Executive Summary
The Netherlands, 31 October 2024

THE EUROPEAN EARTH OBSERVATION ECOSYSTEM - A SYSTEM-OF SYSTEMS BLUEPRINT REFERENCE ARCHITECTURE

1. The European Earth Observation Ecosystem - a system-of systems Blueprint Reference Architecture

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

Planet Earth is undergoing profound regime shifts driven by anthropogenic forcing of the dynamic equilibrium of the Earth system. Climate models predict a profoundly different Earth system, where new equilibria (after passing tipping points) are poorly known. Climate change is often thought about as a scientific problem with a technological solution when the fact is it is largely a social problem with a human solution. 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. This will impose significant challenges to the resilience, stability and security of global society. Europe must maintain approaches that observe the most interesting and relevant planet in the Universe, our home planet Earth, where humanity resides.

Within this context, European Earth Observation (EO) is a fundamental tool providing quasi-synoptic, regular repeat, global coverage, geophysical measurement evidence to assist policy makers, industry and application services to help manage the increasing pressures of the new global society and understanding its impact on long-term sustainability.

Some of the most radical discoveries emerge from curiosity-based research endeavours enabling Climate Action through better knowledge. Europe, led by ESA, has designed, implemented, and operates the most proficient and extensive Earth Observation system in the world. It includes Earth Explorer, Copernicus, Meteorology, Scout, Earth Watch, and PhiSat satellite missions.

A Reference Architecture is a standardized set of guidelines, best practices, and design principles that provides a framework that can be used to develop a European Earth Observation Ecosystem. 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 system.

The European EO Reference Architecture (RA) includes an idealised set of EO system components, guidelines, best practices, and design principles that provides a framework to specify an ideal Earth Observation ecosystem serving the broadest user community. An open framework is foreseen in which contributions from all European stakeholders are welcome to fill gaps and provide a holistic monitoring system of Earth and anthropogenic activities with a high level of known performance and the security that the data provided is authentic. The RA has been elaborated and used as a reference "guide" to determine actions required to sustain and evolve a **European EO Ecosystem documented as a Blueprint** for designing, developing, and deploying satellite systems as well as the ground segment related elements in a holistic interconnected manner.

Given this background, the ***aim*** of the European Earth Observation Ecosystem Reference Architecture (Blueprint) is:

> *In support of European citizens and policies, identify and prioritise actions to implement, sustain, operate, and evolve the performance and capacity of European Earth Observation as the most advanced living EO ecosystem architecture in the world.*

From an ESA perspective, the Blueprint responds the ESA Earth Observation Science Strategy Strategic Areas for Action:

- **A1 Frontier Science and Discovery: a strong foundation:** *the pursuit of discoveries and ideas that have not yet been supported by scientific evidence with new observations, methods or models.*
- **A2 From Science to Benefits: meeting society's needs:** *develop scientific knowledge and capacity to deliver high-quality validated, trusted, actionable information products relevant to national, international and global policy frameworks.*
- **A3 Reducing Critical Knowledge Gaps: taking expedient action:** *maximise the combined impact of the ESA, EUMETSAT, national and EU investments by reciprocal reinforcement and alignment of research priorities to foster research and innovation and the use of EO data to support the green transition and climate action.*
- **A4 Filling Critical Observation Gaps: preparing for tomorrow starts today:** *develop and implement an architectural blueprint for a sustainable EO system-of-systems for guiding long-term ESA research and technology preparation, including bold flagship mission implementation addressing the strategic science priorities.*
- ***Building Partnerships and Cooperation:*** *Promote and strengthen collaboration with national agencies and programmes, international partner space agencies (e.g. EUMETSAT, NASA, JAXA) and other key space actors and space faring nations, expanding ESA and European capacity to address the priority science questions and actively engage in Earth science action.*

ESA EO maintains the role of the European EO system of systems architect tasked to maintain a healthy, competitive and adaptative industrial and technical European landscape in a manner that maximises European capabilities. In this context, the Reference Architecture Blueprint will be maintained by the ESA EOP-FA System Architect Office and will evolve together with the scientific, technical, commercial, societal and political boundaries that govern EO in Europe today.

A version 1.0 of the Blueprint will be published in Q1 2025. This document provides an executive summary report of key findings to date.

2. Key Characteristics and Baseline of the European EO ecosystem

Key characteristics of the European EO ecosystem reference architecture include:

1. **Relevant:** The system of systems approach remains relevant to (scientific and operational) user needs (user led) and can evolve as an ecosystem to continuously improve to meet emerging user needs: *a living EO ecosystem for a living planet*.
2. **Flexibility:** It allows for customization and adaptation to specific user needs, constraints and boundary conditions while maintaining alignment with the overarching architectural vision.
3. **Living:** European EO ecosystem architecture is a living entity that evolves according to user needs, technology evolution and programmatic constraints. As such, the "Blueprint" must evolve accordingly.
4. **Long-term data preservation**: EO data are seen as cultural heritage – long-term records of our planet – and must be securely stored as our legacy (long-term archiving) while easily accessible / usable for different applications requiring historical time series.
5. **Complementarity:** The European EO ecosystem promotes an open framework in which contributions from all European stakeholders are welcome to fill gaps and provide a holistic Systems of Systems EO ecosystem with a high level of performance.
6. **Interconnected:** Components that are connected at different levels to leverage their unique synergy for user needs and enabling complementary space providers to be part of the EO ecosystem.
7. **Standards:** It defines common standards, protocols, and interfaces to ensure consistency and interoperability across different components and implementations.
8. **Verification:** Certification that data are what they claim to be (i.e.. resilience against deep fake data).
9. **Performance:** Data are certified to a declared and traceable performance standard (e.g. to support enforcement of regulations and policy and therefore data need to be valid for legal arbitration).
10. **Modularity and Scalability:** The Blueprint promotes the use of modular components and scalable architectures to facilitate flexibility, adaptability, and growth as user-driven 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 in an optimised manner.
12. **Best Practices and continuous improvement through evolution:** It encapsulates proven methodologies, procedures, quality standards, design patterns, and architectural

principles that are recommended for achieving outcomes efficiently and effectively. The Blueprint foresees a systematic and continuous process of quality and efficiency improvement by evolution based on assessment of lessons learned.

13. **Affordable:** The European EO Ecosystem need to be affordable which means it must be constrained to user needs endorsed by Stakeholders in a manner that trades expansion and impact dilution versus quality and fitness for purpose.

The baseline ESA Reference Architecture for 2030-2050 includes the following components[1]:

1. **User-stakeholder components**: User and stakeholder need management to drive the specification of the European EO ecosystem,
2. **Operational satellite components**: Meteorology and Copernicus missions serving user communities directly linked to everyday socio-economic challenges e.g. weather and ocean forecasting with defined performance, availability and product delivery timeliness,
3. **Reference mission components**: Elements to which other missions are referenced e.g. Sentinel-6 reference altimeter, Sentinel-3 SLSTR reference infrared radiometer, Sentinel-2 the quasi refence land mission – with full international recognition. Future reference missions could include TRUTHS, CO2M and MAGIC/NGGM, while other scientific or operational missions may also become reference missions once proven in flight,
4. **Scientific satellite components:** Earth Explorers missions serving user communities invested in the advancement of curiosity and policy driven Earth system knowledge and space technologies,
5. **Commercial components:** Commercial space and ground segment service providers across the European EO landscape that are complementary to large institutional-class science, operational and/or reference missions.
6. **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. PhiSats).
7. **Auxiliary components**: As HAPS, airborne data, in-situ networks.
8. **Data and Operations Management components**: Federated data management services and user services from near real-time to long term climate data records including long-term data archiving, scientific, experimental, and operational applications,
9. **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),
10. **Ground Segment components**: Continuously evolving ground segment ecosystems leveraging new technologies and approaches to apply EO resources to satisfy user needs in new approaches (e.g. Digital Twin Earth/ Destination Earth).

[1] The Reference Architecture Blueprint is not a replacement for to be viewed as challenging established and currently 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 at this point.

11. **Technical/industrial components**: Advancing innovative space technologies necessary to maintain and evolve the European EO ecosystem including the technical coordination role of ESA. Collectively, the system-of-systems embodied act as a source and repository of knowledge to create new industrial capabilities or develop new capabilities across the European EO landscape, technical communication network,
12. **Predictive modelling and decision-support components**: Digital Twin Earth/Destination Earth modelling and analysis to leverage synergy across all Earth Observation assets,
13. **Partnership components**: Complementing the European EO Ecosystem by strengthening and evolving international partnerships beyond Europe,
14. **Verification and certification components** Services to guarantee the authenticity of data and services, as well as a certification to guarantee a declared and traceable performance standard via European EO Verification and Measurement Performance Certification Services.

The analysis provided in the Blueprint elaborates strategic actions to help steer a new architectural vision for the European EO Ecosystem in the 2040-2060 timeframe. It is a ***living interconnected System –of Systems ecosystem implementation*** that is in continuous evolution and improvement, serving as knowledge generation and diffusion system, providing 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:

A living Earth Observation ecosystem for a living planet.

3. Key Findings

3.1. Sustainability

The current European EO Ecosystem has developed and evolved uniquely over a period of 30+ years based on user/stakeholder need pull, excellent data quality, bold scientific and technical innovation, astute industrial policy, financial and political investments across the European landscape. Not to be underestimated is the ever-present ambition and determination of ESA to leverage the excellence of European space industries and scientific institutions in parallel with the development, maintenance and inter-generation transmission of knowledge and talent embodied in the European space workforce. It has been a massive effort, building on hard-won successes, sometimes difficult lessons learned (with corresponding mitigation embodied in the ECSS standards and internal best practices and processes), innovative and daring targets with significant risk/return balance, and strong industrial and scientific commitment.

The living EO space ecosystem for a living planet stands today as testament of European cooperation and vision embodied in the ESA convention.

It is important to recognise that European policy definition, enactment, monitoring, and assessment takes many years (decades) to complete thus long-term provision of stable EO data are required. Furthermore, scientific development and understanding of the Earth system also requires sustained observations (e.g. the ESA Climate Change Initiative data sets). The considerable data holdings of European EO must be managed with excellent stewardship for applications, not only today, but in the far future. They represent the baseline data set that will be used to monitor climate change and the evidence base that is used to set, monitor and evaluate National, European and International policies, not only in Europe, but in a global perspective.

Nevertheless, the current EO success and the global leadership Europe has earned can be easily lost without strategic ambition and commensurate long-term planning to ensure system continuity and innovative evolution. This is documented in the Reference Architecture Blueprint.

Of paramount importance is recognition that European EO users and stakeholders have invested and continue to invest in EO applications and services because of the promised operational continuity, stability and performance of the European EO Ecosystem.

Foster as a priority the sustained continuity and innovative evolution of the European Earth Observation Ecosystem as an open and inclusive collaborative framework.

Nevertheless, while many elements exist today, a new paradigm is required to maintain, apply, and evolve the existing EO mono-mission profiles developed over the last 40 years. This must embrace a complementary portfolio of modern space technologies building on the tremendous opportunities in the international space economy (e.g. access to space and launcher developments, new, powerful digital technologies – Digital Twinning, and Artificial Intelligence (AI) as a game changer for the synergy exploitation of vast quantities of EO and socio-economic data, the integration of EO into new applications (e.g. finance), dependency of user communities on a stable and sustained EO data stream).

ESA is the architect of the European EO federation that is enabled by a reference architecture defining common standards for developing, interfacing and exploiting all contributing space systems in synergy. The intergovernmental agreements that underpin ESA provide a basis for ensuring that European Earth Observation remains relevant, highly performant and cost effective to meet the needs of its stakeholders and user communities.

The Reference Architecture positions different system of systems elements as building blocks in an open framework in which contributions from all European stakeholders are welcome to fill gaps and provide a holistic monitoring system of Earth and anthropogenic activities with a high level of performance. In this way the Reference Architecture can be used by institutional and commercial EO space providers during mission design (e.g. application of reference missions for inter-calibration, authenticity and certification). It is an enabler for a living Earth Observation ecosystem for a living planet.

3.2. Manging user needs

Managing user needs and expectation is the foundation of the European EO Ecosystem and inclusive management of user needs is fundamental to success. What are the mission performance and derived knowledge product requirements necessary to maintain the leadership of European EO considering the well-established European user base that has been furnished with excellent data for over a decade? In this respect, the proven - although challenging – regular and detailed consultations with all key users and stakeholders lies at the heart of Ecosystem. The success of European EO is equally founded on the excellent performance of EO that meet and often exceed user needs expressed by stakeholders for each EO mission it has developed: this is the hallmark of quality that is embodied in European EO. It has fuelled Europe and ESA with its Member states to be the respected leader for Copernicus, Meteorology, and world class Explorer science missions.

3.3. Heritage

An essential undercurrent, controlling both long-term and short-term success has been the sustained investment in EO development starting with ESA ERS followed by ENVISAT and today, the unique ESA Earth Explorer process. The **Earth Explorer *process*** is important and contributes to future evolution through the development of both missions in orbit but importantly, though mission concepts. While the latter are not selected for flight, they bring enormous progress and innovation that has demonstrably led to new missions with operational sustainability via both the Copernicus and Meteorology programmes. Collectively and uniquely all these missions advance European Earth System Science – although more can be done to leverage synergies. Without the heritage of ESA ERS, ENVISAT and contemporary Earth Explorers it is hard to see how the impressive achievements of both Copernicus and Meteorological missions could have been achieved.

In a modern commercial and institutional space economy the strategic paradigm of the Earth Explorer concept (our world-class scientific missions) deserves reflection: the achievements of the approach (in terms of science, technology, strategic investment, political support and science to operational transition) are outstanding.

The Earth Explorer concept, in coordination with other EO elements (SCOUT, Copernicus, Meteorological missions) remains more relevant today than ever before to enable future evolution of the European EO ecosystem and should be strengthened.

3.4. Principles of global sustainability, science and systems thinking

The European EO Ecosystem integrates the principles of global sustainability, science and systems thinking to support and shape the future trajectory of European Earth Observation initiatives. This means that essential EO infrastructure can be collectively developed to support

Earth System governance architectures (e.g., planetary commons) and sustainable pathway navigational tools (i.e. define, implement, monitor and assess policies, develop and apply combined EO and socioeconomic tools) to support a sustainable Earth system.

An evolving and interconnected system –of systems is necessary to enable Earth Action (i.e. Earth Observation Science Strategy) and near real time strategic applications, including traceable security systems, readiness to address emerging European and international geo-political aspects, fully embrace Artificial Intelligence and other emerging 'big-data' technologies, integrate new technical methodologies while maintaining proven ones, implement, and maintain coherent and traceable constellation inter-calibration and *enable* participation of new national and commercial space providers, amongst others. Both the technical design, scientific products, and political configuration of the EO reference architecture pose a demanding target. This necessarily leverages existing operational systems (e.g. Meteorological missions, Copernicus missions), together with scientific and commercial missions toward a holistic view of the future - notably through advanced ground segment innovation. The interconnected system –of systems requires an agile cross-mission ground segment empowering users with advanced multi-mission data processing capabilities, long-term preservation and transmission of data and knowledge. EO operations and data management activities now rely on an industrial service-based architecture paradigm that is essential to maintain competence in the highly dynamic world of Information Technology today.

As the EO ecosystem diversifies, it is both important and prudent to reflect on these aspects – particularly with respect to the proposed European EO Authentication and Measurement Performance Certification Services and their relevance to the commercial EO landscape.

European EO is in the unique position to have the competence and overall overview of the full mission life cycle. This end-to-end system view on the EO ecosystem needs to be strengthened and better used. Maintain European end-to-end leadership and responsibility in EO.

3.5. Emerging EO trends and challenges

There are many emerging EO trends and challenges that are elaborated in the Reference Architecture Blueprint. They are continually evolving. Examples include: the Earth System has already demonstrated regime change, user needs are becoming more sophisticated and demanding, users increasingly require absolute standard traceable measurements, a new EU space law (EUSL) is in development, the EU Green Deal transition will leverage EO data, the evolving role of EUSPA is gaining momentum, the European launcher crisis is challenging European space sovereignty, the European EO market economy evolution is slow, commercial uptake and dependency on EO solutions is increasing and diversifying, a commercial space in-orbit capability transition is gathering momentum, commercialisation of EO and institutional "data buy" models are developing, long-term sustained funding for EO implementation is unclear, interconnectivity and synergy within the current EO Ecosystem is sub-optimal, civil security is increasingly important in a fragile global context and with specific aspects related to illegal activities, war, famine and migration, EO mission complexity and cost are increasing as user demands become more sophisticated. Increasingly, a reduction in the ecological footprint of space activities is under scrutiny raining financial tension since cost is increased by the implementation of zero debris policies, reduction of the carbon and ecological footprint and the implementation of security protocols.

Despite considerable progress over the last four decades, fundamental challenges remain: EO measurement sampling at the time-and space scales *required* to serve users and policymakers increasingly remains far from user expectation, the increasingly blurred boundary between operational and scientific missions raises programmatic challenges, radio frequency management threatens long term sustainability of some EO observations and systems, and changes in the political and industrial landscapes are all evident, amongst others.

Challenges such as these are opportunities for the European EO Ecosystem design. In the context of European EO Ecosystem several actions, grouped into strategic/programmatic and technical domains have been identified addressing the time horizon until 2060.

The following key strategic / programmatic items for immediate action have been identified:

- **Europe must remain a world leader for EO** by establishing, maintaining, and evolving the most sophisticated and ambitious "global reference" missions to benchmark performance in the European Earth Observation Ecosystem of satellites that constitutes the reference architecture. The design, development and implementation of reference satellite mission capabilities adhering to metrology standards (calibration), which are recognised as such by the international user community is a fundamental backbone to the Ecosystem.
- **Dare to implement missions leveraging the constitution of ESA where a common effort of all its Member States may realise larger outcomes than any single state alone.** This is essential to maintain impetus to the rapidly evolving commercial Earth observation ecosystem that depends on such missions to provide de-risking and a metrology reference for satellite constellation inter-calibration.
- **Integrate the principles of global sustainability science and systems thinking** within the EO ecosystem to support and shape the future trajectory of European`s Earth Observation initiatives. This includes aligning observation capabilities, technologies, data needs, applications and infrastructure with European and International Earth system governance architectures and sustainability/socio-economic frameworks, which recognize that people and nature are intertwined within integrated social-ecological systems (e.g., Planetary Commons, Planetary Boundaries, and post-growth economic models which are integral to the EU Green Deal). This will position Europe as a global leader of influence to help catalyse and unite stakeholders, foster collaborative partnerships with a broader network of entities and ensure that the European EO ecosystem is equipped to effectively monitor the Planetary Commons, Earth System Tipping Points (ESTPs), Planetary Boundaries and integrated social-ecological systems for a sustainable future.
- **Understand and document the limitations of the existing Earth Observation Ecosystem**: while every public science/operational satellite mission is developed for a specific stakeholder-user community, the limitations of a given mission in terms of alternative applications and services, notably in synergy, is not always evident. In this context, new missions such as Biomass, Flex, Forum, ROSE-L, CIMR, CRISTAL, LSTM, CO2M, CHIME amongst others are not yet available in flight to explore and apply. **Understand users' needs for continuity through close dialogue with the scientific and operational user communities.** In particular, the current European EO SoS does

not address the challenge of observation densification to address Earth system and societal processes at the most relevant time and space scales. From the standpoint of sustainability science and systems thinking, the existing EO SoS suffers from the absence of a unifying vision that would inspire the European and international EO Community to engage, contribute, and collectively develop essential EO infrastructure for Earth System governance architectures (e.g., planetary commons) & sustainable pathway navigational tools (e.g., doughnut economics), which ultimately leads to a gap in data acquisition, assimilation & integration within these frameworks. These are important gaps to fill.

- **Establish rules and conditions data ownership for missions within the Earth Observation Ecosystem**: At ESA we have the open and free data policy which governs maximising the beneficial use of the Earth Observation data provided by ESA missions and to maintaining a balanced use of these data for a variety of applications, be it scientific, for public good or commercial. However, in the future EO architecture, in particular, in view of commercial players becoming more prevalent, we will deal a lot with different forms of assets ownerships which will play a role in how effective we will be to 'shape' the reference architecture.
- **Clarify governance for the Earth Observation Ecosystem:** The European EO Reference Architecture and Systems of Systems ecosystem implementation approach provides a governance framework in terms of accountability (Authenticity, Certification), leadership (RA 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).

The following key technical items addressing the shorter and longer time horizon have been identified:

- **Observing the unobserved.** Several parts of the Earth system are not currently observed from space. Observation techniques to measure within the ocean below ~50m and below the Earth surface at relevant time and space scales are either not available or mature or both. In addition, several obvious measurement components are still not completely available from EO (e.g. closure of the Water Cycle, Carbon Cycle, Nitrogen Cycle…and cross their interdependencies, atmospheric chemical species having direct links to climate change, permafrost dynamics, total ocean surface current velocity amongst others). Other gaps exist in the current EO SoS which excludes cross-disciplinary physical transition domains such as the near-Earth geospace, which sits at the interface between Earth system and heliophysics system science. Effort is required to initiate science and industrial challenges to determine feasibility and the promising measurement approaches exploring novel observation techniques e.g. access to the UV or TeraHertz spectrum, VHF frequencies to probe within the earth surface, quantum gravity, VLEO observations and platforms, multi-spectral LIDAR, alternative radar frequencies etc.
- **Quantum sensing** represents a major and unique opportunity for enhanced space-based Earth observation. Indeed, the inherent properties of quantum sensors have a huge potential to add new capabilities and improve the sensitivity, accuracy, resolution of sensors used for studying and observing our planet from orbit. Cold Atom Interferometers could enhance gravimetry missions for flood and drought prediction.

Rydberg atom-based quantum electric field sensors could enhance future microwave radiometry missions to improve our understanding of climate change affecting sea-surface-temperature, sea-surface-salinity and sea-ice concentration. Nitrogen-Vacancy Centre-Based Magnetometers could enable more cost-effective magnetometry constellations for space weather or ocean current monitoring. Using advanced, entangled quantum sensors will enable sensitivities that fundamentally exceed the ones that any classical sensor could ever achieve. A long-term technology roadmap aiming for ultimate sensitivity of sensors will thus need to move through quantum sensing. This will keep ESA's member States at the forefront of Earth observation capabilities. **By 2040, at least one quantum sensor-enhanced EO mission should have been implemented, potentially followed by others in the next decades. The time till entanglement-enhanced quantum sensors have a significant positive impact on EO is hard to predict and might be well after 2050**.

- **Leverage the inherent synergies within the European EO ecosystem to address user needs** by embracing the paradigm of AI and modern computing services. The future European EO Ecosystem Ground Segment must be versatile and able to create seamless multi-mission products and services (leverage the entire system). This entails reinforcing new frameworks that promote multi-mission products starting from a mix of L1 and L2 products from different missions, sensors and sources. To be successful steering this approach from both bottom-up (synergy algorithms/applications) and top down (science strategy) is necessary while learning from rapidly evolving new approaches. The output will be **derived and strategically oriented combined analysis products** addressing different aspects (socioeconomic, integrated view of society within the limits of the Earth, identify gaps to address by new socio-economic focussed EO missions, support environmental KPI (e.g. EU Green Deal) and post growth narratives moving beyond Gross Domestic Product (GDP). Traceability to authenticated and certified sources of data will be key to allow a safe usage of such information.
- **New data-driven scenario-based solutions posing and analysing "what if?" questions** such as Digital Twin Earth (DTE)/Destination Earth engines and visualisation systems working with Level-1 (e.g. though model observation operators) and combination of higher order products provide a way forward. These approaches allow exploration of data in new ways and should be strengthened. Gaps in EO capability identified through such DTE/Destination Earth analyses could provide unique insight for the reference architecture priorities. The limits imposed by big-data systems in terms in I/O throughput (which is a limiting factor to such analyses) and the need to orient towards a common framework for data products e.g. using common adaptive/nested gridding schemes are a notable strategic element to address. New cost-effective systems are required to enable this vision utilizing highly flexible data processing solutions at higher levels complemented by competent toolboxes/libraries etc. The solution must be cost effective and climate neutral (considering the power requirements for modern super-computer and server farm technologies). Processing of lower-level data "on the fly" based on user requests is a fundamental asset to achieve success.
- **Strategically develop intelligent autonomous EO sampling**. Satellite-to-satellite (STS) and satellite-to-ground-to-satellite (STGTS) communication links enable autonomous intelligent EO sampling, using tip-and-cue approaches or as an embedded design approach for specific constellations. Such technology is likely to be essential if very close precision formation flying enabling large antenna aperture synthesis (e.g. EE12 STRATUS and SALIN concepts) is to become a reality. ESA should invest in such

approaches to enable new science missions with a strategic ambition of a fully interconnected EO SoS design in the coming decade. Optical STS and STGTS links and space-based computing (if federated) could also address the growing RF occupancy issue.

- **Efficient and secure relay of payload data for NRT applications.** For specific applications where NRT1H or less information products are required satellite-to-satellite science data communication links are required. This may be further coupled to specific real time processing capability embedded in dedicated ground processing hubs or on-board space platforms. In the latter case, efficient methods to allow complete reconfiguration of in-orbit data processing capability (i.e. compete deletion and reinstall of on-board processing code) would be required. A distinct opportunity is embedded in the emerging IRIS^2 constellation that may be capable of hosting an EO payload.
- Further **invest in the development of transformative digital** solutions (space data space, digital twins, etc.) as a structural trend throughout the geospatial/information ecosystems/partnership/cooperation to ease data access and boost user exploitation within the institutional and commercial marketplace. Fully leverage techniques (including AI) to exploit the multi-mission (i.e. L1 inputs from completely different missions) to leverage the full synergy potential of the EO SoS infrastructure. This must also include the co-analysis of socio-economic data sets to address real-world questions – particularly those with relevance to a world in which a changing climate is set to pose significant challenges.

Various other action items also targeting different time horizons and the various observation families individually are further analysed in this report.

Considering emerging trends and challenges, significant opportunities have been identified for European EO. But effective and decisive action must be taken in a timely manner to capitalise on many aspects. To maintain a relevant European EO ecosystem the opportunities and threats emerging from an extremely dynamic international, industrial, commercial, political, socio-economic, and scientific EO landscape must be continuously captured and assessed.

Emerging trends and challenges will be continuously assessed to identify gaps in the European EO Ecosystem as early as possible to mitigate their impact.

3.6. Baseline for the European EO Ecosystem (the Reference Architecture)

Considering the established missions that are either in orbit or planned today as a starting point an indicative timeline of satellite missions within the Blueprint is provided below. The overview contains for the time being only missions with ESA involvement, or those essential for Missions of Opportunity. As a secondary priority other national missions from ESA MS will be integrated. A third category will be missions from other international agencies, or commercial missions.

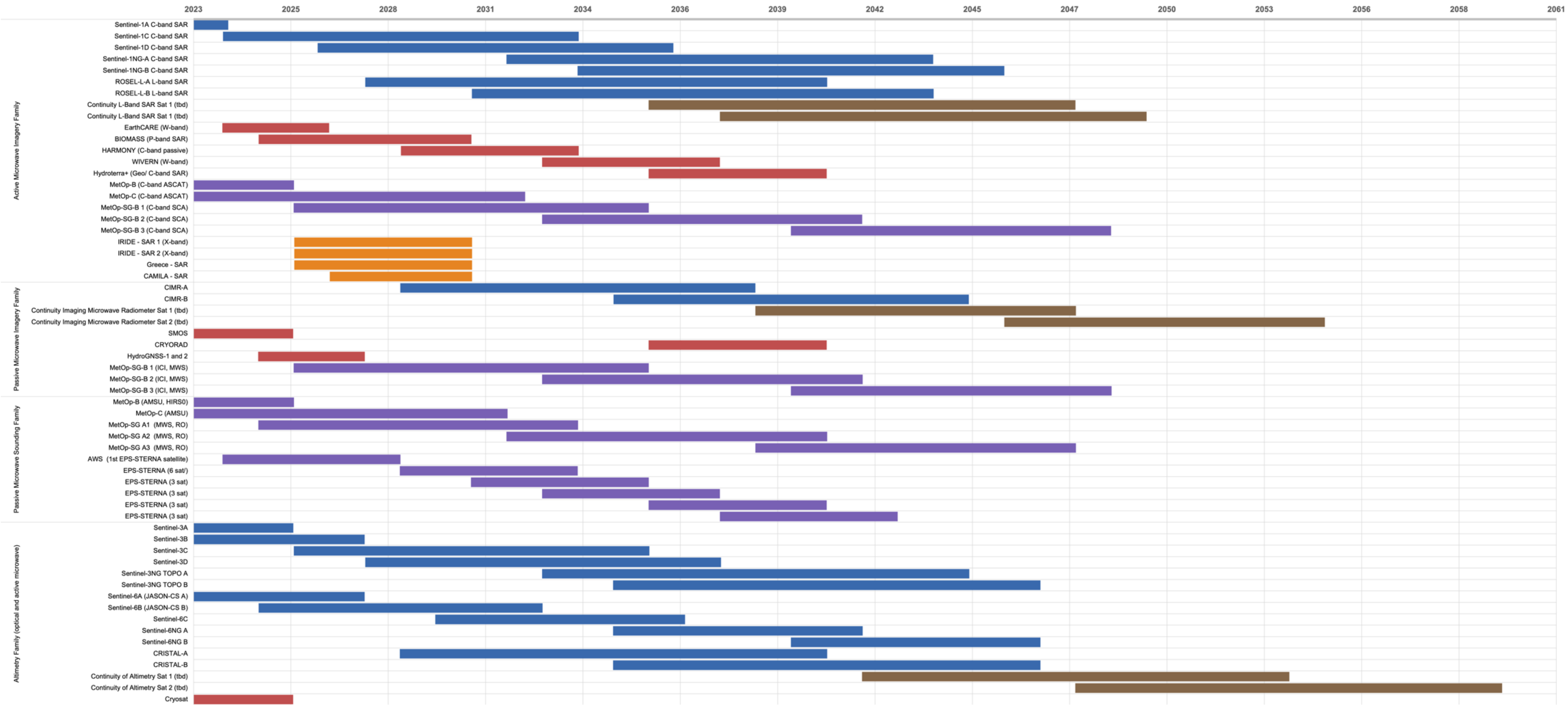
The ***existing*** baseline Reference Architecture starting in 2020 includes the following satellite components (future versions may be expanded to include a full treatment of other international missions that participate in European EO Ecosystem):

- **ESA Earth Explorer missions** are typically designed to address specific scientific questions or challenges related to Earth science. Five Explorer missions have been launched (GOCE, SMOS, CryoSat, Swarm, Aeolus), with EarthCARE just launched, and FLEX, Biomass, FORUM and Harmony missions in development, CAIRT or WIVERN as the next Earth Explorer mission candidates for EE-11, Cryorad, ECO, Hydroterra+ and Keystone as mission candidates for EE-12. They are world first of their kind and carry state-of-the-art payloads capable of measuring various key Earth system parameters with high precision and accuracy pushing the technology and scientific boundaries. These missions contribute valuable data to the 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, therefore they are the foundation of the evolution of the EO systems of System.
- **Copernicus operational missions,** designed to provide long-term accurate, timely, and reliable Earth Observation 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 additional six Copernicus Expansion missions addressing new measurements beyond the original Sentinel-series (CO2M, LSTM, CHIME, CIMR, CRISTAL and ROSE-L), and Next Generation enhanced continuity missions extending Sentinel-1/2/3 and 6 into the 2040+ horizon. (Sentinel-4 and Sentinel-5 discussions will take place in the framework of EUMETSAT operational missions).
- **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 which make use of the successful demonstration of the fourth Earth Explorer Aeolus and the just recently launched Artic Weather Satellite.
- **ESA EarthWatch missions:** The Traceable Radiometry Underpinning Terrestrial- and Helio-Studies, TRUTHS, mission will be a ‘standards laboratory in space’, setting the ‘gold standard’ reference for climate measurements. Carrying a cryogenic solar absolute radiometer and a hyperspectral imaging spectrometer as well as a novel onboard calibration system, TRUTHS will make continuous measurements of incoming solar radiation and reflected radiation providing a metrology reference mission with excellent uncertainty knowledge. 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.

- **ESA Scout missions:** Small satellite solutions delivering value-added science, either by miniaturising existing space technologies or by demonstrating new observing techniques developed within three years within limited budget, from kick-off to launch. Scout missions pave the way to innovative science in a quick and agile fashion and, due to their relatively short preparation and development cycle, they could complement other EO missions or fill temporally some observational gaps. HydroGNSS comprises 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. 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 measure emissions of the greenhouse gases methane (CH4) and carbon dioxide (CO2) at the level of individual industrial facilities and power plants complementing the CO2M Copernicus mission (where the CO2M mission provides a reference mission).
- **PhiSats:** 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 test new and radical EO ideas in a fast and incremental approach that could be used in the demonstration for a more substantial mission concept. For example, FFSCat/Phisat-1 demonstrated the use of AI and two small instruments in orbit in two cubesats; the UPC FMPL-2 in one satellite and Hyperscout from Cosine instrument enhanced with AI capabilities (PhiSat-1) at the instrument and product level. The recently launched Phisat-2 aims to go further using a wider range of AI on-board applications. Future PhiSats will demonstrate in orbit other brand new and innovative technologies and/or new remote sensing techniques and are attractive to some ESA MS particularly in their ability to assist the maturisation of commercial companies in an incremental and sustainable manner.
- **Missions of Opportunity:** Missions of Opportunity 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. Missions of Opportunity 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. Currently MAGIC/NGGM Mission of Opportunity is in Phase B1.

- **National Missions** (not in the focus of the first blueprint): are developed by Member States for national interests and industrial policy (typically within a timeline of political decision). As such, they are valuable complementary elements within a European EO SoS that is maintained by larger class reference missions.

- **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 RNSS-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.
- **Continuity of capability Missions:** Missions that are considered necessary to mitigate future gaps to provide fundamental EO capability in 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.


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-6C
Sentinel-6NG A
Sentinel-6NG B
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CRISTAL-B
Continuity of Altimetry Sat 1 (tbd)
Continuity of Altimetry Sat 2 (tbd)
Cryosat

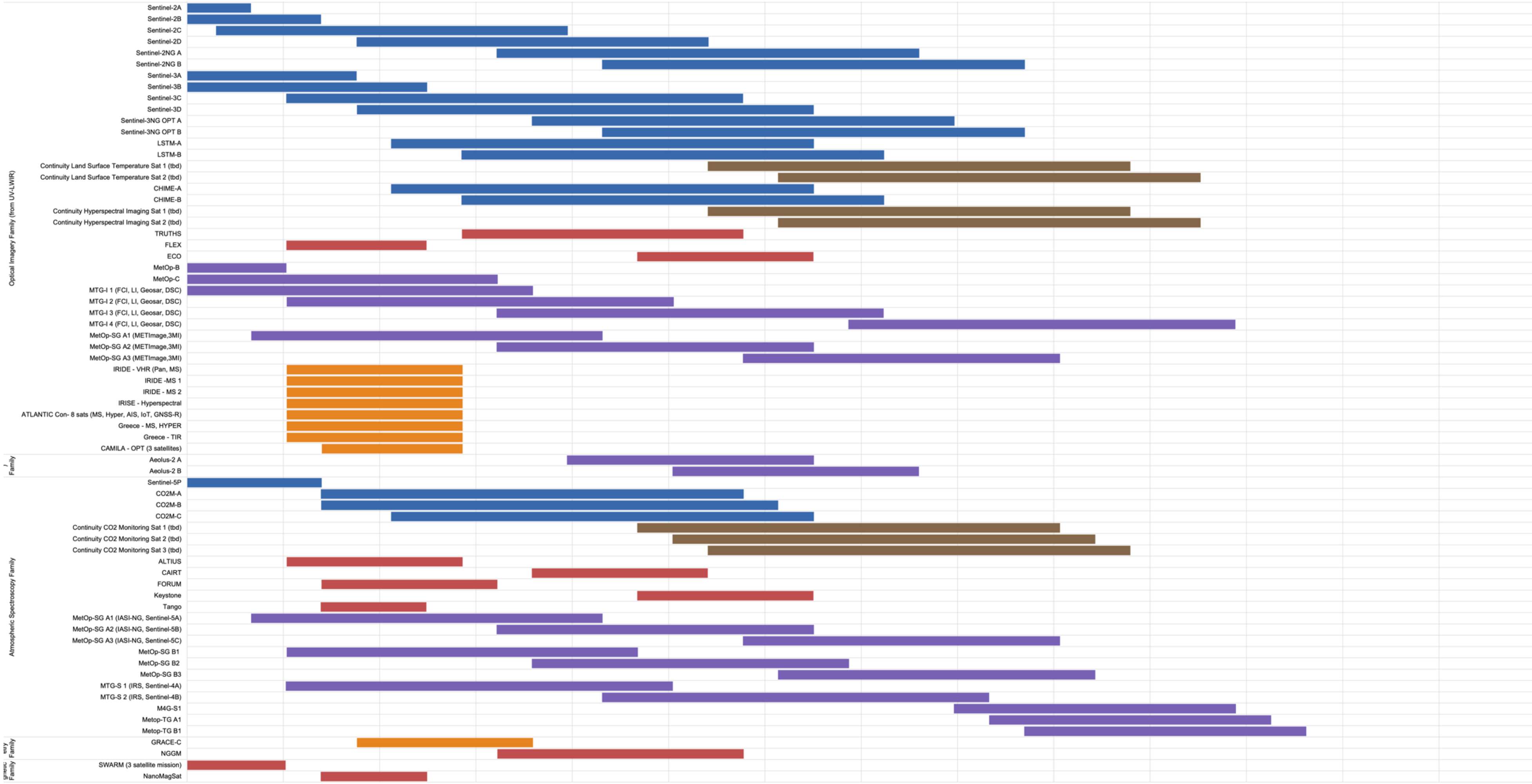

Illustration of the ESA EO System of Systems Reference Architecture ecosystem timeline for 2020-2060. (Colour-coding: Copernicus Missions: BLUE; Meteo Missions: PURPLE: Continuity Missions not yet approved: BROWN; ESA Research Missions: RED: ESA National Programme Missions: ORANGE)

3.7. Ground Segment evolution

The future European EO ecosystem Ground Segment must be a “Michelin 3-star kitchen” to create amazing products and services (leverage the entire system). This entails reinforcing new frameworks that promote multi-mission products starting from a mix of L1 and L2 products from different missions. To be successful steering this approach from both bottom-up (synergy algorithms/applications) and top down (science strategy) is necessary while learning from rapidly evolving new approaches. The output will be derived and strategically oriented combined analysis products addressing different aspects (socioeconomic, integrated view of society within the limits of the Earth, identify gaps to be addressed by new socio-economic focussed EO missions, support environmental KPI e.g. (e.g. EU Green Deal) and post growth narratives moving beyond Gross Domestic Product (GDP). Traceability to authenticated and certified sources of data will be key to allow a safe usage of such information.

Leverage the inherent synergies within the European EO ecosystem by embracing the paradigm of AI and modern computing services (e.g. Digital Twin Earth/Destination Earth).

3.8. EO Gap Analysis Framework

Two approaches are used to set a framework for further (and future) analysis of EO priorities within the EO Reference Architecture Blueprint:

1. The ESA ***Science Foundation Study*** identifying Earth system scientific priorities and gaps,
2. A new paradigm of ***Earth System Stewardship*** that is emerging, recognising that people and nature are entwined within socio-ecological systems.
    a. **Earth System Governance** (*Rockström et al,* 2024[2]), which recognises 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.
    b. **Doughnut Economics** (*Raworth*, 2017[3]) which invites an interdisciplinary and whole-earth approach into ESA Earth Observation Programme. 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.

Each approach has a different aim and by choosing both approaches, the socio-economic aspects as well as the scientific challenges facing ESA can be assessed in terms of mission and capability gaps. The emphasis here is toward complementarity rather competition – both

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[2] 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

[3] Raworth., K (2017): Doughnut Economics: seven ways to think like a 21st century economist, Penguin.

approaches should produce complementary conclusions including science and socio-economic aspects that will guide priorities for ESA EO in the coming decades.

The Reference Architecture Blueprint will adopt a scenario-based approach for T+20 years, T+40 years and T+60 years (IPCC and other organisations show the success of this approach) to perform gap analyses. For the scenario development the ESA internal foresight discussions, scenarios developed by the European Commission (e.g. Futures of civic resilience in Europe, 2040 Scenarios and policy implications) or others will serve as an initial input.

Develop and agree future scenarios for the European Earth Observation ecosystem for different timelines.

4. Fundamental elements of the ESA Reference Architecture Blueprint covering the 2040-2060 period.

4.1. Authenticity

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. To address these issues, new technologies must be further consolidated (e.g. blockchain) to guarantee authenticity of EO data at the appropriate data processing level. Such technologies exist today, and it is mostly a matter of applying them to ESA produced Level-1 and Level-2 products. For higher-order products (e.g. amalgamating different data using synergy/AI processors), authenticity certification rests with the product producer.

To avoid deep fake data, design, develop, implement, evolve, and operate services to certify EO data content authenticity.

4.2. Performance Certification

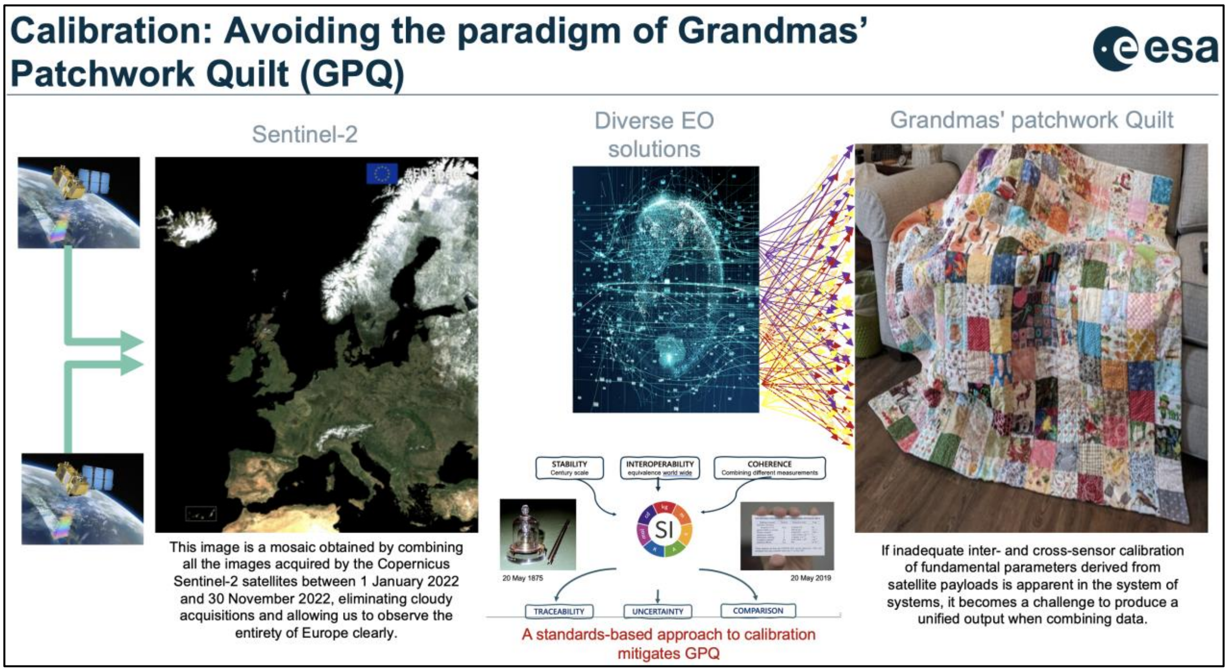
A specific aspect of EO data certification is the scientific content of EO data and the performance uncertainty of the measurements provided to the user community. For a successful application in a court of law, EO data must demonstrate that the measurement data are indeed an accurate representation of the phenomenon in question (e.g. field boundary and crop type, CO2 or methane concentration in a plume, sea level rise 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. Examples include Sentinel-6 (reference altimeter), Sentinel-3 SLSTR (reference infrared radiometer), Sentinel-2 as a reference mission for European land classification, and in the future, missions e.g. CO2M and TRUTHS and others are expected to provide refence mission capability. 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 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.

By taking this approach, reference measurements embedded the Earth Observation Ecosystem will be able to maintain coherent and traceable constellation inter-calibration and *allow* new national and commercial space providers, amongst others, full integration, participation and successful evolution.

As a strategic investment, develop sustained reference class satellite missions and supporting ground system services that form the backbone of the European EO Ecosystem.

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 below. 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.



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.

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 "New 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. This is particularly relevant to the concept of an open EO Ecosystem allowing and enabling a variety of constellations where the ESA MPCS will be fundamental to the success of commercial reduced cost constellation solutions.

As a strategic investment, design, develop, implement, and operate European Measurement Performance Certification Services that can guarantee certification of EO measurement performance uncertainty with well documented traceability to SI standards.

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. It will be even for poorly performing sensors beneficial to have a clear picture of the uncertainty structure and achieved performances.

Effort is required to 'take Climate Action' for all ESA satellite systems by implementing robust SI traceable pre-launch characterisation, on-board payload calibration, verification and validation using fiducial reference measurements (FRM) techniques and cross calibration with other reference missions in flight.

Fundamental to this vision are enhanced in situ reference measurement systems with traceability to SI – referred to as Fiducial Reference Measurements (FRM). FRM are a subset of all potential in situ measurements that are essential to verify, validate and, in some cases calibrate EO data. Considerable effort has been placed on nurturing FRM for a variety of EO products over the last decade together with National Meteorological institutes and CEOS Quality Assurance for Earth Observation (QA4EO). Such pioneering efforts need to be translated into mission requirements where appropriate.

4.3. Mixed Constellation – the full Earth Observation Ecosystem

From a functional perspective, a mixed satellite constellation combines different satellite systems to strategically leverage the strengths of each through synergy (e.g., orbits, latency, coverage, revisit and sampling (at relevant scales for a given application), ground processing, data delivery, operational capacity, resilience through redundancy, new multi-mission synergy products etc.) delivering enhanced performance to meet user/stakeholder requirements. Such a mixed system-of-systems can be defined from different perspectives and basically it is nothing else then taking a step back and considering the synergies within the whole Earth Observation Ecosystem. The EO Ecosystem may include a mixture of institutional science, experimental, operational and calibration reference missions together with commercial satellite systems.

The European Commission has defined a “European Commissions hybrid constellation” by looking at it from a programmatic perspective, more in in terms of the balance of responsibility between institutional and commercial providers:

“The European Commission hybrid-constellation is a combination of institutional and commercial missions to satisfy the user needs of the Copernicus services, with an increasing responsibility of the commercial actors”.

In this context, it is assumed that commercial data would be procured and delivered via e.g. a public-private partnership mechanisms. In the absence of strong user requirements and negotiation, these could ultimately evolve to a lowest common denominator in terms of performance driven by commercial return and minimisation of risk: the more challenging and superior performance satellite system “flagships”/reference mission required capability may fall by the wayside. Nevertheless, the European Commission currently tends to move in this direction. A further complication is the “*Grandmas patchwork quilt*” syndrome in which 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 much of its work to addressing different satellite calibration issues).

A holistic definition for a European EO Ecosystem is:

”The European Earth Observation Ecosystem (satellite) constellation combines different EO systems in different ways to strategically leverage the strengths of each through synergy in a Systems of Systems architecture. It provides verified products and services with certified performance to meet user/stakeholder needs.”

With this definition and in the context of the ESA Reference Architecture Blueprint the European Earth Observation Ecosystem offers distinct opportunities (non-exhaustive list):

1. **Open and inclusive:** an open framework is foreseen in which contributions from all European providers are welcome to fill gaps and provide a holistic monitoring system of Earth.
2. **ESA, as an intergovernmental organisation, is centrally positioned as the architect of the EO Ecosystem** (enabling and empowering full and open participation while upholding performance standards commensurate with ESA EO user expectations).
3. **Observation densification** allowing European policy and applications to be furnished with EO data products at the relevant time and space scales commensurate with those of the observed phenomena.
4. **Implementation of Verification Certification** via a new European EO authenticity certification system (Verification and Measurement Performance Certification Service

(AMPCS)) to be implemented for the Earth Observation Ecosystem. This is a fundamental enabler of a holistic EO Ecosystem vision.

5. **Implementation of Certification of Performance** via a new European EO standards-based Verification and Measurement Performance Certification Service (VMPCS) that may include cross-checking using independent EO data within the Earth Observation Ecosystem. This would be a much-needed service to commercial EO satellite constellation operators based on ESA EO reference missions - a role that is uniquely at the political, financial, and scientific level of ESA. Participation is predicated on provision of observation uncertainty estimates providing the knowledge necessary to fully utilise combined multi-mission data in the correct manner (performance weighting). This is a fundamental enabler of an Earth Observation Ecosystem vision in which reference missions work together with a wide variety of missions in concert with in situ and ground processing services that allow users to fully leverage all EO capability for a given application.
6. **Clear and legally backed-up ownerships** for data, sensors and technology can be established as a federated system of systems ecosystem.
7. **Clear and easy to use data policies.**
8. **Enhanced mission interoperability** by leveraging acknowledged reference missions via calibration transfer (cross-calibration) to other commercial and institutional satellites (e.g. Sentinel-6, Sentinel-2, Sentinel-3 SLSTR, TRUTHS).
9. **Leverage the inherent synergies of a System of Systems** ecosystem to create new synergy products that would otherwise be difficult/impossible to realise in practice.
10. **Consolidation of fragmented European commercial space infrastructure**.
11. **Transition of EO responsibility from institutional dependency to one that allows commercial operators responsibility in relevant areas.** This creates space for institutions to focus on new and next-generation developments (e.g. reference missions typically required by commercial constellation operators). It is important to clearly define the standards that would allow a commercial entity to take up responsibility for sectors impacting the responsibility of ESA based on transparency of monitored applicable performance requirements (i.e. the Verification and Measurement Performance Certification System, VMPCS). A certification will also give (operational) users trust into the sustainability of the data/service provided. Operational users need to be assured that the offer will be for "some time" on the market.
12. **Strategically develop intelligent autonomous EO sampling**. Satellite-to-satellite (STS) and satellite-to-ground-to-satellite (STGTS) communication links enable autonomous intelligent EO sampling, using tip-and-cue approaches or as an embedded design approach for specific constellations.
13. **Enable an efficient and secure relay of EO data** for NRT applications.
14. **Seamlessly integrate a consistent cal/val architecture** cross all missions to maximise interoperability of the data in the downstream usage.
15. **High Altitude Platform Stations (HAPS)** are of growing interest to address some (time critical) regional applications. Such an approach is considered complementary to EO satellite systems e.g. in their own right or potentially offering traceable observations for cal/val activities.
16. **Next generation ground segment:** Within the Reference Architecture and by construction, the EO Mission and Data Management Framework allows for a smooth

federation of existing European EO system solutions at different levels. This includes National data management platforms or Collaborative Ground Segments, and integration services of downstream value adding information that leverage the existing SoS ecosystem, the large portfolio of data it creates, to boost the generation of actionable information derived from EO. The industrial momentum generated by a continuously evolving state-of-the art service-based system, together with an open, well-established and transparent architecture, has the potential to boost opportunities for commercial entities in the entire data management chain, including commercial space system providers complementing and reinforcing the SoS ecosystem and generation of actionable information.

17. **Affordable:** The European EO Ecosystem must be optimised to meet user needs in an affordable manner.

From one perspective, the current EO system is an *un-federated* European Earth Observation Ecosystem that has a programmatic basis rather than a functional basis into which a programmatic **framework can be implemented. It is important to note that the definition of the European Earth Observation Ecosystem is fundamental to the direction of the ESA RA Blueprint.** Models to facilitate the idea of the European Commission hybrid constellations as a public-private-partnership are considered insufficient since it misses aspects of certification, quality and usability resulting in a mixed solution that may devolve to a lowest common denominator of performance linked to operator profit margins. Such a solution cannot leverage all of the potential opportunities of the system-of-systems concept and could very easily do more damage than good to the EO marketplace.

Adopt an ESA definition for the European Earth Observation Ecosystem that is founded on user needs, certified performance and a certain degree of sustainability: "*The European Earth Observation Ecosystem satellite constellation combines different satellite systems in different ways to strategically leverage the strengths of each through synergy in a Systems of Systems architecture. It provides authenticated products and services with certified performance to meet user/stakeholder needs."*

4.4. Governance

The European EO Reference Architecture and Systems of Systems ecosystem implementation approach provides a governance framework in terms of accountability (Verification, Certification), leadership (RA 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). Governance within the SoS ecosystem, once agreed, would be a significant asset to all actors participating in the federated vision.

4.5. Data policy

The vast majority of data/information delivered by Copernicus is made available and accessible to any citizen, and any organisation around the world on a free, full, and open basis. Information on the copyright and licenses for Copernicus can be found at https://www.copernicus.eu/en/access-data/copyright-and-licences. Thanks to the Copernicus free and open data policy as of today (June 2024) the Copernicus Data Space has over 175.000 registered users. The tremendous number of users also helped to establish the Copernicus system as a world-wide accepted reference system.

The Copernicus free and open data policy has established a world-wide Earth Observation community, set Copernicus as the golden reference mission standard, and positioned Europe at the forefront of Earth Observation in all domains. The free and open Copernicus data policy needs to be secured and the benefits of it clearly documented and communicated.

4.6. Gap analysis 2040-2060

This Reference Architecture Blueprint provides a succinct analysis of gaps in the ESA EO SoS ecosystem that are considered priorities to address in the 2030-2060 timescale. Both “mission-specific” gaps (technological gaps) and scientific gaps (as discussed in the EO science foundation study) must eventually be considered (when the Science Strategy is available). The approach considers the following system-of-systems Families:

- 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 aspects such as in-situ networks, reference frames, quantum technologies, opportunistic signals (e.g. GNSS, signal), HAPS etc.

Over 100 “gap findings” and corresponding actions are reported across the full EO ecosystem. They are too extensive to be elaborated in a meaningful manner as part of this executive summary. The findings can be grouped into Strategic/programmatic and technical (overarching ecosystem or mission family specific). Additionally, they can also be mapped according to the timing (immediate actions – longer-term).

4.6.1. Affordability

The European EO ecosystem has seen a huge expansion in the past decade in its response to user driven needs translated into evolving space segment capability, advanced ground segment activities (e.g. Digital Twinning), new applications and services at local, national and international levels, with the promise of significant return on investment. However, the system cannot expand in perpetuity since it becomes unaffordable. Care is required to optimise the future system by avoiding duplication of capability, maximising synergies across missions both in the space-segment but critically ,in the ground segment and down-stream user communities (where new synergies are realised), leveraging new space capability in the commercial sector and preparing optimised supply chains through better coordination of fragmented European industries.

5. Conclusions and Next Steps

The European Earth Observation Ecosystem includes an idealised set of EO system components, guidelines, best practices, and design principles that provides a framework to specify an ideal Earth Observation System serving the broadest user community. In this report, a EO **Reference Architecture** has been elaborated and used as a reference "guide" to determine actions required to sustain and evolve the ecosystem. The reference architecture is **documented as a Blueprint** for designing, developing, and deploying satellite systems as well as the related ground infrastructure in a holistic interconnected manner to serve the needs of user communities and Stakeholders

The EO Reference architecture Blueprint is of strategic importance to address European and national needs for authentic, high-performance, trustworthy EO evidence and knowledge to help manage dynamic economic growth together with the international responsibility of managing climate change, environmental and security issues. The ESA ambition is to design, implement, and operate **the** most integrated earth observation system in the world, combining different satellite systems in different ways to strategically leverage the strengths of each through synergy in a Systems of Systems architecture guaranteeing long-term availability and continuity of high-performance data services and products constituting a unique global knowledge resource to serve users not only today, but for generations to come.

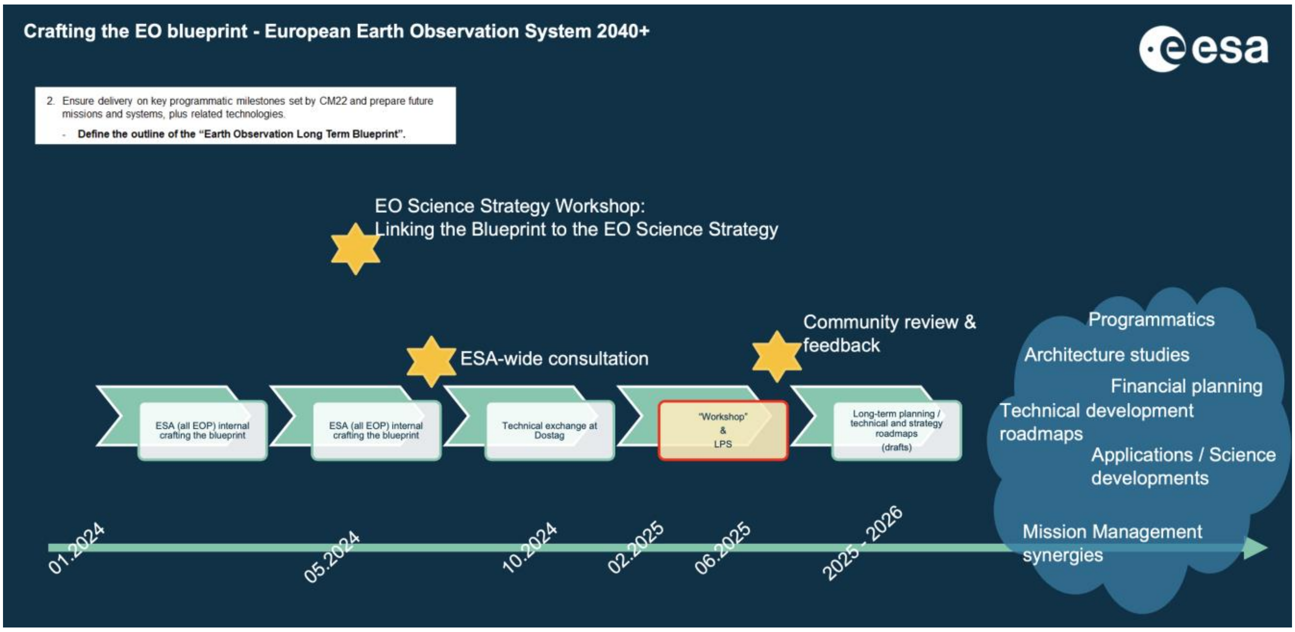
An interconnected living Earth Observation Ecosystem for a living planet

Fundamental to the success of European commercial space, where reference missions provided by institutional means are freely available, and in keeping with ESA foundations, where European MS collaborate within a suitable EO operational framework to achieve things beyond a national horizon/capability, the following strategic direction is paramount to the future of ESA EO:

Develop sustained reference class satellite missions and supporting advanced EO Data Management services that form the backbone of a European EO Verification and Measurement Performance Certification Services.

If Europe does not maintain this role, other Agencies/entities will do so. And with that single action, others ***will*** become *de facto* global leaders in Earth Observation for the foreseeable future.

The Reference Architecture Blueprint will be maintained by the ESA EOP-FA System Architect Office and evolve together with the scientific, technical, and political boundaries that govern EO in Europe today. It is an ESA European Earth Observation Ecosystem vision open and flexible welcoming others to join. Based on the described vision a broader consultation with various stakeholders will be now initiated to formulate a common vision. The broad timeline of activities is presented in the graphic below.



At this point, a new detailed database of relevant missions within the European EO ecosystem is being procured. This is designed to be a "central intelligence" hub for regular assessment of the architecture. In addition, a Community Review and Feedback workshop will be held in January 2025 to present the Blueprint ad seek community feedback. Studies are now running to analyse different configurations of the 2040+ European EO Ecosystem from a science user perspective. Finally, studies to consider the overall Blueprint architecture post 2040 are in preparation.