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CRUSTAL DEFORMATIONS AND THEIR IMPACT ON THE REALIZATION OF A NATIONAL COORDINATE REFERENCE SYSTEM: CASE STUDY AETOLIA-ACARNANIA, WESTERN GREECE

Abstract

Geodesy and crustal deformations are closely related. On the one hand, geodetic techniques are used to estimate deformations contributing in this way to geology, seismology and geodynamics. On the other hand, deformations consist a major challenge in the maintenance of geodetic reference frames. In this work we use GNSS (Global Navigation Satellite System) data and geodetic methods to estimated crustal deformations in the area of Aetolia-Acarnania, western Greece. The analysis of measurements that have been conducted in 2007 and 2023 on trigonometric points showed significant horizontal deformations up to 16.8 cm. The revealed deformations are presented and discussed in terms of their impact on the realization of the national coordinate reference system.

Keywords: crustal deformations, reference system, GNSS networks, Aetolia-Acarnania, Greece.

ДЕФОРМАЦИЈЕ ЗЕМЉИНЕ КОРЕ И ЊИХОВ УТИЦАЈ НА РЕАЛИЗАЦИЈУ НАЦИОНАЛНОГ КООРДИНАТНОГ РЕФЕРЕНТНОГ СИСТЕМА: СТУДИЈА СЛУЧАЈА НА ПОДРУЧЈУ ОКРУГА ЕТОЛИЈА-АКАРНАНИЈА, ЗАПАДНА ГРЧКА

Сажетак

Геодезија и деформације земљине коре су блиско повезане. Са једне стране, геодетске технике се користе за процјену деформација и на тај начин доприносе геологији, сеизмологији и геодинамици. Са друге стране, деформације представљају значајан изазов у одржавању геодетских референтних оквира. У овом раду користимо податке и геодетске методе ГНСС-а (Глобални навигациони сателитски систем) како бисмо процијенили деформације земљине коре у подручју округа Етолија-Акарнанија, у западној Грчкој. Анализа мјерења која су изведена 2007. и 2023. године на тригонометријским тачкама показала је значајне хоризонталне деформације до 16,8 cm. Откривене деформације су приказане и разматране у смислу њиховог утицаја на реализацију националног координатног референтног система.

Кључне ријечи: деформације земљине коре, референтни систем, ГНСС мреже, Етолија-Акарнанија, Грчка.

1. INTRODUCTION

Numerous fields of earth sciences, such as geology and tectonic geodesy, study the deformation of the Earth's crust. Many countries are not subject to tectonic deformations while some others are significantly affected. This depends mainly on the location of the country with respect to the boundaries of the tectonic plates (or microplates) or other deformation sources like e.g. active volcanos. For example, most of the European countries are not affected by tectonic deformations. In Europe, significant active horizontal deformations take place in a limited number of countries, mainly at the southern borders of the Eurasian plate, while vertical motions occur in northwestern Europe due to post-glacial rebound. As far as horizontal distortions are concerned, Greece is mostly affected, followed by Italy. The Greek region is characterized by intense and complex tectonic phenomena, as it is located close to the convergence boundaries of the Eurasian and African plates. As known, the African plate subducts beneath the Eurasian plate with a convergence rate of ~3 cm/year. Moreover, a number of microplates are distinguished in the area like the Aegean, the Anatolian, and the Apulian (Adriatic) plates. Thus, the Earth's crust in (and around) Greece is not uniform but it consists of distinct plates. Moreover, these plates are moving in different directions and with different velocities. Therefore, the crust in Greece undergoes continuous (mostly horizontal) deformations.

Due to the afore-mentioned deformations, the geodetic networks are constantly changing in terms of their shape. In general, the realization of a geodetic reference system in the presence of crustal deformations is a challenging task. As the crust is deforming, the relative positions and, consequently, the coordinates are changing with time. From a geodetic point of view, the question arising here is how these changes affect the realization of a national geodetic reference frame. Here, one should distinguish between the two different ways of realizing a geodetic reference frame, i.e. the conventional realization using geodetic control points and the modern approach, which is based on permanent GPS/GNSS reference stations. A few decades ago, the national Coordinate Reference Systems (CRS) were realized by means of trigonometric points which were established at distances of about 3-5 km. At such distances long time is needed for the crustal deformations to significantly alter the coordinates of neighboring control points. Nowadays, the realization of a national CRS is made by means of permanent GNNS reference stations spaced at several tens of kilometers apart. At such distances the coordinates' changes due to crustal deformations become significant over much shorter timeframes.

In this study we investigate the crustal deformations in the Aetolia-Acarnania region, western Greece. This area is surrounded by a number of regions of different tectonic regimes like the Cephalonia Transform Fault and the gulfs of Patras and Corinth. Although there are no studies focusing exclusively in Aetolia and Acarnania, indications for deformations in the area can be found in more regional studies in western Greece. In our study we use GNSS measurements conducted in 2007 and 2023 to estimate the deformations in Aetolia and Acarnania.

2. SEISMOTECTONIC SETTING OF THE AREA

As depicted in Figure 1, the wider area of Aetolia and Acarnania, is surrounded by a number of significant tectonic features with different characteristics: a) the gulf of Patras and the Corinth gulf in the south known for extensional tectonics and high seismic activity [1], b) the dextral Cephalonia Transform Zone (CTF) in the southwest which accommodates the transition from the subduction of the African plate under the Aegean plate to the continental collision in the north [2], c) the Kyllini Cephalonia Fault (KCF) and d) the Movri-Amaliada Fault Zone (MAFZ) in the northwest Peloponnese. Moreover, the sinistral Katouna-Stamna Fault (KSF) runs across Acarnania and Aetolia close to their common boundary.

The above-mentioned faults play a crucial role in the kinematics of the region. The areas east of Cephalonia and Lefkada and the western part of Aetolia-Acarnania appear aseismic [3, 4]. According to Brooks et al. (2007) this region is considered to be an independent rigid block having different kinematics [5]. More specifically, Vassilakis et al. (2011) and Pérouse et al. (2017) proposed the existence of a region bounded by the Hellenic subduction zone, the CTF, the MAFZ and the KSF delimiting the margins of the Ionian Acarnania block [6, 7]. However, the exact boundary of this block is under discussion. For example, other researchers consider that the margins of this block are represented by the subduction front, the CTF, the Amvrakikos gulf, the KSF and the MAFZ [2**].** Chousianitis et al., 2015 using GPS data revealed two clockwise rotating blocks (curved arrows in Figure 1), one of those affecting the study area [8].

The complex tectonic regime in Aetolia-Acarnania outlined above is expected to lead to crustal deformations. Nevertheless, only few studies provide geodetic evidence of deformations in the area. Hollenstein et al. 2008 [9] analyzed campaign GPS data from the time period 1993-2003 and computed velocities on several points. The estimated velocities of selected points in and around Aetolia-Acarnania are depicted with blue arrows in Figure 1 [9]. The differences among the magnitude and the direction of the arrows indicate the deformations taking place in the area.

In this study we estimate coordinate changes in Aetolia-Acarnania by analyzing GPS data collected in 2007 and 2023. During this time period, a number of strong earthquakes occurred around the study area. Their epicenters are shown with stars in Figure 1 and their characteristics are outlined in Table 1 [10-13]. Based on the published works studying the deformation of these events, no one of these earthquakes is expected to have caused significant displacements (e.g. few cm) in Aetolia and Acarnania. To the best of our knowledge, the longest GPS slip vector in Aetolia-Acarnania is reported during the 2018 earthquake that occurred 45 km SSW from Zakynthos island; it refers to the city of Messologi (south-west Aetolia) and amounts ~5 mm [13]. However, as even small displacements that could have been caused by these earthquakes would lead to biased velocity estimations, in this work we estimate displacements rather than velocities.

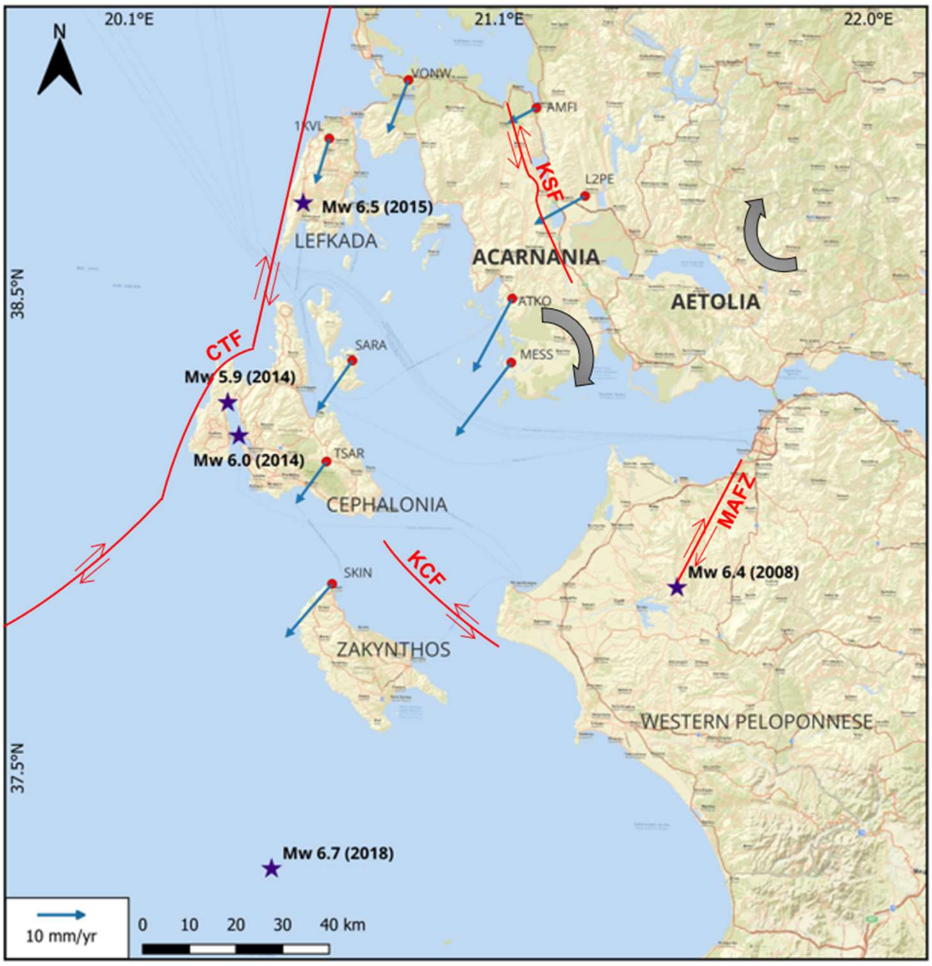

Figure 1. Seismotectonic setting of the wider area of Aetolia and Acarnania. Red lines indicate the major faults and are based on Haddad et al. 2020 [2]. Blue vectors are velocities (relative to Eurasia) on selected points after Hollenstein et al. 2008 [9]. Blue stars depict epicenters of strong earthquakes between 2007 and 2023 [10-13]. Gray curved arrows denote rotation patterns and are after Chousianitis et al. 2015 [8]. CTF: Cephalonia Transform Fault, MAFZ: Movri Amaliada Fault Zone, KCF: Kyllini Cephalonia Fault, KSF: Katouna-Stamna Fault

Table 1. Characteristics of strong earthquakes occurred in the wider area of Aetolia and Acarnania from 2008 to 2023 [10-13]

Date	Area	Magnitude (Mw)
08.06.2008	Movri (NW Peloponnese)	6.4
26.01.2014	Cephalonia	6.0
03.02.2014	Cephalonia	5.9
17.11.2015	Lefkada	6.5
25.10.2018	Zakynthos (45 km SSW offshore from Zakynthos island)	6.7

3. GNSS MEASUREMENTS AND DATA PROCESSING

For the purpose of assessing the crustal deformations in the study area we have conducted new measurements on 15 points which had been measured in 2007 during a nation-wide GPS campaign made for the establishment of HEPOS, the national RTK network of Greece [14]. During the 2007 campaign, a total of 2470 points of the national trigonometric network (i.e. ~10% of the complete network) have been occupied with GPS for the purpose of establishing the official coordinate transformation model between the national CRS and the geodetic reference frame of HEPOS (HTRS07: Hellenic Terrestrial Reference System 2007) [15], which consists a realization of ETRS89 (European Terrestrial Reference System 1989) in Greece [16]. In the 2007 campaign the determination of the HTRS07 coordinates was done by means of static GPS measurements of at least 1-hour duration, ensuring ~1 cm accuracy [14]. Following the same scheme, we re-occupied with GNSS receivers in 2023 15 points located in the study area. These points are shown in Figure 2 together with HEPOS station 001A, which was used as reference station and held fixed during the processing of the baselines using least squares adjustment. The measurements were conducted between 18 and 23 May 2023 using a Hi-Target iRTK5 geodetic receiver capable of tracking GPS, GLONASS, Galileo and BeiDou. The receiver at the station 001A was a Trimble Alloy receiver capable of tracking all GNNSs, as it is the case for all HEPOS stations after the system modernization [17]. The baseline length ranged from 11 to 47 km. A calibrated tribrach was used at the rover site to ensure precise leveling and centering of the GNSS antenna. Three typical examples of the points measured in 2023 are shown in Figure 3. The GNSS data were collected using a cut-off mask of 10 degrees and a sampling interval of 15 s. The observation duration at points with open sky view was one hour. An extended occupation time of

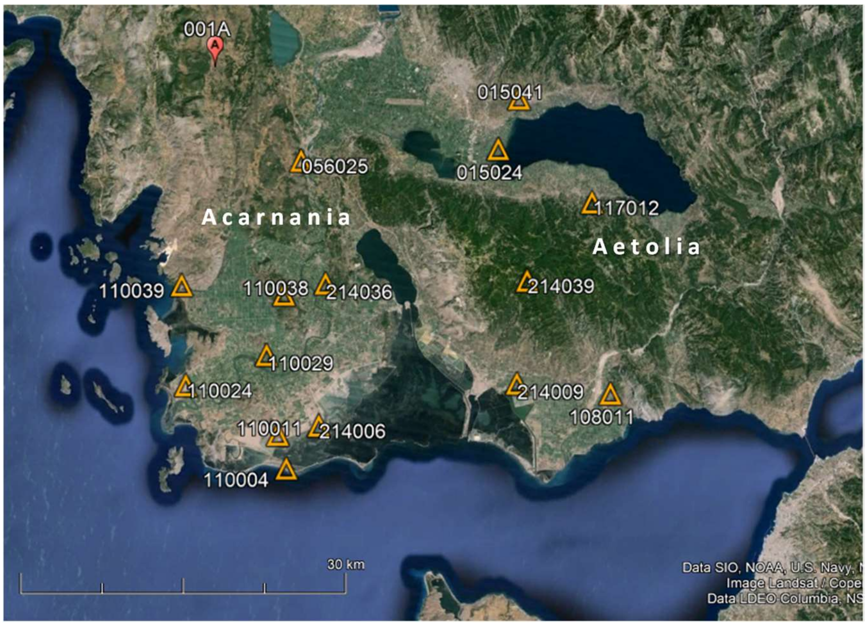

Figure 2. Locations of the HEPOS station 001A (red pin) and the trigonometric points (orange triangles) used in the study

Figure 3. Examples of the measurements conducted in 2023 (points from left to right are: 110024, 214009 and 110038)

1.5 hours was adopted at points 015024, 015041, 110039, 117012 and 214036 where tree canopies are slightly limiting the satellite visibility. The GNSS data processing was done using Trimble Business Center ver. 5.20 office software. A fixed solution was obtained for each baseline. The horizontal precision ranged from 0.003 to 0.011m, while the mean horizontal precision was 0.006 m (1-sigma).

4. RESULTS

The HTRS07 coordinates obtained from the 2023 measurements were compared to those of the 2007 campaign. The differences are given in Table 2. As the official HTRS07 coordinates of the HEPOS stations did not change since 2007 (static nature of HTRS07), the coordinate differences for station 001A are zero. On the contrary, significant coordinate differences were found for the trigonometric points, ranging between 1.5 and 16.8 cm (2D). These values reflect the horizontal displacements (from 2007 to 2023) relative to station 001A. Special attention should be paid in the case of point 110004, as its pillar has been found damaged, exhibiting an inclination. The deviation of the pillar w.r.t. the vertical was measured in the field and was found to be 4.5 degrees, whereas the

Table 2. Coordinate differences between 2007 and 2023

Point	dE (m)	dN (m)	dS (m)
001A	0.000	0.000	0.000
015024	-0.069	0.124	0.142
015041	-0.070	0.153	0.168
056025	0.002	-0.015	0.015
108011	-0.063	0.083	0.104
110004*	-0.101	-0.037	0.108
110011	-0.055	-0.020	0.059
110024	-0.040	0.001	0.040
110029	-0.035	-0.005	0.035
110038	-0.033	0.006	0.034
110039	-0.074	0.041	0.085
117012	-0.087	0.065	0.109
214006	-0.059	0.004	0.059
214009	-0.073	0.082	0.110
214036	-0.016	-0.001	0.016
214039	-0.087	0.086	0.122
(*) Inclined pillar: Results should be considered carefully.			

azimuth of the inclination was estimated to be 71^{o}. Using these values, the coordinates obtained from the baseline processing were corrected to refer to a non-inclined pillar. The coordinate differences given in Table 2 for point 110004 were computed from the reduced coordinates, so they can be considered as approximate displacement of the pillar as if it had not been inclined.

To visualize the spatial distribution of the estimated horizontal displacements, the displacement vectors are shown in Figure 4. It becomes obvious that the eastern part of the study area (Aetolia) is characterized by big displacements exceeding 10 cm. The western part (Acarnania) is characterized by considerably smaller displacements, but, in contrast to Aetolia, they are inhomogeneous. The estimated displacement vector of point 110004 (dashed arrow) generally fits with the displacement pattern in its neighborhood. This consists an indication that the reduction of the pillar inclination was successful.

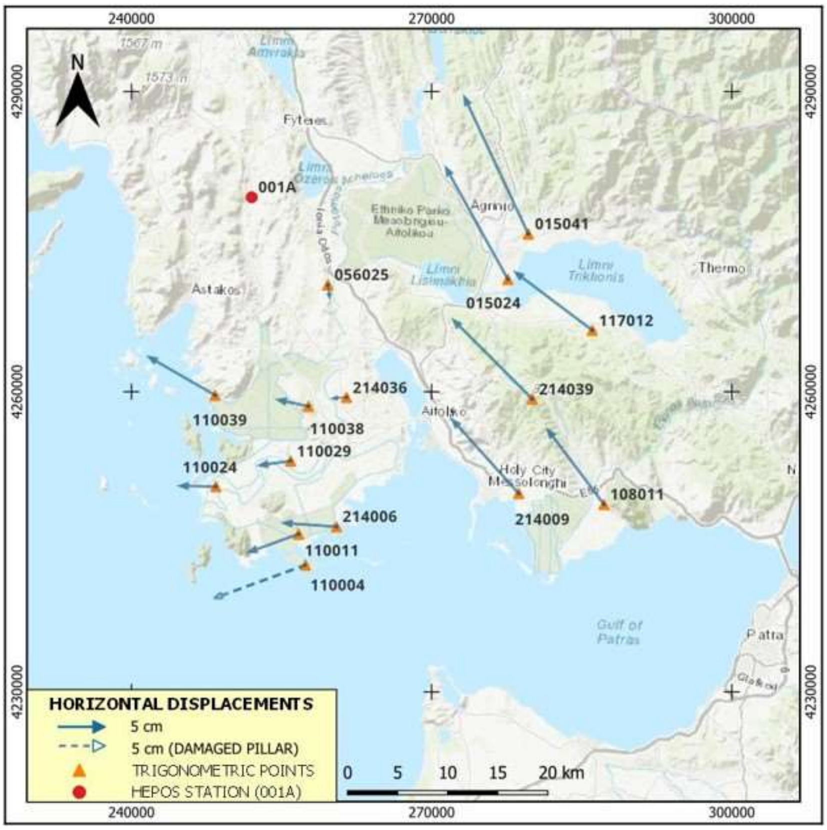

Figure 4. Horizontal displacements relative to station 001A (2007-2023)

Figure 4 illustrates well the cumulative deformations that took place in the study area between 2007 and 2023. This information is important for seismotectonic interpretations. However, from a geodetic point of view, the interest is in the differences between the coordinates of the trigonometric points that were estimated in 2023 and their official national coordinates. These deviations are shown in Figure 5. Comparing Figures 4 and 5 we see similar, but not identical, patterns. This is due to the fact that the national coordinates are biased by inherent errors of the triangulations made in the 60s and 70s when the national trigonometric network was established.

Figure 5 shows the deviations of the 2023 coordinates of the trigonometric points from the official coordinates. To demonstrate how the deformations in the area degrade over time the determination of national coordinates using a GNSS network, Figure 6 illustrates the differences between official values of the trigonometric points and the coordinates estimated in 2007. As we see in Figure 6, in 2007 the horizontal deviations were on the cm level for the vast majority of the points (with the exception of points 214039 and 015024 deviating 3.5 and 8.2 cm, respectively. These small deviations of the 2007 coordinates were expected as the transformation model between HTRS07 and the national CRS was established based on the 2007 campaign. Comparing Figures 5 and 6, the effect of the deformations that took place between 2007 and 2023 become obvious.

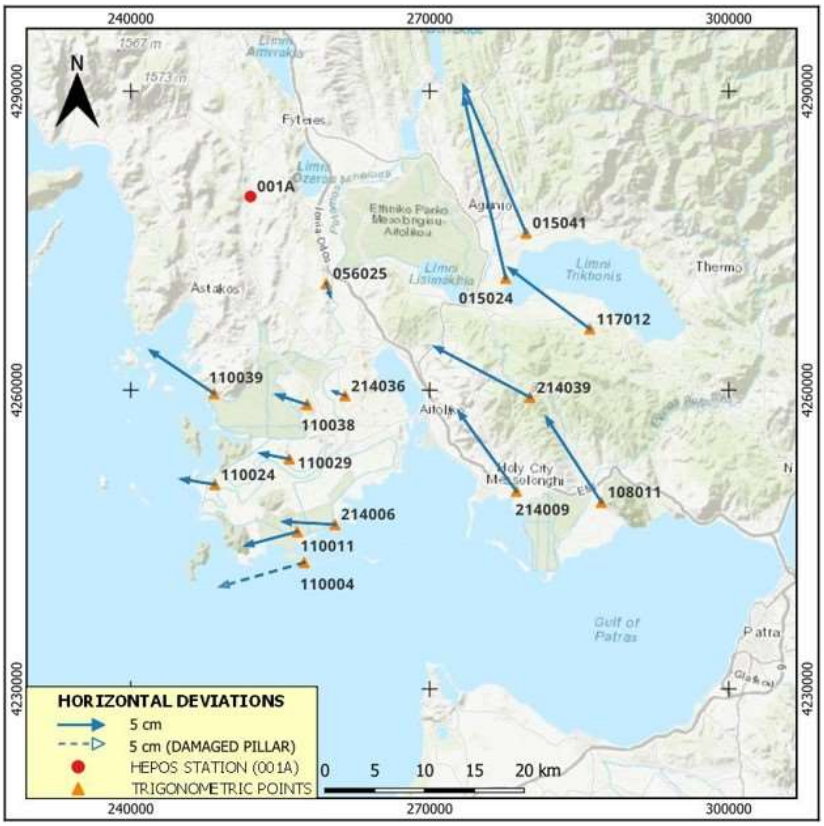

Figure 5. Horizontal deviations between the official national coordinates of the trigonometric points and the coordinates estimated from the 2023 measurements

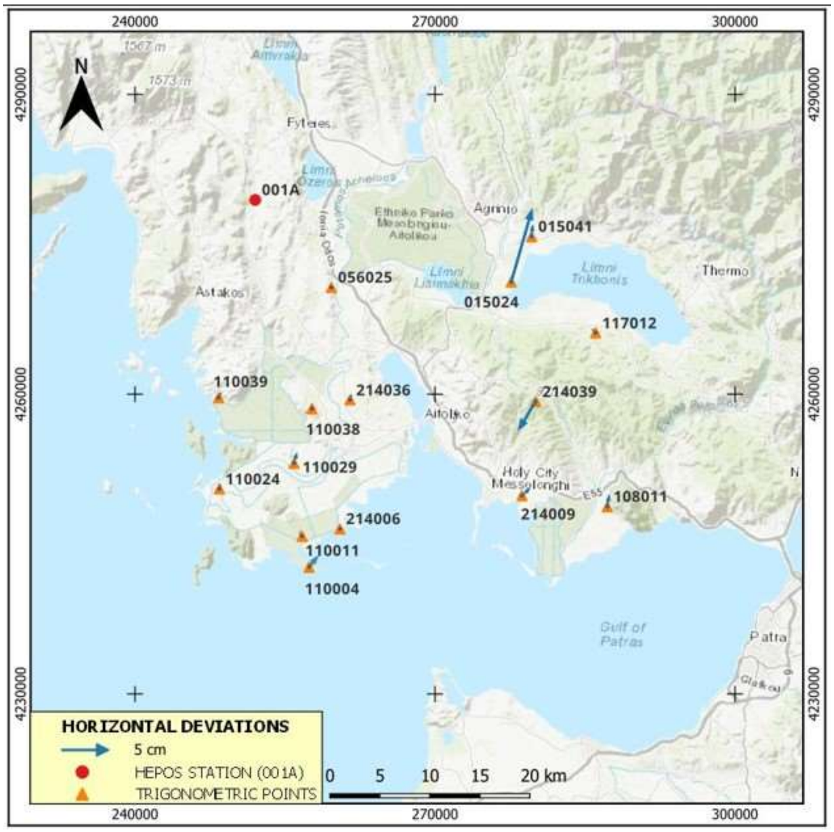

Figure 6. Horizontal deviations between the official national coordinates of the trigonometric points and the coordinates estimated from the 2007 measurements

5. DISCUSSION-CONCLUSIONS

The analysis of the previous section revealed the significant crustal deformations that took place in the study area between 2007 and 2023. On seven of the fifteen examined points the horizontal displacement relative to station 001A exceeded 10 cm, reaching a maximum value of 17 cm. The estimated displacements incorporate the effects of both the constant motions of the involved crustal blocks and the earthquakes occurred within the study time period. However, as mentioned in section 2, no one of these earthquakes is expected to have caused significant displacements (e.g. few cm) in Aetolia and Acarnania. Thus, the revealed displacements can mainly be attributed to ongoing deformations that are taking place in the area due to the complex tectonic regime described in section 2. In any case, the estimation of accurate velocities requires the existence of a dense network of permanent GNSS stations carefully constructed with solid foundations (ideally on bedrock), which would be very useful for understanding and precisely describing the local kinematics.

The inspection of the estimated displacements shown in Figure 4 revealed that the points in Aetolia are characterized by big displacements, whereas the points in Acarnania are exhibiting considerably smaller displacements. Thus, one may assume that the study area is divided into two main crustal blocks with different kinematics. These two blocks are on either side of the left lateral Katouna-Stamna Fault, which appears to be responsible for the abrupt velocity change. This outcome is in accordance with the findings of a recent study by Chousianitis et al., 2024 [18] which demonstrates the key role of the KSF. However, a denser network of points would be required in order to confirm if the KFS is precisely the boundary of the two blocks.

Another observation resulting from the data analysis is that the displacements in Acarnania area are not homogeneous neither in direction nor in magnitude. This finding is in accordance with the velocities reported by Hollenstein et al (2008) indicating a deforming area. However, as between 2007 and 2023 several strong earthquakes stroke between around Acarnania (Table 1), much more data are needed to draw firm conclusions about whether the revealed inhomogeneity is solely due to ongoing deformations or whether it is (also) due to displacements induced by the earthquakes.

From a geodetic point of view, active deformations consist a serious problem as they lead to coordinate changes. For the reasons explained in section 1, the modern way of realizing a national CRS using GNSS reference stations is more susceptible to deformations than the classical realization of a CRS using trigonometric networks. This becomes more obvious based on the results presented in Figure 4. For example, if a surveyor sets every year a GNNS base receiver on point 108011 and checks the coordinates of point 214009, he/she will always find values close to the nominal coordinates of the point, as the relative positions of the two points remain more or less unchanged. In contrast, if the surveyor uses the reference station for this purpose, he/she will find coordinate differences that increase with time.

The maintenance of a national CRS in the presence of crustal deformations is a demanding task. From a theoretical perspective the solution to this problem would be the adoption of a semi-dynamic datum. However, in the presence of both constant and abrupt (due to earthquakes) deformations, the modelling of time-dependent corrections becomes very challenging, as it requires immediate modelling of the deformations caused by each strong event and incorporation into the time-dependent transformation procedure. As long as no decision to adopt a semi-dynamic datum is taken, a way to mitigate the implications of crustal deformations would be the densification of GNSS reference stations in deforming areas.

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