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POSSIBILITIES OF DETECTION OF SEISMIC DISPLACEMENTS IN CENTRAL EUROPE BY ANALYSIS OF HIGH-RATE GPS

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Abstract

The Precise Point Positioning (PPP) analysis technique adapted for monitoring of high-rate coordinate variations from GPS observations is applied for detection of actual displacements related to moderate and light earthquakes. Two approaches are examined: kinematic PPP which is suitable for larger displacements and analysis of residuals from quasi-static PPP which is suitable for detection of minor earthquake related displacements. The potential and limits of these used methods are documented on M 6.3 L'Aquila earthquake and M 4.3 Tatabanya earthquake. Our experiments proved the ability to measure dynamic seismic-related short-term coordinate variations at sub-centimetre level with PPP using GPS 1 Hz satellites observations.

1. INTRODUCTION

Potential of GPS for monitoring the site movements related to the seismic phenomena was firstly recognized by Larson (Larson et al., 2003) and further elaborated in (Larson et al., 2007, Larson, 2009). Their analyses of 1 Hz GPS data using the GIPSY software (Lichren and Border, 1987) and precise International GPS Service (IGS) satellite orbits (Beutler and Mueller, 1994) proved the ability to detect seismic waves related to strong earthquakes with displacements at the level of tens centimeters. Kouba (Kouba, 2003) pointed on possibility to apply Precise Point Positioning (PPP) approach using precise IGS orbits and satellite clocks products (Kouba and Héroux, 2001, Zumberge et al., 1997) to analyze seismic waves induced by large earthquakes. Application of GPS at high sampling rates for monitoring seismic-related phenomena Larson termed as GPS seismology (Larson et al., 2009). Later on, series of studies analyzing high-rate kinematic GPS observations related to great and medium earthquakes have been published (e.g. Avallone et al., 2011, Ji et al., 2004, Wang et al., 2011).

The PPP analysis of 1 Hz sampled data is exhibiting as the most suitable for monitoring the large earthquakes, however the possibilities of application of PPP for moderate seismic events was checked as well (e.g. Avallone et al., 2011). The main advantages of PPP approach are in relatively simple GPS data processing and unambiguous interpretation of measured site position variations. In our paper (Hefty and Gerhatova, 2012) we implemented Kalman filtering to software package ABSOLUTE developed at Slovak University of Technology in Bratislava (Hefty and Gerhatova, 2011) for purpose of monitoring short-term coordinate variations. The objective of this paper is more detailed description of problems related to detection of minor earthquake related displacements by means of PPP based data analysis. The potential and limits of our technique will be documented on two seismic events occurred in Central Europe region – the M 6.3 L'Aquila earthquake and the M 4.3 Tatabanya earthquake.

2. APPLIED METHOD FOR DETECTION OF SEISMIC RELATED DISPLACEMENTS

The PPP processing strategy is taking advantage of un-differenced GPS code and phase observations and utilization of precise satellite orbits and satellite clocks information. The absolute position – geocentric site coordinates related to the International Terrestrial Reference System (ITRS) are obtained without necessity of differencing GPS observations and using observed data from other terrestrial reference sites. The theoretical background for PPP including mathematical model and overview of necessary geometrical and physical correction models are given in (Kouba and Héroux, 2001).

The PPP analysis software package ABSOLUTE was originally developed for processing of static GPS observations. We implemented all the relevant models for corrections and reductions of observed data which are necessary for centimetre precision of site coordinates. In the pre-processing phase are combined dual-frequency carrier phase and code observations from continuous observations not corrupted by phase cycle slips. They are used for estimate of initial non-integer carrier phase ambiguities, ionosphere delays and iono-free pseudoranges for each observing epoch. The final estimate of parameters is based on least-squares adjustment. Besides the static site coordinates are computed the real-valued corrections to initial ambiguities, troposphere zenith delays for selected time intervals (usually 1 or 2 hours) and receiver clock corrections.

In (Hefty and Gerhátová, 2012) is extended the applicability of ABSOLUTE for analysis of 1 Hz sampled GPS observations in kinematic mode. We introduced Kalman filter (Strang and Borre, 1997) in the final phase of data processing for dynamic recursive estimation of set of unknown parameters – site coordinates, correction to initial ambiguities and actual receiver clock correction. The basic idea of application of Kalman filtering for estimation of time-dependent moderate variations of position is progressive update of parameters obtained from previous adjustments by gradually addition of new satellite observations. Troposphere parameters are not estimated as we suppose that the standard models are sufficient to eliminate troposphere effect in the case when the analysis is focused on short-term coordinate changes. The precise satellite orbits and the satellite clocks corrections in 30 s intervals are adopted from the IGS Global Data Centre (IGS, 2011).

The applied strategy for final parameter estimation using the Kalman filtering is given in our paper (Hefty and Gerhatova, 2012). The vector of updated unknown parameters Θ consists of three types of quantities: coordinate increments δX, δY, δZ to the initial site position, receiver clock offset dT and corrections δN_j to initial ambiguities N_j (j = 1, 2, … m), where m is number of all ambiguities of un-differenced phase observations within the time interval of processed data.

$$\Theta = \begin{bmatrix} \delta X & \delta Y & \delta Z & dT & \delta N_1 & \delta N_2 & \cdots & \delta N_m \end{bmatrix}^T$$

Outputs of the processing procedure are the time series of updated parameter estimates $\hat{\Theta}_t$, (t = 1, 2, … n). Our analysis of earthquake related displacements is focused on three elements of $\hat{\Theta}_t$ - the coordinate time series δX_t, δY_t, δZ_t which will be transformed to local coordinates in North-South, East-West and height denoted as n_t, e_t, v_t. The time variability of $\hat{\Theta}_t$ is determined by setting of diagonal elements in the covariance matrix Σ_Θ. In general, the ambiguities N_j are strongly constrained to their previous estimates and the receiver clocks dT are loosely constrained. In this paper we applied constrains for all ambiguities σ_N = 0.0001 m and σ_{dT} = 1.000 m for clock estimates.

Constraining of site coordinates will affect their applicability for studies of site displacements.

The loose constraining of δX, δY, δZ parameters to their previous values in will cause that all earthquake related displacements will be included in the estimated coordinate time series. Such approach we name as *Kinematic PPP*. For earthquake related displacements we applied in (Hefty and Gerhatova, 2012) $\sigma_{\delta X} = \sigma_{\delta Y} = \sigma_{\delta Z}$ = 1.0 m. This approach is suitable if larger displacements are expected.

Setting strong constrains on δX, δY, δZ in Σ_Θ will cause that the earthquake related displacements will be visible in residuals of carrier phase observables. This method we name as *Residuals from quasi-static PPP*. The advantage of such approach is in suppression of coordinate drifts due to effect of non-completely ambiguity modelling residual troposphere effect, etc. Application is suitable for detection of small coordinate variations related to distant earthquakes and to medium-magnitude close earthquakes. For earthquake related residuals we applied here $\sigma_{\delta X} = \sigma_{\delta Y} = \sigma_{\delta Z}$ = 0.0001 m. In the last step the phase residuals are transformed to local coordinates n_t, e_t and v_t suitable for further analyses and interpretation.

Our experience with processing of 1 Hz sampled GPS data proved that analysis of 20 minutes interval of observations is sufficient for convergence of estimated ambiguities at the centimetre level. However, we generally use for all the analysed data sets related to earthquakes at least 60 minutes of GPS observations. For the continuity of estimated coordinate time series is convenient to restrict the final adjustment to satellites which are continuously observed during whole analyzed interval.

3. DEMONSTRATION OF DETECTION OF THE EARTHQUAKE RELATED DISPLACEMENTS – M 6.3 L'AQUILA EARTHQUAKE

For study of the capability of the PPP based analysis of 1 Hz GPS data for monitoring the displacements induced by moderate earthquakes we will use data from 5 GPS receivers observing in the period of the L'Aquila earthquake (Central Italy). The earthquake with magnitude 6.3 and epicentre 42.334°N, 13.334°E occurred on April 6, 2009, 01:32:39 UTC (USGS, 2012). Stations INGP (Preturo), INGR (Roma) and RSTO (Rosseto degli Abruzzi) are part of the Italian: Integrated National Net GPS (Rete Integrata Nationale GPS, http://ring.gm.ingv.it/). The other two, namely ROIO (Poggio di Roio) and CADO (Fossa) GPS stations were installed only four days before the main shock (Cheloni et al., 2010).

Fig. 1 shows distribution of the analyzed GPS stations. Three sites are close to the epicentre, namely INGP – 5.6 km, ROIO – 4.5 km , CADO – 12.9 km, and the other two are more distant: RSTO (66 km) and INGR (87 km). Some details from the analysis procedure will be documented on time series from the station ROIO. In Fig. 2 are shown upgrades of initial values of ambiguities as well as the phase residuals from quasi-static PPP. The ambiguities evolution is not influenced by the earthquake in contrary to phase residuals which clearly indicate the earthquake related displacements. Time series of phase residuals from quasi-static PPP transformed to North-South and East-West coordinate constituents in Fig. 4 can be interpreted as *GPS seismograms*. The noise in N-S is larger than in the E-W direction, however the effect of earthquake is visible in both constituents.

Fig. 1. Analyzed sites with GPS receivers observing with 1 Hz sampling in the period of the L'Aquila earthquake.

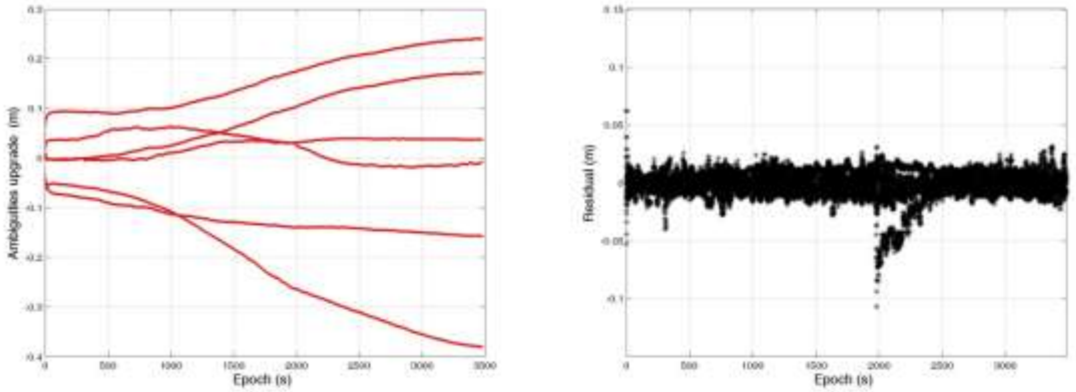

Fig. 2. Station ROIO: Upgrade of ambiguities and phase residuals from quasi-static PPP obtained from analysis of 1-hour interval of GPS observations, April 6, 2009. The time axis starts at 01:00:00 GPS time. The sudden increase of phase residuals is related to occurrence of earthquake at 1:32:00 GPS time.

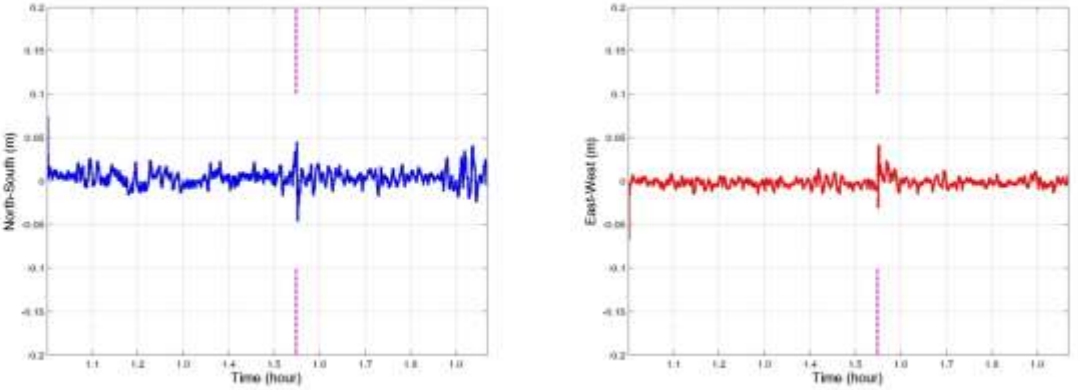

Fig. 3. Station ROIO: Time series of phase residuals from quasi-static PPP transformed to North-South and East-West coordinate constituents. The occurrence of earthquake at 1:32: 54 GPS time is marked by dashed line.

The final outputs from analysis of all five stations are in Fig. 4. GPS observations from CADO, ROIO and INGP unambiguously registered the earthquake induced motions in all coordinate constituents. The observed short-term horizontal displacements are from 23 cm (East-West component of CADO) to 5 cm (North-South component of INGP). The significant variations in Up component are observed at CADO (17 cm) and ROIO (12 cm). For ROIO and CADO also the post-seismic drift is well determined. The time series of all the three sites mentioned are obtained with *Kinematic PPP* approach, application of the *Residuals from quasi-static PPP* approach resulted to similar coordinate time series. At ROIO and CADO stations the GPS receivers were set to 10 Hz rate recordings. Their analysis by Avallone et al. (2011) demonstrated the increased sensitivity to high-rate coordinate variations and better performance in monitoring horizontal coordinate constituents. The expected minor coordinate displacements of RSTO and INGR are analyzed using the *Residuals from quasi-static PPP* approach. In this case the effect of earthquake cannot be positively confirmed in none of the plotted series, even the increased variability in RSTO is observed.

4. ATTEMPT TO DETECT DISPLACEMENTS RELATED TO LIGHT-MAGNITUDE EARTHQUAKE - M 4.3TATABANYA EARTHQUAKE

Observability of the effect of light-magnitude earthquake in PPP analysed GPS 1 Hz records are examined on the Tatabanya earthquake (Hungary, magnitude 4.3, epicentre 47.56°N, 18.31°E) occurred on January 29, 2011, 17:41:37 UTC (USGS, 2012). We processed here the GPS data from the station TATA (Tatabanya) from the Hungarian national active GNSS network (www.gnssnet.hu) which is situated 10.0 km from the epicentre. No earthquake effects are noticeable in phase residuals shown in Fig. 5 and in GPS seismograms shown in Fig. 6. As documented in Fig. 7, no one of the coordinate constituents indicates earthquake related displacements. We emphasise that the variability of the East-West component (Fig. 9) sampled with 1 Hz rate is less than 0.3 cm. Our experience with PPP analysis of GPS 1 Hz data observed in various environments indicates that 0.3 cm is limiting value for detectable seismic-related phenomena.

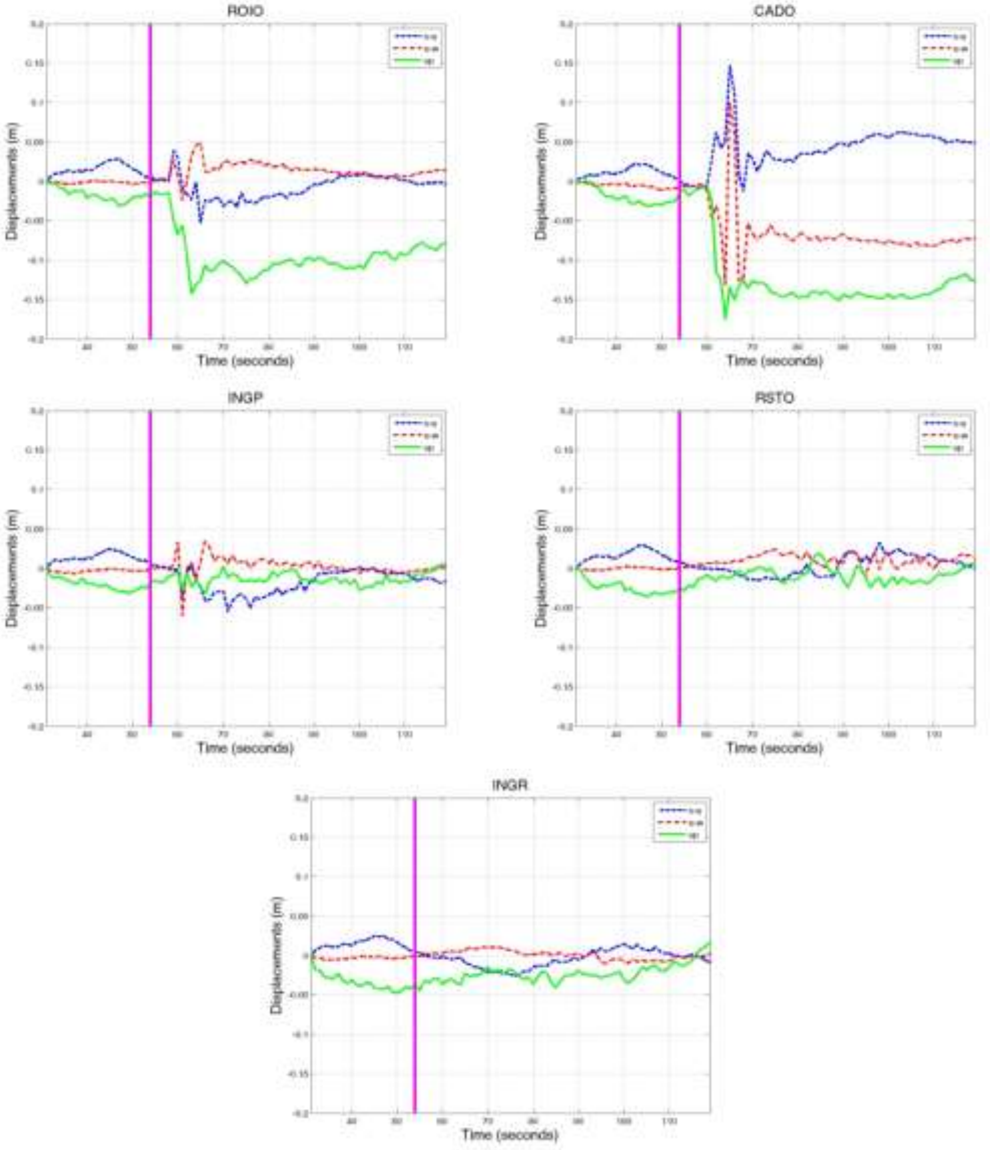

Fig. 4. Horizontal and vertical coordinate shifts of GPS stations ROIO, CADO, INGP, RSTO and INGR related to the L'Aquila earthquake. The time axis starts at 1:32:00 GPS time, the vertical line indicates the occurrence of earthquake in GPS time (1:32:54).

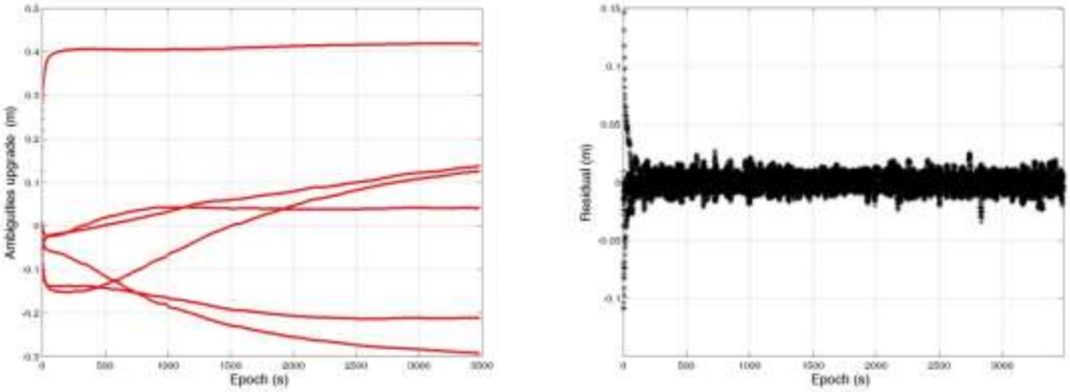

Fig. 5. Station TATA: Upgrade of ambiguities and phase residuals from analysis of 1-hour interval of GPS observations, Jan. 29, 2011. The time axis starts at 17:00:00 GPS time.

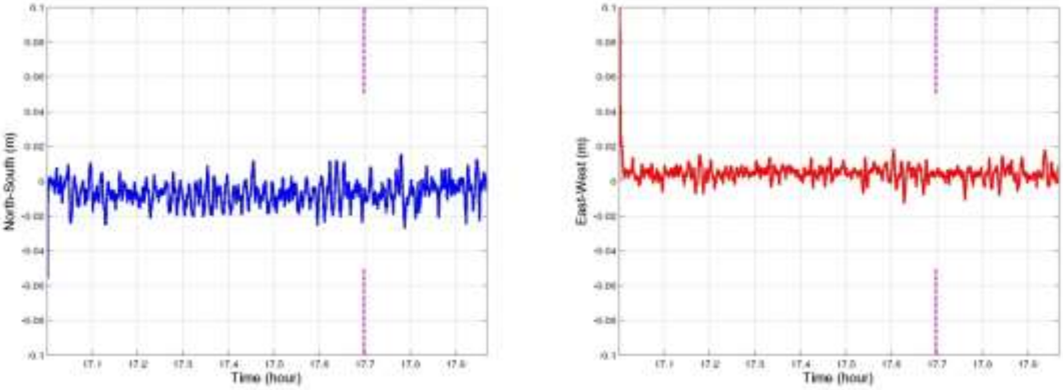

Fig. 6. Station TATA: Time series of phase residuals from quasi-static PPP transformed to North-South and East-West coordinate constituents. The occurrence of earthquake at 17:41:52 GPS time is marked by dashed line.

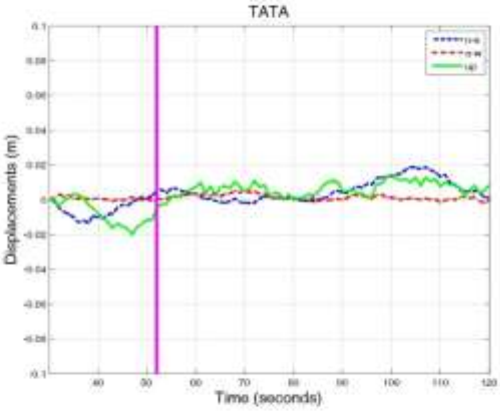

Fig. 7. Horizontal and vertical coordinate evolution of GPS station TATA during the Tatabanya earthquake. The time axis starts at 17:41:30 GPS time, the vertical line indicates the occurrence of earthquake in GPS time (17:41:52).

5. CONCLUSIONS

The applied analysis method using the PPP approach adopted for processing of 1 Hz sampled GPS data demonstrated the possibilities to detect and to monitor the earthquake-related horizontal and vertical displacements. The PPP software package ABSOLUTE was extended for analysis of kinematic GPS observations by implementation of Kalman filtering for final parameter estimation. Two alternatives depending on degree of constraining the adjustment of coordinate parameters proved the potential for detection of irregular positional variations at sub-centimetre level related to great and moderate earthquakes. We succeed in reliable recording displacements related to M 6.3 :L'Aquila earthquake, however no observable effect was noticed during the M 4.3 Tatabanya earthquake. The presented method is efficient for strong earthquakes effects and for stations close to epicentre. For weaker effects more dense records (of order of 10 Hz) may improve the delectability of seismic displacements. Inclusion of GLONASS observation also could increase the accuracy and sensitivity of PPP base earthquake monitoring.

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