Estimation of tectonic velocities using GPS Precise Point Positioning: The case of Hellenic RTK network HEPOS

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Abstract

GPS data recorded at the stations of the Hellenic Positioning System (HEPOS) are processed to estimate station velocities. The Precise Point Positioning (PPP) technique is used to process data spanning from January 2008 to June 2015. A daily solution is computed for each month of the aforementioned time period of 7.5 years. The computed ITRF coordinates are transformed to ETRF2000, so that the estimated velocities refer to ERTS89. Special attention is paid to local effects, like permanent displacements caused by strong earthquakes and the 2011-2012 Santorini volcano inflation.

In order to assess the accuracy and reliability of the results, data from six Greek stations of the EUREF Permanent Network (EPN) were processed in addition to the HEPOS data. The PPP-derived velocities for the Class A EPN stations were found to be consistent with the velocities estimated by EUREF at the 10^{-4} m/yr level. These results confirm the suitability of the PPP technique for the estimation of tectonic velocities of permanent reference stations provided that data spanning over several years are available. Concluding, the estimated tectonic velocities are valuable for the ongoing efforts of estimating a detailed velocity field in Europe and developing a strategy to cope with tectonic motions.

Keywords: *Tectonic velocities; Precise Point Positioning; ETRS89; HEPOS.*

1. Introduction

Greece lies in the boundary region between the Eurasian and the African plate. In addition, the southern part of the country lies on the Aegean plate, a smaller plate which is moving southwest (Papazachos et al., 2000). Furthermore, Greece is the seismically most active area in Europe. Strong earthquakes often cause permanent displacements leading to discontinuities in the time-series of the stations' coordinates. This situation leads to a complex and inhomogeneous velocity field which plays a critical role in the operation of HEPOS. The problem of maintaining a reference frame in seismo-tectonically active areas is being studied at international level. In this context the EUREF Technical Working Group has set up two initiatives: the EPN densification project and the EUREF Working Group on Deformation Models (Bruyninx et al., 2015).

The changes in the geometry of the HEPOS network as a result of the different station velocities have been investigated already during the first two years of operation of the network (Gianniou, 2010). In order to study in detail the velocity field in Greece the National Cadastre and Mapping Agency (NCMA S.A.) analysed 7.5 years of HEPOS data and estimated precise velocities for the network stations. This article describes the dataset used, the processing strategy, the obtained results and their validation. Special attention is paid to the effect of geological phenomena like earthquakes and volcanic activity.

2. Dataset

The dataset used for the estimation of the velocities consists of a total of 104 reference stations, i.e. the 98 HEPOS stations and six Greek EPN stations. The EPN stations offer an excellent opportunity to validate our results, as highly accurate velocities are published by EUREF for the

Class A EPN stations. Among the six used Greek EPN stations, four stations are of Class A (AUT1, DUTH, PAT0, TUC2) and two stations are of Class B (LARM, NOA1). According to the EPN website “Stations are in Class B because of a short time frame of SINEX availability or a higher noise level (including the seasonal variability) of the position time-series”. In particular, stations NOA1 and LARM are characterized as Class B due to noisy observations (http://epncb.oma.be/_productsservices/coordinates/classB_noisy.lst). Although for Class B stations no velocities are published by EUREF we chose to include LARM and NOA1 in the computations, as they allow us to evaluate the PPP-solutions under challenging conditions. The locations of the 104 stations used in the project are shown in Fig. 1. The seventh Greek EPN station DYNG was not incorporated in the processing, because it was included in the EPN computations just in late 2013 (DOY 293), whereas the HEPOS time-series are considerably longer, starting in 2008. Table 1 summarizes the details concerning the time span of the processed data.

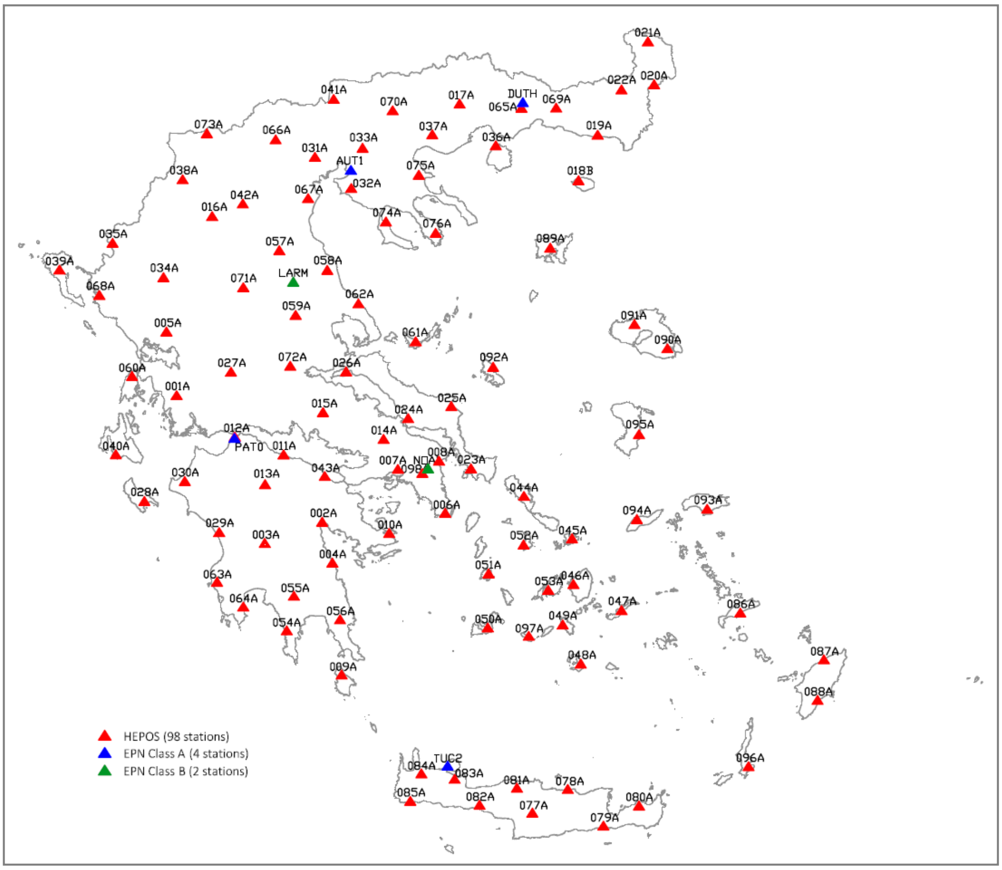

Fig. 1 The locations of the 104 reference stations included in the computations.

Table 1 Data span of the processed data

Stations			**Observations**	
Network	**#**	**Station code**	**Time period**	**Duration (years)**
HEPOS	98	001A-098A	2008.0 - 2015.5	7.5
EPN Class A	4	AUT1	2008.0 - 2015.5	7.5
		TUC2	2008.0 - 2015.5	7.5
		DUTH	2008.7 - 2015.5	6.8
		PAT0	2009.1 - 2015.5	6.4
EPN Class B	2	NOA1	2008.0 - 2015.5	7.5
		LARM	2011.1 - 2015.5	4.4
Total	*104*			

3. Processing strategy

The GNSS data were processed using the Precise Point Positioning technique (Zumberge et al., 1997; Héroux and Kouba, 2001) in static mode and the CSRS (Canadian Spatial Reference System) PPP software. Dual frequency phase observations were used together with IGS final precise orbits (*sp3* files) and clocks (*clk* files) (Kouba, 2003). The ionosphere free linear combination was used to reduce the ionospheric error, while the tropospheric zenith delay was estimated. The processing interval was 30s and the elevation mask 10^{o}. Instead of processing each day of the available data one daily solution was computed for each month. Thus, a time-series of 90 solutions was produced for each of the 101 stations having full data availability (2008.0-2015.5; see Table 1). For the stations DUTH, PAT0 and LARM the time-series consist of 82, 76 and 55 solutions, respectively.

As known, the PPP-estimated coordinates are expressed in the reference frame in which the precise satellite orbits are expressed. Due to the long time span of the processed observations, the precise orbits –and consequently the results– were expressed in two different frames, namely ITRF2005 (IGS05) and ITRF2008 (IGS08, IGb08). In order to have all results expressed in the same frame, the ITRF2005 coordinates were transformed into ITRF2008. Afterwards, the ITRF2008 coordinates were transformed into ERTF2000 (Boucher and Altamimi, 2008). The ETRF2000 coordinates were projected into the main zone of TM87 projection of the national Coordinate Reference System GGRS87 (Greek Geodetic Reference System 1987) (Katsampalos et al., 2010). Before estimating the horizontal velocities, the time-series of the coordinates were inspected for discontinuities of any kind. As expected, discontinuities in the time-series were found for stations in areas where earthquakes and other geological phenomena took place in the time period under consideration (2008.0-2015.5). Detailed results are given in the next section.

4. Results

With the exception of certain stations affected by geological events like earthquakes the vast majority of the obtained time-series are characterized by clear trends. In the following, representative examples of the produced time-series are given.

4.1 Ordinary time-series

Fig. 2 - Fig. 4 depict the time-series for three stations of different horizontal velocities. Fig. 2 refers to a station of relatively small velocity (0.0023 m/yr), Fig. 3 refers to a station of moderate velocity (0.0104 m/yr) and Fig. 4 refers to a station of high velocity (0.0297 m/yr). The solid red lines in Fig. 2-4 represent the linear trends calculated by means of least squares. From Fig. 2 it comes out that the length of the time-series (7.5 years) is sufficient to estimate reliable horizontal velocities, even in the order of 2 mm/yr.

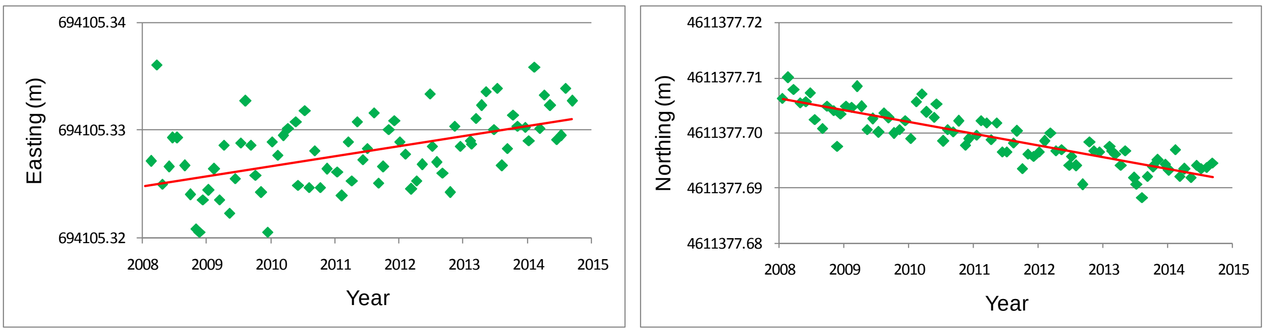

Fig. 2 Time-series for Easting (left) and Northing (right) for a station of relatively small velocity: HEPOS station 021A in northeastern Greece.

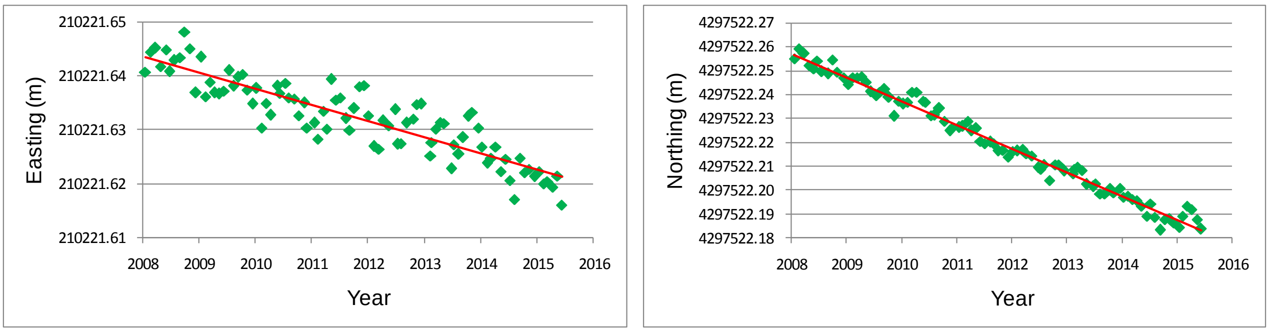

Fig. 3 Time-series for Easting (left) and Northing (right) for a station of moderate velocity: HEPOS station 060A on Cephalonia Island, Ionian Sea.

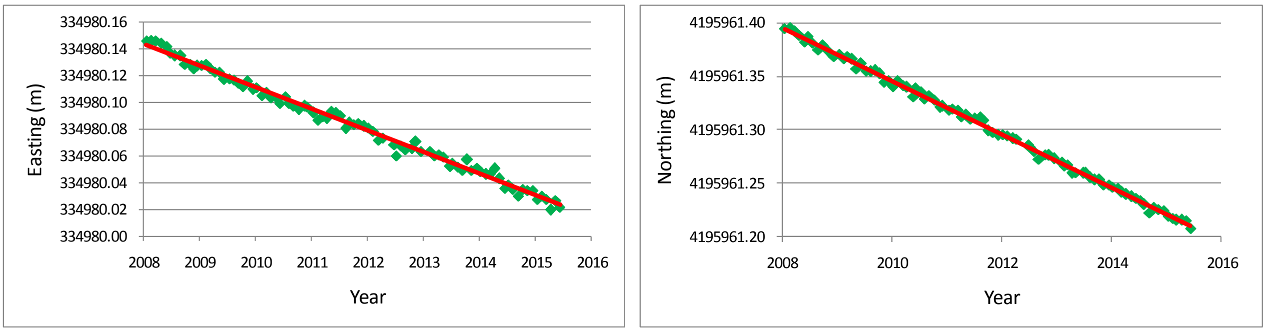

Fig. 4 Time-series for Easting (left) and Northing (right) for a station of high velocity: HEPOS station 013A in northern Peloponnese.

4.2 Time-series with discontinuities due to geological phenomena

On 24 May 2014 a shallow and strong M_w 6.9 earthquake occurred in northeastern Aegean Sea near Samothrace Island (Evangelidis, 2015). The earthquake caused significant permanent displacements of seven HEPOS stations in the wider area of the epicentre (Saltogianni et al., 2015). One of the mostly affected HEPOS stations was station 089A on the island of Lemnos. The effect of the earthquake can clearly be seen in Fig. 5 that gives the coordinates' time series for station 089A. For the estimation of the velocities of the affected stations only the solutions up to epoch 2014.39 were considered, as indicated by the solid red line in Fig. 5 for the case of station 089A.

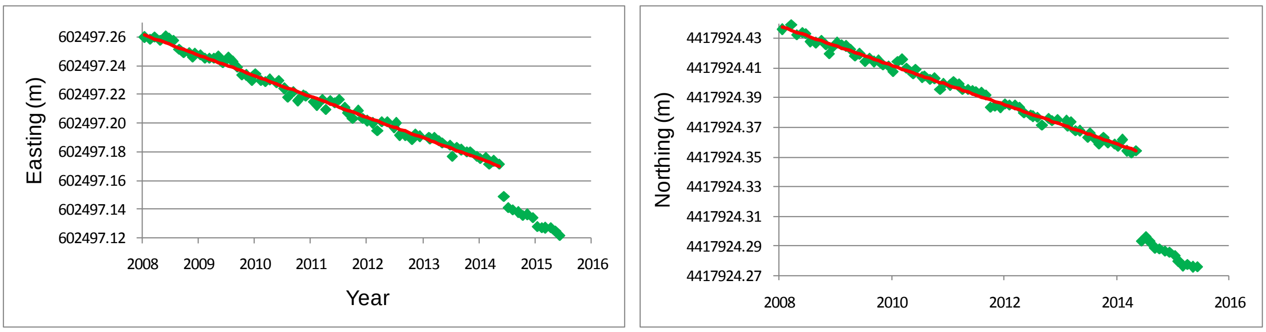

Fig. 5 Time-series for Easting (left) and Northing (right) of station 089A on Lemnos Island, affected by the 2014 Samothrace, North Aegean Sea earthquake.

Another geological event that influenced the produced time-series is the 2011-2012 inflation of the Santorini volcano (Papoutsis et al, 2013). Fig. 6 gives the coordinates' time series for station 048A which is located on the island. For each horizontal coordinate two different velocities have been computed; one velocity before the start of the inflation and one velocity after its end. These velocities are shown in Fig. 6 with purple and red colors, respectively. It is worthy to mention that the estimated velocities before and after the event are practically the same. In the case of Easting they differ 0.2 mm/yr and in the case of Northing they differ 0.1 mm/yr.

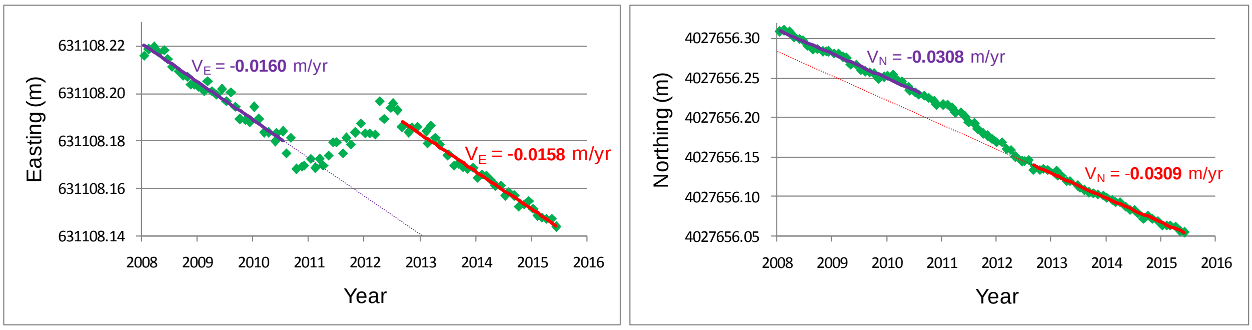

Fig. 6 Time-series for Easting (left) and Northing (right) of station 048A on Santorini Island, affected by the 2011-2012 volcano inflation. Dashed lines denote extrapolation of the linear trends outside of the estimation intervals.

Besides the 2014 Samothrace earthquake and the 2011-2012 inflation of the Santorini volcano three other events were considered for the estimation of station velocities. Table 2 summarizes the geological events of which the effects have been removed.

Table 2 Geological phenomena considered for the estimation of stations velocities

Event	Date	Area	Type
1	14/2/2008	Methoni	Earthquake (Mw 6.7, D: 35 km)
2	8/6/2008	Andravida	Earthquake (Mw 6.4, D: 31 km)
3	26/1/2014 3/2/2014	Cephalonia	Earthquake (Mw 6.1, D: 16 km) Earthquake (Mw 5.9, D: 5 km)
4	24/5/2014	Samothrace	Earthquake (Mw 6.9, D: 11 km)
5	2011-2012	Santorini	Volcano inflation

4.3 Velocity field

The estimated horizontal velocities for all stations participated in the project are depicted in Fig. 7. The obtained velocity field is consistent with previously published results (Nyst and Thatcher, 2004; Chatzinikos et al, 2013) and has the advantage of being based on homogeneous data set, i.e. uniformly distributed stations and long time-series (90 monthly solutions spread over 7.5 years). It is worthy to mention the wide range of the estimated velocities, which spans from the sub-mm/yr level to more than 3 cm/yr, as it is summarized in Table 3. Clearly, Greece is not only the country with the highest ETRS89 velocities in Europe 9 (Gianniou, 2010), but also the country with the highest differences in the velocities.

Table 3 Minimum and maximum estimated ETRS89 velocities

Station	Area	Horizontal velocity	Remark
039A	Corfu Island, Ionian Sea	0.0009 m/yr	Smallest velocity nation-wide
063A	Southwestern Peloponnese	0.0363 m/yr	Highest velocity nation-wide

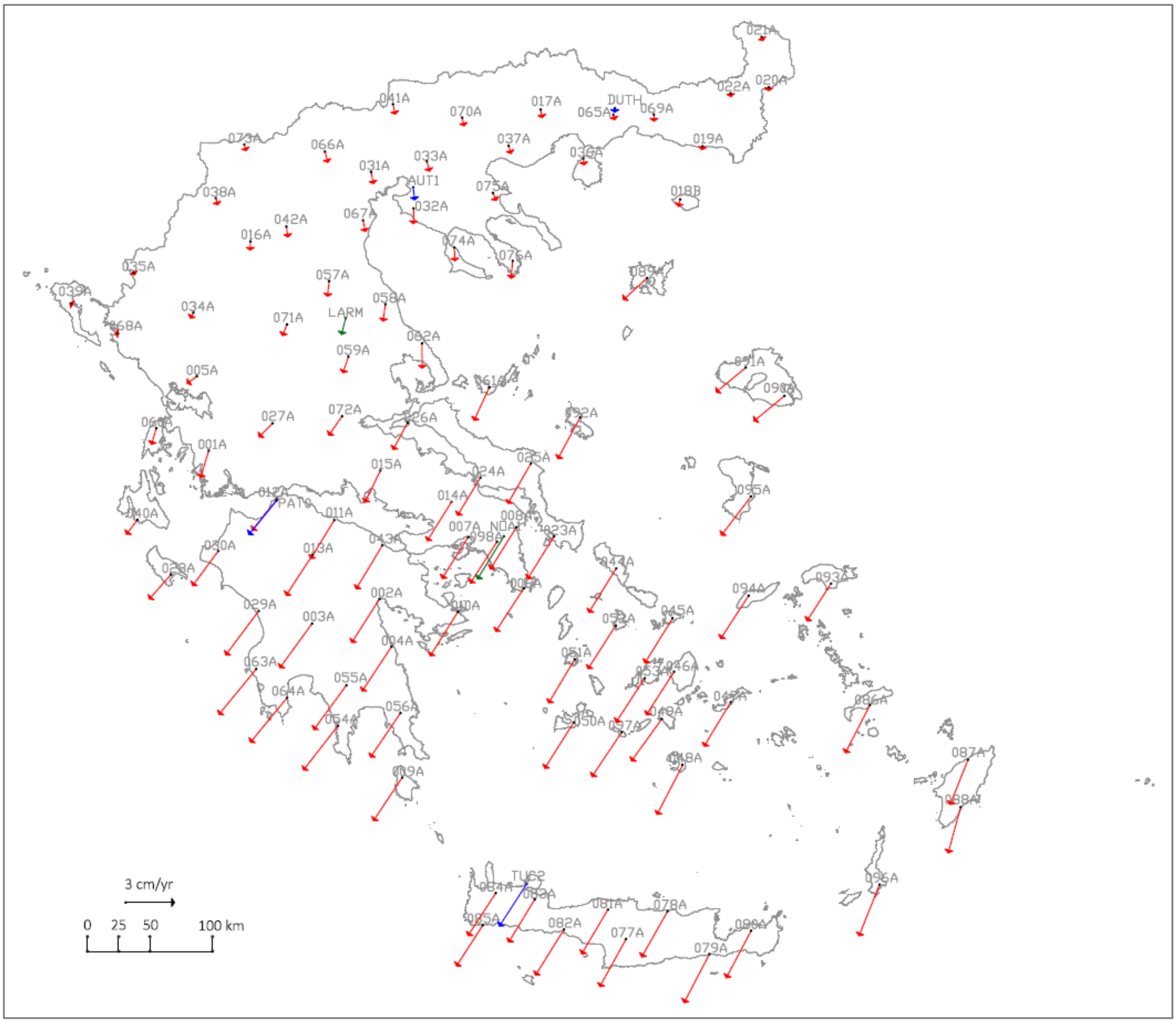

Fig. 7 Estimated horizontal velocities in ETRF2000 for HEPOS stations (red arrows) and EPN Class B stations (green arrows). For comparison reasons the velocities published by EUREF for the EPN Class A stations are also shown (blue arrows).

4.4 Validation of the results

In order to validate the reliability of the results, the estimated ITRF2008(IGb08) velocities of the four EPN Class A stations were compared to the velocities published by EURF (EPN cumulative solution C1875). The comparison results are summarized in Table 4. As can be seen, the estimated velocities agree with the velocities published by EUREF in the order of 10^{-4} m/yr.

Table 4 Comparison of PPP-derived and published ITRF2008 velocities (in m/yr) for the EPN Class A stations

EPN Station	**EPN velocities (m/yr)** (EPN_A_IGb08_C1875.SSC)			**PPP velocities**			**Differences**		
	V_X	**V_Y**	**Y_Z**	**V_X**	**V_Y**	**Y_Z**	**DV_X**	**DV_Y**	**DY_Z**
AUT1	-0.0149	0.0208	0.0041	-0.0152	0.0212	0.0035	0.0003	-0.0004	0.0006
PAT0	0.0016	0.0088	-0.0047	0.0019	0.0086	-0.0053	-0.0003	0.0002	0.0006
DUTH	-0.0168	0.0186	0.0088	-0.0168	0.0193	0.0083	0.0000	-0.0007	0.0005
TUC2	0.0029	0.0100	-0.0095	0.0030	0.0106	-0.0093	-0.0001	-0.0006	-0.0002

The velocities estimated for the two Class B EPN stations are shown in Fig. 8 together with the velocities of the nearby HEPOS stations.

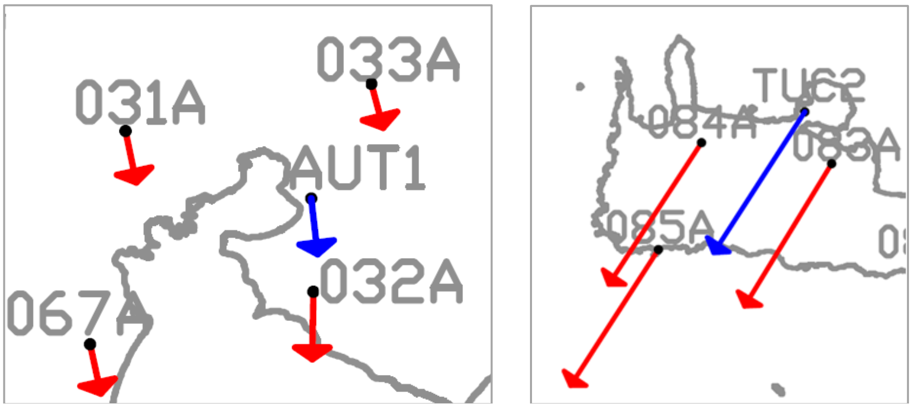

Fig. 8 Estimated horizontal velocities in ETRF2000 for EPN Class B stations AUT1 and TUC2 (blue arrows) and nearby HEPOS stations (red arrows).

5. Conclusions

The processing of 7.5 years of data from the HEPOS and the EPN networks with the PPP technique offered a detailed and accurate velocity field for Greece. The estimated PPP velocities agree in the order of 10^{-4} m/yr with the velocities published by EUREF for the EPN stations. Taking into account that the produced time-series consist of one daily solution per month denotes that using data spanning over several years, even a daily solution per month can be sufficient for achieving highly accurate velocities. The obtained velocity field demonstrates clearly that Greece is the country with the highest ETRS89 velocities in Europe and also the country with the highest differences in the velocities spanning from the sub-mm/yr level to more than 3 cm/yr. Important role in the determination of station velocities play geological phenomena like earthquakes and volcanic activity. The impact of such phenomena must be well studied and removed from the time-series in order not to affect the estimation of the velocities.

Acknowledgments

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