Detecting permanent displacements caused by earthquakes using data from the HEPOS network

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Abstract. Coordinate stability is crucial for every RTK CORS network, especially when network-based RTK is supported. Network-based techniques like VRS, FKP and MAC 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. Tectonic movements should be considered, as they can lead to changes in the stations' coordinates with respect to the coordinate reference frame in which they are expressed. Greece is situated on the boundaries of the Eurasian plate and has different tectonic characteristics compared to the majority of European countries. Moreover, Greece is characterized by strong seismic activity. In certain cases, earthquakes can cause abrupt changes in the station coordinates.

The Hellenic Positioning System (HEPOS) consists of 98 permanent GPS reference stations distributed throughout Greece. During the first years of the operation of HEPOS, several strong earthquakes of different characteristics took place in certain areas of Greece. Data from the HEPOS stations are processed in order to detect possible permanent displacements induced by 8 different earthquakes. The paper presents the processing strategy and the obtained results.

Keywords. HEPOS, GPS, earthquakes, Greece, permanent displacements.

1 Introduction

In the last two decades GNSS measurements are increasingly used for the detection of crustal deformations. The first efforts were made by means of repeated measurements. Such campaigns have been mainly carried out in seismotectonically active regions like western Greece (Kahle et al. (1995)). Much more efficient than the periodic campaigns is the use of permanent reference stations. In Greece the first permanent GPS stations for the observation of tectonic effects were installed in the 1990s (Peter et al. (1998), Hollenstein et al. (2006)). In 2006 the Institute of Geodynamics of the National Observatory of Athens begun installing permanent GPS stations establishing NOANET (Ganas et al. (2008a)), a network consisting today of 12 stations.

Permanent stations for geodynamic research are preferably installed on certain locations, e.g. along faults. On the contrary, stations of networks offering positioning services should be installed on more stable sites. This is also the case for the HEPOS network that is established by KTIMATOLOGIO S.A (Hellenic Cadastre). Although the purpose of the HEPOS network is not the study of local geological phenomena, its stations can be well used for geodynamic research. This is mainly due to the high density of the HEPOS network, which is depicted in Figure 1. First studies proved the usefulness of the HEPOS stations for the detection of permanent displacements caused by

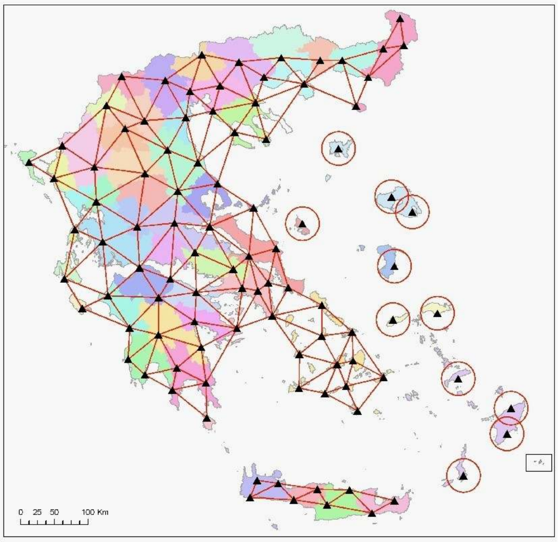

Fig. 1 The 98 reference stations of HEPOS

earthquakes (Gianniou (2010a)) and for the estimation of a deformation field that covers whole Greece (Gianniou (2010b)).

2 Seismic activity in Greece

Greece lies in the boundary region between two major lithospheric plates, the Eurasian and the African plate. In addition, the southern part of Greece lies on the Aegean plate, a smaller plate which is moving southwest (Papazachos et al. (2000)). The Hellenic plate boundary zone is the most seismotectonically active area in Europe. During the last 30 years more than 4500 intermediate-size earthquakes occurred, with several large events among them (Hollenstein (2006)). The high tectonic activity in Greece is shown in Figure 2 that depicts the earthquakes (M>4.5) occurred in the Mediterranean area during the period 2000-2009. Within Greece, the seismic activity is concentrated along the Hellenic Arc. This can be seen in Figure 3 that shows the earthquakes (M>3) occurred in Greece in 2008.

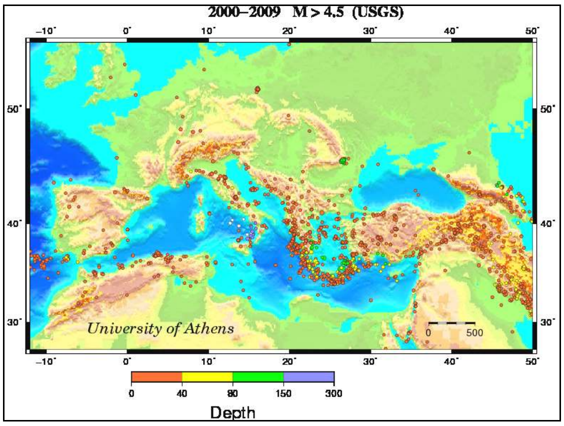

Fig. 2 Seismic activity in Mediterranean
(source: www.geophysics.geol.uoa.gr).

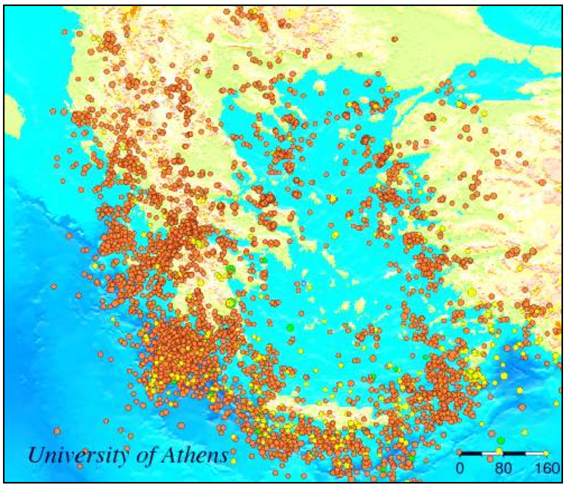

Fig. 3 Seismic activity in Greece
(source: www.geophysics.geol.uoa.gr).

3 Data analysis

3.1 Earthquakes investigated

The impact of an earthquake depends strongly on its characteristics, like magnitude, focal depth, source mechanism and characteristics of the subsurface structures. For the purposes of this work eight earthquakes of different characteristics that occurred between 2008 and 2011 have been investigated. The local magnitudes of these events vary between 3.1 and 6.5, whereas their focal depths range between 10 Km and 86 Km. More details on each earthquake are given in Table 1. Their epicenters are depicted in Figure 4. As can be seen, most of the events occurred close to the Hellenic Arc.

Table 1. Characteristics of the earthquakes investigated.

EQ	Date	Time (GMT)	φ	λ	Depth (Km)	M l
1	06/01/08	05:14	37.11	22.78	86	6.1
2	04/02/08	22:15	38.09	21.94	25	5.0
3	14/02/08	10:09	36.50	21.78	41	6.2
4	08/06/08	12:25	37.98	21.51	25	6.5
5a	15/07/08	03:26	35.85	27.92	56	6.2
5b	>>	03:45	35.92	27.30	10	3.1
6	03/11/09	05:25	37.39	20.35	39	5.6
7	11/02/11	17:16	36.70	21.49	31	4.0
8	01/04/11	13:29	35.64	26.56	63	6.2

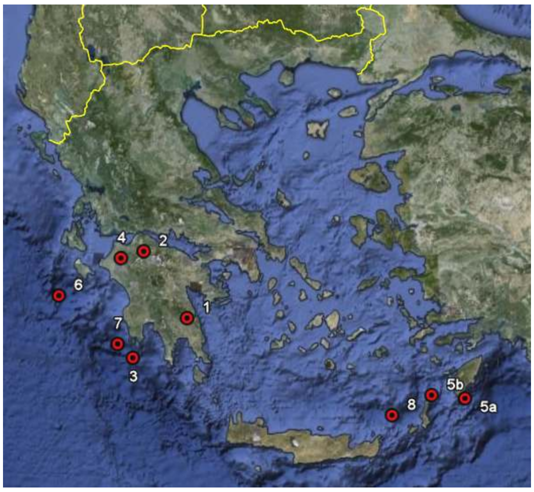

Fig. 4 Epicentres of the earthquakes investigated.

3.2 Data processing

To investigate possible permanent displacements induced by the earthquakes under consideration, data from the HEPOS stations that are located around the epicentre of each earthquake were used. Usually, for geodynamic applications, scientific software packages are used to exploit the highest accuracy achievable from GNSS measurements. However, abrupt changes in the coordinates can also be detected using simpler software packages. Within this work the computations are made using Trimble Total Control ver. 2.73. The baseline processing is done using the following parameters: 13 degrees elevation mask, iono-free linear combination of phase double-differences as observable, fixed phase ambiguities, IGS final precise orbits, NGS antenna phase-centre model, Goad and Goodman tropospheric model.

The basic concept behind this work is to examine the daily solutions in order to detect abrupt changes after the event. Data from several days before and after each earthquake are processed. Each daily solution is produced using 24 hours (00:00-24:00 GPS time) of data sampled at 15 sec interval.

For the estimation of the coordinates there are several alternatives. For example, they can be estimated directly from the baseline solution or after performing a network adjustment. A study based on data from HEPOS stations has shown that these strategies are practically equivalent when using data from dense networks (Gianniou (2010a)). Within this work mainly the first approach was followed.

3.3 Numerical results

In this section diagrams of the estimated daily coordinates are given for each one of the 8 earthquakes described in Table 1. In order to distinguish between the horizontal and vertical positions of the RSs, the ECEF coordinates of the RSs are first transformed to the national system GGRS87 using a 3-parameter transformation and after that projected using the associated TM87 projection. The y-axis of all diagrams is scaled to the same extent (0.05 m), so that comparisons between all cases can be made easily. Diagrams are made for E, N and h for all stations selected to investigate each earthquake. In the following, the results for the most representative station are shown for each event. It is noted that this work focuses only in the detection of horizontal displacements. The detection of vertical displacements is more demanding due to the higher noise in the estimation of the heights.

In the following, three figures are given for each earthquake. The first figure depicts the location of the earthquake's epicentre and the closest HEPOS stations. The next two graphs give the estimated daily coordinates of the probably most affected reference station. On each graph the day of the event is indicated with an arrow.

Figures 5a-5c refer to Earthquake no. 1. Figures 5b-5c give the estimated daily coordinates for the station 004A. As can be seen, there is no obvious permanent change in the coordinates after the event.

Fig. 5a Epicentre of earthquake no. 1 and locations of the surrounding stations.

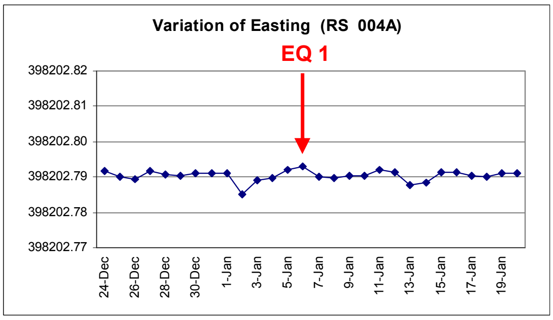

Fig. 5b Earthquake 1: Variation of Easting for RS 004A.

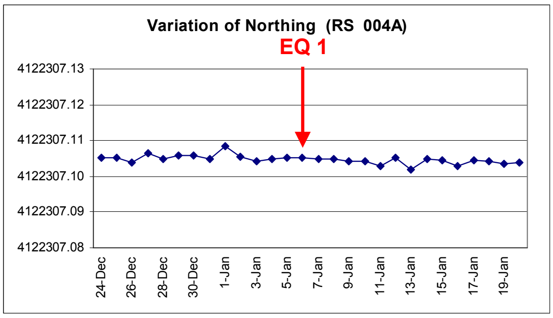

Fig. 5c Earthquake 1: Variation of Northing for RS 004A.

Figures 6a-6c refer to Earthquake no. 2. Figures 6b-6c give the estimated daily coordinates for the station 012A. As can be seen, also in this case there is no obvious permanent change in the coordinates after the event.

Fig. 6a Epicentre of earthquake no. 2 and locations of the surrounding stations.

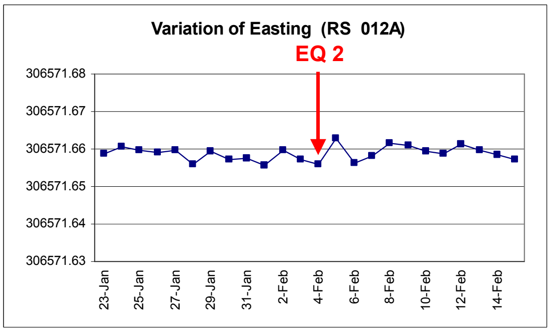

Fig. 6b Earthquake 2: Variation of Easting for RS 012A.

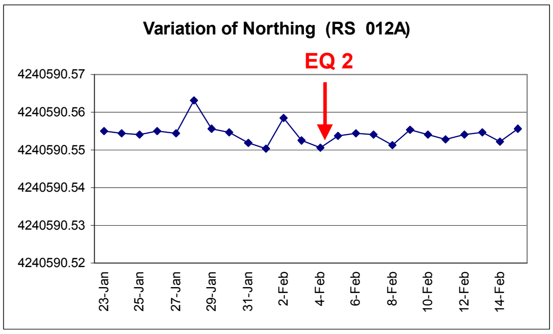

Fig. 6c Earthquake 2: Variation of Northing for RS 012A.

Figures 7a-7c refer to Earthquake no. 3. Figures 7b-7c give the estimated daily coordinates for the station 064A. Unlike the cases of earthquakes no. 1-2, earthquake no. 3 clearly induced a permanent displacement of more than 2 cm towards South and about 1 cm to the West.

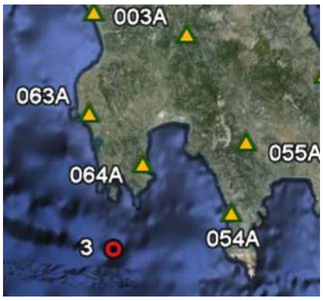

Fig. 7a Epicentre of earthquake no. 3 and locations of the nearest stations.

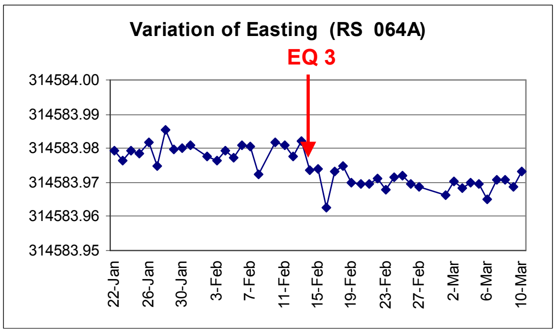

Fig. 7b Earthquake 3: Variation of Easting for RS 064A.

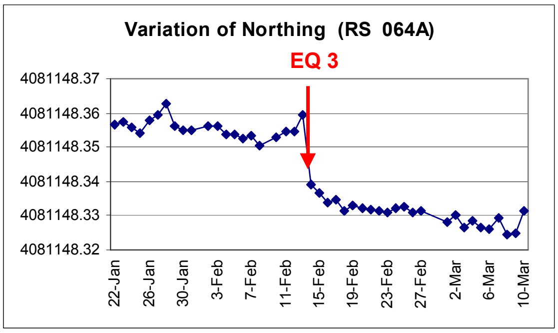

Fig. 7c Earthquake 3: Variation of Northing for RS 064A.

Figures 8a-8c refer to Earthquake no. 4. Figures 8b-8c give the estimated daily coordinates for the station 030A. As in the case of earthquake no. 3, a permanent displacement is detectable, which amounts more than 1 cm to the east. Permanent displacements induced by earthquake no. 4 are detected also by other researchers (Ganas et al. (2008b)).

Fig. 8a Epicentre of earthquake no. 4 and locations of the surrounding stations.

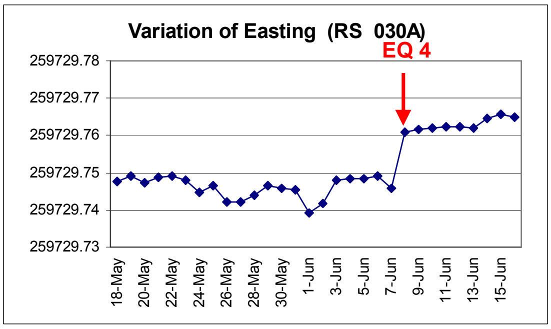

Fig. 8b Earthquake 4: Variation of Easting for RS 030A.

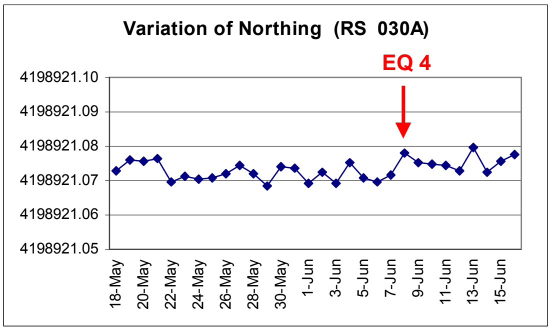

Fig. 8c Earthquake 4: Variation of Northing for RS 030A.

Figures 9a-9c refer to Earthquakes no. 5a-5b, i.e. two earthquakes occurred on July 15, 2008 near the islands of Rhodes and Karpathos. Figures 9b-9c give the estimated daily coordinates for the station 088A. As in the cases of Earthquakes 1-2, there is no obvious permanent change in the coordinates after the event.

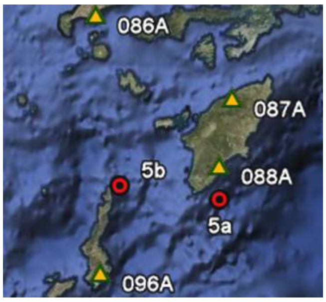

Fig. 9a Epicentres of earthquakes no. 5a and 5b and locations of the nearest stations.

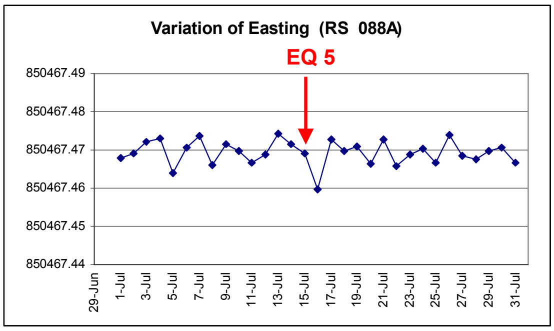

Fig. 9b Earthquake 5a and 5b: Variation of Easting for RS 088A.

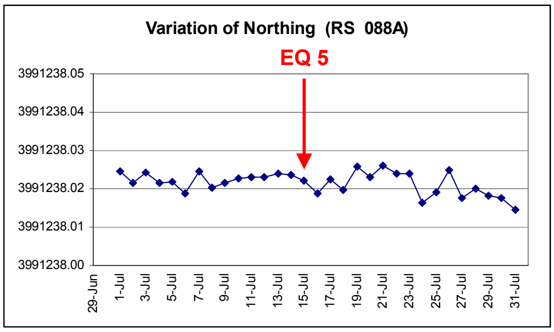

Fig. 9c Earthquake 5a and 5b: Variation of Northing for RS 088A.

Figures 10a-10c refer to Earthquake no. 6. Figures 10b-10c give the estimated daily coordinates for the station 028A. As in the cases of Earthquakes 1, 2 and 4 there is no obvious permanent change in the coordinates after the event. The variation of the daily solutions is higher than in the previously examined cases, which should be further investigated.

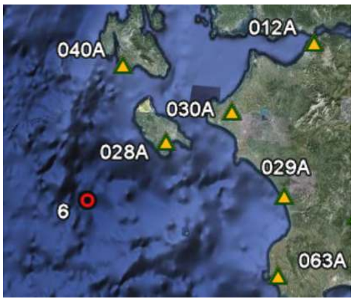

Fig. 10a Epicentre of earthquake no. 6 and locations of the nearest stations.

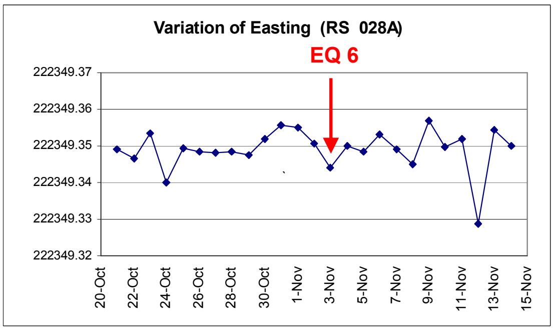

Fig. 10b Earthquake 6: Variation of Easting for RS 028A.

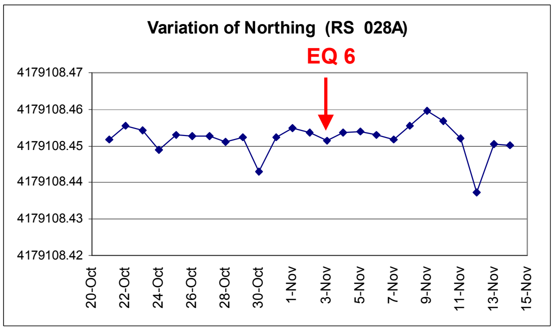

Fig. 10c Earthquake 6: Variation of Northing for RS 028A.

Figures 11a-11c refer to Earthquake no 7. Figures 11b-11c give the estimated daily coordinates for the station 063A. As in the cases of Earthquakes 1, 2, 4 and 6 there is no obvious permanent change in the coordinates of the station after the event.

Fig. 11a Epicentre of earthquake no.7 and locations of the nearest stations.

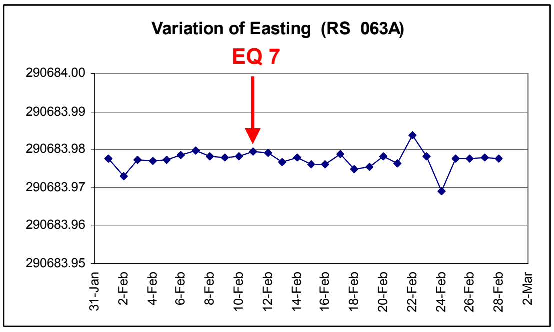

Fig. 11b Earthquake 7: Variation of Easting for RS 063A.

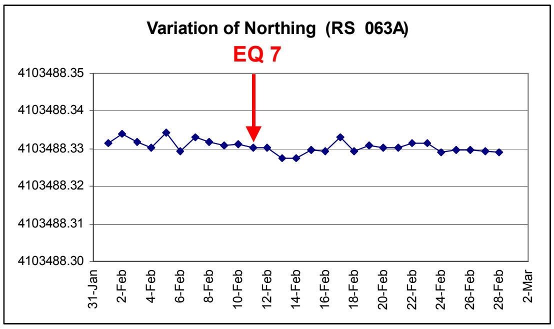

Fig. 11c Earthquake 7: Variation of Northing for RS 063A.

Figures 12a-12c refer to Earthquake no. 8. Figures 12b-12c give the estimated daily coordinates for the station 096A. As in the cases of Earthquakes 1, 2, 4, 6 and 7 there is obvious permanent change in the coordinates after the event.

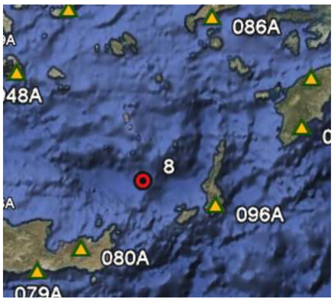

Fig. 12a Epicentre of earthquake no.8 and locations of the nearest stations.

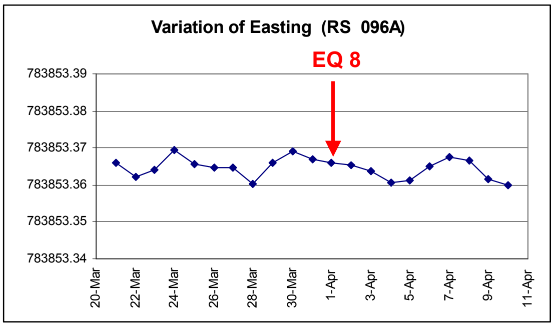

Fig. 12b Earthquake 8: Variation of Easting for RS 096A.

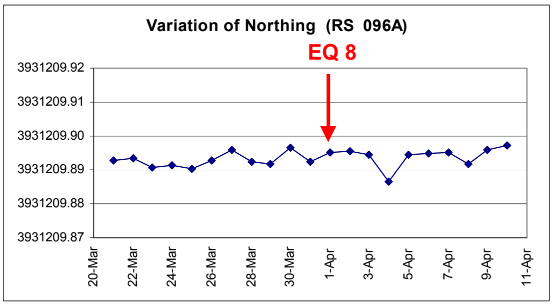

Fig. 12c Earthquake 8: Variation of Northing for RS 096A.

4 Discussion

The analysis of the previous section shows that observations form the HEPOS stations can be used for the detection of permanent displacements induced by earthquakes. A key factor in the procedure followed in this paper is the precision of the estimated daily coordinates, as it defines the magnitude of detectable displacements. As known, the accuracy of a baseline solution depends on many factors like baseline length, ionospheric conditions, multipath, processing algorithms etc. In the case of the eight seismic events investigated here the standard deviation of the daily coordinates varied between 1.1 mm (Earthquake no. 1, Northing of station 004A) and 5.6 mm (Earthquake no. 6, Easting of station 028A). In the case of Earthquake no. 4 a displacement of station 030A of slightly more than 1 cm eastwards could be clearly detected by examining the time series of Easting, the standard deviation of which was 2.8 mm (the value refers to the first segment of the time-series, i.e. from the first day to the day of the event).

5 Conclusions

The high density of the HEPOS network allows the detection of permanent displacements induced by earthquakes. In this work the strongest seismic events that occurred during the first years of operation of HEPOS (2008–2011) have been investigated. Among the eight earthquakes studied, permanent displacements were detected only in two cases. The examination of the estimated movements in connection with the characteristics of the earthquakes may be used for seismological research.

From the perspective of the HEPOS operator, KTIMATOLOGIO S.A. is interested in the frequency and the magnitude of permanent displacements induced by earthquakes. The results of this study are useful for developing the plan for the maintenance of network coordinates.

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