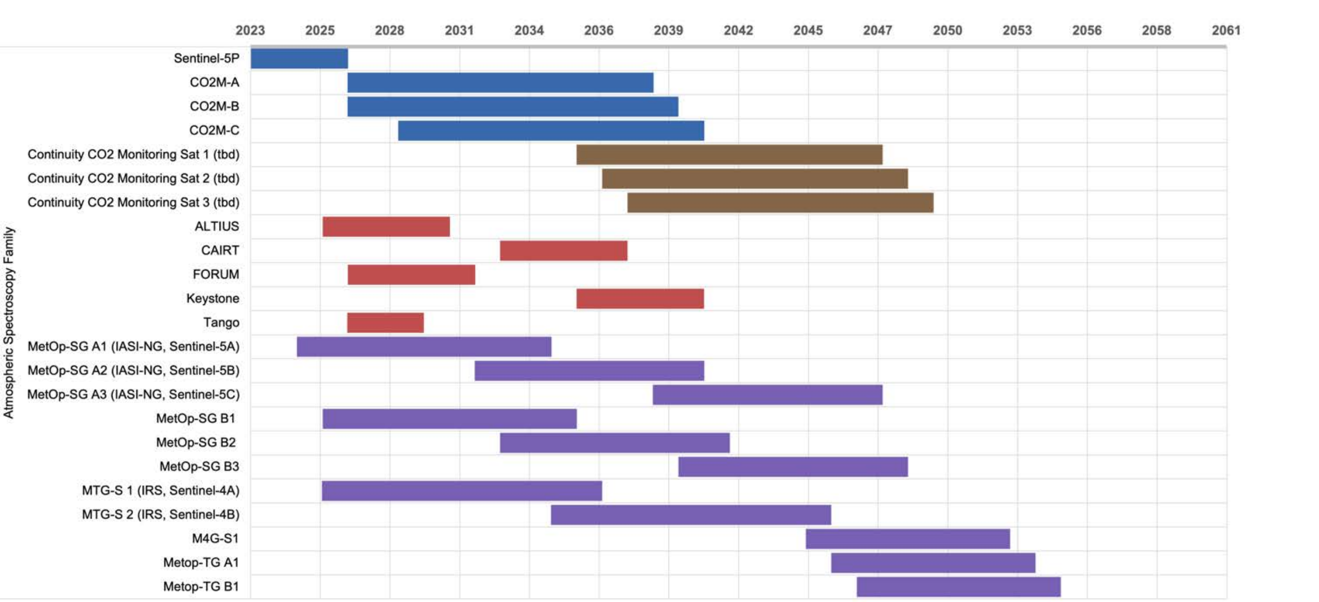


Figure 7.10-1. Illustration of the ESA EO Reference Architecture ecosystem timeline for the Atmospheric Spectroscopy Family for 2020-2060. (Colour-coding: Copernicus Missions: BLUE; Meteo Missions: PURPLE: Copernicus Missions not yet approved: BROWN; ESA Research Missions: RED: ESA National Programme Missions: ORANGE)

Atmospheric spectroscopy has a long and distinguished heritage in Europe, with missions such as GOME, GOME-2, GOMOS, SCIAMACHY, and the currently operational IASI and

Sentinel-5P. This capability is being further strengthened through missions in development and implementation, including IASI-NG, Sentinel-4, Sentinel-5, CO2M, and MTG-IRS. Historically, these missions have been primarily driven by air-quality monitoring requirements; however, emissions monitoring, particularly for CO_2 and CH_4, has now become a central policy and scientific priority. In this context, Earth Explorer concepts have been proposed to target additional trace gases such as NH_3 and N_2O, at spatial scales not achievable with current or planned operational sensors.

Existing and planned spectroscopic missions provide systematic, large-scale global coverage, forming an essential observational backbone. Sentinel-4, operating from geostationary orbit, will deliver a persistent view of Europe and parts of Africa, while polar-orbiting missions ensure global sampling. Nevertheless, this architecture leaves room for complementary missions focused on emissions at city or facility scale, operating in targeted or agile observation modes, as exemplified by concepts such as Scout TANGO.

Sentinel-5P, equipped with the state-of-the-art TROPOMI instrument, has demonstrated exceptional capability by mapping a wide range of trace gases—including NO_2, O_3, SO_2, HCHO, CO, CH_4, and aerosols—with a 2 600 km swath enabling daily global coverage. Its data underpin operational services such as the Copernicus Atmosphere Monitoring Service (CAMS), supporting air-quality forecasting, volcanic ash monitoring for aviation safety, UV radiation warnings, and ozone hole assessment. The follow-on Sentinel-5 instruments onboard MetOp-SG-A 1/2/3 will ensure continuity of these core capabilities through approximately 2025–2050.

The Copernicus CO2M mission represents a major step toward policy-driven greenhouse-gas monitoring, consisting of a constellation of three satellites designed to support the quantification of anthropogenic CO_2 emissions, with additional sensitivity to estimate CH_4 and NO_2 emissions. CO2M forms the space segment of the CO_2 Monitoring and Verification Support capacity (CO2MVS) under CAMS. The first CO2M satellite is planned for launch in 2027, with a minimum design lifetime of 7.5 years, and subsequent satellites providing enhanced revisit and robustness. Each spacecraft carries a high-resolution VIS/NIR/SWIR imaging spectrometer (NO2/CO2) and complementary instruments for cloud, aerosol, and sun-induced chlorophyll fluorescence (SIF) observations, enabling improved separation of anthropogenic emissions from natural fluxes. Estimating emissions down to sources of small and medium strengths remains technically demanding, which is due to the relatively small CO_2 (and CH_4) enhancement(s) compared to its background concentrations, and the stringent precision required for trend detection and compliance monitoring.

Looking forward, CO_2 and CH_4 observations are likely to become legally and economically consequential, as emissions monitoring transitions toward compliance verification and, potentially, enforcement. This elevates requirements on data authenticity, traceability, and quantified uncertainty, implying the need for reference-quality missions, robust cross-calibration, and certification frameworks capable of standing up in regulatory or legal contexts. As policy measures succeed and atmospheric concentrations stabilise or decline, retrieval precision requirements will become even more stringent, reinforcing the need for sustained, SI-traceable reference observations.

[RAB-168]: There remains a gap in measuring CO_2, CH_4, and other greenhouse gases at scales ranging from industrial facilities to cities. Assess mission concepts capable of concurrent, high-spatial-resolution mapping of multiple GHGs with global coverage, beyond current targeted approaches, to close this gap in the European EO ecosystem.

Beyond dedicated atmospheric spectroscopy missions, synergistic use of non-specialised sensors is increasingly valuable. Sentinel-2, and particularly Sentinel-2 Next Generation, will contribute to CH_4 detection at very high spatial resolution using SWIR bands that, while not originally designed for this purpose, are nevertheless suitable for differential approaches. This illustrates the broader architectural opportunity to repurpose existing data streams in innovative ways to address emerging needs.

MTG-IRS will deliver a unique four-dimensional (space–time–height) view of atmospheric thermodynamics over Europe, critical for nowcasting and severe-weather applications. However, optical and infrared sounders remain intrinsically limited in the atmospheric boundary layer, where clouds, surface effects, and weak thermal contrast reduce sensitivity. Complementary approaches—such as microwave hyperspectral sounders, currently under consideration internationally—offer the potential to resolve boundary-layer temperature and humidity with reduced cloud sensitivity, addressing a long-standing EO gap.

[RAB-169]: Study mission concepts capable of resolving atmospheric boundary-layer structure from space, leveraging non-optical techniques where appropriate, to address fundamental limitations of current optical sounding approaches.

Many atmospheric spectroscopy applications are now directly linked to policy implementation and compliance monitoring, placing strong demands on data certification, authenticity, and uncertainty characterisation. This applies equally to institutional and commercial data. ESA is uniquely positioned to act holistically in this role due to its stewardship of reference missions and its comprehensive expertise across spectral, spatial, and temporal domains.

[RAB-170]: Ensure continuity of CO2M-class reference capability beyond the currently planned constellation to provide sustained, policy-relevant CO_2 (and CH_4) observations supporting European and international greenhouse gas reduction commitments.

Aerosol observations remain a cross-cutting challenge. Europe has heritage from POLDER, current capability through Sentinel-3 SLSTR, future enhancement via 3MI on MetOp-SG, and polarimetric capability on CO2M (MAP). Compact polarimetric instruments (e.g. SPEX-type sensors) and LIDAR missions (EarthCARE, Aeolus) further complement this landscape. As in optical imaging, the need for operational backbones, reference calibration, and entrusted data stewardship is central.

[RAB-171]: Ensure an independent, systematic, and high-quality backbone of atmospheric spectroscopic observations across spatial and temporal scales, anchored by globally recognised reference sensors.

[RAB-172]: Ensure an independent, systematic, and high-quality backbone of multi- and hyperspectral imaging observations, providing global reference capability for institutional and commercial EO missions.

Millimetre-wave and sub-millimetre atmospheric spectroscopy provides unique sensitivity to key trace gases and dynamical processes in the stratosphere and mesosphere that are not accessible with infrared or ultraviolet techniques. Europe’s capability in this domain has relied heavily on the long-lived Odin mission designed for atmospheric research and astronomy, launched in 2001 as a Swedish-led satellite with strong European participation (partnering with Canada, France, and Finland). Odin has delivered more than two decades (still operational as of June 2025 with decommissioning planned for 2026) of high-quality observations of ozone, water vapour, nitrogen species, chlorine compounds, and dynamical tracers in the middle atmosphere using millimetre- and sub-millimetre-wave limb sounding, underpinning studies of ozone depletion and recovery, stratospheric chemistry, and climate variability.

As Odin approaches the end of its operational life, no direct European successor is currently in orbit, creating an emerging gap in mm-wave atmospheric spectroscopy. This gap risks loss of continuity in long time series essential for trend detection, model evaluation, and policy-relevant assessments. Within the Reference Architecture Blueprint, this motivates proactive assessment of next-generation mm-wave and THz mission concepts, potentially exploiting advances in detector technology and platform miniaturisation, to ensure sustained European capability for middle-atmosphere composition and dynamics measurements and to preserve the scientific legacy established by Odin.

[RAB-173]: Anticipate and address the emerging gap in millimetre-wave atmospheric spectroscopy as legacy missions (e.g. Odin), by assessing complementary THz and mm-wave mission concepts to ensure continuity of critical observations.

7.9.1.1. Middle and Upper Atmosphere Limb Sounding Gaps.

The middle atmosphere—spanning the stratosphere, mesosphere, and lower thermosphere plays a decisive role in climate coupling, ozone chemistry, radiative balance, and Earth–space interactions. These layers govern key processes such as stratospheric ozone recovery, radiative forcing feedbacks, gravity-wave momentum transport, and the vertical propagation of climate signals from the lower atmosphere into space. They are also the region where anthropogenic influences, including greenhouse gases, space debris ablation products, and potential climate intervention activities, first manifest measurable impacts.

Despite this importance, the middle atmosphere remains systematically under-observed, particularly with respect to vertically resolved composition, temperature, and dynamics. Nadir-viewing instruments lack the vertical resolution required to resolve these processes, and in-situ measurements are sparse, episodic, and geographically limited. Limb-sounding techniques therefore remain essential. Europe has historically led in this domain through missions such as GOMOS, SCIAMACHY, and MIPAS, yet most of these capabilities have now ended or will do so in the coming decade, with no assured successor providing comparable vertical resolution and coverage across the full middle-atmosphere column.

Infrared Limb Imaging (ILI), as developed to Phase-A maturity in the EE11 CAIRT mission concept, represents one of the most advanced and versatile approaches available. CAIRT would have provided continuous, vertically resolved observations from the upper troposphere through the stratosphere and into the mid-mesosphere (~5–80 km), delivering unique information on greenhouse gases (including N_2O and CFCs), ozone recovery processes, gravity waves, long-range pollutant transport, and thermodynamic variability relevant to both climate and numerical weather prediction. It would also have established a critical observational baseline for emerging policy-relevant challenges, including monitoring unintended impacts of climate intervention measures and characterising chemical changes driven by space activities.

Infrared Limb Imaging (ILI) - an atmospheric sounding technique that can provide observations of numerous trace gases with both the vertical and horizontal resolution required for/by the Global Climate Observing System (GCOS) - has been studied up to phase A for the CAIRT Earth Explorer mission concept. Specifically, limb imaging Fourier Transform Spectroscopy is a new instrument technique which is mature for implementation (at SRL5 and TRL5). The observations are versatile and comprehensive and address an observation gap in ESA's Earth Observation strategy, covering an atmospheric domain with altitudes from the upper troposphere into the mid-mesosphere (~5km - 80km) and higher. Throughout this large depth, ILI provides vertically resolved information on atmospheric structure and composition not accessible with existing observations. ILI is therefore well-suited to react to upcoming challenges such as detecting and monitoring potential climate intervention measures as well as quantifying space debris impacts on middle atmospheric composition upon their re-entry. It thus provides the basis for understanding climate forcing and feedbacks as well as changes in the ozone layer induced by these potential new threats. Infrared limb imaging provides vertically- and horizontally-resolved information on greenhouse gases, including CFCs and nitrous oxide (N2O) that also play critical roles in ozone layer recovery. The high vertical resolution of ILI for ozone and water vapour observations in the Upper Troposphere and Lower Stratosphere region (UTLS) would improve numerical weather prediction by data assimilation. Spatially-resolved temperature perturbations could provide unprecedented information on atmospheric gravity waves with the potential to improve global models for climate prediction and weather forecasting. Furthermore, ILI provides unparalleled information to study global long-range transport of tropospheric pollutants and societal challenges due to biomass burning or volcanic eruptions, for example. For several of these scientific topics of societal relevance, ILI is the only known means of securing adequate data.

The CAIRT mission concept was not selected for implementation in 2025 leaves a clear and growing European gap in middle-atmosphere limb sounding at a time when international reliance on legacy missions is increasing and global continuity is uncertain. Without a dedicated European capability, Europe risks losing scientific leadership, weakening its contribution to international climate and ozone assessments, and becoming dependent on non-European data sources for a region of the atmosphere that is fundamental to long-term climate stability, space weather resilience, and planetary stewardship.

[RAB-174]: **There is an internationally recognised gap of infrared limb sounding throughout the middle atmosphere, requiring urgent action for continued measurements of Essential Climate Variables and of ozone- and climate-relevant trace gases, that could only be addressed via thermal infrared limb sounding spectroscopy and imaging, such as proposed for the EE11 CAIRT candidate mission.**

[RAB-175]: **Recognise CFCs and related compounds as potent greenhouse gases and ozone-depleting substances lacking dedicated European monitoring and assess limb-sounding approaches as a viable future solution.**

7.10. Gravimetry Family

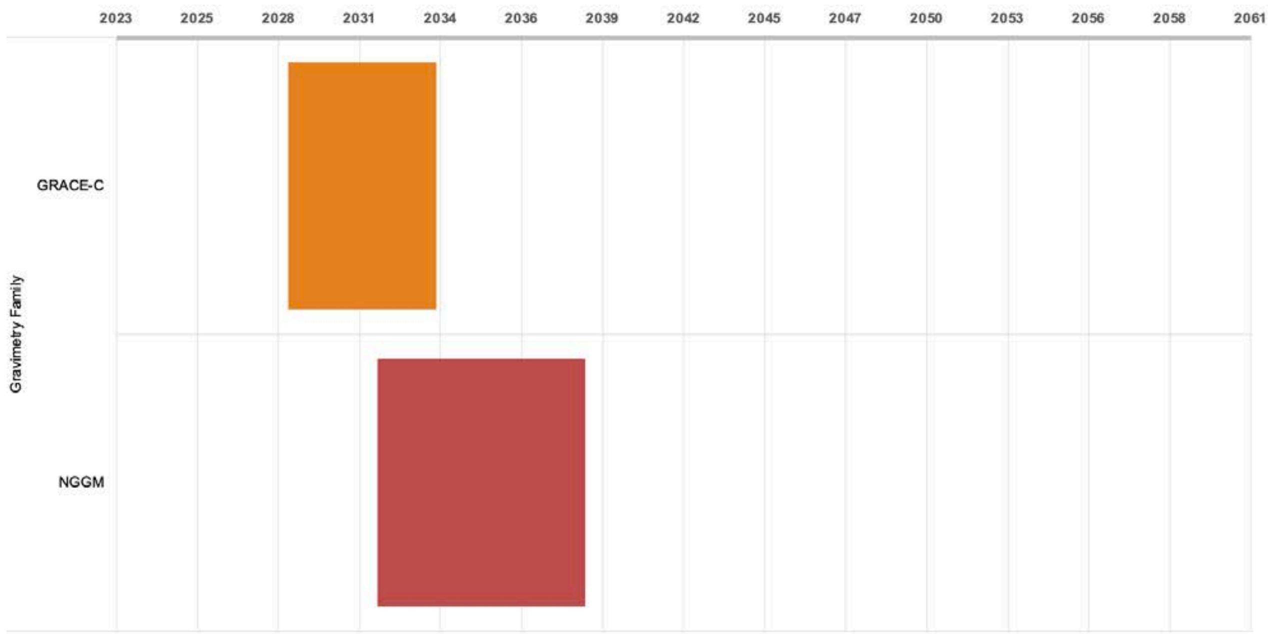


Figure 7.11-1. Illustration of the ESA EO Reference Architecture ecosystem timeline for the Gravimetry Family for 2020-2060. (Colour-coding: Copernicus Missions: BLUE; Meteo Missions: PURPLE: Copernicus Missions not yet approved: BROWN; ESA Research Missions: RED: External missions: ORANGE)

The Next Generation Gravity Mission (NGGM) is a cornerstone capability for the European Earth Observation Reference Architecture because it secures long-term, high-fidelity monitoring of Earth's mass redistribution, a unifying signal that underpins hydrology, cryosphere change, sea-level rise, solid-Earth dynamics, and ocean circulation. NGGM is Europe's contribution to the internationally coordinated ESA-NASA Mass Change and Geosciencs International Constellation (MAGIC), conceived after the transformative successes of GRACE (time-variable gravity) and GOCE (static gravity reference). Architecturally, NGGM provides a second satellite pair flying in an inclined, controlled low-Earth orbit (~70° at ~400 km) that complements a near-polar pair developed by NASA/DLR (GRACE-C). This multi-plane, quasi-Bender constellation design markedly improves spatio-temporal sampling, regional sensitivity, and robustness—capabilities that a single pair cannot deliver.

Technically, NGGM introduces controlled orbit, laser interferometric ranging and advanced accelerometery, targeting step-change gains in precision, latency, and stability such that product accuracy becomes constrained by background geophysical models rather than instrument noise. Programmatically, NGGM bridges science to operations: it extends gravity time series with policy-relevant continuity, aligns with international requirements articulated by IUGG and GCOS, and demonstrates operational gravimetry for Copernicus—notably for water-cycle monitoring, water management, drought and flood early warning, ice-sheet mass balance, geohazards, ocean circulation, and monitoring of climate tipping points.

Strategically for Europe, NGGM preserves leadership in a domain where no passive alternative exists, anchors cross-calibration and model evaluation across EO domains, and provides an indispensable evidence base for climate adaptation, resource management, and risk resilience. Within the Blueprint, NGGM is therefore not a niche mission but a system-level reference, whose continuity, densification, and eventual evolution (including future hybrid or quantum extensions) are essential to maintain Europe's scientific credibility, policy autonomy, and operational readiness in Earth system stewardship.

[RAB-176]: Prioritise NGGM as a cornerstone European mission to extend and enhance gravity time series with higher spatial/temporal resolution, lower uncertainty and latency, meeting IUGG/GCOS needs and demonstrating operational gravimetry for Copernicus.

Looking beyond NGGM/MAGIC, quantum gravimetry offers a different pathway. Following maturation of quantum sensors and in-orbit demonstrations (e.g. under EU initiatives), post-2040 Copernicus gravimetry could benefit from hybrid constellations combining classical and quantum instruments.

The CARIOQA (Cold Atom Rubidium Interferometer in Orbit for Quantum Accelerometery) programme is a European Union–funded initiative (https://carioqa-quantumpathfinder.eu/) that aims to develop and demonstrate quantum sensors (quantum gravimeters/accelerometers) for space, with the near-term goal of flying a Quantum Pathfinder Mission by the early 2030s and laying the groundwork for full quantum space gravimetry missions thereafter.

The EU Horizon Europe has launched Quantum Flagship calls on quantum space gravimetry and in 2025, the EQUIP-G community (https://equip-g.eu/https://equip-g.eu/) began fostering research into quantum gravimeter networks, quantum sensor grand challenges, and the integration of quantum technologies into satellite systems . By 2029, EQUIP-G will submit a roadmap and recommendations to the European Commission for the implementation of a future perennial European Quantum Infrastructure for gravimetry.

[RAB-177]: Europe should strengthen the technology maturation roadmap for spaceborne quantum gravity missions.

Europe's commitment to quantum gravity and spaceborne sensing extends beyond the CARIOQA Pathfinder to a broader programme of studies, technology maturation, and community building aimed at establishing sovereign quantum gravimetry and related capabilities. Encarnação et al. (2025) propose a path towards effective exploitation of quantum sensors in future satellite gravity missions. ESA has sponsored dedicated research into Quantum Space Gravimetry for Earth Mass Transport (QSG4EMT) to define mission concepts, user requirements, error budgets, and constellation designs that exploit quantum instruments' flat error spectra for enhanced gravity field monitoring and Earth-system change detection. This work feeds future mission scenarios that would improve monitoring of continental hydrology, ice mass change, and sea-level signals with reduced low-frequency noise compared with classical accelerometers.

Despite planned advances, a capability gap remains even with MAGIC, present architectures struggle to deliver the spatio-temporal resolution demanded by regional hydrology, rapid extremes, and near-real-time services. Addressing this gap will likely require additional spacecraft, diversified orbital geometries, and/or complementary gravity missions to fully exploit the unifying power of gravity across Earth system science and societal applications.

[RAB-178]: Planning should be initiated for post-NGGM operational continuity and densification of gravimetric observations (e.g.through added spacecraft, optimized constellation geometries, and the phased introduction of quantum gravity sensors).

7.11. Geomagnetic Family

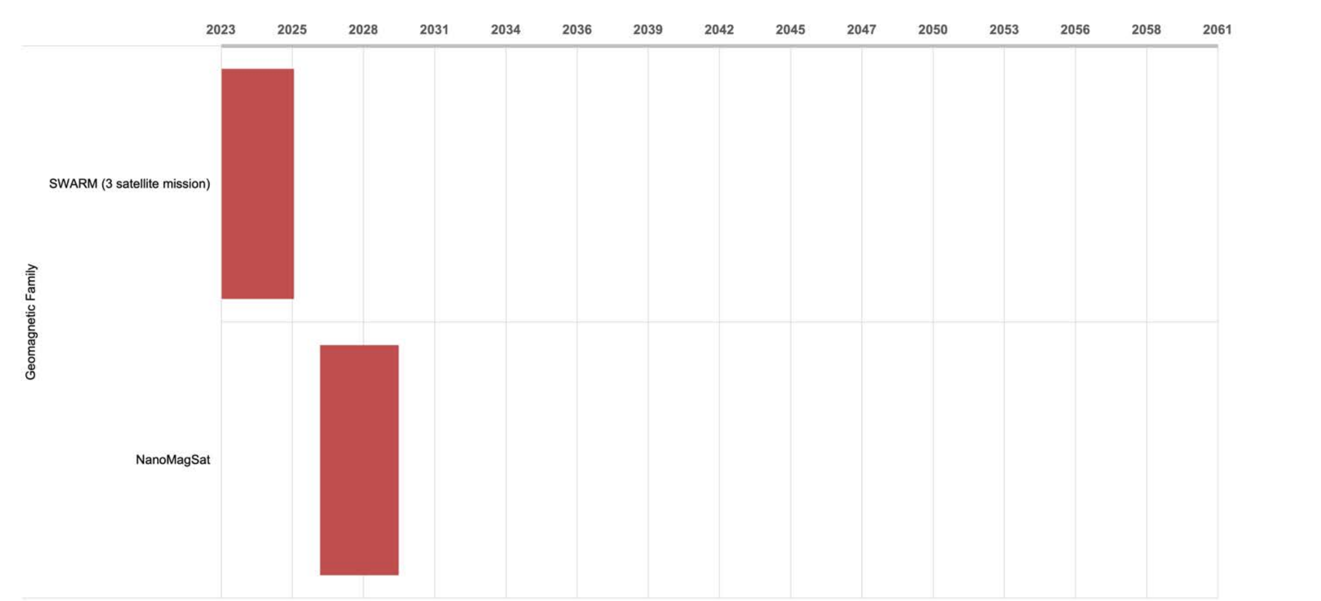


Figure 7.12-1. Illustration of the ESA EO Reference Architecture ecosystem timeline for the Geomagnetic Family for 2020-2060. (Colour-coding: Copernicus Missions: BLUE; Meteo Missions: PURPLE: Copernicus Missions not yet approved: BROWN; ESA Research Missions: RED: ESA National Programme Missions: ORANGE)

Swarm is ESA's flagship geomagnetic mission and reached its ten-year operational milestone in November 2023. It has delivered an unprecedented, high-quality global record of Earth's magnetic field and its temporal variability, spanning signals from the geodynamo in the core (dominant contribution) through lithospheric and ionospheric sources down to weak ocean-tidal magnetic signatures. This scientific return is enabled by Swarm's unique three-satellite constellation architecture, with each spacecraft carrying a fully characterised magnetometry payload consisting of an absolute scalar magnetometer, a vector field magnetometer, and star trackers to provide precise attitude knowledge.

The orbital configuration—two satellites (Swarm-A and Swarm-C) flying in close formation at ~400 km altitude and a third satellite (Swarm-B) at a higher altitude (~500 km)—has proven decisive. It allows spatial and temporal separation of magnetic field sources and has established Swarm not only as a cornerstone Earth Observation mission, but also as a reference mission for heliophysics and Sun–Earth interaction studies. Swarm's secondary objectives explicitly address ionosphere–thermosphere–magnetosphere coupling, linking Earth's atmosphere to the space environment and solar forcing.

The forthcoming NanoMagSat Scout builds directly on Swarm's scientific and technical heritage. NanoMagSat will comprise three identical nanosatellites in inclined orbits, each carrying a miniaturised absolute scalar magnetometer and a self-calibrating vector magnetometer mounted on a boom, together with star trackers. As a Scout-class, low-cost mission, NanoMagSat will deliver a reduced-performance capability relative to Swarm, but it is expected to provide partial continuity of geomagnetic observations. Importantly, Swarm-B—anticipated to operate beyond 2030—offers a valuable opportunity for cross-calibration and validation of NanoMagSat data products during an overlap phase.

Despite this mitigation, NanoMagSat does not replace Swarm in terms of measurement accuracy, stability, and long-term reference quality. Once NanoMagSat reaches end-of-life, the European EO ecosystem faces a clear structural gap in geomagnetic observations, particularly problematic given the long time-series requirements for core dynamics, space-weather impacts, and infrastructure resilience. This strongly motivates the definition of a future operational geomagnetic reference mission, building directly on Swarm's legacy and exploiting the maturity of European magnetometry expertise. Swarm-B could serve as a precursor and calibration anchor for such a programme if continuity is strategically planned.

[RAB-179]: **Swarm has delivered a uniquely rich and globally trusted record of Earth's geomagnetic dynamics. While NanoMagSat Scout will provide partial continuity, its reduced performance relative to Swarm necessitates early mitigation actions within the Reference Architecture.**

[RAB-180]: **A significant post-NanoMagSat gap in European geomagnetic measurement capability is foreseen and must be addressed through a sustained reference mission approach.**

The viability of quantum diamond magnetometer technology (*Halde et al*, 2025) is under investigation by the Canadian Space Agency (CSA) and CNES using airborne demonstrators at 40 km altitude with promising results (https://www.asc-csa.gc.ca/eng/sciences/balloons/stratos.asp). Building on this success, ESA is investigating ways to fly quantum magnetometers that could fly in very low Earth orbit (VLEO) together with air-breathing electric propulsion (ABEP) as part of a roadmap for the next generation of electromagnetic field missions that continue and enhance the measurement of SWARM and NanoMagSat. The target is a low mass instrument that could fly on small satellite platforms. Building on airborne and laboratory results (that can demonstrate sensitivity), an in orbit demonstration of this concept can validate magnetic cleanliness, long-term stability, radiation tolerance, thermal control, and interference mitigation in a realistic spacecraft configuration. Flying at very low altitude increases magnetic signal strength and spatial resolution; coupling with ABEP enables sustained operations and directly tests a key architectural enabler for future electromagnetic field missions. The output of such an IOD would allow early validation of mass, power, and EMC performance on a small-sat platform and reduce barriers to potential future missions/constellations, hosted payloads, and operational follow-on opportunities.

[RAB-181]: Explore quantum diamond magnetometer technology through a staged in-orbit demonstrator programme in Very Low Earth Orbit, integrated with air-breathing electric propulsion , to transition from airborne validation to operational readiness for next-generation electromagnetic field missions.

The Keystone Earth Explorer 12 candidate mission (currently in Phase-0) targets the Mesosphere–Lower Thermosphere (MLT, ~70–120 km), a region critically influenced by solar electromagnetic radiation and energetic particle precipitation. This altitude range is inaccessible to aircraft and balloons and too low for long-lived satellite orbits due to residual drag dominated by atomic oxygen. Keystone aims to observe composition, temperature, and winds across diurnal to seasonal timescales, addressing fundamental gaps in space-weather–climate coupling and documenting the counter-intuitive cooling of the upper atmosphere driven by increasing CO_2 concentrations.

Above ~100 km, the atmosphere transitions from a well-mixed gas to a diffusively separated regime, while solar EUV and X-ray absorption produces the ionosphere. In this environment, electromagnetic forces dominate plasma motion, and geomagnetic field topology controls coupling between the ionosphere, magnetosphere, and solar wind. The Lower Thermosphere–Ionosphere (LTI) transition region—often termed the “ignorosphere”—is where neutral fluid dynamics and plasma electrodynamics coexist and exchange momentum and energy through collisions. This coupling drives variability that directly affects satellite drag, radio-signal propagation, navigation systems, and geomagnetically induced currents at Earth’s surface.

The Daedalus (EE-10), although not selected due to programmatic constraints, proposed a novel on-orbit in-situ “dipper” mission with perigee excursions below 150 km (down to ~120 km) to directly sample these collisional processes. The scientific rationale remains compelling, and continued work by the ESA–NASA ENLoTIS working group confirms the need for coordinated in-situ and remote sensing observations to advance whole-atmosphere and space-weather modelling.

Swarm's secondary objectives, together with the primary goals of Daedalus, CAIRT, and Keystone, share a unifying ambition: to understand vertical and cross-domain coupling between Earth's lower atmosphere, upper atmosphere, and geospace environment. However, current LEO observations at 400–500 km altitude cannot resolve the physics of the LTI region, where coupling processes peak and where observations remain extremely sparse.

[RAB-182]: A critical gap exists in European Earth Observation capability related to the atmosphere–space transition. The neutral–plasma interactions governing the Lower Thermosphere–Ionosphere (100–200 km) remain insufficiently observed and represented in models, requiring renewed mission concepts and architectural attention.

8. CONCLUSIONS

Europe's Earth Observation (EO) future depends on a set of deliberate and interdependent choices: the preservation of those elements that guarantee credibility, continuity, and trust in European EO data; the evolution of those system components that no longer scale with increasing user demand, technological progress, and external pressures; and the intentional preservation of architectural flexibility to accommodate uncertainty, innovation, and future needs. The Reference Architecture Blueprint provides a common framework to make these choices transparent, traceable, and sustainable over the long term.

Europe's future Earth Observation capability will be defined by how effectively it navigates a period of sustained uncertainty characterised by accelerating environmental change, rising societal and policy expectations, rapid technological disruption, and increasing constraints on resources, spectrum, and the space environment. The Reference Architecture Blueprint demonstrates that European Earth Observation Ecosystem (EEOE) has evolved into a foundational public infrastructure underpinning climate and environmental policy, disaster risk reduction, security, economic planning, and long-term Earth system stewardship. In this context, continuity, credibility, resilience, and adaptability are not emergent outcomes of successful missions, but architectural properties that must be deliberately designed, governed, and renewed over multi-decadal timescales across the Ecosystem.

This Blueprint identifies 183 Reference Architecture Blueprint (RAB) actions that together establish a coherent European Earth Observation Ecosystem (EEOE) perspective for the evolution of ESA's Earth Observation Programme in the 2030–2050 timeframe. In line with the ESA Convention, these activities are not intended to prescribe individual programme decisions, but as options to strengthen coordination among Member States and European entities in Earth Observation, enabling collective outcomes that cannot be achieved through national or isolated approaches alone. The Blueprint therefore serves as a strategic alignment instrument, supporting informed decision-making across ESA, the European Union, EUMETSAT, and their respective stakeholders.

A central conclusion of the Blueprint is the need to reduce strategic and technical uncertainty through systematic fore sighting. Long mission lifetimes, extended development cycles, and deep coupling between space, in situ, digital, and service layers mean that reactive decision-making is no longer sufficient. Scenario-based foresight, architectural stress-testing, and early identification of emerging drivers, bottlenecks, and failure modes are considered core governance functions. These activities, and others that will emerge in the coming years, are to be anticipated via fore sighting approaches because they provide the evidential basis for anticipating future user needs, identifying capability gaps before they become critical, and preserving option space under profound uncertainty. Embedded within the Reference Architecture, foresight enables Europe to move from incremental adaptation toward anticipatory, system-level stewardship.

However, foresight must be directly connected to action. Identified gaps—whether in observing capability, temporal sampling, vertical resolution, resilience, or trust—must be addressed proactively through new missions and new architectural patterns, rather than through incremental extension of legacy systems. While continuity of essential observations remains a fundamental asset of the EEOE, particularly for climate records and policy-grade services, many emerging needs cannot be met by today's observing system alone. The Blueprint therefore frames future missions as elements of a coherent, evolving portfolio, explicitly designed to complement existing Copernicus, meteorological, scientific, national, international, and commercial capabilities.

Within this portfolio, the continued evolution and continuity of data streams from Copernicus missions remains central. Copernicus provides Europe's primary operational backbone for policy-grade Earth Observation, delivering sustained, reliable, and quality-controlled data in support of environmental monitoring, climate action, security, and societal resilience. The Blueprint makes clear that Copernicus continuity and evolution must be managed together: safeguarding long-term time series and reference measurements while enabling systematic upgrades in capability, performance, and responsiveness. Copernicus cannot remain static in the face of rising user expectations, digital transformation, and external pressure; yet its evolution must be affordable and carefully managed to avoid undermining trust, interoperability, and long-term comparability.

Meteorological missions, primarily operated through EUMETSAT, form a second indispensable operational backbone. They deliver time-critical observations essential for numerical weather prediction, climate monitoring, aviation and maritime safety, and disaster preparedness. Their operational imperatives - low latency, high availability, and sustained global coverage - differ from those of other mission families, yet they are deeply interlinked with broader environmental and climate objectives. The Blueprint highlights the need for continued evolution of meteorological architectures across both geostationary and low-Earth orbits, and for close coordination with Copernicus, research, and in situ systems to ensure coherence, mutual reinforcement, and efficient use of shared infrastructure. Against this background, the Arctic Weather Satellite and emerging EPS STERNA system follows a rapid development and implementation cycle is a notable example of positive disruptive evolution.

The Blueprint recognises the Earth Explorer missions that remain the primary engine of scientific discovery, measurement innovation, and long-term capability development. The Blueprint consistently reinforces that Earth Explorers are not only precursors to operational systems, but strategic assets in their own right. They enable Europe to pioneer new observing techniques, establish new measurement families, and advance understanding of Earth system processes at a depth and precision that operational missions alone cannot achieve. Importantly, the Blueprint recognises that the value of the Earth Explorer programme extends beyond flown missions: high-quality concepts, preparatory studies, and technology developments constitute a reservoir of knowledge that reduces long-term risk, informs future architectural choices, and prevents premature lock-in to suboptimal observing strategies.

Φ-Sat missions and Scout missions are complementary to Earth Explorers and provide the ecosystem with speed, flexibility, and learning capacity. They enable rapid in-orbit demonstration of new sensing concepts, onboard processing, autonomy, and artificial intelligence that cannot be fully validated on the ground. The Blueprint positions these missions as integral components of the architectural lifecycle, enabling early validation of disruptive approaches and preserving option space for future system evolution. Stepping-Stone missions further provide a critical intermediate layer, allowing new capabilities to mature at meaningful scale before transition into sustained operations.

Commercial missions and services are increasingly central to the European Earth Observation landscape, contributing responsiveness, scalability, and innovation across both space and ground segments. The Blueprint recognises their growing role, while also identifying architectural risks associated with uncoordinated integration, including calibration inconsistency, limited transparency, and vulnerability to market or geopolitical disruption. The strategic conclusion is that commercial capabilities should be embraced and systematically integrated, but anchored to reference-quality measurements, interoperability standards, and certification frameworks to ensure that speed and innovation reinforce, rather than undermine, trust and policy usability.

National and international missions remain essential contributors to Europe's observing capability. National programmes provide diversity, responsiveness, and targeted innovation, while international partnerships extend coverage, reduce duplication, and strengthen global observing systems. The Blueprint emphasises that Europe's leadership depends on its ability to integrate these contributions coherently - leveraging shared standards, reference measurements, and coordinated planning - while preserving European strategic autonomy and values.

Across all mission families, the Blueprint identifies strengthened pre-development activities - including pre-Phase-0 studies, mission concept maturation, and initiatives such as InCubed - as critical enablers. Robust pre-development reduces uncertainty, preserves architectural flexibility, and enables informed trade-offs before major commitments are made. It also strengthens the link between user needs, technological opportunity, and architectural feasibility, ensuring that future missions are both relevant and sustainable. The heart of success for the implementation of the Reference Architecture lies with robust pre-development of future missions and system architectures.

The paradigm shift of AI forecasting and prediction systems presents an excellent example since this is already having a profound impact on the future user/stakeholder needs for future missions. A defining conclusion of the Blueprint concerns the transformative impact of AI on Earth Observation demand and system design. AI-based forecasting and modelling systems for the ocean, atmosphere, and coupled Earth system are rapidly evolving, increasingly complementing and in some cases redefining traditional numerical approaches. Compared to the EEOE of 2025, these systems place new and different demands on observations: not only higher volume, but different combinations of variables, sensitivity, temporal sampling, uncertainty characterisation, and consistency across all domains. AI systems may prioritise observational diversity, statistical completeness, and co-located multi-parameter data over traditional mission-specific optimisation, and may exploit non-traditional data sources, including commercial observations and dense in situ networks, in ways not anticipated by today's architecture. This deserves immediate attention to reduce uncertainty and risk in the evolution of the EEOE.

The Blueprint stresses the need for future observing system design to explicitly anticipate AI-driven user needs, rather than assuming continuity of today's demand patterns. This implies closer co-design between observing systems, in situ infrastructures, and AI developers; greater emphasis on observation-to-observation learning and data assimilation beyond classical frameworks; and renewed attention to long-term consistency, provenance, and uncertainty, which are essential for trustworthy AI training and validation. Far from reducing the need for reference measurements and continuity, AI increases their importance: poorly characterised or drifting observations risk propagating bias and error at scale across AI-enabled forecasting and decision systems.

Resilience emerges as a cross-cutting conclusion. The Blueprint treats resilience not only as the robustness of space assets, but as the capacity of the Earth Observation system to support societal resilience to climate extremes, environmental degradation, and systemic shocks. Learning from heritage missions such as ERS and embedding resilience by design through diversity of observing approaches, redundancy, interoperability, clean-space practices, and spectrum stewardship, are essential to maintaining long-term system integrity.

Throughout this evolving landscape, the Blueprint consistently reinforces the importance of ESA's role as a neutral architect and steward of the European Earth Observation Ecosystem. In an increasingly complex environment of overlapping mandates, commercial participation, AI-driven transformation, and international interdependence, neutral architectural oversight is essential to preserve coherence without centralisation, and innovation without fragmentation. ESA's end-to-end involvement across mission lifecycles, combined with its convening role among European and international partners, uniquely positions it to safeguard trust, continuity, and long-term value.

In accordance with ESA's mandate to act in the interest of its Member States and to foster cooperation with European institutions, a clear strategic orientation emerges: Europe must sustain a core set of reference-class EO missions and associated ground-segment capabilities that provide the benchmark for measurement performance, calibration, and long-term consistency. Such reference capabilities form the foundation upon which Copernicus operational services, EUMETSAT-led meteorological systems, and downstream commercial activities can reliably build. Maintaining European leadership in this area is essential to ensure that standards of EO quality, trust, and interoperability remain aligned with European values, priorities, and policy needs. As the European EO ecosystem expands and diversifies, ensuring data authenticity, traceability, and measurement performance becomes increasingly critical. These attributes are essential not only for scientific excellence, but also for operational service provision, regulatory support, and policy implementation under the Copernicus framework. They are equally important as EO data are increasingly used in economic, legal, and compliance-related contexts. ESA's unique end-to-end involvement across the EO mission lifecycle - from early concept studies and technology maturation through system design, calibration and validation, and long-term data stewardship - positions the Agency to play a central coordinating role in this domain.

Taken together, the Blueprint leads to a clear overarching conclusion. Europe's Earth Observation leadership to mid-century will not be secured by privileging any single mission type, programme line, or data source. It will be secured by sustaining and evolving a balanced, complementary portfolio in which Copernicus and meteorological missions provide stable, policy-grade operational foundations; Earth Explorers drive scientific discovery and measurement innovation; Φ-Sat, Scout, and Stepping-Stone missions accelerate learning and de-risk the future; national and international missions extend capability and cooperation; commercial missions enhance responsiveness within a trusted framework; and observing systems are explicitly prepared to serve the emerging needs of AI-enabled forecasting and Earth system intelligence.

Across proposed RAB actions, five consistent objectives emerge: safeguarding reference-quality continuity as Europe's public EO infrastructure; strengthening architecture-led stewardship across institutional and operational boundaries; enabling scalable digital and artificial-intelligence capabilities that convert data into actionable information while preserving traceability and uncertainty characterisation; embedding resilience and autonomy with respect to the space environment, spectrum use, and supply-chain dependencies; and sustaining innovation pathways while ensuring orderly transition into operational service provision.

The analysis also identifies focus areas that should guide the evolution of the Blueprint towards a 2026 edition. These include clearer mechanisms to link architectural insight to prioritised decision-making; the definition of quantitative performance and continuity envelopes to support transparent trade-offs; explicit architectural treatment of continuity under disruption; and structured transition pathways from experimental systems into sustained operations. As digitalisation and artificial intelligence become intrinsic to the EO value chain, further emphasis is required on architecture-level trust, explainability, provenance, and user feedback mechanisms, supported by appropriate success metrics.

By using the Reference Architecture Blueprint as a living, foresight-driven coordination instrument, Europe can manage uncertainty, embrace technological transformation, and ensure that its Earth Observation Ecosystem remains credible, resilient, and strategically relevant in an AI-driven future. The Reference Architecture Blueprint will continue to evolve as a living framework—supporting coordination, managing long-term uncertainty and risk, and reinforcing Europe's leadership and autonomy in Earth Observation in line with the needs of its users and Stakeholders.

9. REFERENCES

AIRBUS (2025). “Airbus, Leonardo and Thales sign Memorandum of Understanding to create a leading European player in space”, https://www.airbus.com/en/newsroom/press-releases/2025-10-airbus-leonardo-and-thales-sign-memorandum-of-understanding-to

Anderson, K., Ryan, B., Sonntag, W., Kavvada, A. and Friedl, L., (2017). Earth observation in service of the 2030 Agenda for Sustainable Development. *Geo-spatial Information Science*, *20*(2), pp.77-96.

Armstrong McKay, D.I. et al. (2022) ‘Exceeding 1.5°C global warming could trigger multiple climate tipping points’, Science, 377(6611). Available at: https://doi.org/10.1126/science.abn7950.

Arumugam, D., Park, JH., Feyissa, B. et al. (2024). Remote sensing of soil moisture using Rydberg atoms and satellite signals of opportunity. Sci Rep 14, 18025 (2024). https://doi.org/10.1038/s41598-024-68914-6

Bai, X. et al. (2024) ‘Translating Earth system boundaries for cities and businesses’, Nature Sustainability. Nature Research, pp. 108–119. Available at: https://doi.org/10.1038/s41893-023-01255-w.

Ben Bouallègue, Z., M. C. Clare, L. Magnusson, E. Gascon, M. MaierGerber, M. Janoušek et al., 2024: The rise of data-driven weather forecasting: A first statistical assessment of machine learning–based weather forecasts in an operational-like context. Bulletin of the American Meteorological Society, 105(6), pp.E864-E883.

Berger, M., Moreno, J., Johannessen, J. A., Levelt, P. F., & Hanssen, R. F. (2020). ESA’s Sentinel missions in support of Earth system science. Remote Sensing of Environment, 235, 111580. https://doi.org/10.1016/j.rse.2019.111580

Biermann, F. (2021) ‘The future of “environmental” policy in the Anthropocene: time for a paradigm shift’, Environmental Politics, 30(1–2), pp. 61–80. Available at: https://doi.org/10.1080/09644016.2020.1846958.

Chantry, M. and P. Dueben. (2025), Machine learning for numerical weather prediction, https://www.ecmwf.int/sites/default/files/elibrary/81699-machine-learning-for-numerical-weather-prediction.pdf

Daly, H. (2008) Ecological Economics and Sustainable Development, Selected Essays of Herman Daly.

Development, Concepts and Doctrine Centre (DCDC), (2024).Global Strategic Trends Out to 2055, seventh edition, Ministry of Defence, UK, available at https://assets.publishing.service.gov.uk/media/68dba439dadf7616351e4bf8/GST_7_Final_post_pic_change_WEB.pdf

Dueben, P. D. And P. Bauer, (2018) Challenges and design choices for global weather and climate models based on machine learning. Geosci. Model Dev., 11, 3999–4009. https://doi.org/10.5194/gmd-11-3999-2018

Dueben, P., U. Modigliani, A. Geer, S. Siemen, F. Pappenberger, P. Bauer et al. (2021) Machine learning at ECMWF: A roadmap for the next 10 years. ECMWF Technical Memorandum No 878. https://doi.org/10.21957/ge7ckgm

Encarnação, J., Siemes, C., Daras, I., Carraz, O., Strangfeld, A., Zingerle, P., & Pail, R. (2025). A path towards effective exploitation of quantum sensors in future satellite gravity missions. *Advances in Space Research*.

ESA Space Debris Office, (2025). ESA’s Annual Space Environment Report, GEN-DB-LOG-00288-OPS-SD, ESA ESOC, available from https://www.sdo.esoc.esa.int/publications/Space_Environment_Report_I9R1_20251021.pdf

EUMETSAT (2021). EUMETSAT Destination 2030, https://www-cdn.eumetsat.int/files/2021-09/EUMETSAT_Strategy_FULL_Online.pdf

EUMETSAT, (2025). Implications of the end of SSMIS data on OSI SAF products. https://osi-saf.eumetsat.int/community/stories/implications-end-ssmis-data-osi-saf-products

European Commission (2023). EU Space Strategy for Security and Defence, JOIN(2023)9, https://ec.europa.eu/transparency/documents-register/detail?ref=JOIN(2023)9&lang=en

European Commission (2025). Proposal for a Regulation of the European Parliament and of the Council on the safety, resilience and sustainability of space activities in the Union, COM(2025) 335 final, https://eur-lex.europa.eu/procedure/EN/2025_335

European Commission (EC). (2021). Better regulation guidelines (SWD(2021) 305 final). Publications Office of the European Union, https://commission.europa.eu/system/files/2021-11/swd2021_305_en.pdf

European Commission, Joint Research Centre (JRC). (2024). Earth observation strategic research and innovation agenda. Publications Office of the European Union. https://doi.org/10.2760/18985

European Commission. (2021). The EU space programme: Copernicus, Galileo, and EGNOS (Regulation (EU) 2021/696). Publications Office of the European Union.

European Cooperation for Space Standardization. (2022). ECSS system – Description, implementation and general requirements (ECSS-S-ST-00-01C). ESA-ESTEC, Noordwijk, The Netherlands.

European Environment Agency (EEA). (2022). The European environment — state and outlook 2022: Knowledge for transition to a sustainable Europe. EEA Report No 09/2022. https://www.eea.europa.eu

European Space Agency (2023). Space Safety Programme and Zero Debris Approach, ESSB-ST-U-007 Issue 1, available from https://technology.esa.int/upload/media/DGHKMZ_6542582e18e33.pdf

European Space Agency (2024). A Journey into the future of ESA (version 1), ESA Strategic Planning and Foresight Office, Paris.

European Space Agency (2025c) Strategy 2040, https://esamultimedia.esa.int/docs/corporate/ESA_Strategy_2040_InDepth.pdf

European Space Agency. (2012). Envisat mission overview and legacy (ESA TM-2012-14). ESA Publications.

European Space Agency. (2023). ESA strategy 2040: A space agency for Europe. ESA Publications Division. https://esamultimedia.esa.int/docs/corporate/ESA_Strategy_2040_InDepth.pdf

European Space Agency. (2015). Earth Observation Science Strategy, SP-1329_1, https://esamultimedia.esa.int/multimedia/publications/SP-1329_1/SP-1329-1.pdf

European Space Agency (2024). Earth Science in Action for Tomorrow's World. ESA_Earth_Observation_Science_Strategy_issued_Sept_2024.pdf

European Space Agency. (2025b). Earth Explorers: ESA's pioneering science missions for Earth. https://www.esa.int/Applications/Observing_the_Earth/FutureEO/Earth_Explorers_ESA_s_pioneering_science_missions_for_Earth

European Space Policy Institute (ESPI). (2024). A year of transformation: Empowering Europe in Space and Beyond, https://www.espi.eu/wp-content/uploads/2024/01/ESPI_AnnualReport2023.pdf

European Space Policy Institute (ESPI). (2025a). A year of growth: Advancing the European Space Agenda ESPI Annual Report 2024, https://www.espi.eu/wp-content/uploads/2025/03/ESPI-Annual-Report-2024-FINAL_March-2025.pdf

European Space Policy Institute (ESPI). (2025b). Rising Together? The (Re)Convergence of Europe's Space and Defence Industries, https://www.espi.eu/wp-content/uploads/2025/04/ESPI-Report-94.pdf

European Space Science Committee (2025). Earth Observation Groundbreaking Science Discoveries, https://www.essc.esf.org/wp-content/uploads/2025/03/ESSC-ESA-EO-Groundbreaking-Science-Discoveries-v2_compressed_compressed.pdf

EUSPA (2024). EU Space Surveillance and Tracking (EU SST) portfolio, third edition, available at https://portal.eusst.eu

Group for Earth Observation (GEO), (2025). Earth Intelligence For All GEO post 2025 strategy, https://earthobservations.org/storage/documents/Key-Documents/GEO%20Post%202025%20Strategy%20Full%20Document.pdf

Gupta, J. et al. (2024) 'A just world on a safe planet: a Lancet Planetary Health–Earth Commission report on Earth-system boundaries, translations, and transformations', The Lancet Planetary Health, 8(10), pp. e813–e873. Available at: https://doi.org/10.1016/S2542-5196(24)00042-1.

Halde, V., Bernard, O., Brochu, M., Dufresne, L., Fleury, N., Johnson, K., ... & Roy-Guay, D. (2025). Who let the diamonds out?, https://arxiv.org/abs/2509.19179

Hauser, D., Tourain, C., & Lachiver, J. M. (2019). CFOSAT: A new mission in orbit to observe simultaneously wind and waves at the ocean surface. *Space Research Today*, *206*, 15-21.Ho, S-p, Zhou X, Shao X, Chen Y, Jing X, Miller W. Using the Commercial GNSS RO Spire Data in the Neutral Atmosphere for Climate and Weather Prediction Studies. Remote Sensing. 2023; 15(19):4836. https://doi.org/10.3390/rs15194836

Hollmann, R., Merchant, C. J., Saunders, R., Downy, C., Buchwitz, M., Cazenave, A., … Wersinger, D. (2013). The ESA Climate Change Initiative: A European contribution to the generation of essential climate variables. Remote Sensing of Environment, 203, 2–14. https://doi.org/10.1016/j.rse.2017.07.020

Iden, J., Methlie, L. B., and Christensen, G. E. (2017). The nature of strategic foresight research: A systematic literature review. Technological Forecasting and Social Change, 116, 87-97.

Ivanco, M., Ford, E., Burn, K., Ethridge, B., Jacobson, L., Jones, C., and Herrmann, N. (2024, March). A Scenario-Based Approach to Assess Continuity Gaps in Earth Observations. In 2024 IEEE Aerospace Conference (pp. 1-14). IEEE.

Krelina, M, (2024). Quantum Technologies for Air and Space: Quantum-Enhanced Radars and Electronic Warfare: Use Cases and Timelines, JAPCC, 37, https://www.japcc.org/articles/quantum-technologies-for-air-and-space

Kudryavtsev, V., Yurovskaya, M., Chapron, B., Collard, F. & Donlon, C. (2017). Sun glitter imagery of surface waves. part 2: Waves transformation on ocean currents, Journal of Geophysical Research: Oceans 122, 1384–1399.

Lawrence, J. et al. (2020) 'Cascading climate change impacts and implications', Climate Risk Management, 29. Available at: https://doi.org/10.1016/j.crm.2020.100234.

Lawrence, M. et al. (2024) 'Global polycrisis: the causal mechanisms of crisis entanglement', Global Sustainability. Cambridge University Press. Available at: https://doi.org/10.1017/sus.2024.1.

Lenton, T. M., D.I. Armstrong McKay, S. Loriani, J.F. Abrams, S.J. Lade, J.F. Donges, M. Milkoreit, T. Powell, S.R. Smith, C. Zimm, J.E. Buxton, E. Bailey, L. Laybourn, A. Ghadiali, J.G. Dyke (eds), 2023, The Global Tipping Points Report 2023. University of Exeter, Exeter, UK. https://global-tipping-points.org/

Lenton, T.M. et al. (2023b) 'Quantifying the human cost of global warming', Nature Sustainability, 6(10). Available at: https://doi.org/10.1038/s41893-023-01132-6.

Lenton, T.M. et al. (2024) 'Remotely sensing potential climate change tipping points across scales', Nature Communications, 15. Available at: https://doi.org/10.1038/s41467-023-44609-w.

McNally, A., C. Lessig, P. Lean, E. Boucher, M. Alexe, E. Pinnington et al. (2024). Data driven weather forecasts trained and initialised directly from observations. arXiv preprint arXiv:2407.15586

Madani K. (2026a) Water Bankruptcy: The Formal Definition, Water Resources Management, 40 (78) doi: 10.1007/s11269-025-04484-0

Madani K. (2026b) Global Water Bankruptcy: Living Beyond Our Hydrological Means in the Post-Crisis Era, United Nations University Institute for Water, Environment and Health (UNU-INWEH), Richmond Hill, Ontario, Canada, doi: 10.53328/INR26KAM001

Madelon, R., Rodríguez-Fernández, N. J., Van der Schalie, R., Kerr, Y., Albitar, A., Scanlon, T., ... & Dorigo, W. (2021, July). Towards the removal of model bias from ESA CCI SM by using an L-band scaling reference. In *2021 IEEE international geoscience and remote sensing symposium IGARSS* (pp. 6194-6197). IEEE.

Merchant, C. J., Embury, O., Bulgin, C. E., Block, T., Corlett, G. K., Fiedler, E., … Donlon, C. (2019). Satellite-based time-series of Earth system variables: A review of recent advances and remaining challenges. Surveys in Geophysics, 40, 109–158. https://doi.org/10.1007/s10712-018-9471-0

Milkoreit, M. et al. (2024) 'Governance for Earth system tipping points – A research agenda', Earth System Governance, 21. Available at: https://doi.org/10.1016/j.esg.2024.100216.

OECD (2025). Strategic Foresight Toolkit for Resilient Systems: A Comprehensive Foresight Methodology to Support Sustainable and Future-Ready Public Policyhttps://www.oecd.org/publications/foresight-toolkit-for-resilient-public-policy-9ad1cd60-en.htm

Organisation for Economic Co-operation and Development (OECD), (2025), Measuring Science and Innovation for Sustainable Growth, OECD Publishing, Paris, https://doi.org/10.1787/3b96cf8c-en.

Organisation for Economic Co-operation and Development. (2021). Earth observation for public policy: Managing data for informed decision-making. OECD Publishing, Paris. https://doi.org/10.1787/c1d6f6e3-en

Pearce, J. V., Veltcheva, R. I., Peters, D. M., Smith, D., and Nightingale, T. (2019). Miniature gallium phase-change cells for in situ thermometry calibrations in space. *Measurement Science and Technology*, *30*(12), 124003.

Pultarova, T., (2024). SpaceX Starlink satellites made 50,000 collision-avoidance manoeuvres in the past 6 months. What does that mean for space safety? " Jul. 2024. [Online]. Available: https://www.space.com/spacex-starlink-50000-collision-avoidance-maneuvers-space-safety

Raworth., K (2017): Doughnut Economics: seven ways to think like a 21st century economist, Penguin.

Richardson, K. et al. (2023) 'Earth beyond six of nine planetary boundaries', Science Advances, 9(37). Available at: https://doi.org/10.1126/sciadv.adh2458.

Richardson, K. et al. (2023). Earth beyond six of nine planetary boundaries. Sci. Adv. 9, eadh2458. DOI:10.1126/sciadv.adh2458.

Ripple, W.J. et al. (2023) 'Many risky feedback loops amplify the need for climate action', One Earth. Cell Press, pp. 86–91. Available at: https://doi.org/10.1016/j.oneear.2023.01.004.

Rockström, J. et al. (2009). A safe operating space for humanity, Nature, 461. Available at: https://doi.org/10.1038/461472a.

Rockström., et al. (2024). The planetary commons: A new paradigm for safeguarding Earth-regulating systems in the Anthropocene. PNAS. 121 (5) e2301531121. https://doi.org/10.1073/pnas.2301531121

Sathyendranath, S., Brewin, R. J., Brockmann, C., Brotas, V., Calton, B., Chuprin, A., ... & Platt, T. (2019). An ocean-colour time series for use in climate studies: the experience of the ocean-colour climate change initiative (OC-CCI). *Sensors*, *19*(19), 4285.

Selva, D., & Krejci, D. (2012). A survey and assessment of the capabilities of Cubesats for Earth observation. *Acta Astronautica*, *74*, 50-68.

SpaceNews (2026). No more free rides: it's time to pay for space safety. https://spacenews.com/no-more-free-rides-its-time-to-pay-for-space-safety

SpaceX (2026). "Starlink is beginning a significant reconfiguration of its satellite constellation", https://x.com/michaelnicollsx/status/2006790372681220530

Steffen, W. et al. (2015) 'The trajectory of the anthropocene: The great acceleration', Anthropocene Review. SAGE Publications Inc., pp. 81–98. Available at: https://doi.org/10.1177/2053019614564785.

Tassa A, Willekens S, Lahcen A, Laurich L and Mathieu C (2022) On-Going European Space Agency Activities on Measuring the Benefits of Earth Observations to Society: Challenges, Achievements and Next Steps. Front. Environ. Sci. 10:788843. doi: 10.3389/fenvs.2022.788843

Tassa A, S. Willekens, A. Lahcen, L. Laurich and C. Mathieu Charlotte, (2020):On-Going European Space Agency Activities on Measuring the Benefits of Earth Observations to Society: Challenges, Achievements and Next Steps, Frontiers in Environmental Science, 10, DOI=10.3389/fenvs.2022.788843

Thomas, B., Piironen, P., Cuadrado-Calle, D., Lia, E., & Ayllon, N. (2025). Millimeter-and Submillimeter-Wave Technologies for Space Passive Remote Sensing Instruments. *IEEE Journal of Microwaves*.

Trenberth, K. E., Fasullo, J. T., & Balmaseda, M. A. (2014). Earth's energy imbalance. Nature Climate Change, 4(10), 911–917. https://doi.org/10.1038/nclimate2384

UNOOSA (1966). Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies, https://www.unoosa.org/oosa/en/ourwork/spacelaw/treaties/outerspacetreaty.html

UNOOSA (1971). Convention on International Liability for Damage Caused by Space Objects, https://www.unoosa.org/oosa/en/ourwork/spacelaw/treaties/introliability-convention.html

UNOOSA (1976). Convention on Registration of Objects Launched into Outer Space, https://www.unoosa.org/oosa/sk/ourwork/spacelaw/treaties/introregistration-convention.html

Wang et al (2024), XiHe: A Data-Driven Model for Global Ocean Eddy-Resolving Forecasting, https://api.semanticscholar.org/CorpusID:267411739}

WEF (2025). World Economic Forum (WEF) Global Risks Report 2025, 20th Edition Insight report, 104pp., ISBN: 978-2-940631-30-8 available from https://reports.weforum.org/docs/WEF_Global_Risks_Report_2025.pdf

Wiebe, K., Zurek, M., Lord, S., Brzezina, N., Gabrielyan, G., Libertini, J., ... & Westhoek, H. (2018). Scenario development and foresight analysis: exploring options to inform choices. Annual Review of Environment and Resources, 43(1), 545-570.

World Economic Forum (WEF). (2025). The executive's playbook on earth observation. World Economic Forum. https://reports.weforum.org/docs/WEF_The_Executive%E2%80%99s_Playbook_on_Earth_Observation.pdf

World Meteorological Organization (WMO). (2022). Global Climate Observing System (GCOS) implementation plan 2022. WMO-No. 1291, Geneva.

Wunderling, N., von der Heydt, A., Aksenov, Y., Barker, S., Bastiaansen, R., Brovkin, V., Brunetti, M., Couplet, V., Kleinen, T., Lear, C. H., Lohmann, J., Roman-Cuesta, R. M., Sinet, S., Swingedouw, D., Winkelmann, R., Anand, P., Barichivich, J., Bathiany, S., Baudena, M., Bruun, J. T., Chiessi, C. M., Coxall, H. K., Docquier, D., Donges, J. F., Falkena, S. K. J., Klose, A. K., Obura, D., Rocha, J., Rynders, S., Steinert, N. J., and Willeit, M. (2023). Climate tipping point interactions and cascades: A review, EGUsphere [preprint], https://doi.org/10.5194/egusphere-2023-1576, 2023.

Zhu, X.X., Xiong, Z., Wang, Y. *et al.* On the foundations of Earth foundation models. *Commun Earth Environ* **7**, 103 (2026). https://doi.org/10.1038/s43247-025-03127-x

10. ANNEX-1 HISTORICAL EARTH EXPLORER CALLS AND PROPOSALS

1st Call for Opportunity Mission Proposals

COM1 (ref: PB-EO(98)53) – release of Call approved at PB-EO on 26-27 May 1998 in Wales, UK. 27 valid Proposals were received by deadline of December 1998.

Notably proposals included the first iteration of proposals submitted for Swarm, BIOSAR (now BIOMASS), REFIR (early FORUM concept), FLEX, and GEOSCIA (now Sentinel-4). The VAGSAT concept later became SWIMSAT in the 1st Call for Opportunity Missions – and though not selected ultimately was implemented in the form of the French-Chinese CFOSAT mission.

The selection of the first two Earth Explorer Opportunity missions CryoSat (EE1) and SMOS (EE2) was approved by PB-EO in May 1999, with ACE kept as "hot spare" (ref: PB-EO(99)37).

Ref	Proposed Mission	Living Planet Challenges [ESA(2015), SP-1329]
COM1-01	MIMOSA	C2, C5
COM1-04	SVO	G1, G4
COM1-05	GEOSCIA	A3, A1
COM1-07	H2R2	A3
COM1-08	EOLE	A4
COM1-09	SWARM	G5
COM1-10	STREAMS	A3, A1
COM1-11	CREME	A1, A5
COM1-12	VAGSAT	O4, A2
COM1-13	ACE	A3
COM1-14	BIOSAR	L2, A2
COM1-15	SIMSA	G3, L5, L2, L3, O1, O3,
COM1-16	SMOS	L1, L2, L5, O4, O5, A2
COM1-17	ACLISCOPE	A1, A3, A4
COM1-18	DIAMANT	O1, O3, L1, L3, L4
COM1-19	ECOSPACE	O1, O4, A1, A2, A3
COM1-20	R3SAT	A1, A2, A4
COM1-21	SCOPE	A3, A2, A1

COM1-22	TROPEX	O3, O2, A2
COM1-23	ECOMON	O1, O3, O4
COM1-24	FOS	L1, L2, G1, A3
COM1-26	REFIR	A1, A3
COM1-27	SWIFT	A3, A4,
COM1-29	FLEX	L2, L5
COM1-30	Bi-SAR	L3, L4, C2
COM1-31	ARAMIS	L2, L3, L5, C3, C1, O1
COM1-33	CRYOSAT	C1, C3
Total: 27		

1st Call for Core Missions – CCM1

CCM1 – release of the Call for Core Explorer Mission Ideas was approved at PB-EO in May 2000. 10 valid Proposals were received by the deadline. See ESA - Five candidate core missions presented at Granada 2001.

Notably proposals included the first iteration of proposals submitted for Carbonsat (now CO2M), SPECTRA (now CHIME), and updated GEOSCIA++ concept (now Sentinel-4).

Ref	Proposed Mission	Living Planet Challenges [ESA(2015), SP-1329]
CCM1-01	CLOUDS	A1, A4
CCM1-02	EarthCARE	A1, A3
CCM1-03	W_WISE	A3, A2, A1
CCM1-04	CARBOSAT	A3
CCM1-05	WALES	A1, A3
CCM1-06	WATS	A1, A4
CCM1-07	ACECHEM	A3, A1
CCM1-08	GEOSCIA++	A3, A1
CCM1-09	SPECTRA	L3, L2
CCM1-10	LICODY	G2, O2, O5
Total: 10		

2nd Call for Opportunity Missions – COM1

The release of the 2nd Call for Explorer Opportunity Missions was in 2001. 25 valid proposals were received by the deadline.

SNOWSAT was a predecessor to CoReH2O – approved as a candidate EE7 mission. BIOMASCA was the predecessor to BIOMASS (subsequently approved as EE7). The reproposed REFIR mission concept is a forerunner of FORUM (subsequently approved as EE9).

Ref	Proposed Mission	Living Planet Challenges [ESA(2015), SP-1329]
COM2-02	SNOWSAT	C3, C2, C1
COM2-04	MIMOSA	C2, C5, C5
COM2-06	SOIR	A1, A3, A2
COM2-07	CIWSIR	A1, A3
COM2-08	EVINSAR	G1, G4
COM2-09	FOURIER	A3, A1
COM2-13	SWIMSAT	O4, A2
COM2-16	PETREL	O5, O2
COM2-18	EGPM	A1, A2
COM2-20	BIOGEOSAT	O1, O4
COM2-21	GOMAS	A1, A2, A3
COM2-23	REFIR	A2 A1
COM2-26	IMAGINE	G5, G4
COM2-27	CARBOSAT	A3, A2
COM2-29	SWARM	G5
COM2-32	GeoTROPE	A3, A1
COM2-33	SAND	L1, L2, L3, L5
COM2-35	TROC	A3
COM2-36	OLIVIA	A3, A2
COM2-38	BIOMASCA	L2, A2
COM2-40	BIOSAT	L2, L5, A2
COM2-41	VOICE	L2, A2, G1, C1
COM2-42	EOVIREX	O4, A3, L2

COM2-45	ACE+	A1, A3
COM2-46	TRUTHS	A1, A2
Total: 25		

2nd Call for Core Missions – CCM2

The release of the 2nd Call for Core Earth Explorer mission ideas was in March 2005 after approval by September PB-EO (see PB-EO(2004)82).

24 Proposals were received by the deadline of 15 August 2005.

Note that the PREMIER proposal preceded the revised concept in the CAIRT EE11 proposal, and the FLEX proposal preceded successful selection of candidates from the following COM3 call in 2010. The WaTER proposal was a precursor to the approved SWOT mission, and the CIWSIR is a preview of the revised CloudIce Proposal submitted to COM3, and subsequently approved as the ICI instrument on MetOp-SG-B.

Ref	Proposed Mission	Living Planet Challenges [ESA(2015), SP-1329]
CCM2-01	GOMAS	A1, A2, A3
CCM2-02	PREMIER	A3, A1
CCM2-03	LVTM	L3, L2
CCM2-04	CIWSIR	A1, A3
CCM2-05	MATH-AWC	A1
CCM2-06	SPACE WAVES	A1, A3
CCM2-08	HABITAT	G1, G2, L3
CCM2-09	Du-DROPS	A1, A4
CCM2-10	GeoTROPE-R	A3
CCM2-11	Kioto+	L3, L2
CCM2-12	FLEX	L2, L5
CCM2-13	ACCURATE	A3
CCM2-14	KLIMA	A1, A3
CCM2-15	OLIVIA	A3
CCM2-16	ILAC	A3
CCM2-17	BIOMASS	L2, A2, L1
CCM2-18	TRAQ	A3

CCM2-20	WatER	L2, A2, L5
CCM2-21	CARISMA	C2, L2
CCM2-23	A-SCOPE	A3
CCM2-24	PHYTOSAT	O4, O3
CCM2-25	CoReH2O	C3, C1
CCM2-26	ECOsat	A3, A1
CCM2-27	EM-SAS	G5, A5
Total: 24		

3rd Call for Opportunity Missions – COM3

The release of the 2nd Call for Explorer Opportunity Missions (EE8) was in October 2009 after PB-EO approval of the call in September (ESA/PB-EO(2009)96).

31 proposals were received by the deadline of 15 April 2010.

Note the Z-Earth proposal preceded the successful approval of the CNES CO3D constellation 3d photogrammetry mission (without the lidar). The SGR-ReSI instrument proposal preceded the GNSS demo on UK TechDemoSat-1 (TDS-1), the receiver on CYGNSS, and the updated version of the receiver flying on the HydroGNSS Scout mission. The LITE (ASIM) instrument became the ASIM transient luminous events instrument on the ISS.

Ref	Proposed Mission	Living Planet Challenges [ESA(2015), SP-1329]
COM3-01	SuperSAR	G1, C2, L1
COM3-03	EXCALIBUR	A2, A3, O2, L2
COM3-04	WINDS	A4, A3
COM3-05	OCAPI	O1, O2, O4
COM3-06	GWACS	A1, A3
COM3-08	CloudIce	A1, A3
COM3-09	e.motion	G2, C2, O5
COM3-10	NITROSAT	A2, A3, L2
COM3-11	PPM	A1, C3
COM3-12	MLT-LIDAR	A1, A3
COM3-13	FloRad	A1, A4
COM3-14	SpeCL	L2, L1

COM3-15	LEAF	L2, L1, G2
COM3-16	SGR-ReSI	O4
COM3-18	GLACIES	C2, L5
COM3-19	TRUTHS	A2, A1
COM3-20	FORUM	A1, A3
COM3-21	TES-GAP	G1, L1
COM3-23	FLEX	L2, L5
COM3-24	CarbonSat	A3, A2, L2, O4
COM3-25	SIMACC	A3, A5
COM3-26	LITEE	A2, A3, L1
COM3-27	SIGNAL	C2, C3, C4
COM3-28	ACCURATE	A1, A3
COM3-29	MAGEAQ	A3, A5
COM3-30	HYPEX	L1, L3, O4
COM3-32	GEOSAT	G1, C2, G4, A1
COM3-33	TIREX	L1, L2, O1
COM3-34	METIS	L5, L1, C5
COM3-35	Z-Earth	G2, G1, C2
COM3-36	TOPASE	A1, A3
Total:	**31**	

1st Call for EE9 Fast-Track Earth Explorer Missions (reclassified from Opportunity Missions)

The Call for proposals for mature EE9 concepts, as so called "fast-track" missions (following PB-EO(2015)30 under the strict financial constraints as imposed by option A), was released on 23 November 2015 (PB-EO(2015)45, rev.1). 17 proposed EE9 mission concepts were received by the deadline of 24 June 2016 and evaluated by ESAC (ESA/PB-EO(2016)49). However, the Call was unsuccessful and led to no mission concept being compliant with the financial ceiling of 120 MEuros CaC (and total cost of 200MEuros 2016 e.c.). No candidate from the following list was selected based on the strict Programmatic guidelines.

Notably, the E-GRASP proposal is now being implemented as GENESIS – as an ESA reference frame mission. SESAME was reproposed later to the EE10 Call as STEREOID (i.e. HARMONY), and GeoSTAR2e was reproposed later to EE10 as G-CLASS (later Hydroterra).

Ref	Proposed Mission	Living Planet Challenges [ESA(2015), SP-1329]
CEE9-002	GeOCAPI	O1, O2, O4
CEE9-003	MAGEAQ	A3
CEE9-004	E-GRASP	C2, C3, C4, C5, L2, L3, O1, O2, O5, G1, G2, G3 and G4)
CEE9-005	HYPEX-2	L1, L3, L4, O1
CEE9-007	TMAX	L3, L2, L1
CEE9-008	SKIM	O2, O4
CEE9-009	NITROSAT	A2, A3, A1, L1, L2, L3, O1, O3
CEE9-010	TWIST	O1, C4
CEE9-012	Raven	A3, A2, A1
CEE9-016	TRUTHS	A2, A1
CEE9-017	LOCUS	A3, A5, A2
CEE9-019	e.motion2	C2, C4, O5, G2, L5
CEE9-023	SESAME	C1, C2, C3, L1, L2, G1, G3
CEE9-024	PANGEA	A3, G5
CEE9-025	GeoSTARe	A1, G1, C2
CEE9-026	MISRlite	A1, A3, A4
CEE9-027	FORUM	A1, A3
Total: 17