

# Regional reference network augmented precise point positioning for instantaneous ambiguity resolution

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**Abstract** Integer ambiguity fixing can significantly shorten the initialization time and improve the accuracy of precise point positioning (PPP), but it still takes approximate 15 min of time to achieve reliable integer ambiguity solutions. In this contribution, we present a new strategy to augment PPP estimation with a regional reference network, so that instantaneous ambiguity fixing is achievable for users within the network coverage. In the proposed method, precise zero-differenced atmospheric delays are derived from the PPP fixed solution of the reference stations, which are disseminated to, and interpolated at user stations to correct for L1, L2 phase observations or their combinations. With the corrected observations, instantaneous ambiguity resolution can be carried out within the user PPP software, thus achieving the position solutions equivalent to the network real-time kinematic positioning (NRTK). The strategy is validated experimentally. The derived atmospheric delays and the interpolated corrections are investigated. The ambiguity fixing performance and the resulted position accuracy are assessed. The validation confirms that the new strategy can provide comparable service with NRTK. Therefore, with this new processing strategy, it is possible to integrate PPP and NRTK into a seamless positioning service, which can provide an accuracy of about 10 cm anywhere, and upgrade to a few centimeters within a regional network.

**Keywords** Precise point positioning · Regional augmentation · Atmospheric delay modeling · Integer ambiguity resolution

## 1 Introduction

Precise point positioning (PPP) technique has been demonstrated to be a powerful tool for various applications, such as precise orbit determination of low earth orbiting satellites, kinematic positioning of moving platforms, GPS meteorology, precise timing (Zumberge et al. 1997; Kouba and Héroux 2001; Gao and Shen 2001; Bisnath and Gao 2007). However, traditional PPP requires a convergence time longer than 30 min to achieve desired positioning accuracy of 10 cm. In addition, the inevitable data discontinuity caused by cycle slips, data gaps and loss-of-locks, especially in the urban areas, may need a process similar to the initialization, namely re-initialization, in order to retain the desired accuracy. It is noticed that the initialization and re-initialization are the major limitation on PPP for rapid and real-time positioning (Bisnath and Gao 2007). In order to shorten the initialization time and improve the accuracy, integer ambiguity fixing approaches for PPP have been developed in recent years (Gabor and Nerem 1999; Ge et al. 2008; Laurichesse et al. 2008; Collins et al. 2008; Li and Zhang 2010). All the studies show that the initialization time can be shortened to about 15 min by applying integer ambiguity resolution. On the other hand, algorithms that make use of atmospheric delays of previous epochs have been developed to bridge the observation discontinuities (Banville and Langley 2009; Geng et al. 2010; Zhang and Li 2010a). Although the efficiency of these algorithms have been demonstrated, but they may fail when a data gap lasts longer than several minutes or occurs during large atmospheric fluctuations. Therefore, it is still a task to further

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shorten the initialization time compared to the performance of the widely used Network Real Time Kinematic (NRTK) services (Han 1997; Gao et al. 1997; Raquet et al. 1998; Ge et al. 2010).

In PPP processing, ionosphere-free observations (L3) are usually used and tropospheric delays are estimated as unknown parameters because no precise atmospheric delay models can be derived from such a sparse global reference network. Afterwards, the L3 ambiguities are expressed by wide-lane (WL) and narrow-lane (NL) ambiguities which are then fixed, respectively. The large noise of the range observations needed definitely for WL ambiguity fixing and the short NL wavelength results in a long time for initialization or ambiguity-fixing. One possible solution to further shorten the fixing time is to retrieve the atmospheric delays as corrections from data of a dense network, for example, a Continuous Operation Reference Station (CORS) network which has been widely established all over the world. Ge et al. (2010) proposed a NRTK strategy using pre-fit undifferenced observation residuals of the reference network to remove biases and recover the integer feature of the ambiguities at user stations, so that PPP with ambiguity-fixing can be carried out at user stations.

In this contribution, we present a novel method that can augment global PPP service by making use of available regional reference networks to generate atmosphere delay corrections from the post-fit residuals derived from PPP solution with ambiguity-fixing. With the precise atmospheric delay model in addition, PPP with instantaneous ambiguity fixing can be achieved at user stations, so that PPP can have the equivalent performance to the NRTK.

## 2 Regional augmentation PPP method

In order to fix integer ambiguity in PPP, we need precise satellite orbits and clocks to keep the inaccurate modeling as small as possible and the uncalibrated fractional offsets (UFOs) to recover the integer feature of the integer ambiguity. The generation of the real-time orbits and clocks are quite mature under the framework of the IGS Real-Time Pilot Project launched in 2007 (<http://www.rtigs.org>). The strategies can be found in a number of publications (Pérez et al. 2006; Mireault et al. 2008; Ge et al. 2009; Melgard et al. 2009). IGS also provides the predicted ultra-rapid orbits updated every 6 hours for real-time applications. Although the ultra-rapid orbits does not have the same accuracy of the rapid orbits of few centimeter (Dow et al. 2009), the high correlation between the radial orbit component and satellites clocks allows the orbital errors to be compensated by the clock estimation. It would meet the demands of rapid ambiguity resolution (AR) in real-time PPP (Zhang and Li 2010b). The approaches to estimation of UFOs for PPP ambiguity-fixing

are referred to Ge et al. (2008); Laurichesse et al. (2008); Collins et al. (2008); Li and Zhang (2010). In this paper, we concentrate on the precise representation of the atmospheric delays to shorten the ambiguity-fixing time. Therefore, in this section we will present a new method to derive accurate atmospheric information from a regional CORS network to augment PPP for the instantaneous ambiguity-fixing. Spatial and temporal behaviors of atmospheric delays will be examined carefully and the interpolation and prediction of atmospheric delays will be investigated and verified thoroughly.

### 2.1 Zero-differenced regional augmentation information

Assuming that the residual errors of satellite orbit and clock are neglected in PPP, the simplified phase observation equation can be written as following:

$$L_i^k = \rho_{i_g}^k - I_i^k + T_i^k + \lambda(f_i - f^k) + \lambda N_i^k + \varepsilon_i^k, \quad (1)$$

where the subscripts  $i$  and  $k$  represent receiver and satellite, respectively,  $L$  denotes phase observation,  $\rho_g$  denotes the non-dispersive items,  $I$  is the ionospheric delay,  $T$  is the tropospheric delay,  $f_i$  is the receiver UFOs,  $f^k$  is the satellite UFOs,  $N$  is the zero-differenced (ZD) integer ambiguity,  $\lambda$  is the wavelength,  $\varepsilon$  is the measurement noise. The phase center offsets and variations and phase wind-up (Wu et al. 1993) must be corrected in advance.

With the precise satellite orbits, clocks and UFOs, PPP fixed solution is carried out on all stations of a regional CORS network with fixed station coordinates using L3 observations. Receiver clocks are estimated epoch-wisely and the dry component of tropospheric delays is corrected with a priori model composed of zenith dry delay and mapping function, for example Saastamoinen model (Saastamoinen 1972) and GMF (Boehm et al. 2006), respectively. The remaining zenith wet delay (Zwd) is estimated as piece-wise constants. Instantaneous ambiguity-fixing and data gap handling are performed epoch by epoch.

The L1 and L2 integer ambiguities can be easily derived once the WL and NL ambiguities are fixed. The zenith wet delay can be obtained accurately. All quantities in Eq. (1) are accurately known except for the ionospheric delay  $I_i^k$ , which is then derived straightforwardly as follows

$$I_i^k = \rho_{i_g}^k - L_i^k + T_i^k + \lambda(f_i - f^k) + \lambda N_i^k + \varepsilon_i^k, \quad (2)$$

where  $L_i^k$  can be the L1, L2 and a combination of L1 and L2 phase observations. From Eq. (2), the accuracy of calculated ZD ionospheric delay depends mainly on the quality of the estimated UFOs. The NL UFOs are estimated primarily with carrier phases, while the WL UFOs are derived from both pseudo-range and carrier phase together. Both estimates have an uncertainty of about one to two tenth of the corresponding wavelength, thus sufficient for ambiguity-fixing.

It should be noted here that the errors of the WL UFOs will be brought into the calculated ionospheric delays directly. But this will not affect the subsequent elimination of ionospheric delays at user stations. Assuming that the UFOs of satellite  $k$  and receiver  $i$  are biased with amount of  $Bias_i$ ,  $Bias^k$ , respectively, the sum of estimated satellite and receiver UFOs  $f_i^k$  can be expressed by its true value  $\hat{f}_i^k$  and the biases as

$$f_i^k = \hat{f}_i^k + Bias_i + Bias^k. \quad (3)$$

Let  $\hat{I}_i^k$  the true ionospheric delay value, and  $I_i^k$  the estimated ionospheric delay based on the biased UFOs. Combining Eqs. (2) and (3), we have

$$I_i^k = \hat{I}_i^k + Bias_i + Bias^k. \quad (4)$$

Applying the interpolation described in Sect. 2.2 to the biased ionospheric delays from a set of reference stations to one satellite, the effect of the satellite UFO bias in the interpolated delay is exactly  $Bias^k$  because  $\sum_{i=1}^n \alpha_i = 1$ . As the UFO for this satellite provided to users is biased by the same value, this bias will be compensated with the biased interpolated correction. On the other hand, the  $Bias_i$  part acted on the estimated ionosphere correction is the same to all visible satellites at the user station as  $\sum_{i=1}^n \alpha_i Bias_i$ . It can be absorbed by user receiver clocks. Therefore, such systematic biases in UFOs have no effect on ionospheric corrections and the ambiguity-fixing at the user stations.

The tropospheric delays of the CORS stations can be retrieved from the residuals of the ionosphere-free observations, which can be written as

$$T_i^k = L_{3i}^k - \rho_{ig}^k - \lambda(f_i - f^k) - \lambda N_i^k - \varepsilon_i^k. \quad (5)$$

Afterwards, the same interpolation can be employed to obtain the tropospheric delays at the user stations as for the ionospheric delays.

In most of the NRTK systems (Han 1997; Gao et al. 1997; Raquet et al. 1998), double-differenced (DD) atmospheric delays are derived to represent its distance-dependent variations, whereas ZD delays are retrieved and provided to user stations in this paper. Although the derived ZD atmospheric delays might not reflect the true atmospheric refractions because of the functional correlation between clocks and ambiguities, the internal consistency can provide precise corrections for user stations to remove the related effect and to recover the integer feature of ambiguities. The decorrelation of the relationship between satellites and stations in the DD case makes it possible to disseminate the corrections on the station base and provides the opportunity to select reference stations and to interpolate the corrections by the users.

## 2.2 Interpolation of atmospheric delays

To this end, we have been able to retrieve the atmospheric corrections from a regional network for ZD measurements. Such local information could be generated epoch by epoch on reference stations at server end. In this section, we turn to investigate how to interpolate ZD atmospheric corrections precisely at user end with the estimated atmospheric corrections from sever end.

One critical issue on NRTK is the interpolation of the distance-dependent biases for user stations. Over the past few years, in order to represent the distance-dependent biases, several methods have been developed. The typical methods include linear combination method (LCM) (Han 1997), linear interpolation method (LIM) (Wanninger 1995; Wübbena et al. 1996), distance-based linear interpolation method (DIM) (Gao et al. 1997), lower-order surface model (LSM) (Wübbena et al. 1996), and least-squares collocation method (LSCM) (Raquet et al. 1998). Theoretically, it is difficult to say which one is better. Dai (2002) conducted a comparative study on the abovementioned interpolation methods, and concluded that their performances are very similar.

The above methods are primarily applied to DD mode in network RTK. Modifications should be made to adapt atmospheric interpolation of ZD mode in PPP. The modified LCM (MLCM) formulas are expressed from Eq. (6) to (8). In MLCM, the interpolation coefficients could be estimated according to Eqs. (6) and (7), and then the interpolated atmospheric corrections are calculated following Eq. (8).

$$\sum_{i=1}^n \alpha_i = 1, \quad \sum_{i=1}^n \alpha_i (\hat{X}_u - \hat{X}_i) = 0, \quad \sum_{i=1}^n \alpha_i^2 = \text{Min} \quad (6)$$

$$\text{MLCM} : \begin{pmatrix} 1 & 1 & \cdots & 1 & 1 \\ \Delta X_{1u} & \Delta X_{2u} & \cdots & \Delta X_{n-1,u} & \Delta X_{n,u} \\ \Delta Y_{1u} & \Delta Y_{2u} & \cdots & \Delta Y_{n-1,u} & \Delta Y_{n,u} \end{pmatrix} \cdot \begin{pmatrix} \alpha_1 \\ \alpha_2 \\ \vdots \\ \alpha_n \end{pmatrix} = \begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix} \quad (7)$$

$$\hat{v}_u = \sum_{i=1}^n \alpha_i \hat{v}_i, \quad (8)$$

where  $n$  is the number of reference stations;  $\alpha_i$  denotes the interpolation coefficient;  $u$  and  $i$  are indices for the user station and the reference stations, respectively;  $\hat{X}_u$  and  $\hat{X}_i$  are station coordinates in the local horizontal plane system;  $\Delta X_{iu}$  and  $\Delta Y_{iu}$  are the plane coordinate differences between the user and reference station;  $\hat{v}_i$  is the ZD ionospheric delay;  $\hat{v}_u$  is interpolated ionospheric delay at user station. In a similar way, tropospheric path delay can be interpolated.

### 2.3 Instantaneous ambiguity fixing

Once the ZD ionospheric and tropospheric path delays are generated epoch-wisely using the method presented in Sect. 2.1, spatial atmosphere modeling is employed to interpolate ionospheric and tropospheric path delay. It should be mentioned that short-term prediction is required due to the latency of the data transmission. The ZD carrier phase observations at user stations corrected with the interpolated atmospheric corrections can be used for PPP with instantaneous ambiguity-fixing. A cascade ambiguity fixing strategy using wide-lane observations (Lw), L3, L1 and L2 observations sequentially is applied to instantaneous ZD ambiguity fixing. First, Lw phase observations after applying the atmospheric corrections are used for resolving WL ambiguities. Afterwards, ambiguities in the L3 solution are replaced by NL ones with the fixed WL ambiguities and NL fixing is carried out. If the NL cannot be fixed on this step, next we attempt to fix the ambiguity of L1 and L2 by making use of the interpolated atmosphere corrections and the fixed solution with Lw observations as well. Finally, the L3 solution with fixed ambiguity is reconstructed by fixed WL and any of NL, L1 and L2 ambiguity in order to obtain the final position, because the L3 combination is not influenced by ionosphere interpolation. In the above procedure, integer ambiguity fixing is undertaken several times for various observations but using the LAMBDA method (Teunissen 1995). The flow chart of the cascade ambiguity fixing strategy is shown in Fig. 1.

Once the ambiguities are fixed, the atmospheric delays can also be derived from the observations at the user stations in the similar way as for the reference stations. Because of the strong temporal and spatial correlations of the ionospheric and tropospheric delays, the predictions based on the derived delays at the user stations are usually better than that interpolated from the reference stations. With the more accurate atmospheric corrections, the Lw residuals will be reduced and consequently the efficiency of the ambiguity fixing will be improved. Furthermore, the improvement on the coordinates of the fixed Lw solution will bring in stronger a priori constraint into L3 solution to obtain a more reliable fixing for NL ambiguities. For ambiguity fixing using L1 and L2 observations implemented in the cascade fixing strategy, a similar improvement should be available as for the Lw solution. Therefore, the predicted atmospheric delays based on the fixed solution at user stations are also employed for the instantaneous ambiguity fixing

### 3 Experimental validations

In order to validate the proposed method, four reference stations (DAYI, DUJY, JITA and PUJI) from Chengdu CORS network in Chengdu, China are chosen as regional augmen-

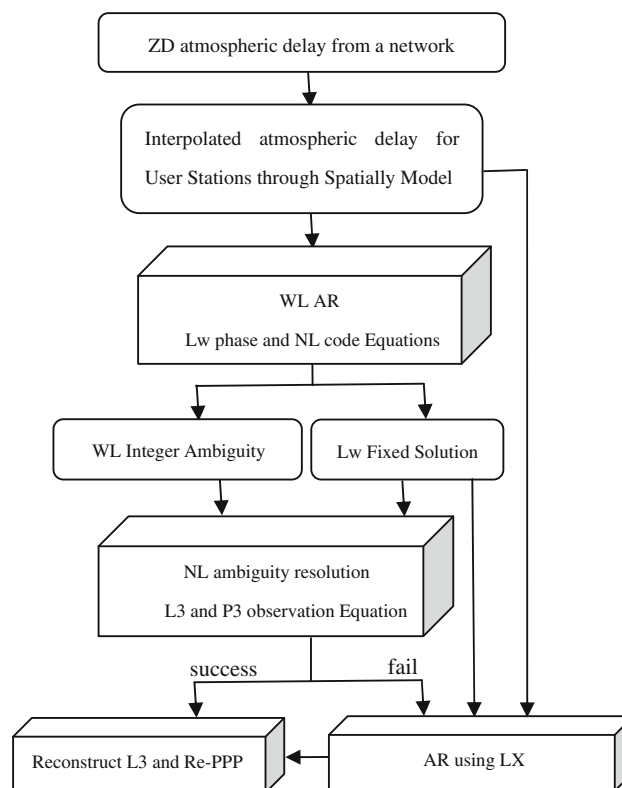


Fig. 1 Flow chart of cascade AR strategy

tation stations, and station CDKC is taken as roving station. The deployment of the network stations is shown in Fig. 2, in which the solid triangles represent augmentation stations while the solid circle indicates the roving station. The averaged inter-station distance is about 60 km.

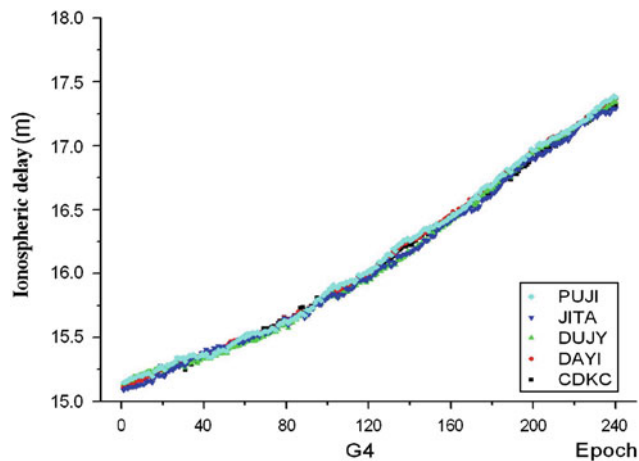
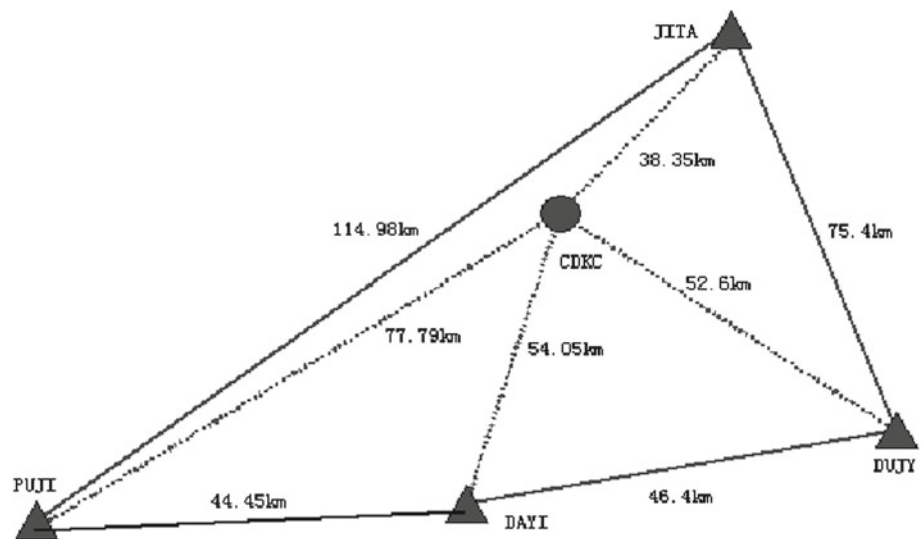
The orbit and clock corrections of the global PPP service are from the predicted ultra-rapid orbits (Dow et al. 2009) and real-time estimated clocks (Zhang and Li 2010b). The satellite UFOs are computed from a set of global distributed stations with 12 stations within China in order to have a better fit to the region (Li and Zhang 2010).

With the above global PPP service, we process the GPS data at the stations of the regional network in PPP mode and fix the integer ambiguities. The rover station CDKC is also processed as a reference station in advance in order to obtain the atmospheric delays for assessing of the interpolated from the other reference stations. The atmosphere delays are derived using the method presented in Sect. 2.1. The interpolated atmospheric corrections are applied to the user stations for PPP with ambiguity fixing.

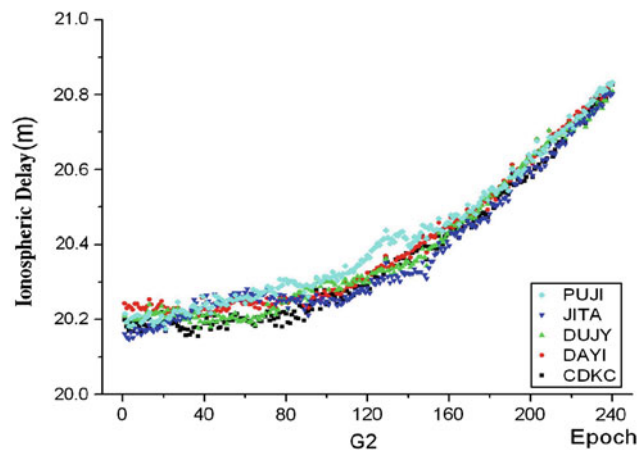
#### 3.1 Retrieved atmospheric corrections

The estimated ZD ionospheric delays are typically illustrated in Figs. 3 and 4 for PRN04 and PRN02, respectively. One can see that strong temporal correlation between neighbor-

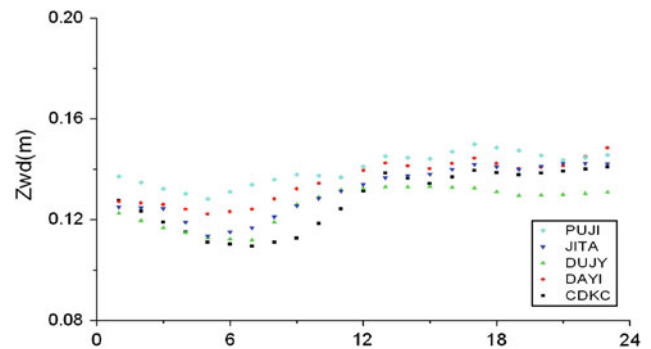
**Fig. 2** Illustration of the testing network of reference and rover stations, denoted by solid triangle and circle, respectively



**Fig. 3** Ionospheric delay of PRN04 on five stations



**Fig. 4** Ionospheric delay of PRN02 on five stations  
ing epochs and spatial correlation between stations exist for ionospheric delay. It is the fundamental to interpolate and predict the ionospheric delay for a rover station using the estimated ionospheric delays from a CORS network.



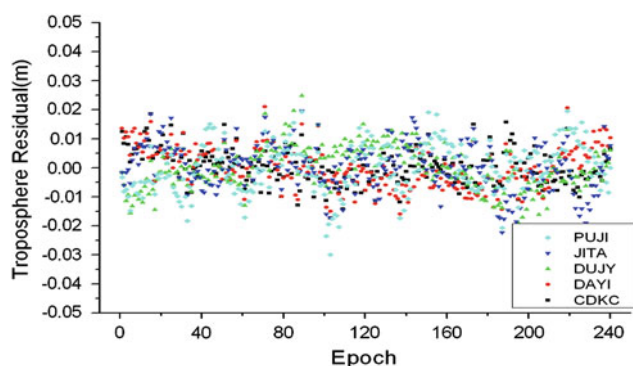
**Fig. 5** Zenith wet delay (Zwd) on five stations

The typical Zwd values estimated in PPP on the five stations are illustrated in Fig. 5. Similar to ionospheric path delay, temporal and spatial correlations also exist in Zwd between different stations. The Zwd values on five stations are close together, and their variation behaves in a similar tendency. Therefore, it is also feasible to interpolate the Zwd for a rover station using the estimated tropospheric delays from a CORS network.

In addition, tropospheric residuals are also computed using the method in Sect. 2.1 and illustrated in Fig. 6. It is observed that the residuals are rather small after Zwd is estimated. Therefore, only Zwd is taken into account in spatial troposphere modeling since its residual could be neglected.

### 3.2 Interpolated atmospheric corrections

Taking the ZD atmospheric delays retrieved at the four augmentation stations, the atmospheric delays of the rover station CDKC are interpolated epoch by epoch with the MLM method in Sect. 2.2. The resulted interpolations are compared with the values retrieved in the same way as for the reference



**Fig. 6** Troposphere residual of PRN4 on five stations

stations to assess the accuracy of the interpolation. Figure 7 shows representatively the differences of two typical satellites. The differences are generally smaller than 4 cm and the RMS is about 2 cm, which will have absolutely no effect on WL ambiguity-fixing, and the systematic trends on the plots could have a slight impact on L1 and L2 ambiguity-fixing but negligible. Tropospheric interpolation errors are illustrated in Fig. 8. The interpolation accuracy of the tropospheric zenith delay is better than 1 cm. Thus, the interpolated ZD atmospheric delay is accurate enough for instantaneous AR.

### 3.3 Instantaneous ambiguity fixing

With the interpolated atmospheric delays, ZD observations of L1, L2 and Lw at station CDKC are corrected. Next, we perform the PPP solution with ambiguity fixing for CDKC station using the instantaneous AR method described in Sect. 2.3. Ambiguity fixing is carried out with data of a single epoch without any constraints between epochs for ambiguity, coordinates, and receiver clocks. Figures 9 and 10 present the position differences of the PPP fixed solution with respect to the static solution. Figure 9 gives the result of the Lw fixed solutions while Fig. 10 shows that of the L3 fixed solutions. From Figs. 9 and 10, cm-level accuracy is achievable using

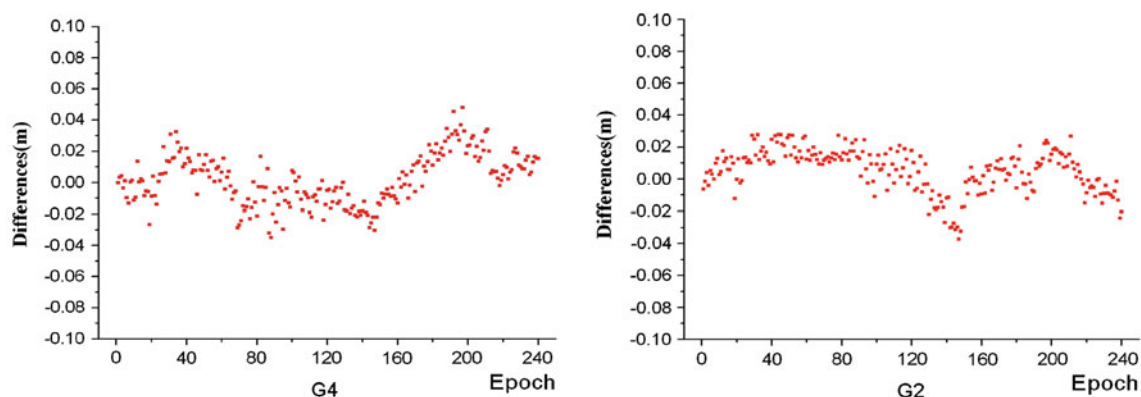
PPP with instantaneous ambiguity-fixing with the help of regional augmentation information. The differences of Lw solutions are usually within 10 cm. The differences of the fixed L3 solutions are mostly within 5 cm, much higher than that of Lw solution since L3 is free of ionospheric biases.

The predicted ionospheric delays derived from the fixed solution at the user station are also derived and applied as corrections for the ambiguity fixing. Figure 11 shows the differences between the estimated and predicted corrections. Comparing to the differences of the interpolated ionospheric delays of the reference stations shown in Fig. 7, the predicted ones have a precision of few millimeter whereas the interpolated ones of centimeter level. With the predicted ionospheric delays the fixing efficiency the Lw solutions can be improved. Consequently, the NL ambiguity fixing can also be improved due to the improvement of the fixed Lw solutions.

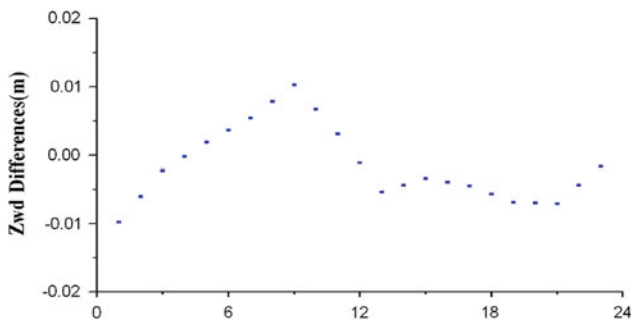
## 4 Conclusions and discussion

We have developed a new strategy to augment PPP with a regional reference network, so that instantaneous ambiguity fixing can be achieved for users within the coverage. Through the PPP processing with ambiguity fixing strategies for the regional stations using precise orbits and clocks and UFOs of the global PPP service, atmospheric slant delays of L1 and L2 frequency are retrieved precisely. Using these derived delays, atmospheric corrections at user stations are interpolated. The corrected observations are almost free of atmospheric delay and the small orbit and clock biases can be further reduced, so that instantaneous ambiguity resolution of L1 and L2 and their combinations are achievable.

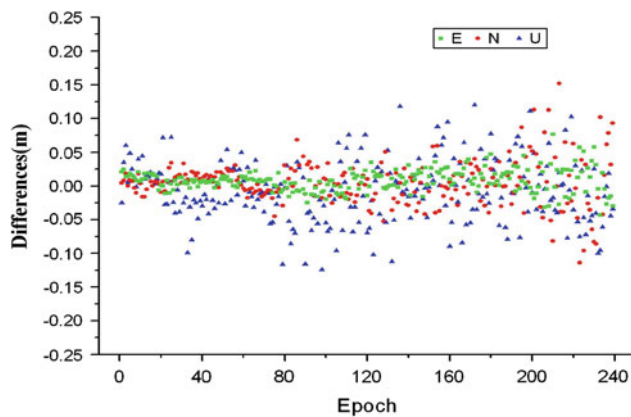
The strategy has been validated experimentally with a regional network of four reference stations and one rover receiver. From the experimental results, the interpolated ionospheric slant corrections have a RMS value of of 2 centimeters. The tropospheric delays can be represented by the zenith path delays at the reference stations because the resid-



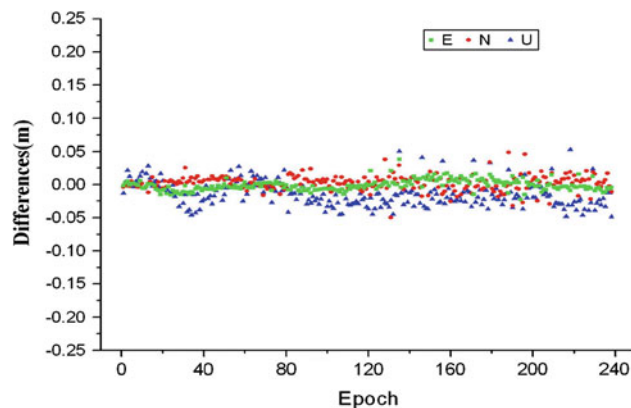
**Fig. 7** Differences between the estimated and interpolated ionospheric delays for satellite PRN04 (*left*) and PRN02 (*right*)



**Fig. 8** Differences between the estimated and interpolated Zwd at the user station



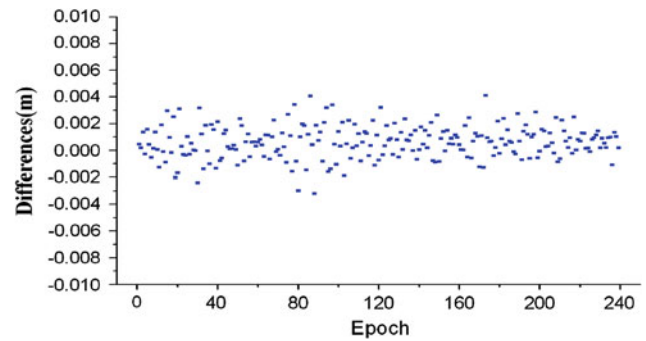
**Fig. 9** Position differences of Lw fixed solutions



**Fig. 10** Position differences of L3 fixed solutions

uals of the slant delays are negligible. With the interpolated atmospheric corrections, instantaneous ambiguity fixing is available at the user station with the cascade fixing approach presented in this paper. The accuracy of the ambiguity fixed positioning solutions is about 3–5 cm.

Comparing to the current NRTK approaches, the ZD atmospheric corrections can be derived station by stations. This is very easily to be realized for reference network with a large number of stations which is a hard task for current NRTK



**Fig. 11** Differences between the estimated and interpolated ionospheric delays based on previous data at the user station for satellite G04

approaches. The information can also be broadcasted on station base to release the real time communication burden.

With the new strategy, PPP and NRTK service can be integrated into a unique system at least at the user end. Within the integrated system, current PPP accuracy of 10 cm is available globally and centimeter accuracy can be achieved if regional augmentation information is provided.

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