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POTENTIAL OF PRECISE POINT POSITIONING USING 1 HZ GPS DATA FOR DETECTION OF SEISMIC-RELATED DISPLACEMENTS

Ján HEFTY * and Ľubomíra GERHÁTOVÁ

Department of Theoretical Geodesy, Faculty of Civil Engineering,
Slovak University of Technology, Radlinského 11, 813 68 Bratislava, Slovak Republic
**Corresponding author's e-mail:* jan.hefty@stuba.sk

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ABSTRACT

The Precise Point Positioning (PPP) analysis technique adapted for monitoring of moderate high-rate coordinate variations from GPS observations is applied for measuring actual displacements related to 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 displacements. Results from simulated horizontal movements of GPS antenna as well as analyses of 1 Hz GPS data from M 9.0 Sendai earthquake, M 6.3 L'Aquila earthquake and M 4.3 Tatabanya earthquake are shown. Our experiments proved the ability to measure dynamic seismic-related short-term coordinate variations at sub-centimetre level with PPP and to detect both strong and weak seismic signals using GPS satellites observations.

KEYWORDS: high-rate GPS, GPS seismology, precise point positioning, earthquake related displacements

1. INTRODUCTION

The GPS satellite positioning applied for geokinematic and geodynamic research is usually aimed at monitoring of long-term site displacements accompanied with periodic variations, predominantly of seasonal nature. For such applications the GPS observations are sampled in 30 s or longer intervals and the site coordinates are evaluated on daily or weekly basis. The high-rate recordings, e.g. with 1 s sampling (or even with sampling frequency up to 100 Hz) which are feasible for majority of recent GPS receivers, are used predominantly in navigation or for kinematic surveying applications. However, there exist several geodynamic phenomena like landslides, volcano tectonics, earthquakes, etc. where the high-rate records of observed GPS satellites may provide substantial information.

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 (Lichten 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 centimetres. Kouba (Kouba, 2003) pointed on possibility to apply Precise Point Positioning (Zumberge et al., 1997) approach using precise IGS orbits and satellite clocks products (Kouba and Héroux, 2001) for analysis of seismic waves induced by large earthquakes. Application of GPS at high sampling rates for monitoring seismic-related phenomena Larson termed 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 method 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 are in relatively simple GPS data processing and unambiguous interpretation of measured site position variations. The objective of this paper is to further examine possibilities of application of PPP for detection of position oscillations and post-seismic offsets induced by earthquakes of various intensities. Our analysis of GPS observations with 1 Hz sampling is based on utilization of software package ABSOLUTE developed at Slovak University of Technology in Bratislava for multi-GNSS positioning using un-differenced code and phase observations (Hefty and Gerhátová, 2011). The algorithms of ABSOLUTE were originally designed for static positioning when the site coordinates are assumed to be stable during the observation interval, usually for period of 24 hours or at least for periods longer than 1 hour. The option for kinematic data processing yielding new position for each observed epoch is implemented for purpose of monitoring short-term coordinate variations by inclusion of Kalman filtering for final parameter estimation. For detection of larger displacements we will apply standard approach when the final independent 1 Hz coordinate estimates are used for description of station position variations. In case when only smaller displacements (less than several centimetres) are expected, we will analyze carries phases residuals resulting from strongly constrained kinematic positioning.

2. APPLIED ANALYSIS METHOD

The Precise Point Positioning (PPP) processing strategy is taking advantage of un-differenced GNSS code and phase observations and utilization of precise satellite orbits and satellite clocks information. The absolute position – geocentric site coordinates related to the International Terrrestial Refernce System (ITRS) are obtained without necessity of differencing GNSS 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 developed at Slovak University of Technology for processing of static GNSS 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 also 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, 2011) is extended the applicability of ABSOLUTE to GLONASS and GIOVE satellites by introducing bias parameters necessary for combination of observations from various GNSS. Next extension of processing options of ABSOLUTE applied for analyses in this paper is aimed to kinematic PPP. 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 form 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 in 15 min intervals and the satellite clocks corrections in 30 s intervals are adopted from the IGS Global Data Centre (IGS, 2011). The vector of unknown parameters $\boldsymbol{\Theta}$ consists of three types of quantities: coordinate increments δX, δY, δZ to the initial site position X_0, Y_0, Z_0, receiver clock offset dT and corrections δN_j to initial ambiguities N_j ($j = 1, 2, \ldots m$), where m is number of all ambiguities of un-differenced phase observations within the time interval of processed data.

$$\Theta = \begin{bmatrix} \delta X & \delta Y & \delta Z & dT & \delta N_1 & \delta N_2 & \cdots & \delta N_m \end{bmatrix}^T \quad (1)$$

The vector of GPS observations at epoch t_i ($i = 1, 2, \ldots n$) consists of p pairs of iono-free combinations from code P and phase L measurements. They are obtained from simultaneous observations of p satellites performed at the epoch t_i.

$$\mathbf{b} = \begin{bmatrix} P_1 & L_1 & P_2 & L_2 & \cdots & P_p & L_p \end{bmatrix}^T \quad (2)$$

The quantities P_k and L_k ($k = 1, 2, \ldots p$) in (2) represent the observed code and phase observables after subtraction of the corresponding quantities computed with initial parameter values X_0, Y_0, Z_0 and N_1 , N_2 , … N_m.

Linearized observation equation has then form

$$\mathbf{b} = \mathbf{A}\Theta + \mathbf{e} \quad (3)$$

with design matrix $\mathbf{A}$ and the observation noise vector $\mathbf{e}$. As we assume mutually independent observations their covariance matrix $\boldsymbol{\Sigma}_\mathbf{b} = E[\mathbf{e}\ \mathbf{e}^T]$ is diagonal with variances σ_P^2, σ_L^2 characterizing the variability of code and phase measurements.

The general concept of Kalman filtering is based on updating of the initial values of parameters (or parameters resulting from previous processing). The initial estimate denoted here for transparency as $\boldsymbol{\Theta}_{\text{old}}$ will be improved using the new set of observations, denoted here as $\mathbf{b}_{\text{new}}$. The new (updated) estimate of parameters $\boldsymbol{\Theta}_{\text{new}}$ is then obtained as linear combination of the initial estimate $\boldsymbol{\Theta}_{\text{old}}$ and the new observations $\mathbf{b}_{\text{new}}$

$$\boldsymbol{\Theta}_{\text{new}} = \boldsymbol{\Theta}_{\text{old}} + \mathbf{K}\left(\mathbf{b}_{\text{new}} - \mathbf{A}_{\text{new}}\boldsymbol{\Theta}_{\text{old}}\right) \quad (4)$$

where $\mathbf{K}$ is the Kalman gain matrix and $\mathbf{A}_{\text{new}}$ is design matrix relating new observations $\mathbf{b}_{\text{new}}$ with set of parameters $\boldsymbol{\Theta}_{\text{old}}$. The vector $\mathbf{b}_{\text{new}}$ - $\mathbf{A}_{\text{new}}\ \boldsymbol{\Theta}_{\text{old}}$ represents mismatch between new measurements and old estimate (Strang and Borre, 1997). Eq. (4) can be simply modified as

$$\boldsymbol{\Theta}_{\text{new}} = \boldsymbol{\Theta}_{\text{old}} + \boldsymbol{\varepsilon} \quad (5)$$

where the vector $\boldsymbol{\varepsilon}$ denotes the error of prediction of parameters. We assume, that the elements in $\boldsymbol{\varepsilon}$ are independent, with known covariance matrix $\boldsymbol{\Sigma}_{\boldsymbol{\Theta}} = E[\boldsymbol{\varepsilon}\ \boldsymbol{\varepsilon}^T]$, which is in our case diagonal.

Application of Kalman filtering for dynamic upgrade of parameters $\boldsymbol{\Theta}$ is based on series of GPS observation vectors $\mathbf{b}_t$ related to epochs t_i (i = 1, 2, … n) and known design matrices $\mathbf{A}_t$. The predicted estimate of $\boldsymbol{\Theta}_t(-)$, (prediction is denoted here with sign -) is based on information from previous epoch t-1 (Strang and Borre, 1997). As the prediction of parameters is considered the final updated estimate (denoted here with +) from previous epoch t-1

$$\hat{\boldsymbol{\Theta}}_t(-)=\hat{\boldsymbol{\Theta}}_{t-1}(+) \tag{6}$$

The corrected (updated) estimate $\hat{\boldsymbol{\Theta}}_t(+)$ using observation $\mathbf{b}_t$ from epoch t is according to (4)

$$\hat{\boldsymbol{\Theta}}_t(+)=\hat{\boldsymbol{\Theta}}_{t-1}(-)+\mathbf{K}_t\left(\mathbf{b}_t-\mathbf{A}_t\hat{\boldsymbol{\Theta}}_{t-1}(-)\right) \tag{7}$$

For correcting the estimate from epoch t-1 three matrices are involved, namely the predicted covariance matrix

$$\mathbf{P}_t(-)=\mathbf{P}_{t-1}(+)+\boldsymbol{\Sigma}_{\boldsymbol{\Theta},t} \tag{8}$$

the gain matrix

$$\mathbf{K}_t=\mathbf{P}_t(-)\,\mathbf{A}_t^T\left[\mathbf{A}_t\,\mathbf{P}_t(+)\mathbf{A}_t^T+\boldsymbol{\Sigma}_{\mathbf{b},t}\right]^{-1} \tag{9}$$

and the corrected covariance matrix

$$\mathbf{P}_t(+)=\left(\mathbf{I}-\mathbf{K}_t\,\mathbf{A}_t\right)\mathbf{P}_t(-) \tag{10}$$

Outputs of the introduced processing procedure are the time series of parameter estimates $\hat{\boldsymbol{\Theta}}_t$.

Our analysis of earthquake related displacements is focused on three elements of $\hat{\boldsymbol{\Theta}}_t$ - the coordinate time series δX_t, δY_t, δZ_t which will be subsequently transformed to local coordinates in North-South, East-West and height denoted as n_t, e_t, v_t. The time variability of $\hat{\boldsymbol{\Theta}}_t$ is defined by setting of diagonal elements in the covariance matrix $\boldsymbol{\Sigma}_{\boldsymbol{\Theta}}$. In general, the ambiguities N_j are strongly constrained to their previous estimates and the receiver clocks dT are loosely constrained (the actual clock estimates are independent from thein previous values). In this paper we applied constrains for all ambiguities σ_N = 0.0001 m and σ_{dT} = 1.000 m for receiver clock estimates.

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

The loose constraining of δX, δY, δZ parameters in $\boldsymbol{\Sigma}_{\boldsymbol{\Theta}}$ will cause that all earthquake related displacements will be included in estimated coordinate time series. Such approach we name as 'Kinematic PPP'. For earthquake related displacements we applied here $\sigma_{\delta X} = \sigma_{\delta Y} = \sigma_{\delta Z}$ = 1.000 m.

Setting strong constrains on δX, δY, δZ in $\boldsymbol{\Sigma}_{\boldsymbol{\Theta}}$ will cause that the earthquake related displacements will be visible in residuals of carrier phase observables L_k in (2). 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. 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 $\sigma_{\delta X} = \sigma_{\delta Y} = \sigma_{\delta Z}$ = 0.001 m.

The residuals from code P and phase L observations realized at epoch t will be evaluated as

$$\mathbf{r}_t^{(L,P)}=\mathbf{b}_t-\mathbf{A}_t\hat{\boldsymbol{\Theta}}_t(+) \tag{11}$$

By extracting p elements related to phase observables from the $2p$-dimensional vector $\mathbf{r}_t^{(L,P)}$ we will obtain the vector of phase residuals $\mathbf{r}_t^{(L)}$. This vector reflects besides the observation errors also the discrepancy between the actual site position and the position determined from quasi-static PPP (the actual coordinates are treated as stable for limited time interval). The $\mathbf{r}_t^{(L)}$ vector will be used for estimating the actual coordinate deviation from the mean position by least-squares solution of equation

$$\begin{bmatrix} dX_t \\ dY_t \\ dZ_t \end{bmatrix}=\mathbf{B}_t\,\mathbf{r}_t^{(L)} \tag{12}$$

where $\mathbf{B}_t$ is design matrix relating the residuals of phase measurements to local coordinate shifts. Finally, the time series of dX_t, dY_t, dZ_t which will be 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 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. TESTS OF DATA PROCESSING METHODS ON SIMULATED HORIZONTAL MOVEMENTS

For evaluation of possibilities and accuracy limits of PPP for detection of moderate site displacements we performed series of experimental GPS observations with 1 Hz data recording. Besides the static GPS positioning processed in kinematical mode, we performed experiments with GPS antenna mounted on mechanical device simulating periodic horizontal movements. The simulator constructed at Institute of Geodesy at Technical University of Brno enables horizontal harmonic motion in straight line with amplitude 5 cm and with mean frequency 0.82 Hz. It is possible to set the line of motion in arbitrary azimuth; the vertical movements of antenna are expected to be zero.

Table 1 Results from experimental evaluation of applied processing strategies

Processing strategy	RMS differences between modelled and observed positions of GPS antenna		
	North-South (mm)	East-West (mm)	Up (mm)
PPP kinematic	7.7	5.1	11.8
Residuals from quasi-static PPP	7.6	4.2	12.5

Figure 1 shows time series in North-South (*n*), East-West (*e*) and Up (*v*) components estimated from 20 min interval of 1 Hz records of GPS observations in experiment performed on July 6, 2011. The processed interval of data started at 9 h 30 min with GPS antenna in static position and ends at 9 h 50 min of GPS time. At 9 h 43 min started simulation of harmonic movements of GPS antenna lasting 60 sec. Second period of movements taking 60 sec started at 9 h 46 min. The antenna during the 2 min interval between moving periods remained in opposite position. The orientation of the simulator enabled horizontal movements with 3.7 cm in *n* component and 3.4 cm in *e* component. The plots document the sensitivity of GPS processed in PPP kinematic mode for detection of horizontal movements with 5 cm amplitude.

The detailed view of 30 sec interval of harmonic motion of antenna mounted on simulator and the GPS estimated position is in Figure 2. Estimated GPS *n* and *e* coordinate constituents are at cm level consistent with the modelled positions of moving antenna. Because of aliasing (frequency of the simulator is f_s = 0.82 Hz, the sampling frequency of GPS is f_{GPS} = 1 Hz) the observed oscillation is with frequency f_a = 0.18 Hz. It is evident that for detection and reliable description of displacements with frequencies higher than 0.25 Hz, the GPS sampling frequency f_{GPS} = 1 Hz is not sufficient and f_{GPS} should be increased at least to 2 Hz or even to 5 Hz or 10 Hz. The potential of application of high-rate GPS recordings for kinematic monitoring was successfully examined e.g. in (Avallone et al., 2011; Wang et al., 2011).

To investigate the accuracy limits of PPP for monitoring dynamic phenomena during short intervals we analyzed various data-sets of observations: i/ the GPS antenna was static, ii/ with antenna changing the static position to harmonic movements, iii/ the static position and harmonic movements were alternated. The analyses were restricted to separated 300 sec intervals with the long-term drift eliminated from GPS data. Results from 10 sets of observations performed under various situations are summarized in Table 1. Both processing strategies – 'Kinematic PPP' and 'Residuals from quasi-static PPP' lead to similar RMS differences between modelled and observed positions of GPS antenna. The values in Table 1 demonstrate the potential of presented processing and analysis technique for detection of sudden displacements in horizontal coordinates and height. It is worth mentioning that the values of RMS differences obtained from comparisons of shorter intervals (150 sec or 90 sec) are slightly lower than those given in Table 1. It is the evidence of some residual systematics that influences GPS estimated coordinates in kinematic mode.

4. ANALYSIS OF 1 HZ GPS DATA RELATED TO GREAT EARTHQUAKES

For demonstration of capability of kinematic PPP to monitor position oscillations related to great earthquakes we used 1 Hz GPS data from March 11, 2001 during the Sendai earthquake with epicentre near East Coast of Honshu, Japan (38.297°N, 142.372°E), magnitude 9.0, occurred at 05:46:24 UTC (USGS, 2012). Figure 3 shows distribution of analyzed IGS stations from which are the high-rate 1 Hz sampled GPS data available. We used the 1 s observations from the IGS LEO Working Group database (IGS, 2011). The MIZU and USUD (IGS permanent stations in Japan with distances from epicentre 143 km for Mizusawa and 429 km for Usuda) observations analyzed with ultra-rapid precise satellite orbits and clocks shortly after the Sendai earthquake documented enormous position shifts (Banville and Langley, 2011).

Figures 4 and 5 show horizontal and vertical oscillations of MIZU and USUD resulting from our analysis using the ABSOLUTE software in kinematic mode. The represented displacements are relatively to the initial coordinates at the first epoch of the plotted interval. Both plots unambiguously demonstrate larger than 0.5 m short-term displacements in all three coordinate constituents. Evident also are the post-seismic displacements in horizontal position at meter level for site MIZU and decimetre level for East-West component for site USUD. The vertical post-seismic deformation (20 cm for MIZU and 7 cm for USUD) is indicated from the plotting; however the insufficient ambiguity modelling may give rise to similar effect.

The other four analyzed stations are situated more than 2000 km from the epicentre. As shown in Figure 6, the IGS sites SHAO (Shesan, China, 2082 km from epicentre) and PETS (Petropavlovsk, Russia, 2063 km from epicentre) are unambiguously indicating displacements related to the earthquake. The range of SHAO coordinate variations (15 cm and more in horizontal constituents and height) is significantly larger than the range of observed

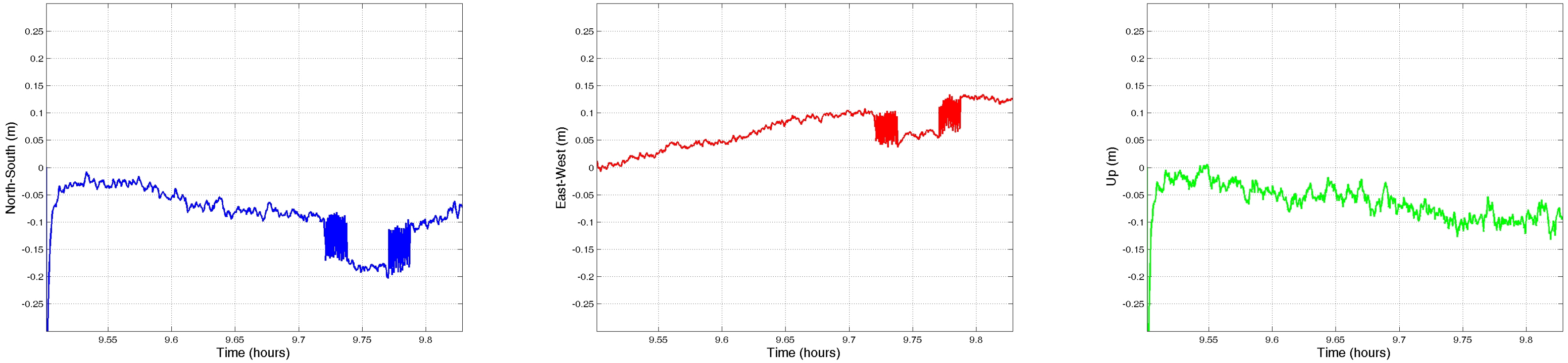

Fig. 1 Time series in North-South, East-West and Up coordinate constituents estimated from 20 min interval of 1 Hz records of GPS observations with GPS antenna mounted on mechanical device enabling simulation of periodic horizontal movements. The forced movements were activated twice for 60 seconds.

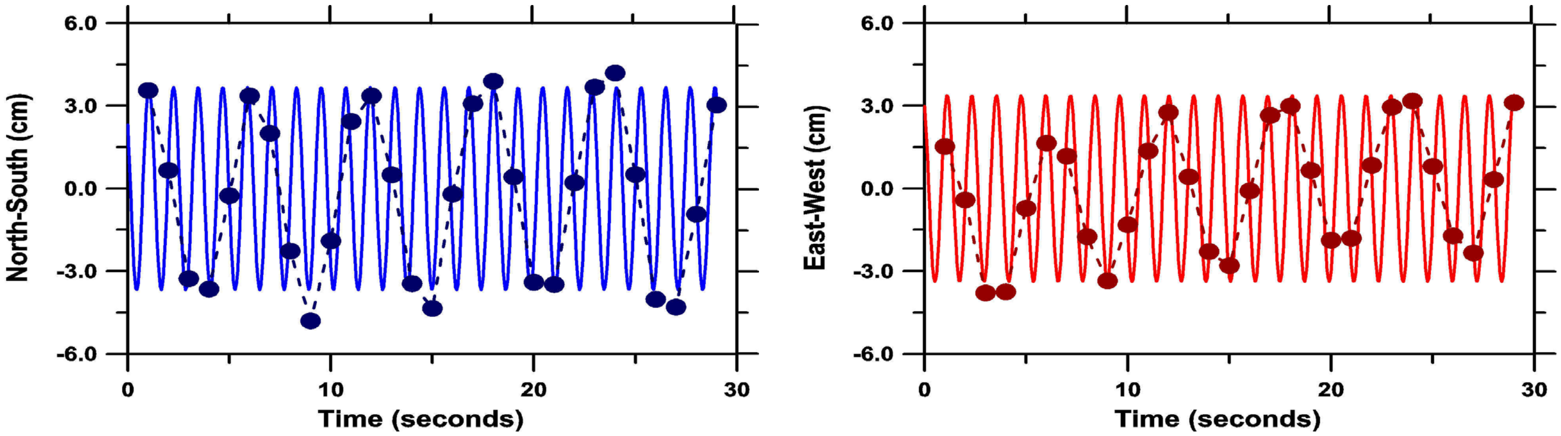

Fig. 2 Simulated harmonic horizontal movements (solid lines) and GPS measured position (dots and dashed lines) – detail from 30 sec of analysed data.

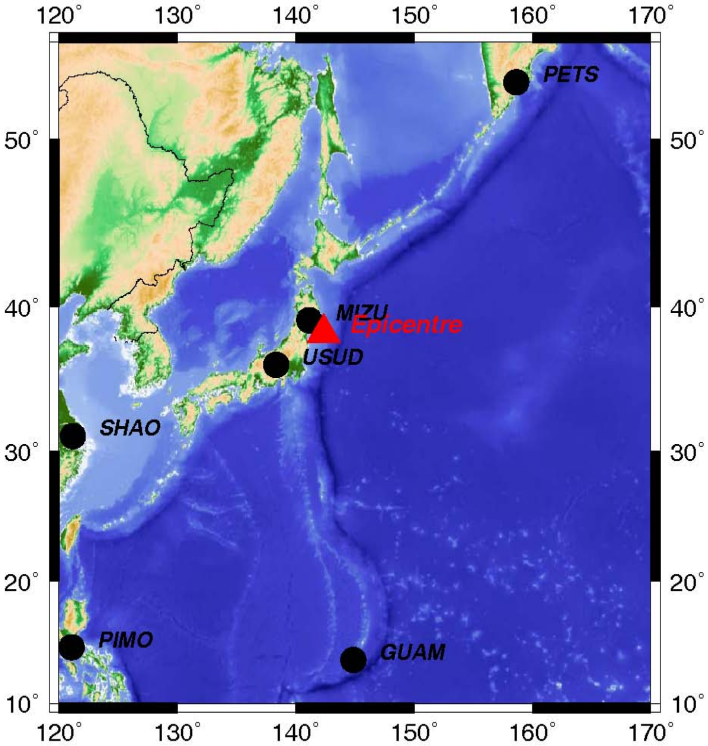

Fig. 3 Distribution of IGS stations from which the high-rate 1 Hz sampled GPS data during the Sendai earthquake are available.

coordinate displacements in PETS (about 10 cm in horizontal components and 7 cm in up component) despite the stations are in same distance from epicentre. The evidence of earthquake related displacements in the other two IGS sites GUAM (Dededo, Guam, 2727 km from epicentre) and PIMO (Quezon City, Philippines, 3317 km from epicentre) shown in Figure 6 is not proved for all coordinate constituents. The GUAM East-West about 10 cm variations are well observed, the North-South ~ 5 cm displacements are only slightly exceeding the noise of the time series. The 10 cm displacement of the up component is also visible in the time series; however it cannot be excluded that it is spurious effect related to ambiguity mismodelling. The PIMO coordinate evolution is relatively stable with increased variability of North-South and East-West components (~ 6 cm) 700 s after occurrence of the earthquake. The causality of observed height variations with earthquake cannot be confirmed.

The results of PPP processing of 1 Hz GPS data with ABSOLUTE software in kinematic mode with Kalman filtering using IGS orbits in 15 min intervals and satellite clocks in 30 s intervals are capable to monitor seismic-related displacements at sites situate over 2000 km far away from the epicentre of great earthquake.

5. POSSIBILITIES OF DETECTION DISPLACEMENTS RELATED TO MODERATE-MAGNITUDE AND LIGHT-MAGNITUDE EARTHQUAKES

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 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).

Figure 7 shows the distribution of 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). 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'. 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 (Fig. 8). 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.

Observability of the effect of light-magnitude earthquake in GPS 1 Hz records will be 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. In Figure 9 are plotted time series of local coordinate constituents obtained from analysis of residuals from quasi-static PPP. No one of the series 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. The quality of information related to earthquake induced displacements could be increased if the higher sampling rate (e.g. 10 Hz) GPS recordings are available for analyses. Especially, in case of weak earthquake related effects with short-term variability (less than 1 s) the analysis of 0.1 s sampled GPS data is capable to detect displacements that remained undetected with 1 Hz sampling as documented e. g. in (Avallone et al., 2011).

6. 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 developed at Slovak University of Technology in Bratislava 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 earthquake related displacements even for sites more than 2000 km away from epicentre of Honshu M 9.0 earthquake and more than 80 km away from epicentre of M 6.3 L'Aquila 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

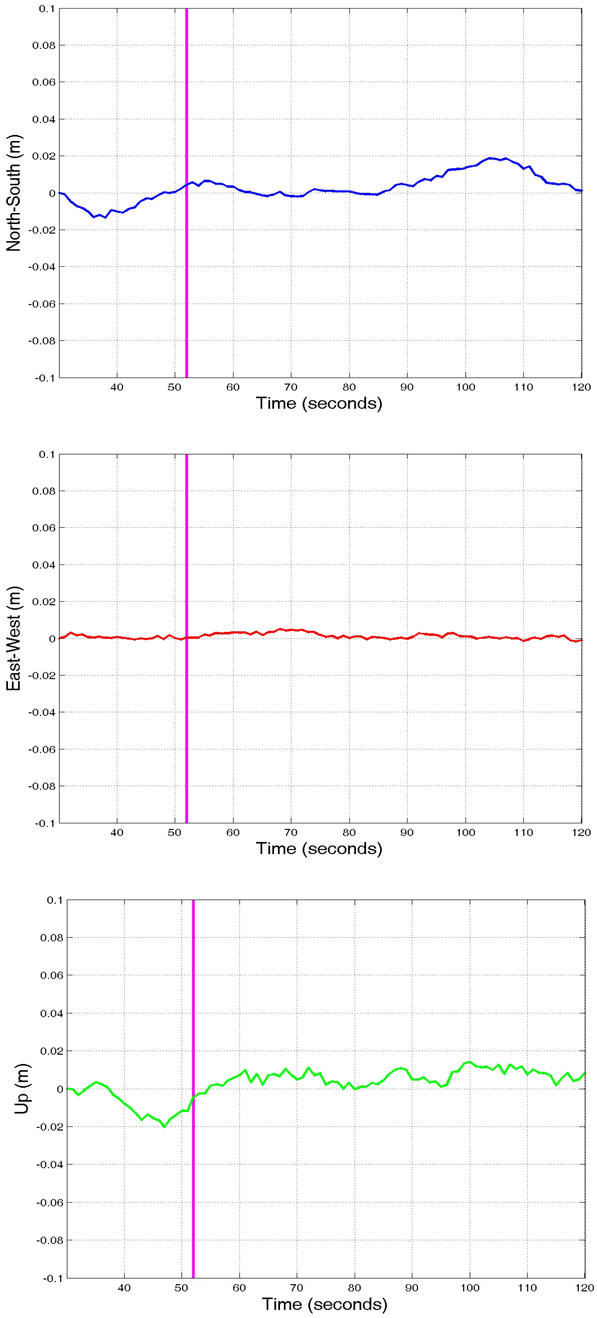

Fig. 9 Horizontal and vertical coordinate time series of GPS station TATA during the Tatabanya M 4.3 earthquake. The time axis starts at 17:41:00 GPS time, the vertical line indicates the occurrence of earthquake in GPS time (17:41:52).

increase the accuracy and sensitivity of PPP based earthquake monitoring.

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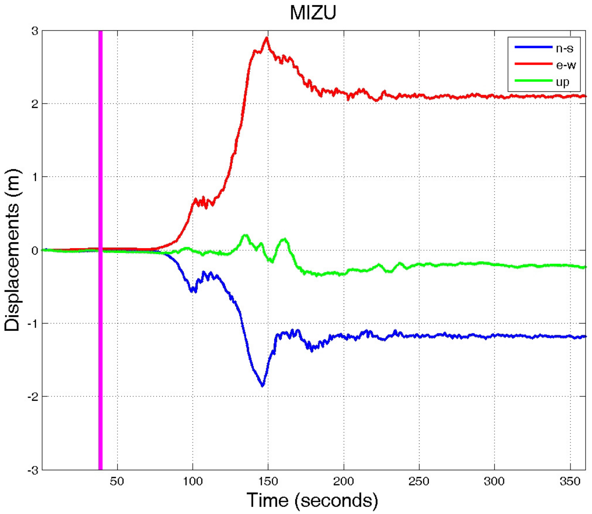


Fig. 4 Horizontal and vertical coordinate shifts of IGS station MIZU related to the Sendai earthquake. The time axis starts at 5:46:00 GPS time, the vertical line indicates the occurrence of earthquake in GPS time (5:46:39).

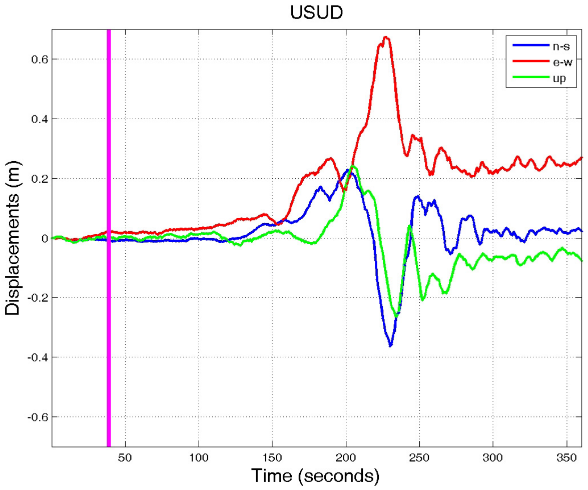


Fig. 5 Horizontal and vertical coordinate shifts of IGS station USUD related to the Sendai earthquake. The time axis starts at 5:46:00 GPS time, the vertical line indicates the occurrence of earthquake in GPS time (5:46:39).

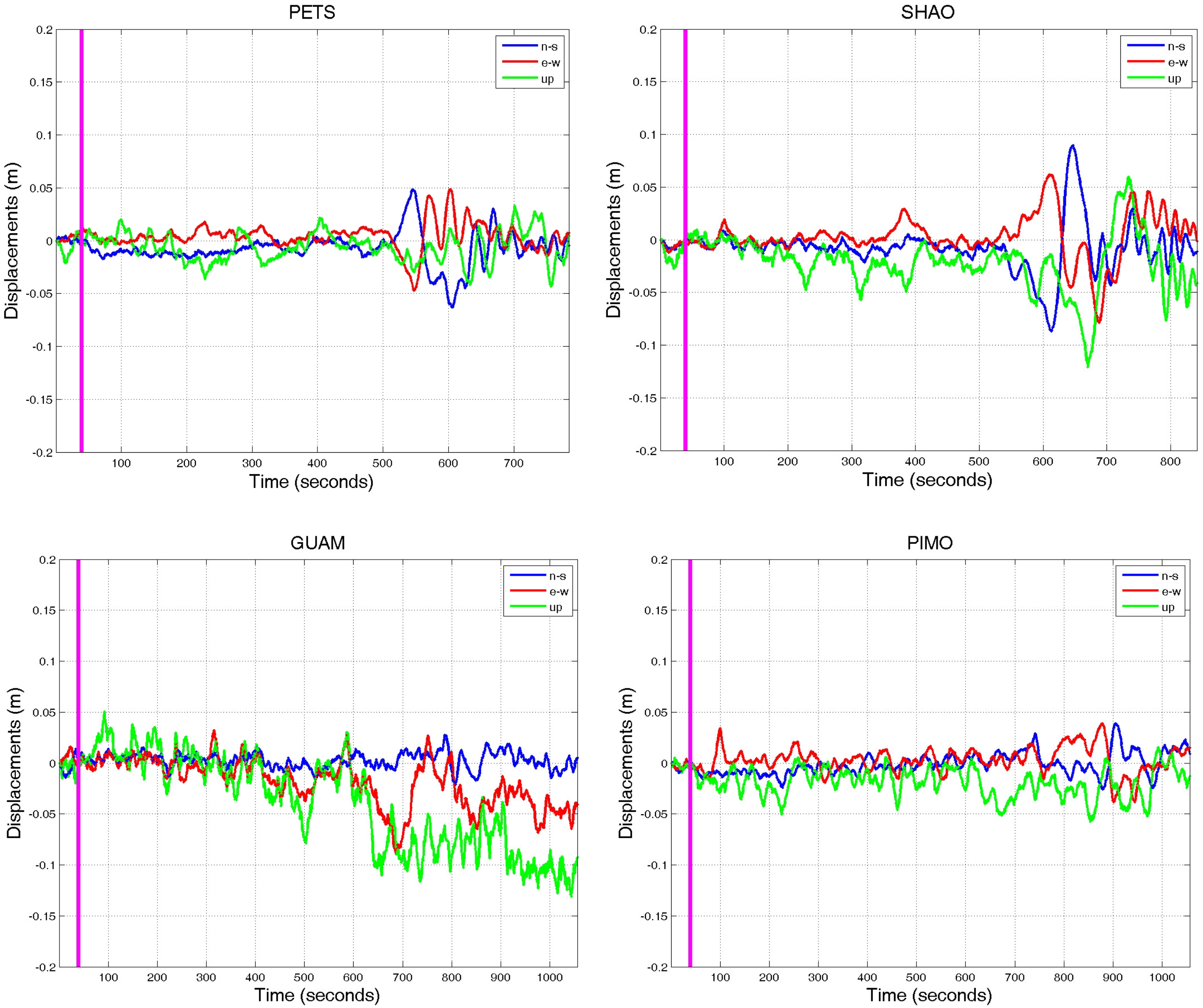
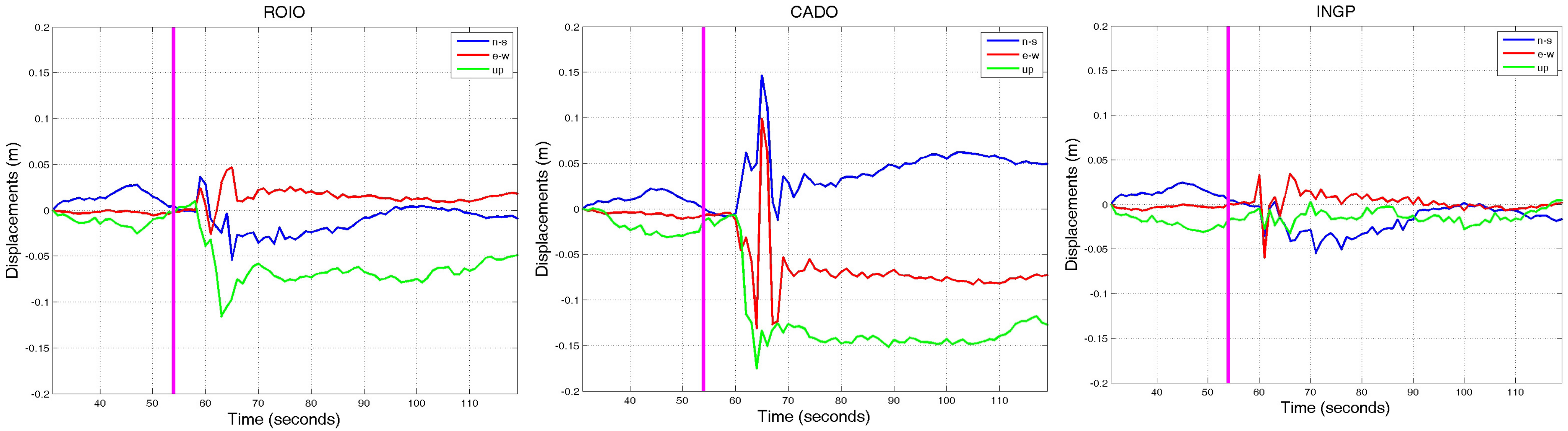


Fig. 6 Horizontal and vertical coordinate shifts of IGS stations PETS, SHAO, GUAM and PIMO related to the Sendai earthquake. The time axis starts at 5:46:00 GPS time, the vertical line indicates the occurrence of earthquake in GPS time (5:46:39).



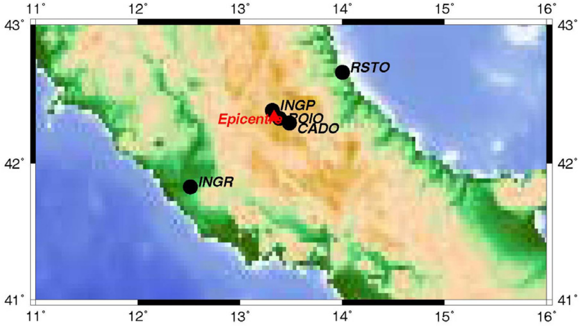


Fig. 7 Analyzed sites with GPS receivers observing with 1 Hz sampling in the period of the L'Aquila earthquake

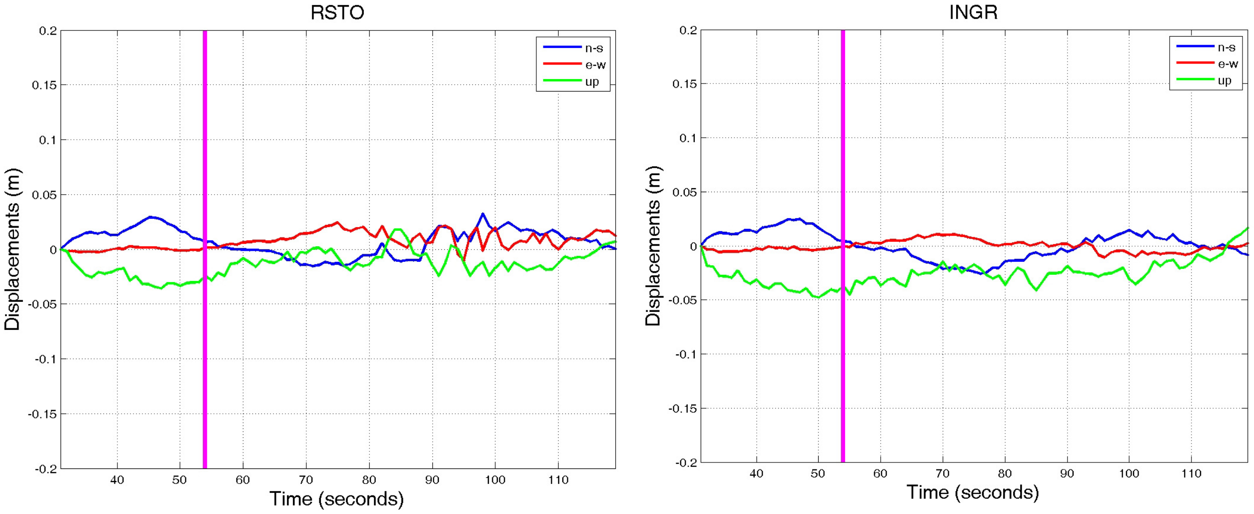


Fig. 8 Horizontal and vertical coordinate shifts of GPS stations ROIO, INGP, CADO, RSTO and ING related to the L'Aquila earthquake. The time axis starts at 1:32:00 GPS time, the vertical line indicates the occurrence of earthquake in GPS time (1:32:54).