SCIENTIFIC AND TECHNICAL DESCRIPTION
of the European Plate Observing System (EPOS) Research Infrastructure

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SCIENTIFIC AND TECHNICAL DESCRIPTION OF EPOS

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EXECUTIVE SUMMARY

This document represents the scientific and technical description of the European Plate Observing System (EPOS) Research Infrastructure. It belongs to the set of documents required by the European Commission to build EPOS-ERIC.

Understanding how the Earth works as a system is critically important to modern society. Society needs resources to support home life, industry and business and it needs security in the face of natural hazards. Volcanic eruptions, earthquakes, floods, landslides, tsunamis, weather, and global climate change are all Earth phenomena impacting on society. Similarly, depleting natural resources can also damage our economy because affecting safety and sustainability of the environment. To take measures to prevent the effect of natural and anthropogenic phenomena on society we need to understand more about Earth's chemical and physical processes responsible for them. Solid Earth science by bringing together many diverse disciplines such as geology, seismology, geodynamics, geodesy, volcanology, geomagnetism as well as chemistry and physics as they all apply to the workings of Earth, is the place where to find answers on how to maintain the Earth a safe, prosperous, and habitable planet. Indeed, Earth science data can contribute to more effective decision making, producing information that can be used to identify emerging environmental problems and changes and to monitor ongoing natural phenomena. However, unravelling physical and chemical processes responsible for phenomena impacting planet Earth and society, requires harmonized and freely accessible data and services that allow innovative, multidisciplinary and cross-disciplinary research. Providing this, is the mission of EPOS.

EPOS brings together European nations and combines solid Earth science infrastructures and their associated data and services together with the scientific expertise into one integrated delivery system for the solid Earth. By improving and facilitating the integration, access, use, and re-use of solid Earth science data, data products, services and facilities, EPOS is developing a holistic, sustainable, multidisciplinary research platform to provide coordinated access to harmonized and quality controlled data from diverse Earth science disciplines, together with tools for their use in analysis and modelling. EPOS is designed to foster scientific, technological, and ICT innovation for successfully addressing global challenges in Earth science.

This *Scientific and Technical Description* of EPOS begins with describing the objectives of the EPOS infrastructure, its expected progress beyond the state of the art and its added value in terms of scientific and societal impact (Chapter 1). The document continues with defining the EPOS architecture and its essential elements: National Research Infrastructures, Thematic Core Services, Integrated Core Services, Executive Coordination Office (Chapter 2). Thenceforth, the activities of the EPOS infrastructure are described (Chapter 3) by detailing the contents of the EPOS data and services provision as well as the operational performances of this research platform. The last part of the document (Chapters 4 to 6) specifically addresses the requirements of the ERIC regulation in terms of quality control of the offered services, integration into European and global network, importance of the infrastructure for the carrying out of European research programmes, contributions to the implementation of the European Research Area (ERA), to the effective access to the European research Community, to the mobility of knowledge and/or researchers within the ERA, to the dissemination and exploitation of the achievements, and finally the risk management.

1. The EPOS Perspective

1.1 Background

Solid Earth science is concerned with the internal structure and dynamics of planet Earth, from the inner core to the surface; it deals with chemical and physical processes covering wide temporal and spatial scales, from microseconds to billions of years and from nanometres to thousands of kilometres (Figure 1).

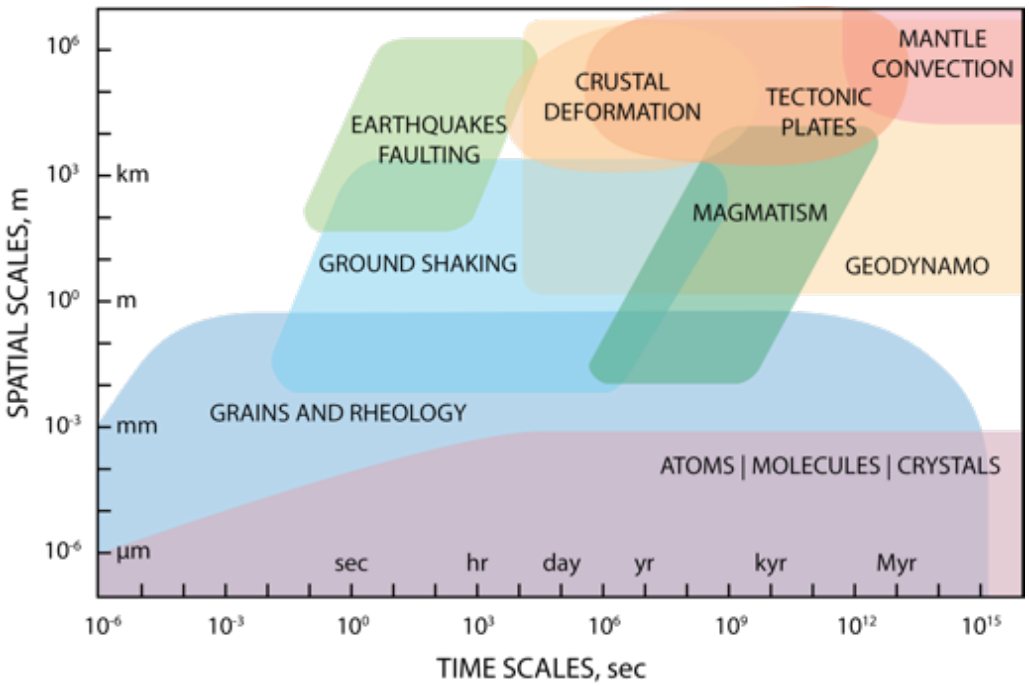

Figure 1. *Temporal and spatial scales of solid Earth chemical and physical processes (modified after Hwang et al., 2014[1]).*

Geo-processes are irrespective of national frontiers and disciplines boundaries. Therefore, scientific investigations into these processes would tremendously benefit from seamless, trans-national integration of geographically distributed measurements through existing and new observing systems, which, equally, should be irrespective of national frontiers. This holds as well for the transnational access to calibrated data from the different scientific domains and disciplines in solid Earth science. Open access to quality-controlled data and scientific products is an essential step forward and paramount to unravelling and interpreting geo-processes with the final goal of forecasting their impact on the environment and society. Earth surface and sub-surface dynamics, including volcanic eruptions, earthquakes, floods, landslides and tsunamis, are all natural phenomena impacting on society by damaging economy, security, and harming the safety of the environment and planet's population. Of comparable weight in harming the environment and future societies is the non-sustainable exploitation of natural resources for which Earth scientists can provide remedies as well as novel ways for geo-resource exploration in response to emerging resource

[1] L. Hwang, T. Jordan, L. Kellogg, J. Tromp, R. Willemann (2014) Advancing solid Earth system science through high-performance computing 2119 EPS, One Shields Avenue University of California Davis, CA 95616 geodynamics.org

scarcity. Hence, understanding how planet Earth works as an interconnected system of processes is critically important to modern society. Consequently, solid Earth science, bringing together many diverse disciplines such as geology, seismology, geodynamics, geodesy, volcanology, geomagnetism as well as chemistry and physics, is the domain where the entire Earth System and its phenomena can be unravelled and better understood.

Presently, European countries together own and operate a mosaic of hundreds of impressive distributed but separated Research Infrastructures (RIs) that includes networks, observatories, temporary deployments of instrumentation, and laboratories and modelling facilities for solid Earth studies. A sustainable infrastructure for long-term European plate observations that harmonizes and integrates multidisciplinary solid Earth data acquired through diverse observing systems and optimizes their free access, is a prerequisite to innovative research for a better understanding of the chemical and physical processes that control Earth dynamics. This, in turn, allows the Earth science community to make a step change in developing new concepts and tools for key answers to scientific and socio-economic questions concerning geo-hazards and geo-resources as well as Earth science applications to the environment and to human welfare.

1.2 Vision and Mission

The study of planet Earth is necessarily multidisciplinary and requires the access to data and products generated by different communities in different data formats and with different procedures. The investigation of solid Earth dynamics and tectonic processes controlling earthquakes, volcanic eruptions, unrest episodes and tsunamis relies on the analysis of seismological data, ground deformations inferred from terrestrial and satellite observations, geological and petro-chemical studies, laboratory experiments and on computational Earth science to unravel the chemical and physical processes occurring at depth.

The EPOS ***vision*** is to foster innovation in such multidisciplinary research, utilizing human capital, in terms of both skill and knowledge, and infrastructures across different fields, technologies, and disciplines, to make possible a better understanding of the Earth surface and sub-surface dynamics and to use this progress in science for the assessment of geo-hazards and the secure and sustainable use and exploitation of geo-resources.

According to its vision, the EPOS ***mission*** is to create a single sustainable, permanent and distributed infrastructure that integrates the diverse and advanced European Research Infrastructures for solid Earth science under a common framework. EPOS gives open access to geophysical and geological data and modelling tools, enabling a step change in multidisciplinary scientific research spanning different fields, including seismic and volcanic hazards, environmental changes as well as long-term sustainability of geo-resources. The EPOS approach will enable the scientific community to study the same phenomena from a multidisciplinary point of view and at different temporal and spatial scales (from laboratory to field and plate tectonic). EPOS brings together Earth scientists, national research infrastructures, ICT (Information & Communication Technology) experts, decision makers, and public to develop new concepts and tools for accurate, durable, and sustainable answers to societal questions concerning geo-hazards and those geodynamic phenomena (including geo-resources) relevant to the environment and human welfare.

By improving and facilitating the integration, access, use, and re-use of solid Earth science data, data products, services and facilities, EPOS aims at transforming the European research landscape, driving discovery and developing solutions to geo-related challenges facing the European society. EPOS thereby also establish the basis for Europe to maintain and extend a leading role in solid Earth science research as no such system as comprehensive as EPOS is currently available in the world.

1.3 Objectives

The EPOS overarching goal is to establish a comprehensive multidisciplinary research platform for the benefit of Earth science worldwide. The ground-breaking nature of the EPOS federated approach relies on joining the capacity of delivering high-quality standardized and multi-disciplinary data, the involvement of ICT experts in guaranteeing novel e-science opportunities and the leverage effect of users' engagement.
In general, EPOS when fully operative will:

- stand for a scientific vision and approach in which innovative multidisciplinary research is made possible for a better understanding of the chemical and physical processes controlling Earth dynamics;
- sustain a long-term plan to facilitate the integrated use of data, data products, services and facilities from new and existing distributed European research infrastructures, for solid Earth science;
- work for appropriate financial and legal solutions to manage the distributed Pan-European research infrastructures participating in the integration plan by securing their sustainability at national level and a common and shared policy for open access and transparent use of data and facilities.

In more details, EPOS aims at building an integrated research infrastructure to advance our ability in responding to fundamental scientific and socio-economic questions related to geo-hazards and geo-resources by:

- implementing thematic services (e.g. seismology, volcanology, geodesy, geology, see Section 2 for details on the EPOS Thematic Core Services, TCS);
- ensuring integration of the implemented thematic services within the full EPOS framework, covering legal, governance and financial aspects, and technical connection to the novel e-science solution for the integration and accessibility of solid Earth science data, products and services (i.e. the Integrated Core Services, ICS, see Section 2 for details);
- developing the ICS to provide interoperability, data management and access to services;
- creating optimal conditions for the central coordination of the new infrastructure through EPOS-ERIC;
- ensuring long-term financial and legal sustainability for EPOS-ERIC and implemented services;
- harmonizing the EPOS data and services provision with national priorities and strategies;
- further gaining users' trust and awareness of the impact of the new research exploitation platform;
- integrating EPOS in the global science community to enhance the EPOS services;
- fostering training, outreach and international cooperation.

In short, EPOS is developing a comprehensive, sustainable, multidisciplinary distributed infrastructure to provide coordinated access to harmonized and quality controlled data from diverse solid Earth science disciplines, together with tools for their use and re-use in analyses and modelling.

1.4 Unique values of EPOS

Following its mission of providing a single infrastructure covering the whole solid Earth domain, EPOS is connecting many diverse disciplines and classes of geo-infrastructures that until now operated separately. To reach such an unprecedented level of scientific integration, EPOS has been conceived, planned and built as "*a single, Pan-European, sustainable and distributed infrastructure*". Indeed, EPOS is distinctive in its architecture and disciplinary coverage and its ambition is unique in terms of:

- extent of the partnership and effective engagement of the involved communities (EPOS is integrating services that cover all of Europe and engages the entire Euro-Mediterranean area);

- integration of multidisciplinary data (observations, simulations and data products), and services (for data discovery, mining, visualization, processing and modelling) through a unique and novel integrated environment to foster use and re-use of quality controlled standardized data and products;
- access to facilities (experimental laboratories and data repositories) and instrument pools for temporary experiments;
- access to long-term data archives wherever available from National Research Infrastructures and International Research Infrastructure implemented by scientific communities and interoperable with the ICS;
- novel e-infrastructure concepts for interoperability and provisions of distributed data following open science commons;
- ability to progress our fundamental understanding of solid Earth processes (high scientific impact);
- enhanced integrated contribution to geo-hazard assessment and geo-resources exploitation (high societal impact);
- long-term governmental and financial perspective.

The Pan-European dimension of EPOS is demonstrated by the number of countries engaged in its integration plan, by the involvement of international organizations and, most importantly, by the numerous research institutions bringing more than 250 national research infrastructures into the EPOS data and service provision.

The IT innovation potential of the EPOS infrastructure involves facilitating the integration, use and re-use of solid Earth science data, data products, services and facilities, based on distributed national research infrastructures across Europe, therefore contributing to the European data infrastructure.

EPOS brings together and combines national solid Earth science infrastructures and their associated data and services together with the scientific expertise into ***one integrated delivery system for the solid Earth***.

2. The EPOS Architecture

The EPOS architecture has been planned and designed by assembling key elements to allow the enterprise to work as a single, but distributed, sustainable research infrastructure. These key elements belong to four complementary categories (Figure 2):

a) National Research Infrastructures (NRIs);
b) Thematic Core Services (TCS);
c) Integrated Core Services (Central Hub, ICS-C and Distributed, ICS-D);
d) EPOS-ERIC Executive Coordination Office (EPOS-ERIC ECO).

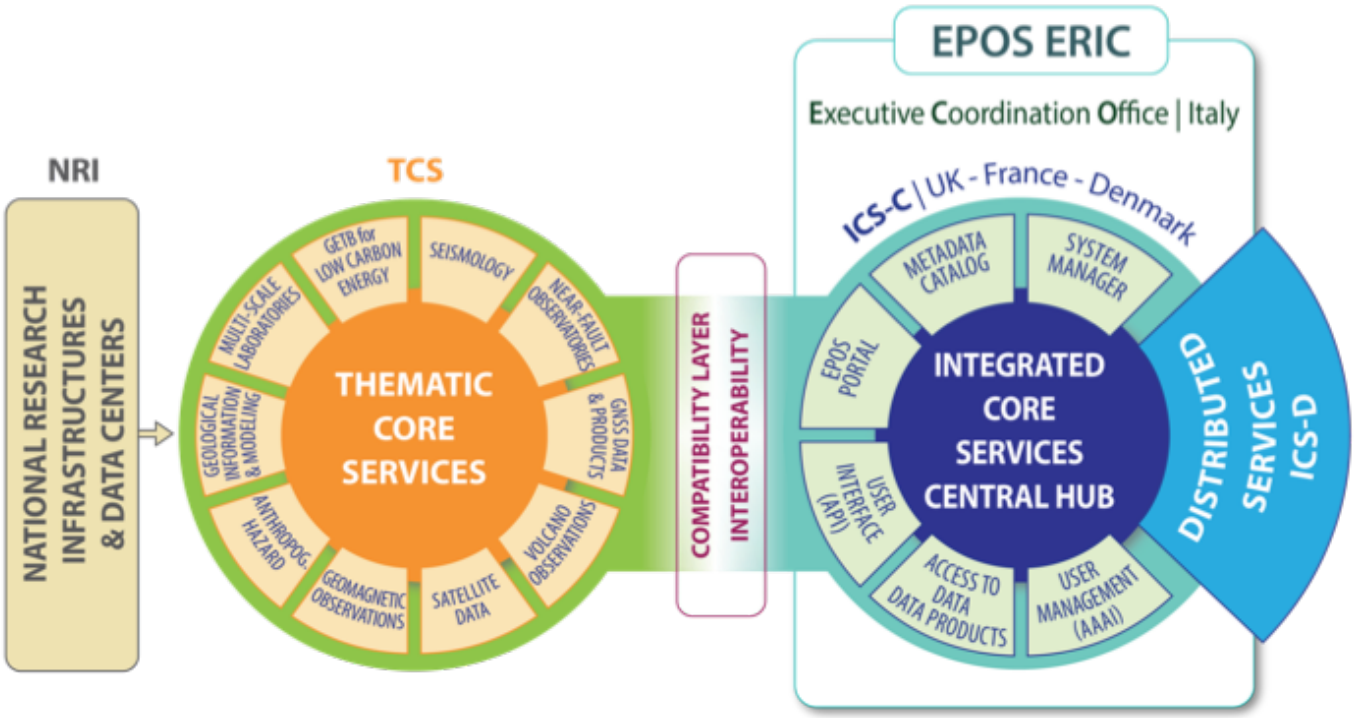

Figure 2. *Main elements of the EPOS Architecture, the Integrated Core Services Central Hub (ICS-C) and the Executive and Coordination Office (ECO) belong to the EPOS-ERIC legal subject.*

2.1 National Research Infrastructures

The **National Research Infrastructures (NRIs)** represent the underpinning EPOS data providers that guarantee access to data and products. NRIs contribute to EPOS while being owned and managed at national level; NRIs have a significant economic value both in terms of construction and yearly operational costs. The latter are typically covered by national investments that must continue during EPOS operation. The EPOS architecture ensures that new RIs can be integrated as they become operational in future.

2.2 Thematic Core Services

The **Thematic Core Services (TCS)** represent the community-specific integration (e.g., seismology, volcanology, geodesy, geology; see Figure 2 for the list of TCS involved in the implementation phase). They act as transnational governance frameworks where data and services are provided to answer scientific questions and where each community discusses their specific implementation, best practices and sustainability strategies as well as legal and ethical issues. The TCS were designed taking into account the requirements of the different EPOS communities. The fact that such a variety of TCS contributes to EPOS demonstrates the multidisciplinary breadth of the integration plan and the potential impact of the community-building aspect of EPOS. TCS are interoperable with ICS thanks to the Compatibility Layer (section 2.3).

2.3 Integrated Core Services

The **Integrated Core Services (ICS)** represent the novel e-infrastructure that provides integrated access to multidisciplinary data, products (including synthetic data from simulations, processing and visualization tools), service and software for different stakeholders, including, but not limited, to the scientific community (i.e., users). The key element of the ICS in EPOS is the central hub (ICS-C) that is jointly operated by research organizations in the selected countries. The ICS-C is the novel e-infrastructure where users can discover and access data and data products available in the TCS and NRIs as well as have access to services for integrating and analysing multidisciplinary data. The technical interface between TCS and ICS is the **Compatibility Layer**, which guarantees communication and interoperability. The ICS-C e-infrastructure includes the EPOS portal and its key functions: the Application Programming Interface (API), the metadata catalogue, the system manager and the services allowing the data discovery, the interactions with users as well as the access, download and integration of data. The ICS-C also provides access to distributed resources that form the **Integrated Core Services - Distributed (ICS-D)** and includes access to supercomputing facilities as well as to visualization, processing and modelling tools that need not be centralised. ICS-D may be (a) additional computing and storage facilities procured by EPOS-ERIC; (b) nodes providing general software services; (c) back-up facilities of ICS-C for resilience and performance.

2.4 EPOS-ERIC Executive Coordination Office

The **Executive Coordination Office (ECO)** is the Headquarter of the EPOS-ERIC legal seat which is located at the Istituto Nazionale di Geofisica e Vulcanologia (Rome, Italy). The ECO has the central role of coordinating the entire infrastructure including the operation of the integrated (ICS) and thematic (TCS) services.
The EPOS governance structure is summarized in Figure 3 and detailed below.
The **General Assembly (GA)** of members is the governing body of the infrastructure. The GA is composed of representatives of the EPOS-ERIC members, with voting rights and observers, with no voting rights. The GA is responsible for the overall direction and supervision of EPOS-ERIC. Its duties include: appointing the Executive Director and the members of the external advisory boards (see below); adopting the implementing rules, the annual budget and the decisions on contributions; approving the admission of new Members/Observers; creating advisory bodies if deemed necessary; deciding on any other matters that are necessary to fulfil the task of EPOS-ERIC. Moreover, the GA decides on: proposals for amending the Statutes; termination of membership or observer status; extension the EPOS-ERIC duration period; termination of EPOS-ERIC.

The **Executive Director** is the legal representative of EPOS-ERIC. S/he, supported by the ECO, is directly responsible to the GA for all aspects of the EPOS activities, namely the day-to-day management of EPOS-ERIC in accordance with the Statutes and the Implementing Rules.

The **Services Coordination Committee**, representing all the TCS and the ICS, informs and assists the Executive Director in formulating and executing the EPOS Annual Work Plan by verifying the operational performances of the infrastructure. The Service Coordination Committee fosters harmonization of data and metadata standards across the TCS optimizing the allocated resources for data archiving and service provision.

External advisory boards (i.e. Scientific Board and Ethics Board) are in charge of monitoring the quality of EPOS-ERIC activities, providing external evaluations on activities development and results achievement. Their evaluation reports and recommendations are annually discussed by the General Assembly.

The **ICS-C Office** is a body in charge of the operational activities performed by the central hub of the integrated core services. This body acts under the coordination of the ECO Executive Director and addressing the indications of the Service Coordination Committee.

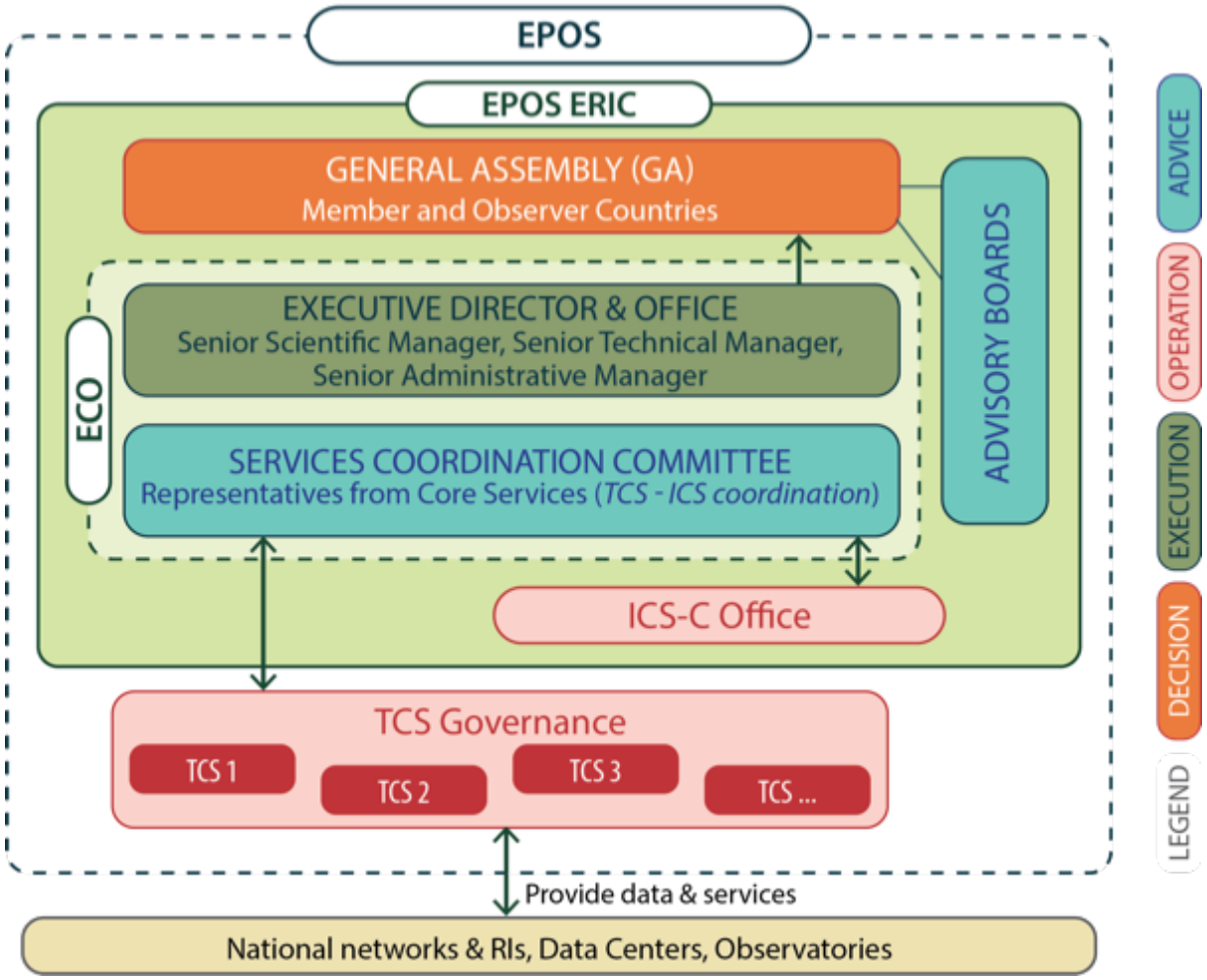

Figure 3. *The EPOS-ERIC governance structure.*

3. The EPOS Activities

The provision of data and services (namely, **D**ata, **D**ata products, **S**oftware and **S**ervices, **DDSS**) and their interoperability for a broad community of users, including but not limited to scientists, is enabled in EPOS by the combined efforts of the Thematic Core Services and the Integrated Core Services (see Figure 2).
The TCS-ICS technical integration, necessary to ensure DDSS provision, is guaranteed by the definition of standards and protocols for interoperability and by innovative solutions for data management plans, processing, preservation and deposition, including data traceability and user accountability.

3.1 Thematic Core Services: structure and provision

As detailed below, EPOS includes TCS with different character, covering different scientific disciplines in the whole solid Earth domain and providing a large number and variety of services. Nonetheless, all TCS are organised following a structure coherent and compliant with the EPOS architecture.

3.1.1 Thematic Core Services structure

The Thematic Core Services (TCS) structure is designed to ensure that their legal and governance, financial, and technical components are correctly interconnected within each TCS for the delivery of DDSS at the European level. The main elements in each TCS structure are:

- **National Research Infrastructures** (NRIs): national infrastructures (individual or groups of NRI) producing and delivering data, products and services.
- **National Consortia** to federate NRIs might be created for the harmonization of national contribution.
- **TCS Consortium:** to enable TCS to set up a governance structure for community building and service provision to EPOS-ERIC. The participation to a TCS is ruled out by the signature of the Consortium Agreement. A TCS Consortium may take three different legal forms, depending on each TCS decision: i) joint responsibility among partners with a coordination as decided by the consortium board, ii) designated, permanent host institution acting as a coordinator on a long term basis, iii) creation of a legal entity acting as host and coordinator.
- **Service Providers** (SP): legal entities in charge of ensuring access to DDSS by coordinating data management and integration. Remote or virtual access is provided by identified SPs through the EPOS Integrated Core Services (ICS) and also directly by the single SP; the services offered by each SP have to be approved by the TCS and by EPOS as part of the DDSS catalogue and require compatibility and inter-operability with the ICS service provision. The legal entity representing a SP is in charge **to sign service contract/s** with the EPOS-ERIC. To enforce an effective legal framework, each DDSS supplier will sign a Supply Letter allowing the SP/s to re-distribute data and products.

3.1.2 Thematic Core Services provision

The Data, Data products, Software and Services (DDSS) provision (including physical access to facilities) in EPOS is guaranteed by the TCS through their respective service provider/s. DDSS elements are identified by the TCS community, validated by EPOS-ERIC, and developed in a way that can be ingested by the ICS-Central Hub. The TCS described below, closely working with the ICS, are in charge of harmonizing and coordinating the DDSS provision to be provided by SP making them interoperable and fully integrated into the EPOS-ERIC delivery framework.

Data and Data Products integrated in EPOS are classified, according to a scientific-driven taxonomy specific

to EPOS, into different levels as follows: **Level 0**, raw data (e.g. seismograms); **Level 1**, products from (nearly) automated procedures (e.g. earthquake locations, soil CO_2 flux); **Level 2**, products from scientific investigations (e.g. earthquake source models, chemical analyses of rocks); **Level 3**, integrated products from complex analysis or community shared products (e.g. hazard maps, ash dispersal modelling).

TCS Seismology

The EPOS TCS Seismology provides and coordinates services for archiving, curating and making accessible seismological data, products, software and other tools, and computational seismology workflows. Building on existing organizations (ORFEUS, EMSC, EFEHR)[2], and fully integrated with the ICS-C, the TCS Seismology services cover all taxonomy levels:

- Seismological Data services: seismic waveforms (including strong-motion) and metadata from permanent and temporary networks and from ocean-bottom seismometers, derived parametric data (e.g. acceleration parameters for engineering) and metadata (levels 0 and 1); station information, temporary and OBS deployment coordination and data handling support (levels 2 and 3).
- Seismological Products services: locations, magnitudes and other parametric earthquake information collections for recent and historical earthquakes (bulletins and catalogs), including authoritativeness assessments (level 1); advanced products like moment-tensors, seismic source models, and shaking and damage estimates (levels 1 and 2); a community platform for product staging and evaluation and a site response evaluation tool (levels 2 and 3).
- Earthquake Hazard and Risk services: access to seismic hazard and risk assessment products, results, and computation tools and support, including hazard maps, risk maps and scenarios; access to underlying (input) data like tectonic fault maps and models, GMPE (Ground Motion Prediction Equations) data, geotechnical, geological and site conditions inventories; exposure and vulnerability data and tools for processing, analysing and interpreting (seismic) building response and infrastructure risk (levels 2 and 3).
- Computational Seismology services: access to IT platforms allowing computational workflow definition and execution for data- and CPU-intensive processing (e.g. synthetic data generation based on complex 3D Earth models from global to local scale), massive data mining, and visualization (level 3); integration with the EPOS-ICS computational Earth science services.

TCS Near Fault Observatories

The Near Fault Observatories (NFO) are advanced research infrastructures based on local networks of multi-parametric sensors continuously recording high resolution near fault data related to faulting and earthquake generation processes over a broad time interval. The EPOS TCS NFO provides virtual access to such data and derived high quality data products and services relying on a Pan-European network of in-situ observatories (NFOs[3]), including permanent GEO supersites (MARsite[4]) and to computational platforms. This TCS makes available through both federated services and the EPOS ICS-C a large set of data, products, services and software of various taxonomy levels:

[2]Observatories and Research Facilities for European Seismology (ORFEUS, www.orfeus-eu.org) including European Integrated Data Archive (EIDA); European-Mediterranean Seismological Centre (EMSC, www.emsc-csem.org); European Facilities for Earthquake Hazard and Risk (EFEHR, www.efehr.org

[3] European Near Fault Observatories (Alto Tiberina Observatory, Italy; Corinth Observatory, Greece; South Iceland Seismic Zone, Iceland; Valais Observatory, Switzerland; Irpinia Observatory, Italy; Vrancea Observatory, Romania)

[4] Supersite projects: Marmara Supersite (marsite.eu/)

- In-situ seismic and geodetic data; to this end the TCS build on already existing organizations (ORFEUS[2], EUREF[5]) for integrating and distributing these data through community-shared approaches (level 0).
- In-situ specific NFO data: multidisciplinary data and metadata collected in-situ through small-scale and specific monitoring networks (electro-magneto telluric, geochemical, geological, gravity, strain-tilt-meter and other multidisciplinary data) deployed in the near fault observatories, including borehole data (levels 0 and 1).
- Virtual Laboratory: virtual access to dissemination and exploitation platforms for online engagement and knowledge-sharing initiatives to multidisciplinary high-level products (levels 1, 2, and 3) and services for describing the anatomy of active faults and the causative physical processes generating earthquakes. Storing and making available all the existing geo-referenced information related to the monitored areas is a fundamental activity for the learning sector at all levels upon which building educational experiences for both the students and population.

The NFOs are ideal environments to test new algorithms for real time analysis of multidisciplinary data that can provide interpretations useful to decision makers to ground their actions. To this end the TCS is developing Testing Centres and Transnational Access facilities.

TCS GNSS Data & Products

The EPOS TCS GNSS (Global Navigation Satellite System) Data & Products provides virtual access to GNSS geodetic observations and derived products as well as to metadata (levels from 0 to 2) in close cooperation with already existing Pan-European (EUREF[5]) and national infrastructures, and to software and tools to facilitate the cross-disciplinary use of geodetic data and the use/re-use of these data from other disciplines. In particular, this TCS provides:

- GNSS Data: quality-controlled data processed with standardized algorithms.
- GNSS Data Products: derived products such as site coordinate time-series and velocities, strain rate maps and contributions to ground deformation studies.
- Software and processing tools: virtual access to community shared software and tools in order to facilitate cross-disciplinary use of geodetic data.

TCS Volcano Observations

The EPOS TCS Volcano Observations provides virtual access to data, data products and services relying on a structured network of volcano observatories, also including permanent GEO supersites (MEDSUV and FUTURVOLC)[6] and to computational platforms and physical access to volcanological resources. This TCS relies on existing organizations (ORFEUS[2] and EUREF[5]) for integrating seismological and geodetic data through community shared approaches. In particular, this TCS makes available:

- Volcanological Data: seismic, geodetic, geochemical, petrological, and environmental (e.g. meteorological in co-located geochemical/geophysical stations) data and metadata (levels 0 and 1).
- Volcanic Hazard and Risk products: multidisciplinary volcanic and hazard products, e.g. geo-volcanological maps, chemical/physical data on rocks, ashes, and fluids, eruptive parameters, thermal characteristics of lavas, eruption rates, and examples of hazard maps (levels 2 and 3).
- Computational Volcanology: access to IT platforms allowing computational workflow definition and execution for data- and CPU-intensive processing, massive data mining and visualization (level 3); integration with the EPOS-ICS computational Earth science services (lava flow scenarios, hash plume emission, etc.).

[5] European Reference Frame sub-commission of the International Association of Geodesy (EUREF, www.euref.eu)
[6] Supersite projects: Mediterranean Supersite Volcanoes (med-suv.eu/); FUTURVOLC (futurevolc.hi.is/)

- Physical Access: transnational access to facilities of volcano observatories for scientists and temporary deployments of mobile pool of multi-disciplinary instruments and/or rock samples collections.

TCS Satellite Data

The EPOS TCS Satellite Data provides virtual access to data products and services relying on existing national initiatives (EPOSAR, GDM, 3D-Def, MOD, COMET)[7] and on computational platforms aimed at the development of new products based on satellite data made available by the European Space Agency (ESA) and other national space agencies. This TCS makes available:

- Geodetic deformation: SAR displacement maps and time series for the analysis of tectonic, volcanic and geo-resource exploitation areas (level 1).
- Deformation source mechanism: products and services (levels 2 and 3) to retrieve 3D displacement maps and information on source mechanisms of observed ground deformations by integrating satellite EO products (level 1), GNSS measurements and in situ observations.
- Computational platforms: virtual access to computational platforms allowing for on-line processing of satellite data for (i) ground deformation map generation, (ii) retrieval of source mechanisms of observed ground deformations, and (iii) estimation of three-dimensional surface displacements.

This TCS also provides access to Earth Observation services managed by space agencies (ESA and other national space agencies) to facilitate the access to and the use of satellite images Earth Observations through the exploitation of shared thematic platform.

TCS Geomagnetic Observations

The EPOS TCS Geomagnetic Observations provides virtual access to data, data products and services of various level of taxonomy relying on existing organizations (INTERMAGNET, WDCG, IMAGE, ISGI)[8]. This TCS makes available data and data products of various taxonomy levels:

- Geomagnetic data: data from magnetic networks, airborne and shipborne magnetic surveys, auroral zone variometer networks as well as magneto-telluric data (levels 0 and 1).
- Geomagnetic products: global and regional geomagnetic field and conductivity models (levels 2 and 3).
- Computational Geomagnetism: virtual access to computational platforms for compilation of lithospheric conductivity models.

TCS Anthropogenic Hazards

The EPOS TCS Anthropogenic Hazards (AH) provides virtual access to data, products and services associated with induced seismicity and other anthropogenic hazards evoked by exploration and exploitation of geo-resources. In particular, this TCS makes available:

- AH data and data products collected in so-called episodes (i.e. the encapsulated dataset comprehensively describing a geophysical process induced or triggered by human technological activity in the field of exploration and exploitation of geo-resources): access to a time-correlated collection of geophysical data representing the physical processes (e.g. seismic, deformation data), data associated with the technological activity (e.g. well head pressure, water level data) causing the process and all other relevant geo-data describing the environment in which the technological activity takes place (e.g. geological, geo-mechanical data), and relevant metadata (levels 1 and 2).

[7] Operational infrastructures for processing Earth Observation data and combining satellite information of planet Earth with terrestrial measurements and modelling tools

[8] International Real-time Magnetic Observatory Network (INTERMAGNET, intermagnet.org/); World Data Centre for Geomagnetism (WDCG, wdc.bgs.ac.uk/); International Monitor for Auroral Geomagnetic Effects (IMAGE, space.fmi.fi/image/beta/?page=home); International Service of Geomagnetic Indices (ISGI, isgi.latmos.ipsl.fr/presenta.htm)

- Flexible Computational Platform: access to i) implemented specialized software library and computational resources, ii) tools for AH analysis and IT platform for supercomputing, iii) users' workspace area for analyses and storage of elaborated data products and results, iv) tools for visualisation of all types of AH data and products.
- Problem-oriented customized services designed for the analysis and discrimination of correlations between technological activity, geophysical processes and resulting geo-hazard: access to services dedicated to episodes analyses such as Multi-hazard simulator for multi-hazard/multi-risk assessment in exploration and exploitation of geo-resources, services to rate interactions between technology operations and seismic deformation, services for geophysical data analyses, services for quantitative probabilistic assessments of anthropogenic seismic hazards and services for outreach, dissemination and communication.
- Collaborative platform: access to the intercommunity social functions of the platform, e.g. upload/download data and codes to the common workspace.

TCS Geological information and modelling

The EPOS TCS Geological information and modelling provides virtual access to data, data products and services of various level of taxonomy relying on existing organisations (EuroGeoSurveys - OneGeologyEurope). This TCS makes available:

- Geological Data: multi-scale data including borehole, sample and analysis, and geophysical data (levels 1 and 2).
- Geological Products: geological, subsurface (e.g. temperature, aquifers) and geo-hazard maps (e.g. landslides, surface faulting) (level 3).
- Computational Geology: virtual access to dissemination and exploitation platforms for borehole visualization, including visualization of logs, sampling/coring intervals, analyses and geological 3D-4D models, and structural geology models.

TCS Multi-scale Laboratories

The EPOS TCS Multi-scale Laboratories provides virtual access to data, data products and services of various level of taxonomy and physical access to laboratories for the use of analytical and experimental facilities. In particular, this TCS makes available:

- Laboratory Data: analytical and experimental data on volcanic ashes and magmatic rocks, experimental data on rock properties, paleomagnetic data, and data on analogue modelling materials (levels 0 and 1).
- Laboratory Products: data products on volcanic ashes, magmatic rocks, magmas, rock/fault properties and rock systems, paleomagnetic data and analogue modelling repositories (levels from 0 to 3).
- Physical Access: transnational access to experimental and micro-analytical facilities (e.g. high temperature/high pressure, electron microscopy, micro-beam, analogue modelling, and paleomagnetic laboratories).

TCS Geo-Energy Test Beds for low carbon energy

The EPOS TCS Geo-Energy Test Beds (GETB) for low carbon energy provides physical access to GETB facilities to scientists, small/medium enterprise (SME) and business partners to perform and/or participate in experiments in this unique facility. This TCS also provides virtual access to data and protocols from GETB experiments where possible.

3.2 Integrated Core Service

The Integrated Core Services (ICS) are the key technological components within the EPOS architecture. ICS is the place where integration of DDSS provided by the various TCS occurs, and where end users can access and process DDSS elements. Figure 4 depicts TCS, ICS-C, ICS-D and users relationships in EPOS and details the expected user categories corresponding to the identified EPOS stakeholders. In order to provide leading edge functionalities and, at the same time, optimising the usage of already existing resources at European level, ICS design includes two main components: a) Integrated Core Services Central Hub (ICS-C), an integrating node that is built, run and maintained within the perimeter of EPOS-ERIC; b) Integrated Cores Services – Distributed (ICS-D), that are existing visualization or computational resources (e.g. HPC National centres) used by ICS-C, and for which appropriate procurement policies are required.

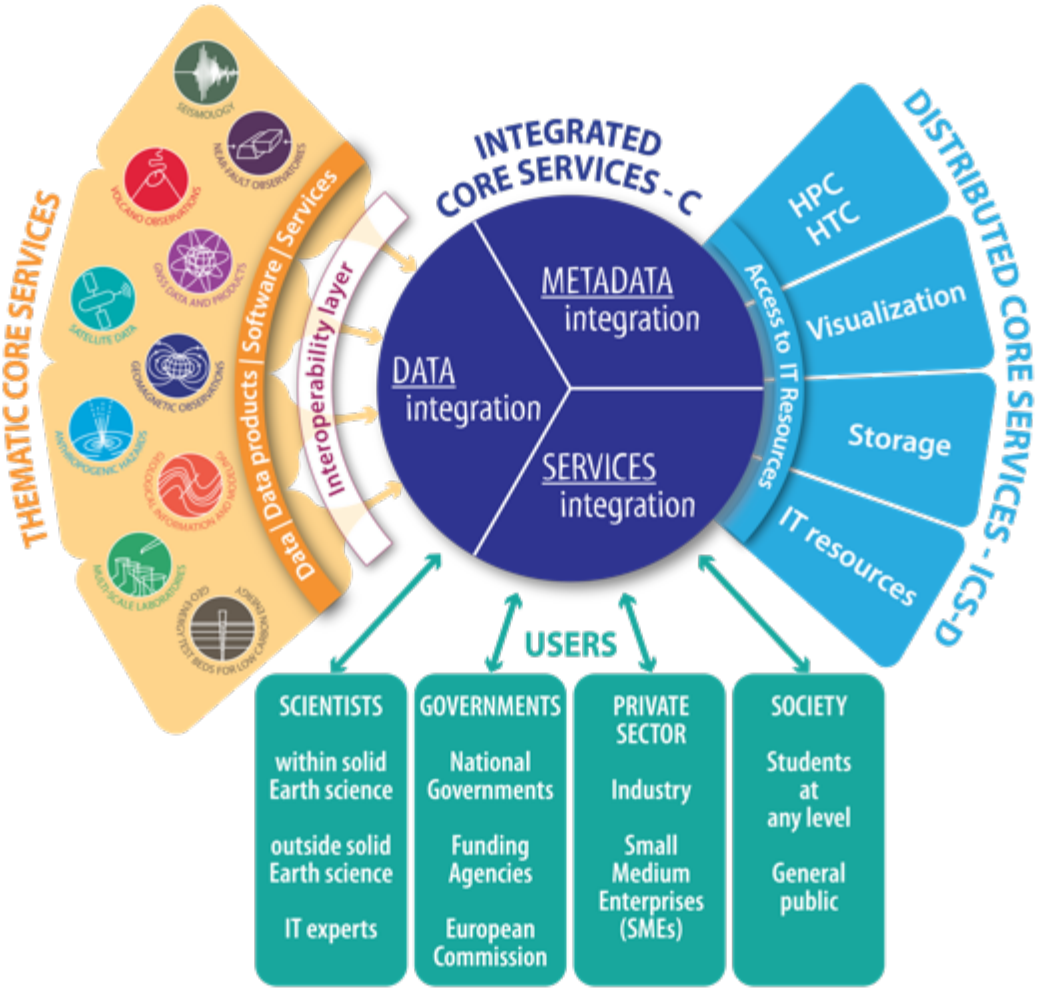

Figure 4. *TCS, ICS-C, ICS-D and USERS relationships in EPOS.*

3.2.1 Integrated Core Services Central Hub

The Integrated Core Services Central Hub (ICS-C) is the e-Infrastructure designed to ensure that the technical, but also governance and financial dimensions, are fully coherent with the EPOS architecture and the delivering of the required services at European level (Figure 4).

The main elements of the ICS-C are:

a) user interface (or web portal), where the integrated set of DDSS provided by TCS, the computational and visualization tools, and the collaborative functionalities are made available and accessible to end-users (i.e. scientists, policy maker, citizens);
b) API layer, which ensures programmatic access to EPOS ICS-C functionalities by providing a machine-to-machine interface;
c) Metadata Catalogue, which contains all the information needed to run the EPOS ICS-C system (i.e. metadata about Users, Software, Resources, Data), the metadata catalogue is the view of the ICS-C system over the outer world;
d) system management software, a set of software modules (e.g. system orchestrator, message bus and others) that provide the functionalities required to satisfy users requests;
e) interoperability layer, a set of technologies, partially provided by TCS (e.g. web-services to access TCS data or data products) and partially by ICS (e.g. connectors to map TCS web services response to the ICS metadata catalogue), that enable the ICS-TCS communication and in particular the exchange of metadata and other information; such layer is also intended to integrate visualization and computational resources from ICS-D (see next section).

3.2.2 Integrated Core Services - Distributed

The Integrated Cores Services – Distributed (ICS-D) represent services from external computing facilities (Figure 4). These include High Performance Computing (HPC) resources for modelling and simulation according to the requirements of the Earth science community, and High Throughput Computing (HTC) clusters for data intensive applications such as data mining.

The data workflow is managed by the EPOS ICS-C in order to provide the end user with appropriate computational services, even though actual computations are provided by ICS-D. Additional ICS-D services provide visualization and processing capabilities. ICS-C will develop provisions for communicating with these external services in a seamless manner also through procurement policies.

A specialization of ICS-D services would be the Computational Earth Science (CES), which consists of specific hardware and/or software solutions for computational problems in Earth science.

3.3 Methodology and criteria for TCS-ICS validation

EPOS is adopting a dynamic validation process, agreed with the community, for thematic services (TCS) and the central hub (ICS-C) to continuously verify the fitness for purpose of the infrastructure. The process is dynamic in the sense that TCS not mature enough to be validated will remain in a roadmap for a given time window to be further implemented for validation.

The general principles adopted to define the validation criteria are as follows:

- quality-controlled provision of DDSS elements;
- functionality, system performance and robustness of the ICS;
- data policy and access rules coherent with the EPOS general principles following Open Access to FAIR data (i.e. making data available for use, reuse, and redistribution by anyone with no discrimination against fields of endeavour or against persons or groups);

- effectiveness of the Data Management Plan;
- effectiveness of TCS governance structure compliant with the EPOS-ERIC governance model;
- engagement of Service Provider/s capable to ensure data and service provision and interoperability with ICS-C;
- financial information coherent with the EPOS guidelines and Cost Book.

4. EPOS Quality Strategy

For the provision of the DDSS, EPOS relies on national and trans-national research infrastructures and scientific communities that have a long lasting expertise in data standardization and data quality control. This is the first step of data quality control for the EPOS provision. As second step, the EPOS DDSS provision is implemented and harmonized to optimize the process of data quality management. The EPOS TCS are responsible for quality assurance concerning data, products and services provided for each specific community. The ICS are responsible to verify the quality of metadata and interoperability among the different TCS. The Service Coordination Committee acts as an internal audit, since it involves staff trained for this process. External audit on quality assurance and quality control is also foreseen through external advisory boards. The Service Coordination Committee is in charge of guiding a continuous process of review and assessment to verify that the EPOS DDSS provision is operating as envisioned, finding out improvements and preventing identified problems.

TCS organization ensures the availability of human resources and skills to maintain the quality assessment, also including training of personnel engaged in data provision.

Most of the research infrastructures integrated in EPOS through the TCS and the ICS participate to international organizations and programs and are already committed to provide standardized quality-controlled data. The harmonization on data standardization and management, coordinated within each TCS by the TCS themselves and between different TCS assisted by the ICS, guarantees the optimization of achievements and the full exploitation of quality control management within the EPOS Delivery framework.

DDSS provision for the EPOS operational phase is the outcome of a validation process managed in synergy with the communities (section 3.3). This guarantees a shared approach for a quality management process within the EPOS infrastructure.

5. Integrating the EPOS RI into European and global networks

The EPOS infrastructure is one of several ESFRI initiatives in the environmental science domain. However, EPOS is special in this framework as it is a single infrastructure representing solid Earth science. This puts EPOS in the special position to have many, diverse, and significant potentials to synergistically interact with other initiatives both in Europe and worldwide not only in the solid Earth domain, but also in the atmospheric, marine and biodiversity, and e-science domains.

The global perspectives of the EPOS infrastructure rely on:

- exchange of data and interoperability of services within individual communities at the level of data providers;
- participation to international programs and global initiatives;
- contributions to global cooperation among research infrastructures.

The numerous national and international research infrastructures and scientific communities (Thematic Core Services) participating to the EPOS integration plan are already engaged in international initiatives for data sharing and service implementation and distribution at global level. Nevertheless, EPOS collaborative framework creates the conditions to establish new collaborations and focuses the existing collaborations to tackle common challenges in data science and in the specific domain fields of scientific research. Being involved at different levels in numerous initiatives dealing with international infrastructures and scientific projects, EPOS contributes in creating the international collaborative framework necessary to promote the sharing of scientific results and observational data at global level. Moreover, EPOS architecture and the implemented IT solutions facilitates the active participation in all relevant discussions concerning interoperability, metadata, e-infrastructures and the evolution of virtualized IT services for research in Europe and worldwide.

6. Specific ERIC requirements addressed by EPOS

The EPOS infrastructure fully meets the requirements set out in the Article 4 of the ERIC regulation.

6.1 Fostering participation in European research programs

The EPOS infrastructure fosters the Pan-European integration of research infrastructures for solid Earth science as well as the harmonization of the Pan-European services with national strategies and initiatives. Integration of solid Earth data, products and services is essential for scientific progress including assessing geo-hazards and mitigating the associated risks and sustainably managing geo-resources.

Coordinating such integrated data and services at European level and harmonizing them with national programmes and strategies is effective to guarantee maintenance, operation, and implementation of thematic and integrated services. By ensuring sustainability through a coordinated framework including technical, legal and governance, and financial aspects, EPOS is facilitating the participation of the solid Earth science community in European research programs and projects and will guarantee the exploitation of the results in the long-term. The EPOS research infrastructure is designed to foster and monitor the execution of community research at European level and to integrate national research programs into the Pan-European perspective.

6.2 Strengthening and structuring the European research area (ERA)

The EPOS research infrastructure is contributing to strengthen and structure the European Research Area (ERA) underpinning the position and competitiveness of Europe as a global player for Earth observations and data assimilation in geo-sciences. The EPOS infrastructure is creating the collaborative framework necessary to promote the sharing of scientific research results and observational data through FAIR principles, consequently facilitating the participation and the collaborations of different member states through a single integrated approach.

Moreover, EPOS ensures community building by increasing the capability to use research data by providing the functioning for access to data, products and services. The aware use and re-use of solid Earth data by different stakeholders, not limited to specific domain scientists, is the effective way to promote understanding of and preparedness to geo-hazards including the safe exploitation of geo-resources.

European innovation in solid Earth science is represented by both technological development of innovative observing systems and social progress by creating skills and human capital capable to manage the impacts of natural and anthropogenic phenomena on the environment and society.

6.3 Guaranteeing effective access

Following its mission of giving open access to geo-scientific data, products, services and software (DDSS), EPOS will always guarantee an effective access to the infrastructures to the European research community (composed by researchers from members states and from associated countries) but also to any potential data and services providers within solid Earth science, scientists within and outside solid Earth science, including IT scientists, National and regional governments and authorities, young researchers and students, private sector, and, more in general, to any potentially interested person (public, generally speaking). A EPOS user is any person who is interested in using the infrastructure and its services at European and global level. Core users include scientists and students. The users potentially interested in the EPOS data, products and services belong to a wide variety of entities, ranging from science to policy, from the public to the private sector, from mass media to operational monitoring agencies.

6.4 Contributing to mobility

The EPOS infrastructure effectively contributes to the distribution of knowledge and mobility of researchers within the European Research Area (ERA) by:

- fostering the integrated use of solid Earth data and metadata;
- facilitating the use and re-use of existing high-quality standardized data;
- engaging scientists to share data products and results of scientific researches making them accessible through open data policies and FAIR principles;
- promoting trans-national access to European facilities (e.g. analytical and experimental laboratories, instrument pools) and natural laboratories (e.g. volcanoes) for the European students and researchers;
- providing access to scientific authoritative information necessary for awareness and preparedness to geo-hazards;
- sharing policies and strategies to manage environmental information in ethically consistent ways;
- participating to e-science innovation by contributing to the European Data Infrastructure and to the design of EOSC for facilitating the access to federated computational resources;
- creating balanced and ethically consistent frameworks to engage the private sector both as suppliers and users of the infrastructure;
- harmonizing national strategies to implement research infrastructures and observing systems in a Pan-European sustainable platform.

6.5 Contributing to dissemination and training

The EPOS dissemination and communication strategy is designed to promote understanding for a full and effective exploitation of the EPOS infrastructure. Communication strategies and activities are in place to ensure effective communication with stakeholders with the final goal of strengthening the long-term mission for Pan-European integration of research infrastructures for solid Earth science. Communication and dissemination activities are coordinated by the ECO with support from the communities in order to raise awareness of the EPOS infrastructure, unlock innovation potential and increase societal and economic impacts. In practice, EPOS has to:

- adopt a dissemination plan for each type of stakeholder category;
- elaborate and update appropriate dissemination material to promote EPOS to each target audience;
- foster and maintain EPOS's visibility and flagship at global level.

EPOS also promotes training activities both at the EPOS-ERIC level and at the thematic communities (TCS) level dedicated to train users of the EPOS infrastructure and/or trainers as well as to educate any potential stakeholder on how to exploit the EPOS infrastructure. Training represents a further effective way to communicate with target audience and users. In practice, EPOS will:

- elaborate feasible strategies to engage trainers and users;
- establish a training plan for selected stakeholders;
- develop feasible tools for facilitating training initiatives in coordination with TCS communities.

In particular, the EPOS Training Plan is designed by focusing on i) instructing the already aware/engaged, but also new potential, stakeholders on how to best exploit the services provided by diverse scientific communities and utilise the evolving technology for the using and re-using of data and products; ii) forming the next generation of scientists; iii) improving the capability of society as a whole to understand the scientific achievements in solid Earth science and their societal relevance. The plan is structured in "key actions" tailored to specific target audiences. The content of the Training Plan benefits of contributions from the IT team to train users on data science and e-science innovation and in particular on the exploitation of TCS and ICS services, ICS-TCS interoperability.

The EPOS architecture and its capability to generate data and products fostering re-use and re-compilation of multidisciplinary data through novel services will allow the infrastructure contributing to form the next generation of data scientists and managers. Training to create skills for implementing and operating data and service provision as well as for managing the infrastructure is essential to maintain the human capital and unlock the innovation potential.

6.6 Risk Assessment and Mitigation

EPOS has established a risk management framework to ensure that the operational phase of the infrastructure and the implementation of new services will advance coherently with its vision and mission. The aim of any risk management is, when risks are identified, to undertake mitigation actions and contingency plans to eliminate or reduce risks to an acceptable and manageable level.

For EPOS infrastructure, the risk identification involves determining which risks or threats are likely to affect the enterprise in terms of operational capacity (data and service provision), exploitation of results (attractiveness of users) and impact for science and society.

The EPOS Risk Management Policy sets out the principles, outlines the priorities, and instructs the Executive Coordination Office to put in place and to follow the EPOS Risk Management Plan. The Policy and the Plan are supported by a dynamic EPOS Risk Register, which is regularly reviewed by the General Assembly. The *Risk Management Policy* provides the overarching "ground rules" and has to be approved by the General Assembly. It affirms the EPOS commitment to risk management, assigns responsibilities, and sets the EPOS priorities out. The *Risk Management Plan* will cover the processes and activities to be undertaken in order to give effect to the Risk Management Policy (mitigation actions and contingency plans). The *Risk Register* represents a frequently updated database listing all the identified risks, the current assessment of the threat(s) they represent to EPOS, the entities responsible for taking appropriate actions,

the potential actions and their current status. The General Assembly will be responsible for regular review of the potentially most significant threats and will inform the ECO of its decisions and measures taken to mitigate these risks.

The risk categories mapped in the Risk Register are listed below and described in Annex I.

- Maintenance and Operation of TCS data and service provision
- Maintenance and Operation of ICS-C and its interoperability with TCS
- Financial framework for sustainability
- Governance and legal frameworks for sustainability
- Synchronization with national strategies
- Outcomes of impact assessment and exploitation of results.

Certainly, unforeseen and unforeseeable risks can always occur. These are, respectively, the types of risk that were not or cannot be accurately forecast or mitigated before their occurrence. Unforeseen risks will be limited as much as possible, thanks to a careful analysis of challenges and bottlenecks in the different risk areas. Any risk management plan has however an element of unforeseeable risk, no matter how careful is the planning process.

Undoubtedly, making the EPOS platform of services operational depends on the following actions and support running in parallel at both national and European level:

- ensure support to TCS from National Research Infrastructures (NRI);
- support from national initiatives and in-kind contributions to the implementation of the services;
- funding of national and European projects in order to further develop new service components;
- third-party contributions from the private and governmental sector.