Tectonic deformations in Greece and the operation of HEPOS network

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Abstract

Today, networks of permanent reference stations are broadly used for the realization of national Geodetic Reference Systems. Furthermore, single-base GNSS positioning is progressively being replaced by network-based techniques like VRS, FKP and MAC. These techniques model the error sources in order to eliminate the distance-dependent errors in relative GNSS geodetic positioning. The effective modelling of the error sources requires highly accurate coordinates of the reference stations. Site displacements can affect the estimation of error models, degrading the performance of the network. Besides monumentation instabilities and other issues, site displacements can also be caused by tectonic activity.

Unlike the majority of European countries, Greece is characterized by strong tectonic activity. Moreover, the Greek area extends over different tectonic plates having individual velocities. This results in a complex velocity field. The situation has to be taken into account in the operation of the Hellenic Positioning System (HEPOS), an RTK network consisting of 98 permanent GPS reference stations distributed throughout Greece. HEPOS is operational since the end of 2007. Observations collected at the HEPOS stations for more than two years have been processed in order to estimate the velocity characteristics of each station. This paper describes the processing strategy and presents the results, which reveal an inhomogeneous deformation field. The impact of station displacements on the network operation is discussed.

1 Existing knowledge on tectonic activity in Greece

Greece lies in the boundary region between two major tectonic plates, the Eurasian and the African plate (Figure 1). In addition, the southern part of Greece lies on the Aegean plate, a smaller plate which is moving southwest (Papazachos et al., 2000). This situation leads to a complex deformation field.

1.1 Results obtained by analyzing EPN data

The different tectonic characteristics of Greece when compared to central Europe have been easily confirmed by analyzing the EPN data. Using the coordinate velocities V_X V_Y V_Z, 3D velocity vectors were computed for three selected stations in central Europe as well as for three Greek EPN stations. At the time of writing, a total of six EPN stations operate in Greece, however velocities are issued only for the three older stations. The velocities are computed in ETRF2000 using the EUREF solution C1570. The names and the locations of the six stations are given in Figure 2. The computed velocity vectors are given in Table 1. By examining the values in Table 1, it can be concluded that:

- The velocities of the Greek stations are roughly one order of magnitude higher than those of the stations in central Europe.
- The velocity of AUT1 in Northern Greece (Thessaloniki) is considerably smaller than those of NOA1 (Athens) and TUC2 (Chania). The higher velocities of NOA1 and TUC2 were expected because both belong to the Aegean plate.

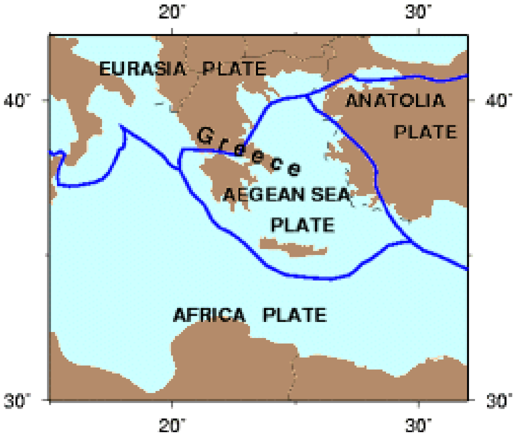

Fig. 1 Approximate boundaries of the Aegean Sea plate (*source: USGS*)

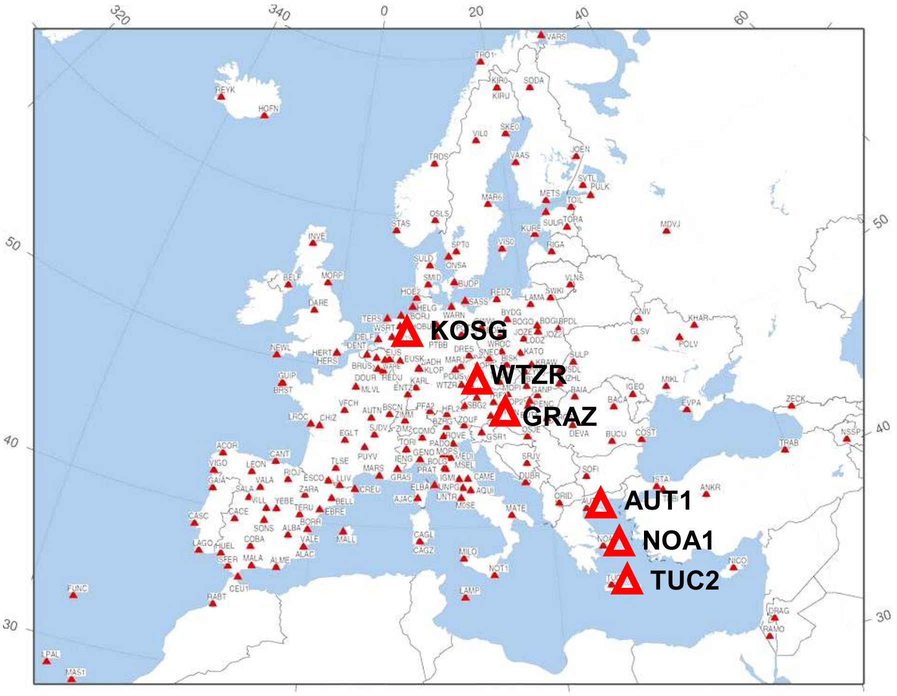

Fig. 2 The locations of the six EPN stations referred in Table 1.

Table 1 Velocity vectors for different EPN stations .

Country	**Station**	**3D velocity vector** [mm/year]
Holland	KOSG	0.0007
Germany	WTZR	0.0008
Austria	GRAZ	0.0011
Greece (Northern)	AUT1	0.0090
Greece (Central)	NOA1	0.0307
Greece (South)	TUC2	0.0312

In addition to the above example, the 3D velocity vectors for all EPN stations have been computed and examined. Table 2 gives the 18 EPN stations having the highest velocities (values are sorted in ascending order). It can be seen that:

- NOA1 (Athens) and TUC2 (Crete) are the most tectonically active stations within the EPN network; their velocities exceed 3 cm/year.
- AUT1 is significantly more stable having a 3D velocity of less than 1 cm/year.

Table 2 The EPN stations with the highest velocities.

Country	Station	Vx	Vy	Vz	V_{3D}
Israel	RAMO	-0.0013	-0.0052	0.0069	0.0087
Greece	**AUT1**	**0.0024**	**0.0021**	**-0.0086**	**0.0092**
Israel	DRAG	0.0015	-0.0026	0.0092	0.0097
Finland	VAAS	0.0047	0.0016	0.0087	0.0100
Sweden	VIL0	0.0040	0.0001	0.0095	0.0103
Spain	ALBA	-0.0084	-0.0017	-0.0073	0.0113
Sweden	SKE0	0.0048	0.0010	0.0111	0.0121
Iceland	HOFN	0.0076	0.0022	0.0114	0.0139
Portugal	PDEL	-0.0114	0.0078	-0.0094	0.0167
Greenland	THU3	-0.0123	-0.0102	0.0074	0.0176
Greenland	KELY	-0.0140	-0.0114	0.0001	0.0181
Iceland	REYK	-0.0118	-0.0155	-0.0011	0.0195
Greenland	QAQ1	-0.0153	-0.0142	0.0009	0.0209
Turkey	TUBI	0.0047	0.0190	-0.0089	0.0215
Turkey	ANKR	0.0120	-0.0216	-0.0018	0.0248
Greece	**NOA1**	**0.0196**	**-0.0096**	**-0.0212**	**0.0304**
Greece	**TUC2**	**0.0197**	**-0.0095**	**-0.0224**	**0.0313**

1.2 Results obtained from research projects

In order to determine the deformation field in Greece, several research projects have been carried out during the last two decades. These projects estimated the so-called geodetically derived velocities using GPS measurements. Figure 3 shows the velocities obtained from six different studies after unifying the results and expressing them in a Eurasia-fixed frame (Nyst and Thatcher, 2004). The similar characteristics of the points belonging to the Aegean plate are obvious.

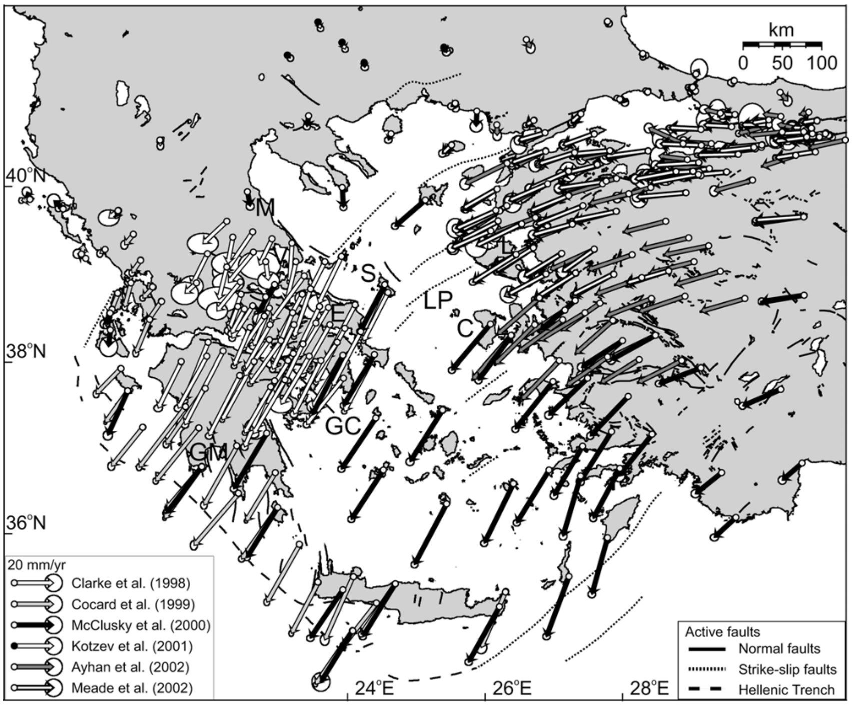

Fig. 3 Geodetically derived velocities relative to Eurasia (Nyst and Thatcher, 2004)

2 Tectonic displacements estimated by HEPOS

As discussed above, the deformation field in Greece is inhomogeneous. In order to estimate the boundaries of the rigid elements and the respective deformation zones a dense network of points is required. HEPOS consists of 98 permanent reference stations distributed throughout Greece (Figure 4) offering good opportunities for geodynamic research. Details about HEPOS can be found in *Gianniou et al.* (2009).

The HEPOS network is fully operational since the end of 2007. Within this study, the data from the first two years of operation of HEPOS were analyzed.

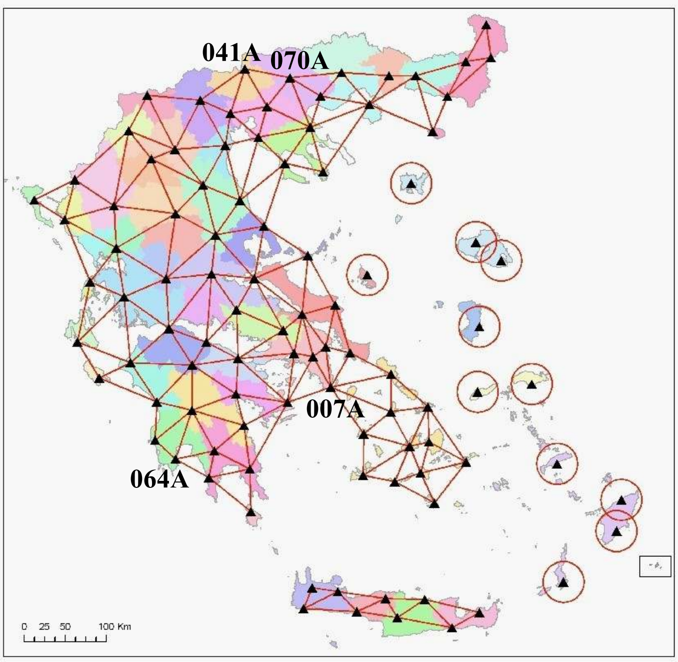

Fig. 4 The HEPOS network and the locations of stations 041A, 070A, 007A and 064A.

2.1 Processing strategy

To obtain coordinate time-series, a solution was computed for every month from October 2007 to December 2009. Each monthly solution was computed using 48 hours of data collected at all stations. The baselines were processed using IGS final orbits and a least-squares network adjustment is performed in ITRF2005 to compute the monthly solution. As a first step we focused on the estimation of relative deformations within the HEPOS network. The main target was to estimate the magnitude of the relative deformations, so there was no necessity to transform the results from ITRF2005 to HTRS07 or ETRF2000. In order to compute relative deformations, station 041A was chosen as reference. The coordinate rates of 041A were subtracted from all stations. In this way, station 041A appears stable in time and the changes in coordinates of all other stations are given with respect to 041A. Although, the relative deformations could have been expressed with respect to any HEPOS station, station 041A was chosen as reference because it lies in the northern part of the network (Figure 4) and has the advantage of being one of the most stable HEPOS stations with respect to ETRS89.

2.2 Dynamic characteristics of the stations

Following the above described processing schema, the coordinate time-series for all stations were produced. By analyzing these time-series three major categories of stations were distinguished:

- Stations showing zero-trend
- Stations showing a constant trend
- Stations showing both constant trend and abrupt variations

In the following, typical examples are given, based on the results for stations 070A, 007A and 064A. As can be seen in Figure 4 stations 007A and 064A lie on the Aegean Sea plate. Figures 5-6 refer to station 070A, Figures 7-8 to station 007A and Figures 9-10 to station 064A. For comparison purposes the range of Y-axis and the grid interval are the same in all figures. As can bee seen in Figures 5-6, station 070A shows practically no-trend. This was expected because 070A is located next to station 041A. Examining the results for station 007A, the significant trend in the coordinate variations becomes obvious. This behavior is well explained by the fact that station 007A lies on the Aegean Sea plate. Similar trends like those of 007A were detected also for station 064A. However, in the case of station 064A, besides the constant trend, abrupt variations are also detectable (Figure 10). The abrupt change of about 2 cm in Northing of station 064A is due to a strong earthquake that stroke on 14.2.2008, having its epicenter in the sea about 60 Km SW of station 064A. The effects of this earthquake were the strongest among four different cases investigated by analyzing daily solutions. Details can be found in *Gianniou* (2010).

2.3 Deformation field

Examining Figures 5-10 we can say that, within the observation period of 2 years, the coordinates varied from about 0 cm (station 070A) up to about 9 cm (station 064A). In order to

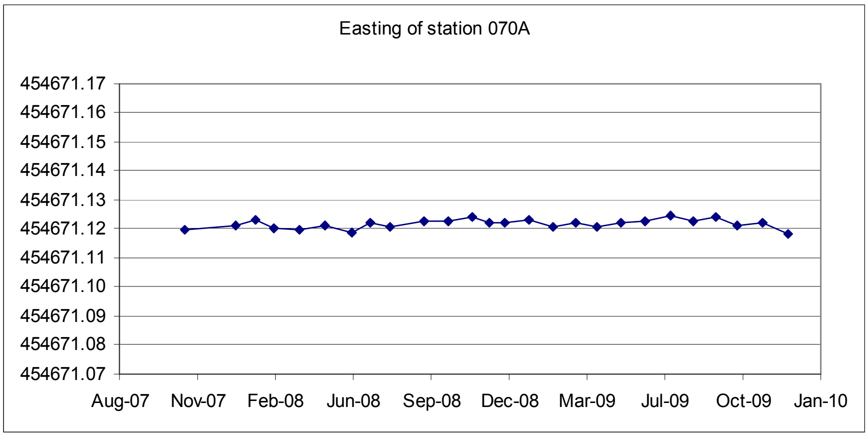

Fig. 5 Example of “zero” trend: Station 070A (Easting)

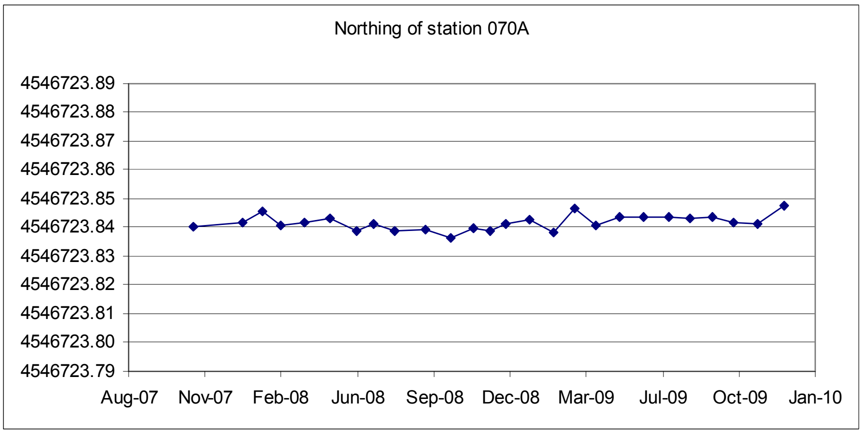

Fig. 6 Example of “zero” trend: Station 070A (Northing)

obtain an overview over the complete network, horizontal translation vectors were estimated for all stations. These translation vectors are given in Figure 11. Observing the translation vectors it becomes obvious that the deformation field of Greece is strongly inhomogeneous. The stations lying on the Aegean plate show totally different characteristics than the stations in northern Greece.

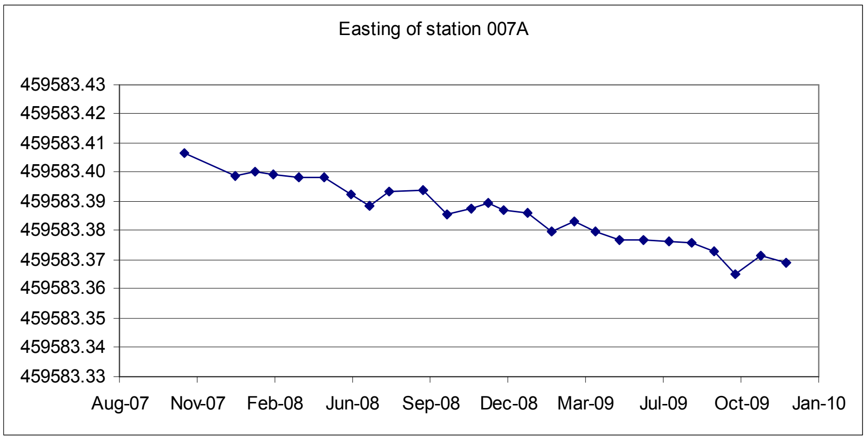

Fig. 7 Example of constant trend: Station 007A (Easting)

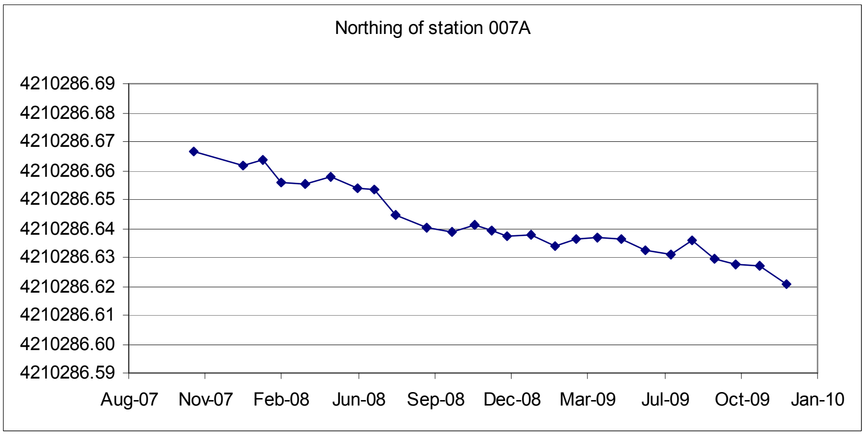

Fig. 8 Example of constant trend: Station 007A (Northing)

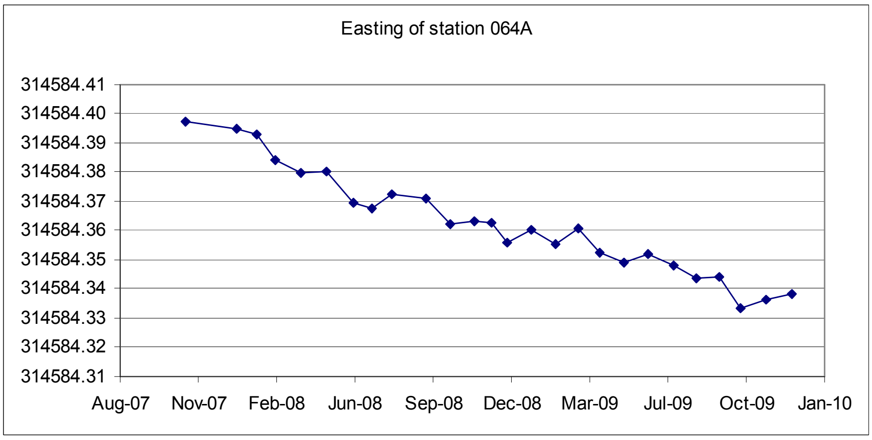

Fig. 9 Example of constant trend and abrupt change due to an earthquake (stroke in February 2008): Station 064A (Easting). The abrupt change affects practically only Northing (see Figure 10).

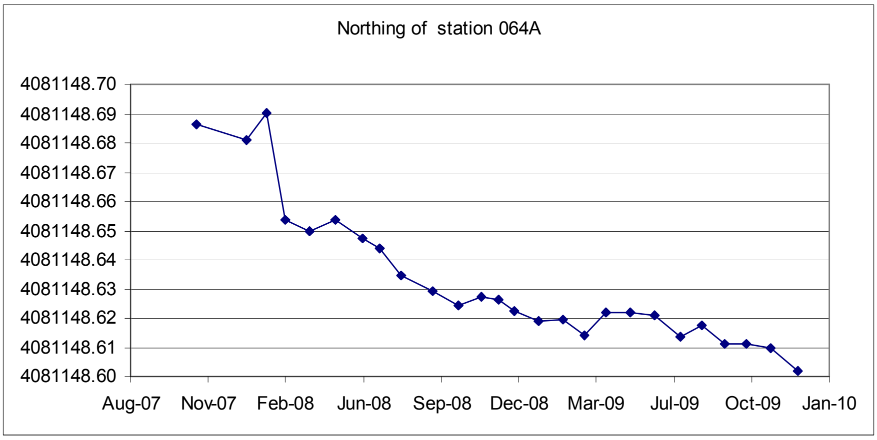

Fig. 10 Example of constant trend and abrupt change due to an earthquake (stroke in February 2008): Station 064A (Northing).

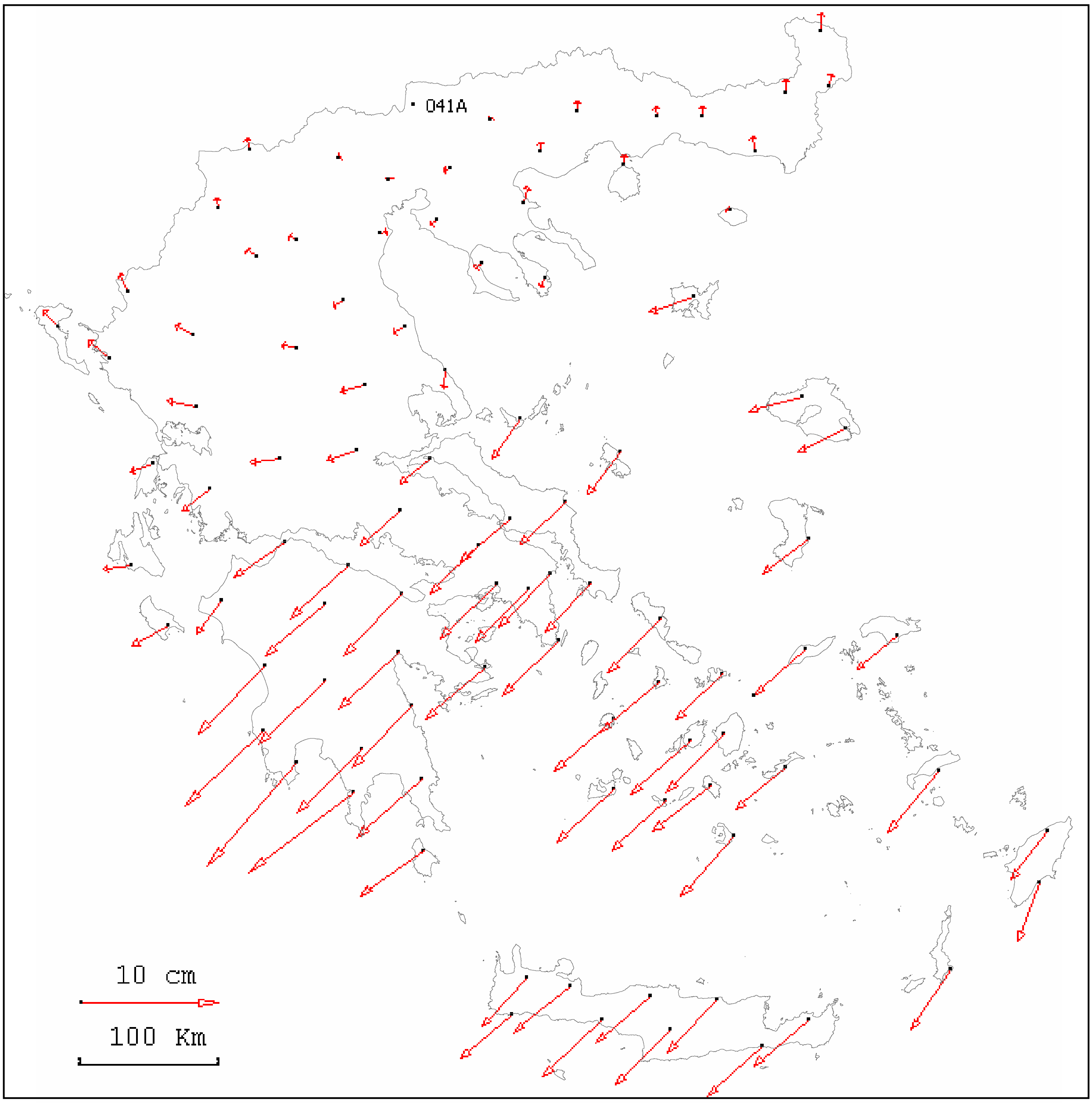

Fig. 11 Horizontal displacements of the HEPOS stations within the first 2 years of operation.

3 Summary and discussion

The purpose of this study was to investigate the impact of tectonic deformations on the geometry of the HEPOS network. For the operation of any RTK network it is important that the coordinates of the stations are estimated with high accuracy at the 1 cm level. For the effective error modelling and the ambiguity resolution within the network the relative accuracy of the station coordinates is even more important than the absolute accuracy. For this reason we estimated relative displacements rather than absolute values. As can be seen in Figure 11, there are significant relative movements between the northern and the southern part of the network. However, the relative motions within each part are quite small. This offers the possibility to consider two sub-networks (with an overlap at the transition zone) and to model each sub-network separately. This strategy together with other alternative scenarios is currently under evaluation in order to find the best way to treat the effects of tectonic deformations.

The results of this study are valuable not only for the operation of HEPOS but also for geodynamic research. Within this study relative displacement have been estimated rather than tectonic velocities which are used in geodynamic research. Although, the displacement estimated within this study cannot be compared directly to the tectonic velocities estimated by other projects, the estimated strain fields can be compared. The results of this study verify the exiting knowledge about the strain field in Greece, e.g. *Kahle et al.*(1995), *Hollenstein et al.* (2006), *Nyst and Thatcher* (2004). This becomes obvious by comparing the Figures 3 and 11. So it can be concluded that the high density and the homogeneity of the HEPOS data allow the reliable determination of the boundaries of the Aegean Sea plate and the deformation zones. As next steps the expression of the results in ETRS89 and the estimation of station velocities are planned.

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