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# Estimating Zenith Tropospheric Delay Based on GPT2w Model

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**ABSTRACT** To precisely and conveniently estimate zenith tropospheric delay (ZTD), troposphere refractivity is deduced through global pressure and temperature 2w (GPT2w) model and surface meteorology devices, ZTD is estimated based on integration of refractivity in the zenith direction. When surface meteorological measurements are absent, all parameters including surface meteorology and lapse rate are estimated by GPT2w. Validation is carried out using observed data in the year 2012 at 8 international GNSS service (IGS) stations. Results indicate that when surface meteorological parameters are available, the annual accuracy is improved by 27% than Saastamoinen model. Meanwhile, annual bias of the other scheme is decreased by 21% than the GPT2w+Saastamoinen model. For most stations, the bias shows seasonal characteristics, high elevation, high longitude and low latitude can bring less bias.

**INDEX TERMS** Zenith tropospheric delay (ZTD), GPT2w model, refractivity, meteorological parameters.

## I. INTRODUCTION

Tropospheric delay is well-known as one of the primary error sources in global navigation satellite system (GNSS) [1]. Different from the ionospheric delay, tropospheric delay cannot be eliminated by multi-frequency combination. More specifically, it varies from about 2m at the zenith to over 20m at lower elevation angle between receiver and satellite. As generally accepted, tropospheric delay can be mapped onto any direction through the zenith tropospheric delay (ZTD) and the corresponding mapping function. ZTD can be described as sum of the zenith hydrostatic delay (ZHD) and the zenith wet delay (ZWD) [2]. The former caused by dry-gas molecules is responsible for more than 90% of the whole delay, the latter due to distortions of water vapour shows a stronger variability both in the deterministic and turbulent part. Because of fickle water vapour, precisely estimating ZWD is very difficult.

To date, various ZTD models including Hopfield model and Saastamoinen model have been proposed. These two models must depend on in-situ meteorological parameters, when surface meteorological measurements are absent, they will become invalid [3]. ZTD can be expressed as the integral of tropospheric refractivity in the zenith direction, and refractivity can be deduced on the basis of tropospheric meteorology. Radiosonde is the primary operational instrument carried by a balloon, equipped with devices to measure pressure, temperature, humidity, etc., and provided with a radio transmitter for sending the information to the user. However, radiosonde is high cost and not available at any places. To precisely estimate ZTD without radiosonde, the key is to get the tropospheric refractivity at any height. Different from radiosonde, we can also calculate refractivity through some meteorological models. So far, the famous meteorological models include the University of New Brunswick (UNB) series and the Global Pressure and Temperature (GPT) series [4], [5].

UNB3m model is the advanced version of UNB series and has been widely adopted. It can effectively output five atmospheric parameters including pressure, temperature, water vapor pressure, temperature lapse rate, water vapor pressure height factor, and all these parameters vary with latitude and day of year. However, the resolution of UNB3m is 15°, and it does not take longitude into consideration. GPT2 model is based on 10 years (from 2001 to 2010) of monthly mean profiles for pressure, temperature and specific humidity. The outputs are pressure, temperature, the water vapor pressure and their lapse rate. Compared with GPT2 model which has the spatial resolution of $5^\circ \times 5^\circ$, GPT2w model adds the lapse rate of water vapor and the weighted mean temperature,

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the resolution is also improved as 1° × 1°. Reference [6] conducts GPT2w+Saastamoinen model for estimating ZTD over Asian area, this new model can estimate ZTD without surface meteorological measurements. However, according to this combination model, only pressure, temperature and water vapour pressure estimated by GPT2w model are provided for Saastamoinen model, meteorological lapse rate is still treated as constant.

In order to precisely and conveniently estimate ZTD, we can get meteorological lapse rate from GPT2w model, the in-situ meteorological parameters can be got through surface meteorological measurements. Once these measurements are not available, we can also retrieve meteorological parameters through GPT2w model. After we get the in-situ meteorological parameters and their vertical lapse rate, tropospheric refractivity can be deduced, then more accurate ZTD can be acquired. The chief advantages of our method are mainly focused on twofold. On the one hand, without dependence on radiosonde, tropospheric refractivity is estimated on the basis of more precise meteorological lapse rate. On the other hand, when surface meteorological measurements are not available, our model can also efficiently work.

The rest of this paper is organized as follows. Section 2 discusses some related models and the proposed model. In Section 3, new model is validated with IGS tropospheric delay data. Some conclusions are drawn in Section 4.

## II. METHODOLOGY AND MODELS

### A. CONVENTIONAL METHODS

Hopfield model and Saastamoinen model can estimate ZTD based on surface meteorology [7]–[9]. In Hopfield model, refractivity at any height can be given by

$$\begin{cases} N_{dh} = N_{d0}\left(\dfrac{h_d - h}{h_d - h_0}\right)^4 \\ N_{wh} = N_{w0}\left(\dfrac{h_w - h}{h_w - h_0}\right)^4 \end{cases} \tag{1}$$

where $h$ is the height above the sea level,$h_d$ the equivalent dry height, $h_w$ the equivalent wet height, $h_0$ the altitude corresponding to station. $N_{dh}$ and $N_{wh}$ refer to the hydrostatic and wet refractivity at height$h$, respectively. $N_{d0}$ and $N_{w0}$ stand for the hydrostatic and wet refractivity at earth surface, respectively. In Hopfield model, $N_{d0}$ and $N_{w0}$ can be calculated as [10]

$$\begin{cases} N_{d0} = 77.6\dfrac{P_0}{T_0} \\ N_{wh} = 3.73 \times 10^5 \dfrac{e_0}{T_0^2} \end{cases} \tag{2}$$

where $P_0$, $T_0$ and $e_0$ are the atmospheric pressure, temperature and water vapor pressure at the earth surface, respectively. Meanwhile, $h_d$ and $h_w$ can be given by

$$\begin{cases} h_d = 40136 + 148.72(T_0 - 273.16) \\ h_w = 11000 \end{cases} \tag{3}$$

ZTD can be expressed as the integration in the zenith direction, i.e.,

$$\begin{cases} Z_d = 10^{-6} \times \int_{h_0}^{h_h} N_{dh} dh = 1.552 \times 10^{-5} \times \dfrac{P_0}{T_0}(H_h - h_0) \\ Z_w = 10^{-6} \times \int_{h_0}^{h_w} N_{wh} dh = 7.465 \times 10^{-2} \times \dfrac{e_0}{T_0^2}(H_w - h_0) \end{cases} \tag{4}$$

where $Z_d$ refers to the ZHD, $Z_w$ the ZWD. According to Saastamoinen model, troposphere can be divided as two layers. The first is from the earth surface to 10km height, during in which the lapse rate of temperature is 6.5°C/km. The second is from the 10km height to the stratospheric top at 70km, during in which the temperature keeps constant. Therefore, during atmospheric refraction integral, the refractive index function can be expanded according to the zenith distance trigonometric functions and termwise integrated. ZTD can be finally given by [11], [12]

$$\begin{cases} Z_d = 0.002277 \times \dfrac{P_0}{f(\varphi, h_0)} \\ Z_w = 0.002277 \times \dfrac{e_0}{f(\varphi, h_0)}(\dfrac{1255}{T_0} + 0.05) \\ f(\varphi, h_0) = 1 - 0.00266\cos(2\varphi) - 0.00028h_0 \end{cases} \tag{5}$$

where $\phi$ is the latitude of the observer position. Through analyzing Hopfield model and Saastamoinen model, we can get the conclusion that tropospheric refractivity decides ZTD, and the meteorological lapse rate in these models is unreasonable.

### B. METHOD WITHOUT METEOROLOGICAL MEASUREMENTS

To get rid of meteorological measurements, [6] has proposed the ZTD model, in which meteorological parameters and ZTD are estimated by GPT2w and Saastamoinen model. GPT2w model can calculate $r(t)$ as [4], [5], [13]

$$r(t) = A_0 + A_1\cos\left(\frac{\text{doy}}{365.25}2\pi\right) + B_1\sin\left(\frac{\text{doy}}{365.25}2\pi\right) + A_2\cos\left(\frac{\text{doy}}{365.25}4\pi\right) + B_2\left(\frac{\text{doy}}{365.25}4\pi\right) \tag{6}$$

where doy is the day of year. Values of $A_0$, $A_1$, $B_1$, $A_2$ and $B_2$ are saved as an ASCII-file, which can be downloaded at *http://ggosatm.hg.tuwien.ac.at/DELAY/SOURCE/.* Inputs of GPT2w model are ellipsoidal coordinates (latitude, longitude and height) of the site and the modified Julian date. The outputs are values of pressure $p$, temperature $T$ and its lapse rate $dT$, specific humidity $Q$ and lapse rate of water vapor pressure $.\lambda$. The water vapor pressure $e$ can be deduced through $P$ and $Q$, i.e.,

$$e = \frac{Q \cdot P}{(0.622 + 0.378Q)} \tag{7}$$

The underlying routine evaluates (6) at four grid points surrounding the target location before extrapolating the output data vertically to the desired height and interpolating parameters from four points to the observational site in horizontal direction. The correction of the pressure, temperature and water vapor pressure for the height difference between the station and grid can be carried out as (2) in [6]. For the model proposed in [6], meteorological lapse rate is still unreasonable, which can deteriorate the accuracy.

### C. PROPOSED METHOD

Same as (4), ZTD can be expressed as the refraction integral in the zenith direction, and tropospheric refractivity at $h$ can be estimated as

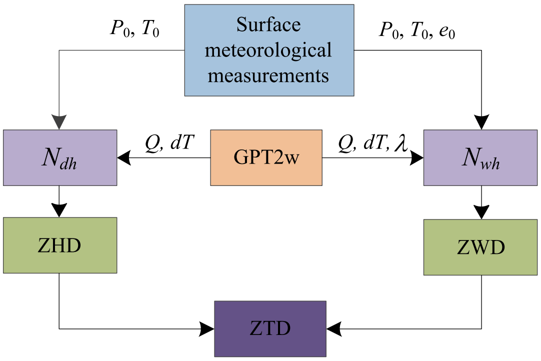
$$\begin{cases} N_{dh} = k_1 \dfrac{P_h}{T_h} \\ N_{wh} = (k_2 - k_1)\dfrac{e_h}{T_h} + k_3 \dfrac{e_h}{T_h^2} \end{cases} \tag{8}$$

where $k_1 = 77.604\text{K/Pa}$, $k_2 = 64.79\text{K/Pa}$, $k_3 = 377600\text{K}^2/\text{Pa}$. $P_h$, $T_h$, $e_h$ in (8) can be acquired through two ways. One is the radiosonde carried by a balloon, and the other is based on surface meteorological parameters and their lapse rate. We can easily measure surface meteorological parameters, but estimating lapse rate also depends on radiosonde. Similar to [6], we can also get the lapse rate based on GPT2w model. After we get the in-situ meteorological parameters including $T_0$, $P_0$, $e_0$, $dT$ and $\lambda$, we can acquire meteorological parameters at any altitude, i.e.,

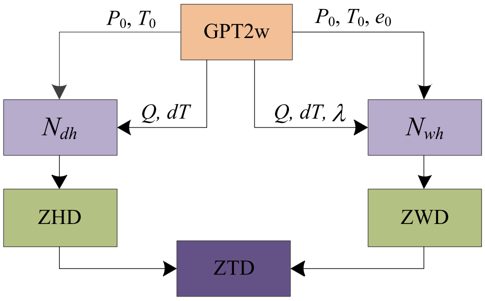
$$\begin{cases} T_h = T_0 + dT \cdot dh \\ P_h = P_0 \cdot \exp\{-g_m \cdot dM_{tr} / \\ \qquad [R_g \cdot T_0 \cdot (1 + 0.6077Q)] \cdot dh\}/100 \\ e_h = e_0 \cdot (100 \cdot P/P_0) \wedge (\lambda + 1) \end{cases} \tag{9}$$

where $T_h$, $P_h$ and $e_h$refer to the temperature, pressure and water vapor pressure at $h$ height above the sea level, respectively, $dM_{tr} = 0.028965\text{kg/mol}$, $R_g = 8.3143\,\text{J/K/mol}$, $g_m = 9.80665\text{m/s}^2$. As above, lapse rate can be estimated by GPT2w model, related devices measure surface meteorology, meteorology parameter at $h$ height can be further estimated, then tropospheric refractivity can be deduced according to (8). Based on refractivity, ZTD is finally estimated, we name this way as model A. Once surface meteorological measurements are absent, $T_0$, $P_0$ and $e_0$ can also be precisely acquired by GPT2w, which is named as model B. Fig. 1 shows the concrete principle of new model.

The parameters in Fig. 1 are same as above, $P_0$, $T_0$ and $e_0$ denote the surface meteorology, $dT$ the lapse rate of temperature, $Q$ the specific humidity, .$\lambda$ the lapse rate of water vapor pressure. $N_{dh}$ and $N_{wh}$ refer to the hydrostatic and wet refractivity at height$h$, respectively. As shown in Fig. 1(a), surface meteorological parameters including temperature, pressure and water vapor pressure can be measured by some devices, and GPT2w can output their vertical lapse rate. Based on surface meteorological parameters and their lapse rate, tropospheric refractivity can be deduced, then ZHD and ZWD can be expressed as integration of refractivity in the zenith direction. As shown in Fig. 1(b), if related devices are not available, GPT2w can also output surface meteorological parameters. Different from conventional ZTD methods, meteorological lapse rate employed by our method is estimated by GPT2w, rather than constant. Because radiosonde is not employed, our proposed models can conveniently estimate ZTD.



(a) Model A, surface meteorological measurements are available



(b) Model B, surface meteorological measurements are absent

**FIGURE 1.** Principle of two new models.

**TABLE 1.** Information of stations.

| Stations | longitude /° | latitude /° | Height/m |
|---|---|---|---|
| BJFS | 115.88 | 39.60 | 98.3 |
| XIAN | 108.98 | 34.17 | 509.1 |
| SHAO | 121.20 | 31.92 | 22.00 |
| LHAS | 91.10 | 29.63 | 3622.0 |
| TWTF | 121.16 | 24.95 | 203.1 |
| KUNM | 102.80 | 25.03 | 2019.0 |
| URUM | 87.61 | 43.81 | 858.8 |
| WUHN | 114.35 | 30.52 | 25.8 |

## III. VALIDATION WITH IGS TROPOSPHERIC DELAY DATA

### A. MONTHLY BIAS

International GPS service (IGS) has provided final troposphere products and surface meteorology since 1998. ZTD products are very precise with small uncertainties and can be treated as true values. Eight IGS stations located respectively in eastern, western, southern and northern China are selected to validate the proposed models. The concrete information can be seen in Table I. Fig. 2 shows the comparisons between IGS-ZTD and model-ZTD over the year 2012 at the station XIAN, BJFS, TWTF and LHAS. It is obvious that the ZTD values of station LHAS are obviously least. This may be due to high height of LHAS, which leads to low atmospheric pressure and water pressure. Because GPT2w can

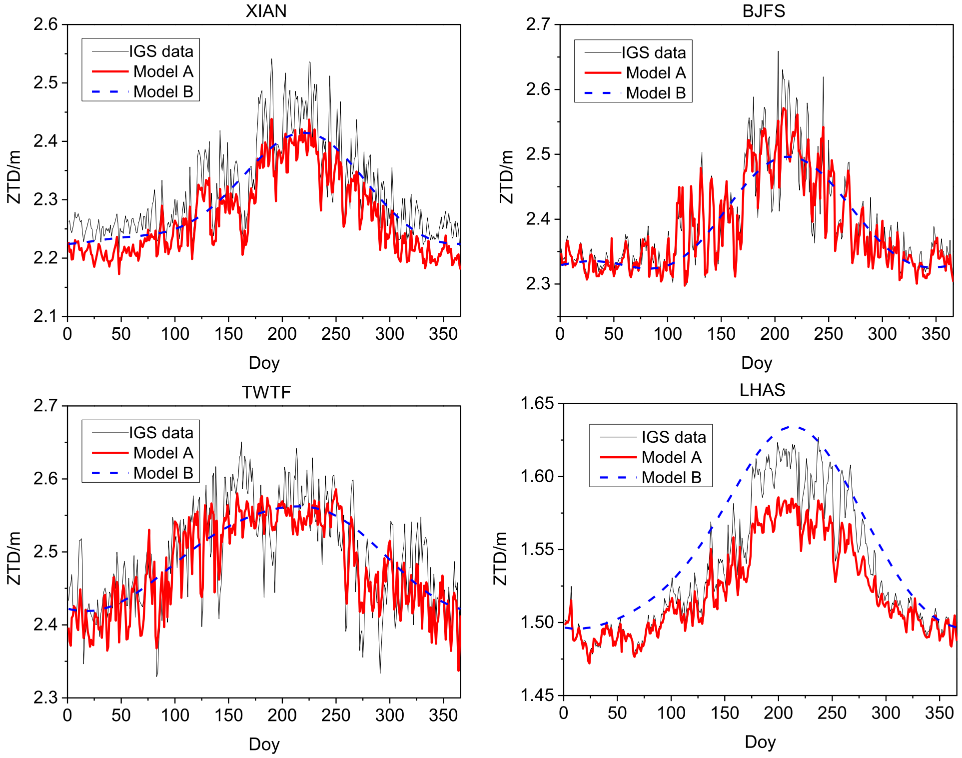


**FIGURE 2.** ZTD of different models at four stations.

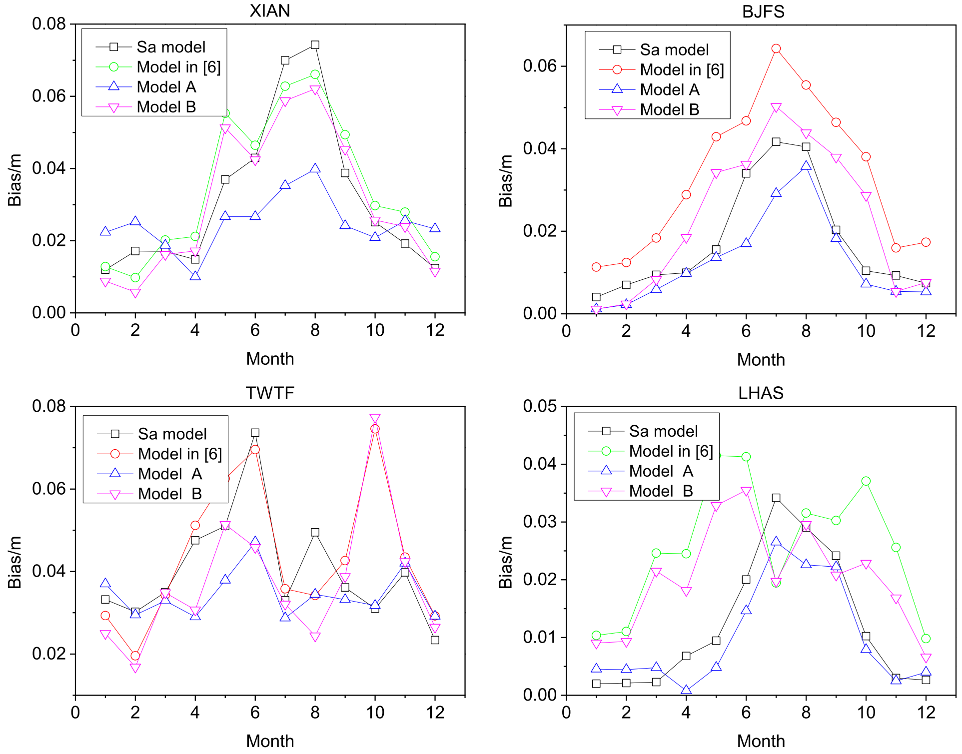


**FIGURE 3.** The monthly bias of different models at four stations.

only describe general trend of surface meteorology, model B is more smooth than model A.

In general, the meteorology during each season vary largely, to conduct further analysis of the four models with the change of time, especially the change caused by seasonal factors, the data of year 2012 are selected as the sample, and the bias of each month is analyzed. The statistical results are shown in Fig. 3, similar Saastamoinen model and model in [6]

**TABLE 2.** Annual bias of different models (units: cm).

| Stations | Sa model | Model A | Model in [6] | Model B |
|---|---|---|---|---|
| BJFS | 1.74 | 1.25 | 3.32 | 2.28 |
| XIAN | 3.14 | 2.48 | 3.48 | 3.07 |
| SHAO | 3.63 | 3.28 | 4.98 | 3.66 |
| LHAS | 1.22 | 1.16 | 2.56 | 2.02 |
| TWTF | 4.03 | 3.44 | 4.39 | 3.72 |
| KUNM | 2.17 | 1.30 | 3.09 | 2.09 |
| URUM | 1.77 | 1.04 | 2.53 | 1.51 |
| WUHN | 4.22 | 3.39 | 5.16 | 4.20 |
| Mean | 2.74 | 2.15 | 3.57 | 2.81 |

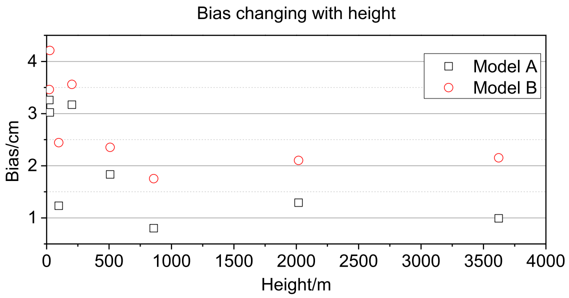


**FIGURE 4.** Annual bias (stations sorted by height increasing).

are employed as reference. As shown in Fig. 3, four models have obvious seasonal features, the bias in summer are larger while that in winter are smaller. High water vapor pressure in summer leads to this consequence. Because water vapor pressure in winter is low, the values of ZWD are relatively small, accuracy of traditional ZTD models increases, for some months during this time, the bias of different models is similar, and the proposed two approaches may even perform worse than the existing approaches. It has been noted that the seasonal variation of ZTD depends on latitude, mainly due to season variation, for some areas with low latitude in China, the meteorology has weak seasonal variations.

### *B. YEARLY BIAS*

The ZTD values of 8 IGS stations in China are calculated, Table II shows the annual bias of four models. As Table II, for the total stations involved in the validation, the mean bias of model A is 2.15 cm, better than the Saastamoinen model. Annual bias for the model B is 2.81 cm, which are better than that for the GPT2w+S model proposed in [6]. Annual bias of the proposed two schemes is decreased by 27% and 21% than the similar models, respectively.

### *C. SPATIAL CHARACTERISTICS OF BIAS*

The altitude and longitude fluctuations in China area vary largely, the spatial distribution of annual average bias is analyzed, which is carried on three aspects: height distribution, longitude and latitude distribution. The distribution characteristics of bias in height and latitude /longitude at an annual average are shown in Fig. 4 and 5.

Because annual bias for all the four ZTD models has already been list in Table II, Fig. 4 and 5 only display tendency of our approaches. As shown in those figures, bias values vary with height, with magnitude appearing larger at low elevation, smaller at high elevation. This coincides with the actual phenomenon that high areas, decreasing humidity and low temperature can lead to very few ZTD variations. As height increasing, the air gets thicker and thicker, so atmospheric pressure decreases with increasing altitude at a decreasing rate. For China area, with latitude decrasing or longitude inceasing, the air turns to be much wetter, bias is more obvious.

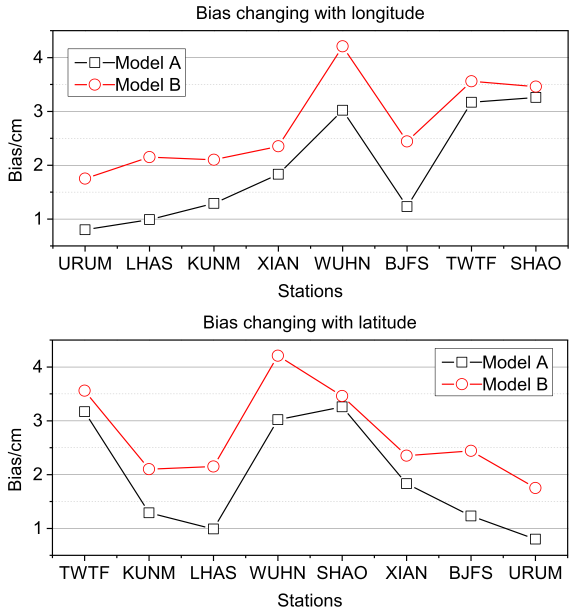


**FIGURE 5.** Annual bias (stations sorted by longitude/latitude increasing).

## IV. CONCLUSION

In this paper, for precisely and conveniently estimating ZTD, new models based on tropospheric refractivity are proposed. Refractivity is deduced on the basis of surface meteorology and their vertical lapse rate, to get rid of the dependence on radiosonde, GPT2w model is employed. Comprehensive tests are conducted, consequences show that when surface meteorology is measured by related devices, GPT2w model estimates their lapse rate, the annual bias is 2.15 cm, which is better than Saastamoinen model and can satisfy the need of tropospheric delay correction for real-time navigation and position in satellite system. The annual bias for the model in which all meteorology parameters are estimated by GPT2w are 2.81 cm, which are better than GPT2w+Saastamoinen model. For the most stations, the bias shows seasonal characteristics. And there is a decreasing tendency for the estimation bias with the increasing latitude and height of station, as well the decreasing longitude. Because radiosonde is not employed, our proposed models can conveniently work.

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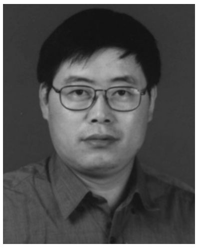

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