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# Temporal point positioning approach for real-time GNSS seismology using a single receiver

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[1] High-rate Global Navigation Satellite Systems (GNSS) has an increasing number of applications in geohazard monitoring. GNSS-derived displacements can provide important information for magnitude estimation and fault slip inversion, which is critical for seismic and tsunamigenic hazard mitigation. In this paper, we propose a new approach to quickly capture coseismic displacements with a single GNSS receiver in real time. The new approach can overcome the convergence problem of precise point positioning, and also avoids the integration process of the variometric approach. Using the results of the 2011 Tohoku-Oki earthquake, it is demonstrated that the proposed method can provide accurate displacement waveforms and permanent coseismic offsets at an accuracy of few centimeters, and can also reliably recover the moment magnitude and fault slip distribution. Citation: Li, X., M. Ge, B. Guo, J. Wickert, and H. Schuh (2013), Temporal point positioning approach for real-time GNSS seismology using a single receiver, Geophys. Res. Lett., 40, 5677-5682, doi:10.1002/2013GL057818.

### 1. Introduction

[2] Rapid source and rupture inversion for large earthquakes is critical for seismic and tsunamigenic hazard mitigation [*Allen and Ziv*, 2011; *Ohta et al.*, 2012]. However, the saturation of broadband seismometers and problematic integration of strong-motion data into displacements make this difficult in real time [*Wang et al.*, 2013]. High-rate Global Navigation Satellite Systems (GNSS) (e.g., 1 Hz or higher frequency) measures displacements directly and can provide reliable estimates of broadband displacements, including static offsets and dynamic motions of arbitrarily large magnitude [*Larson et al.*, 2003; *Bock et al.*, 2004]. GNSS-derived displacements can be used to quickly estimate earthquake magnitude, model finite fault slip, and also play an important role in earthquake/tsunami early warning [*Blewitt et al.*, 2006; *Wright et al.*, 2012; *Hoechner et al.*, 2013].

[3] Currently, there are two primary strategies for real-time GNSS processing: relative baseline/network positioning and precise point positioning (PPP) [*Zumberge et al.*, 1997]. The disadvantage of relative positioning (RP) is that the solutions are influenced by movements of the reference stations [*Ohta* 

<sup>1</sup>German Research Centre for Geosciences (GFZ), Potsdam, Germany. <sup>2</sup>Wuhan University, Wuhan, Hubei, China. *et al.*, 2012]. Additionally, the computational load increases very quickly as the network gets larger [*Crowell et al.*, 2009]. In contrast, PPP can provide "absolute" seismic displacements related to a global reference frame defined by the satellite orbits and clocks with a single GNSS receiver [*Kouba*, 2003; *Wright et al.*, 2012; *Li et al.*, 2013a]. However, real-time PPP requires precise satellite orbits and clock corrections and also needs a long (re)convergence period, of about 30 min, to achieve centimeter-level accuracy [*Collins et al.*, 2009].

[4] Colosimo et al. [2011] proposed a variometric approach to overcome the difficulties of the two aforementioned, presently adopted, approaches for GNSS seismology. This approach is based upon the time single differences of the carrier phase observations recorded by a single GNSS receiver at a given ground station. The time series of the station velocities are estimated, and these velocities are integrated to provide coseismic displacements. However, eventual biases of the estimated velocities accumulate over time and display as a drift in the coseismic displacements. The assumption of a linear drift limits the integration interval to few minutes [*Branzanti et al.*, 2013]. If the entire period of seismic shaking lasts longer than few minutes in the case of large earthquakes, the drift value could be large and cannot be fully removed by a linear detrending.

[5] In this paper, we propose a new approach for estimating coseismic displacements with a single receiver in real time. The approach overcomes not only the disadvantages of the PPP and RP techniques, but also decreases the described drift in the displacements derived from the variometric approach. The coseismic displacement could be estimated with few centimeters accuracy using GNSS data around the earthquake period. The efficiency of the new approach is validated using 1 Hz GNSS data, collected during the Tohoku-Oki earthquake (Mw 9.0, 11 March 2011) in Japan.

## 2. Description of the New GNSS Analysis Method

[6] The linearized equations for carrier phase and code observations can be expressed as follows,

$$l_{r,i}^{s} = -u_{r}^{s} \cdot x - t^{s} + t_{r} + B_{r,i}^{s} - I_{r,i}^{s} + T_{r}^{s} + \varepsilon_{r,i}^{s}$$
(1)

$$p_{r,j}^{s} = -u_{r}^{s} \cdot x - t^{s} + t_{r} + I_{r,j}^{s} + T_{r}^{s} + e_{r,j}^{s}$$
(2)

where,  $l_{r,j}^s$ ,  $p_{r,j}^s$  denote "observed minus computed" phase and code observations from satellite *s* to receiver *r* at frequency *j* (*j*=1,2);  $u_r^s$  is unit direction vector from receiver to satellite; *x* denotes receiver position;  $T_r^s$ ,  $I_{r,j}^s$  denote tropospheric and ionospheric delay;  $t^s$ ,  $t_r$  are clock errors of satellite and receiver;  $B_{r,j}^s$  is phase ambiguity;  $e_{r,j}^s$ ,  $\varepsilon_{r,j}^s$  are measurement noise of carrier phase and code.

[7] In order to achieve the most precise position estimates with GNSS, the phase center offsets and variations, and

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station displacements by tidal loading must be considered. Phase wind-up and relativistic delays must also be corrected according to the existing models [*Kouba and Héroux*, 2001], although they are not included in the equations. The ionospheric delays can be estimated as unknown parameters or eliminated by using dual-frequency phase and code data. The tropospheric delay is corrected with an a priori model, and the residual part is described as a random walk process [*Boehm et al.*, 2006]. The receiver clock is estimated epoch-wise as white noise. Furthermore, real-time precise satellite orbit and clock products are now available online via the International GNSS Service (IGS) real-time pilot project (RTPP) [*Caissy et al.*, 2012; *Dow et al.*, 2009].

[8] For real-time PPP processing, the phase ambiguities are estimated together with the receiver position, receiver clock, and residual tropospheric delays. The ambiguities need some time to converge (e.g., 30 min) to the correct values, until enough observables are used in the filter. There will be a big disturbance in the displacement sequence during the convergence period (see Figure a1 in auxiliary material). In the variometric approach, ambiguities are eliminated using the time difference of phase observations and thus the convergence process is not required. Although the velocities can be estimated with a high accuracy, the integration process from velocities to displacements may lead to accumulated drift if longer than few minutes (see results in *Colosimo et al.* [2011] and/or Figure a2 in auxiliary material).

[9] In fact, for the seismological applications, we are mainly interested in the position variation relative to the position before the earthquake. Generally, the receiver position before the earthquake is well known. Assuming that the receiver position at the epoch  $t_0$  (before the earthquake) is  $x(t_0)$ , the ambiguities  $B(t_0)$  can be estimated along with the receiver clock  $t_r(t_0)$  and tropospheric delay  $T(t_0)$  (fixed to a priori model) parameters at this epoch as,

$$B(t_0) + t_r(t_0) + T(t_0) = l(t_0) + u(t_0) \cdot x(t_0) + t^s(t_0) - \varepsilon(t_0)$$
(3)

[10] In our processing, all the error components are carefully considered following the PPP model. When the receiver position  $x(t_0)$  is well known, the ambiguities  $B(t_0)$  with a certain accuracy can be expected. Then we hold the estimated ambiguities  $B(t_0)$  fixed in the subsequent epochs. At the epoch  $t_n$ , the positions  $x(t_n)$  can be estimated as,

$$u(t_n) \cdot x(t_n) - t_r(t_n) - T(t_n) = -l(t_n) - t^s(t_n) + B(t_0) + \varepsilon(t_n)$$
(4)

[11] As the ambiguities are held to fixed values instead of being estimated as unknown parameters, the convergence process will not be required. Furthermore, the positions  $x(t_n)$  are estimated directly and thus the integration process is also avoided. We substitute the equation (3) into the equation (4) and have,

$$u(t_n) \cdot x(t_n) - \Delta t_r(t_0, t_n) + \Delta T(t_0, t_n) = u(t_0) \cdot x(t_0) + \Delta l(t_0, t_n) + \Delta t^s(t_0, t_n) - \Delta \varepsilon(t_0, t_n)$$
(5)

[12] It can be found that the accuracy of the position estimates  $x(t_n)$  is mainly affected by the variation of the tropospheric delay from the epoch  $t_0$  to  $t_n$ . Generally, the variation of the tropospheric delay is at centimeter level for few tens of minutes. Therefore, the position estimates are reasonably presumed to be with a good accuracy at centimeter level.

[13] We can see that equation (5) is in the same form as the time-differenced equation of phase observations between the epoch  $t_0$  and  $t_n$ . This is equivalent to calculating the position at epoch  $t_n$  relative to the well-known position at epoch  $t_0$ . This method is based on observations from a single receiver. Therefore, we refer to it as the temporal point positioning (TPP) method in the following sections. In our approach, an accurate initial position at epoch  $t_0$  (i.e., the receiver position before the earthquake) is important for achieving high-accuracy displacements. Figure a3 shows the displacement results using initial position with different accuracies.

# **3.** Application of the Developed Analysis Method and Results

[14] The 2011 Mw 9.0 Tohoku-Oki earthquake (11 March 2011, 05:46:23 UTC) in Japan is one of the best recorded large-magnitude earthquakes in history, by GNSS, as Japan has one of the most dense GNSS ground networks in the world. This network is operated by the Geospatial Information Authority of Japan (GSI) and consists of more than 1200 continuously observing GNSS stations (the GNSS Earth Observation Network System, GEONET) all over Japan (http://www.gsi.go.jp/).

[15] First, the 1 Hz GEONET GPS data (dual frequency) before the earthquake was processed to evaluate the accuracy of the proposed TPP method. Twenty minutes of displacements from 00:00 to 00:20 (GPST) on 11 March 2011, at GNSS station 0986, is shown in Figure 1. We compare the displacements, derived from the real-time TPP solution, using different orbit and clock products. The black lines show the results using broadcast orbit and clock (BOBC solution), which is routinely available from the GNSS receiver itself in real time. The red lines are the results using precise satellite orbit and clock solutions (POPC solution). The satellite orbit is generally predicted for real-time applications as its dynamic stability. Here the ultrarapid orbit, updated every 3 h and provided by GFZ, is applied. The clock corrections have to be estimated and updated much more frequently [Zhang et al., 2011] due to their short-term fluctuation. We process 1 Hz data from 80 to 90 globally distributed real-time IGS stations using the GFZ's EPOS-RT software [Ge et al., 2011] in simulated real-time mode (a strictly forward filter) for generating precise GNSS clock corrections at a 5 s sampling interval.

[16] Real-time orbit and clock corrections are reliant on an internet connection for transmission to monitoring stations, but the reality is that the internet connection and communication infrastructure could be destroyed during large earthquakes. In these cases, satellite clock corrections have to be extrapolated, although predicted ultrarapid satellite orbits from the IGS or GFZ can be downloaded in advance. Here we also evaluate how our products would be degraded during large earthquake, when the real-time stream would be unavailable. The results using the precise predicted orbit and extrapolated clock (POEC solution) are shown by the blue line.

[17] From Figure 1, we can see that there is no obvious drift for even a 20 min period in the horizontal components of TPP-derived displacements when precise orbit and clock corrections are applied. In the vertical component, there is only a small drift of a few centimeters. When only broadcast orbit and clock products are available, the drifts in the



**Figure 1.** Displacements derived from real-time temporal point positioning (TPP) solution. The red line shows the result using precise satellite orbit and clock (POPC solution), the blue line is the result using precise orbit and extrapolated clock (POEC solution), and the black line is the result using broadcast orbit and clock (BOBC solution). Twenty minutes interval of 00:00–00:20 (GPST) on 11 March 2011, at GNSS station 0986 (GEONET). From top to bottom are the results in north, east, and up components, respectively.

displacement series are clearly visible, especially in the vertical component. The drift values for 20 min are several centimeters in the horizontal components, and a few decimeters in the vertical component. If we compare this result (TPP with BOBC) and Figure a2 result (variometric approach with BOBC), we can see that the two approaches display similar accuracy level. In the scenario that we can only use extrapolated satellite clocks due to failure of the internet connection. the drift values are several centimeters in the horizontal components, and about one decimeter in the vertical component. This is several centimeters worse than the precise clocks results, but much better than the broadcast orbit and clock results, particularly in the vertical component. Obviously, the accuracy of orbits and clocks plays a crucial role, and the differences among POPC, POEC, and BOBC are reduced to few centimeters if only the first 3-4 min is considered.

[18] We calculated the root mean squares (RMS) of the drift errors at 20 min of 80 evenly distributed GEONET stations. The results for the different orbit and clock products are summarized in Table 1. The drifts of the BOBC solution can reach up to 9.1, 7.8, and 28.2 cm in north, east, and up directions, respectively. The precise orbit and clock corrections can remarkably improve the accuracy to 2.9, 2.3, and 5.8 cm in the corresponding directions. It is even comparable to the accuracy of PPP after convergence period. With the extrapolated satellite clocks, accuracies of 5.3, 4.7, and 11.3 cm can be achieved in three components, respectively. Although these accuracies are degraded compared to the POPC solution, it significantly improves the BOBC solution. From these results, we also found that the vertical component is the most sensitive to the quality of the orbit and clock products.

[19] We reprocessed the 1 Hz GPS data (dual frequency) collected by GEONET stations during the 2011 Tohoku-Oki earthquake using the TPP method in real-time mode. The coseismic displacement waveforms, for the 20 min period around the entire seismic shaking at GNSS station 0986, are shown in Figure 2. The TPP waveforms using precise satellite orbits and clocks are shown by the blue line. The postprocessed PPP waveforms, which have an accuracy of

few centimeters [*Kouba*, 2003; *Wright et al.*, 2012], can be regarded as a reference, and are shown by the red line. The comparisons between them show that the TPP waveforms are quite consistent with the PPP results at a few centimeters accuracy during the entire shaking period. When only broad-cast orbits and clocks are applied to the processing, the performance of the TPP method is degraded to about one decimeter in the horizontal components and about two decimeters in the vertical component, as indicated by the black line.

[20] For comparison, we also process all the data using the variometric approach. All the error components are carefully corrected following the PPP and/or TPP model. The cumulative displacements at GNSS station 0986 are shown in Figure a2, illustrating typical behavior. Although precise orbits and clocks are applied, there are drifts up to few decimeters in the cumulative displacements. Compared to Figure 2, one can see that the TPP method can improve the displacement accuracy for POPC solution if the duration is longer than few minutes.

[21] The permanent coseismic offset is the important information for magnitude estimation and fault slip inversion. In Figure 3, we compare the permanent coseismic offsets of 80 evenly distributed stations derived from the TPP solution and the postprocessed PPP solution. The postprocessed PPP results, TPP results using precise satellite orbit and clock, and TPP results using broadcast orbit and clock are shown, respectively, by the red, green, and purple arrows. It is found that the permanent TPP coseismic offsets agree with PPP ones very well in both horizontal and vertical components when precise orbit and clock corrections are applied. The

**Table 1.** Root Mean Squares of the Drift Values at Eighty Evenly-Distributed GEONET Stations

RMS	North (cm)	East (cm)	Up (cm)
BOBC solution	9.1 2 9	7.8	28.2
POEC solution	5.3	4.7	11.3



**Figure 2.** Comparison of the coseismic displacement waveforms derived from real-time TPP solution and postprocessed precise point positioning (PPP) solution. The red line shows the postprocessed PPP result as a reference for TPP results, the blue line is the TPP result using precise satellite orbit and clock (POPC solution), and the black line is the result using broadcast orbit and clock (BOBC solution). A 20 min interval around the entire period of seismic shaking on 11 March 2011, at GNSS station 0986 (GEONET) is shown. From top to bottom are the results in north, east, and up components, respectively.

RMS values of the differences between the two solutions are 3.0, 2.1, and 5.6 cm in north, east, and vertical components, respectively. The TPP results using broadcast orbits and clocks show some disagreements with the PPP results; the RMS values of the differences between them are found to be 8.2, 7.0, and 22.9 cm in north, east, and vertical components. The results show that the TPP method can

provide reliable permanent offsets, especially if precise orbit and clock corrections are available.

[22] We derive the spatial distributions of the fault slip using the coseismic displacements obtained from the real-time TPP solution with broadcast orbit/clock, TPP with precise orbit/clock, and postprocessed PPP solution, respectively. In the same way as done by *Wang et al.* [2013], we employ



**Figure 3.** A comparison of the permanent coseismic offsets derived from real-time TPP solution and postprocessed PPP solution on horizontal components and on vertical components, respectively. The red arrow denotes the postprocessed PPP result as a reference for TPP results, the green arrow denotes the TPP result using precise satellite orbit and clock, and the purple arrow is the result using broadcast orbit and clock.



**Figure 4.** Comparison of the inverted fault slip distributions derived from real-time TPP solution and postprocessed PPP solution. From left to right are the inversion results derived from postprocessed PPP, real-time TPP using precise orbit/clock, and real-time TPP using broadcast orbit/clock, respectively.

a slightly curved fault plane, parallel to the assumed subduction slab. The dip angle increases linearly from 10° on the top (ocean bottom) to 20° at about 80 km depth. To avoid any artificial bounding effect, a large potential rupture area of  $650 \times 300$  km is used. The upper edge of the fault is located along the trench east of Japan, on the boundary between the Pacific plate and the Eurasian plate. The patch size is  $10 \times 10$  km. The rake angle determining the slip direction at each fault patch is allowed to vary between  $90^{\circ} \pm 20^{\circ}$ . Green's functions are calculated based on the CRUST2.0 model [*Bassin et al.*, 2000] in the relevant area.

[23] The three inversions result in moment magnitudes of Mw 8.90, 8.96, and 8.97, respectively. The maximum slip of the three inversion results is 21.0, 23.0, and 23.3 m, respectively. The inverted fault slip distributions are shown in Figure 4. The postprocessed PPP result is considered to be the most reliable and is taken as the reference. The inversion results of real-time TPP with precise orbits/clocks and the postprocessed PPP solution are quite consistent with each other not only in the moment magnitude, but also in the slip distribution pattern. TPP using broadcast orbits/clocks leads to an underestimation of the moment magnitude and fault slip values to an extent. The comparison of the three inversion results shows that the TPP method can provide a reliable estimation of earthquake magnitude and of the fault slip distribution, especially when precise satellite orbit and clock corrections are used.

### 4. Conclusions

[24] A new approach for real-time GNSS seismology using a single receiver was presented. The performance of the proposed TPP approach is validated using 1 Hz GEONET data collected during the 2011, Mw 9.0 Tohoku-Oki earthquake.

[25] When real-time precise orbit and clock corrections are available, the displacement waveforms, derived from TPP, are consistent with the postprocessed PPP waveforms at an accuracy of few centimeters during the entire shaking period, even for a period of 20 min. The TPP permanent coseismic offsets agree with PPP ones very well with RMS values of 3.0, 2.1, and 5.6 cm in north, east, and vertical components, respectively. The results of the fault slip inversions also indicate that the TPP method can provide a reliable estimation of moment magnitude and even of the fault slip distribution. If just the broadcast orbits and clocks are available, the displacement accuracy will be degraded to some extent and this leads to underestimations of the moment magnitude and fault slip values.

[26] In the discussion in section 2, we consider the GNSS observations to be free from cycle slips during the earthquake period. In practice, several methods of cycle-slip fixing [e.g., *Zhang and Li*, 2012; *Geng et al.*, 2010; *Li et al.*, 2013b] can be used to correct the phase observations when cycle slips occur. Furthermore, a joint processing of multi-GNSS (e.g., GPS, GLONASS, Galileo, and BeiDou) data will significantly increase the number of available satellites and thus enhance the reliability of our approach.

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