A new PPP algorithm for deformation monitoring with single-frequency receiver

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Considering the applications of deformation monitoring, PPP (precise point positioning) with single-frequency (SF) receivers has the advantages of stand-alone, absolute positioning and cost efficiency. However, the existing SF PPP methods can be hardly implemented for deformation monitoring directly due to their limited precision of submeter level. For this purpose, an innovative approach is presented in this paper with several improvements to the existing approaches: firstly, the SEID (Satellite-specific Epoch-differenced Ionospheric Delay) model is adopted in SF kinematic PPP to handle the ionospheric delays for SF receivers embedded in networks of dual-frequency (DF) receivers; secondly, according to the dynamic characteristic of the monitor station, a combination of kinematic PPP and sliding window based static PPP algorithm is adopted. To confirm the availability of the algorithm for deformation monitoring with SF receiver, a seismic experiment is carried out on an earthquake simulation platform. Comparable positioning precision with 1.5 cm for horizontal and 2.2 cm for vertical is achieved by SF PPP with respect to RTK (real-time kinematic) solution. The new deformation monitoring algorithm with SF receiver can be treated as an effective and low cost way to realize some types of geological hazard monitoring in a wide range.

1. Introduction

The potential of GPS (Global Positioning System) deformation monitoring has been widely recognized (Jin *et al.* 2007; Banerjee *et al.* 2008; Shi *et al.* 2010) in recent years. To date, there are two approaches that can be used in deformation monitoring with GPS: network solution (Bock *et al.* 1986; Blewwit 1989; Wang *et al.* 2002) and PPP (Zumberge *et al.* 1997; Ge *et al.* 2008). For network positioning, at least one station must be fixed or tightly constrained to its known position (Larson *et al.* 2003; Bock and Prawirodirdjo 2004; Bock *et al.* 2011), although it is normally displaced by the deformation. Therefore, the displacements

estimated for other stations are affected by the displacement of the fixed station. In the PPP approach, satellite clocks and orbits are fixed to pre-estimated precise values, and the coordinates can be estimated station by station in the reference frame defined by the orbits and clocks. PPP, with the advantages of stand-alone and absolute positioning, has been widely applied to measure displacements in recent years (Kouba 2003; Fang *et al.* 2013; Hung and Rau 2013).

Nowadays, a growing number of continuous GNSS (Global Navigation Satellite System) operational stations have been constructed or are being constructed. Usually, the locations of these stations are precisely selected in order to get better

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solutions for various applications, such as surveying, navigation, and so on. However, there are so many threatening deformations in nature that human and material resources are not enough to monitor all the deformations. Monitoring is only carried out for relatively important areas, and most hazard-prone regions are not monitored. In case of geological hazards, like landslides, the disaster is almost impossible to avoid unless it is monitored all the time. To solve these problems, the existing monitoring system must be strengthened. SF GPS receiver can be used for a wide range of monitoring station constructions due to its low prices and ability to work all day, all weather. Huge amounts of deformation data and troposphere information (obtained with GPS (Bevis *et al.* 1992), which is closely related to rainfall) can be obtained from these GPS monitoring stations, and this can be used for analyzing the discipline of geological hazard.

However, only submeter level precision has been demonstrated for SF PPP; SF receiver has been hardly regarded as an effective tool in deformation monitoring. One crucial challenge in SF PPP is the mitigation of ionospheric delay. For SF receiver, the ionospheric delay cannot be removed through linear combination on different frequencies as DF measurements. To overcome this difficulty, a large number of researches focused on GPS-derived ionospheric modelling with dual-frequency receivers have been published (Mannucci *et al.* 1998; Schaer 1999; Rocken *et al.* 2000; Janssen and Rizos 2005). However, these models are developed for large regions with low resolution across spatial and temporal, which are usually not accurate enough for precise applications. More recently, Deng *et al.* (2009) developed a new ionospheric model known as SEID to capture the small scale and rapid ionospheric disturbances, and the efficiency of this new approach has been demonstrated for retrieving tropospheric delays with mixed SF and DF receivers. The precision of SF static PPP is presented by Zou *et al.* (2010). As DF CORS networks have been widely spread, and it is still growing rapidly all around the world; Densification of the dual-frequency network with single-frequency receivers in these regions is an applicable choice to balance the huge GPS deformation monitor demands and economic considerations. As we use SF PPP with SEID in kinematic mode and there is no introduction about this until now, its performance is tested in this paper.

On the other hand, even though SF receivers can obtain comparable precision with DF receivers, it is still not precise enough to meet the demands of deformation monitoring. Therefore many researches have been done to solve this dilemma. Side real filtering (Bock *et al.* 2000;

Radovanovic 2000; Choi *et al.* 2004) is used to eliminate systematic errors (such as multipath) related to station environment and geometric structure of satellites. Spatial stacking (Larson 2009) uses the spatial correlation feature between different stations to eliminate the common errors, such as the residual ionospheric delay, which has not been eliminated by linear combination. But for SF receiver, as the ionospheric delay is handled by nearby stations with SEID, the characteristic systematic errors are disturbed by nearby stations, so side real filtering and spatial stacking methods cannot be used for this SF receiver processing algorithms. Yao and Zhang (2012) put forward a PPP algorithm based on sliding window and used it in earthquake monitoring with DF receiver, but they assumed that the monitoring stations were totally static before deformation, so they did not consider the length of the sliding window. In this paper, we considered the balance between possible small deformations of the monitoring station and the precision of static PPP based on sliding window, and analyzed the selection criterion of sliding window. We also made some modifications about the deformation test.

The new algorithm deformation monitoring with SF receiver is realized by two steps: firstly, the SEID model is used to handle the ionospheric delay in SF kinematic PPP; secondly, a combination of kinematic PPP and static PPP based on sliding window is adopted. The new algorithm is validated with SF data of a simulated earthquake experiment carried out by an earthquake simulation platform located at Wuhan University. The ionospheric delay is handled by nearby-stations of Wuhan CORS network with SEID model.

2. Method

2.1 SEID

Deng *et al.* (2009) proved that time differenced ionospheric delays from nearby stations can be used to efficiently remove the ionospheric effect of SF data. Using the ionospheric single layer model, time differenced ionospheric delays of reference stations can be fitted to a plane by a linear function of IPP (Ionospheric Pierce Point), and epoch differenced ionospheric delay of rover station can be interpolated.

It must be pointed out that an arbitrary real-value differs not only for different satellite-station pairs but also for different continuously tracked data pieces of the same pair is introduced into the simulated observation, and thus can never be cancelled by forming differenced observations between stations and satellites. However, it can be absorbed by the ambiguities in ambiguity-float PPP. In

addition, the SEID model has nothing to do with the coordinates of reference stations, and can still be used even when deformation happens at reference stations.

2.2 The new PPP algorithm

Static PPP has a potential for millimeter-centimeter high accuracy, but because it needs a rather long period to get a coordinate resolution, it is unable to meet the monitoring requirements of the monitoring stations with rapid deformation rate. Kinematic PPP mode is suitable for deformation monitoring with epoch resolution, but the usage is limited by its centimeter-decimeter accuracy.

In kinematic PPP mode, because of the randomness of the object's movements, it is difficult to establish an accurate state equation. In kinematic PPP processing, the coordinate parameters are independent between adjacent epochs, only the ambiguities and troposphere estimate and corresponding variance-covariance is transferred to the next epoch. Each epoch must solve at least three coordinate parameters and a receiver clock parameter, the strength of the equation is weak and can be easily affected by

observation errors and noises, so the precision of the coordinates is relatively worse. In static mode, we assume the monitoring station is static, and all the observations are used to estimate three station coordinates and other parameters. Long periods of observations can reduce the observation errors and the effect of noises; thus the precision of coordinates and ambiguities are higher than in kinematic resolution.

Generally, in deformation monitoring, the monitoring station is static or with small deformations before the occurrence of a disaster. With this *a priori* information, a combinational PPP algorithm of kinematic PPP and static PPP based on sliding window can be designed. The algorithm can overcome both the long period demands of observations of static PPP and the low accuracy of kinematic PPP.

The new PPP algorithm with SF receiver is realized mainly by two steps: the handling of ionospheric delay of SF receiver with SEID model and the adoption of combinational PPP algorithm for improving the positioning accuracy. The flow chart of the strategy is shown in figure 1.

We can see from figure 1 that, after the handling of ionospheric delay with SEID model, the filtering estimation followed. Each epoch is firstly estimated in kinematic PPP mode. If the monitoring station

Figure 1. Flow chart of the new PPP algorithm (the dotted lines refer to the next epoch).

is already marked as deformation, a kinematic PPP with the kinematic variance–covariance information of the former epoch is carried out. If the monitoring station is not marked as deformation in the former epoch, a deformation test is carried out. If the epoch does not meet the deformation test, estimate the coordinate of monitoring station in static PPP mode with all the measurements in the sliding window, and transfer the ambiguities, tropospheric parameters, and their corresponding variance–covariance information to the next epoch. If a deformation is detected, carry out a kinematic PPP with the kinematic variance–covariance information of the former epoch, mark the epoch with deformation, transfer the variance–covariance of kinematic PPP to the next epoch, release the static constraints of kinematic PPP, and turn the PPP to kinematic mode for the following epochs.

Each epoch can get two coordinates: a coordinate from kinematic PPP filter and a high-accuracy static PPP coordinate estimated with all the observations in sliding window. If a deformation happens, a difference between the two coordinates appears. There are two coordinate time series before deformation. Deformation is relatively easy to be detected because of the high precision and stability of this PPP algorithm. Two criteria are used in this paper.

1. Coordinate difference test. The threshold for this coordinate difference test is set according to the statistical properties of the difference of the two coordinate time series. Here the threshold is set to be 3σ (standard deviation of the coordinate difference).
2. Consistency test of coordinates. The epoch-wise static coordinate is obtained with observations of a large sample, and the epoch-wise kinematic coordinate is obtained with a relatively small sample of observations. T-distribution is used to test the consistency regarding the mathematical expectation of the two coordinates. In actual process, $\hat{X}_i$ is the kinematic PPP coordinate estimate, X_i is the static PPP coordinate estimate, $Q_{\hat{X}_i \hat{X}_i}$ is the weight reciprocal of $\hat{X}_i$, $t_{(\alpha/2)}$ denotes the t -distribution of a confidence level α with f degrees of freedom (Wang et al. 2006).

$$P \left\{ -t_{(\alpha/2)} < \frac{\hat{X}_i - X_i}{\hat{\sigma}_0 \sqrt{Q_{\hat{X}_i \hat{X}_i}}} < t_{(\alpha/2)} \right\} = p = 1 - \alpha \quad (1)$$

where

$$\hat{\sigma}_0 = \sqrt{\frac{V^T P V}{f}}, \quad f = r - t. \quad (2)$$

The value for $\hat{\sigma}_0$ is obtained with the kinematic PPP filter at the current epoch, where V is the vector of the residuals, P is the weight matrix, r is the number of measurements, t is the number of parameters. The value for α is set to be 0.003.

The 3σ and α used are experimental. In practical application, the reliability and success rate of the monitoring station can be further ensured by the state of nearby stations. Meanwhile, if there are other means of deformation monitoring, they can be considered as supplementary and an enhancement of the above-mentioned deformation test.

The length of the sliding window is decided by two factors: (1) it should ensure the accuracy of static PPP with the observations in the sliding window; (2) it should minimize the possible inaccurate effect of static constraint caused by small deformation for kinematic PPP. As a trade-off between maximizing the precision for static PPP resolution and minimizing the possible effect of static constraint for kinematic PPP, a length of 4 hours is selected. With 4 hours' observations, the static PPP can get a centimeter level accuracy (Tétreault et al. 2005; Geng 2010). The short length and the sliding characteristic of the window can ensure the reliability of the static constraint. Constraint with *a priori* information obtained from static PPP based on sliding window can promise a high accuracy resolution with kinematic PPP.

The new PPP algorithm can solve the long time dependence problem of static PPP and the low accuracy of kinematic PPP. According to the characteristics of this algorithm, it is more suitable for the deformation monitoring of regions with considerable risks, such as landslides, avalanches, mudslides, earthquakes, and so on.

3. Experiments

3.1 Method validation

3.1.1 Data

A CORS network composed of 75 stations with DF receivers of Jiangsu, China is selected. The averaged separation of the reference stations is about 51 km. Data of day 277–283 in 2011 is analyzed.

3.1.2 Data processing scheme

The performance of the new algorithm with SF observation is compared with the existing approaches with a large amount of GPS data. The following approaches are taken into consideration

and referred to as approach A, B, C and D, respectively. PPP of all the approaches are handled in kinematic mode.

- A. SF PPP (Shi *et al.* 2011).
- B. SF PPP with SEID model.
- C. DF PPP.
- D. The new PPP algorithm with SF observation.

IGS final orbits, clocks, and DCB are held fixed in all the processing; the absolute antenna phase centers, the wind-up corrections, and the station displacement from the IERS conventions 2003 (McCarthy and Petit 2004) were applied. An elevation-dependent weighting strategy was applied (Gendt *et al.* 2003). The tropospheric delays are calculated with Saastamoinen model and Niell mapping function using predicted meteorological parameters, and the remaining are estimated as a random walk process. Receiver clocks are estimated epoch by epoch. New ambiguity is inserted once a cycle slip is detected and observations identified as outliers are down-weighted. GIM from CODE are applied in solution A. For Methods B and D, the ionospheric delay of each station is handled by its nearest four DF reference stations (figure 2).

3.1.3 Result and discussion

The position accuracy is measured by the differences of the estimates and the coordinates obtained from Bernese GPS Software version 5.0 (Dach *et al.* 2007). Daily RMSs of the differences were computed for all the stations. Figure 3 shows the distribution of the daily RMS of the four methods. For each method, there are about 500 daily RMSs. The mean RMS of the methods is listed in table 1.

From figure 3, Method A with SF PPP has the largest RMS of about 0.120 m for horizontal and 0.3 m for vertical components. Methods B, C and D have significantly better results than Method A. Therefore, even with GIM ionospheric product and an empirical model derived by the stochastic process for each satellite (Shi *et al.* 2011), SF PPP still cannot get comparable result with DF PPP. The slightly better result by Method C over Method B indicates that the SEID model can greatly eliminate the ionospheric delays of SF observations, and the precision of SF PPP with SEID is almost comparable with DF ionospheric-free PPP resolution. Method D has the smallest RMS of 0.015, 0.014, and 0.022 m in north, east, and up directions, respectively. Comparing the 3D RMS with Methods B and C, Method D has an improvement

Figure 2. The displacements of 75 CORS stations with DF receivers of Jiangsu, China.

Figure 3. Daily RMS distribution of north (black bar), east (red bar) and up (blue bar) components for about 75 sites from 277 to 283 in year 2011 with Methods A, B, C and D. Note that RMS quite abnormal are excluded.

Table 1. Median RMS in north, east and up directions for the four methods.

Method	N (m)	E (m)	U (m)
A	0.117	0.127	0.298
B	0.030	0.032	0.073
C	0.023	0.024	0.053
D	0.015	0.014	0.022

of about 183% and 108%, respectively. The results indicate that the new method can reduce the effects of error terms, and improve positioning accuracy, especially in the up direction.

3.2 Seismic experiment validation

3.2.1 Experiment

To test the performance of deformation monitoring with SF receiver and the new PPP algorithm, an earthquake simulation experiment is carried out by an earthquake simulation platform located at Wuhan University. A reference receiver is set 30 m away from the simulations platform. The receivers used are of DF; original DF data is used to form a RTK resolution. With GrafNav software (URL 1), a 30-m baseline can get millimeter accuracy RTK solution, and it is set to be the truth benchmark. A subnetwork of Wuhan CORS is used to handle

the ionospheric error for SF PPP with SEID model. A sampling interval of 1 s data is collected to capture the details of the receiver antenna movements. The displacement of simulation platform and the nearby CORS reference stations are shown in figure 4.

Before the experiment, at least a period of 4 hours' data is collected to meet the demands of static PPP with sliding window (this is not a problem for a continuous monitoring station). Then the platform, suspended by spring is pressed downward and released suddenly, generating a damping vibration in vertical direction; after that the pole mounted with antenna is wobbled in the horizontal direction.

3.2.2 Result and discussion

The coordinate difference between the new PPP algorithm with SF observations and the original DF double difference (DD) RTK resolution are shown in figure 5. It is illustrated in figure 5 that the antenna moved downward at the beginning, and then followed a vertical and a horizontal vibration. The PPP and RTK estimates are quite consistent with the actual seismic experiment, and both algorithms can exactly capture the deformation of antenna during the seismic experiment. The coordinate estimates of SF PPP with SEID model agree with RTK at 2 cm level in all three directions.

Figure 4. Simulation platform and the displacement of nearby CORS stations.

Figure 5. Coordinate time series of the new PPP algorithm with SF observation, DD RTK and the difference between them.

4. Conclusions and discussion

First the performance of SF PPP, SF PPP with SEID model, traditional DF PPP and the new PPP algorithm with SF observation is tested with a CORS network. The result shows that the capability of SEID model for eliminating ionospheric delay is almost comparable with ionospheric-free combination, and SF PPP with SEID model can get comparable precision with DF PPP. The new PPP algorithm is validated with a large number of stations. The results show that it can reduce the effects of error terms and improve the positioning accuracy.

The new PPP algorithm for deformation monitoring with SF receiver is tested with a seismic experiment. The result shows that with SEID model and the combinational PPP algorithm, a

single receiver can get a comparable result with RTK, and it can effectively capture the deformation of receiver during the earthquake.

The new algorithm with SF can promise a high accuracy of deformation monitoring. According to the characteristic of the new algorithm and the cost efficiency of SF receiver, it is possible for a wide range of constructions for deformation monitoring of potential hazards such as landslides, avalanches, mudslides, earthquakes, and so on.

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