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RESULTS OF GEODETIC MEASUREMENTS DURING THE JANUARY 2010 EFPALIO EARTHQUAKES AT THE WESTERN TIP OF THE GULF OF CORINTH, CENTRAL GREECE

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ABSTRACT
The results of geodetic GNSS measurements on the EYPA station (bult by INSU CNRS from France) in Corinth Gulf in Greece are analyzed. Data is analyzed in the time interval before and after the earthquakes, which occured in January 2010. Results confirm vertical and horizontal co-seismic shifts of EYPA station of the order of 4 cm and 1 cm.

KEYWORDS: Global Navigation Satellite System (GNSS), earthquakes

1. INTRODUCTION

Corinth Gulf in Greece is the place of frequent occurrence of earthquakes. To detect them, a network of permanent and temporary seismic stations has been deployed in that area. The region hosts also one permanent GNSS station. The geographical distribution of the permanent observing stations is shown in Figure 1.

Research workers of the Department of Geophysics, Faculty of Mathematics and Physics of the Charles University in Prague, Czech Republic in cooperation with the University of Patras, Greece are, amongst other things interested in interpretations of seismic data and in developments of tectonic models. The authors of this paper have been asked to cooperate on the GNSS observations processing for intervals around the earthquake to test possible permanent postseismic deformation.

On 18 January, 2010, an earthquake occurred in the Efpalio area, with moment magnitude Mw 5.3. Its epicentre was close to the GNSS permanent station EYPA. Then on 22 January, 2010, the second moderate size earthquake (Mw 5.2) happened; it had an epicentre at a large distance (about 5 km) from the EYPA station. The two largest events were accompanied by a sequence of aftershocks which lasted almost six months. Both M5+ shocks exhibited normal faulting along ~E-W trending planes. Parameters of both earthquakes are described in Table 1 (taken from Sokos et al., 2012).

2. GNSS DATA AND PROCESSING STRATEGIES

The goal was to process the data from the EYPA permanent GNSS station. The EYPA data was downloaded from the Internet (https://gpscope.dt.insu.cnrs.fr/chantiers/corinthe/).

Table 1 Hypocenters and centroids calculated for the two largest shocks of the Efpalio sequence.

Datum	(H) Hypocenter Lat. (^{o}N)	Long. (^{o}E)	H-depth (km)	(C) Centroid Lat. (^{o}N)	Long. (^{o}E)	C-depth (km)	Mo (Nm)
Jan 18, 2010 15:56	38.419	21.915	6.6	38.422	21.941	4.5	0.97e17
Jan 22, 2010 00:46	38.429	21.962	8.0	38.430	21.964	6.0	0.70e17

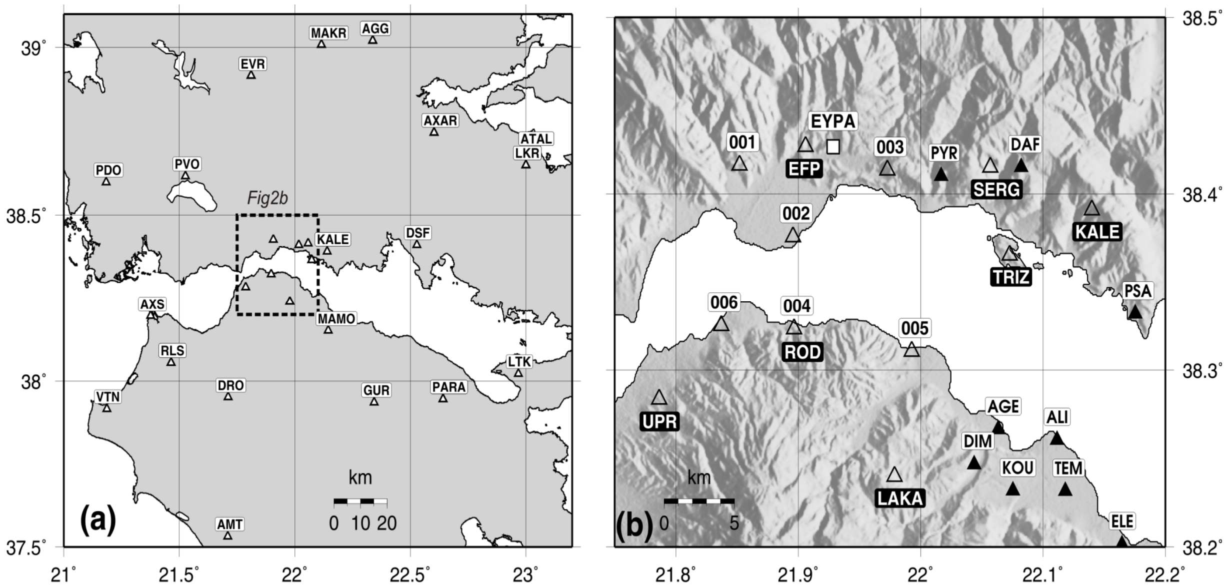

Fig. 1 Geographical distribution of the GNSS permanent observing stations. The permanent GNSS station EYPA is also shown.

The daily RINEX files with 30 sec sampling contain dual frequency GPS code and phase observations. We used two independent techniques to analyse the data during the earthquakes:

(a) Precise Point Positioning (PPP)

(b) Network solution

The PPP technique (Zumberge et al., 1997) can be applied autonomously, thus using observations from a single station and without any need of differencing. It requires, however, a careful modelling of all errors. Additionally, precise global satellites orbit and clock products are required. The final products of the International GNSS Service (Dow et al., 2005) have been used. The position of the station is then estimated directly in the coordinate reference frame of the orbits and clocks. The 24-hour PPP position solutions have been used, since sub-daily PPP solutions are weaker due to possible insufficient convergence of the initial ambiguity solutions. The PPP processing was done with the CSRS-PPP on-line service, operated by the Geodetic Survey Division, Canada Centre for Remote Sensing. (http://webapp.csrs.nrcan.gc.ca/field/CSRS_PPP_updates_e.html).

The network solution was analysed using the Bernese GPS software (Dach et al., 2007) with the strategy developed for and applied at GOP - an EUREF local analysis centre (e.g. Dousa and Filler, 2003). In the network mode, by differencing between two stations and two satellites, eliminates satellite and receiver clocks (and frequency dependent biases) and effectively reduces various other error sources, which dependent on a baseline length. In the network mode, the code observations are used only to approximately synchronize the receiver clocks during the pre-processing stage. The coordinate results are then based on phase observations only. Integer initial ambiguities can then be resolved and fixed at integers for double-differenced observations, strengthening the results, especially when using short observing sessions. This advantage has been used to study the window-dependent solution accuracies, see section 3.2.

Additional 19 stations from the EUREF permanent network - EPN (Bruyninx, 2003) were used (Fig. 3), implicitly those previously configured for a specific campaign for a densification of the reference frame in the Czech Republic (Dousa et al, 2011). The stations were selected according to

- coverage over the main part of Europe,
- providing long term, high quality data,
- serving as a priori fiducial stations for a reliable datum definition on a daily basis.

The network over a large region enables the estimation of total tropospheric path as well as it provides a good geometrical distribution of the fiducial stations. The EPN's coordinate residual time series (http://epncb.oma.be) were applied for the assessment of data quality.

3. PROCESSING RESULTS

3.1. PPP SOLUTION

The individual PPP horizontal (E-W, N-S) and vertical coordinate diffetences are plotted in Figure 4. The time on the x-axis is expressed in Modified Julian Date (MJD). The coordinate difference time-series are approximated by the method of the an-harmonic analysis (see Vaníček, 1971). The result shows systematic shifts in both E-W and vertical directions

Table 2 Shift of the EYPA station position, as determined by GPS observations (PPP solutions) and compared with the static displacement calculated from the seismic model.
(value -3.10 in Up component is for earthquake 18th Jan 2010)

Determined shift	from GPS (PPP)	from seism. Model COULOMB 3.1 code
N-S	-0.13 (0.02) cm	-0.31 cm
E-W	1.22 (0.07) cm	0.78 cm
Up	-(3.10+1.00) (0.10) cm	-3.12 cm

(up to 40 mm). The *rms* of the daily solution is characterized by 3 mm, 6 mm and 11 mm in N-S, E-W and vertical directions, respectively.

To estimate systematic shifts between the mean coordinates before and after the earthquake we used an-harmonic analysis too, but with the estimating constant members only. Additionally, the critical day of 18 January, 2010 (MJD 55214) was excluded from the analysis. The result of this analysis is shown in Figure 5 and estimated differences of the individual components are in Table 2.

3.2. THE NETWORK SOLUTION

As mentioned above, for the processing of daily sessions the standard strategy used in the GOP local analysis centre has been used. A few characteristics should be summarized here:

- IGS final products consistent with ITRF2005 (Altamimi et al, 2005) and IGS05 PCV (antenna Phase Center Variation) models,
- integer ambiguity resolution based on QIF strategy (Mervart, 1995),
- daily coordinate solutions expressed in the ITRF2005 reference frame by applying an iterative procedure for selecting the final, consistent set of fiducial stations.

The time-series of daily independent North, East and Up coordinate differences are shown in Figure 6. The typical daily solution repeatability (based on 40 days and all the stations) is about 1-2 mm and 4-6 mm in horizontal and vertical coordinates, respectively. This is in a good agreement with the latest re-processing results which was based on 15-year data span) (Dousa and Vaclavovic, 2011).

Additionally, we applied a 24-hour sliding window to estimate hourly coordinates. Such results are, however, significantly correlated due to 23 hours of common data used in two consecutive solutions. Two solutions are thus plotted in Figure 7 – the 24-hour independent coordinates (squares) and the 24-hour hourly sliding-windows coordinates (circles). Although the movement related to the 18th January earthquake is clearly visible in the figure, the changes are smoothed and shifted due mixing the data before and after the event.

In the sliding window solution with a higher resolution, we have noticed an "artificial variations" in the up and east components, which can be an artefact of the processing itself. The BOGO station was the most affected (Fig. 8), with the amplitude of 2 mm and 6 mm in the North and Up coordinates, respectively. Since the analyzed data have been gathered during a winter period, the effects of periodically varying snow or ice coverage on the antenna radome could cause such effects. However, the observed amplitudes are approaching the level of repeatability, estimated from long-term daily solutions. Thus, such sub-daily variations cannot be estimated using up-to-date processing strategies. The observed effect will be studied further, in order to understand its nature, i.e., if it is an artificial or real effect.

Using the network mode, we could test the dependence of the accuracy on the session length, to assess the potential of GNSS to monitor co-seismic deformations of these M5+ earthquakes and in particular their precise timing. The daily files were thus processed in 24h, 12h, 6h, 4h, 3h, 2h and 1h sessions. The accuracy of the position estimated in a short session is decreasing due to the difficulty of an integer ambiguity resolution and remaining strong correlations between float ambiguities and other parameters (similar as for PPP solutions). To reduce these limitations, we have developed a specific strategy which applies daily sessions for an integer ambiguity resolutions, while independent coordinate solutions are based on a short data session (e.g., 1h - 12h). The trick consisted of the introducing and fixing integer ambiguities (resolved previously on a daily basis) also into the individual short solutions for coordinate estimates. Although commonly resolved ambiguities may introduce some additional correlation between the short-session results, we assumed that these are small and can be neglected.

Figure 9 shows results for the two stations so one can see the performance of a smooth (precise) time-series (GOPE) and those affected by the earthquakes (EYPA). The accuracy still decreases with an increased time-resolution, but much less than without applying the above mentioned trick with ambiguities. The dependency function was finally derived using results from all the 19 stations of the network (with a smooth coordinate time-series), Figure 10.

4. A SEISMOLOGIC INTERPRETATION

The EYPA position changes derived from the GNSS observations have been seismically interpreted. The seismic model, consisting of the centroid moment tensor solution and a simple finite/extent planar fault with a constant slip, has been processed with the COULOMB v. 3.1 software (by our colleagues from the Charles University in Prague). The results from the GPS measurements (shift was computed after both earthquakes) and from the static model (only for 18th Jan) are summarized and compared in Table 2. There is a very good agreement amongst them. For the earthquake of 18 January 2010, the GPS measurements confirm particularly well centriod depth and its position in the E-W direction. If the centroid would have been only by ~2 km farther west from its position of Table 1, then the value of the E-W static shift would have had an opposite sign and thus it would contradict the GPS measurements.

Another interesting phenomenon discovered by the GNSS data is the periodic behaviour of the station EYPA, especially in the vertical direction. It is detectable even before the earthquake, and also after it. It is well visible in the network solution. This effect may have a physical origin, but it can be a result of the data processing, too.

It is also interesting to see what happened later on after the earthquake. Theoretically, the station can return, with a delay, at least partly, to its original position. The processing of our data by the PPP technology during the three months after the earthquake, see Figure 11, seems to confirm it only in vertical direction.

5. CONCLUSION

The GNSS technology has recently achieved its well-deserved place and it is able to position perturbations caused by the earthquakes, including earthquakes of a moderate size as in this paper (M5+). To obtain good results, it is optimum to have the observing station near the epicentre. The results obtained from our analyses correspond well with seismological model available.

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REFERENCES

Altamimi, Z., Collilieux, X., Legrand, J., Garayt, B. and Boucher, C.: 2007, ITRF2005: A new release of the International Terrestrial Reference Frame based on time series of station positions and Earth Orientation Parameters, J. Geophys. Res., 112, B09401, doi: 10.1029/2007JB004949.

Altamimi, Z., Collilieux, X. and Métiviers, J.: 2011, ITRF2008: an improved solution of the international terrestrial reference frame, J. of Geodesy, 85/8, 457–473 doi: 10.1007/s00190-011-0444-4.

Bruyninx, C.: 2004, The EUREF Permanent Network: a multi-disciplinary network serving surveyors as well as scientists, GeoInformatics, V7, 32-35.

Dach R., Hugentobler, U., Fridez, P. and Meindl, M.: 2007, Bernese GPS Software v. 5.0. Astronomical Institute, University of Bern.

Dow, J.M., Neilan, R.E. and Gendt, G.: 2005, The International GPS Service (IGS): Celebrating 10th Anniversary and Looking to the Next Decade, Adv. Space Res., 36/3, 320–326.

Dousa, J. and Filler, V.: 2003, Multi-year solution of the GOP EUREF subnetwork, In: Report on the Symposium of the IAG Subcommission for the European Reference Frame (EUREF), Torres, J. A. and H. Hornik (eds.), Bundesamt fur Kartographie und Geodasie, Frankfurt am Main, EUREF publ. No 12, 380–385.

Dousa J., Filler, V., Simek, J., Kostelecky J., Kostelecky, J. jr. and Novak, P.: 2011, The new implementation of ETRS89 in the Czech Republic: Campaign EUREF-Czech-2009, Geod. a kart. obzor, 57/99(2), 30–42, (in Czech, for the English version see: http://www.pecny.cz/ - GNSS/EUREF-Czech-2009).

Dousa, J. and Vaclavovic, P.: 2011, Results of the GNSS reprocessing effort at GOP, presented at EGU General Assembly, April 4-8, 2011, Vienna.

Mervart, L.: 1995, Ambiguity resolution techniques in geodetic and geodynamic application of the Global Positioning System, Ph.D. Thesis, Astronomical Institute, University of Bern.

Sokos, E., Zahradnik, J., A. Kiratzi, A., Jansky, J., Gallovic, F., Novotny, O., Kostelecky, J., Serpetsidaki, A. and Tselentis, G.-A.: 2012, The January 2010 Efpalio earthquake sequence in the western Corinth Gulf (Greece), Tectonophysics, 530–531, 20 March 2012, 299–309.

Vaníček, P.: 1971, Further development and properties of the spectral analysis by least-squares. Astroph. and Sp. Scie., 12, 10–33.

Zumberge, J.F., Heflin, M.B., Jefferson, D.C., Watkins, M.M. and Webb, F.H.: 1997, Precise point positioning for the efficient and robust analysis of GPS data from large networks, J. Geophys. Res., 102(B3), 5005–5017.

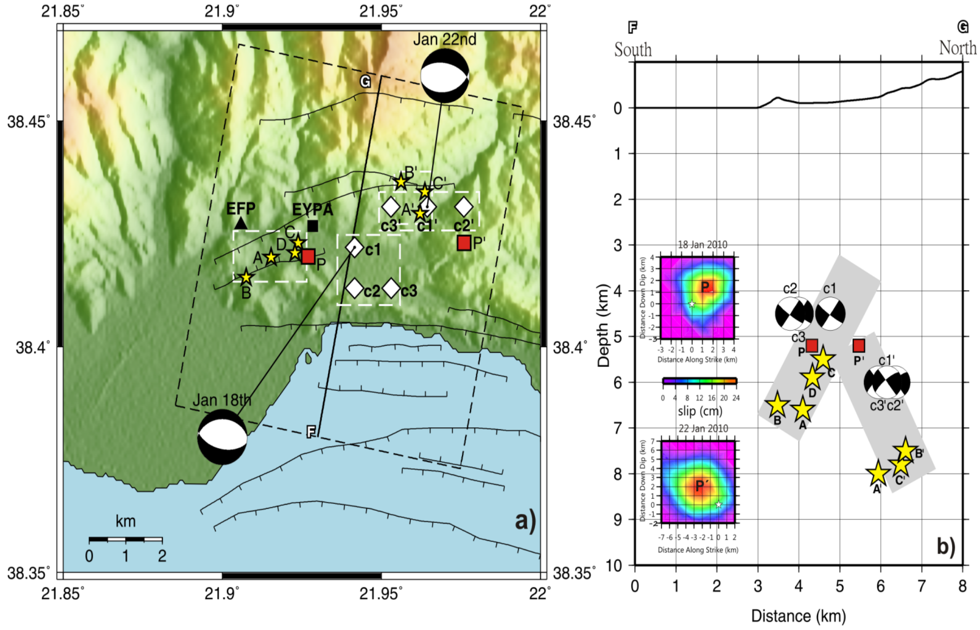

Fig. 2 Earthquakes on 18th and 22nd January 2010. Asterisks show alternative positions of the epicentres. Diamonds and Squares depict alternative positions of centroids. The preferred positions of centroids are accompanied with 'beachballs', representing the earthquake focal mechanism.

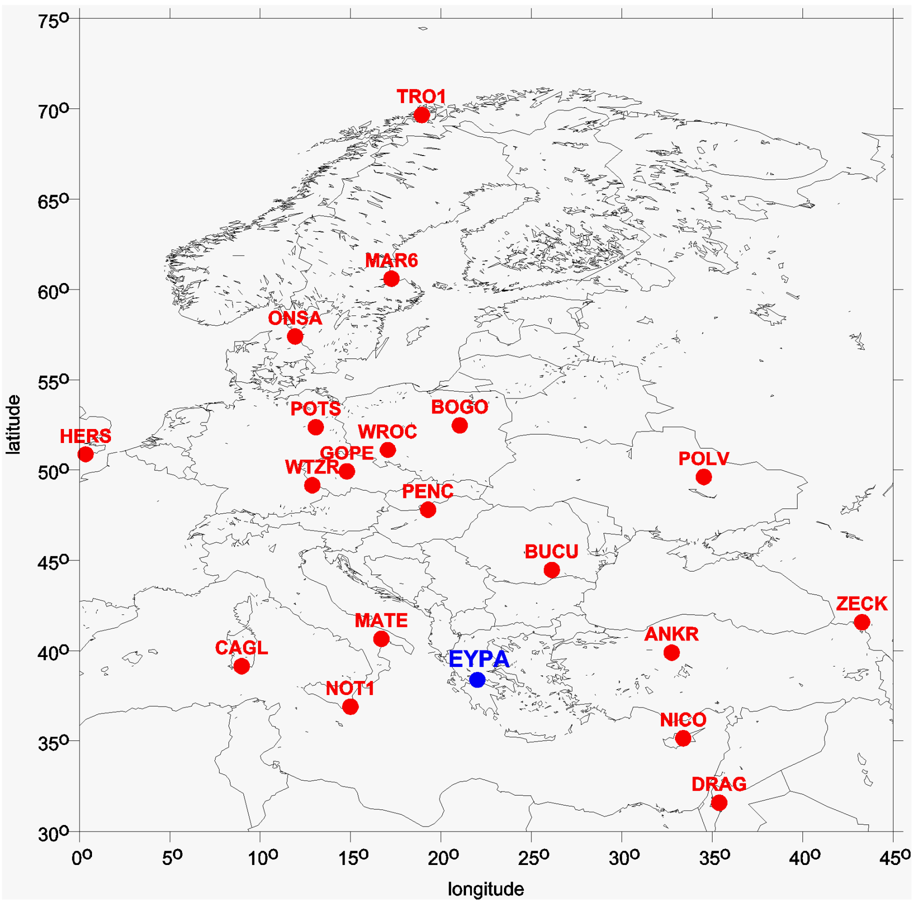

Fig. 3 A portion of the EUREF permanent network, EPN (Bruyninx, 2003), used here for the network analysis.

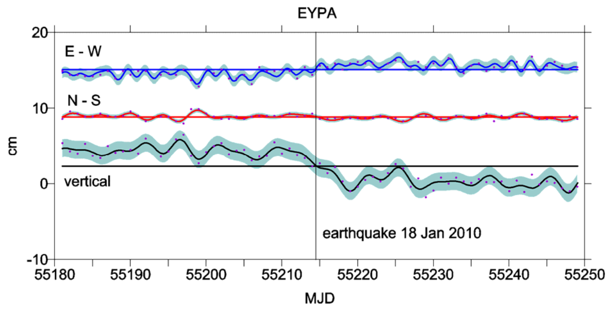

Fig. 4 The individual horizontal (E-W, N-S) and vertical coordinate differences – daily PPP solution smoothed by an-harmonic analysis. The coordinates are positive towards East, North and Up. Time scale is in so called Modified Julian Date (MJD).

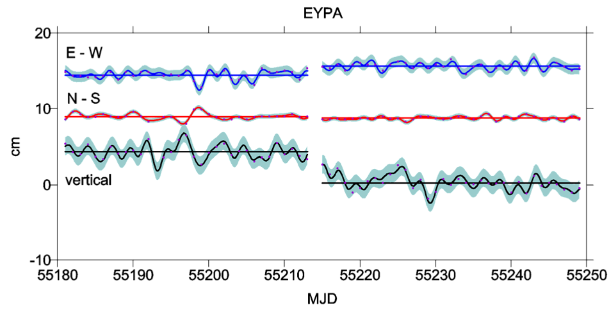

Fig. 5 Systematic shift of EYPA coordinate differences expressed as a difference between the mean values before and after Jan 18, 2010.

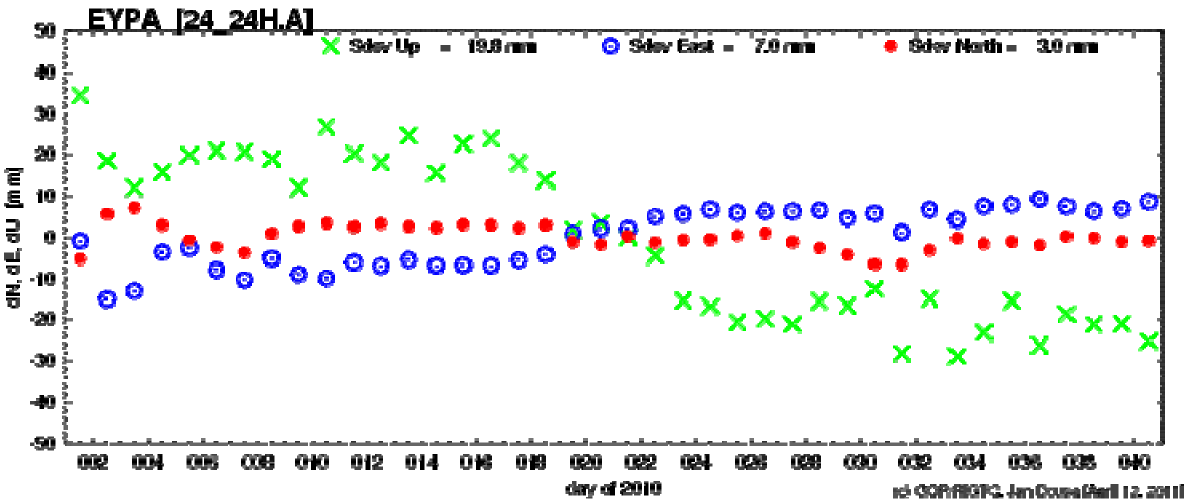

Fig. 6 The time-series of daily independent North, East and Up coordinate differences for EYPA.

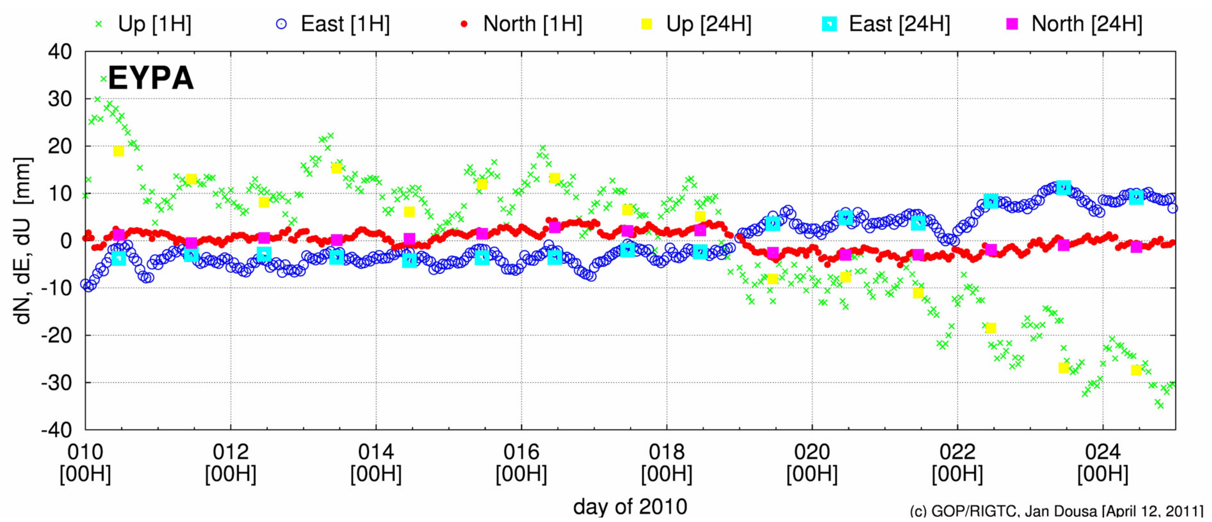

Fig. 7 The 24-hour independent (squares) and the 24-hour hourly sliding-windows coordinate differences (circles) for the EYPA station

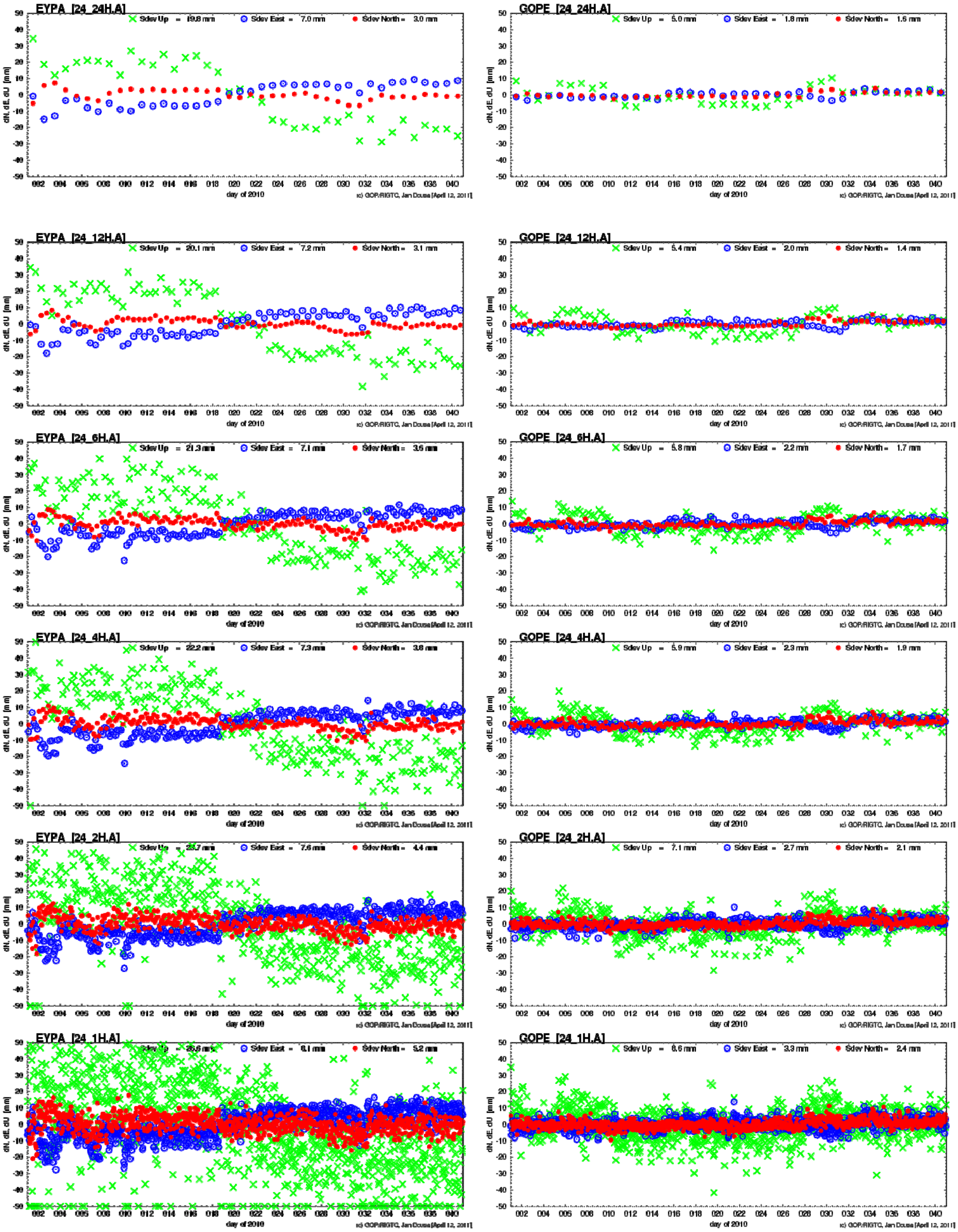

Fig. 9 Comparison of daily and sub-daily results for EYPA and GOPE (Czech Republic) stations (on the horizontal axis is time in "day of year", on the vertical axis is dN, dE, dU in mm).

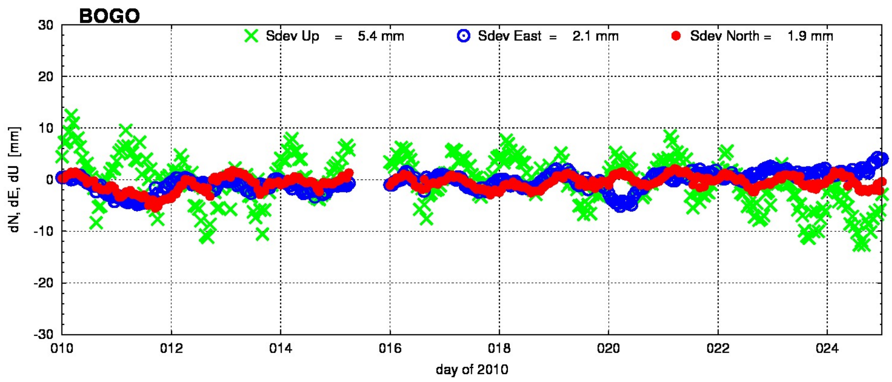

Fig. 8 Coordinate time series based on 24-hour sliding window (station BOGO).

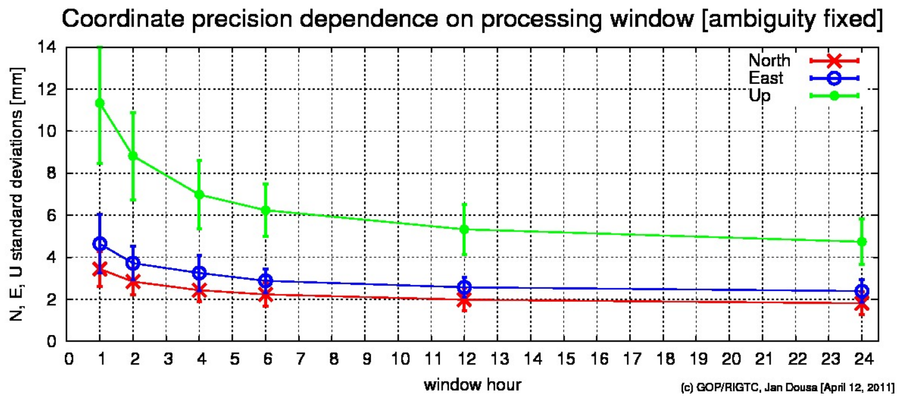

Fig. 10 The session length dependency function derived from all the 19 stations.

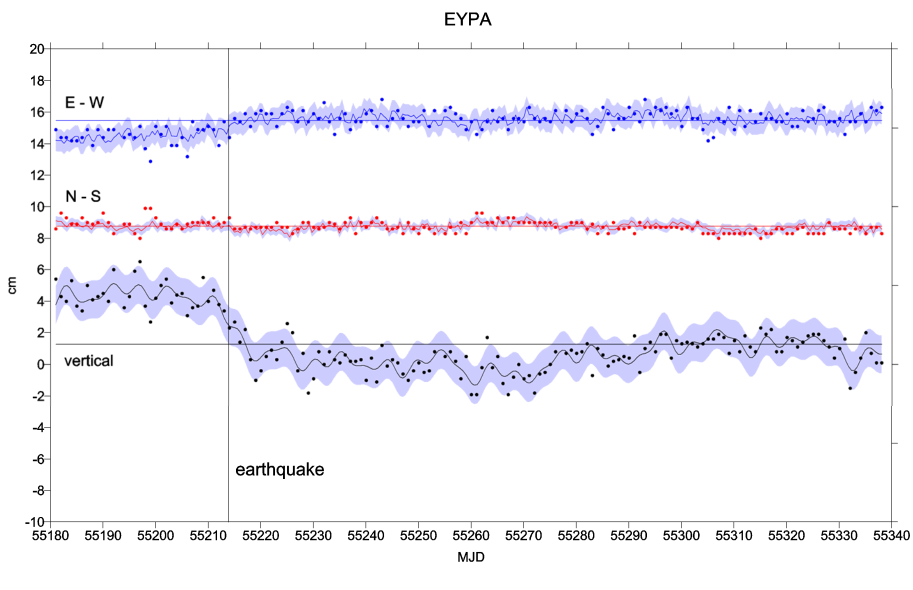

Fig. 11 GPS results for the EYPA, three months after the earthquake.