Chapter 12
Single-Epoch Integer Ambiguity Resolution for Long-Baseline RTK with Ionosphere and Troposphere Estimation

Denghui Wang, Chengfa Gao and Shuguo Pan

Abstract A new single-epoch ambiguity resolution for long baseline RTK, on the basis of the ionosphere-weighted model, is proposed in this paper, which is applicable to several hundred km baselines by using linear combination of the measurements, including the double-differential wide-lane combination and ionosphere-free combination carrier-phase observation equations and UofC model. By the correct ambiguity and double-differential atmosphere delay, the real-time atmosphere model was established to provide predicted value for a new risen satellite. The establishment of real-time atmosphere predicted model, estimating the relative tropospheric zenith delay and the regional ionospheric parameters, is proved to reach an acceptable accuracy. Test data from the multiple reference station GPS networks in Chongqing, consisting of 36 baselines from 40 to 350 km, were used to evaluate the performance of the proposed approach. It is showed that the proposed algorithm can reduce the effect of the ionosphere and troposphere on the network AR and the true integer ambiguity could be achieved in a short time after the establishment of the predicted atmosphere model.

Keywords Ambiguity resolution · Network RTK · UofC · Real-time atmosphere model

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12.1 Introduction

In the larger scale multiple reference station (MRS) network, the performance of the long baseline over 100 km is greatly degraded due to the spatial correlation error, such as the atmosphere model error and the satellite orbit error. The correct ambiguity of the baseline can not only be used in simulating the regional atmosphere error, but also in providing the condition for generating the no-differential ambiguity of the reference stations. The authors have developed a new single-epoch ambiguity resolution for long baseline RTK, on the basis of the ionosphere-weighted model [1] applicable several hundred km baselines by using double-differential observations. The strategy estimates the ionosphere and the troposphere error by generating several kinds of linear combination of the measurements; including the double-differential wide-lane combination and ionosphere-free combination carrier-phase observation equations and University of Calgary Model (UofC model). What is more, the establishment of real-time atmosphere predicted model, estimating the relative tropospheric zenith delay and the regional ionospheric parameters, and integer ambiguity criterion method, using the residual atmosphere delay and residual measurements, is described in the paper.

However, the method mentioned above is focused only on single baseline ambiguity resolution and ambiguity quality control for kinematic positioning. The adjustment of the network could be done in generating the higher-accuracy regional real-time atmosphere model. The performances of the test come from Chongqing using the receivers made by Trimble, the other from Jiangsu equipped with the receivers made by Leica. It is showed that the proposed algorithm can reduce the effect of the ionosphere and troposphere on the network ambiguity resolution (AR) and the true integer ambiguity could be achieved in a single epoch after the establishment of the predicted atmosphere model. On the other hand, due to its epoch-by-epoch nature, the proposed approach is insensitive to cycle-slips, rising or setting satellites, or loss-of-lock.

In this paper, Firstly, the observation equations and the predicted atmosphere modeling methods are analyzed in Sect. 12.2. Secondly, the AR strategy and ambiguity verification condition are introduced in Sect. 12.3, and the algorithm is investigated and tested in Sect. 12.4, including the comparison between the predicted model and the empirical one, the effect of this approach on the ambiguity estimating, and especially the single-epoch ambiguity success rate in network. Finally, the concluding remarks are described in the last section.

12.2 The Observation Equations

In this section we will introduce the single-baseline model that forms the basis of our study.

$$\begin{aligned}\nabla\Delta P_{k,l}^{i,j} &= \nabla\Delta\rho_{k,l}^{i,j} + \nabla\Delta\frac{\eta}{f^2} + \nabla\Delta T_{k,l}^{i,j} + \nabla\Delta O_{k,l}^{i,j} + \nabla\Delta m_{k,l,P}^{i,j} + \nabla\Delta\varepsilon_{k,l,P}^{i,j} \\ \nabla\Delta\Phi &= \nabla\Delta\lambda\phi = \nabla\Delta\rho_{k,l}^{i,j} + \lambda^j\nabla\Delta N_{k,l}^{i,j} + (\lambda^i - \lambda^j)\Delta N_{k,l}^{i} - \nabla\Delta\frac{\eta}{f^2} \\ &\quad + \nabla\Delta T_{k,l}^{i,j} + \nabla\Delta O_{k,l}^{i,j} + \nabla\Delta m_{k,l,\phi}^{i,j} + \nabla\Delta\varepsilon_{k,l,\phi}^{i,j}\end{aligned} \tag{12.1}$$

where ∇ is single-difference between satellite i and j; Δ is single-difference between receiver k and l; Φ is carrier-phase measurement (m); ϕ is carrier-phase measurement (cycle);P is pseudorange measurement (m); ρ is geometric range between satellite and receiver antenna phase center (m); η is Total Electron Content in transmission path $\eta = 40.28\,TEC$; T is troposphere delay in transmission path (m); λ is carrier wave length of the satellite (m); $N$is carrier-phase ambiguity (cycle); $O$is satellite orbital error (m); $m$is multipath delay; $\varepsilon_\phi\varepsilon_P$ is measurement errors of carrier-phase and pseudorange including receiver and satellite hardware delay, plate motions error and Tidal error.

For the single-baseline over 100 km, the atmosphere, satellite orbit and multipath effects are the main error sources that influence the success rate of integer ambiguity. The empirical atmosphere model is used in this study, providing a predicted value for the atmosphere delay at the initialization period. The orbital error could be reduced or eliminated by using the International GPS Service (IGS) ultra-rapid ephemeris, which have twenty-four hours' prediction orbit, instead of broadcast orbits, especially for distances exceeding 100 km. Also the multipath effect could be avoided by using daily repeated property of GNSS multipath signal in the software and antenna fairing in the hardware to improve the quality of the measurement.

12.2.1 The Empirical Atmosphere Model

12.2.1.1 The Troposphere

A predicted correction value could be obtained from the empirical troposphere models, for example, Hopfield, Saastamoinen [2] and UNB3 [3]. These models give the similar value when the satellite's elevation angle is upon 20 degree. Due to the different environmental conditions, the temperature, air pressure and water vapour content are quite different around the world. Hopfield and Saastamoinen models rely on the real meteorological inputted parameters and UNB3 model has a good performance only in North America compared with the other empirical models.

In this study, the meteorological inputted parameters are composed of temperature and pressure from global pressure and temperature model (GPT) (Boehm et al. 2007) and the partial pressure of water vapour from Unb3 model. Global mapping function (GMF) is used to be the mapping function of the priori troposphere model, which the zenith troposphere delay is computed by Saastamoinen model.

After the ambiguity is fixed, the un-model terms are applied to remain the residual tropospheric zenith delay. The relative tropospheric zenith delay would be estimated for the purposed of compensating the empirical model for a setting, or a new-risen GPS satellite.

12.2.1.2 The Ionosphere

The Klobuchar model and global ionosphere maps model (GIM) are mentioned in the paper. The Klobuchar model is relatively easy to obtain a 50 percent rms ionospheric error reduction [4] and GIM model could not provide real-time ionosphere parameters. The accuracy of these two empirical ionosphere models is not good enough, which influences the long-range ambiguity estimated without using ionosphere-free combination.

In the paper, for the purpose of reducing the ionospheric delay, previous GIM model parameters are used to provide a predicted value and the ionosphere-weighted model is used to give a reasonable weight of the ionospheric delay. Once the ambiguity is fixed, the regional ionospheric parameter model would be established, by using polynomial fitting method. It would provide a higher accuracy of the ionspheric delay to a new-risen satellite, instead of the empirical model.

12.2.2 The Observation Model

To the GNSS dual frequency receiver, four measurements could be obtained. According to the observation equation, reasonable combination observation is of benefit to understand and solve problems in GNSS application. The linear combination can be formed as

$$\nabla\Delta R = i\nabla\Delta\lambda\phi_1 + j\nabla\Delta\lambda\phi_2 + m\nabla\Delta P_1 + n\nabla\Delta P_2 \tag{12.2}$$

where R is the combination measurement; i, j, m, n is the combination factors.

In the paper, four kinds of combination measurements are applied in the proposed ambiguity resolution algorithm. In order to decrease the influence of the atmosphere delay and weaken the correlation of the unknown parameter, various kinds of LCs are used in estimating ambiguity and atmospheric delay. However, any linear combinations would amplify the measurement noise to the original measurement. Due to the different combinations with different measurement noise value [5], the chosen of the combinations should provide the optimum performance.

12.2.3 The Observation Weighting Schemes

In this study, we assume that the four double-differential original measurements are not correlated [6], and that the predicted DD-atmosphere delay is correlated. With these assumptions the observation vector of observations and the covariance matrix could be written as:

$$L = \begin{bmatrix} \Phi_1 \\ \Phi_2 \\ P_1 \\ P_2 \end{bmatrix}, \quad Q_L = 4\sigma_{\Phi_1}^2 \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \frac{f_1^2}{f_2^2} & 0 & 0 \\ 0 & 0 & k^2 & 0 \\ 0 & 0 & 0 & \frac{f_1^2}{f_2^2} \cdot k^2 \end{bmatrix} \tag{12.3}$$

In the covariance matrix, k is the ratio of the standard errors of the pseudorange and the carrier phase. We consider the standard error of L1 term is $\sigma_{\Phi_1} = 6$ mm and $k = 100$. In order to get the linear combinations of the original equations, we use transformation matrix notation, so that we can rewrite Eq. (12.2) generally for any linear combinations LCs as follows:

$$L_c = TL = \begin{bmatrix} \Phi_{i,j} \\ \Phi_{k,l} \\ R_{i,m} \\ R_{j,n} \end{bmatrix}, \quad T = \begin{bmatrix} \frac{i\lambda_{i,j}}{\lambda_1} & \frac{j\lambda_{i,j}}{\lambda_2} & 0 & 0 \\ \frac{l\lambda_{l,k}}{\lambda_1} & \frac{k\lambda_{l,k}}{\lambda_2} & 0 & 0 \\ i & 0 & m & 0 \\ 0 & j & 0 & n \end{bmatrix} \tag{12.4}$$

And the covariance matrix of the transformed observation vector LC becomes:

$$Q_{Lc} = TQ_LT^T \tag{12.5}$$

The elevation-dependent weighting scheme [7] is also used in this study by changing the variance of the original observation. With the assumptions that the predicted DD-atmosphere delay is correlated and the no-differential atmosphere delay is uncorrelated.

12.3 The AR Strategy for Long Baseline

In this section, we introduce the AR strategy for the long baseline RTK with estimation of ionosphere and troposphere terms in three steps. With the help of ambiguity criterion method, the true integer ambiguity and previous epochs are used to establish the real-time predicted atmosphere model.

12.3.1 Ambiguity Resolution

In general, most articles have used either wide-lane LC of carrier-phase measurement or the Melbourne-Wübbena (MW) wide-line LC [8]. In despite of wide-lane LC of carrier-phase measurement has a low DD noise, the ionospheric delay cannot be eliminated and influences the accuracy of the wide-lane ambiguity. On the other hand, MW wide-lane LC cancels out not only the ionosphere term but also geometry and troposphere terms. Due to the noise of the MW, the MW LC can not provide the optimum performance in a short period. To improve the conventional way, UofC model is used in the ambiguity resolution to increase redundant observation thereby the observation equation is not rank deficient. And for estimating the tropospheric delay and L1 ambiguity, ionosphere-free LCs is utilized.

With the ambiguity fixed, the least square estimation of the real-time relative tropospheric zenith delay is used to provide a predicted tropospheric delay to a new-risen satellite, instead of the empirical atmosphere model. For the ionospheric delay, the regional maps are produced as well and are also used to support AR of the new-risen satellite on the average 90 % of the initial carrier phase ambiguities can be resolved reliably [9].

Step 1. *Wide-lane Ambiguity Estimated*

Compared with the ionosphere-weighted model, UofC model $(i = 0.5, m = 0.5 \text{ or } j = 0.5, n = 0.5)$ is used in estimating the ambiguity. The observation matrix notation can be written as:

$$V = L - BX \tag{12.6}$$

Where [10]:

$$L = \begin{bmatrix} \Delta\nabla\Phi_{1,-1} - \Delta\nabla\rho - \Delta\nabla T \\ \Delta\nabla\Phi_{1,0} - \Delta\nabla\rho - \Delta\nabla T \\ \Delta\nabla UofC_1 - \Delta\nabla\rho - \Delta\nabla T \\ \Delta\nabla UofC_2 - \Delta\nabla\rho - \Delta\nabla T \\ \Delta\nabla B \end{bmatrix}, \quad X = \begin{bmatrix} \Delta_{1,-1} \\ \Delta\nabla N_{1,0} \\ \Delta\nabla I \end{bmatrix}$$
$$B = \begin{bmatrix} \lambda_{1,-1} & 0 & -\lambda_{1,-1}\frac{f_2 - f_1}{f_2\lambda_1} \\ 0 & \lambda_1 & -1 \\ 0 & \lambda_1/2 & 0 \\ -\lambda_2/2 & \lambda_2/2 & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{12.7}$$

It is noted that the ionospheric delays are modeled as unknown variables and the tropospheric delay is modified by the empirical troposphere model. The use of the priori weighted ionosphere has been discussed as sated.

If the real-time regional ionospheric model is not obtained, the sample values of the ionosphere delays can be taken from the empirical ionosphere model. And the models have a different accuracy as shown in Sect. 12.4.With the assumptions that the predicted DD-atmosphere delay is correlated and the DD-LCs is no-correlated for the different pairs of satellites, it indicated the covariance matrix should be written as:

$$Q_\varepsilon = \begin{bmatrix} Q_{Lc}^1 & 0 & \cdots & \cdots & 0 \\ 0 & Q_{Lc}^2 & & & \vdots \\ \vdots & & \ddots & & \vdots \\ \vdots & & & Q_{Lc}^{n-1} & 0 \\ 0 & \cdots & \cdots & 0 & Q_{\Delta\nabla\varepsilon} \end{bmatrix} \tag{12.8}$$

After the regional maps are produced with making use of carrier-phase measurement and the correct integer ambiguity, the ionospheric delay de-correlates with the pairs of the satellites, and the effect of the ionospheric delay on DD observables varying with time and location in the ionosphere [11]. So the variance of the ionosphere can be given as [12]:

$$\sigma_B^2 = \sigma_\infty^2 \left(1 - e^{-2(|\tau|/T + |\delta|/D)}\right) \tag{12.9}$$

Where: τ, Receiver sampling interval; T, Correlation time for the DD ionosphere set as 64 min; δ, Baseline length; D: Correlation distance set as 1,500 km; $\sigma_\infty^2 = 2\ \mathrm{m}^2$.

According to the accuracy of the ionosphere model, the true wide-lane ambiguities can be obtained by the kalman-filter with ionosphere estimation in the initial stage. When the regional real-time ionosphere model could be obtained, the correct value of the wide-lane ambiguity can be resolved immediately.

Step 2. *L1 Ambiguity Estimated by Kalman filter*

After the wide-lane ambiguity fixed, the ionosphere-free LC and the correct wide-lane ambiguity can be used to estimate the L1 ambiguity, the observation matrix notation is:

$$L = \begin{bmatrix} \Delta\nabla N_{1,-1} \\ \Delta\nabla\Phi_{ion-free} - \Delta\nabla\rho - \Delta\nabla T \\ \Delta\nabla UofC_1 - \Delta\nabla\rho - \Delta\nabla T \\ \Delta\nabla UofC_2 - \Delta\nabla\rho - \Delta\nabla T \\ \Delta\nabla B \end{bmatrix}, \quad X = \begin{bmatrix} \Delta\nabla N_1 \\ \Delta\nabla N_2 \\ \Delta\nabla T_{slant} \end{bmatrix} \tag{12.10}$$

We can see that the ionosphere delay has no effect on the observation measurement, and the true wide-lane ambiguity would control the DD-observation noise so that we can get the true L1 and L2 ambiguity in a short period. In the strategy, the estimated states by kalman filter include the ambiguity of L1 and L2, double-differenced slant tropospheric delay.

In the initial stage, the relative tropospheric zenith delay could not be obtained thereby we have to improve the limit of elevation to 15(in degree).And the correlations between the different pairs of satellite should be considered, too. After initialling process, the relative tropospheric zenith delay could be used to replace the empirical model. The variance $\sigma^2_{\Delta\nabla T}$ and process noise $D_{\Delta\nabla T}$ of the troposphere can be given as [13]:

$$\begin{aligned} \sigma^2_{\Delta\nabla T} &= [MF(E^i) - MF(E^j)]^2 \times E[(RTZD)^2] \\ E[(RTZD)^2] &= 0.4844^2 \times \left(0.0012 + 1.485 \times 10^{-5} \times D\right)(\mathrm{m}^2) \\ D_{\Delta\nabla T} &= [MF(E^i) - MF(E^j)]^2 \times D[(RTZD)^2] \\ D[(RTZD)^2] &= \frac{0.0004}{3600} \times \tau(\mathrm{m}^2) \end{aligned} \tag{12.11}$$

The LAMBDA method is used to get the integer ambiguity of L1 and L2 terms on an epoch-by-epoch basis or single-epoch. In general, the ratio threshold (which is set as 3) can be easily gotten in 10 epochs, and the fixed ambiguity of L1 and L2 can also be checked by the wide-lane ambiguity directly.

Step 3. *Real-time Atmosphere model*

With the known coordinates of the reference stations and the true integer ambiguities, the geometric-free LC and ionosphere-free LC are used to generate the DD- ionospheric delay and tropospheric delay respectively. The ionospheric gradient parameters could be used to represent this character of the regional ionospheric delays. The ionospheric gradient parameters can be expressed as [14]:

$$\begin{aligned} \Delta\nabla I^{i,j}_{k,l} &= vI^j_l \cdot f^j_{l,IPP} - vI^i_l \cdot f^i_{l,IPP} + vI^i_k \cdot f^i_{k,IPP} - vI^j_k \cdot f^j_{k,IPP} \\ vI^j_k &= a_0 + a_1 dL + a_2 dB \end{aligned} \tag{12.12}$$

IPP is the ionospheric pierce point. And the kalman filter should be used to estimate the ionospheric gradient parameters. For the DD-measurements, the difference code biases for satellites and receivers have been eliminated.

To the tropospheric delay, the relative tropospheric zenith delay is real-time achieved by least squares adjustment. The equation is shown as [13]:

$$\begin{aligned} \Delta\nabla T^{i,j}_{k,l} &= ZTD_l \times [MF(E^j_l) - MF(E^i_l)] - ZTD_k \times [MF(E^j_k) - MF(E^i_k)] \\ &\cong [MF(E^j_l) - MF(E^i_k)] \times RTZD_{k,l} \end{aligned} \tag{12.13}$$

12.3.2 Ambiguity Criterion Method

Incorrect ambiguity can influence the generation of real-time atmospheric error badly, so it is necessary to maintains controls of quality strictly on the ambiguity. For the baseline, the residuals from DD measurements should be statistically acceptable by comparing the ratios of the covariance matrix. And the difference between the known coordinates and the coordinates, which is obtained by the integer ambiguity, could be considered as a detection threshold. The test shown in Sect. 12.4 proves the ambiguity criterion method which is mentioned here.

For each DD ambiguity in the network, the sum of the integer ambiguities around any baseline triangle in an MRS network should equal zero. Therefore, after all of the ambiguities of the closed loop resolved, the constraint condition should be used to verify that the fixed ambiguities are correct. If all the network ambiguities satisfy the constraint conditions for the entire network, then this verification can be used to check the correctness of the network ambiguities and generate the real-time regional atmosphere model of the entire network.

Finally, for single-epoch observations of the satellite pair, a new ambiguity solution was proposed, using the linear combination of the four measurements, with the estimation of ionosphere and troposphere.

12.4 Test Results and Analysis

A 24 h DD data set observed in Chongqing, China in November 2010 was used to test the performance of the proposed strategy for network AR. The test network consisted of 9 reference stations as shown in Fig. 12.1. The receivers at these stations were Trimble dual-frequency receivers equipped with TRM55791

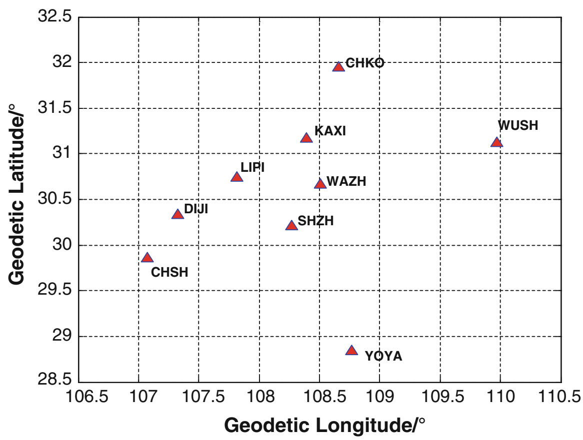

Fig. 12.1 Chongqing GPS reference network

antennas and the epoch interval is 15s. Nine reference stations formed 36 baselines, whose length were 40 to 350 km.

The effect of ionosphere and troposphere is a major inhibitor to long-range single-epoch AR among reference stations. In the study, we choose the high-elevation satellite to estimate the relative tropospheric zenith delay and the regional ionosphere model.

The comparison has been done among the true atmospheric delay, the empirical model and the predicted real-time model.

Figure 12.2 shows the comparison on the effect of ionosphere(two satellites, one was a risen one and the other was a fall one), which indicates that the regional predicted model has an acceptable accuracy within twenty centimeters of error and it is no direct relation between the accuracy of the predicted model and the satellite elevation. By the predicted ionosphere model, the wide-lane ambiguity could be estimated in one or two epochs. Figure 12.3 shows an example of the low-elevation satellite result with 133 km baseline by simple implementation of the strategy. The upper plots indicate the predicted real-time troposphere model have a good performance. Two satellites, a risen-one elevation from 11° to 17°and a setting-one elevation from 14° to 10°, are used. The model standard deviation was 9.6, 17.9 mm for the predicted model, and 28.3, 41.9 mm for the empirical model.

At the initialization period, the predicted atmospheric delay was obtained by the empirical atmosphere model and the wide-lane ambiguity of the high-elevation satellite could be achieved immediately. After the real-time atmosphere model was established, the single-epoch integer ambiguity of the low-elevation satellite is easy to go through the ambiguity criterion method by the proposed ambiguity solution. Compared to conventional method, the proposed strategy has very good effect on the wide-lane ambiguity resolution.

As shown in the Fig. 12.4, the proposed strategy for long baseline RTK seems to work well on the wide-lane ambiguity. The fluctuation of the wide-lane ambiguity could be limited within 0.2 cycles. Two satellites were shown in the figure, one has great ionosphere influence when the satellite's elevation is low and the other data was collected on the solar noon. Compared with the double-frequency LC and the MW LC, the proposed could achieve a true wide-lane ambiguity in a short period and is not sensitive to cycle-slips, rising or setting satellites. However, the performance of the wide-lane ambiguity relies on the accuracy of the

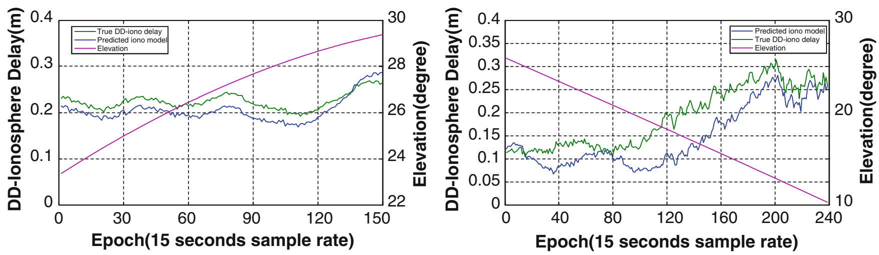

Fig. 12.2 The comparison on the effect of ionosphere

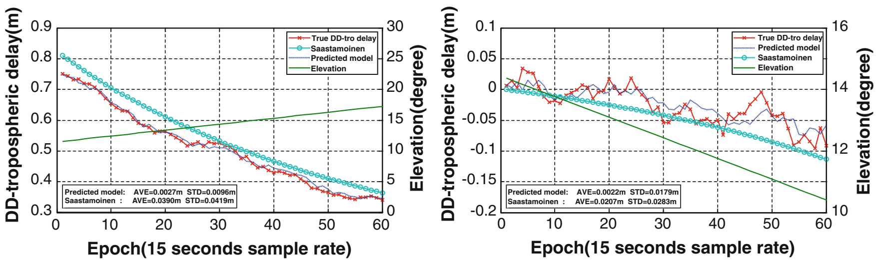

Fig. 12.3 The comparison on the effect of troposphere

predicted ionosphere model. The proposed real-time ionosphere predicted model need a long initialization time and the salient point error of the ionospheric is not considered. And it is worth further improvement to ensure the real-time ionospheric model work well to support AR of the satellite.

In the Fig. 12.5, the proposed method on L1 ambiguity resolution with slant troposphere estimated by kalman filter was shown. The example of the result with 150 km baseline, used 6 satellites and the epoch interval was 15 s. Compared with the conventional method with tropospheric zenith delay estimated by kalman filter, the new method could get the higher accuracy of the float ambiguity and the shorter convergence time. The ratio of the LAMBDA method also indicated the new method could get a reliable result of the L1 and L2 ambiguity in a short time.

12.5 Concluding Remarks

This study focuses on medium- to long-range AR among the base lines of a MRS network and the establishment of real-time atmosphere predicted model. A new single-epoch ambiguity resolution for long baseline RTK, on the basis of the ionosphere-weighted model, is proposed in this paper. The method is applicable to several hundred km baselines by using linear combination of the measurements,

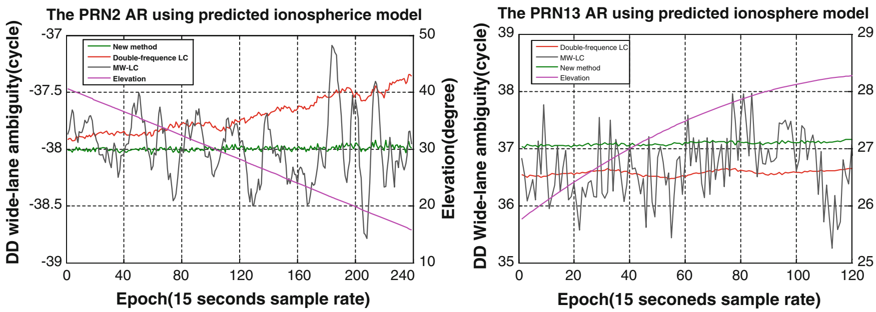

Fig. 12.4 The AR effect on the wide-lane ambiguity

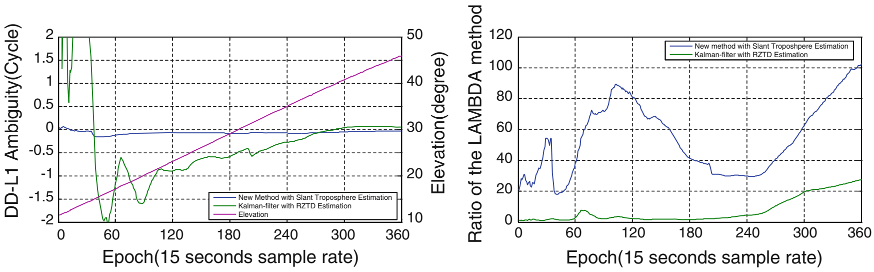

Fig. 12.5 The comparison on the effect of troposphere

including the double-differential wide-lane combination and ionosphere-free combination carrier-phase observation equations and U of C model. The establishment of real-time atmosphere predicted model, estimating the relative tropospheric zenith delay and the regional ionospheric parameters, is proved to have an acceptable accuracy. What is more, with the help of the real-time atmosphere model the ambiguity could be achieved immediately. Test data from the MRS GPS networks in Chongqing, consisting of 36 baselines from 40 to 350 km, were used to evaluate the performance of the proposed approach. However, the method mentioned above is focused only on single baseline ambiguity resolution and ambiguity quality control for kinematic positioning. The adjustment of the network will be done in generating the higher-accuracy regional real-time atmosphere model.

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