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# GNSS Calibration Report

## EGMS SERVICE DOCUMENTATION



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# Introduction

## Scope & Document Organization

This document outlines the development and implementation of the gridded Global Navigation Satellite System (GNSS) velocity model for the European Ground Motion Service (EGMS). It provides a comprehensive overview of the estimation methodologies used, the modeling results obtained, and the associated uncertainties.

Document Structure:

- Section 1: Summarizes the approach for calibrating EGMS products with the GNSS velocity model.
- Section 2: Describes the methodologies employed for the estimation of the gridded GNSS velocity model, including quality assessments.
- Section 3: Provides an overview of the key features, including input data, methodology, and quality control, of the generated EGMS GNSS models.
- Appendix: Presents performance and regional analysis examples of EGMS GNSS models.

The specifications and format of the gridded model product are detailed in Reference Document [RD4], aligning with the project's technical and operational requirements.

## Reference Documents

ID	Reference or Related Document	Date	ID	Source or Link/Location
RD1.	Algorithm Theoretical Basis	25/10/2023	EGMS-D3-ALG-SC1-2.0-006	EGMS Original Consortium
RD2.	Product User Manual	17/05/2022	EGMS-D4-PUM-SC1-2.0-007	EGMS Original Consortium
RD3.	End User Interface Manual	16/11/2023	EGMS-D5-UIM-SC2-061	EGMS Original Consortium
RD4.	Product Description and Format Specification	25/10/2023	EGMS-D6-PDD-SC1-2.0-009	EGMS Original Consortium
RD5.	Quality assurance and control report – Harmonization Test	22/10/2021	EGMS-D10.1-QCR-SC1-3.0-012	EGMS Original Consortium
RD6.	Quality assurance and control report	02/11/2023	EGMS-D10.7-QCR-SC2-078	EGMS Original Consortium

**Table 1 Reference Documents**



# 1. GNSS and EGMS: A holistic approach

The EGMS is engineered to deliver deformation monitoring products within a rigorously defined and accurate geodetic framework. Utilizing the synergistic capabilities of InSAR and GNSS, EGMS provides high-resolution local measurements across a broad spatial scale.

This integration is crucial for producing accurate deformation measurements throughout Europe, addressing the limitations posed by the sparse distribution of GNSS permanent stations, which are typically located 50-60 kilometres apart. InSAR offers detailed, local-scale measurements (up to tens of kilometres) that are relative to specific spatial references, while GNSS provides absolute spatial data over larger extents. The strategic combination of these technologies significantly enhances EGMS's ability to deliver precise ground deformation products across a wide geographic scale.

This section explains the technical reasons for employing a gridded GNSS model to calibrate InSAR data, discusses the selection of the reference frame, and describes the spatiotemporal characteristics essential to the EGMS product portfolio. This ensures the service's ability to meet the varied demands of geospatial analysis across Europe.

## 1.1. Rationale for Implementing a Gridded GNSS model

To establish a robust, pan-European calibration reference for InSAR data, rigorous preprocessing of GNSS station data is imperative. Singular GNSS stations exhibit properties critical to this effort:

- They are susceptible to local motion influences, which are better captured through dense InSAR measurements.
- Large-scale motions (>50 km) are anticipated to maintain consistent velocities over extended durations.
- Temporal gaps in the observational records of many GNSS stations pose challenges for achieving complete coverage within EGMS product timelines.

Hence, adopting a gridded approach is essential for extracting spatially consistent velocities at scales exceeding 50 km.

A gridded GNSS model allows for the integration of data from multiple stations within discrete spatial cells or grid points. This enables the interpolation and extrapolation of velocity information across broader geographic areas. By leveraging a gridded GNSS model, the calibration process becomes more robust, providing enhanced accuracy and reliability for pan-European InSAR applications.

## 1.2. EGMS reference frame

A well-defined GNSS velocity solution serves as the standardized reference frame for converting EGMS Basic products into Calibrated/Ortho products [RD1,RD4]. The service requires a homogeneous, high-quality reference solution covering the entire European continent in terms of velocities and time series availability. This reference frame must fully align with the geodetic framework endorsed by EUREF<sup>1</sup>.

Currently, EGMS operates using the ETRF2000 reference frame, a realization of the European Terrestrial Reference System 1989 (ETRS89). Within this context, ETRF2000 is considered more robust than ETRF2014 due to its improved alignment with European tectonic realities,

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<sup>1</sup> <http://www.euref.eu/>



minimizing discrepancies and ensuring greater regional consistency, [Bruyninx et al. 2012]. The comparison here is specific to ETRF realizations and does not directly compare ETRF with ITRF, as these systems serve regional and global scopes, respectively. The new ETRF2020, derived from ITRF2020, is anticipated to offer even more precise and stable reference coordinates.

ETRS89, specifically designed for Europe, is linked to the International Terrestrial Reference Frame (ITRF), ensuring coordinate and velocity stability across stable European regions by aligning with the motion of the Eurasian (EURA) continental plate, [Altamimi et al. 2011]. The ITRF, maintained by the International Earth Rotation and Reference Systems Service (IERS), provides the foundational geodetic standard to which regional systems like ETRS89 are tied; for more information visit: <https://www.iers.org/IERS/EN/DataProducts/ITRS/ITRS.html>.

In tectonically active regions like the Mediterranean, complex geological processes such as subduction, continental collision, and strike-slip faulting cause significant crustal deformations. These movements, including the horizontal shifts along fault lines, must be precisely accounted for in geodetic measurements. Additionally, the Fennoscandian uplift, driven by post-glacial rebound, results in vertical land movements as the Earth's crust rebounds from the weight of melted ice sheets. While this uplift affects vertical positioning, it does not significantly impact the horizontal stability of the ETRS89 reference frame, [Johansson et al. 2002].

### 1.2.1. Reference frame evolution

To address these complexities, EGMS is preparing to transition from ETRF2000 to a new realization based on ITRF2020, the latest global geodetic standard. This upgrade is highly anticipated within the GNSS community due to the enhanced accuracy and stability it offers [IGN ITRF2020]. ITRF2020 integrates extensive and long-term data series from multiple geodetic techniques (VLBI, SLR, GNSS, DORIS), providing higher precision in station positions and velocities. This comprehensive integration allows for better modelling of geophysical processes, crucial for applications such as satellite altimetry, precise orbit determination, and regional sea level change estimates. [Altamimi et al. 2016].

However, the implementation of ITRF2020, initially planned for 2022, is facing delays due to the operational readiness of national GNSS authorities. Despite these challenges, EGMS does not view the adoption of ITRF2020 as critical. The minimal adjustments typically required with successive global reference frame updates ensure that operations will continue smoothly, maintaining the high precision necessary for monitoring ground motions and other geodetic applications, see [Delva et al. 2022] and references therein.

## 1.3. Spatiotemporal Referencing of EGMS Products

EGMS products follow spatiotemporal referencing guidelines outlined below. More details can be found in [RD1].

### EGMS Basic

- *Temporally:* Aligned with a temporal model evaluated at the earliest available acquisition time in each time series.
- *Spatially:* Processed relative to a local reference point within each production unit, subsequently realigned (i.e., re-referenced) by subtracting a statistical measure representing the average of all time series within the production unit, thereby mitigating reference point noise.



### EGMS Calibrated

- *Temporally:* Aligned with a temporal model evaluated at the earliest available acquisition time in each time series.
- *Spatially:* The average velocity component [mm/yr] of Basic products on long spatial scales (50+ km) are referenced to the ETRF2000, utilizing the A-EPND grid (refer to Section 2.1.1).

### EGMS Ortho

- *Temporally:* Fixed to a specific date.
  - Extrapolated (if necessary) to temporally align time series from ascending and descending tracks, employing the average velocity of each time series.
  - Interpolated to achieve a uniform temporal sampling, excluding long data gaps and, where applicable, the snow-covered season.
- *Spatially:* Directly derived from Calibrated products, hence referenced to ETRF2000.

## 1.4. Generation and Validation of Calibrated and Ortho Products

### Product Generation

Calibrated products are referenced to the ETRF2000 frame by calibrating the long-wavelength (50+ km) velocity components in the Basic product, utilizing the GNSS model (see Section 2). Ortho products are subsequently derived from Calibrated products. The model estimation process, detailed in Section 2.4, includes estimating the uncertainty of velocity vectors at each grid point, which is vital for generating EGMS Calibrated and Ortho products. More information on the calibration algorithm is available in [RD1].

### External validation

The external validation<sup>2</sup> of Calibrated and Ortho products involves using a discrete number of pre-selected GNSS stations. The rationale behind this lies in the quasi-independence of the non-linear aspect of time series information from individual GNSS stations and corresponding InSAR products. This independence is maintained due to the application of a gridded linear model (refer to Section 1.1), where no single GNSS station directly influences EGMS product generation, and non-linear GNSS components are disregarded. As a result, stations employed for quality control of products do not require exclusion from the gridded model generation. This approach is particularly relevant for regions with a limited number of high-quality GNSS stations, like Germany, where exclusion of any stations from model generation would compromise the accuracy of the results.

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<sup>2</sup><https://land.copernicus.eu/en/technical-library/validation-methodologies-and-procedures/@@download/file>



## 2. The EGMS GNSS model - A-EPND

### 2.1. Input data

EGMS utilizes two primary GNSS solutions along with a supplementary source on a European scale:

- **Main Source:** EPND Stations (Section 2.1.1)
  - EUREF Permanent Network Densification Product Portal [<https://epnd.sgo-penc.hu>]
- **Secondary source:** NGL stations (Section **Error! Reference source not found.**)
  - Nevada Geodetic Laboratory [<http://geodesy.unr.edu>]
- **Supplementary source:** EUDV stations (Section 2.1.3)
  - EUREF WG on European Dense Velocities [[http://pnac.swisstopo.admin.ch/divers/dens\\_vel/](http://pnac.swisstopo.admin.ch/divers/dens_vel/)]
  - Provides velocities only
  - Primarily used for Switzerland (outside EGMS area of interest, but essential to avoid border effects)

#### 2.1.1. EPN Densification program (EPND)

The EPN Densification Program (EPND) by EUREF integrates national GNSS network solutions according to EUREF standards. It involves 28 Analysis Centers (ACs) mostly using Bernese software v5.2 (<http://www.bernese.unibe.ch>). All European countries contribute, except Germany, Switzerland, and Croatia.

Integration occurs at the product level, with ACs delivering processing results in SINEX format with full variance-covariance information. After quality control, integration employs CATREF software, also used for ITRF solutions. EPND solutions undergo annual updates. The current station count exceeds 3,500 but is filtered down to approximately 2,500 due to short observation periods and/or apparent velocity bias.

With improvements to the filtering approach, the station count could surpass 4,000. However, further growth is constrained by practical and operational national needs. Additionally, the meteorological community, particularly the EUMETNET GNSS Water Vapour Programme (E-GVAP), serves as a long-term GNSS input data source with different standards and requirements.

Further details on EPND are available at <https://epnd.sgo-penc.hu>.

#### 2.1.2. Nevada Geodetic Laboratory (NGL)

To enhance the sampling and coverage of the A-EPND model, EPND data is augmented with velocity and time series information from the Nevada Geodetic Laboratory (NGL, <http://geodesy.unr.edu/>). NGL employs the GIPSY-X software and Precise Point Positioning (PPP) approach to routinely process and analyse over 17,000 stations worldwide daily. However, the provided solution lacks robust quality control, and many NGL stations have short observation time series.

While the NGL solution includes over 4,800 stations in Europe, inconsistencies in time series length and station solution quality are observed, with significant overlap with the EPND dataset.

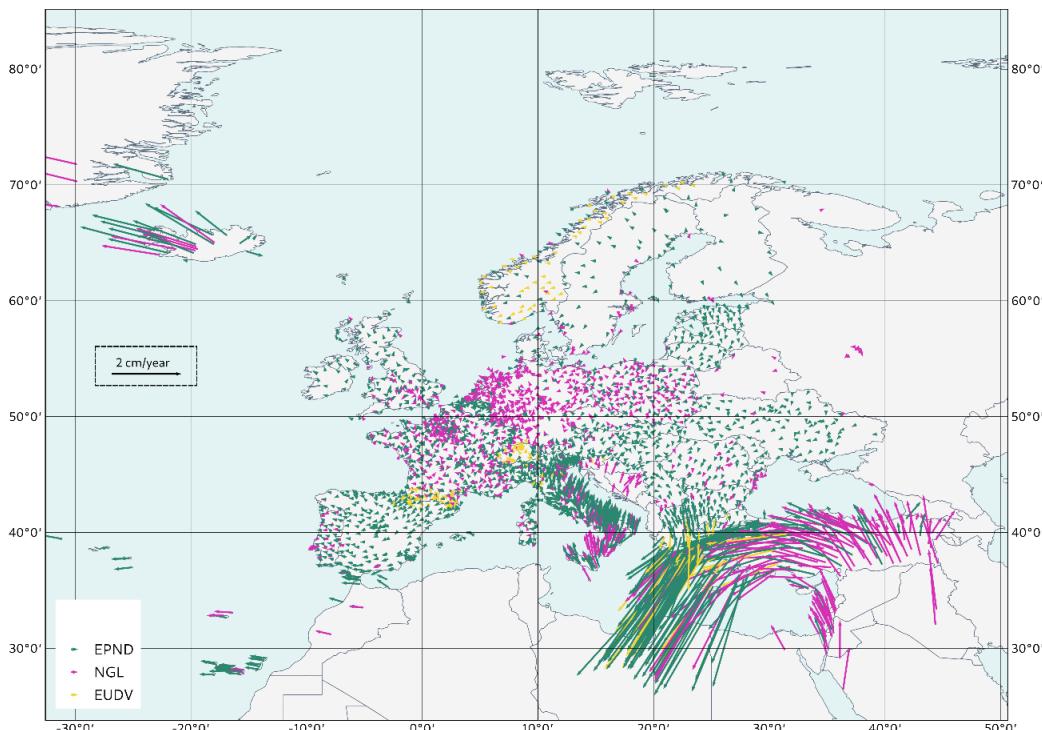
Therefore, NGL data integration into the A-EPND model necessitates rigorous quality control procedures.

### 2.1.3. European Dense Velocities (EUDV)

EUREF's Working Group on European Dense Velocities (EUDV<sup>3</sup>) serves as an additional data source, supplementing areas with limited coverage in the EPND and NGL datasets. EUDV collects velocity solutions across Europe for statistical analysis, incorporating data from EPND and NGL. However, it does not perform homogenization and lacks time series information. While not a comprehensive solution, EUDV provides valuable supplementary data for generating the A-EPND grid, particularly in regions with sparse GNSS information, such as Switzerland, aiding in the mitigation of border effects.

### 2.1.4. Summary

The spatial coverages of the datasets visualized in Figure 1 illustrate their complementarity. For the A-EPND grid generation, EPND is the primary input. NGL data supplement the coverage over Germany and Bosnia, while EUDV contributes to areas such as Switzerland. Stations not already included in the EPND dataset are considered when incorporating NGL and EUDV data into the A-EPND solution.



**Figure 1 Distribution of the EPND, NGL and EUDV stations, showing horizontal velocities.**

<sup>3</sup> [http://pnac.swisstopo.admin.ch/divers/dens\\_vel/](http://pnac.swisstopo.admin.ch/divers/dens_vel/)



## 2.2. Merged GNSS database

To ensure adequate spatial coverage and product quality for the EGMS, various GNSS resources are utilized. The primary dataset, EPND, forms the foundation, supplemented by NGL velocity solutions and time series, converted to the ETRF2000 reference frame.

The pre-filtering protocol involves several steps:

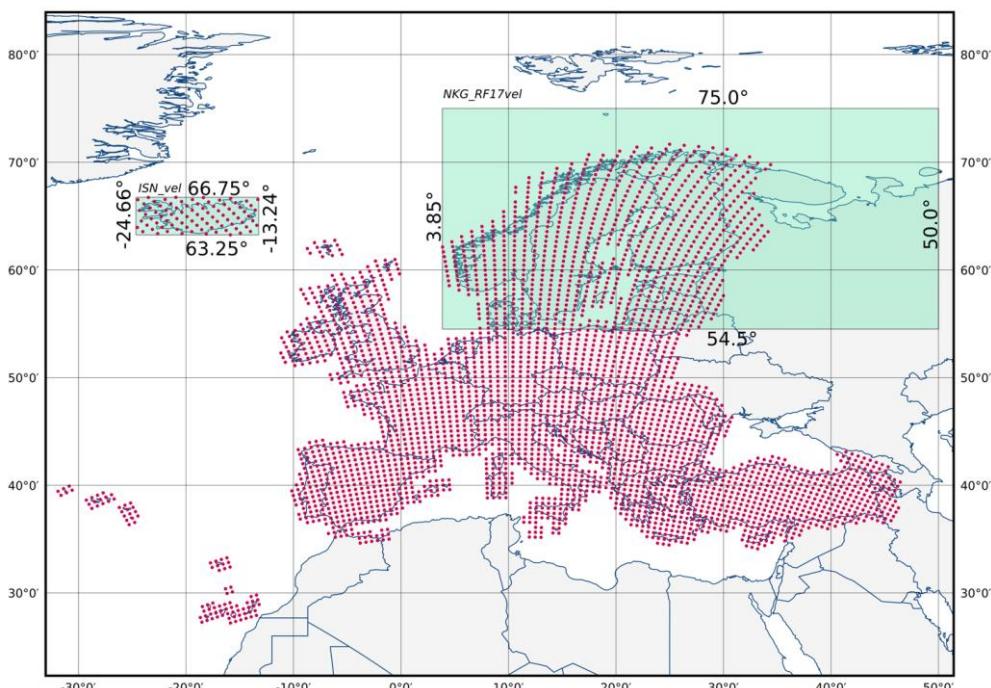
- **Step 0:** Initial data harmonization, removing outliers and low-quality periods.
- **Step 1:** Selection of applicable stations based on the following criteria:
  - Minimum<sup>4</sup> three years of time series within the EGMS production cycle interval.
  - Velocity filtering using Robust Mahalanobis Distance (RMD) for unsupervised classification, detailed in [Magyar et al. 2022], and summarized at <https://epnd.sgo-penc.hu/veloci-raptor/>:
    - Non-representative velocities (mainly due to local effects) are removed.
    - Multivariate statistical analysis & unsupervised classification.
    - No artifacts in the time series (e.g., offsets due to instrument change or obvious local motion).
    - Stations with significant non-linearities removed, but seasonality accepted.
  - Removal of non-representative velocities and stations with significant non-linearities.
- **Step 2:** Supervised quality control through visual inspection, enhancing decisions of the Machine Learning algorithm if necessary.

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<sup>4</sup> A small number of stations with shorter time series than 3 years have been included after manual quality control.

## 2.3. A-EPND grid specifications

The projection used in the EGMS is the Lambert Azimuthal Equal Area European grid (LAEA, EPSG:3035). The final GNSS model is calculated at about 3,800 points in a regular 50x50 km grid, covering the whole EEA39 region. Figure 2 shows the valid grid points of the A-EPND model.



**Figure 2** The valid grid points of the A-EPND model. The two green boxes show the extent of two existing models used for trend remove-restore in the A-EPND estimation, see Section 2.4.1.

## 2.4. Model Estimation

Using the merged database described in Section 2.2 as input, the following procedure is used to generate a GNSS velocity model on a regular grid covering the area described in Section 2.3. The estimation builds on Least-Squares Collocation (LSC), a concept pioneered by [Moritz 1973]. The methodology has been successfully applied earlier to derive velocity models on a regional level, e.g., Switzerland [Egli et al 2007], the Alps [Sanchez et al 2018], and even on a pan-European scale [Steffen et al 2019].

LSC can be applied to arbitrary data, as a purely analytical approximation method [Graffarend, 1976]. For doing so, it is necessary to properly define and select several parameters and to introduce appropriate extensions. In the case of the A-EPND model estimation, some adaptations of the input signals are necessary in order to apply basic LSC methodology.

The A-EPND solution is estimated as follows, using the merged database (see Section 2.1 and 2.2) as input.

### 1. Trend remove:

- Transform GNSS observations from ITRS to ETRF2000. This removes the main horizontal trend, caused by the Eurasian plate motion, see Section 0.
- Remove other known systematic trends using models (Fennoscandia, Iceland)
- Model and remove effects of active tectonic plates (Aegean/Anatolian region)
- Mean reduction of residual Up component

## 2. Least Squares Collocation (LSC):

- a. Covariance modelling
- b. Estimation – with covariance model accounting for colored noise
- c. Low-pass filtering

## 3. Trend restore:

- a. Restore the mean reduction of the Up component and modelled systematic trends, except the Eurasian plate motion.

These steps will be further described in the following sections.

### 2.4.1. Trend remove

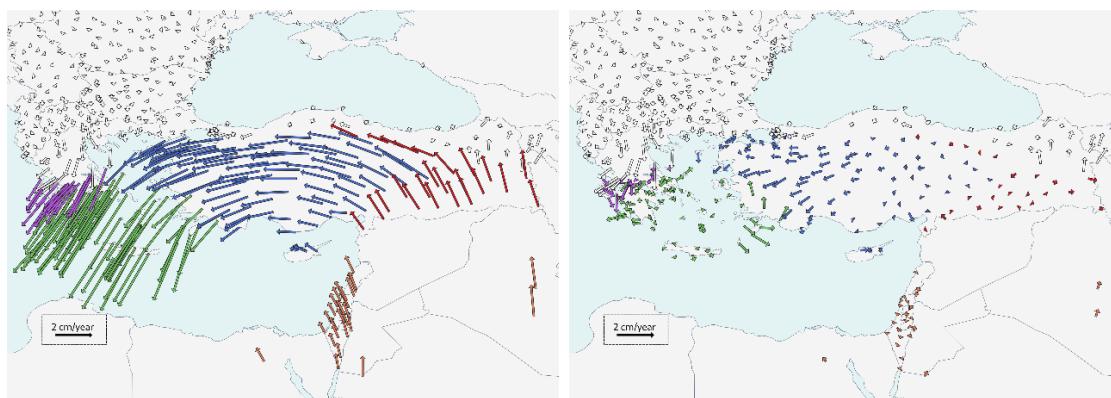
The LSC allows for predicting the trend free signal on a given grid from observations (trend + signal + noise). This requires that spatially systematic linear trends of horizontal and vertical velocity components are removed prior to the calculation of spatial covariances.

On a European continental scale, three regions with significant trends are identified and the trends eliminated:

- The Fennoscandian region, affected by postglacial rebound.
- Iceland, where the plate boundary crossing the island causes a trend-like velocity field, which is difficult to model with sparse station coverage.
- Eastern Mediterranean, where the Aegean and Anatolian plates rotate towards the west with respect to the Eurasian plate.

For Fennoscandia and Iceland, the trend is removed using the two existing deformation models NKG\_RF17vel [Vestøl et al. 2019] and ISN\_vel\_beta [Kierulf et al. 2019], respectively. The extent of the applied models is shown in Figure 2.

In the eastern Mediterranean, a modified clustering method after [Savage 2018] was first applied to group the stations into five clusters with well-distinguishable velocity patterns. Second, Euler pole parameters for each cluster were estimated [Goudarzi et al. 2014]. For the pole parameter estimation, the robust iterative method RANSAC [Fischler and Bolles 1981] was used to avoid bias in the pole parameters due to the non-rigid motion of the Anatolian and Aegean Plates. Using the estimated Euler pole parameters for each cluster, the modeled trend at the stations is calculated and removed. [Figure 3 Clusters and residual velocities at the Mediterranean region](#). shows the five clusters and the residual velocities in the Mediterranean region.



**Figure 3 Clusters and residual velocities at the Mediterranean region. Left panel: clustering results. Right panel: residual horizontal velocities in each cluster.**



## 2.4.2. Least-squares collocation

In the LSC method, the initial step involves selecting a covariance model based on the pairwise distance ( $d_{i,j}$ ) between stations, using a Gauss-Markov first-order function (1). The model's two primary parameters, variance ( $C_0$ ) and correlation length ( $d_0$ ), are derived by fitting it to the empirical covariance estimates. Here, the variance indicates the dispersion of data values around their average, while the correlation length measures the spatial and temporal range over which the stations' data points are interconnected.

$$C(d_{i,j}) = C_0 \cdot e^{-d_{i,j}/d_0} \quad (1)$$

The estimation of  $C_0$  and  $d_0$  utilizes a bootstrapping technique, employing resampling methods with varied observational data around the test grid to ensure statistical robustness and precision in parameter approximation, as detailed in Section 2.4.3.

Subsequently, the method entails the computation of covariance matrices for the signal ( $C_{obs}$ ), noise ( $C_{nn}$ ), and new points ( $C_{grid}$ ), derived from the observed signals  $v_{obs}$ .

$$v_{grid} = C_{grid}^T (C_{obs} + C_{nn})^{-1} v_{obs} \quad (2)$$

$$\sigma_{grid}^2 = C_0 - C_{new}^T (C_{obs} + C_{nn})^{-1} C_{grid} \quad (3)$$

This equation facilitates the computation of values  $v_{grid}$  at the model grid points, alongside their standard deviations  $\sigma_{grid}$ .

## 2.4.3. Signal covariance modelling

Initially, the Gauss-Markov 1<sup>st</sup> order covariance model **Error! Reference source not found.** was chosen among four candidate covariance function models, considering parameter uncertainties and residual values. The parameters  $C_0$  and  $d_0$  of the selected signal covariance function were determined for each of the three spatial components (North, East, Up) of all trend-free velocities, represented on the surface of the GRS80 reference ellipsoid. The 2D horizontal function parameters were derived by averaging the parameters estimated for the North and East components, respectively [Steffen 2019].

However, when applying the straightforward model fit assuming white noise, the estimated  $C_0$  value (i.e., variance) of the 2D horizontal component was found to be twice as high as that for the vertical component. This contradicts expectations, given the higher sensitivity of GNSS to the horizontal components. The unrealistic horizontal signal variance is attributed to larger residual trend-like signals (e.g., in Italy or Iberia) that cannot be effectively modeled and removed from the horizontal direction, indicating that the noise content is not white for the dataset.

To obtain a more realistic estimate of horizontal uncertainty, special attention was given to the  $C_0$  parameter, as the stochastic model of the LSC is highly dependent on it - a higher estimated value of  $C_0$  leads to a higher estimated uncertainty at the end of the collocation process.

Empirical tests revealed that the remaining trend-like signal has negligible effects on the velocity estimation itself. The effect on the estimated velocities  $v_{grid}$  of applying slightly different values for  $C_0$  is negligible. However, for the purpose of improving the horizontal uncertainty estimates  $\sigma_{grid}$ , the concept introduced in [Bos et al. 2013] and their HECTOR software was applied. This method incorporates a power law + white noise model instead of a purely white noise model. The derived statistics, based on velocity uncertainty estimates from all EPND stations, indicated a 2D horizontal to vertical variances ratio of 1:3.4. Therefore, in accordance with the HECTOR



analysis, the following stochastic parameters were selected for the continental collocation process:

	$C_0$	$d_0$
2D horizontal	0.23	90 km
vertical	0.78	130 km

**Table 2 Estimated covariance model parameters**

#### 2.4.4. Border effects

The trend remove-restore based on the described clustering method generally works well for handling the Aegean and Anatolian plate boundaries. However, for several grid points near the boundaries, some bias might be present in the detrended signal due to the slightly bigger residual velocities in the region. To eliminate this effect, distance constraints between stations situated on neighboring plates with larger relative velocities were applied through the  $C_{obs}$  signal covariance and  $C_{grid}$  cross-covariance matrices [Steffen 2019].

These matrices can be calculated using Equation (1) which reveals the functional relationship between covariance and the distance between different observation and grid points. The covariance (and correlation) will decrease with increasing distances between observation or grid points. Using this property, the correlation between adjacent stations and grid points sitting on either plate can be decreased if the calculated pairwise distances are artificially increased during the assembly of the matrices. Specifically, a +1000 km distance is added to the calculated pairwise site distances  $d_{i,j}$  if the two stations (*i* and *j*) are on different plates with high relative velocity (Equation 4).

$$d_{i,j} = \begin{cases} d_{i,j} & \text{if } j \notin [\text{unstable plates}] \\ d_{i,j} + 1000 \text{ km} & \text{if } j \in [\text{unstable plates}] \end{cases} \quad (4)$$

This approach provides smaller correlations between the resulting velocities, yielding a consistent velocity transition at plate boundaries.

#### 2.4.5. Lowpass filtering

To retain only wavelengths of the signal longer than 180 km in the final A-EPND model, a Gaussian low-pass filter implemented directly in the functional model was used [Willberg et al. 2020]. The filtering parameter was chosen as twice the estimated correlation length.

#### 2.4.6. Trend restore

In Fennoscandia and Iceland, where deformation models were applied for trend removal, the trend at the grid points was restored using the same model, now applied in the model grid points.

In the eastern Mediterranean region, the grid points were initially assigned to one of the five clusters as the cluster number of the station nearest the grid point. Then, in a post-processing step, a number of grid points along the cluster edges were rearranged using a more detailed plate boundary model released by [Taymaz et al 2007]. Finally, the trend was calculated and restored using the assigned cluster's estimated Euler pole parameters.



#### **2.4.7. Quality control**

Model validation involves comparing the initial velocities of stations in the input dataset with those predicted by the model. This comparison is conducted by collocating GNSS site locations and analysing the differences between the original and modelled velocities for each component.



## 3. EGMS GNSS Models

Within the current EGMS framework contract, two A-EPND models were developed:

- [A-EPND 2022](#): the initial model released in 2022.
- [A-EPND 2023](#): an updated version created during the 2023 production cycle.

The following sections outline the details of each model generation, starting with the input data (GNSS stations) and providing an overview of the quality control measures. While the methodology discussed in previous sections applies to both models, additional attention is given in the sections covering the "A-EPND 2023" model to highlight methodological improvements to the model's robustness.

### 3.1. EGMS GNSS Model 2022

#### 3.1.1. Input Data

Following the protocols outlined in Sections 2.1 and 2.2, a consolidated database of velocity and time series was compiled, comprising a total of 3,891 stations:

- EPND: 2,493 stations
  - Utilizing the latest solution D2150, covering GNSS products from GPS week 1500 (October 2008) to week 2150 (March 2021), along with SINEX solutions from 32 national networks.
- NGL: 1,212 velocity and time series solutions
- EUDV: 186 velocity estimates

NGL stations are included in the database only if EPND solutions are unavailable and meet the quality thresholds set by EPND. Otherwise, NGL information is excluded.

### 3.1.2. Model

Drawing from the analysis in Section 0 and the input data detailed in Section 3.1.1, the A-EPND model for the year 2022 was developed. Figure 4 illustrates vertical velocities, while Figure 5 depicts 2D horizontal velocities using colour representations.

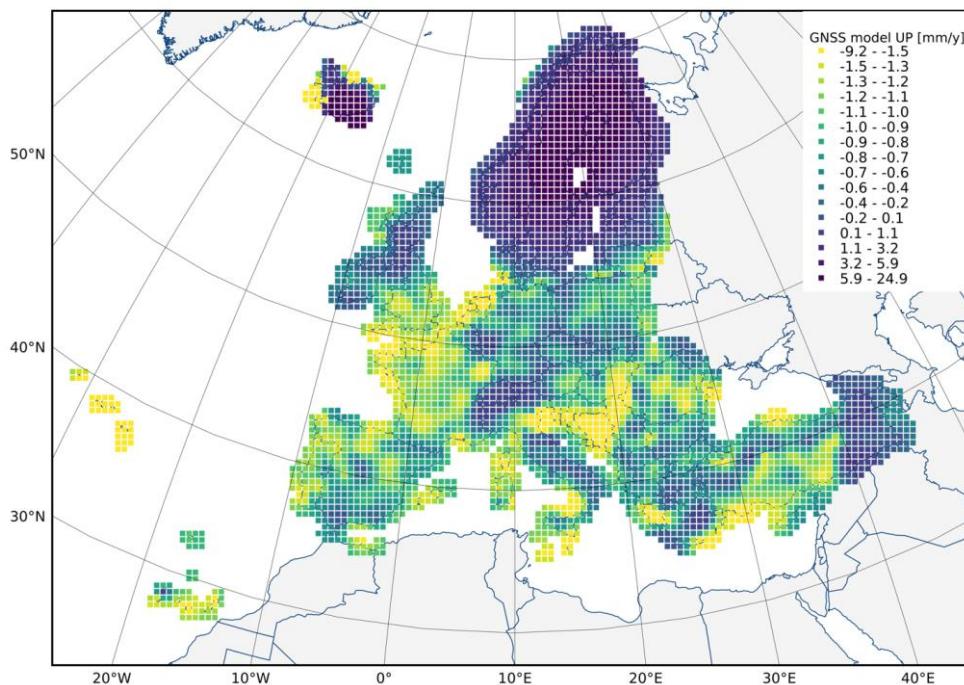


Figure 4 The magnitude of the vertical velocity component of the A-EPND 2022 model

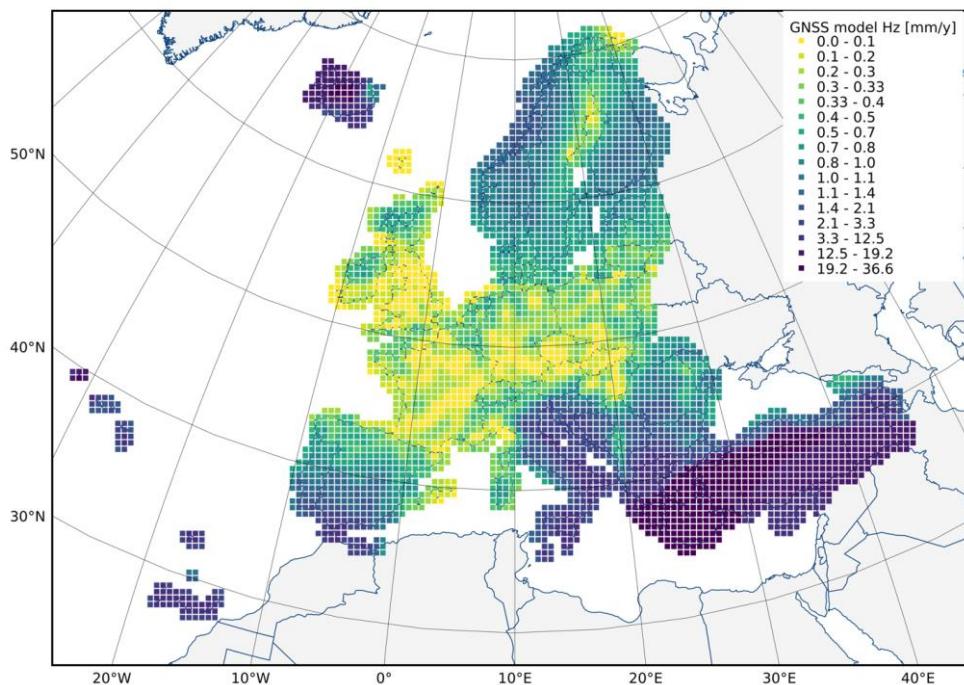
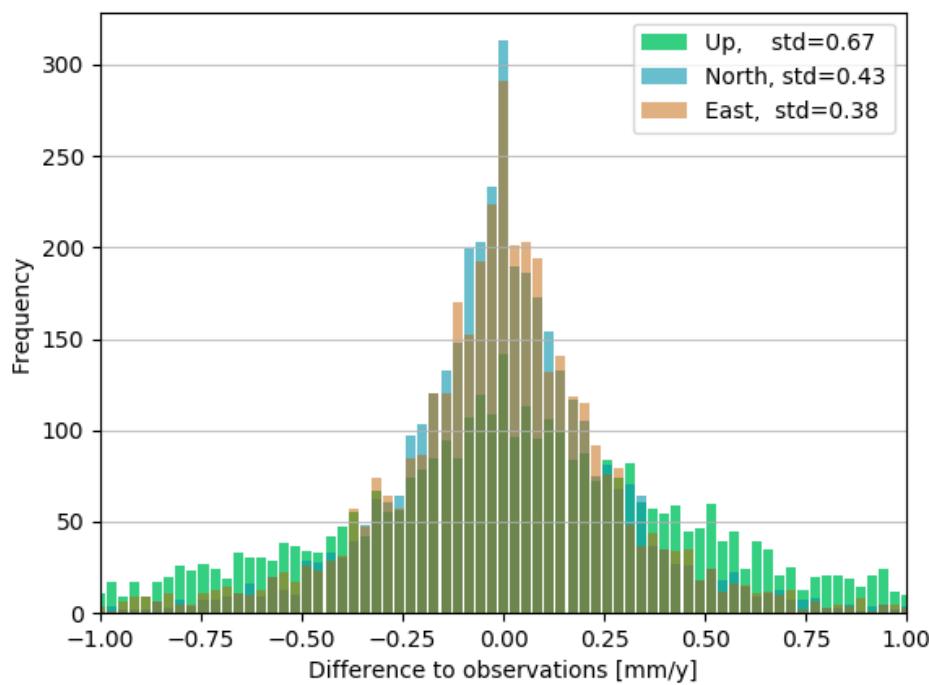


Figure 5 The magnitude of the horizontal velocity component of the A-EPND 2022 model

Following the iterative removal of outliers, the histogram plot illustrates the distribution of residuals between the model predictions and GNSS observations for each component. The majority of residuals are concentrated around zero, indicating a high degree of model accuracy. The residual differences exhibit a normal distribution, further validating the model's reliability. No significant outliers were identified, confirming the robustness and precision of the model. The RMS errors were determined to be 0.43 mm/year for the North component, 0.38 mm/year for the East component, and 0.67 mm/year for the Up component. Refer to Figure 6 for the final histograms illustrating these results.



**Figure 6 Histogram: Input vs. A-EPND 2022 Model Velocities.** The histogram visualizes the deviation between input velocities and those reconstructed from the A-EPND model 2022.



## 3.2. EGMS GNSS Model 2023

### 3.2.1. Data Integration and Network Expansion

The 2023 iteration of the A-EPND model includes extensive data updates, characterized by a significant increase in the number of GNSS stations across various networks:

- EPND: Increased from 2493 to 2567 stations.
- NGL: Increased from 1212 to 1812 stations, predominantly in Sweden.
- EUDV: Increased from 186 to 337 stations, despite the impending termination of EUDV<sup>5</sup>.

The most notable expansion is in Sweden, where approximately 500-600 stations have been added to the Nordic Geodetic Commission (NGL) network. This growth results from the inclusion of an additional year's data and collaborative efforts with local municipalities and Lantmäteriet for data homogenization.

Lantmäteriet played a crucial role in standardizing the diverse, partially independent networks in Sweden, facilitating the expansion of the Swedish GNSS network. Despite their primary focus on local-scale reference frame maintenance, the inclusion of these stations into the EGMS GNSS model significantly enhances data coverage and granularity. This improvement marks a substantial enhancement in the overall quality and spatial coverage of the GNSS data used in the model.

### 3.2.2. Enhancement and Impact Analysis

The 2023 A-EPND model update shows changes in velocity components relative to the 2021 model.

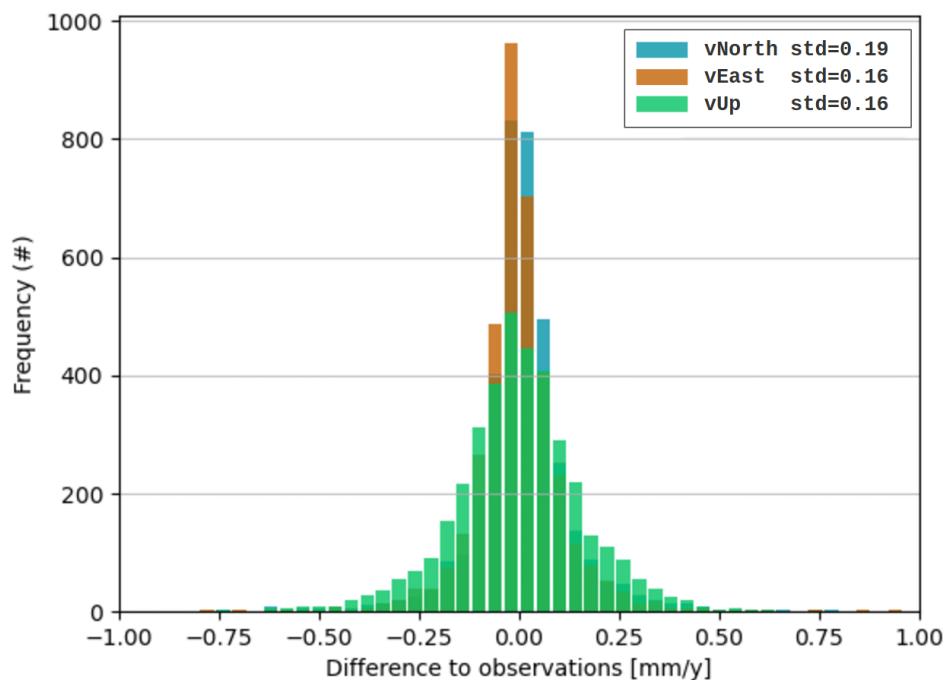
Statistical analysis reveals a normal distribution of these differences, with standard deviations of 0.19 mm/year for the North component (vNorth), 0.16 mm/year for the East component (vEast), and 0.16 mm/year for the Up component (vUp). This indicates consistent measurement quality and model reliability across epochs. Refer to Figure 7 for a visual representation of the velocity component differences.

Figure 8 illustrates the spatial distribution of differences in the North and East (horizontal) velocity components. These shifts, shown in millimeters per year through a color gradient on the map, suggest improved geophysical data accuracy in the model update, potentially due to new station data and enhancements in processing techniques. The standard deviation (std) for each component is provided in the legend, indicating the variability within each set of differences. Geospatial analysis identifies specific changes in these horizontal components, primarily across Southern Europe.

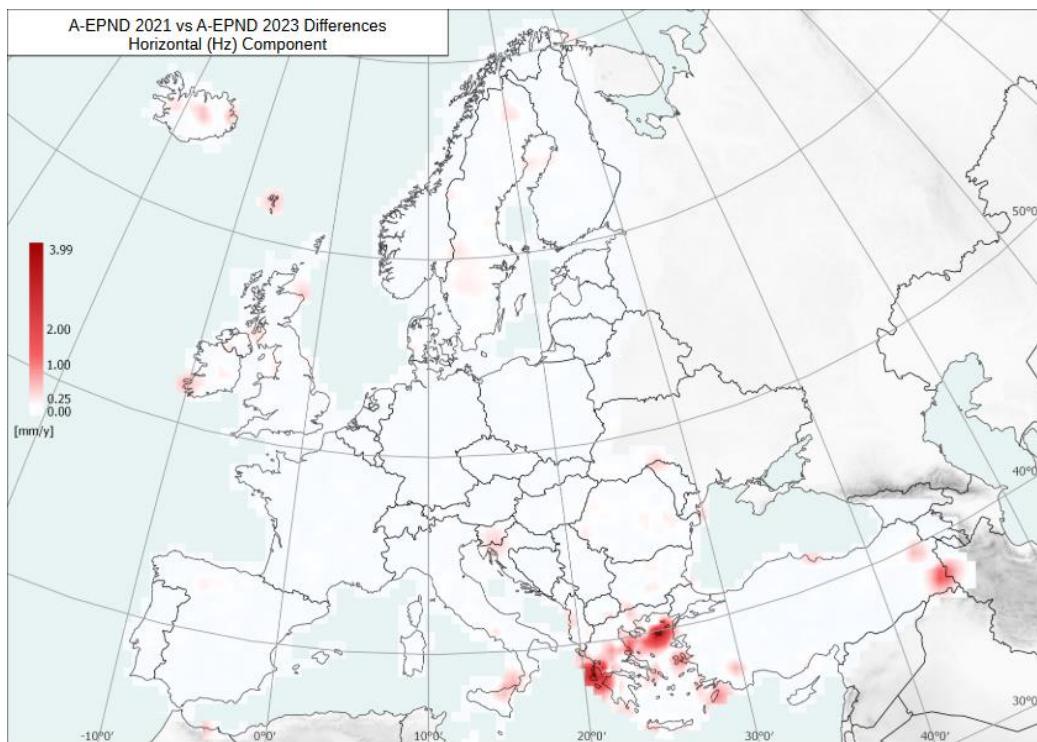
Figure 9 shows the spatial distribution of differences in the Up component (vertical) velocities between the A-EPND models of 2023 and 2021. The map uses color coding to indicate variations, highlighting areas of deviation from the previous model version. Despite the challenges in measuring vertical shifts due to atmospheric influences, the map clearly displays variances in vertical (Up) component velocities.

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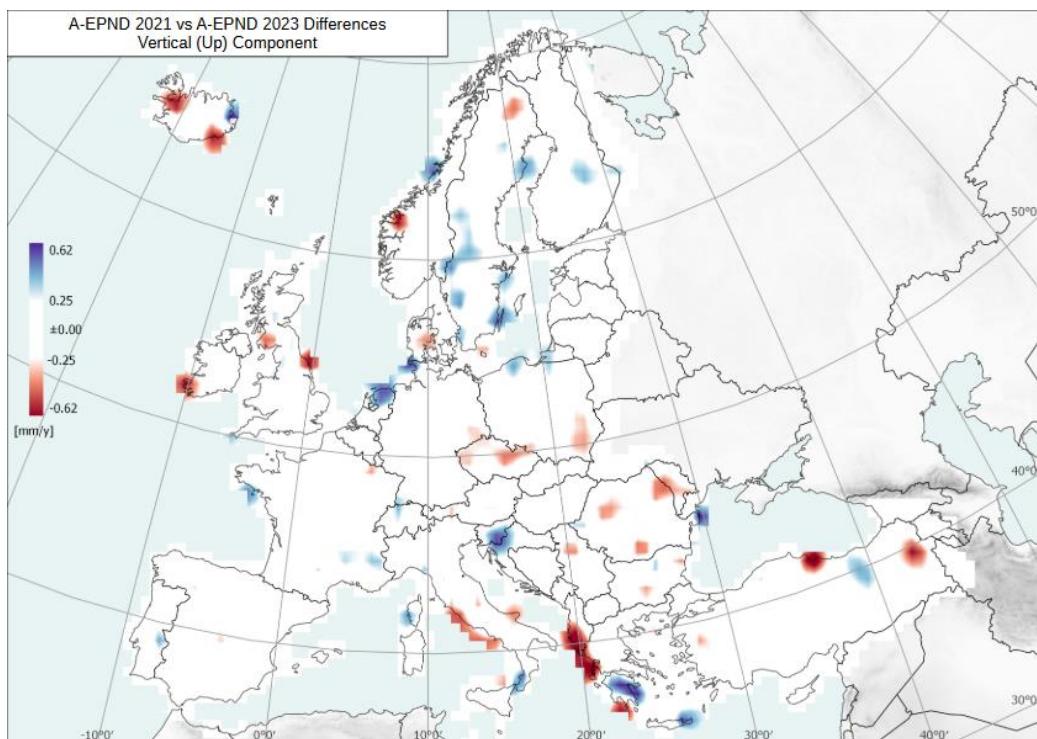
<sup>5</sup> [https://pnac.swisstopo.admin.ch/divers/dens\\_vel/index.html](https://pnac.swisstopo.admin.ch/divers/dens_vel/index.html)



**Figure 7 Histogram of A-EPND 2021 vs. A-EPND 2023 Model Velocities.** The histogram of velocity differences between the A-EPND 2021 model and the A-EPND 2023 model velocities -



**Figure 8 Map of Horizontal (Hz) Component Differences Between A-EPND 2021 vs 2023.** The map shows the spatial distribution of changes in horizontal velocity components across Europe. The colour scale represents the magnitude of differences in millimetres per year (mm/y), with red indicating an increase and blue a decrease in velocity.



**Figure 9 Map of Vertical (Up) Component Differences Between A-EPND 2021 vs 2023.** The map illustrates the differences in the vertical (Up) velocity component. The colour scale represents changes, with red denoting upward movement and blue downward.

### **Impact of Additional Swedish GNSS Stations on the EGMS Grid**

As an additional consideration, the integration of more Swedish GNSS stations is assessed for its effect on the EGMS grid. Despite the significant increase in data points, the homogeneity of the velocity data and the established smoothing process are expected to prevent substantial alterations in the grid.

### **Specific Model Improvements**

The discrepancies noted between the 2022 and 2023 models, particularly along the plate boundary in Greece, are attributed to refined data processing and error correction. Key improvements include:

- Correction of data errors at the Lemnos station (LEMN), notably affected by the 2014 earthquake, resulting in a more accurate representation of non-linear time series evolution in this area.
- Enhanced data quality in the seismically active regions of Western Greece, especially around Lefkada and Kefalonia, leading to a more reliable model output.

These changes, while localized, have a broader impact due to the nature of the gridding process, which can propagate single-station adjustments across multiple grid nodes.

#### **3.2.3. Methodological Continuity**

To maintain methodological rigor, the grid-generation process was kept unchanged. As a result, all observed variations in the 2023 model are direct outcomes of the enhanced input dataset and refined data processing for specific stations. This approach ensures that the updates to the model are entirely data-driven, preserving the scientific integrity and continuity of the EGMS A-EPND model.



## 4. Acknowledgements

- EUREF Working Group on EPN Densification (EPND):
  - Charter: <https://epnd.sgo-penc.hu/working-group-charter/>
  - Data portal: <https://epnd.sgo-penc.hu>
- Nevada Geodetic Laboratory: <http://geodesy.unr.edu/> [Blewitt et al. 2018]
- EUREF Working Group on European Dense Velocities (EUDV):
  - Charter: <http://www.euref.eu/TWG/WGdocs/WG-EU-dense-vel-charter-v2.pdf>
  - Data portal: [http://pnac.swisstopo.admin.ch/divers/dens\\_vel/](http://pnac.swisstopo.admin.ch/divers/dens_vel/)

## List of abbreviations

Abbreviation	Name	Reference
AOI	Area of Interest	
ATS	Average Time Serie	
ATSD	Detrended Average Time Series	
CLC	CORINE Land Cover	
CLMS	Copernicus Land Monitoring Service	
DEM	Digital Elevation Model	
DS	Distributed Scatterer	
EEA	European Environment Agency	<a href="https://www.eea.europa.eu/en">https://www.eea.europa.eu/en</a>
EGMS	European Ground Motion Service	<a href="https://land.copernicus.eu/en/products/european-ground-motion-service">https://land.copernicus.eu/en/products/european-ground-motion-service</a>
EPN	EUREF Permanent Network	
EUREF	Reference Frame Sub-commission for Europe	<a href="http://www.euref.eu/">http://www.euref.eu/</a>
GNSS	Global Navigation Satellite Systems	
InSAR	Interferometric Synthetic Aperture Radar	
IPE	InSAR Processing Entity	
IPR	Intellectual Properties Rights	
KPI	Key Performance Indicators	
LAEA	Lambert Azimuthal Equal Area	
MP	Measurement Point	
ORIGINAL	OpeRational Ground motion INsar Alliance	
ORR	Operational Readiness Review	
PS	Persistent Scatterer	
QC	Quality control	
RD	Related Documents	
SCR	Signal to Clutter Ratio	
stddev	Standard deviation	
TS	Time Series	

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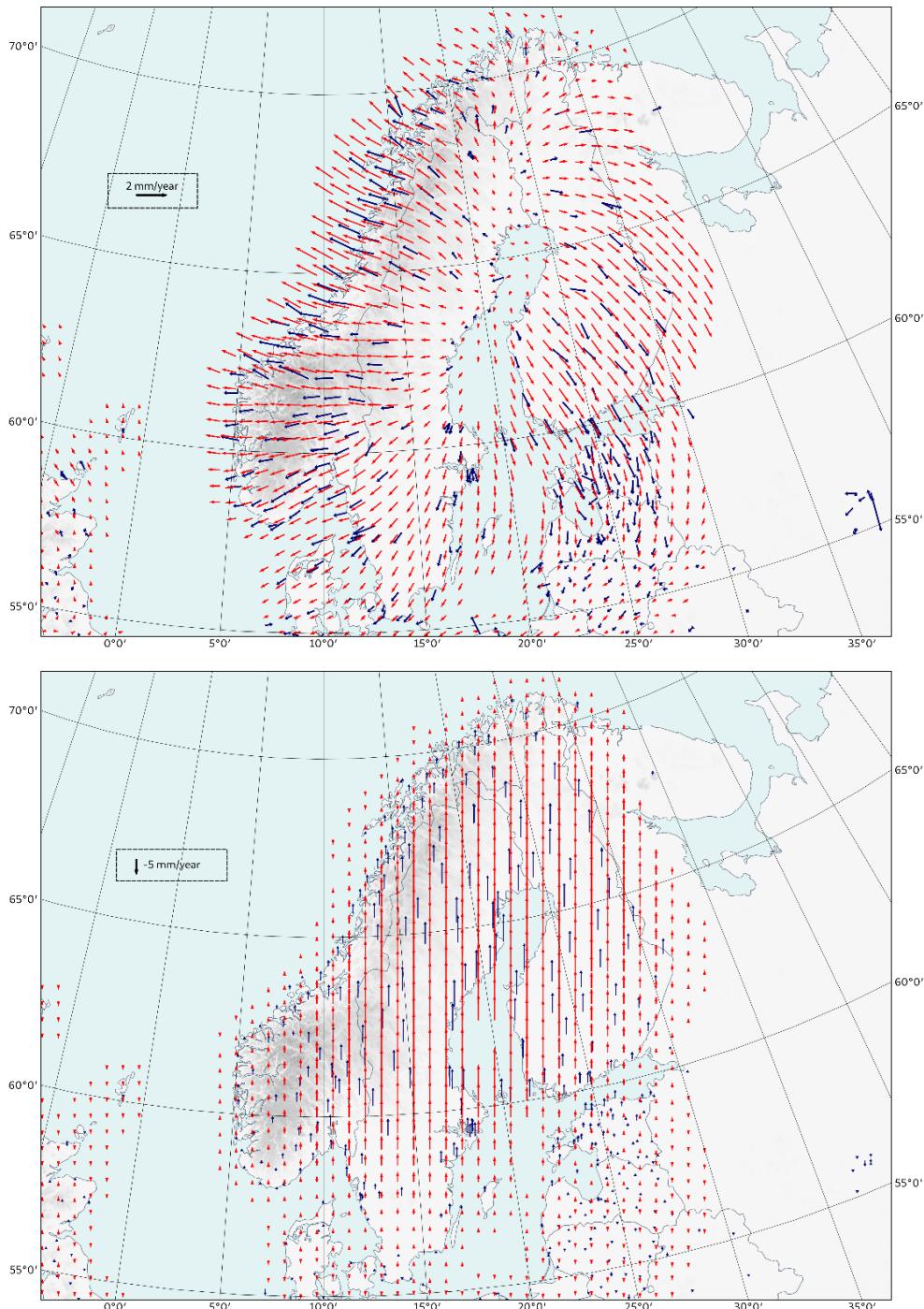
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## 5. Appendix: Regional Analysis

### 5.1. Fennoscandia

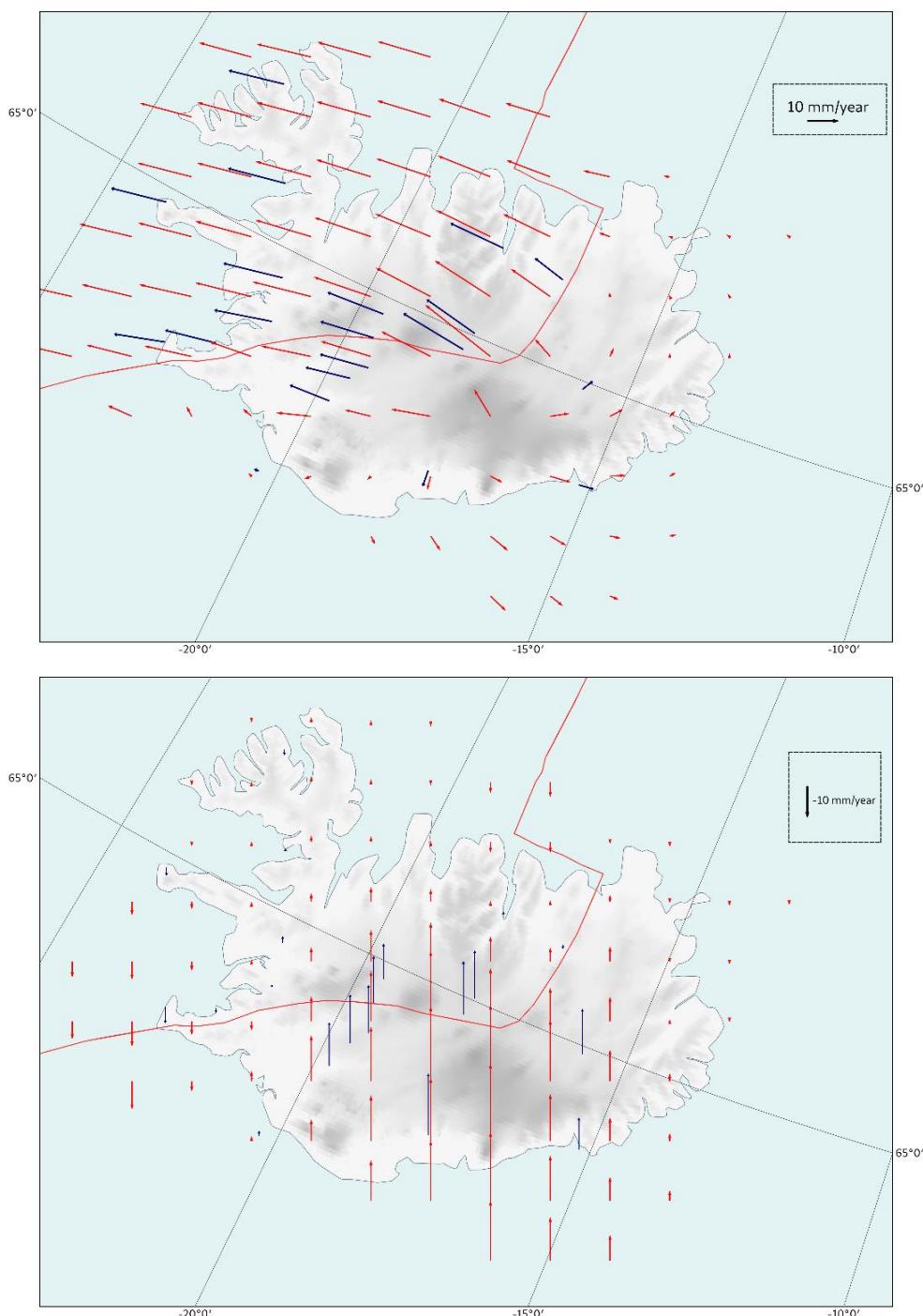
The signal in the Fennoscandia region is dominated by upwards and lateral motion caused by postglacial rebound [Vestøl 2019]. Figure 10 shows the A-EPND, version 2022, model results in this region.



**Figure 10 A-EPND model – Fennoscandian region. Top panel: 2D horizontal velocities, Bottom panel: vertical velocities. The red arrows indicate the model results, while the dark blue arrows are the estimated velocities at the GNSS stations.**

## 5.2. Iceland

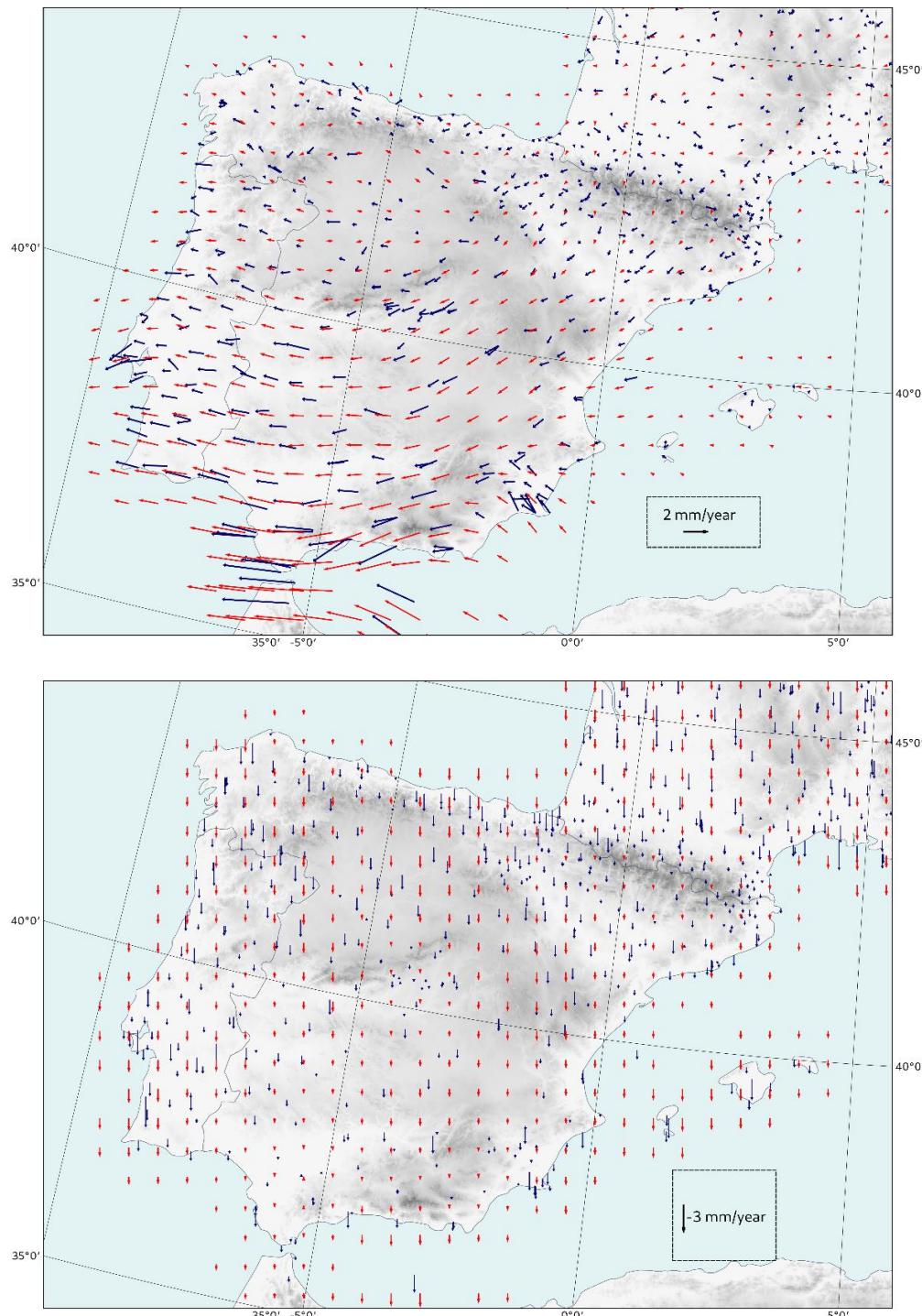
Iceland is located on the Mid-Atlantic Ridge, separated by the diverging North American and Eurasian Plates. Thus, due to ETRS89 being the reference datum for the A-EPND model, the eastern part of the island shows relatively low horizontal velocities, while the western part is dominated by the westwards motion of the North American Plate relative to the Eurasian Plate. In addition, Iceland is still experiencing postglacial rebound, resulting in an upwards motion component in the southeastern part of the island, with a maximum around the glacier Vatnajökull. The A-EPND model, version 2022, results for Iceland are shown in Figure 11.



**Figure 11 A-EPND model – Iceland. Top panel: 2D horizontal velocities, Bottom panel: vertical velocities. The red arrows indicate the model results, while the dark blue arrows are the estimated velocities at the GNSS stations.**

### 5.3. Iberian Peninsula

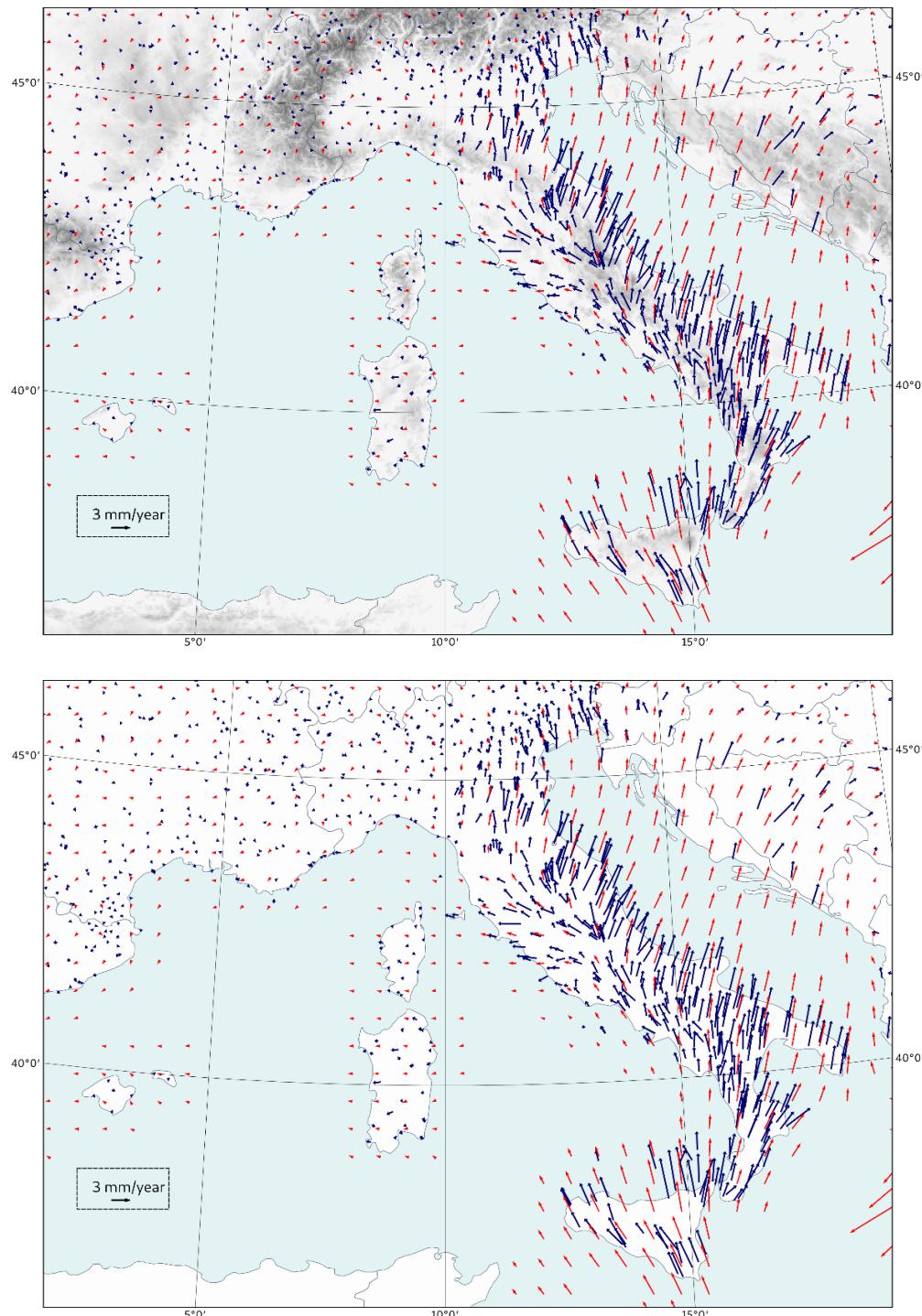
Near the Strait of Gibraltar, the converging movement of the African and Eurasian Plates induces a predominant westward horizontal displacement concerning ETRS89. Vertical displacement is minimal in comparison. The A-EPND model, version 2022, results for this region are shown in Figure 12.



**Figure 12 A-EPND model – Iberian region. Top panel: 2D horizontal velocities, Bottom panel: vertical velocities. The red arrows indicate the model results, while the dark blue arrows are the estimated velocities at the GNSS stations.**

## 5.4. Italy

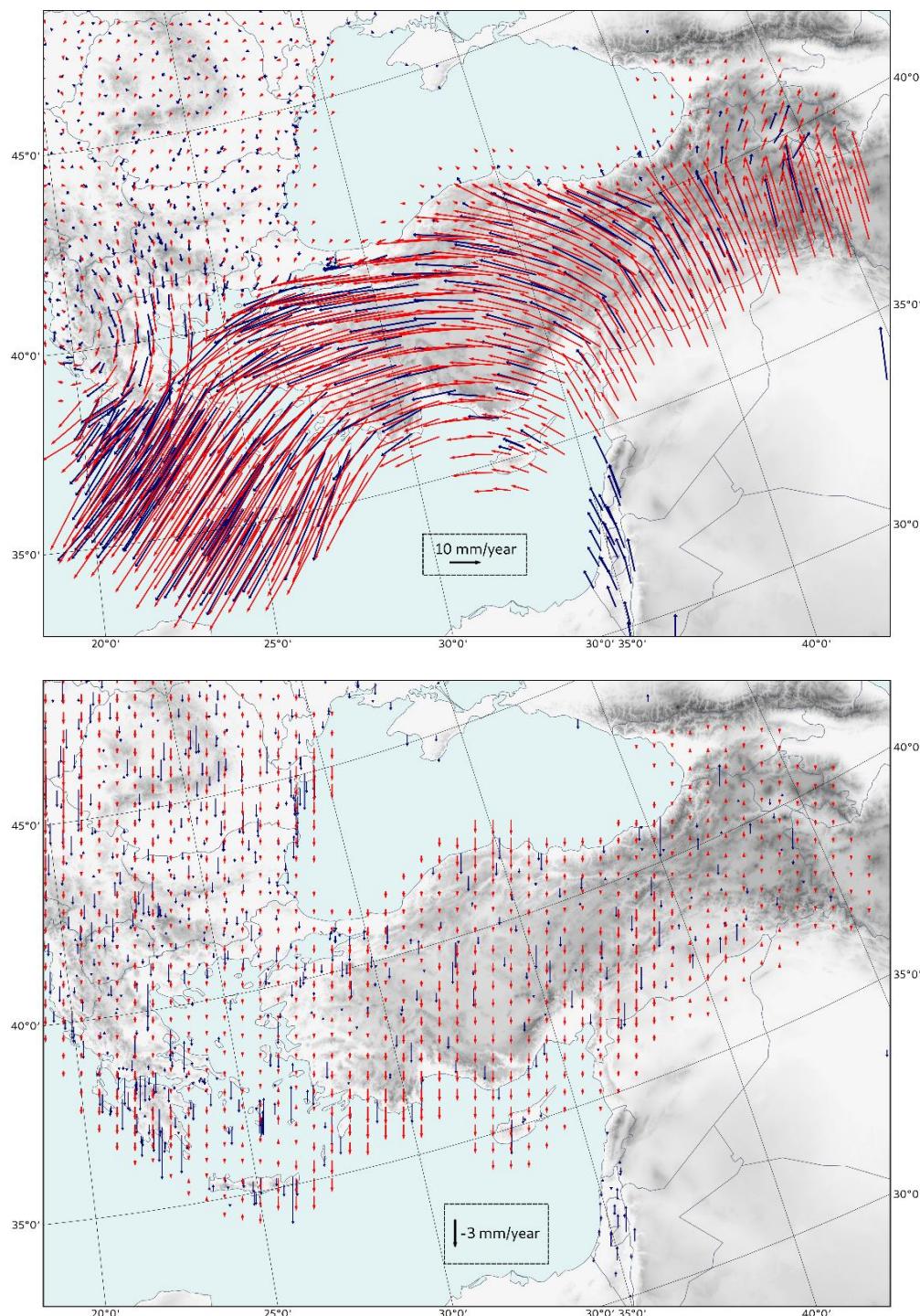
The Italian Peninsula is sandwiched between the converging African and Eurasian Plates, causing a counterclockwise horizontal rotation pattern relative to ETRS89. The A-EPND model, version 2022, results for this region are shown in Figure 13.



**Figure 13 A-EPND model – Italy. Top panel: 2D horizontal velocities, Bottom panel: vertical velocities. The red arrows indicate the model results, while the dark blue arrows are the estimated velocities at the GNSS stations.**

## 5.5. Eastern Mediterranean

In the eastern Mediterranean, several tectonic units move with distinct patterns relative to each other, as described in Section 2.4.1. Both the Aegean and the Anatolian Plates have a relatively large westwards horizontal motion with respect to the Eurasian Plate. The A-EPND model, version 2022, results for the Aegean and Anatolian regions are shown in Figure 14.



**Figure 14 A-EPND model – Aegean and Anatolian regions. Top panel: 2D horizontal velocities, Bottom panel: vertical velocities. The red arrows indicate the model results, while the dark blue arrows are the estimated velocities at the GNSS stations.**



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