GGOS tropospheric delay forecast product performance evaluation and its application in real-time PPP

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ABSTRACT

Tropospheric delay is one of the main error sources in Global Navigation Satellite System (GNSS) precise positioning, as the GNSS signal is influenced by refraction when travelling through the troposphere. Generally, tropospheric delay is estimated as a parameter in GNSS data processing. With the increasing demand for GNSS real-time applications, high-precision tropospheric delay augmentation information is essential to enhance convergence speed and precision of positioning. The Global Geodetic Observing System (GGOS) Atmosphere provides total zenith tropospheric delay (ZTD) forecast grid data, globally, one day in advance, where the time resolution is 6 h and spatial resolution is 2.5° × 2°. Here, the GGOS ZTD forecast product is assessed compared with ZTD information from global IGS sites, including an analysis of the spatial and temporal distribution of its error and the weather influence on its precision. Ultimately, the application effect of the GGOS Atmosphere ZTD forecast product in real-time precise point positioning (PPP) is examined. The results show that the positioning precision and the speed of convergence are obviously advanced, especially in the U direction, which informs the potential for real-time application of GGOS forecast products.

1. Introduction

In the global navigation satellite system (GNSS), the tropospheric delay along slant path is approximately 2 m–20 m, which is an error source that must be considered (Ruiqiong et al., 2015). Therefore, improving the precision of tropospheric delay correction is essential to achieve real-time and fast multi-GNSS precise positioning (Miaomiao et al., 2014). The zenith tropospheric delay includes two parts, the ZHD (Zenith Hydrostatic Delay) and ZWD (Zenith Wet Delay). The tropospheric delay on the signal path in GNSS observations is derived from the zenith tropospheric delay of the receiver through the mapping function (Mendes, 1999). Traditional models, such as Hopfield, Saastamoinen, Black and others (Hopfield, 1969; Saastamoinen, 1972; Black, 1978), whose correction accuracy ranges up to decimeter or centimeter level, need meteorological parameters. Since it is difficult in practice to obtain the meteorological parameters at the measuring station, more reliable tropospheric delay models have been established to improve the accuracy of geodetic space technology. These include the tropospheric key parameters empirical model, which offers high-precision tropospheric delay without any auxiliary information (Yao et al., 2015). Collins and Langley (1997) established the UNB model for the promotion and application of the Wide Area Augmented Navigation System (WAAS) in the United States, which has strong applicability in North America. Similarly, the EGNOS model (Dodson et al., 1999; Penna et al., 2001; Ueno et al., 2001) is a zenith tropospheric delay correction model adopted by European Geostationary Navigation Overlay Service (MOPS, 1999). Yao et al. (2013) established the GZTD model based on the spherical harmonic function, and then improved it to the GZTD-6h model, which effectively improved the time resolution of ZTD estimation (Yibin et al., 2015). Krueger et al. (2004) established the TropGrid model (Krueger et al., 2004), which was upgraded to TropGrid2 by Schuler (Schüler, 2014) (2014). Several studies have proven that ECMWF is more accurate than NCEP (Yu et al., 2010; Chen et al., 2011; Decker et al., 2012) (Yu et al., 2010; Chen et al., 2011, 2012; Decker et al., 2012). Boehm (Boehm et al., 2007) established global pressure and temperature (GPT) model using the Numerical Weather Model (NWM) product ERA-40 provided by the European Center for Medium-Range Weather Forecast (ECMWF) and has been widely used in practice. (Kouba, 2009; Petit and Luzum, 2010; Shu et al., 2011; Shengjie and Fu Zhi Kang, 2013; YangYu et al., 2013; JvangChen and Wang, 2014). Lagler et al. (2013) improved and optimized some of the deficiencies of the GPT model and built a new empirical model (GPT2). Based on the GPT2 model, Boehm et al. (2014) extended the parameters and increased spatial resolution to establish.
Once the GPT2 series model is released, many scholars have evaluated the accuracy and application effect of the GPT2 series model. The results show that the precision is considerably high (Schindelegger et al., 2015). It is worth noting that empirical models are modeled on the basis of the Numerical Weather Model (NWM) product. In the post-processing of GNSS data, many scholars also have started to acquire the ZTD from the NWM products available on the Internet. Therefore, with the improvement of the Earth observation network and the increase in available observed data, tropospheric delay correction has transitioned from a simple closed data model to a comprehensive model that relies on a large amount of external data.

Furthermore, numerical meteorological forecast data derived from meteorological observations also has become an effective means to calculate ZTD (Emardson et al., 1998). For example, according to the analysis data provided by the European Center for Medium-Range Weather Forecasts (ECMWF) and the reanalysis and forecast data provided by the United States National Centers for Environmental Prediction (NCEP) (Bromwich and Wang, 2005), Boccara G evaluated the accuracy of NCEP/NCAR reanalysis and ECMWF analyses in the lower stratosphere over Antarctica (Boccara et al., 2008). The results showed that this information can be used in high-precision ZTD research and applications. In the GGOS Atmosphere project, based on ECMWF numerical meteorological data and the Marini (1972) projection function, the Vienna University of Technology released the VMFG series of global tropospheric zenith delay products: VMFG and VMFG_FC (Boehm et al., 2007). Implementation and testing of the gridted Vienna Mapping Function 1 (VMF1) has been done by J. Kouba (2008). The new gridted Vienna Mapping Function (VMF1) was implemented and compared to the well-established site-dependent VMF1, directly and by using precise point positioning (PPP). The hydrostatic ZPD's of the gridted VMF1 compare with the site-dependent VMF1 ZPD's with RMS of 0.3 cm, subject to some biases and discontinuities of up to 4 cm, which are likely due to different strategies used in the generation of the site-dependent VMF1 data. Global tropospheric delay products can achieve satisfactory correction effects in their modeling data source regions (Dodson et al., 1999). However, many scientific applications require their availability in near-real-time. So far, there are more and more studies on the global accuracy and applicability of tropospheric forecasting products. Here J. Boehm presented coefficients of the VMF1 as well as the hydrostatic and wet zenith delays that have been determined from forecasting data of the ECMWF and provided on global grids (Boehm et al., 2009). The comparison with parameters derived from ECMWF analysis data shows that the agreement is at the 1 mm level in terms of station height. The study showed that these new products (VMF1-FC and hydrostatic zenith delays from forecast data) can be used in real-time analysis of geodetic data without significant loss of accuracy. However, IGS precise products have some latency, ranging from 17 h to 18 day before the final product can be obtained (Hadas and Bosy, 2015), studies have only carried out tropospheric products post-test of standard single point positioning, and they have not performed application testing of the tropospheric forecasting products in real-time Precise Point Positioning. In the last decade, the IGS real-time service (RTS) was developed. IGS officially announced the real-time service (RTS) service on 1 April 2013, which provides Global Positioning System (GPS) real-time orbit and clock correction and experimental GLONASS corrections, making it possible to conduct real-time PPP at a global scale (Caissey et al., 2012). The IGS’s ultra-rapid orbit and clock products are used to generate the near real-time regional troposphere model which greatly improves the height accuracy in simulated real-time PPP scenarios. Although IGS RTS has solved the latency issue of precise satellite orbit and clock products, the long convergence time still remains a challenging factor for real-time PPP (Shi et al., 2014). In fact, PPP convergence highly depends upon an accurate estimation of troposphere delays. There are quasi-real-time or real-time and forecast models that are based on tropospheric delay obtained through GNSS observation processing. Wang et al. (2013) assessed the near real-time PPP-inferred troposphere parameter, using Centre National d’Etudes Spatiales (CNES)’s real-time corrections (Wang and Chai H, 2013), and found a mean bias of approximately 6.5 mm and a root mean square (RMS) error of approximately 13 mm for the zenith wet delay compared to those using post-mission products. Hadas et al. (2013) assessed the benefits of near real-time regional troposphere model for PPP (Hadas et al., 2013). Li et al. (2011) investigated the regional atmosphere augmentation for real-time PPP with instantaneous ambiguity resolution (Li et al., 2011). Li’s method however requires the user to send approximate coordinates to the server in order to receive an interpolated troposphere delay from the server. Such two-way communication mode would increase the user’s communication cost and limit the server’s maximum number of allowed connections. Shi et al. (2014) introduced a strategy which consists of modeling ZWD estimates inside a real-time GNSS reference network thanks to optimal fitting coefficients (OFCS) (Shi et al., 2014). Both can be delivered to real-time PPP users through the Internet. However, when a roving station is outside the CORS network or cannot obtain regional ZTD correction data due to network or other reasons, high-precision global ZTD models can be applied in real-time PPP instead. Therefore, it is also necessary to study the effect of real-time available troposphere forecasting products on reducing the convergence time for (near) real-time PPP.

GGOS Atmosphere publishes a global zenith tropospheric delay forecasting product with a 6 h temporal resolution and 2.5° × 2° spatial resolution one day in advance for real-time GNSS data processing, enabling various real-time GNSS users to get real-time high-precision tropospheric delay augmentation information and improve positioning efficiency. Based on the previous studies, this paper assesses the global accuracy of GGOS ZTD forecast products and examines the effect of

Fig. 1. The distribution of IGS stations.
their products on real-time precise point positioning, which is conducive to making full use of existing resources and provides users with tropospheric augmentation services. Furthermore, tropospheric delay also affects the measurement of very long baseline interferometry, the orbital Doppler positioning system and synthetic aperture radar interferometry. Thus, the accuracy of the tropospheric delay forecasting product is analyzed, which is beneficial to a refinement of the tropospheric forecasting product and enhances its applicability.

In this paper, the global accuracy of GGOS Atmosphere tropospheric forecast data is systematically evaluated. Meanwhile, its accuracy in different weather conditions and the application’s performance in real-time PPP are investigated.

### 2. Product performance evaluation

#### 2.1. Data description and processing strategy

The products used in this paper are the GGOS Atmosphere global tropospheric delay forecast products and the IGS tropospheric delay data, both from 2016. IGS-ZTD are used as a reference to analyze the global performance of GGOS forecast ZTD products.

#### 2.1.1. GGOS atmosphere forecast ZTD data

GGOS Atmosphere developed a tropospheric model based on ECMWF data (Böhm and Schuh, 2013), providing ZTD forecast products for global users one day in advance. The tropospheric delay parameters provided by GGOS Atmosphere include ZHD and ZWD, and the coefficients of the projection function, VMF1. These parameters are provided in the form of a global grid based on a spatial resolution of 2.5° × 2° (longitude × latitude), and a temporal resolution of 6 h. The ZHD and ZWD on the grid point are added to get the ZTD forecast value of the zenith troposphere delay.

![Fig. 2. The variation of monthly average bias STD and RMS.](image)
2.1.2. IGS ZTD data

IGS provides zenith tropospheric delay products from tracking stations around the world. It uses six different software packages from seven analytics centers around the globe, calculating the ZHD using the GPT model and the Saastamoinen model, and estimating the ZWD as a parameter, of which a weighted average is computed to get the ZTD. Global ZTD products announced by IGS are accurate to 4 mm (Xianling, 2009) and can be used as a reference standard to evaluate other ZTD products. This paper selects ZTD time series of more than three hundred IGS stations in the world, and the locations of each station are shown in Fig. 1. Table 1 gives statistical information about the temporal, spatial resolution and continuity of the two ZTD products.

Due to inconsistent location between the grid points of GGOS products and the IGS stations, the GGOS-ZTD in each grid have been height-reduced and interpolated to IGS stations before comparing with IGS-ZTD.

The ZTD of IGS stations calculated by the GGOS forecasting product data is compared with the ZTD time series released by IGS, which is the standard reference value, to obtain the residuals. The ZTD accuracy for each site is expressed as the bias, STD and RMS error of the difference between the calculated GGOS-ZTD and the reference IGS-ZTD. The computation formula is as follows in (1), and the temporal and distribution characteristics are detailed analyzed afterwards.

$$
\text{bias} = \frac{1}{N} \sum_{i=1}^{N} (ZTD_{i}^{\text{GGOS}} - ZTD_{i}^{\text{IGS}}),
$$

$$
\text{STD} = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (A_{i} - \mu)^2}; A_{i} = ZTD_{i}^{\text{GGOS}} - ZTD_{i}^{\text{IGS}}, \mu = \frac{1}{N} \sum_{i=1}^{N} A_{i}
$$

$$
\text{RMS} = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (ZTD_{i}^{\text{GGOS}} - ZTD_{i}^{\text{IGS}})^2}
$$

In the formula, $ZTD_{i}^{\text{GGOS}}$ is ZTD of the station calculated by the GGOS tropospheric forecast products at time $i$, $ZTD_{i}^{\text{IGS}}$ is the ZTD of the station published by IGS at time $i$, and $N$ means total time amount in the statistics. Average deviation (bias) measures the average degree of divergence between GGOS-ZTD and IGS-ZTD, standard deviation (STD) measures the degree of dispersion between GGOS ZTD forecast products, and root mean square error (RMS) measures precision of GGOS ZTD forecast products with respect to IGS-ZTD products.

2.2. The temporal and spatial distribution characteristic of GGOS forecast product precision

In order to provide real-time PPP users with more intuitive and practical accuracy, linear interpolation and height conduction have been conducted before precision evaluation. For real-time application of GGOS-ZTD forecast products, the ZTD forecast values from 2016 are linearly interpolated to obtain a sequence with a time resolution of 5 min, which is compared with a ZTD time series of 333 IGS stations. Then, the precision of the forecasted product is evaluated by analyzing the statistics bias, STD and RMS.

As seen from Table 2, compared with IGS-ZTD, the annual mean bias, mean STD and mean RMS of GGOS-ZTD are, respectively, $-0.57$ cm, $1.83$ cm and $1.63$ cm. The accuracy of the tropospheric delay model currently used in wide area augmentation systems is approximately $4$ cm. The statistical results in Table 2 show that none of the deviation bias, STD and RMS of GGOS-ZTD relative to IGS-ZTD at each station are more than $4$ cm. The maximum RMS is $3.5$ cm while the highest precision reached was $0.72$ cm, better than the empirical model. Therefore, the grid-based GGOS tropospheric delay forecast product is accurate enough to meet the needs of GNSS users for tropospheric delay correction, and has broad applicability to other geodetic techniques.

To analyze the seasonal variation features of GGOS-ZTD, bias, STD

![Fig. 3. The variation with latitude of annual average bias STD and RMS.](image-url)
and RMS monthly statistics are calculated for 333 IGS stations, which is shown in Fig. 2. As seen from Fig. 2, bias, STD and RMS all have obvious seasonal effects. In the Northern Hemisphere, bias is negative and has significant seasonality, deviation ascends from January to July and descends from July to December. The values of STD and RMS, which gradually increase from February to August and decrease from August to December, show the same seasonal effect. Accordingly, seasonal variations in the southern hemisphere show the opposite phenomenon due to opposite seasons and climate conditions. Normally, the climate in summer is complicated and changeable, and the content of the water vapor that influences the ZTD is highest and the most variable in summer. There is an irregular perturbation in ZTD variation, for which the overall summer bias, STD and RMS are larger than those in winter. It is worth noting that the accuracy of the products in the southern hemisphere is generally lower than that in the northern hemisphere, which may be related to there being fewer IGS stations used for assessment in the southern hemisphere and that some stations are located in marine areas.

The globally spatial distribution of ZTD is mainly associated with latitude (MOPS, 1999). Fig. 3 shows the variation with latitude of annual mean bias, STD and RMS. The trend of bias with latitude is not obvious. While RMS and STD appear approximate symmetry in the northern and southern hemispheres, which increases with latitude at low latitudes and decreases with latitude at high latitudes. Figs. 5–7
display the global distribution of bias, STD, and RMS, respectively. As seen from the figure, the values of error are higher at the middle and low latitudes and lower at high latitudes. Meanwhile the errors of ZTD over the ocean and at the junction of land and sea are larger. At low latitudes, the atmospheric pressure in the equatorial region is stable, while the water vapor changes are relatively active. The condition in the high latitudes is the opposite. Due to the complex and changeable water vapor in mid-latitude regions and the oceanic monsoon at land-sea junctions, ZTD in these areas is prone to irregular disturbances and violent fluctuations, making the error of forecast ZTD become larger, as bias, STD and RMS also grow larger. The content of the water vapor that influences the ZTD is highest and the most variable in the equatorial region. Taking into consideration small amount of analyzed stations in the equatorial region, the mechanism for large bias and small RMS in the equatorial region is complicated and need further research. Fig. 4 shows the variation characteristic with elevation of annual mean bias, STD and RMS. The bias appears as a wavy trend as the height increases, with no obvious regular relationship to elevation. The STD and RMS, whose variation tendencies are more explicit, increase with raising elevation, except for the 150–250 m range. The STD and
RMS are greatest below 0 m, at 1.98 cm and 2.28 cm, respectively. Between 0 and 150 m elevation, STD increases from 1.54 cm to 1.73 cm and RMS increases from 1.73 cm to 1.95 cm. There is a further increase in STD and RMS in the elevation range of 250–4000 m. Among stations above 2000 m, the average STD is 1.65 cm and the RMS is 2.15 cm. This is because ZTD distribution, whose value decreases with height, is closely related to elevation. In addition, stations below 0 m or above 2000 m are scarce, and the data is of poor quality. Meanwhile, the impact of coarse height reduction coefficients becomes more significant with increasing height.

The GGOS-ZTD error time series (bias, STD, RMS) from 8 IGS sites are selected for detailed analysis, as shown in Figs. 8–10. The details about these stations are illustrated in Table 3. Through comprehensive comparisons, the accuracy of GGOS tropospheric delay forecast products in the alrt, bake and cas1 stations are relatively higher. The alrt station is located in the upper latitudes of the northern hemisphere, where the climate is stable throughout the year with less irregular disturbances of the ZTD. Therefore, the volatility of the predicted product bias, STD and RMS here is relatively small. The bake station is situated in the mid-high latitudes of the Northern Hemisphere. Fluctuations of the STD and RMS values are extreme from June to August, when the northern hemisphere is in summer and the weather varies

![Fig. 8. The Time Series of bias in 8 sites.](image)
dramatically, which accounts for relatively large error of the forecast ZTD. During the rest of the year, when the climate is mild with little change in water vapor, the product accuracy is higher. The cas1 station is located in the middle and high latitudes of the southern hemisphere, where weather is relatively stable and the estimated GGOS-ZTD is accurate.

On the other side, the stations with large error include the aira, bako, ckis, guat and shao sites. Among them, the aira and shao site are situated in the low-latitude area of the northern hemisphere while bako, ckis and guat site are located near the equator. Note that climate change and water vapor variation is more apparent at low latitudes. In addition, the shao site is along a coastline, the aira station and the bako station are seated at the junction of land and sea, where the turbulent weather gives rise to strong variation in ZTD. Nevertheless, the temporal resolution of the GGOS Atmosphere forecast product is 6 h. It is difficult to precisely predict ZTD variation in spite of linear interpolation. Taking into account the fact that the elevation of the guat sites are above 1000 m, height reduction errors are included, making the deviation between GGOS-ZTD and IGS-ZTD more significant. The above case confirms that the precision of GGOS tropospheric delay prediction products is related to the station location and the local climate.

Fig. 9. The Time Series of STD in 8 sites.
2.3. Accuracy evaluation of GGOS forecast product under special weather conditions

To study the accuracy of GGOS tropospheric delay forecasting products in different weather conditions, this paper selects the GGOS-ZTD error time series of Shanghai IGS station shao in July 2016, as shown in Fig. 11. According to the chart, the RMS fluctuation curve of ZTD prediction products in the shao site is consistent with local rainfall situations. The bias and RMS of ZTD forecast products are usually larger on the day before or on the day of rainfall. Specifically, the absolute value of bias is greater than 2 cm and RMS is more than 3 cm. The accuracy of predicted ZTD is lower, especially in heavy rain, such as July 2, July 11 and July 28, when the absolute value of bias and RMS reaches 4 cm and the forecast is inaccurate. While in fair weather, the bias and RMS of GGOS-ZTD were relatively lower, indicating the high precision of the forecasting products. During fair weather, the RMS is generally less than 2 cm, as on July 21, when the accuracy was up to 0.89 cm. Rainfall causes a drastic fluctuation in water vapor, which in turn has a large impact on ZTD. The ZTD forecast of GGOS does not take the occurrence of rainfall events into consideration. Therefore, the accuracy deteriorates on rainy days and improves on sunny days, which provides a reference for the real-time application of products.
3. System differences between GGOS-ZTD products and IGS-ZTD products

In the following, the systematic differences between the GGOS Atmosphere tropospheric delay forecast products and the IGS-published ZTD are modeled to further analyze the accuracy of the GGOS Atmosphere tropospheric delay products and to provide a reference basis for integrating GGOS-ZTD and other tropospheric delays when establishing a multi-source tropospheric delay model.

3.1. Linear fitting

Suppose the ZTD values observed by each IGS station were Y and the ZTD value calculated by GGOS Atmosphere interpolation were X, then the data of each station from 2016 are linearly fitted to calculate the fitting coefficient (proportional error a and fixed error b) of 333 stations according to the formula $Y = a \times X + b$. The coefficients are significant according to the F-test, indicating that there is a certain degree of discrimination between the two data sources and that significant system differences between them need further evaluation.

3.2. Distribution characteristics of system difference coefficients

Figs. 12 and 13 show the global distribution of the systematic difference coefficients a and b. As seen from Fig. 12, the value of a in the vicinity of the equator is basically less than 1, and the variation of a in high latitudes, which is not significant, is approximately 1. The difference of a in mid-latitudes is obvious. The area where a is significantly greater than 1 is likely correlated with extreme station elevation. Over the ocean or at a junction of land and sea, especially in the west coast of South America and the Himalayas, the value of a is much higher than 1 or lower than 1. There are irregular disturbances in ZTD variation in these areas, which may be derived from complicated topography and active climate, for specific reasons that require further study. As shown in Fig. 13, the distribution of coefficient b corresponds to coefficient a.

The proportional error a and the fixed error b are noticeably distributed with the change of latitude. Except for some abnormal values, the spatial distribution appears symmetrical in the northern and southern hemispheres. The trend in system difference coefficients with latitude is also related to the regional climate. Due to the relatively stable climate in high latitudes, the proportion errors and fixed errors of GGOS troposphere products are small. However, the climate in the middle latitudes is complicated and volatile, which makes system differences more significant.

<table>
<thead>
<tr>
<th>IGS station</th>
<th>Latitude/°</th>
<th>Longitude/°</th>
<th>Elevation/m</th>
<th>Special features</th>
</tr>
</thead>
<tbody>
<tr>
<td>aira</td>
<td>31.82N</td>
<td>130.60E</td>
<td>314.64</td>
<td>near a coastline</td>
</tr>
<tr>
<td>alrt</td>
<td>82.49N</td>
<td>62.34W</td>
<td>78.11</td>
<td></td>
</tr>
<tr>
<td>bake</td>
<td>64.32N</td>
<td>96.00W</td>
<td>4.40</td>
<td></td>
</tr>
<tr>
<td>bako</td>
<td>6.49S</td>
<td>106.85E</td>
<td>158.18</td>
<td>on an island &amp; equatorial regions</td>
</tr>
<tr>
<td>cao</td>
<td>66.28S</td>
<td>110.52E</td>
<td>22.55</td>
<td></td>
</tr>
<tr>
<td>ckis</td>
<td>21.20S</td>
<td>159.81W</td>
<td>18.40</td>
<td>equatorial regions</td>
</tr>
<tr>
<td>guat</td>
<td>14.59N</td>
<td>90.52W</td>
<td>1519.87</td>
<td>high altitude &amp; equatorial region</td>
</tr>
<tr>
<td>shao</td>
<td>31.10N</td>
<td>121.20E</td>
<td>22.09</td>
<td>along a coastline</td>
</tr>
</tbody>
</table>

Table 3 Information of 8 IGS stations.

Fig. 11. The Time Series of bias RMS STD at shao site in 2016.07.
3.3. Spherical harmonic fitting of system difference coefficient

Boehm et al. (2007), for the first time, applied 9-order 9-degree spherical harmonics to establish a global surface temperature and pressure empirical model (GPT model) and achieved favorable results. 

Yao et al. (2012) used the spherical harmonic method to model the global atmospheric weighted average temperature (GWMT model), which reduced the number of model parameters and met the precision requirements of water vapor inversion in GNSS meteorology. This illustrates that the spherical harmonic function has significant advantages and application potential in the characterization of spherical

Table 4
Information and bias of 8 IGS stations.

<table>
<thead>
<tr>
<th>IGS station</th>
<th>Latitude/°</th>
<th>Longitude/°</th>
<th>Elevation/m</th>
<th>a-bias</th>
<th>b-bias</th>
</tr>
</thead>
<tbody>
<tr>
<td>aira</td>
<td>31.82N</td>
<td>130.60E</td>
<td>314.64</td>
<td>−0.0161</td>
<td>0.0222</td>
</tr>
<tr>
<td>bake</td>
<td>64.32N</td>
<td>96.00W</td>
<td>4.40</td>
<td>−0.0446</td>
<td>0.0742</td>
</tr>
<tr>
<td>irkm</td>
<td>52.22N</td>
<td>104.32E</td>
<td>502.32</td>
<td>0.0520</td>
<td>−0.1138</td>
</tr>
<tr>
<td>zim2</td>
<td>46.88N</td>
<td>7.47E</td>
<td>956.40</td>
<td>−0.0003</td>
<td>−0.0179</td>
</tr>
<tr>
<td>dgav</td>
<td>7.27S</td>
<td>72.37E</td>
<td>−64.75</td>
<td>0.0080</td>
<td>−0.0170</td>
</tr>
<tr>
<td>str1</td>
<td>35.31S</td>
<td>149.01W</td>
<td>800.04</td>
<td>0.0079</td>
<td>−0.0238</td>
</tr>
<tr>
<td>tibd</td>
<td>35.40S</td>
<td>115.35E</td>
<td>241.38</td>
<td>−0.0074</td>
<td>0.0110</td>
</tr>
<tr>
<td>yarr</td>
<td>29.05S</td>
<td>115.35E</td>
<td>241.38</td>
<td>0.0359</td>
<td>−0.0800</td>
</tr>
</tbody>
</table>

Table 5
The statistical precision of the spherical harmonic model.

<table>
<thead>
<tr>
<th></th>
<th>Bias</th>
<th>RMS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>mean</td>
<td>max</td>
</tr>
<tr>
<td>Internal (325)</td>
<td>a</td>
<td>0.0000</td>
</tr>
<tr>
<td></td>
<td>b</td>
<td>0.0000</td>
</tr>
<tr>
<td>External (8)</td>
<td>a</td>
<td>0.0044</td>
</tr>
<tr>
<td></td>
<td>b</td>
<td>−0.0181</td>
</tr>
</tbody>
</table>

Yao et al. (2012) used the spherical harmonic method to model the global atmospheric weighted average temperature (GWMT model), which reduced the number of model parameters and met the precision requirements of water vapor inversion in GNSS meteorology. This illustrates that the spherical harmonic function has significant advantages and application potential in the characterization of spherical

Fig. 12. The global distribution of systematic difference coefficient a.

Fig. 13. The global distribution of systematic difference coefficient b.
physical parameters (Krueger et al., 2004). This paper adopts a similar idea to establish a spherical harmonic function model, in which the system differential coefficients $a$ and $b$ are expanded into a function of location according to formula (2).

$$a_i = \sum_{n=0}^{1} \sum_{m=0}^{n} P_n^m (\sin \varphi) \cdot [A_{nm}^i \cos (\lambda m) + B_{nm}^i \sin (\lambda m)] (i = 0, 1)$$ (2)

In the formula, $P_n^m$ is the Legendre polynomial, $\varphi$ and $\lambda$ are, respectively, latitude and longitude.

The systematic difference coefficients $a$ and $b$ of GGOS-ZTD are fitted by an 11-order 11-degree spherical harmonic function based on position (Longitude $\lambda$, Latitude $\varphi$), on the premise that accuracy requirements are met without introducing excess parameters. After solving the coefficients $A_{nm}^i$ and $B_{nm}^i$ by means of linear regression, the systematic difference coefficients $a$ and $b$ between the GGOS-ZTD and the IGS-ZTD can be calculated anywhere in the world, which can be applied to eliminate systematic differences in GGOS tropospheric delay correction.

In order to check the precision of spherical harmonic function, the spherical harmonic model is established by 325 stations, 8 IGS stations (4 in northern hemisphere and 4 in southern hemisphere) not included in the fitting are reference of external precision evaluation of $a$ (slope) and $b$ (intercept). The systematic difference coefficients $a$ and $b$ of these 8 stations are calculated by spherical harmonic model and then used to revise GGOS-ZTD at UTC 12:00 in DOY 10, 50, 100, 250.

The locations of 8 IGS stations and the bias of $a$ and $b$ between spherical harmonic function and linear fitting are presented in Table 4 as well. Besides, the systematic difference coefficients $a$ and $b$ at the 333 stations are inverse-calculated through spherical harmonics, which are compared with previous a and b values obtained from linear fitting, the statistical precision of mean bias and RMS of the spherical harmonic model are shown in Table 5. As shown in Table 5, whether stations included in the fitting or not, the RMS of systematic difference coefficients are small, which demonstrate accurate accuracy of spherical harmonic model. The resulting ZTD are expressed as GGOS-ZTD. The bias between GGOS-ZTD and IGS-ZTD are compared with the bias between GGOS-ZTD and IGS-ZTD. And the statistic results illustrated in Table 6. The results shows that the difference between GGOS-ZTD and IGS-ZTD are reduced with system correction. That the change is not obvious might because that these systematic difference coefficients $a$ and $b$ are fitting at from the scale of the year, the ZTD will also be affected by tropospheric condition at that moment.

To ensure as many modeling data as possible, systematic difference coefficients $a$ and $b$ of GGOS-ZTD are fitted by an 11-order 11-degree spherical harmonic function at 333 IGS stations in the actual process. The systematic difference coefficients $a$ and $b$ at the 333 stations are inverse-calculated through spherical harmonics, which are compared with previous a and b values obtained from linear fitting, as shown in Fig. 14. Statistical results of bias and RMS are shown in Table 7.

From Fig. 14 and Table 7, it can be seen that the difference coefficient of each station system calculated by the spherical harmonic model is in good agreement with the system difference coefficient obtained from linear fitting. The average bias of the proportional error and the fixed error are $-0.0041$ and $0.0096$, respectively, which are both negligible. The RMS values are $0.0329$ and $0.0715$, respectively, which indicate that the precision of the 11-order spherical harmonic model is considerably high and can be used in the system model error correction on a global scale.

4. Product application effect in real-time PPP

PPP is a key technology to realize global real-time precise positioning and navigation in the advanced research field of GNSS positioning. The application of the tropospheric delay model and products for real-time positioning is currently a research focus. This article attempts to use GGOS tropospheric delay prediction products for real-time PPP positioning to test its enhancement performance.

To inspect the effect of GGOS Atmosphere tropospheric delay forecast products on real-time positioning, GPS observations are processed on September 1st, 2015 of 165 IGS tracking stations shown in Fig. 15. The GGOS-ZTD with and without system error correction are processed on September 1st, 2015 of 165 IGS tracking stations shown in Fig. 15. The GGOS-ZTD with and without system error correction are calculated on an experimental station. The method to use various ZTD products in real-time PPP in this article is ZTD-constrained PPP referring to Y. Yao et al. (2017) (Yao et al., 2017), in which the zenith tropospheric delay parameter GGOS-ZTD is introduced as an virtual observation at each experiment period, with RMS as external constraints. During the test, the positioning results using GGOS-constrained PPP are compared with that using traditional PPP to analyze the application effects of GGOS tropospheric delay forecast products. ZTD-constrained PPP adds a virtual observation for ZTD and its corresponding constraint to the observation equation. If we use $n$ satellites and 1 receiver, observing equations and constraint equations are listed as formulas (3) and (4) (Yao et al., 2017).

$$\begin{bmatrix} \Delta p_l^1 \\ \Delta \phi_l^1 \\ \Delta p_c^1 \\ \Delta \phi_c^1 \\ \Delta ZT \end{bmatrix} = \begin{bmatrix} -\mu & I & M_{net} & R \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \Delta X \\ c_{\delta \tau \rho} \\ \Delta ZT_B \\ B_c \end{bmatrix} + \begin{bmatrix} \epsilon_{p_c} \\ \epsilon_{\phi_c} \\ \epsilon_{Q_c} \\ \epsilon_{ZT D} \end{bmatrix}, Q_{\delta \tau \rho}, Q_{ZT D}$$ (3)

$$\Delta ZT = ZT_{\delta \tau \rho} - ZT_{I} - ZT_{\delta \tau \rho}$$ (4)

where $\Delta p_l$ and $\Delta \phi_l$ denote the residual part of pseudo-range and phase observations of the ionosphere-free combination, respectively; $\Delta ZT$ denote the residual of tropospheric delay; The superscripts from 1 to n in the equation denote the satellite number; the left vector term denotes the ‘observed minus computed’ observations; $\mu$ is a matrix composed of the unit vectors between the receiver and the satellite; the corresponding to the station coordinates vector $\Delta X$; I is a matrix of $2 \times n$ rows and one column, of which each element is one, corresponding to the clock parameters $c_{\delta \tau \rho}$; vector R corresponds to the ambiguity parameters vector $B_c$; $M_{net}$ is a matrix composed of a wet projection function and
corresponds to parameter $\triangle Z_{TW}$; $\epsilon_{PC}$ and $\epsilon_{PC}$ denote pseudo-range and phase measurement noise, respectively; $\xi_{ZTD}$ denotes ZTD measurement noise; $Z_{Trvir}$ is ZTD virtual observation value, $Z_{TH}$ and $Z_{Tw}$ are modelled ZHD and ZWD, $\xi_{ZTD}$ is corresponding noise, $Q_{L}$ denotes the stochastic model of 'observed minus computed' observations; $Q_{ZTD}$ is stochastic model of $Z_{Trvir}$. In this study, $Z_{TH}$ and $Z_{Tw}$ are given by the empirical Saastamonien model, and the mapping function is the Niell Mapping Function (NMF; Niell, 1996).

PASSION software, which was developed by the authors' laboratory, was used to process the data in the PPP methods mentioned above. More details of the corresponding processing strategies are shown in Table 8.

**Fig. 14.** The comparison of systematic difference coefficients between linear fit and the spherical harmonic model in 333 IGS sites.

**Table 7**
The statistical precision of the spherical harmonic model.

<table>
<thead>
<tr>
<th>Bias</th>
<th>Mean</th>
<th>Max</th>
<th>Min</th>
<th>RMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>−0.0041</td>
<td>0.1146</td>
<td>−0.1414</td>
<td>0.0329</td>
</tr>
<tr>
<td>b</td>
<td>0.0096</td>
<td>0.3485</td>
<td>−0.2400</td>
<td>0.0715</td>
</tr>
</tbody>
</table>
The zenith tropospheric delay of four GGOS grid points around the IGS station at 00:00:00, September 1st, 2015 are acquired, and then calculated to the station location through exponential function height reduction and bilinear interpolation. Next, the systematic diurnal variation is calculated to the station location through exponential function height reduction followed by an assessment of the performance improvements by real-time PPP with GGOS products augmentation over the conventional troposphere estimation approach. The real-time precise point positioning is conducted with the tropospheric delay respectively corrected by GGOS-ZTD (GGOSS) with system difference correction, GGOS-ZTD without systematic difference correction and traditional-model-ZTD (tra).

4.2. Real-time precision point positioning result analysis

Fig. 16 demonstrates the east/north/up coordinate solutions with three troposphere strategies during 1 h after the initialization in UTC, 0:00, September 1, 2015 at adis, lpal, zamb and mdvj stations. The information about stations are illustrated in Table 9.

At the adis station, the convergence of the three tropospheric strategies in the E and N directions is consistent, and the positioning accuracy is equivalent in the horizontal orientation. conspicuous improvements can be detected in the U component rather than the horizontal component, where RMS accuracies using GGOS forecast products with or without systematic differences being rectified are satisfactory. However, without GGOS virtual observation, the coordinate solution fluctuates strongly between 0 and 15 min. After 15 min, the positioning accuracy still deviates from the other two strategies. Consequently, GGOS tropospheric forecasting products improve the positioning accuracy and convergence condition of the U direction at the adis station.

The situation at lpal station is different. With GGOS-ZTD constraints, the positioning results are better than the results without GGOS virtual observation, and not only in the U direction. The positioning precision is relatively higher in the horizontal E direction as well. The accuracy with two GGOS tropospheric correction strategies is consistently high. However, the positioning accuracy without GGOS tropospheric correction fluctuates significantly and deviates greatly in the E and U directions in the 0–30 min period. It is not until 45 min after initialization when its positioning result reaches the same as the other strategies. Generally, GGOS tropospheric delay forecast products significantly reduce the convergence time of real-time PPP models in different directions.

Similar to the lpal station, the precision of three tropospheric strategies at zamb station is consistent in the N direction. While in the E and U directions, the positioning results are most accurate when using GGOS tropospheric delay forecast products with systematic error rectification, and GGOS-ZTD positioning accuracy is equivalent with it. Nevertheless, traditional PPP's solution has larger error and fluctuates up and down, the height solution converged after 1 h, but only approximately 15 min are required with GGOS troposphere augmentation. In general, convergence time is shortened and positioning results are more stable and accurate when introducing GGOS forecasting products.

The coordinate solution results fluctuate wildly and convergence is slower at the mdvj station. The deviation of the traditional positioning solution is notable relative to the solution of GGOS-ZTD in all three directions in the 10–20 min period. After 20 min, the positioning accuracy in the E direction reaches agreement, while the results in the N and U directions are still less accurate. It is after 45 min that traditional PPP positioning results tend to be consistent with the other two strategies. Consequently, GGOS-ZTD greatly improves the positioning convergence in both the horizontal and elevation direction. The GGOS-ZTD caused a significant increase in convergence time at the majority of stations. The convergence time is shorter in adis and zamb station, less than 15 min. However, the convergence time in lpal station in E-direction reached approximately 20 min. While in mdvj station, both horizontal and vertical components were hard to converge into 10 cm in a short time. It is not until 40 min that the vertical positioning solution tend to be stable. Although the weather in four station is fair at that time, there were moderate rain at the following hours in lpal and mdvj station. The subsequent active tropospheric condition might have a negative impact on the precision of GGOS forecast product and the positioning results.

The two horizontal coordinate solutions with GGOS troposphere augmentation converge slightly faster than traditional PPP. And the convergence of the vertical solution is significantly improved using the GGOS ZTD forecasting products.

In Fig. 17, there are the horizontal and vertical average positioning
RMS accuracies of all 165 IGS tracking stations after 4 selected initialization periods, namely, 10, 20, 30 and 40 min. In the horizontal directions, the positioning precision using GGOS forecast products is better. A shorter initialization time of 10 min, however, does not bring significant improvements as the horizontal RMS accuracy differs slightly (i.e., 21.77 cm and 21.64 cm versus 21.63 cm). For the height solution, the RMS accuracy is improved from 25.5 cm without GGOS-ZTD to 19.24 cm and 19.32 cm with GGOS-ZTD and GGOS-ZTD with systematic difference correction, respectively, which is a much more significant improvement than the horizontal counterpart. After 40 min of initialization, the positioning accuracies of traditional strategy are 8.14 cm in the horizontal direction and 7.97 cm in the vertical direction. Whereas when GGOS-ZTD and GGOS-ZTD with systematic difference correction are applied, the RMS accuracies in different

![Fig. 16. Real-time PPP positioning solutions of station adis, draw, mdvj and zamb.](image)

Table 9

<table>
<thead>
<tr>
<th>IGS station</th>
<th>Latitude/°</th>
<th>Longitude/°</th>
<th>Elevation/m</th>
<th>Special features</th>
<th>Weather</th>
</tr>
</thead>
<tbody>
<tr>
<td>adis</td>
<td>9.03N</td>
<td>38.77E</td>
<td>2439.15</td>
<td>Ethiopia (high-elevation)</td>
<td>Cloudy</td>
</tr>
<tr>
<td>lpal</td>
<td>28.76N</td>
<td>17.89W</td>
<td>2207.00</td>
<td>Spain (high-elevation)</td>
<td>Cloudy</td>
</tr>
<tr>
<td>zamb</td>
<td>15.43S</td>
<td>28.31E</td>
<td>1324.91</td>
<td>Zambia (medium-elevation)</td>
<td>Cloudy</td>
</tr>
<tr>
<td>mdvj</td>
<td>56.02N</td>
<td>37.21E</td>
<td>257.40</td>
<td>Russia (low-elevation)</td>
<td>Sunny</td>
</tr>
</tbody>
</table>
directions are reduced to 6.44 cm, 5.76 cm and 6.81 cm, 5.75 cm, respectively. According to the statistics, GGOS forecasting products upgrade positioning precision to some degree.

In summary, GGOS troposphere forecasting products can augment real-time PPP in terms of positioning accuracy and convergence by eliminating the troposphere effects on the coordinate solution, especially in the U direction.

5. Conclusions

Compared with the global ZTD data published by IGS stations throughout the year 2016, this paper analyzes and evaluates the precision of the tropospheric delay forecast products developed by GGOS Atmosphere based on ECMWF data. The temporal and spatial distribution characteristics of bias and RMS are analyzed and the systematic differences between GGOS-ZTD and IGS-ZTD are modeled. In addition, the application performances in GNSS navigation and positioning are evaluated.

(1) Compared with the ZTD data released by IGS, the average bias, STD and RMS of GGOS Atmosphere ZTD are −0.57 cm, 1.63 cm and 1.83 cm, respectively, which indicates that the GGOS Atmosphere ZTD forecasting products are accurate enough to meet the needs of the users of GNSS real-time navigation for tropospheric delay correction and have broad applicability to tropospheric delay correction in space geodetic measurement technology.

(2) The seasonal variation characteristic of the bias and RMS of GGOS-ZTD are analyzed. The monthly average errors show an obvious seasonal feature with large values in summer and small ones in winter. Affected by the variable water vapor, the error of GGOS-ZTD forecast products in summer is relatively large.

(3) The bias of GGOS-ZTD relative to IGS-ZTD varies little with latitude. However, STD and RMS is small in high latitudes and equatorial areas and relatively large in middle and low latitudes. Moreover, bias appears to first increase and then decrease with increasing elevation, while the trend of RMS with elevation is not remarkable.

(4) There is a certain degree of distinction between GGOS and IGS data. The systematic difference coefficients a and b are modeled by spherical harmonic functions, and the inner precision of the model is proven to be considerably high.

(5) The geographical distribution characteristics of systematic difference coefficients a and b are evident. There is little change in the equatorial and high latitudes, where their values are close to 1 and 0, respectively. While the differences at the mid-latitudes and those at the sea-land interface are distinct. Furthermore, there is no obvious relationship between coefficients and elevation.

(6) The application performance of GGOS tropospheric delay forecasting products on GNSS positioning is favorable. GGOS forecasting products help eliminate the troposphere effects and accelerate PPP convergence compared with traditional PPP. The improvement is especially significant in the vertical direction.

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