REAL-TIME TROPOSPHERIC PRODUCT ESTABLISHMENT AND ACCURACY ASSESSMENT IN CHINA

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ABSTRACT:

Tropospheric delay has always been an important issue in Global Navigation Satellite System (GNSS) processing. Empirical tropospheric delay models are difficult to simulate complex and volatile atmospheric environments, resulting in poor accuracy of the empirical model and difficulty in meeting precise positioning demand. In recent years, some scholars proposed to establish real-time tropospheric product by using real-time or near-real-time GNSS observations in a small region, and achieved some good results. This paper uses real-time observing data of 210 Chinese national GNSS reference stations to estimate the tropospheric delay, and establishes ZWD grid model in the country wide. In order to analyze the influence of tropospheric grid product on wide-area real-time PPP, this paper compares the method of taking ZWD grid product as a constraint with the model correction method. The results show that the ZWD grid product estimated based on the national reference stations can improve PPP accuracy and convergence speed. The accuracy in the north(N), east(E) and up(U) direction increase by 31.8%,15.6% and 38.3%, respectively. As with the convergence speed, the accuracy of U direction experiences the most improvement.

1. INTERDUCTION

Tropospheric delay has always been an important issue in GNSS processing. In general, the tropospheric delay can be divided into two components: a hydrostatic component mainly caused by dry gases of the air, and a non-hydrostatic (wet) component due to water vapor (Davis et al., 1985). Precise data processing needs to carefully eliminate the influence of tropospheric delay error. Therefore, many scholars have proposed a variety of tropospheric delay correction models, such as Hopfield (Hopfield et al.,1969), Saastamoinen (Saastamoinen,1972),GPT(Böhm et al.,2007), UNB3(Collins and Langley,1997) and ITG series models(Yao et al.,2015), which are all empirical models. However, the tropospheric delay is closely related to the atmospheric environment, which is mainly affected by temperature and pressure as well as water vapor content in the air. Empirical models are difficult to simulate complex and volatile atmospheric environments, resulting in poor accuracy of the empirical model and difficulty in meeting precise positioning demand.

In recent years, some scholars proposed using numerical weather models (NWM) to improve the accuracy of tropospheric delay models. Lu et al. used the NWM model to assist precise point positioning(PPP), which can significantly improve the multi-system GNSS and single BDS PPP positioning performance (Lu et al.,2016,2017). But the NWM model needs to provide precise meteorological parameters, and its applicability is limited. In addition, some scholars propose to establish real-time or near-real-time tropospheric product by using real-time or near-real-time GNSS observations. Li et al. established a real-time troposphere product using regional reference stations to facilitate the rapid fixing of real-time PPP ambiguity. The accuracy of real-time tropospheric products can reach about 2 cm, significantly reducing the ambiguity fix time (Li et al. 2011). Shi et al. introduced a method to determine the optimal fitting coefficients (OFCs) of local troposphere models and the results showed that the convergence performance of GPS PPP solutions, especially the height component, could be greatly improved(Shi et al.2014,2015). It is noted that the experiment in the study of Li et al. and Shi et al. were carried out in a small region, in which the maximum baseline distance was less than 200 km and the height difference was less than 26 m. With the OFCs model, de Oliveira et al. (2017) tested the local troposphere model in a larger area over France with a maximum height difference of 1651 m. The modeled ZWDs present an accuracy of around 1.3 cm with respect to the IGN (Institut National de l’Information Géographique et Forestière) final ZTD products available at: ftp://rgpdata.ign.fr/pub/products.(de Oliveira et al. 2017).

In this paper, we use real-time BDS&GPS&GLONASS combined PPP method to estimate the tropospheric delay of 360 GNSS reference stations in China in real time (the reference stations are about 200 km apart). In data processing, this paper constrains the true coordinate of stations to improve the accuracy of real-time PPP troposphere estimation. The line of sight tropospheric delay is usually expressed by the Zenith Total Delay (ZTD) of receivers with mapping functions. The ZTD is usually expressed as the sum of hydrostatic and non-hydrostatic parts, i.e., Zenith Hydrostatic Delay (ZHD) and Zenith Wet Delay (ZWD) (Davis et al. 1985). The ZHD was modeled with the Saastamoinen model and ZWD was estimated as an additional epoch-wise parameter (Ahmed et al. 2016). The GMF model was used for the mapping function of ZHD and ZWD, and gradient correction was also introduced to correct for the gradient effect in the horizontal direction of the tropospheric delay. Then, we use the reference stations’ ZTD to set up the real-time tropospheric delay grid model in China, and the grid size is 1

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degree by 1.5 degree. In order to evaluate the accuracy of the real-time tropospheric delay grid model product, other reference station without involved in the calculation for accuracy assessment is used, the RMS of the real-time grid tropospheric product is statistically analyzed. The results show that the real-time tropospheric delay product can significantly improve the accuracy of real-time differential, and accelerate the convergence of real-time PPP. Compared with the plane direction, the convergence performance of elevation direction is improved even greater.

2. MATERIALS AND METHODS

2.1 Calculation process

In this paper, a real-time tropospheric calculation software is developed. The software includes a ZTD estimation module, a grid estimation module, a product broadcasting module, an accuracy assessment module, and a position monitoring module. Fig.1 shows the flow chart of real-time tropospheric product establishment and accuracy assessment. First of all, the ZTD estimation module receives the reference stations’ observing data stream, and broadcast ephemeris, DCB, and other table files which can be downloaded at IGS FTP web site (cddis.gsfc.nasa.gov/pub/gps/products/), and receives wide-area differential products including real-time orbit and clock products broadcasted by the National Geomatics Center of China(NGCC). Using PPP method, the ZTD and ZWD of the reference station is estimated. Then, the grid estimation module interpolates the grid points to obtain the tropospheric grid product based on the ZWD results of the reference stations. After that, the product broadcasting module receives the tropospheric grid data stream in the standard format and then advertises the products. Evaluation of tropospheric grid product is performed by the assessment module and results are compared with the ZWD of stations. Finally, the position monitoring module uses the real-time observation data of the reference stations, wide-area differential products, and tropospheric grid product to perform PPP calculations, which are used to monitor the accuracy of positioning results of the tropospheric grid model for PPP in real time.

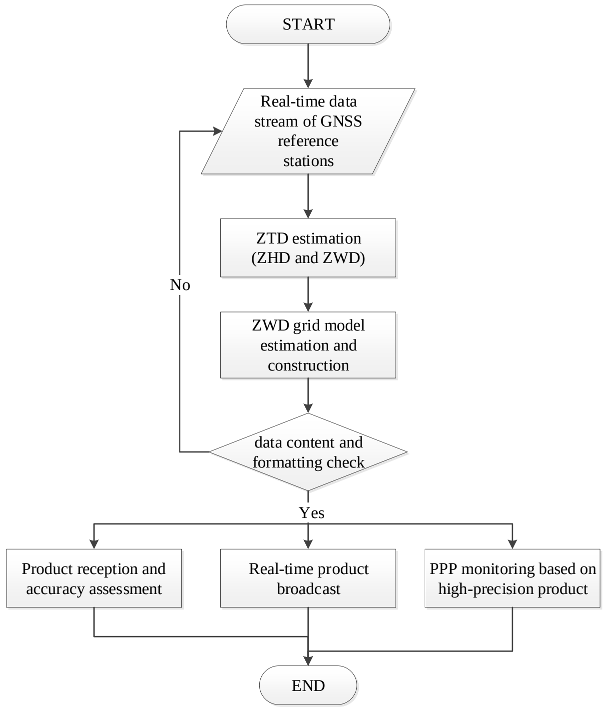

Figure 1. Flow chart of real-time tropospheric product establishment and accuracy assessment

2.2 Data Resources

China has vigorously developed the construction and application of GNSS reference stations in recent years. In China, the National Administration of Surveying, Mapping and Geoinformation organized the construction of Chinese national continuous operating reference stations for modern surveying, and 360 national reference stations for satellite navigation and positioning have been evenly established throughout the country (Chen et al.2017). Of this number, 210 stations can receive data from four global navigation satellite systems, thereby providing continuous data for BeiDou positioning as well as other related research.

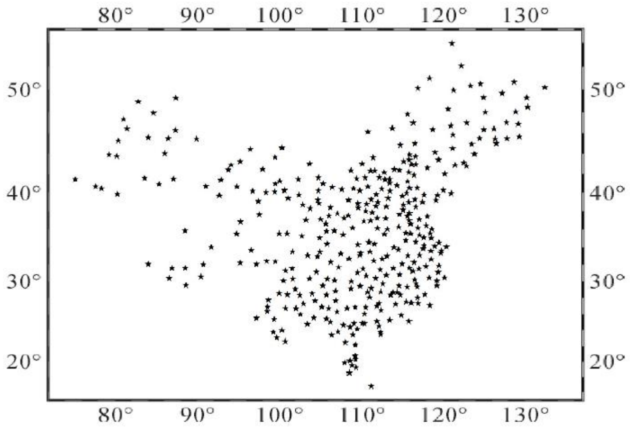

Figure 2. The distribution of Chinese national GNSS reference stations (This figure is a schematic diagram of the topic and does not involve national territory information)

2.3 ZTD Estimation

The ZTD estimation of the reference stations uses a non-differential PPP method. Compared with the traditional double-insertion network solution method, the estimated model of this method is simple, there is no correlation between stations and stations, and it is not necessary to introduce long-distance stations to estimate the absolute delays.

The estimation method calculates ZHD and ZWD separately, ZHD is calculated using Saastamonien model, and ZWD is calculated as PPP underestimate parameter. Since the elevation angle is usually not 90 degrees, a projection function needs to be introduced to convert the oblique path delay to the tropospheric delay in the zenith direction. The GMF model is used as projection function for both the ZHD and ZWD. In addition, gradient corrections have been introduced to correct the effects of gradients in the horizontal direction. The ZTD of the reference stations can be expressed as:

$$\mathrm{ZTD} = Z_{HD} m_{hyd} + Z_{WD} m_{wet} - d_T \qquad (1)$$

where Z_{HD} = ZHD of reference station
Z_{WD} = ZHD of reference station
m_{hyd},m_{wet} = corresponding GMF model projection functions
d_T = horizontal gradient correction

d_T can be expressed as:

$$d_T = -\frac{d[m_{wet}]}{d\theta}[G_E \sin(\varphi) + G_N \cos(\varphi)] \qquad (2)$$

where m_{wet} = wet delay projection function without considering the azimuth
θ = satellite elevation angle
φ = azimuth angle
G_N, G_E = components of the horizontal gradient in the north direction and the east direction

2.4 Grid Interpolation

The traditional tropospheric correction method uses standard meteorological data to model. However, because the standard meteorological model is difficult to reflect the actual conditions of the stations, the error of this model is large. The tropospheric delay grid model established by PPP takes into account the actual conditions of the stations, the effectiveness and accuracy are improved, and the tropospheric delay at any point within the grid can be obtained by interpolation.

The grid estimation module is mainly based on the plane interpolation of the reference stations’ ZTD and ZWD. Because the ZHD can be obtained through model modification with enough accuracy, so the ZWD is broadcasted. Firstly, reference stations are formed into a dense triangulation network, and then the ZTD of each reference station is planned to the corresponding sea level tropospheric delay ZTD_{ki}.

$$ZWD_{ki} = \alpha B_{ki} + \beta L_{ki} + \sigma \qquad (3)$$

where $\alpha, \beta, \sigma =$ three unknowns of plane constraint
$B_{ki}, L_{ki} =$ the latitude and longitude of the station after domestication

Let vector e=$\begin{bmatrix}\alpha\\ \beta\\ \sigma\end{bmatrix}$.

Then, it is judged that the tropospheric grid point j is located in the triangle k (k is the triangle number, k1, k2, k3 are the three vertices of the triangle). For the zenith tropospheric delay at the triangle vertices k1, k2, k3, there is a coefficient matrix:

$$\mathrm{C} = \begin{bmatrix} B_{k1} & L_{k1} & 1 \\ B_{k2} & L_{k2} & 1 \\ B_{k3} & L_{k3} & 1 \end{bmatrix} \qquad (4)$$

$$\mathrm{e} = C^{-1} * \begin{bmatrix} ZWD_{\mathrm{k1}} \\ ZWD_{\mathrm{k2}} \\ ZWD_{\mathrm{k3}} \end{bmatrix} \qquad (5)$$

Finally, the ZWD at the grid point j is

$$ZWD_j = \mathrm{C} * \mathrm{e} \qquad (6)$$

2.5 Real-time Product Broadcasting

The tropospheric grid coverage ranges from 70 to 145 degrees east longitude, 7.5 to 55.5 degrees north latitude, and it is divided into 2.5 bands by latitude and longitude, forming 30 bands with a total of 720 grid points. Due to the large number of grid point data, a method of broadcasting troposphere correction information by band is adopted, and each band has 24 grid points. The coding structure of real-time tropospheric product is shown in table 1:

Data content			Size(bits)		
Synchronization identification			8		
Reserved			4		
Version			8		
Effective information length			12		
Message number			11		
Seconds count in the day			17		
Latitude min(B_{min})			11		
Latitude max(B_{max})			11		
Longtitude min(L_{min})			12		
Longtitude max(L_{max})			12		
Differential Latitude(△B)			6		
Differential Longtitude (△L)			6		
Grid point mask 1	ZWD 1	Accuracy factor 1	1	8	3
Grid point mask 2	ZWD 2	Accuracy factor 2	1	8	3
	……		1	8	3
Grid point mask n	ZWD n	Accuracy factor n	1	8	3
Free bits			*		
Inspection location			24		

Table 1. Encoding structure of real-time tropospheric product

3. RESULTS AND DISCUSSION

3.1 Grid Interpolation Accuracy

Tropospheric grid product cannot be directly used for real-time precise single-point positioning by users, and it is necessary to calculate the ZWD at the measurement point through a certain interpolation method. Based on the height reduction coefficients, this paper uses the exponential function to perform height reduction and inverse distance weighted interpolation, and then obtains the ZWD. In order to analyze the extent of accuracy loss caused by interpolation, we select a IGS station JFNG which does not participate in the calculation of ZWD as the measurement point for analysis. We obtain the ZWD of the station’s location based on the grid product interpolation, and compare it with the ZWD estimated by the reference stations through the PPP method.

Figure 3 shows that comparison of ZWD value between grid interpolation with PPP calculation at the JFNG station on March 23,2018. Tropospheric wet delays are compared every 15 minutes. According to statistics, the RMS value of the ZWD difference after the PPP convergence is 0.9695cm, which is less than 1cm. It can be seen that the precision of the interpolation of grid products satisfies the requirement of wet delay constraint in PPP.

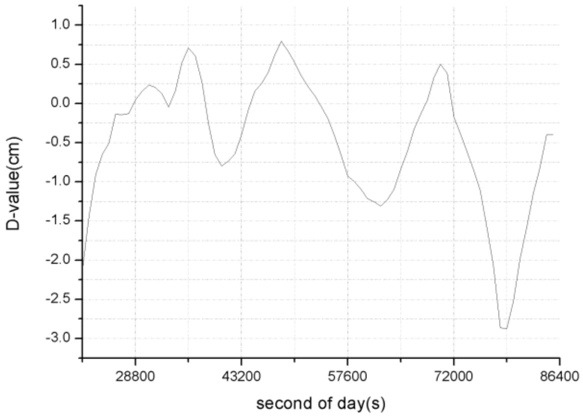

Figure 3. Comparison of ZWD value between grid interpolation and PPP calculation

3.2 PPP accuracy and convergence speed

In order to analyze the influence of tropospheric grid product on wide-area real-time PPP, the following experiments were designed in this paper: Two identical receivers are connected to one GNSS antenna, receive real-time wide-area differential products including orbit and clock proucts broadcasted by NGCC at the same time, and perform real-time PPP based on combined observations without ionosphere. One receiver adopts the ZWD of the grid product interpolation as the zenith tropospheric wet delay constraint, and the other receiver uses a linear parameter estimation method to estimate the ZWD. In addition, ZHD is estimated using the Saastamonient model. Station’s coordinate is estimated by dynamic solution.

Figure 4 shows that when the tropospheric wet delay uses the ZWD grid product as a constraint, the convergence speed of PPP at the measurement point increases significantly, especially in the U direction.

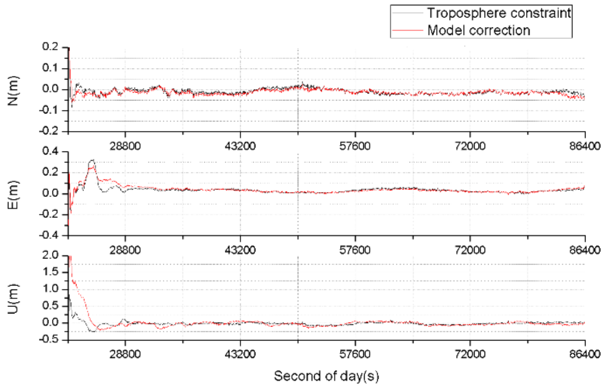

Figure 4. Comparison of PPP convergence speed

In addition, Table 2 shows that comparing the accuracy of the model correction method, the positioning accuracy of the strategy that taking the ZWD grid product as a constraint is improved obviously. The accuracy in the N, E, U direction increase by 31.8%,15.6% and 38.3%, respectively. Satellites. These results shows that the ZWD grid product estimated based on the national reference stations can improve PPP accuracy and convergence speed (Yao et al. 2017). As with the convergence speed, the accuracy of U direction experiences the most improvement. It reduces from 0.34m to 0.21m, more than 1 cm improved.

Direction	Troposphere constrait	Model correction
N	0.015m	0.022m
E	0.027m	0.032m
U	0.021m	0.034m

Table 2. Comparison of PPP accuracy

4. CONCLUSION

In this paper, multi-system GNSS observations are used to model the wide-area tropospheric wet delay using the non-differential PPP method. In addition, a real-time broadcasting data format of tropospheric grid product is proposed and a set of tropospheric wet delay estimation and dissemination systems is established in China. As can be seen from Table 2 and Figure 4, the tropospheric grid product effectively improves the positioning accuracy and convergence speed of the wide-area PPP, especially in the elevation direction, the accuracy is increased by one-third.

However, due to the fact that tropospheric grid product have been interpolated twice from estimation to user, a certain loss of precision has been caused. In the follow-up study, on the one hand, further refinement of the interpolation algorithm is needed to reduce the loss of precision in product interpolation. On the other hand, using more dense GNSS stations for tropospheric delay modeling can create tropospheric grid products with higher spatial resolution.

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