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The alignment of PPP-derived coordinates to a local geodetic reference system through a reliable velocity field: case study in Greece

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ABSTRACT The main scope of this work is to present a reliable and rigorous method for efficiently converting the coordinates estimated by precise point positioning (PPP) to Greece's official geodetic reference system, i.e. the Hellenic Geodetic Reference System of 1987 (HGRS1987). The HGRS1987 is a hybrid geodetic reference system, assimilating classical (spatial distances, angles, directions, and azimuths) and space observations (global positioning system and Doppler measurements). For this purpose, it is necessary to know the velocities at each given arbitrary point in the Hellenic region (continent and islands). Therefore, we built a velocity model derived from a recent study for Greece. Appropriate coordinate conversions between various reference frames (global, regional, and local) are crucial in addition to a reliable velocity field. The method for transforming PPP-derived coordinates to the Greek geodetic system was assessed by comparing the coordinates (official versus computed) at 130 benchmarks located throughout the country. The computed and official coordinates coincided by 7.4 cm, which can be considered acceptable given the following factors: a) the official acceptance of the 8.3 cm root mean square; b) the use of a designated velocity model; and c) the application of several coordinate transformation algorithms. This kind of methodology could also be applied in any old geodetic reference system, worldwide.

Key words: PPP, velocity model, terrestrial reference frames, local geodetic system, transformation.

1. Introduction

The advent of Precise Point Positioning (PPP) in 1997 (Zumberge *et al.*, 1997) has enabled the use of Global Navigation Satellite Systems (GNSSs) receivers for surveying and geodetic purposes. At first, the accuracy of the PPP technique was low but, as technology advanced, research produced even more accurate results, reaching centimetre levels (Psychas *et al.*, 2021; Li *et al.*, 2022a, 2022b). Depending on the year of GNSS signal occupancy, the coordinates calculated from PPP initially refer to the orbit frame, i.e. one of the versions of the International Terrestrial Reference Frame (ITRF). In general, a number of variables, including the occupation time, the quantity of tracked satellites and the methods of solution, affect PPP-related accuracy.

Most countries have established an official geodetic reference system, widely known as a geodetic datum (Torge *et al.*, 2023). This official geodetic reference system is a crucial component of the cartographic and geodetic infrastructure of a country. As a result, a local geodetic reference system should be rigorously transformed from the PPP-derived coordinates (with respect to an ITRF). Nevertheless, it is not always that straightforward. There are certain difficulties even in connecting a local datum to a contemporary terrestrial reference frame (TRF). Firstly, it is common for a local geodetic datum to carry systematic errors; as a result, modern TRF coordinates eventually become less accurate (Cai, 2000; Haasdyk and Janssen, 2011). The second, and arguably most significant issue, is that the velocities of the points must be taken into account when transforming between a local datum and a current TRF (Bosy, 2014; Chatzinikos *et al.*, 2015; Crook *et al.*, 2016; Cheng *et al.*, 2020). This is dictated by the fact that the transformation between these two frames (modern TRF and local datum) is realised in a certain epoch. Thus, a rigorous transformation imposes the transition of any epoch to the reference epoch to achieve a greater level of accuracy.

In Greece, the official local geodetic reference system is the Hellenic Geodetic Reference System of 1987 (HGRS1987) (HEMCO, 1987; Veis, 1995). It is connected to the European Terrestrial Reference Frame of 2005 (ETRF2005) (Altamimi, 2005) through its densification in Greece, called the Hellenic Terrestrial Reference System of 2007 (HTRS07) (Katsambalos *et al*., 2010). The root mean square (*RMS*) of the transformation between HTRS07 and HGRS1987 reaches 8.3 cm nationwide (Kotsakis and Katsambalos, 2008; Katsambalos *et al.*, 2010). The transformation between HGRS1987 and HTRS07 was fixed at epoch 2007.5. Hence, the existence of a reliable velocity field plays a crucial role in the successful transformation between modern TRF and HGRS1987, since the epoch of the official transformation must be constrained in 2007.5. Furthermore, it is important to emphasise that Greece exhibits complex geotectonic and geophysical activity (Müller *et al.*, 2013; Chousianitis *et al.*, 2015; Bitharis *et al.*, 2017, 2023), which is reflected in the corresponding velocity field. The terms "reliable velocity field" corresponds to velocity estimation that reflects as closely as possible the real three dimensional (3D) velocities without severe inconsistencies and biases. As described henceforth, the velocity field reliability of this study was assessed using external validation points.

Though the PPP technique can reach centimetre-accuracies after long-term (e.g. many hours) occupations (Kouba and Héroux, 2001; Ge *et al.*, 2005, 2008; Hou and Zhu, 2023; Li *et al.*, 2023), the transformation between PPP-derived coordinates and HGRS1987 coordinates has specific consistency limitations due to the aforementioned transformation *RMS*. This is mainly caused by systematic inconsistencies of the HGRS1987 coordinates. In the present study, we describe a solid methodology for the robust transformation from PPP (ITRF) coordinates to HGRS1987 coordinates. In particular, we initially built a velocity model for Greece based on the results of a recent study (Briole *et al.*, 2021). We tested our methodology on a final set of 130 benchmarks for the National Triangulation Network (NTN), which were occupied with GNSS observations. We focused only on the HGRS1987 projection coordinates (easting and northing components of the Transverse Mercator projection).

2. Methodology

This section outlines the procedure used to convert the coordinates derived from PPP to HGRS1987.

2.1. Velocity model for Greece

Being velocities a necessary component in the application of the methodology, the estimation of the velocity model is critical. Considering information from 329 sites in Greece, Serbia, North Macedonia, Albania, Bulgaria, and Turkey, we used 3D velocities derived from the study of Briole *et al.* (2021). Briole *et al.* (2021) processed GPS-only data for the 2000-2020 time span. Two hundred eighty-two stations were located in Greece and 47 were located in surrounding countries. The analysis was carried out only for stations with an acquisition period of over two years and velocity uncertainty greater than 1.0 mm/yr. In total 20 stations did not fulfil the two-year acquisition requirement. For these stations, the velocities were estimated using interpolation techniques from neighbouring stations. The velocities refer to ITRF2014 (Altamimi *et al.*, 2016). The objective was to use bilinear interpolation (Press *et al.*, 1992) to define the velocities for all NTN benchmarks in Greece (continent and islands). The first group of 329 sites is displayed in Fig. 1.

Initially, an evaluation is made on the quality of the interpolation results. Three hundred two sites were selected and served as the foundation for the velocity model. The main selection criterion was the uniform distribution of the stations. As cross-validation sites, the remaining 27 locations were chosen (again, an effort was made to select stations uniformly distributed all over the country). The discrepancies between the official (as published) and the predicted (from the model) velocities were evaluated for the set of cross-validation points. Table 1 displays the statistics for the official and anticipated velocities, while Fig. 2 illustrates the horizontal discrepancies between them.

Table 1 - Statistics of the differences between the official and the estimated velocities at the cross-validation set of points (Δv_E: east component differences, Δv_N: north component differences, Δv_U: up component differences, and Δv_{hor}: horizontal differences). Values are in mm/yr.

Quantity	Δv_E	Δv_N	Δv_U	Δv_{hor}
Min	-1.3	-1.2	-2.6	0.1
Max	1.3	1.2	1.4	1.8
Mean	0.2	0.0	-0.2	0.8
Std	0.6	0.7	1.0	0.4
Median	0.2	-0.1	0.0	0.8
RMS	0.6	0.7	1.0	0.9

As shown in Table 1 and Fig. 2, the velocity model produced results that were comparatively acceptable. For instance, the *RMS* of the horizontal velocities is 0.9 mm/yr, whereas the *RMS* of the up component was 1.0 mm/yr. Thus, a triplet of anticipated velocities could be computed at any random point inside the Hellenic area. We deemed the aforementioned *RMS* of 0.9 mm/yr and 1.0 mm/yr for horizontal and vertical differences, respectively, as acceptable for two reasons: a) the inhomogeneous geophysical behaviour of the country (the velocities are largely deviating, depending on the location of the stations) and b) the inventible interpolation error. Steffen *et al.* (2022) investigated different velocity interpolation methods, based on least squares collocation, performing similarly to our results for the accuracy of the interpolated velocities.

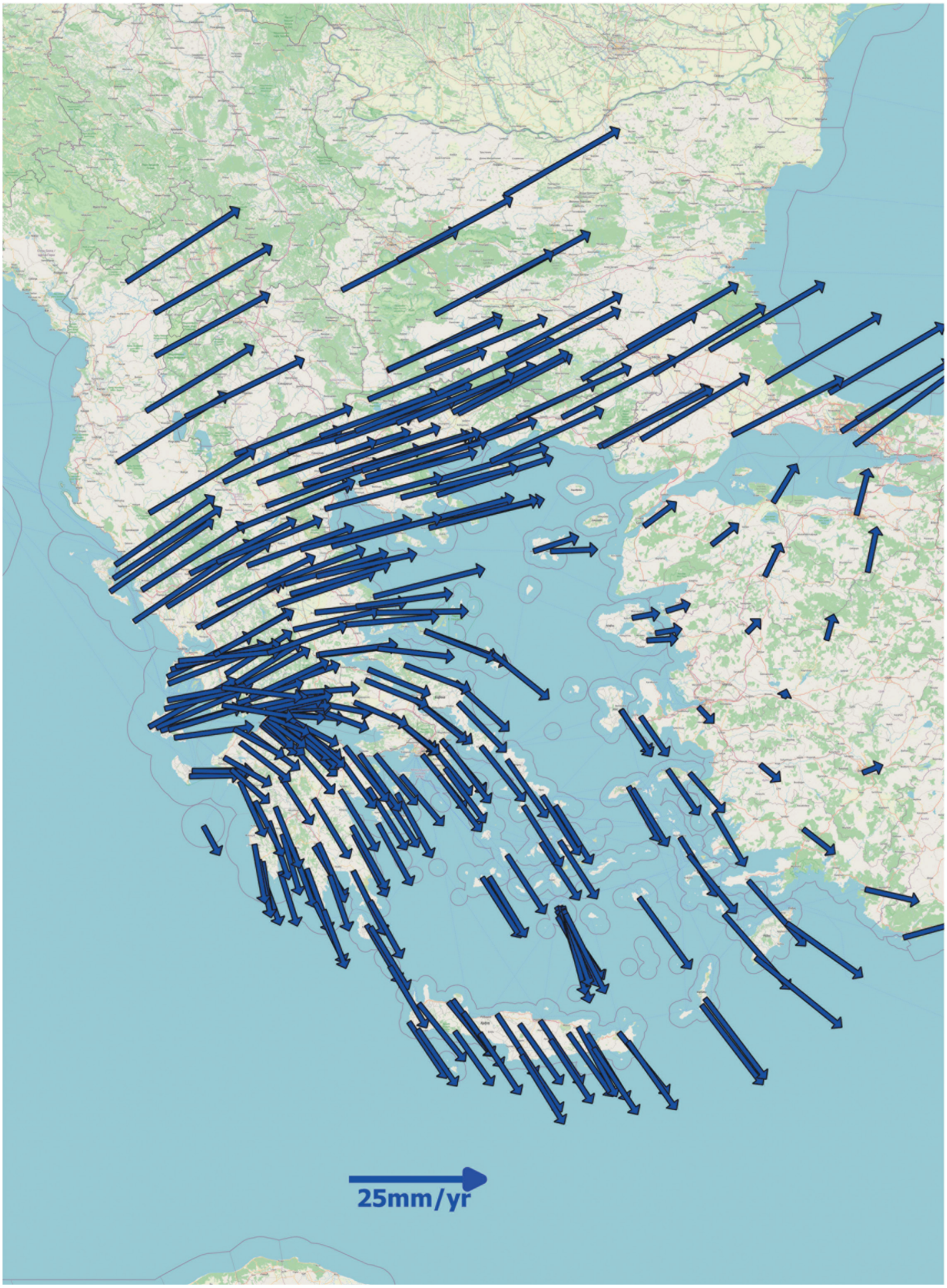

Fig. 1 - The horizontal velocities as estimated by Briole *et al.* (2021).

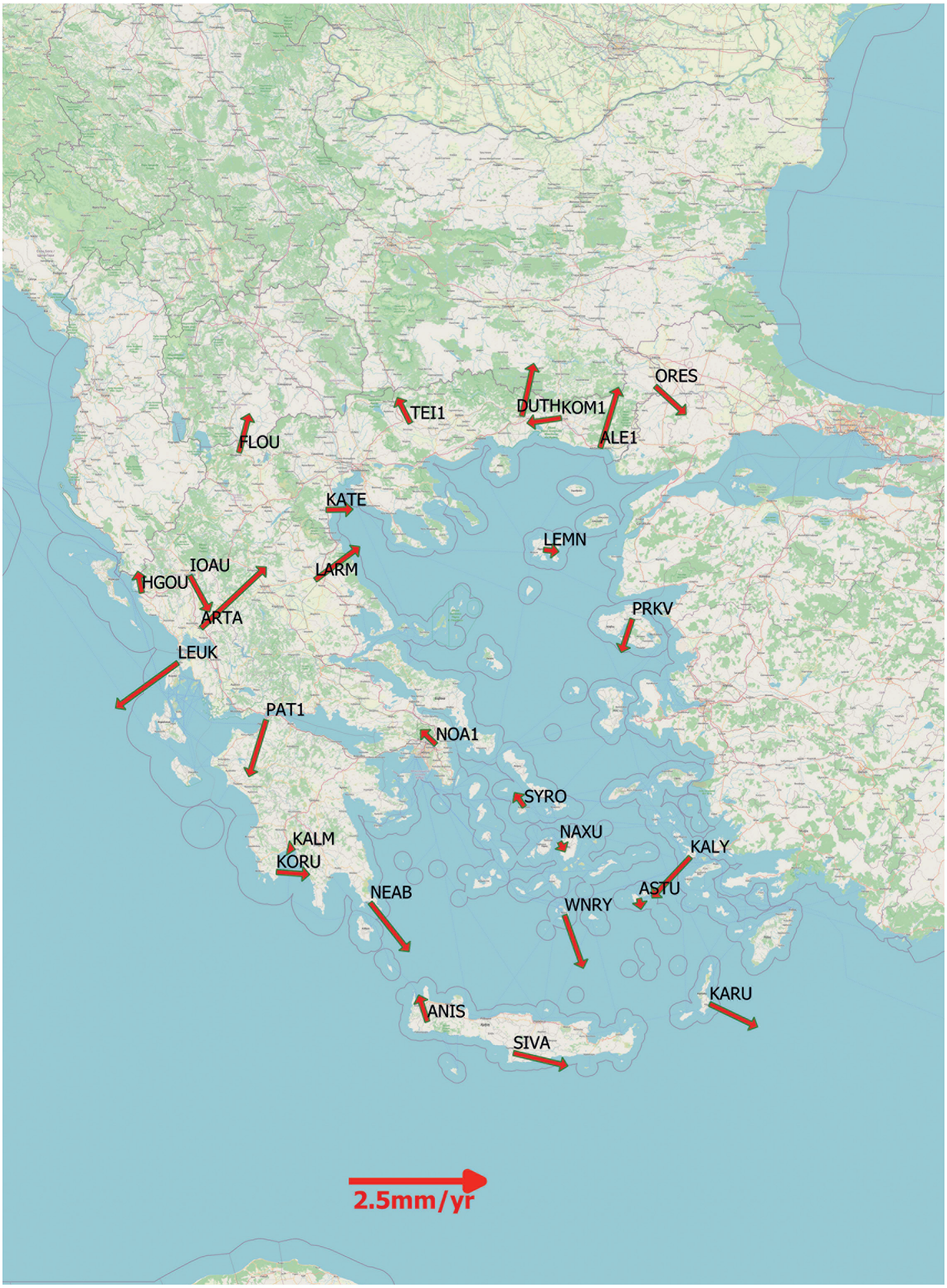

Fig. 2 - The differences between predicted and official velocities at the cross-validation set of 27 stations in Greece.

2.2. Transformations between different ITRFs and ETRS89

PPP-derived coordinates initially refer to an arbitrary ITRF at a certain epoch *t*. The aim is to transform the ITRF-wise coordinates to ETRF2005 (epoch 2007.5). As per the introduction, HGRS1987 is directly connected to ETRF2005 (epoch 2007.5). Taking this into account, we applied the EUREF transformation tool (Bruyninx, 2023). The required TRF (ETRF2005), the reference epoch (2007.5), the related coordinates, and the 3D velocities of the set of stations were the outputs of the EUREF tool. The inputs were: a) the starting TRF (depending on the epoch of PPP occupation), b) epoch *t* (depending on the epoch of PPP occupation), c) the Cartesian coordinates (estimated PPP coordinates with respect to an ITRF at epoch *t*), and d) the velocities (from the aforementioned velocity model) of a set of stations.

It should be underlined that if the initial ITRF did not coincide with ITRF2014, a proper velocity transformation should have been implemented. The velocity transformation was dictated because the velocity field referred to ITRF2014. For the sake of the reader, we recall the formula for velocity transformation (Altamimi *et al.*, 2016) between an arbitrary TRF and ITRF2014, as follows:

$$\begin{bmatrix} v_x \\ v_y \\ v_z \end{bmatrix}^{ITRFyyyy} = \begin{bmatrix} v_x \\ v_y \\ v_z \end{bmatrix}^{ITRF2014} - \begin{bmatrix} \dot{t}_x \\ \dot{t}_y \\ \dot{t}_z \end{bmatrix}^{ITRF2014} - \dot{D} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}^{ITRF2014} - \begin{bmatrix} 0 & -\dot{R}_z & \dot{R}_y \\ \dot{R}_z & 0 & -\dot{R}_x \\ -\dot{R}_y & \dot{R}_x & 0 \end{bmatrix}^{ITRF2014} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}^{ITRF2014} \quad (1)$$

where $([t_x\ t_y\ t_z\ D\ R_x\ R_y\ R_z]^T)^{ITRF2014}$ are the rates of the transformation parameters of ITRF2014 (*t* for translations, *D* scale, and *R* for rotations, respectively) and $([v_x\ v_y\ v_z]^T)^{ITRF2014}$, $([v_x\ v_y\ v_z]^T)^{ITRFyyyy}$ is the velocity triplet with respect to ITRF2014 and to other ITRFs, respectively.

2.3. From HTRS07 to HGRS1987

The conversion of the 3D HTRS07 coordinates to projection coordinates and orthometric height with respect to HGRS1987 was the last stage of the methodology. The Hellenic Cadastre (www.ktimatologio.gr) uses the HEPOS Transformation Tool software (HEPOS_TT) to accomplish this type of transformation. The 3D HTRS07 coordinates were transformed to projection coordinates east and north, using HEPOS_TT (HGRS1987 utilises the Transverse Mercator of one zone). It is important to note that the accuracy of the height transformation was not assessed, thus the work was carried out with the projection coordinates only.

The analysis was based on the comparison between the officially provided coordinates at the Greek NTN benchmarks and the estimated HGRS1987 projection coordinates, obtained using the aforementioned approach. Fig. 3 provides an overview of the approach followed.

3. Numerical application

The list of stations includes challenging regions in terms of their geodynamic activity, such as the Ionian Islands, Santorini, Crete, and the Corinthian Gulf. However, there are certain areas with no data (e.g. western Macedonia, Cyclades). In the end, GNSS RINEX data were gathered from 141 NTN benchmarks. The benchmark occupancy period ran from 2006 to 2023. The removal of 7 benchmarks was necessary due to their low occupation time (less than 30 min). Therefore, a set of 134 benchmarks was eventually processed (see the next step).

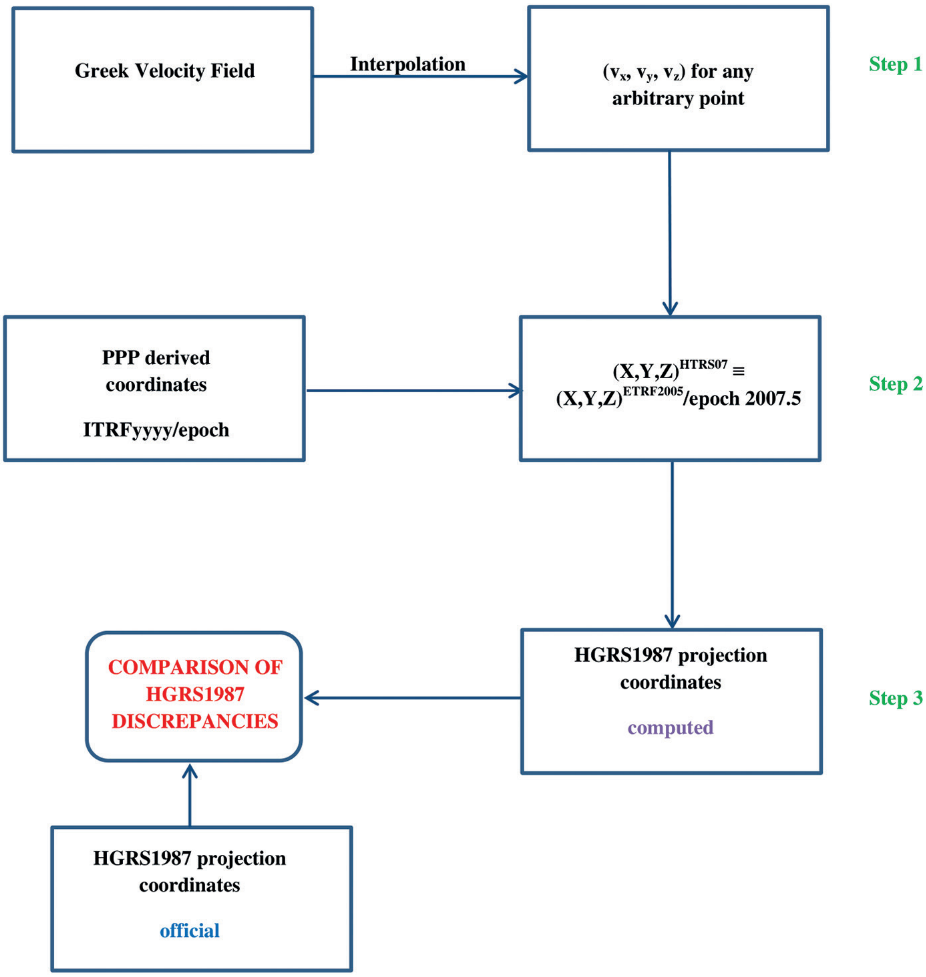

Fig. 3 - Flowchart of the method for transforming the PPP-derived coordinates to HGRS1987 and comparison of the results.

3.1. PPP processing

The following software programmes were used for PPP processing: CSRS-PPP (Tetreault *et al.*, 2005) and PRIDE PPP-AR (Geng *et al.*, 2019). The formula used to estimate each coordinate component (X, Y, and Z) was:

$$\hat{x}_i^{ITRFyyyy}(t) = \frac{w_i^{NRCAN} x_i^{NRCAN} + w_i^{Pride} x_i^{Pride}}{w_i^{NRCAN} + w_i^{Pride}} \quad (2)$$

where $\hat{x}_i^{ITRFyyyy}(t)$ is the adjusted component (X, Y, Z) of the station with respect to an ITRF solution at epoch t, $w_i^{NRCAN} = \frac{1}{(\sigma_i^{NRCAN})^2}$ the weight of the CSRS-PPP-related component (inverse of the component variance), and $w_i^{Pride} = \frac{1}{(\sigma_i^{Pride})^2}$ the weight of the PRIDE PPP-AR-related component (inverse of the component variance). The largest difference between CSRS-PPP and PRIDE PPP-AR solutions in terms of 3D Euclidean distance for a point was found to be 2.1 cm.

Objections may be raised with regards to PPP coordinate weighting, described in Eq. (2). For example, the estimated standard deviations (*STD*s) may be too optimistic (low uncertainties). Additionally, due to different software configurations, the results might not be directly comparable. In general, these doubts are reasonable and should be taken into account. However, in the specific case, we did not observe any unrealistic (optimistic) uncertainty: the lowest one was found at around 1 cm, for both software programmes (CSRS-PPP and Pride). In addition, there was significant agreement on the uncertainties for both software programmes at the same stations. Furthermore, as mentioned in the previous paragraph, the largest 3D difference between the two software programmes was at the level of 2 cm, which can be considered more than adequate for the present study, since the *RMS* of the transformation from ETRS89 to HGRS1987 is 8.3 cm, nationwide.

3.2. Numerical application of the strategy

We followed the strategy described in section 2. The comparison between the official and computed HGRS1987 coordinates at the NTN benchmarks was determined as follows:

$$\delta s_{hor_i} = \sqrt{\left(E_i^{official} - E_i^{computed}\right)^2 + \left(N_i^{official} - N_i^{computed}\right)^2} \quad (3)$$

where δs_{hor_i} is the horizontal discrepancy between official and computed HGRS1987 coordinates, respectively, $E_i^{official}$, $E_i^{computed}$ the easting and $N_i^{official}$, $N_i^{computed}$ the northing projection coordinates of the HGRS187, respectively.

Four benchmarks were rejected because their horizontal discrepancies exceeded 1 m. The unreliable NTN benchmarks were most likely the source of these discrepancies. The number of NTN benchmarks annually occupied is displayed in Fig. 4.

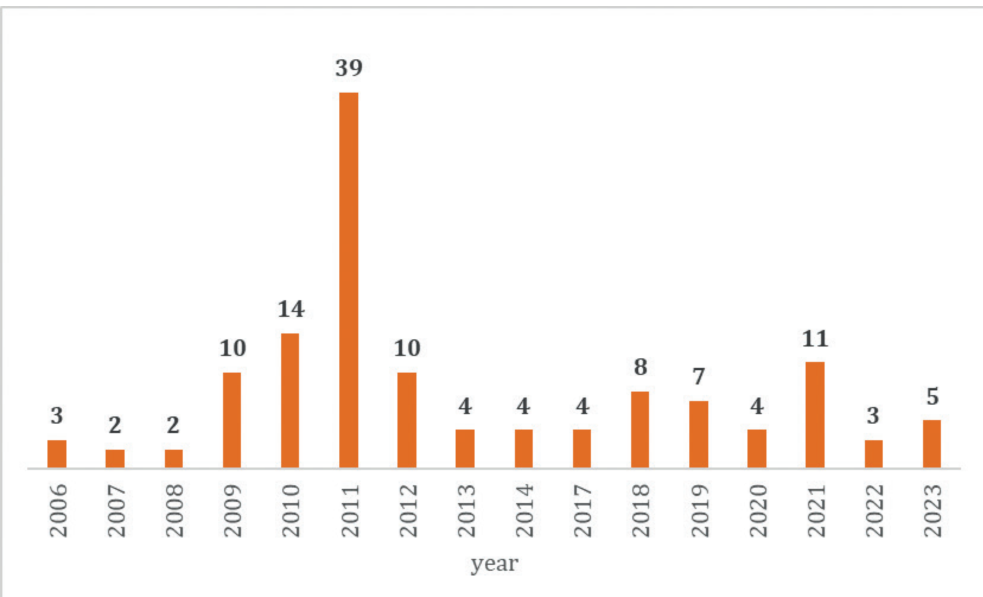

Fig. 4 - Number of NTN benchmarks occupied per year.

Lastly, a total of 130 benchmarks were used as test points. Table 2 provides their statistics, while Fig. 5 illustrates the horizontal discrepancies. The horizontal differences (*RMS*) are categorised into three distinct categories (0-9.9 cm, 10-19.9 cm, and > 20 cm) in Fig. 6.

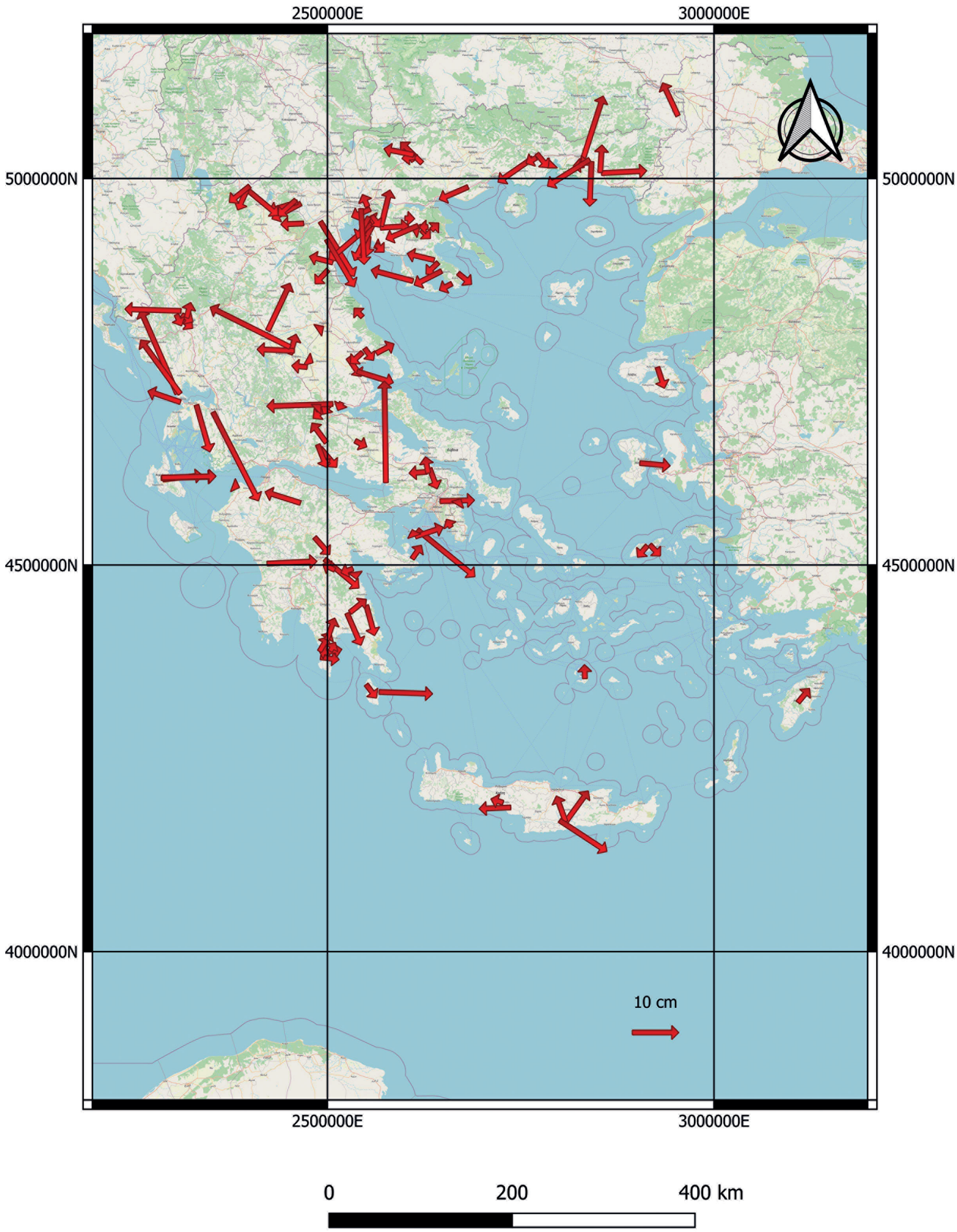

Fig. 5 - Final set of 130 NTN benchmarks and their horizontal discrepancies.

Table 2 - The statistics of the differences between the official and the estimated velocities at the cross-validation set of points (δE: easting differences, δN: northing differences, and δS_{hor}: horizontal differences). Values are in cm.

Quantity	δE	δN	δS_{hor}
Min	-17.2	-19.1	0.1
Max	12.4	21.9	21.9
Mean	-0.1	-0.5	6.0
Std	5.3	5.2	4.4
Median	0.0	-0.3	4.8
RMS	5.3	5.3	7.4

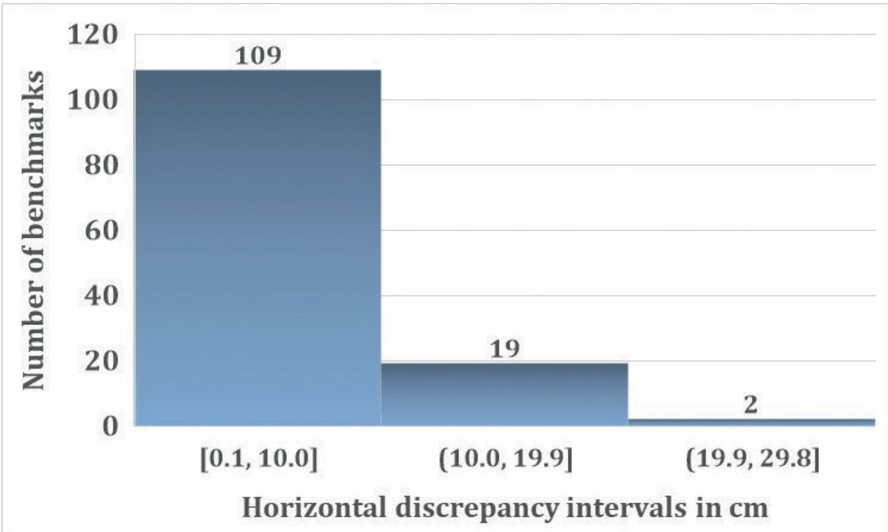

Fig. 6 - *RMS* categorisation for the horizontal discrepancies. The label over the bars indicates the number of benchmarks belonging to each category.

The suggested methodology performs with a *RMS*, for the HGRS1987 horizontal discrepancies, which is less than 7.5 cm (7.4 cm), Editor according to aforementioned Figs. 4, 5, and 6, and Table 2. In this context, it may be recalled that the nationwide *RMS* for the transformation from HTRS07 to HGRS1987 is 8.3 cm. The discrepancies do not appear to have increased, even for regions with severe geotectonic behaviour (the Ionian Islands, Santorini, Crete, Rhodes, and the area in the vicinity of the Corinthian Gulf). Furthermore, out of 130 benchmarks, 109 (83.2%) have discrepancies less than 10 cm, whereas only 2 have discrepancies greater than 20 cm. Additionally, it can be observed that the vector discrepancy spatial variability does not follow any consistent pattern nationwide nor in particular regions (such as northern and western Greece).

3.3. Dependence between the epoch of occupation and HGRS1987 horizontal discrepancies

Subsequently, an evaluation of the relationship between the corresponding HGRS1987 inconsistencies and the occupation epoch was carried out. As previously stated, HTRS07 was implemented at epoch 2007.5. Potential dependence can be the sign of an issue with the velocity field the study was using. For example, if the occupancy epochs are seen to start from 2007.5 and, at the same time, their related differences are routinely getting larger, basically, it signifies that the velocities exhibit inconsistencies that can contaminate the transformation. The relationship between the horizontal discrepancies and the occupation epochs is depicted in Fig. 7.

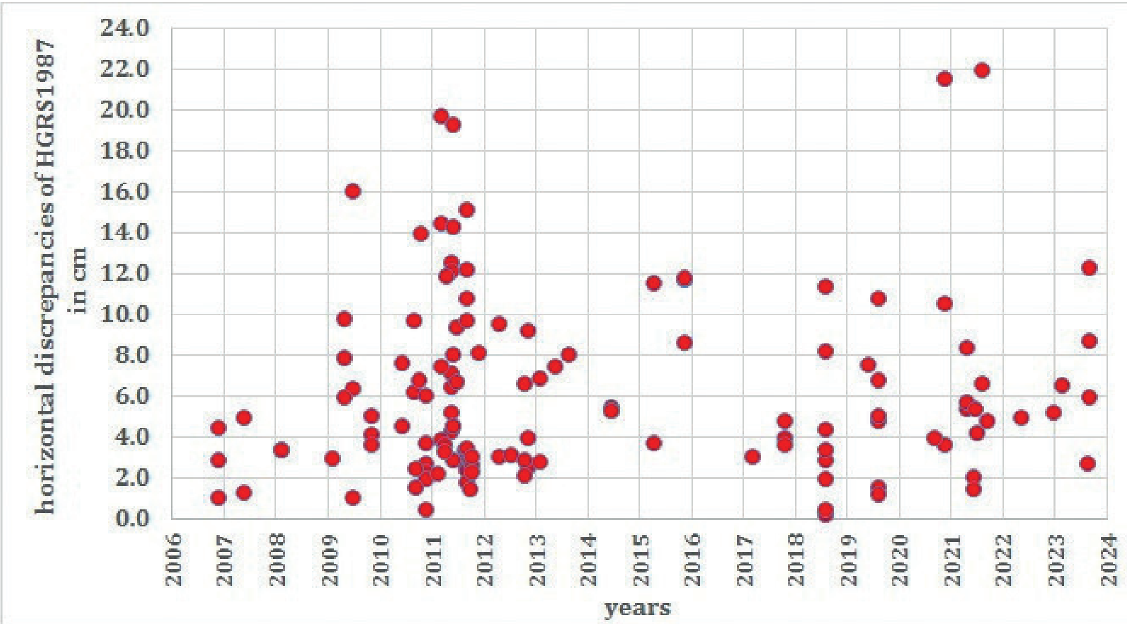

Fig. 7 - The dependence between occupation epochs and HGRS1987 horizontal discrepancies.

Fig. 7 suggests that there is no actual relation between these two parameters (-0.05 is the corresponding correlation factor). As a result, there is very little correlation between the occupation epochs and the horizontal differences. This result validates the robust velocity model applied in this investigation.

3.4. Dependence between the occupation time and HGRS1987 horizontal discrepancies

The relationship between the occupation time and the HGRS1987 horizontal discrepancies was also examined, in addition to the prior analysis. This type of assessment provides an idea of the amount of occupation time required for reliable conversions from PPP to HGRS1987. Fig. 8 illustrates how these two parameters are correlated. The occupation time and the horizontal discrepancies in HGRS1987 are not significantly correlated (correlation factor = 0.05). Nonetheless, it appears that a significant variation in the discrepancies might occur for an occupation time less than two hours. In order to be cautious, the recommendation is for the occupation time to be at least two hours.

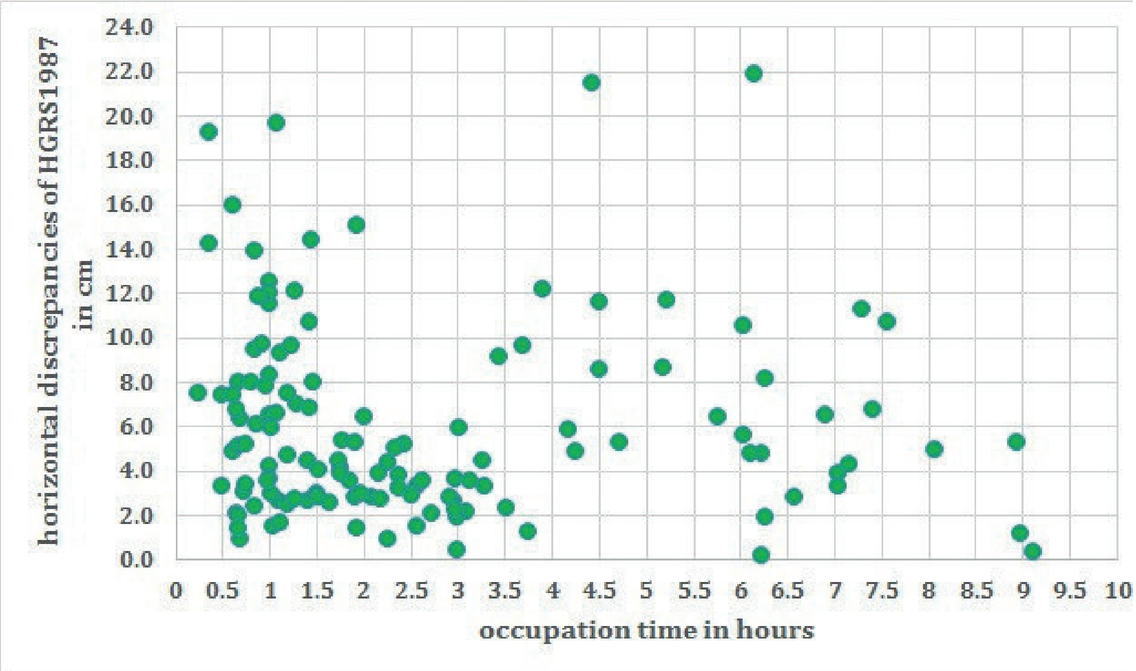

Fig. 8 - The dependence between occupation time and HGRS1987 horizontal discrepancies.

4. Conclusions

The PPP-derived coordinates were transformed to the local geodetic reference system of Greece (HGRS1987) through the following steps: a) estimation of a reliable velocity field obtained from the analysis of Briole *et al.* (2021); b) conversion of the ITRF-related coordinates to ETRF2005; and c) conversion of the ETRF2005 coordinates to HGRS1987. Throughout the study, the related methodology for this type of transition was analytically examined. The findings were assessed by comparing the coordinates computed at 130 NTN benchmarks (located throughout the continental country and its islands) with the official projection coordinates.

In contrast to the officially released *RMS* of 8.3 cm, the comparison displays a *RMS* for the horizontal discrepancies (computed against officially released velocities) at the level of 7.4 cm. Additionally, we note that the horizontal disparities of HGRS1987 do not significantly correlate with the occupancy epoch, indicating the high performance of the calculated velocity field. Horizontal discrepancies and occupation time are not correlated; however, it appears that the occupation time should be at least two hours.

In the future, more NTN benchmarks in specific regions of Greece should be occupied and examined to verify that the transformation *RMS* remains at or below the 8.3 cm limit. This should be carried out by organised campaigns under state supervision.

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