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A new European service to share GNSS Data and Products

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Abstract

This paper describes the new GNSS data and product services that have been developed within the context of the EPOS (European Plate Observing System) European Research Infrastructure Consortium (ERIC), which is part of the European Strategy Forum on Research Infrastructures. These services, optimized for Solid Earth research applications, endeavour to harmonise, and standardise Global Navigation Satellite System (GNSS) data collection and processing. They have been implemented by the members of the GNSS Data & Products (EPOS-GNSS), one of the Thematic Core Services (TCS) of EPOS with the active support of national and pan-European infrastructures (in particular the Regional Reference Frame Sub-Commission for Europe (EUREF) of the International Association of Geodesy). The optimized use of data from dozens of diverse European GNSS networks, installed not specifically for geodynamic studies, created additional requirements from an organizational and technical point of view, the solutions for which we describe in this article.
The data flows from data suppliers and analysis centers to the various TCS Data & Product Portals are described, as well as their integration into the overall EPOS system. This is made through GLASS (GNSS Linkage Advanced Software System), a dedicated software package developed since 2016,

whose architecture and functionalities are detailed here. Time series and other GNSS products computed at the several analysis centers are described as are the quality control steps that are performed. Finally, several user cases are presented that demonstrate how different stakeholders (from data providers to scientists) can benefit from the efforts being carried out by the EPOS-GNSS community.

Keywords: GNSS, Data Management; Products for Solid Earth; Infrastructure; Software Development

1. Introduction

GNSS observations acquired using geodetic instruments and techniques have proven in the last decades to be an essential tool to monitor and quantify geodynamic processes. GNSS stations are able to detect deformation processes at different temporal scales, ranging from secular (tectonics and glacial isostatic adjustment) to second (volcanism and seismology), with an unprecedent accuracy [e.g., Altamimi et al., 2017; Fernández et al., 2017; Melgar et al., 2020; Kierulf et al., 2021; Briole et al., 2021].

The mission of the EPOS-GNSS TCS is to provide, in the context of EPOS, open access to GNSS data, metadata, products, and software in support of the Solid Earth sciences in Europe. Most of the European continent and its margins are covered by dense networks of GNSS CORS (Continuous Operating Reference Stations) maintained by many agencies with different technical and scientific objectives. During the H2020 EPOS Implementation Phase project that ended in 2019, approximately 5000 GNSS stations with the potential to be included in the EPOS network have been identified (cf. Figure 1).

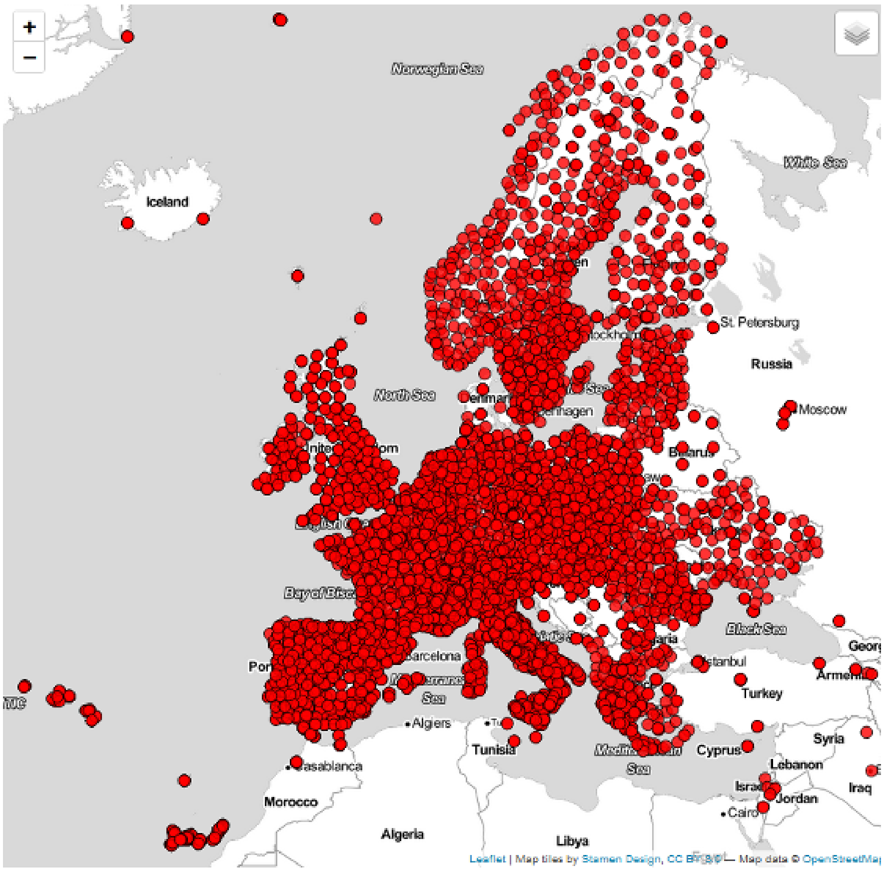

Figure 1. GNSS CORS identified during the EPOS Implementation Phase project in Europe and surrounding areas.

However, most of these GNSS stations have been installed for geo-referencing applications (mainly surveying) and only about 350 of them were providing open access to their data in a coordinated way through the EUREF Permanent GNSS network. Until EPOS, there had yet been no effort in Europe to coordinate the provision of data and products for Solid Earth applications of all available European CORS. This differs from other regions of the globe, like Japan [Sagiya, 2004] and Western USA [Herring et al., 2016], where dedicated GNSS networks were implemented using centralized and consistent projects with the main objective of producing information to study and monitor natural phenomena.

Consequently, the optimized dissemination and use of the data from European GNSS networks for Solid Earth studies created additional challenges from an organizational and technical point of view that are being tackled through EPOS-GNSS.

EPOS-GNSS aims to consolidate the disperse GNSS activities in Europe to provide access to all the GNSS data and products through two gateways: the EPOS-GNSS Data Gateway and the EPOS-GNSS Product Portal (cf. Figure 2). This has facilitated the interface with the Integrated Core Service (ICS) of EPOS (https://www.ics-c.epos-eu.org/) where all multidisciplinary data and products made available by the different TCSs are discoverable. These two EPOS-GNSS gateways run all the webservices that are necessary to make the data and products from the other EPOS-GNSS Service Providers available to the ICS. As a direct consequence, the content distributed by the two GNSS gateways to the ICS mainly depends on the underlying distributed GNSS Service and Data Providers, which, in turn, have no direct link with the ICS anymore, but are still crucial for the functioning of the EPOS-GNSS and its data and product provision to the ICS.

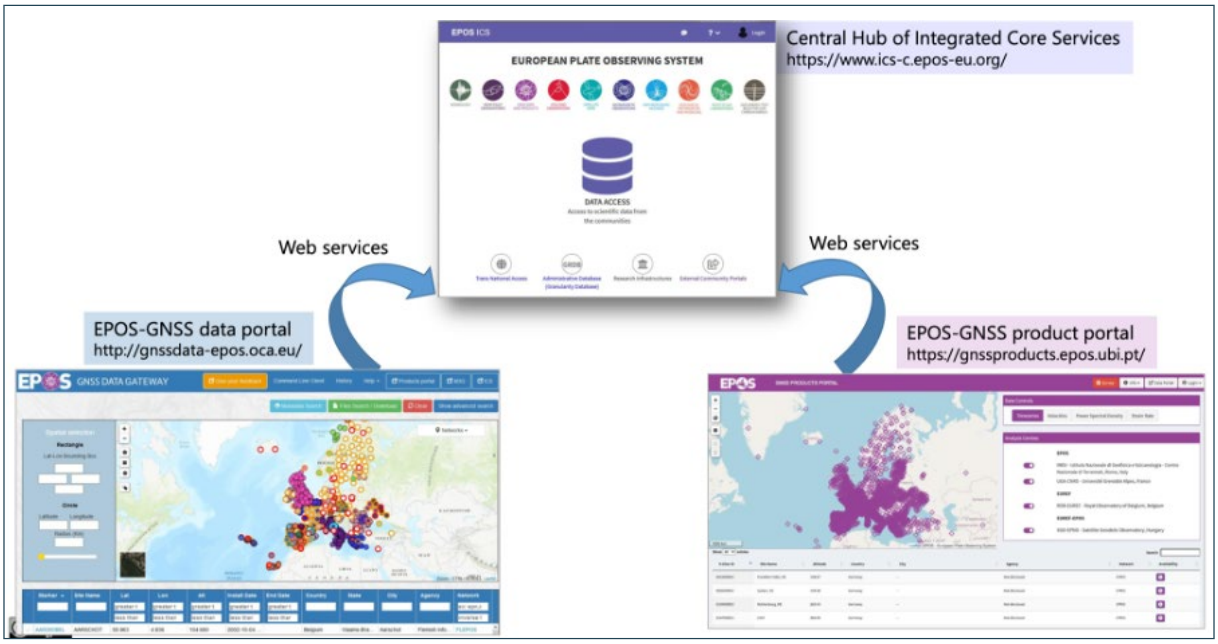

Figure 2. Organization scheme of GNSS Portals in EPOS.

2. New GNSS Services

EPOS-GNSS defined a total of 20 services which will lay the foundation to realize its missions. Table 1 summarizes these services that are divided in 4 pillars. Most of these services, except for the EUREF services, are new services that have been designed and implemented specifically to satisfy the needs of the EPOS community.

One of the goals of this paper is to present an overview of these services and their present status, which will be given in the next sections.

SERVICE GROUP	DESCRIPTION OF SERVICES
GOVERNANCE	TCS Governance and Outreach
DATA DISSEMINATION	Provision of quality-checked RINEX data and station metadata of EPOS-GNSS stations; Operation of EPOS-GNSS Data Gateway and monitoring of the node infrastructure and synchronizations
PRODUCT DISSEMINATION	Computation and provision of positions, velocities, and time series of EPOS-GNSS stations, and Strain rates; Provision of EUREF GNSS data and products; Operation of EPOS-GNSS Product Portal
SOFTWARE PROVISION	Maintenance and Development of GLASS software: databases, tools & webservices

Table 1. Group of Services implemented by the EPOS-GNSS TCS.

2.1 Governance

The above-mentioned EPOS-GNSS objectives are being implemented formally by eleven institutions from ten different countries, who signed a Consortium Agreement in 2020 to operate the pan-European EPOS-GNSS services necessary to achieve these goals. The EPOS-GNSS Service Providers consists of a multidisciplinary team with experience in the management (quality control and dissemination) of data and metadata from GNSS networks and analysis of the derived products specifically for Solid Earth studies. In addition, it is supported by a strong group of IT experts. However, these EPOS-GNSS collaborations are not limited to the EPOS-GNSS Service Providers, but also involve GNSS Data Providers, researchers, and other stakeholders.

The Consortium Agreement also defines the EPOS-GNSS governance framework (cf. Figure 3). All of these components are in place since the beginning of 2021. The Consortium Board defines the long-term strategy to be implemented by the Executive Board, which coordinates the different pillars. This board is counselled by two External GIA Committees: the Data Provider Committee and the User Feedback Group. The Data Provider Committee consists of the representatives of agencies who allow their GNSS data to be redistributed through the EPOS data portal. To ensure the voices of both data providers and users are considered, two representatives of each External Advisory Committee have a seat on the EPOS-GNSS Consortium Board.

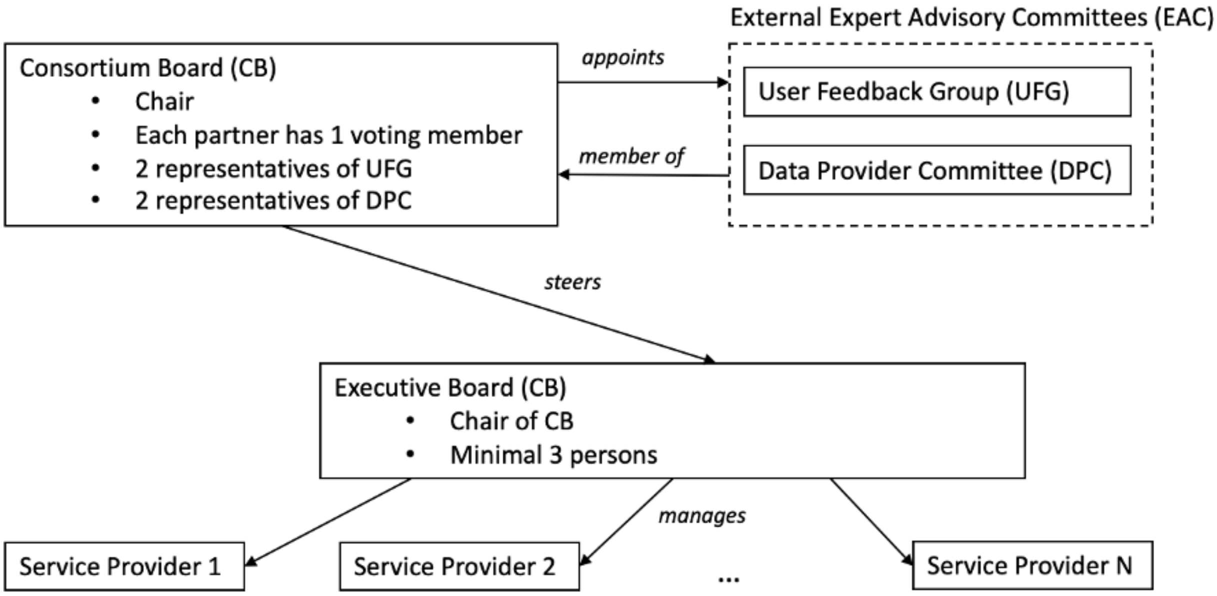

Figure 3. Governance structure of the EPOS-GNSS Data & Products.

2.2 GNSS Data Dissemination

2.2.1 Workflow to disseminate validated GNSS data and metadata

The EPOS GNSS data and metadata dissemination system integrates several independent nodes as well as a GNSS station metadata collection service (M^{3}G, maintained at ROB, Belgium, see section 2.2.3), through a central gateway, the EPOS-GNSS Data Gateway (maintained at CNRS-OCA, France, cf. Figure 4). As mentioned in the introduction, the EPOS-GNSS Data Gateway makes the data and metadata from the numerous GNSS data suppliers discoverable.

Currently EPOS-GNSS focuses on the distribution of daily RINEX data at a 30-second rate. To provide open and free access to their daily RINEX data, the station operators must i) sign the EPOS-GNSS data supplier letter; ii) provide station metadata (equipment information, data license, data ownership, etc.) to M^{3}G (see section 2.2.3); and iii) make their data available at a data repository linked to an EPOS-GNSS data node.

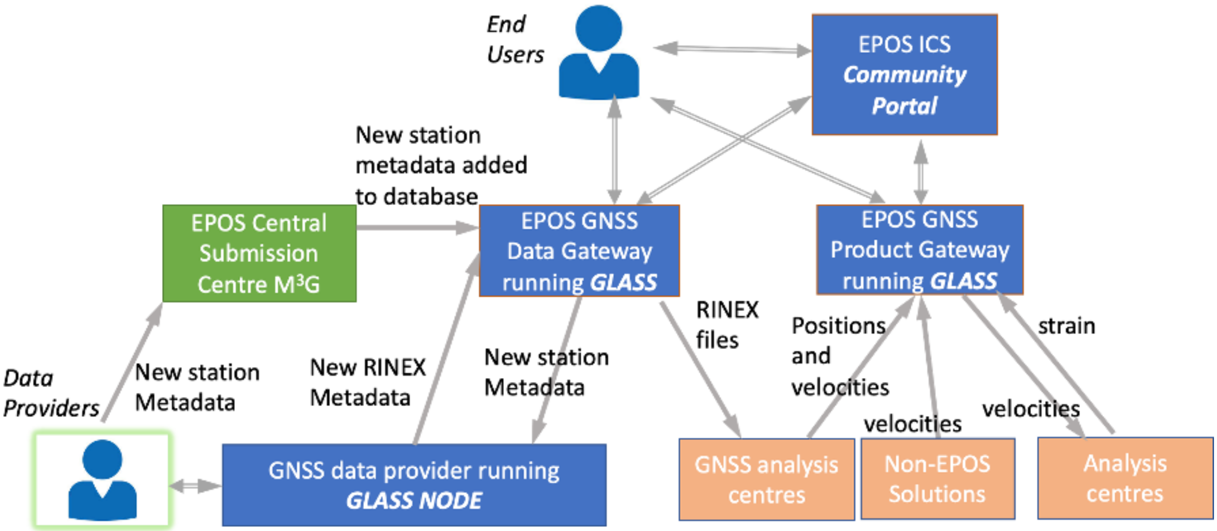

Figure 4. Data Flows within the EPOS-GNSS framework as seen by a Station Manager and End User.

Each of the EPOS-GNSS data nodes uses GLASS (Geodetic Linkage Advanced Software System) (see section 2.4), as a virtualization level on top of the data repository itself. GLASS also indexes the GNSS data files, validates GNSS data with respect to station metadata synchronized from the central metadata database located at the Data Gateway, computes data quality metrics, and stores all information in the local node database. GLASS then ensures the synchronization of this local database with the EPOS-GNSS Data Gateway. In this perspective, the GNSS quality control process, performed at each EPOS-GNSS data node with the G-Nut/Anubis software [Václavovic and Douša, 2016], is crucial in order to control which data can be made discoverable and if a status warning must be associated to the data. Data with critical inconsistencies between the RINEX header and the M^{3}G information related to the instrumentation (antenna, receiver and radome types, eccentricity), or the file name, or the file format (e.g., RINEX 2 or RINEX 3) will not be discoverable at the Data Gateway (it remains however discoverable at the local nodes). Data with minor inconsistencies on the instrumentation (e.g., antenna or receiver number, coordinate deviations) or on the receiver tracking parameters (e.g., frequency acquisition, elevation cut-off) will be available on the Data Gateway with a specific warning status in the associated file metadata. Finally, some data quality criteria are checked (e.g., number of cycle slips, number of epochs, and expected number of observables) and if out of range, a warning status is issued in the file metadata. Hence, most of the effort required to ensure the distributed RINEX data conform with the EPOS requirements is done at the EPOS local data nodes and the EPOS-GNSS Data Gateway via metadata synchronization processes that allow the system to take into account the verification and validation of the data.

2.2.2 Access to GNSS data and metadata

The EPOS-GNSS Data Gateway offers three ways to access to data and metadata: a web client, a command line client and a RESTfull API. The web client (https://gnssdata-epos.oca.eu, cf. Figure 5), which is maintained at CNRS-OCA (France), is a convenient and attractive way to visually explore available data and metadata. Its main interface allows an easy and quick visualization, selection and filtering of stations using geographical, temporal, organization (agencies, networks) or name criteria. An advanced search interface offers selection criteria among all the station, file and quality control metadata (e.g., instrumentation, percentage of data availability, minimum years of data). With criteria set up, a detailed view of all the station or file metadata is shown. Station metadata can be downloaded in 3 different formats (JSON, GeodesyML and IGS Site Log), and file metadata (e.g., url, size, md5) in one format (JSON). The RINEX files that meet the selection criteria can also be downloaded directly.

The command line client, available for download at the GNSS Data Gateway, provides the same functionalities. The user can automatically retrieve station and file metadata as well as RINEX files. This client is therefore particularly suitable for massive, regular, or automatic data download. Finally, the RESTfull API allows to interface the GNSS Data Gateway with any existing software or programming language to get metadata.

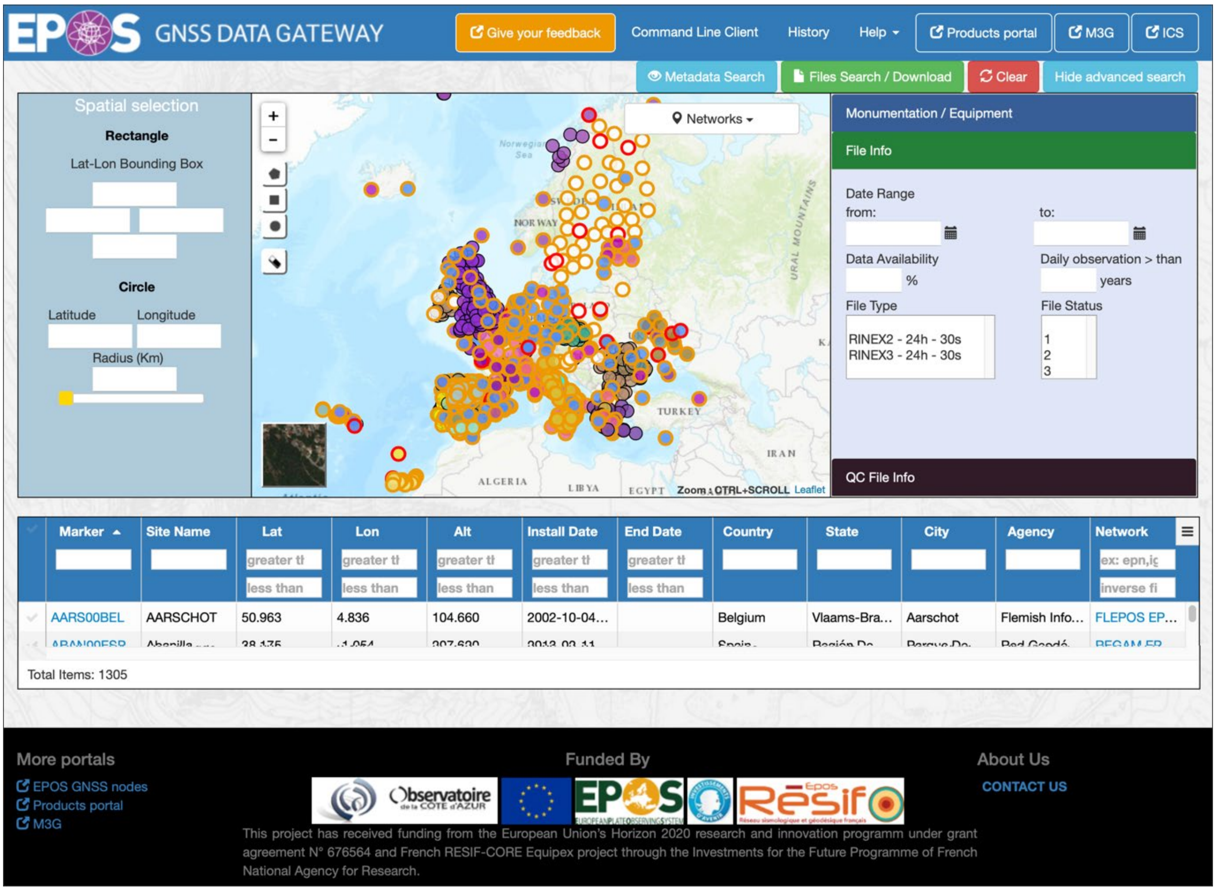

Figure 5. Web client of the EPOS-GNSS Data Gateway, one of the three available ways to discover and access the EPOS-GNSS metadata and data.

2.2.3 Collection, validation and distribution of GNSS station metadata

The GNSS station metadata that are used in the EPOS-GNSS framework to verify the correctness of the RINEX headers originate from M^{3}G (Metadata management and distribution system for multiple GNSS networks, https://www.gnss-metadata.eu). GNSS station managers use M^{3}G to submit, validate and distribute the metadata of their GNSS stations including information on station ownership, the equipment installed at the station, its monumentation and environment, and eventually co-located instruments. From M^3G the station metadata of EPOS stations automatically flow to the EPOS-GNSS Data Gateway from where it then gets distributed throughout the EPOS-GNSS delivery framework, as shown in Figure 4.

GNSS station metadata can be submitted and retrieved using the M3G GUI as well as API. In addition, M^3G has been developed to ensure full harmonization between the GNSS station metadata distributed through EPOS and EUREF [Bruyninx et al., 2019] and it uses the latest GNSS metadata standards issued by the International GNSS Service (IGS). Some of these GNSS station metadata are provided to M^3G by other EPOS TCS, like the Near-fault Observatories and Volcanology TCSs. By submitting their GNSS metadata to M^3G, EPOS ensures harmonization of GNSS metadata across EPOS TCSs. Currently, the system provides access to standardized station metadata of more than 2700 GNSS stations from which 1300+ are integrated in EPOS.

With the aim of aligning with FAIR data principles, M^3G also collects Digital Object Identifiers (DOI) and data licenses. In addition, unless indicated otherwise by the data provider, M^3G automatically attributes the CC-BY license to all EPOS data. Hence the data of all EPOS GNSS stations have a data license associated with them. Concerning the DOI, the majority of the EPOS GNSS data still have no associated DOI. This is a general problem within the GNSS community and the EPOS-GNSS TCS is actively pursuing the usage of DOIs.

2.2.4 Current Status

Up to now, more than 65 agencies have signed the EPOS-GNSS data supplier letter, inserted their GNSS station metadata in M^3G (total of 1300+ stations) and offered to provide daily RINEX data to EPOS (Figure 6).

Ten EPOS-GNSS nodes (cf. Figure 7), in addition to the Data Gateway and the Product Portal, are presently operating or in the process of being set up. Apart from node providing access to the data from a specific country or network, the node network includes two pan-European nodes accepting station data from all over Europe: the

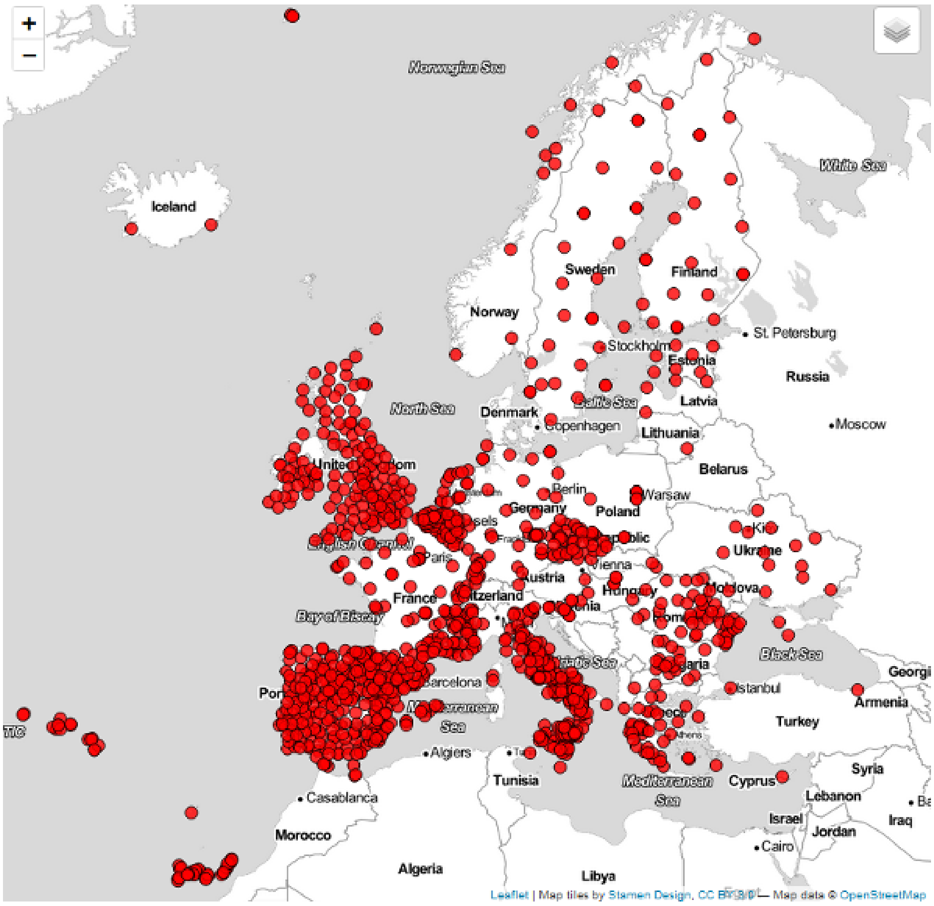

Figure 6. Permanently tracking GNSS stations willing to share their daily data with EPOS.

Figure 7. Map of the EPOS-GNSS node infrastructure. Blue circles indicate the localisation of the local nodes (currently operating or in the process of being set up) and red circles indicate the localisation of the Data Gateway and the Product Portal.

EUREF node (providing access to EUREF data) and the pan-European EPOS-GNSS node. As these nodes are operating on a pre-operational basis, several of them are still in the process of gathering historical data or setting up the daily population of their databases for the automatic ingestion of new incoming data. As a result, the data of 30% of the above 1300+ station are presently not yet discoverable from the Data Gateway. However, it is expected that this situation will gradually improve in the near future. In the meantime, over 3 million daily RINEX files are already available from the Data Gateway.

In addition, in the background, EPOS-GNSS continues to be in contact with several potential GNSS data providers to extend the EPOS-GNSS station network.

2.3 GNSS Products

2.3.1 Objectives and stakeholders

The objective is to facilitate the access and the use of GNSS derived products, so that they can be more easily analysed and interpreted, including by non-geodetic experts such as geophysicists, seismologists, structural geologists, hydrologists, modelers, oceanographists, meteorologists, data scientists, or by mapping agencies or engineering offices (cf. Figure 8).

EPOS GNSS therefore permits the access to products with a high standard of quality. Those products, represented in Figure 9, include:

- **SINEX files** (Solution Independent Exchange format), that provide position information in a standard format commonly used by geodesists to exchange solutions, to compute their own multiyear solution, or to combine with additional GNSS data.

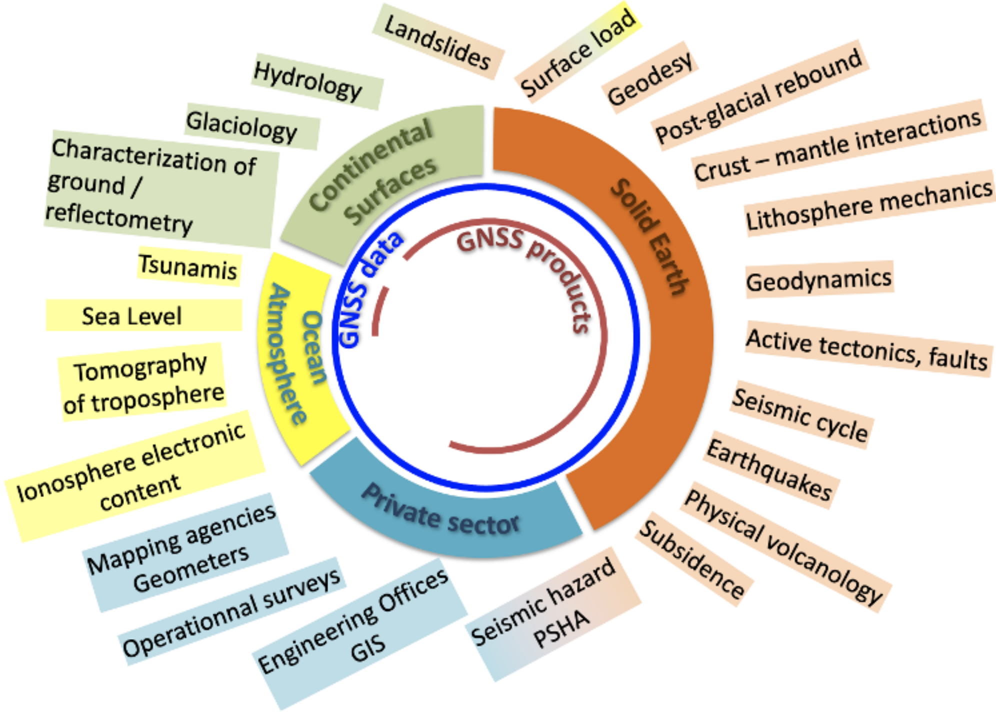

Figure 8. The different scientific domains in which GNSS data and products can be used.

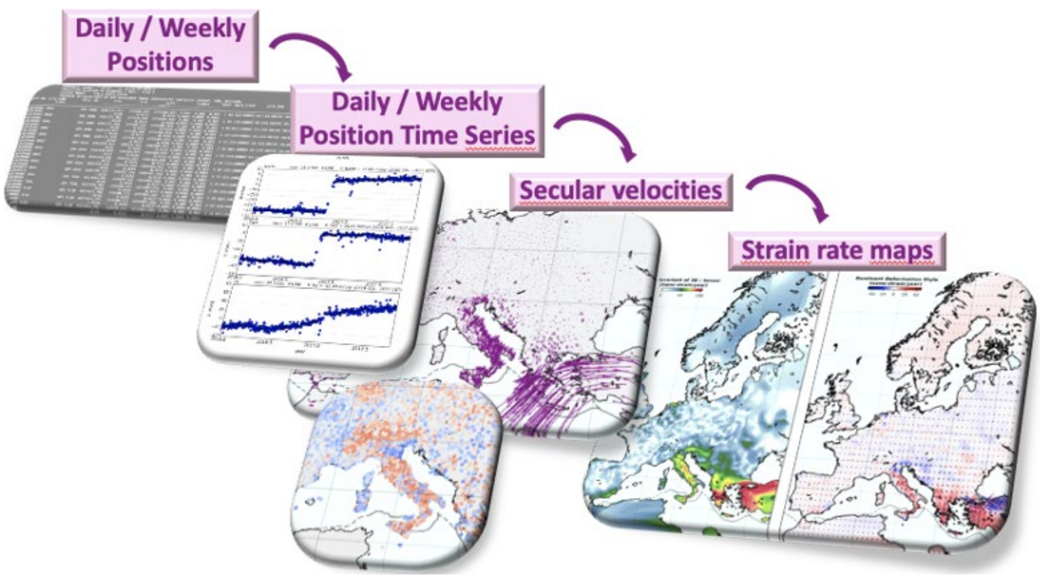

Figure 9. GNSS products generated and distributed through EPOS-GNSS Products Portal: SINEX files, position time series, secular velocities, strain rate maps.

- **Position time series**, that provide the evolution of the 3D position of each site with time. Daily and weekly position time series are available in various formats (JSON, pbo, sol).
- **Secular velocities**, that provide the 3D secular velocity of each site. This secular velocity represents the average long-term displacement rate at each site, from which transient movements related to, e.g., earthquakes, volcanoes or hydrology have been removed.
- **Strain rate maps**, that provide deformation values computed over a grid that covers the whole Europe. The strain values are reference frame independent. They include the dilatation, the shear strain, and the values and orientation of the maximum and minimum components of the strain tensor.

2.3.2 The different product labels, their specificities, and their providers

The GNSS products distributed through the EPOS-GNSS Products Portal are organized into three categories: EPOS, EUREF, EUREF-EPOS (described below). The different solutions are generated by 5 Pan-European Processing Centers (INGV, Italy; CNRS-UGA, France; LTK, Hungary; WUT, Poland; and ROB, Belgium) and ~30 Regional Analysis Centers (cf. Figure 10). An additional Pan-European service provider is in charge of the computation of strain rates (LM, Sweden). Figure 11 shows the organizational scheme being developed by EPOS-GNSS to create and disseminate through the Products Portal (UBI, Portugal) the different products calculated by the different Analysis Centers.

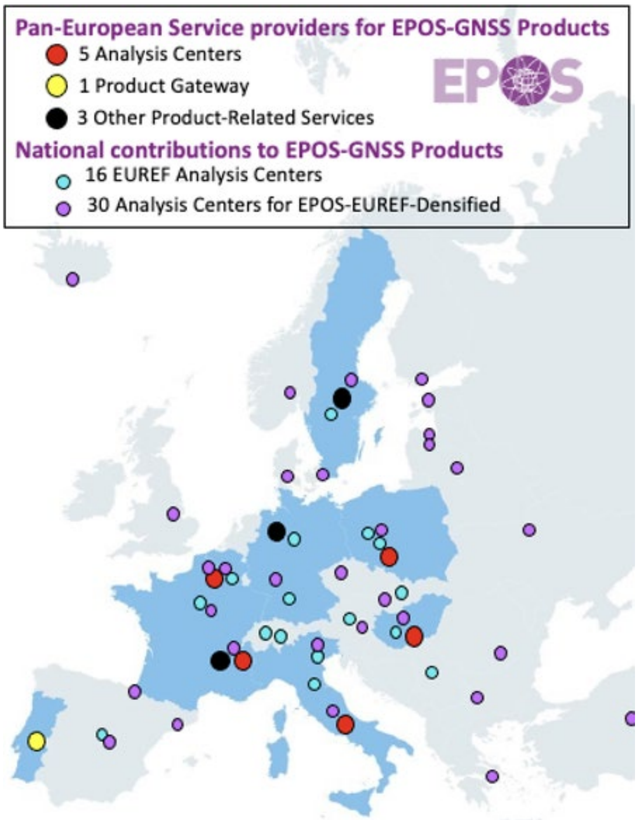

Figure 10. Service providers for the GNSS products generated and distributed through EPOS-GNSS Product Portal.

2.3.2.1 *EPOS solutions*

Two independent solutions are developed specifically for EPOS: one solution processed in double-difference (DD) mode at UGA (France), and one solution processed using the Precise Point Positioning (PPP) strategy at INGV (Italy). These two Analysis Centers process all available data for the EPOS stations, which means that the processed observations are openly available from EPOS-GNSS Data Gateway, with available and verified metadata, thus respecting the principles of open science and reproducibility. The processing strategies are fully documented (https://gnssproducts.epos.ubi.pt/documentation) and use open-source software packages: GAMIT/GLOBK [Herring et al., 2018] and GIPSY-OASIS [Bertiger et al., 2010]. The solutions are aligned with the IGb14 reference frame and distributed either with respect to ITRF2014 [Altamimi et al., 2016] or with respect to stable Eurasia [Altamimi et al., 2017]. Each one of these two solutions is internally consistent, meaning that it has been generated from raw data (RINEX files) at one single Pan-European processing center with one strategy. Those solutions are specifically designed for geophysical studies, including the study of slow deformations or transient movements.

The main products include daily positions (i.e., SINEX files) and multi-year solutions (i.e., position time series). The double difference solution is automatically updated with data at day-2 (rapid solution) and day-25 (sub-final

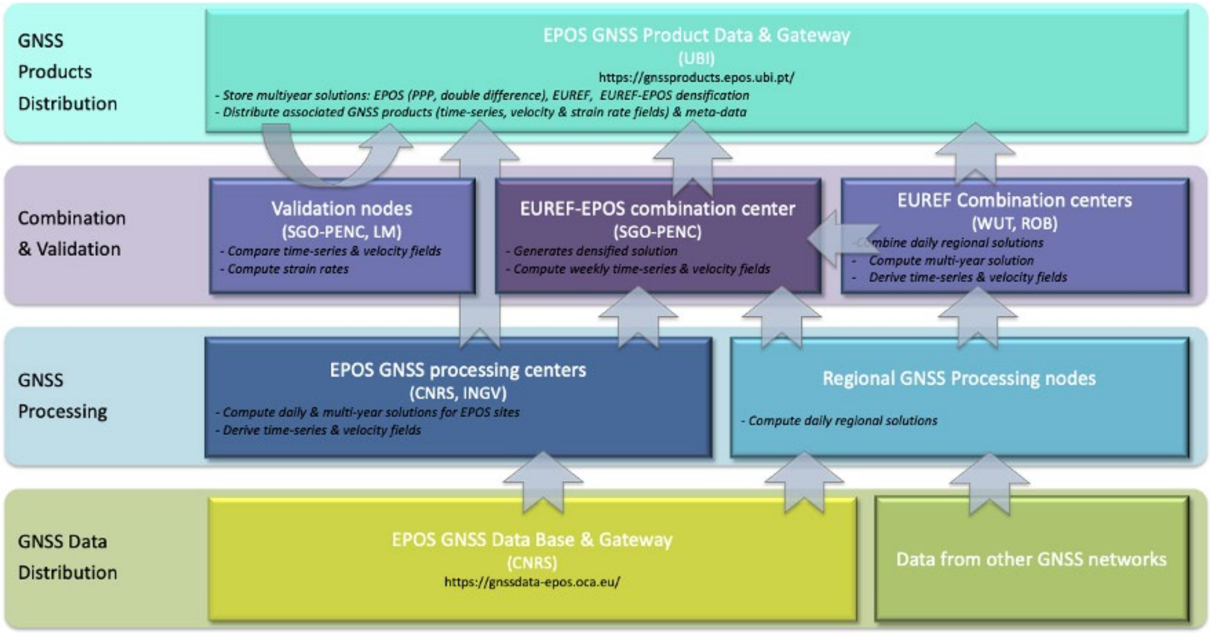

Figure 11. Organisation scheme for the creation and dissemination of the products provided by EPOS-GNSS.

solution). The PPP solution is updated on a regular basis. Both solutions are analysed and validated by each Analysis Center (UGA and INGV, respectively), with automated outlier rejection, and introduction of discontinuities in time series. An independent cross-comparison and validation between both solutions is then performed by the Pan-European Combination Center located at LTK (Hungary). Positions time series from both solutions are compared using CATREF [Altamimi et al., 2007], outliers and inconsistencies are identified and returned to both Analysis Centers until final validation.

For each solution, velocities are also computed and available from the Product Portal (cf. Figure 12 that exemplifies the derived velocities for the vertical component). The generation of the velocities is made using MIDAS software [Blewitt et al. 2016], that enables a statistical analysis of the raw time series in which any documented jump (e.g., antenna changes, earthquakes) has been flagged. This allows for a robust trend estimation of the secular velocity of each station that is not affected by local jumps or transient movements.

2.3.2.2 *EUREF solution*

The original solution from EUREF is also made available through the EPOS-GNSS Product Gateway. This solution is using open data, namely the RINEX files available from EPN (EUREF Permanent Network) Data Centers, with available and verified metadata. Daily position solutions for part of the network stations are computed at 16 EPN Regional Analysis Centers (AC) using one of three geodetic software packages: BERNESE [Dach et al., 2015], GAMIT/GLOBK [Herring et al., 2018] and GIPSY-OASIS [Bertiger et al., 2010]. Each station is processed by at least 3 Analysis Centers to ensure redundancy and increase reliability. Those local solutions are then combined using Bernese to provide daily and weekly combined positions aligned to IGb14 by applying no-net-translation. This combination is done by the EPN Analysis Combination Center hosted at WUT (Poland). Each individual solution is compared with the combined solution to identify and reject outliers and finally, transformed into a SINEX file. These Pan-European position solutions are updated each week.

Multi-year position and velocity solutions (cf. Figure 13) are then estimated by the EUREF Reference Frame Coordinator at ROB (Belgium) by combining daily SINEXs generated by WUT using CATREF software [Altamimi et al., 2007]. The position and velocity solutions are aligned to IGb14 with minimal constraints on 14 parameters. Outliers are rejected by visual inspection of time series, position and velocity discontinuities are introduced, and station classification based on multiple criteria including velocity uncertainties from Hector software [Bos et al., 2013] and velocity variability.

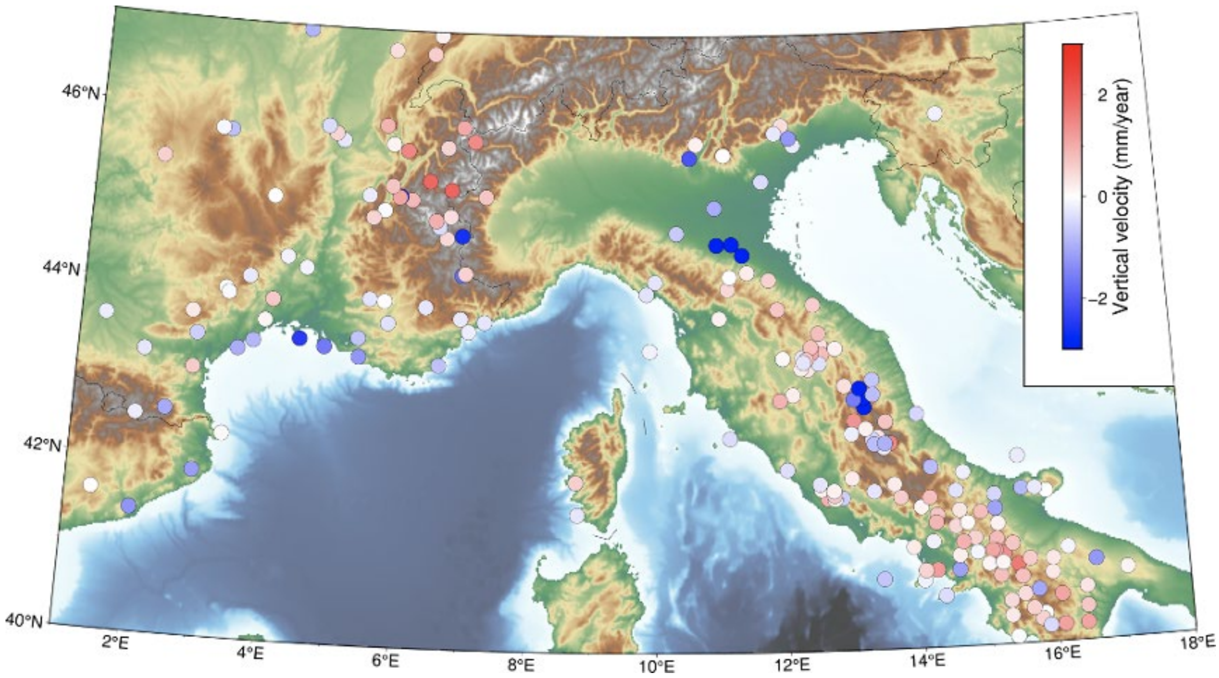

Figure 12. Secular vertical velocities from the EPOS velocity solution processed in double-difference mode. Zoom over Italy and southern France.

The coordinates/velocities of the EPN multi-year solution are regularly updated (each 15 weeks). The primary goal of this solution, specifically designed for geodesy and reference frame studies, is to provides a densification of ITRF over Europe and an access to European Terrestrial Reference Frame (ETRF/ETRS89).

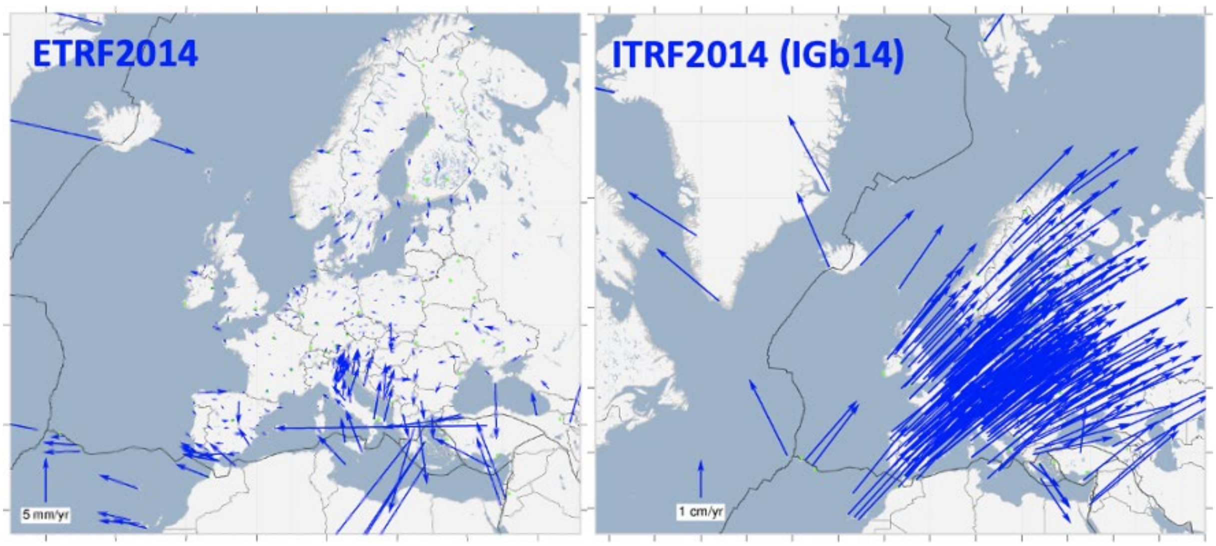

Figure 13. Horizontal velocity solution at stations from EUREF Permanent Network in the ETRF2014 and ITRF2014.

2.3.2.3 *EUREF-EPOS solution*

A densification product is also made available from the portal, resulting from the joint collaborative effort between EPOS and EUREF. The objective is to provide a densified velocity field, including also non-EPOS stations that are not yet providing their RINEX data to EPOS.

Daily solutions from the 2 EPOS Pan-European Analysis Centers and the 30 regional EUREF Analysis Centers are combined into a multi-year solution by the EUREF-EPOS combination center. The regional daily solutions are generated with either BERNESE, GAMIT/GLOBK or GIPSY software packages. Weekly combined position time series are generated using CATREF, velocities using CATREF, MIDAS and Hector software packages. Outliers are rejected by automated and visual inspection of time series, position and velocity discontinuities are estimated, velocities are filtered, and finally non-representative stations because of poor data quality or monumentation are removed from the distributed solutions.

This solution (cf. Figure 14) is meant to provide the end-user with a solution generated by experts in geodesy that includes as many GNSS sites as possible in Europe. Since the raw data and metadata are not yet available at all stations, some velocities might have to be taken with caution, but this densified product provides an integrated view of the secular velocity field in Europe.

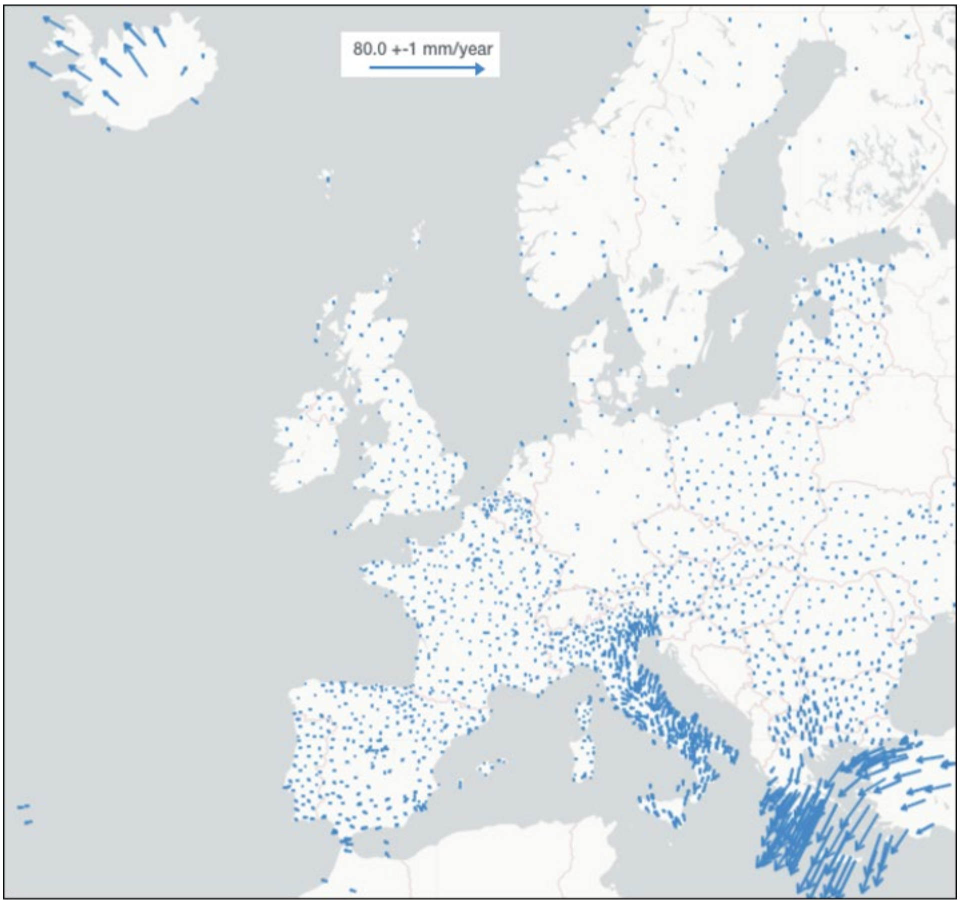

Figure 14. Secular velocity field with respect to stable Europe of the EUREF-EPOS densified product.

2.3.2.4 *Strain rate products*

A strain rate product generated at LM (Sweden) is made available using the EUREF-EPOS densified velocity field as input because it is the most complete in terms of spatial coverage. Strain rates are computed using the software StrainTool developed by Anastasiou et al. [2019a, 2019b] which is essentially a combination of the strain rate calculation software of Shen et al. [2015] and the plotting tool GMT [Wessel et al., 2013]. StrainTool is integrated in a local processing chain which can, if wished, automatically calculate strain rates for the whole of Europe and additionally for interesting areas with high geodynamic activity at a finer grid spacing. A quality check of the results is performed by visual inspection and comparison to previous strain rate results. If needed, the analysis is repeated after adjustment of input data and parameters to StrainTool. The files made available receive corresponding metadata: a DOI number is minted and a corresponding landing page is generated.

2.3.3 Access to GNSS products and metadata

The access to the GNSS products is centralized through a unique portal: https://gnssproducts.epos.ubi.pt/ (cf. Figure 15) which is maintained at UBI (Portugal).

The EPOS-GNSS Products Portal has similar features as the ones described for the Data Gateway (cf. section 2.2.2): the selection and filtering of stations can be done using geographical, organization (agencies, networks), analysis centers, or name criteria, for the different products provided.

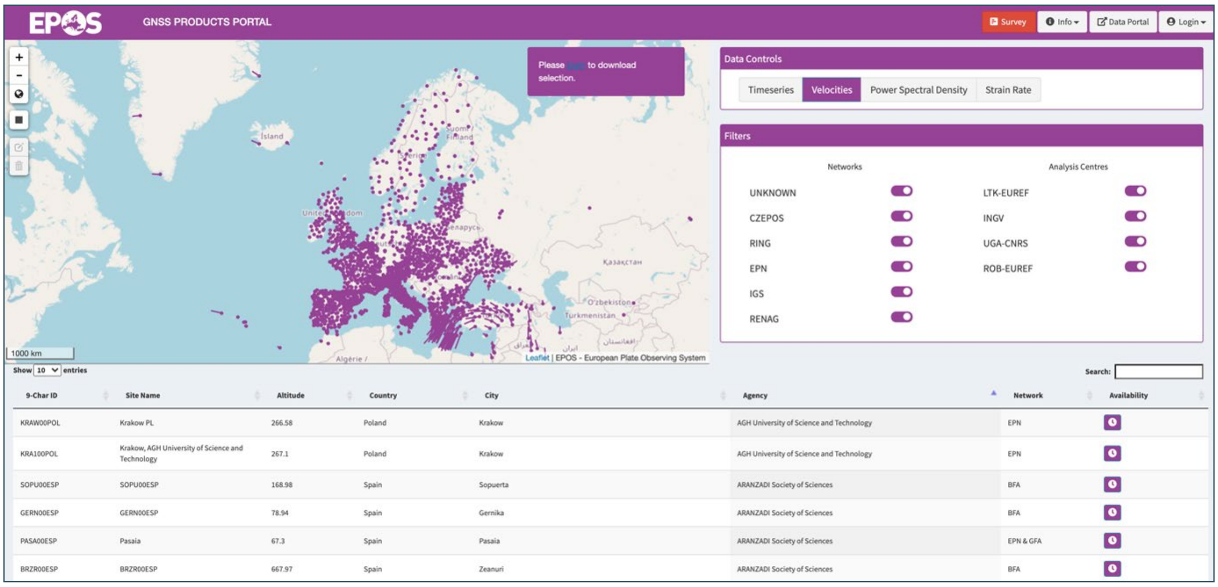

Figure 15. Web client of the EPOS-GNSS products portal.

The option of a unique portal is intended to facilitate access by the user and to compare and retrieve the different solutions that are made available by the EPOS-GNSS service providers. In fact, as explained in the previous sections, different solutions computed by different analysis centers are provided to the user, namely for time-series and velocities. In addition, power spectral density plots using the residuals (i.e., signal minus fitted model) for the East, North and Up components are also presented for the user to have an additional important measure of the quality of the estimated solutions. Figure 16 presents an example of the visualization of these different products in the EPOS-GNSS Product Portal that can be downloaded in a multitude of formats to be further processed by the user.

As explained before (cf. section 2.3.2), the different products are updated regularly. The Analysis Centers upload the solutions using the sftp protocol in a reserved area of the Products Portal server in order that the new solutions can be parsed and added to the related tables of the common EPOS-GNSS database that is shared by all the different nodes (see next section for more details). The security and compliance of the Portal to the European General Data Protection Regulation (GDPR) was analysed using the PADRES Tool [Pereira et al., 2022] developed within the scope of the TCS software development.

2.4 Software Provision

2.4.1 Description of the software

GLASS, a distributed software architecture to disseminate quality-controlled GNSS Data and Products, started to be developed during the EPOS Preparatory Phase. It has been developed by a joint effort of five European groups at UBI (Portugal), CNRS-OCA (France), INGV (Italy), GOP (Czech Republic), IMO (Island) and ROB (Belgium). The

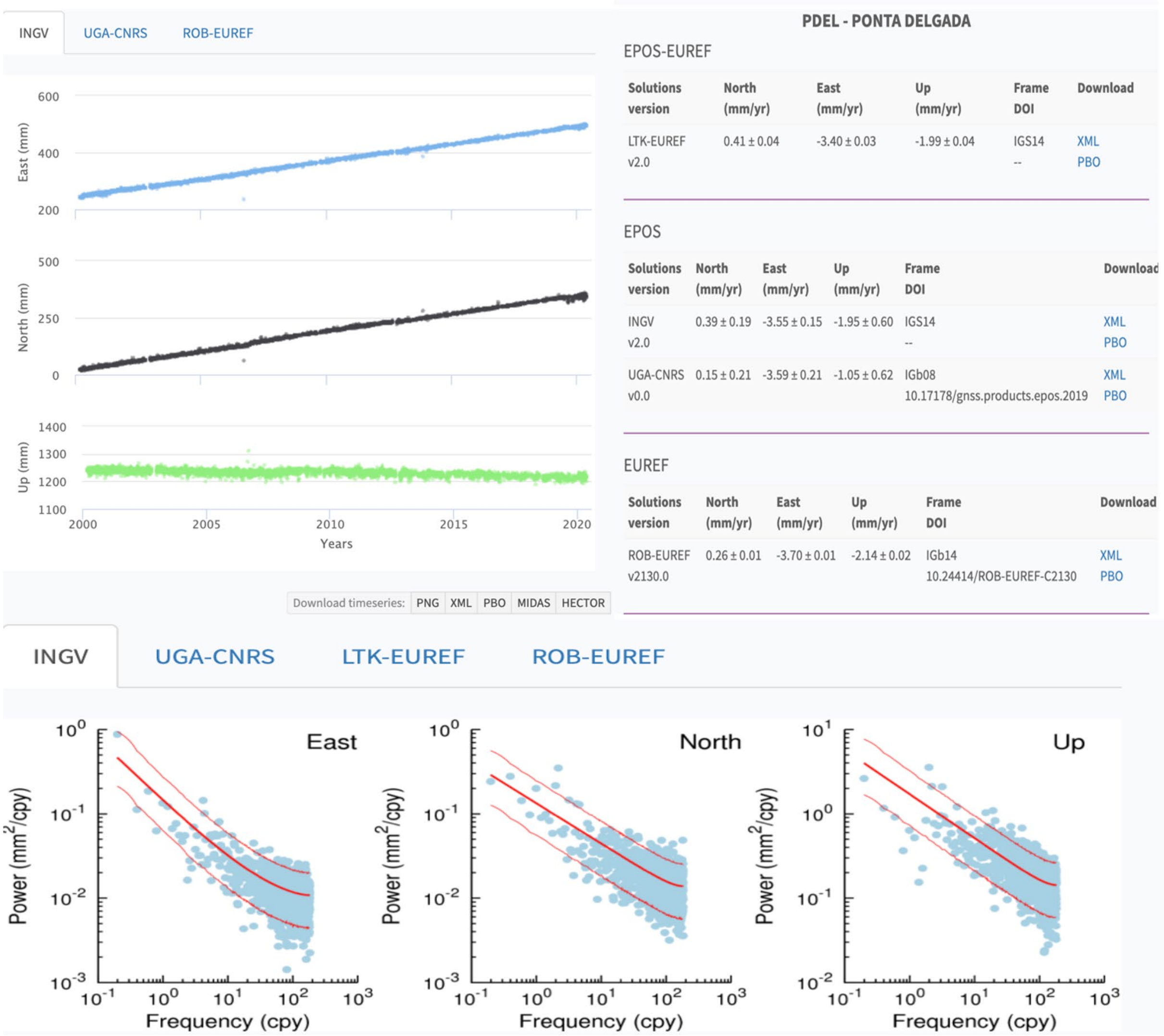

Figure 16. Example of the estimated time-series (upper left), velocity solutions (upper right), and associated power spectral density plots using the INGV solution for PDEL00PRT.

goal was to implement an integrated package to be installed at all levels of a single/multi-level GNSS infrastructure. This package is constituted by several components:

– A common database scheme (including metadata, data & products);
– Web Services for queries and data mining on the data and metadata;
– Quality Control tools;
– Submission and Validation of metadata;
– Tools to guarantee synchronization and consistency of the databases;
– Tools to guarantee redundancy and uniqueness of data and metadata.

GLASS follows a standard three-tier in which the functional logic, data access, data storage, and user interfaces are developed and maintained as independent modules on the same or separate platforms. Conceptually, all GLASS components can be installed in a single server, or, as it is the case of EPOS, in a distributed environment where there are several nodes (cf. Figure 7) managing separate repositories (that can be remotely accessible) with a particular node being the Data Gateway (and managing the stations metadata) and another the Products Portal.

Installed on each GLASS node, this software package is especially designed to collect and store GNSS metadata (station, file location and QC metadata) and to disseminate both the data and products, and associated metadata, to the users.

As shown in Figure 17, the GLASS package is composed of several independent software designed to handle each one of the tasks of the process. The metadata are stored in a PostgreSQL database, the data themselves staying in their “Data Repositories” (the logical entities where the RINEX files are uploaded and stored and that also enables their access via some file server protocol). Two webservices both provide a REST API to interact with the database: one for inserting called Flask Web Service Server (FWSS, in python and using the framework Flask) and one to query the metadata called EPOS GLASS Framework (in Java). A tool in python, monitor-dgw, was developed for managing the station metadata received from the M3G and to convert them to a JSON format understood by FWSS. The index-GD and RunQC tools (in python and perl) are used for extracting and generating File and Quality Control metadata and sending them to FWSS for insertion in the database. RunQC itself uses Anubis (https://gnutsoftware.com/software/anubis/) to analyze the RINEX file quality and to generate the RINEX File Quality Information metadata. As described in section 2.2.2, the metadata are synchronized between the nodes of the EPOS-GNSS Data Node Network which is done with the EPOS Synchronization System. An optional GUI is included to manage the metadata specific to each Data Nodes. Finally, in order to explore and download the data and their associated metadata, a web and a command line client, called GLASS web client and Pyglass, respectively, were developed for interacting with the EPOS GLASS Framework webservice. The GLASS Web client notably serves also as the GUI for the Data Gateway.

The access to the products is done through a particular GLASS node that interacts with the user through a GUI managed by another dedicated webservice (see section 2.3.3). This node stores station metadata and an extended version of the database to hold information on the derived GNSS products.

Problems related to the GLASS service orientated architecture built on web services are discussed further in Manteigueiro et al. [2020]. Here procedures and mechanisms for authentication and authorization are described, particularly how systems can aggregate user multiple identities.

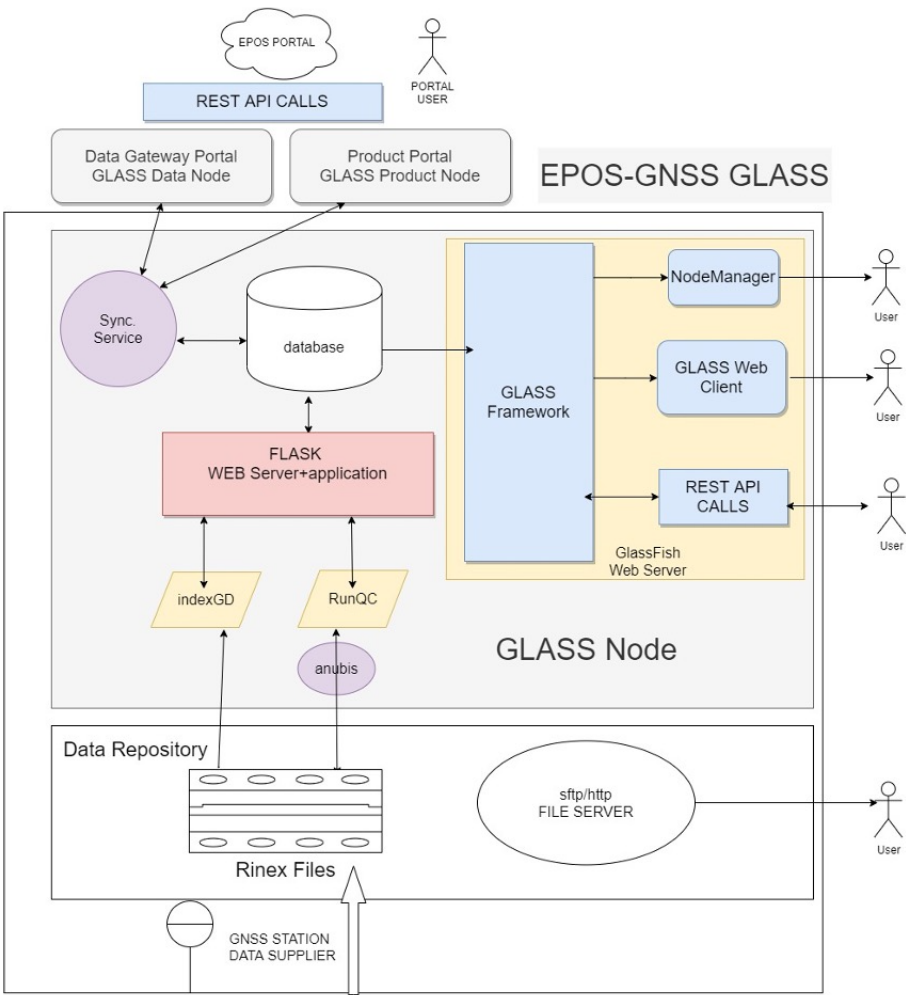

Figure 17. The main components of the EPOS-GNSS GLASS system.

2.4.2 GLASS status and future development

GLASS, although fully operational, is in constant development to add new features and correct bugs internally identified or reported by the users. To facilitate testing and development, a virtual machine image is available with all software installed and configured that can be downloaded at https://gitlab.com/gpseurope/, where all GLASS software is publicly available.

Currently, work is underway to seamlessly add hourly high-rate (1 Hz) RINEX data into the system. Tools for monitoring more closely the node network have been implemented and are currently under review. More data and metadata such as DOIs and Quality Control XML files provided by Anubis are also planned to be made available soon.

3. Examples (Use Cases)

3.1 Providing data

The minimal requirement for GNSS stations to provide data to EPOS is that:

– The GNSS station is presently active or, in case of a decommissioned station, can provide at least 3 years of daily RINEX data to EPOS.
– The GNSS station and its metadata are maintained according to EPOS guidelines (https://gnss-metadata.eu/guidelines).
– The daily RINEX data of the station are open and freely available.

In addition, agencies providing GNSS data to EPOS need to formalize this through the signature of the EPOS GNSS data supplier letter (template available from https://gnss-metadata.eu/Guidelines/EPOS-GNSS_Supplier_Letter.docx). By doing so, the data owner gives EPOS the permission to redistribute its data. After the signature of this letter, it is necessary to insert the station metadata in M^{3}G and select the data node through which the data will be made discoverable within EPOS.

More details on how to integrate a GNSS station in EPOS can be found in the detailed step-wise "Procedure for including GNSS stations in EPOS" available from https://gnss-metadata.eu/guidelines.

3.2 Data node hosting

In the EPOS-GNSS framework, we group together different types of local nodes (currently 10). Some are intended to become national nodes with the objective to gather the distribution of the different networks or providers on the territory, others, for large networks, are specific to a network. One of the nodes disseminates the EUREF GNSS data for which the authorization has been obtained. Another node, the pan-European node, proposes an associated data repository for those who would like to distribute their data but would not have the capacity to manage the archive and distribution part or who would not have the opportunity to group with other dissemination partners closer to them nationally or thematically. We expect the entry of few new data nodes in the node infrastructure, at least to cover the GNSS data distribution in some thematic areas developed in other EPOS TCS (e.g., Volcanology and Near Fault Observatory), and to hopefully cover the European territory more homogeneously.

Hosting an EPOS-GNSS node should not be undertaken without a clear idea of the constraints related to its installation and maintenance but would be worth to think about. That is why we describe the main lines here while the detailed guidelines to host a data node and to be a data node manager are provided in the "Guidelines for setting-up and operating an EPOS-GNSS data node" available from https://gnss-metadata.eu/guidelines.

Regarding the creation and installation of the node, the first thing to do is to contact the node infrastructure coordinator team at the Data Gateway (gnss-dgw@oca.fr), the software coordinator (software@gnss-epos.eu) and the M3G-team (m3g@oma.be) to announce the wish to install a node. A preliminary discussion will define whether the solution to host and manage a node is the most suitable. For example, below a certain number of stations to disseminate, it is more appropriate to either distribute the data through the community Pan-European node or to group them with other national institutes or thematic groups on a national or thematic node. It should also be ensured that the node does not already exist outside of EPOS and that it will only host EPOS data, else the designed system will fail.

Once decisions are made, the node and configuration letters can be sent to the node infrastructure coordinator, and software can be installed, either with a virtual machine with all the necessary software or directly on a server. The node should access the data repository to be able to generate the file and quality control metadata. It is also necessary to check that the server on which the data is located can run the python and perl software necessary to generate the metadata, and that the web service dedicated to insert the metadata into the database is accessible from this server. The database itself must be accessible from and to the Data Gateway. The metadata consultation web service must be accessible at least from the M3G and the Data Gateway.

As far as the maintenance of the node is concerned, the manager must update the software, monitor the availability of the node, and make sure that the database is fed with metadata and synchronized with the data gateway.

3.3 Providing products

Additional Regional Analysis Centers are welcome to provide daily position solutions to be included in the EUREF-EPOS densification products especially if those solutions include stations located in areas that are currently not well covered by EPOS.

3.4 Analyse EPOS-GNSS products

3.4.1 Use Case 1: Secular displacements and strain rate maps of Spain

To study the active tectonics of a given area, it is useful to get information about the present-day displacements and deformation rates. In such case, the secular velocities rotated with respect to stable Europe can be used, as well as the strain rate grids. We recommend to use the EUREF-EPOS densification product, as it is the one providing the largest density of velocities. But in areas that are well covered by EPOS stations, velocities from EPOS products can also be informative as they are self-consistent solution allowing for the characterization of slow deformation rates.

Figure 18 presents the example of the Iberian Peninsula where a small but significant westward movement is visible with respect to stable Europe. The largest strain is mostly concentrated in the Betic Cordillera in Southern Spain and south of Portugal, where a westward movement of ~3-4 mm/year with respect to stable Europe generates a right-lateral strike slip deformation and the clockwise rotation of mainland Spain associated with the extension of the Alboran domain as a response to the subduction rollback [Borque et al., 2019; Echeverria et al., 2013; Koulali et al., 2011; Vernant et al., 2010].

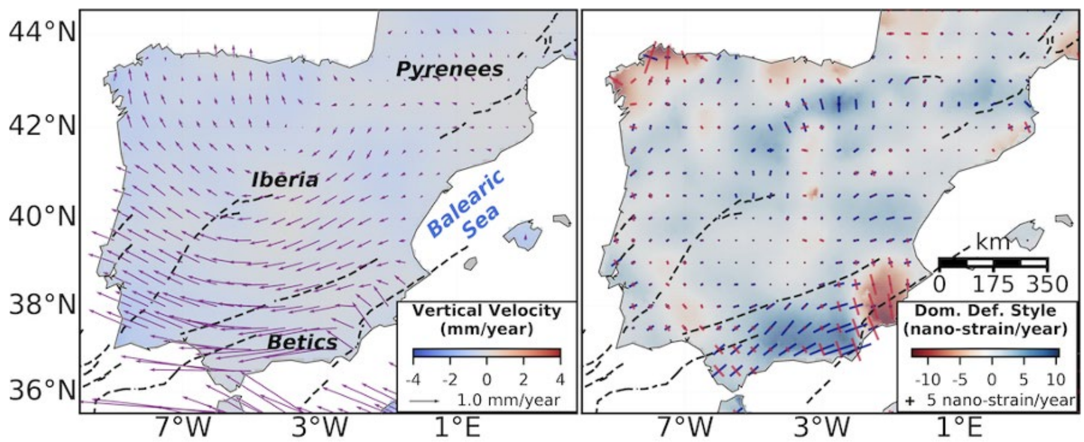

Figure 18. Interpolated horizontal and vertical velocity fields with respect to stable Europe (left) and associated strain rate map and deformation style (right) in Spain (from Piña Valdes et al., subm). Dashed lines represent the main tectonic structures.

3.4.2 Use Case 2: Position time-series in volcanic unrest area

In case of a volcanic unrest in Europe, volcanologists will be interested to follow the position changes of GNSS stations located close to the volcanic activity to monitor its spatial and temporal evolution. In such case, rapid solution of EPOS products can be used since the solution in double difference is updated automatically 2 days after the data acquisition. To analyse the evolution of the deformation that preceded the volcanic unrest, time series from other analysis centers can also be used. Additionally, velocity and strain rate products can provide a view of the background deformation in the volcanic area.

Figure 19 shows the example of the deformation observed at the Mount Etna volcano. The comparison between observed and modelled GPS velocity fields shows different phases of inflation (Figure 19a and Figure 19c) and de- flation (Figure 19b) occurred before and after an eruption onset at Mount Etna (Italy) in 2013 [modified from Bruno et al., 2016].

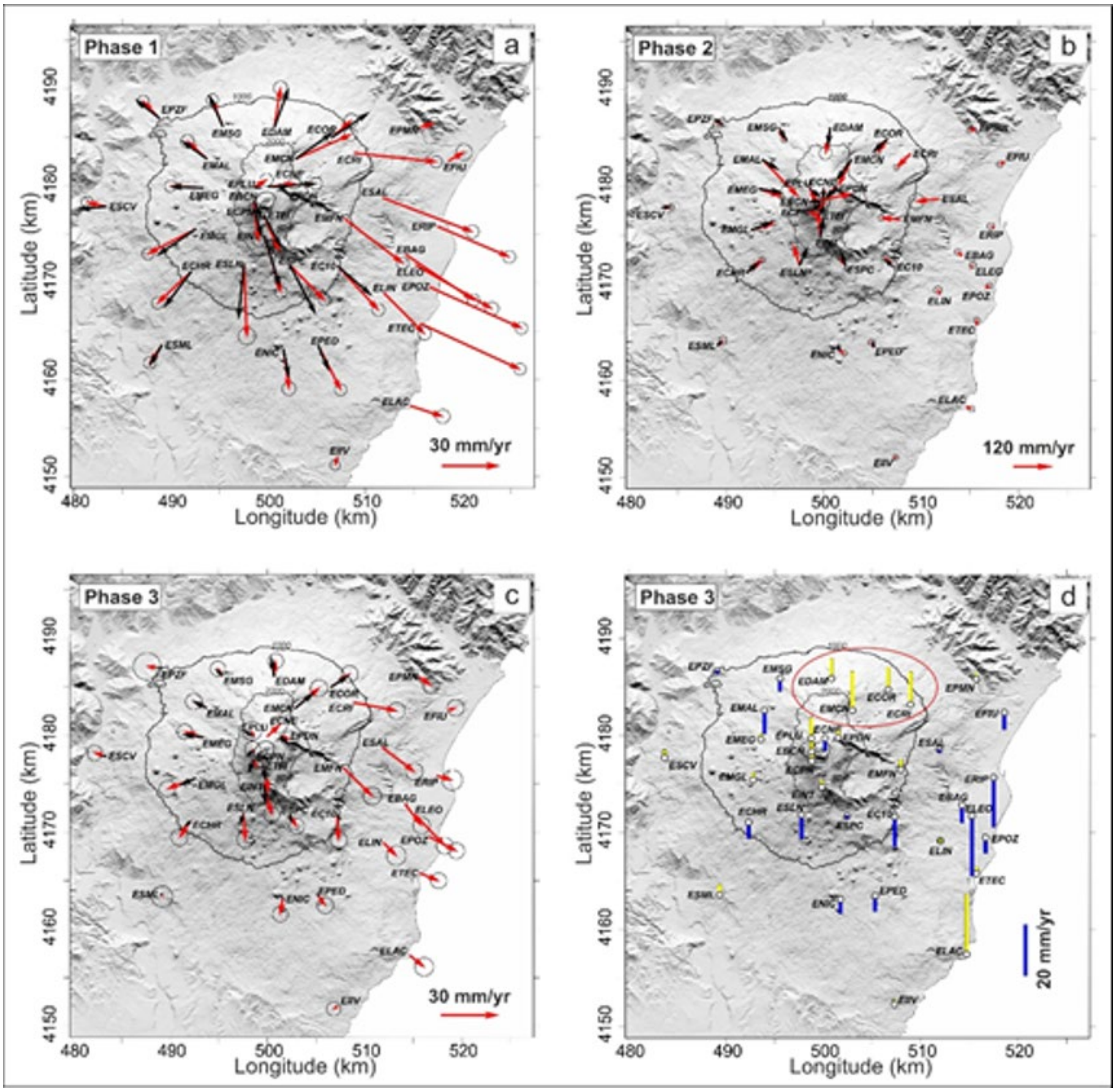

Figure 19. Recorded (red and grey arrows) and modelled (black arrows) horizontal CGPS velocity fields for the phases: (a) 26 April 2012-14 February 2013, (b) 15 February 2013-30 April 2013, (c) 20 May 2013-25 October 2013. Grey arrows were not considered in the modelling. (d) Vertical velocities (yellow rectangles for positive values and blue ones for negative values) for the third phase (20 May 2013-25 October 2013). The red circle highlights the CORS stations in the NE sector of Mt. Etna that show the anomalous ground deformation pattern.

A more recent example is the eruption initiated in September of 2021 of the Cumbre Viejo volcano in La Palma, Canary Islands. Figure 20 shows the time-series of the coordinates in the three components (North, East, and Up) where the transient deformation associated to this eruption, from late September, is clearly visible. One of the goals of the EPOS-GNSS is to start to present solutions for stations being affected for events like the Cumbre Viejo eruption with the minimal possible delay (few days).

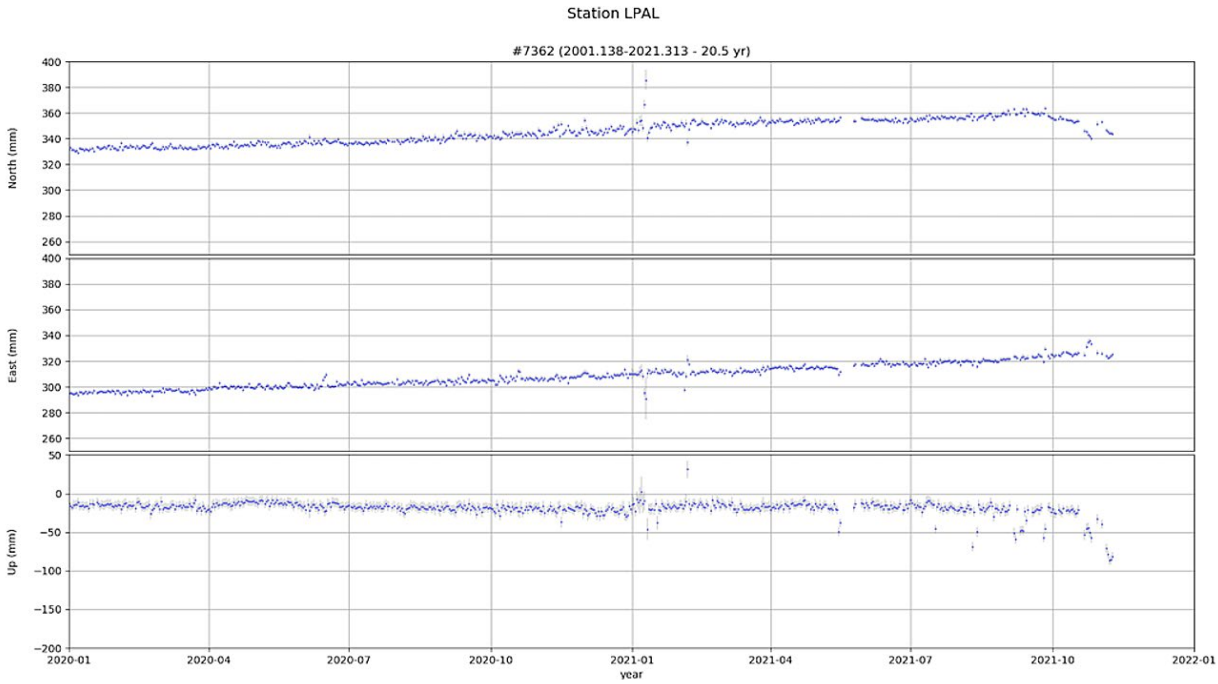

Figure 20. Time-series of the positions for the LPAL station since January 2020.

3.4.3 Use Case 3: 2016 earthquake sequence in Italy

If a seismologist wants to analyze a past seismic crisis in Europe, the daily position time series can provide information about the ground displacements at GNSS stations located close to the earthquakes. Time series from the EPOS solutions can be used to extract the static displacement associated with the mainshocks, the post-seismic deformation that follows them, and pre-seismic transients if any. Additionally, velocity and strain rate products can provide a view of the background deformation in the seismically active area.

Figure 21 presents the seismic sequence that struck Central Italy in 2016. The Amatrice earthquake (Mw 6.0) initiated the sequence on August 24th, 2016. It was then followed by a M $_w$6.5 earthquake near Norcia on October 10th, 2016 and then by the M $_w$5.5 Campotosto on January 18th, 2017.. The time series for the different stations show clear static offsets associated with each one of these three main earthquakes. The amplitude of the offset varies from one station to the other, depending on the distance to the epicenter. Transient deformation following a characteristic logarithmic evolution follows the earthquakes and indicates that post-seismic relaxation took place in the months following the earthquakes.

3.4.4 Use Case 4: Constraining models of glacial isostatic adjustment

Geodynamicists can use EPOS-GNSS products to constrain their models dealing with tectonic plate dynamics, post-glacial or erosional isostatic rebound, gravitational potential energy, slab detachment, dynamic topography or any other relevant processes covered by our data. In such case, the recommended products are the velocities from EUREF-EPOS because they offer the better spatial density. Additional velocities, time series and strain rates products available from the portal can also be used depending on the needs.

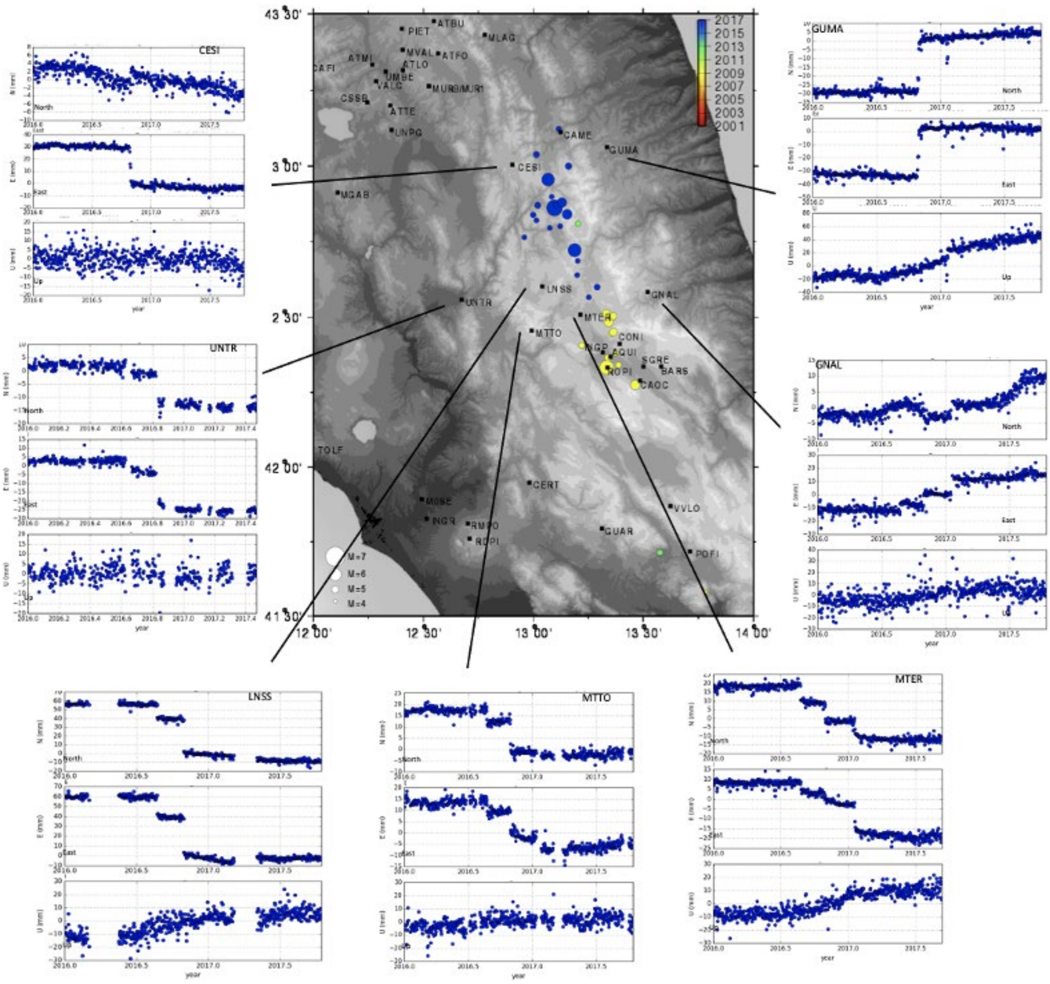

Figure 21. Map of the seismicity color-coded by time of occurrence, surrounded by position times series of GNSS stations showing the displacements associated with the 2016 central Italy earthquake sequence. The locations of GNSS stations are shown by black squares.

Figure 22 shows the glacial isostatic adjustment signal in Fennoscandia where a strong vertical uplift that locally exceeds 10 mm/year, centered on the north-eastern Swedish coast, is associated with a divergent horizontal velocity field that generates a NW-SE extension [Johansson et al., 2002; Nocquet et al., 2005; Lidberg et al., 2007; Kierulf et al., 2021]. The vertical velocities from the EUREF-EPOS solution agree, at first order, very well with land uplift model of Vestøl et al. [2019]. In the southernmost latitudes the model could be refined with second order features to fit the pattern of the vertical displacement rates.

4. Conclusions

4.1 Outlook

It has been a long journey since the EPOS-GNSS community has initiated its activities with the main goal of offering centralised and open access to GNSS data and products for Solid Earth research. Today, an established group of data providers and service providers enable access to quality-controlled GNSS data and products that are serving not only EPOS researchers, but also other communities that use these GNSS data and derived products for technical and scientific applications.

EPOS-GNSS has achieved several important milestones:

a) Establishment of the governance framework with the aim that the entire community, from data providers to end-users, will be represented and their efforts recognized.

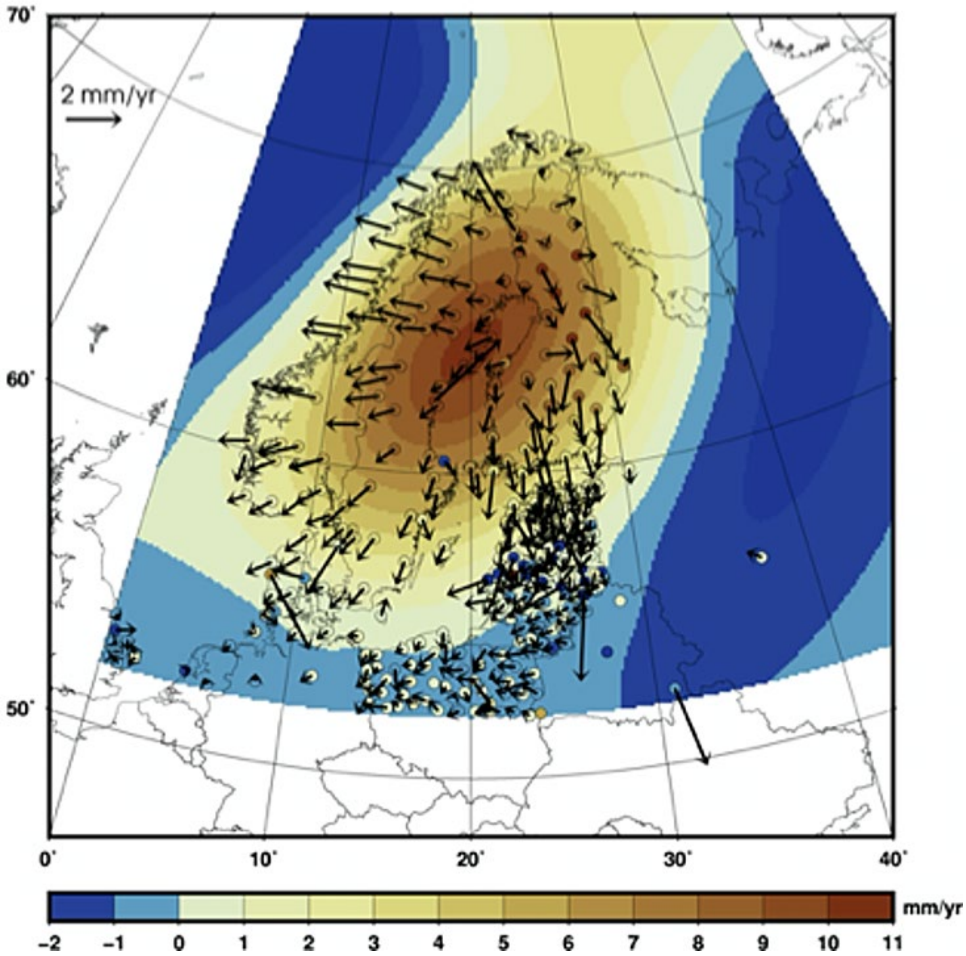

Figure 22. Horizontal & Vertical velocities of EUREF-EPOS solution compared to model of Glacial Isostatic Adjustment NGK2016LU [Vestøl et al. 2019].

b) GLASS development – a new complete software package for the dissemination of GNSS data & products guaranteed with several quality control checks.
c) Products dissemination – internally consistent GNSS solutions associated with the dedicated products (time-series, velocities, and strain-rates) created from a big data set using state-of-art methodologies.

4.2 Next steps

EPOS GNSS will continue to pursue important goals to serve the scientific community in the coming years, particularly:

a) Data Availability – extend the GNSS data distributed through EPOS with additional GNSS stations. Because it should improve their visibility, as well as the perennity and quality of their data and products, Data Providers are encouraged to make their data and metadata available through EPOS.
b) Migration to new GNSS data formats such as RINEX v3.x and RINEX v4.x – GLASS is already able to handle RINEX v3.x and long names but most of the historical data are still only available in RINEX v2.x with short names (which creates additional difficulties in international repositories like the ones made available by EPOS since the duplication of the same code in different countries is more probable). EPOS GNSS is encouraging the data providers to deliver data in RINEX v3.x only and plans to start disseminating RINEX v4.x as soon as a significant number of stations are providing the data in this new format.
c) Dissemination of high-rate data – several related Solid Earth studies (e.g., GNSS-Seismology; Volcanology) demand the access to higher rates than currently provided. This also implies to make available hourly files instead of daily files as is currently, which will also improve the latency how the files are made available.

d) Reduction of the product latency – as discussed, an important effort by the EPOS-GNSS community is to make regular the release of new solutions for the products but such objective has been limited by the EPOS financial constraints that impedes the operationalization as desired of all planned services.
e) Reaction to events – this goal is correlated with the previous one: to be capable to provide timely solutions that can contribute for a better understanding of Solid Earth phenomena. The example described in section 3.4.2 for the recent eruption in La Palma (Canary Islands) is indicative of the potential contributions and the current limitations that exist.
f) Development of GLASS 2.0 – the experience gained by the installation and usage of early GLASS versions has revealed several aspects that need to be improved, in particular to guarantee that all nodes are regularly updated with the latest versions of the applications that are used by GLASS (e.g., python, Anubis).
g) Respect FAIR data principles – Collection of Digital Object Identifiers (DOI) for the GNSS data sets to better align the data with the FAIR (Findability, Accessibility, Interoperability, and Reuse) of digital asset principles.

However, even with all these challenges ahead, EPOS-GNSS can be considered today as the first European attempt to coordinate the activities of the very large scientific GNSS community with a focus on seeking to provide the community with tools to monitor and better understand Solid Earth. This effort benefits also other geodetic communities, namely EUREF and many national agencies, which are essential partners to pursue the EPOS-GNSS goals.

Acknowledgments. This effort to implement the GNSS-EPOS services and products is only possible due to many individual contributions from the members of the External Advisory Committees, the responsible persons for the daily operation of the GNSS stations, IT experts, etc… In the impossibility to include all as co-authors, their names and affiliations are permanently listed at https://gnss-epos.eu/collaborators.html. To them, our sincere appreciation.
The UGA-CNRS solution was performed using the GRICAD infrastructure (https://gricad.univ-grenoble-alpes.fr), which is partly supported by the Equip@Meso project (reference ANR-10-EQPX-29-01) of the programme Investissements d'Avenir supervised by the Agence Nationale pour la Recherche, and the CIMENT infrastructure (https://ciment.ujf-grenoble.fr), which is supported by the Rhône-Alpes region (GRANT CPER07_13 CIRA: http://www.ci-ra.org) and France-Grille (http://www.france-grilles.fr). The UGA-CNRS processing center has been supported by a grant from Labex OSUG@2020 (Investissements d'avenir – ANR10 LABX56).
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