A zenith tropospheric delay correction model based on the regional CORS network

Huang Liangke\textsuperscript{1,2}, Liu Lilong\textsuperscript{1,2} and Yao Chaolong\textsuperscript{1,2}

\textsuperscript{1}College of Geomatic Engineering and Geoinformatics, Guilin University of Technology, Guilin 541004, China
\textsuperscript{2}Guangxi Key Laboratory of Spatial Information and Geomatics, Guilin 541004, China

Abstract: Tropospheric delay is a primary error source in earth observations and a variety of radio navigation technologies. In this paper, the relationship between zenith tropospheric delays and the elevation and longitude of stations is analyzed using the zenith tropospheric delay final products of International GNSS Service (IGS) stations from 2011. Two new models are proposed for estimating zenith tropospheric delays from regional CORS data without meteorological data. The proposed models are compared with the direct interpolation method and the remove-restore method using data from Guangxi CORS. The results show that the new models significantly improve the calculated precision. Finally, the root mean square (RMS) errors of the new models were used to estimate the surface precipitable water vapor (PWV) value at CORS station, which was determined to be less than 2 mm.

Key words: regional CORS; zenith tropospheric delay; regional modeling; new model; precision analysis

1 Introduction

Tropospheric delay is well-known to be a major source of error in GPS surveying. Many empirical tropospheric delay models have been established based on global radiosonde data, including the Saastamoinen model and the Hopfield model\cite{1}. Because of large spatial-temporal heterogeneities in the lower atmosphere, these empirical models can easily result in residual tropospheric errors that are several centimeters at the zenith\cite{2} and are highly variable between different seasons and regions\cite{3}. However, it is very difficult for empirical models to satisfy the accuracy requirements for various GPS surveys, such as regional precipitable water retrieved\cite{4}, atmospheric InSAR corrections\cite{5,6} and precise point positioning\cite{7}. Recently, many regional GPS networks have been constructed, such as the GPS Earth Observation Network (GEONET, Japan), the Southern California Integrated GPS Network (SCIGN, USA) and the Satellite Positioning Service of the German State Survey (SAPOS, Germany)\cite{8}. Therefore, it is feasible to construct a regional tropospheric model using precise tropospheric data from reference stations. For example, Dai\cite{9} has established a precise tropospheric model that is suitable for the Hong Kong area based on Hong Kong CORS stations, and Song\cite{10} established a new tropospheric delay model over China (named the SHAO-C model). Numerous methods have been conducted for creating precise regional tropospheric models, such as the direct interpolation method (DIM)\cite{11}, ordinary Kriging model\cite{12,13}, remove-rerestore method (RRM)\cite{14}, and projection extension method\cite{15}. The advantage of the DIM and the Kriging models is that they can simply calculate the tropospheric delay at a kinematic station from reference station data; however, these models are only suitable for...
small, flat areas and require the area of reference stations should be intensive. The RRM is suitable for undulating areas, but the model depends on the accuracy of the empirical model and measured meteorological data. The projection extension method can interpolate the tropospheric delay at kinematic stations with a high level of accuracy, especially in high altitude areas, but the model must be given more accurate meteorological data. Therefore, it is necessary to create an improved tropospheric delay correction model.

In this paper, two new zenith tropospheric delay models were established using zenith tropospheric data from regional CORS reference stations. The models did not require meteorological data and only use data related to the time and position of the station. The software GAMIT was used to estimate the zenith tropospheric delay of the reference stations. The accuracies of the proposed models were compared with the direct interpolation method and remove-restore method using measured data from Guangxi CORS. Finally, the new models were used to estimate the surface perceptible water vapor of CORS station.

2 Variations in ZTD with station position

2.1 Variations in ZTD with elevation

To study the dependence of ZTD on elevation, the 2011 zenith tropospheric delay final products from 28 IGS stations were obtained from the IGS center (ftp://cdsis.gsfc.nasa.gov) for use in the variation analysis. All zenith tropospheric products are divided into four parts. Each part corresponds to one season and is used to analyze the relationship between the seasonal mean ZTD value and the elevation of the station. The statistical results are shown in figure 1.

Figure 1 shows the seasonal mean ZTD dependence on station elevation and that this dependence has almost the same trend for all seasons. Figure 1 also shows that the ZTD changes with elevation present negative index characteristics. The ZTD dependence on elevation can be expressed by the following formula:

\[
ZTD(h) = A_0 \exp(-A_1 h)
\]  

(1)

where \(h\) is the elevation of the reference station or kinematic station, \(ZTD(h)\) is the ZTD elevation, and \(A_0\), \(A_1\) are the model parameters.

2.2 Variations in ZTD with longitude

According to previous investigations, the ZTD shows linear changes in the horizontal direction\(^{[9,16]}\). To further study the dependence of ZTD on the horizontal station position, the 2011 ZTD final products at WUHN station and SHAO station are used to analyze how the ZTD varies with longitude. The WUHN and SHAO stations are at almost the same latitude and elevation and have about a 7 degree longitude difference; therefore, they can be used to demonstrate the variation of ZTD with longitude. The monthly mean, seasonal mean and annual mean ZTD values were determined from the 2011 ZTD final products at these stations. The results are listed in table 1 and table 2.

Table 1 shows that the difference in the monthly mean ZTD value at the two stations is generally small. The largest difference is approximately 1.8 centimeters in July and August, 2011. Table 2 shows that the seasonal mean ZTD value and annual mean ZTD value of the two stations are also generally similar. The spatial variations in the ZTD clearly primarily depend on the latitude and elevation of the GPS station, and do not correlation with longitude. Therefore, the effects on ZTD at the horizontal direction are mainly caused by latitude. In addition, it is possible that the ZTD changes linearly with latitude.
Table 1  2011 monthly mean ZTD values at WUHN and SHAO stations (unit: m)

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>WUHN</td>
<td>2.395</td>
<td>2.408</td>
<td>2.417</td>
<td>2.440</td>
<td>—</td>
<td>2.617</td>
<td>2.616</td>
<td>2.621</td>
<td>2.590</td>
<td>2.494</td>
<td>2.470</td>
<td>2.414</td>
</tr>
<tr>
<td>SHAO</td>
<td>2.398</td>
<td>2.405</td>
<td>2.417</td>
<td>2.432</td>
<td>2.482</td>
<td>2.607</td>
<td>2.634</td>
<td>2.639</td>
<td>2.573</td>
<td>2.485</td>
<td>2.481</td>
<td>2.411</td>
</tr>
</tbody>
</table>

Note: — indicates the absence of the data.

Table 2  Seasonal mean ZTD values and annual mean ZTD values at WUHN and SHAO stations (unit: m)

<table>
<thead>
<tr>
<th>Site name</th>
<th>Longitude (degree)</th>
<th>Latitude (degree)</th>
<th>Elevation (m)</th>
<th>Spring</th>
<th>Summer</th>
<th>Autumn</th>
<th>Winter</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>WUHN</td>
<td>114.3</td>
<td>30.4</td>
<td>22.0</td>
<td>2.422</td>
<td>2.617</td>
<td>2.568</td>
<td>2.426</td>
<td>2.508</td>
</tr>
<tr>
<td>SHAO</td>
<td>121.2</td>
<td>30.9</td>
<td>25.8</td>
<td>2.418</td>
<td>2.621</td>
<td>2.566</td>
<td>2.430</td>
<td>2.509</td>
</tr>
</tbody>
</table>

3  Data analysis and establishment of new model

3.1 Data sources

In this paper, five days of GPS data are selected from Guangxi CORS; for April 22 and May 30, 2010 and June 8, June 30 and August 4, 2012. Some necessary meteorological data were provided by Guangxi meteorological stations. Each CORS station contains a daily observation file with data recorded at a 15 s sample interval. The XIAN, WUHN and SHAO sites are used for the joint solution in this test project. The location of Guangxi CORS stations and meteorological stations are shown in figure 2.

3.2 Data processing method

The GPS data are processed using the GAMIT version 10.35 software. The GAMIT parameter setting are as follows: the ZTD is calculated at a 2 hour interval for each station; the prior zenith tropospheric model is the Saastamoinen model; the tropospheric mapping function is the GFM; and the satellite elevation cut-off angle is set to 15°. Because the GAMIT software estimates the ZTD with an accuracy better than 1 cm\textsuperscript{[19]}, GAMIT ZTD estimates can be used as reference values in this paper.

3.3 Establishment of new models

Figure 3(a) shows the ZTD time series at JZ01 CORS station during the five selected days, and figure 3(b) shows the ZTD time series on August 4, 2011 for different CORS stations. From figure 3(a), it is obvious that the ZTD has an irregular variation for the same CORS station in different seasons. However, as shown in figure 3(b), the ZTD variations display almost the same variations over time for the different stations. Therefore, a regional ZTD model that is only related to a station's time and position can be established using a precise analysis of the reference stations' ZTDs. As analyzed in section 2, for large areas, the new model (named the EHB model) can be expressed by the following formula:

\[ ZTD_i(h, \phi, t) = A_0(t) + A_1(T) \exp(-A_2(t)h_i) + A_3(t)\phi \]  \hspace{1cm} (2)

where \( ZTD_i(h, \phi, t) \) is the zenith tropospheric delay calculated at reference station \( i \) at period \( t, h_i, \phi_i \) indicate the elevation and latitude of station \( i \), respectively, and \( A_j(t), (j = 0, 1, 2, 3) \) are the model parameters for the \( t \) moment and are related to the time. Therefore, at least four known reference stations are needed to estimate the model parameters, which can be estimated using an iteration method that rapidly converges. The function \( A(t) \) is related only to the time; therefore, \( A(t) \) can be expressed as follows:

\[ A_i(t) = a_0 + a_1t + a_2t^2 + a_3t^3 + \cdots + a_nt^n \]  \hspace{1cm} (3)

where \( a_0, a_1, \cdots, a_n \) are the polynomial coefficients for parameters \( A_i(t), (i = 0, 1, 2, 3) \) at period \( t \), respectively. The polynomial coefficients in equation (3)
can be determined by a least squares fit, and the polynomial order can be selected automatically using the statistical significance hypothesis test\textsuperscript{18}. Therefore, we can calculate a station's ZTD at any period after estimating the behavior of the function $A(t)$.

For medium and small areas, only ZTD dependencies on elevation were considered, and differences depending on the horizontal component were eliminated. The new model (named the EHT model) can be expressed by the following formula:

$$ZTD_i(h,t) = A_0(t) + A_1(t)\exp(-A_2(t)h_i)$$

(4)

where $ZTD_i(h,t)$ is the zenith tropospheric delay calculated for reference station $i$ at period $t$, and the other variables are as previously explained. Apparently, the parameters of the new model can be estimated with only three known reference stations.

4 Assessment of new models' precision

4.1 Validation of new models

To validate the new models, GPS data from 10 stations in the Guangxi CORS network are used, covering an area from approximately $21^\circ$N – $25^\circ$N in latitude and $107.5^\circ$E – $110.5^\circ$E in longitude. Six reference stations are used to calculate the model parameters ($JZ01$, $JZ09$, $JZ17$, $JZ19$, $JZ22$, and $JZ25$) and four stations are treated as check stations. The GAMIT software program was used to estimate ZTDs using measured data from the six reference CORS stations taken
Huang Liangke, et al. A zenith tropospheric delay correction model based on the regional CORS network

on August 4, 2011. In RRM, the Saastamonien model was used as the empirical model. However, there is no meteorological sensor installed adjacent to the GPS antennas, so the measured meteorological data were not available for the GPS stations. In addition, many meteorological sensors are not located near GPS stations. Because of this, the surface temperature and pressure data of the CORS stations must be interpolated from the nearest meteorological stations\cite{19}. The pressure at a GPS station can be computed using the following formula:

\[ P_{\text{GPS}} = P_{s}(1 - 0.0000226(H_{\text{GPS}} - H_{s}))^{5.225} \]  

and the temperature at a GPS station can be computed as

\[ T_{\text{GPS}} = (T_{s} - 273.16) - 0.0065(H_{\text{GPS}} - H_{s}) \]  

where \( P_{s} \) is the meteorological station pressure in mbar, \( T_{s} \) is the meteorological station temperature in Celsius, \( P_{\text{GPS}} \) is the GPS station pressure in mbar, \( T_{\text{GPS}} \) is the GPS station temperature in Celsius, \( H_{\text{GPS}} \) is the GPS station elevation in meters, and \( H_{s} \) is the meteorological station elevation in meters.

In this section, the ZTDs of three check stations (JZ05, JZ18, and JZ26) are calculated using the DIM, RRM, EHBT and EHT models. The results are compared with the GAMIT solution (table 3 and figure 4).

<table>
<thead>
<tr>
<th>Site</th>
<th>EHBT model</th>
<th>EHT model</th>
<th>DIM</th>
<th>RRM</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Max bias</td>
<td>Min bias</td>
<td>RMS</td>
<td>Max bias</td>
</tr>
<tr>
<td>JZ05</td>
<td>13.4</td>
<td>3.5</td>
<td>8.4</td>
<td>23.9</td>
</tr>
<tr>
<td>JZ18</td>
<td>18.8</td>
<td>0.5</td>
<td>9.4</td>
<td>34.2</td>
</tr>
<tr>
<td>JZ26</td>
<td>16.3</td>
<td>2.0</td>
<td>8.8</td>
<td>36.2</td>
</tr>
</tbody>
</table>

Table 3 Statistics of residuals for zenith tropospheric delay in different models (Unit: m)

\[ \text{Figure 4} \quad \text{Comparison of zenith tropospheric delay accuracy in different models} \]
Table 3 and figure 4 show that the RRM provides the worst result, with an average RMS of 34.5 mm for the three check stations. The precision of the DIM is similar to that of the EHT model, with average RMS values of 16.9 mm and 19.6 mm, respectively. The precision of the EHBT model (which is less than 10 millimeters) is better than that of the three other methods. The precision of the RRM is wholly dependent on the precision of the Saastamoinen model and the measured meteorological data. Additionally, if we only consider the bias caused by the Saastamoinen model, then the precision is close to 4–5 cm. Therefore, a poor result will be obtained when the RRM is used to estimate the ZTD. The EHT model only considers the variation in ZTD with elevation and ignores latitude variations, which results in low precision. The DIM is only suitable for flat, small areas and therefore is not expected to produce high precision results in the large test area.

To validate and evaluate the precision of the EHBT model in poor weather conditions, such as on a rainy day, the model is applied at check station JZ12 for one day of rainy data (August 4, 2011). The reference stations are the same six reference stations mentioned previously. On this day, only the JZ12 site has rainy conditions, with a rainfall of 6.9 mm; the rest of reference sites are sunny. The ZTD of site JZ12 is calculated using the four methods mentioned previously. The results are compared with that of the GAMIT solution. The results are shown in figure 5.

Figure 5 shows the ZTD residuals using the 4 different methods. The RMS values of the 4 methods are 11.6 mm, 23.1 mm, 34.1 mm and 41.9 mm, respectively. It is apparent that the precision of the EHBT model is higher than the three other methods. Therefore, the EHBT model can ensure good precision even when used for data obtained in rainy conditions. The meteorological conditions had changed sharply at the JZ12 site because the JZ12 site had the only rainy conditions among all of the reference stations on August 4, 2011. In addition, the JZ12 site is near the Beibu gulf sea, resulting in a larger elevation difference between the JZ12 check station and reference stations. These differences must have caused a large loss of precision using the 3 other methods based on the analysis of section 1. However, because the EHBT model accounts for horizontal changes and elevation effects and is not affected by the precision of the meteorological data, the EHBT model can obtain a precise ZTD calculation in rainy weather conditions.

Because the EHT model is not suitable for large areas, we tried to change the selection of known reference stations. In this section, an improved selection of known reference stations is used according to the principle of CORS virtual reference stations21. This principle implies that the nearest 3 reference stations between the reference station and the kinematic station (a check station in this test) should be selected as the known reference stations. This is known as the Triangle method. However, the selection of known reference stations in all reference stations is defined as the Network method. To validate the Triangle method in the EHT model, three check stations (JZ05, JZ18 and JZ26) are tested using the EHT model for one day of data (August 4, 2011). The known reference stations are selected using the Triangle method outlined above. The ZTD of the three check stations is calculated using the Triangle method and the Network method, respectively. The results are compared with that of the GAMIT solution (Fig. 6).
Figure 6 shows that at JZ05 and JZ26, the accuracy of the derived ZTD using the Triangle method is improved by 51% and 72%, respectively, compared to the Network method. The RMS at JZ05 and JZ26 was 8.6 mm and 6.9 mm, respectively. A comparative precision was found at JZ18 using the two methods. At JZ18, because the distance between JZ18 and the nearest three known reference stations was large, there was a large loss of precision, and the horizontal component of the ZTD was neglected for the two methods. However, the distance between sites JZ05 and JZ26 and their reference stations was less than that for JZ18. This allowed the horizontal component of the ZTD to be neglected; hence, the use of the Triangle method with the EHT model was allowed. This greatly improved the results for sites JZ05 and JZ26. Based on the above analysis, using the Triangle method with the EHT model is suitable for medium and small areas.

Finally, the ZTD distribution was derived using the EHBT model in the test area on August 4, 2011, as shown in figure 7.

4.2 Estimation of precipitable water vapor using the EHBT model

In this section, the accuracy of the EHBT model for estimating the PWV is validated. First, the hydrostatic zenith delay (ZHD) is calculated by using the Saastamoinen model\(^5\). The formula is expressed as follows:

\[
ZHD = \left(2.2779 \pm 0.0024\right)P_s/\left[1 - 0.00266 \cos(2\lambda) - 0.00028H\right]
\]

where \(P_s\) is the total pressure (hPa) at the earth’s surface, \(\lambda\) is the latitude, and \(H\) is the height above the ellipsoid (in kilometers). The zenith wet delay (ZWD) is obtained by subtracting the ZHD from the ZTD that was estimated using the EHBT model. The ZWD is subsequently multiplied by a conversion constant \(K\):

\[
PWV = KZWD
\]

The constant \(K\) is defined as follows:

\[
K = 10^5/\rho R_s(k_3/T_m + k_2)
\]

where \(R_s\) is the specific gas constant for the water vapor, \(\rho\) is the density of water, \(k_3 = 22.1\ \text{K/hPa}\), \(k_2 = 3.739 \times 105\ \text{K}^2/\text{hPa}\), and \(T_m\) is the weighted mean temperature of the atmosphere. The value of \(T_m\) is from
a model determined to be suitable for eastern China (20°N - 50°N latitude and 100°E - 130°E longitude) and is defined as follows:

\[ T_m = 44.05 + 0.81 T_s \]  

(10)

where is the surface temperature in. This can subsequently be converted into precipitable water vapor. Afterwards, the PWVs of sites JZ05, JZ12, JZ18 and JZ26 are calculated using the EHBT model. The results are compared with those from the GAMIT software (Fig. 8).

Figure 7 Distribution of the zenith tropospheric delay in the EHBT model

Figure 8 Time series of the estimated PWV values by the EHBT model
Figure 8 shows the good agreement between the EHBT model and the GAMIT solution. If the PWV estimated by GAMIT is treated as a reference value, the RMS values for the four sites are 1.4 mm, 1.8 mm, 1.5 mm and 1.4 mm, respectively. Therefore, the RMS of the EHBT model is better than 2 mm when used to estimate the site surface of PWV. To a certain extent, the temporal and spatial resolution can be improved using the EHBT model because the model is only related to the time and position of each station.

5 Conclusions

Because of the increasing precision requirements of GPS applications, it is important to establish a precise tropospheric correction model for GPS surveying. In this paper, two new models are validated using measured observation data from Guangxi CORS and meteorological data from the meteorological site. For the EHBT model, results show a significant improvement compared to other methods, especially for rainy weather conditions, in which the model can maintain a RMS of 11.6 mm. The EIT model is not suitable for the large areas but still displayed good precision when used for medium and small areas with the Triangle method. Finally, the RMS of the EHBT model that was used to estimate the surface PWV values of CORS station is less than 2 mm. Because of the limited data obtained in this test project, further research is necessary to apply the new models to other areas.

Acknowledgments

We would like to thank Guangxi Bureau of Surveying, Mapping and Geoinformation for providing the test CORS data.

References


