

A Comprehensive Evaluation and Analysis of the Performance of Multiple Tropospheric Models in China Region

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Abstract—Tropospheric path delay is an important error source in range measurements of many Earth observation systems. In this paper, the accuracy of 9 zenith hydrostatic delay (ZHD) and 18 zenith wet delay (ZWD) models are assessed using benchmark values derived from 10 years (2003-2012) of radiosonde data recorded at 92 stations in China region. Our study confirms that ZHD can be well modeled with an accuracy of several millimeters by using surface meteorological observations. ZHD derived from the European Center for Medium-Range Weather Forecasts (ECMWF) has the best agreement of 2.8 mm with the radiosonde data in China region, while the Baby ZHD model achieves the second-best with an accuracy of 6.0 mm. All the ZWD models can only estimate the ZWD with an accuracy of a few centimeters. ECMWF can provide ZWD estimation with the best accuracy of 21.4 mm, followed by the Baby semi-empirical, Hopfield, Goad and Goodman, Askne and Nordius, Saastamoinen, Callahan, and Berman 74 ZWD models whose errors are below 40 mm. We find that in China region all the ZWD models perform better in winter than in summer and have higher accuracy in high latitudes than low latitudes. The performance of the 18 ZWD models are further validated in a Global Positioning System (GPS) precise point positioning (PPP) computation at 6 GPS stations in China. The PPP results also confirm that ECMWF is the best model. Considering its performance and simplicity, we conclude that Saastamoinen is the optimal ZWD model for the China region.

Index Terms—Performance evaluation, Radiosonde, Tropospheric delay, ZHD (Zenith hydrostatic delay) model, ZWD (Zenith wet delay) model

I. INTRODUCTION

The presence of terrestrial atmosphere can cause path delays to radio signals as they transmit from satellites or quasars to the surface of the Earth. Tropospheric delay is a major error source in many space geodetic techniques such as the very long base interferometry (VLBI), satellite altimetry, satellite laser ranging (SLR), interferometric synthetic aperture radar (InSAR) and global navigation satellite system (GNSS) [1]–

[8]. Tropospheric path delay, commonly reaching a value of 2.3 meter in the zenith, can be divided into two parts: a hydrostatic component and a wet component [9]. The hydrostatic delay is induced by dry gases of the air and accounts for more than 90% of the total tropospheric delay [9]. The wet delay is due to water vapor in the atmosphere and usually contributes less than 10% of the total tropospheric delay [9].

To achieve a high level of observation accuracy using these geodetic techniques, the tropospheric delay must be compensated properly. Over the past a few decades, many empirical tropospheric models have been developed to estimate tropospheric hydrostatic and wet delays [9]–[11]. These models provide a convenient and effective way to correct tropospheric delays and have been widely used in many geodetic techniques such as GNSS positioning and InSAR [1], [11]. Compared to the hydrostatic delay, it is more difficult to model the wet delay because of the high variability of water vapor in both spatial and temporal domains [1], [9], [12], [13].

The availability of a large number of tropospheric models offers users great flexibility of choice in their applications. However a practical problem is that which model is the most accurate or suitable one under a particular observation environment. For different applications, the observation environments including user geographical location, altitude of observation site, the type of applications (real-time or post-mission), observation season/time, availability of auxiliary data such as temperature, pressure, and relative humidity, may vary significantly. The atmospheric properties, particularly the water vapor that is a primary contributor to wet delay, vary considerably from location to location [14]. For different applications, the requirements for tropospheric models are different too. In satellite altimetry, altimetry measurements are required to have an accuracy of a few (1–3) centimeters in order to monitor the ocean dynamics [15], [16]. In GNSS meteorology, the accuracy of hydrostatic model is the most important consideration since the precipitable water vapor (PWV) directly depends on the performance of hydrostatic model. In some GNSS applications where meter-level accuracy is acceptable, the users may be more concerned with the time than the accuracy. Thus the convenience of using a tropospheric model is more important than its accuracy.

The straightforward way to correct the tropospheric effect in range observations is to use a tropospheric model in combination with necessary meteorological data that are

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obtained from ground observations or from other models [17]. Accuracy of cm-level is achievable if proper tropospheric model is selected [18]. However an improperly selected tropospheric model may severely degrade the performance of tropospheric delay compensation. It is thus necessary to comprehensively and systematically investigate the performance of each tropospheric model under various conditions before it is employed in practice.

A lot of studies have been conducted to evaluate the performance of different tropospheric models. Janes et al. evaluated two hydrostatic delay models and six wet delay models based on benchmark values derived from the US Standard Atmosphere and the US Standard Atmosphere Supplements [19]. By using one-year's radiosonde data from 50 globally distributed stations, Mendes systematically assessed the performance of 4 hydrostatic delay models and 12 wet delay models [9]. In that research, it was found that the Saastamoinen model has the best global accuracy in the estimation of both hydrostatic and wet troposphere delays. Li et al. conducted a systematic research on the zenith tropospheric delay with 3-year radiosonde data recorded at one station in Hong Kong [11]. Research results showed that the Askne and Nordius model performed best and the Saastamoinen model achieved a relatively poor accuracy in Hong Kong region. Qu et al. compared the tropospheric delay corrections derived from Saastamoinen, Hopfield, and EGNOS models with zenith tropospheric delay data obtained from 36 globally distributed International GNSS Service (IGS) stations and they indicated that EGNOS model can be applied in GNSS real-time positioning and navigation [20]. Dodo and Idowu assessed the performance of three tropospheric delay models for African GNSS network and they found that the refined Saastamoinen model performed better than the modified Hopfield and Neill model [21]. Recently, Tuka and El-Mowafy conducted a study to compare the performance of several hydrostatic delay and wet delay models at six selected IGS stations [22]. In their comparison, they used the Saastamoinen model as reference and indicated that all of the models employed in their study could achieve better performance at mid-latitude regions than at the equator.

China has a massive GNSS market and is progressively developing the Chinese BeiDou Navigation Satellite System (BDS) [23]. With the rapid progress of the BDS, the number of GPS and BDS users is growing significantly. One typical example is the extraordinarily large number of GNSS-enabled smartphone users in China. It is expected that the GNSS users (including BDS users) will continue to grow in the next years. However, over the years no study has been conducted to comprehensively evaluate the performance of different tropospheric models for the China region. Some of the work discussed above focused on local applications (e.g. [11], [21]) but not China region. Global performance evaluation of different tropospheric models has been conducted (e.g. [9], [22]). However, the China region was not a focus in those studies. The massive GNSS user market and the large landmass covering various climate zones in China demand an investigation of which tropospheric model can provide the most

accurate corrections. Furthermore, more and more GNSS meteorology applications are being developed in China [24]–[26], in which precise tropospheric hydrostatic modeling is needed in order to retrieve water vapor data precisely. Identifying the most precise hydrostatic model is thus also very valuable for China region.

This study presents a comprehensive evaluation of the performance of 9 hydrostatic and 18 wet delay models with respect to reference hydrostatic and wet delays, respectively. The reference delays are derived from radiosonde data collected at 92 stations in China over a 10-year period from 2003-2012. In addition to the overall performance, we also assess their temporal performance in different seasons and spatial performance at various latitude zones. In order to validate the performance of the tropospheric models through a real-world application, a further study is carried out to apply these models in a kinematic GPS precise point positioning (PPP) application. This is achieved by utilizing the tropospheric models to correct tropospheric delay of GPS data in the PPP computation. The work presented in this paper will provide valuable references for many users and applications of the tropospheric models, particularly for the massive GNSS users and manufacturers in China.

This paper is structured as follows. In section II, we will introduce the method to derive hydrostatic and wet delays from radiosonde data. Section III describes 9 hydrostatic and 18 wet delay models to be studied in this work. An introduction of the radiosonde measurement and its accuracy analysis is presented in section IV. The performance of the tropospheric models with respect to radiosonde data and in kinematic PPP are discussed in section V. Conclusions and final remarks are given in section VI.

II. THEORETICAL BACKGROUND FOR TROPOSPHERIC DELAY

In the zenith direction, the total tropospheric delay can be expressed as [27]:

$$\Delta L = 10^{-6} \int_H^{\infty} N \cdot d_z \quad (1)$$

where ΔL is the total tropospheric delay (unit: m); H is the height of observation station over mean sea level (unit: m); N is the atmospheric refractivity (unitless) that can be modeled as below [28]:

$$N = k_1 \cdot \frac{P_d}{T} + k_2 \cdot \frac{e}{T} + k_3 \cdot \frac{e}{T^2} \quad (2)$$

where P_d and e are the dry air and water vapor partial pressures (unit: hPa), respectively; T is the temperature (unit: K); k_1 , k_2 , and k_3 are refractivity constants and their values used in this study are listed in Table I. The water vapor partial pressure e can be derived as below [29], [30]:

$$e = 6.1121(1.0007 + 3.46 \times 10^{-6} \cdot P) \cdot RH \cdot \exp \left\{ \frac{[18.729 - (T - 273.15)/227.3](T - 273.15)}{T - 15.28} \right\} \quad (3)$$

where P is the total pressure (unit: hPa); RH is relative humidity (unitless).

TABLE I
REFRACTIVITY CONSTANTS (FROM RÜEGER 2002 [31])

k_1 (K/hPa)	k_2 (K/hPa)	k_3 (K ² /hPa)
77.6890	71.2952	375463

Using the equation of state, we can expressed the air density ρ as [9]:

$$\rho = \frac{P_d}{T \cdot R_d} + \frac{e}{T \cdot R_w} \quad (4)$$

where P_d , T and e have been defined in (2); $R_d=287.053 \text{ J} \cdot \text{K}^{-1} \cdot \text{kg}^{-1}$ and $R_w=461.495 \text{ J} \cdot \text{K}^{-1} \cdot \text{kg}^{-1}$ are the gas constants for dry air and water vapor, respectively. The hydrostatic refractivity N_h can be calculated as:

$$N_h = k_1 R_d \rho \quad (5)$$

Considering (2), (4), and (5), we derived the wet refractivity N_w

$$N_w = \left(k_2 - k_1 \frac{R_d}{R_w} \right) \cdot \frac{e}{T} + k_3 \frac{e}{T^2} \quad (6)$$

Substituting (5) and (6) into (1), we get

$$\Delta L = 10^{-6} \int_H^\infty N_h \cdot d_z + 10^{-6} \int_H^\infty N_w \cdot d_z \quad (7)$$

The first term on the right-hand side of (7) is termed tropospheric hydrostatic delay. The last term in (7) is known as tropospheric non-hydrostatic delay. For the sake of convenience, we use the term “wet delay” to substitute the “non-hydrostatic delay” although this term is not very precise as the hydrostatic delay also contains a small contribution from the wet delay. In this study, the reference values for both hydrostatic and wet delays are obtained from radiosonde data. They are used as benchmark to evaluate the performance of various tropospheric hydrostatic and wet models. The radiosonde sensors can measure several meteorological parameters such as the pressure, temperature, and relative humidity. Taking the characteristic of exponential decreasing of the atmospheric refractivity into account, the formulas for zenith hydrostatic and wet delays from the radiosonde measurements can be derived:

$$\Delta L_h = 10^{-6} \sum_i \left[(H_i - H_{i+1}) (N_{h_{i+1}} - N_{h_i}) / (\ln N_{h_i} - \ln N_{h_{i+1}}) \right] \quad (8)$$

$$\Delta L_w = 10^{-6} \sum_i \left[(H_i - H_{i+1}) (N_{w_{i+1}} - N_{w_i}) / (\ln N_{w_i} - \ln N_{w_{i+1}}) \right] \quad (9)$$

where ΔL_h and ΔL_w are the zenith hydrostatic delay (ZHD) and zenith wet delay (ZWD) (unit: m), respectively; H_i denotes the height of a given layer i (unit: m). N_{h_i} and N_{w_i} are the hydrostatic and wet refractivity at a given layer i , respectively.

III. DESCRIPTIONS OF TROPOSPHERIC HYDROSTATIC AND WET MODELS

Several studies have shown that the calculation formula for the hydrostatic delay is theoretically derivable based on the assumption that the air is an ideal gas and that the troposphere satisfies the hydrostatic equilibrium [27], [32], [33]. The ZHD can be calculated by:

$$\Delta L_h = 10^{-6} k_1 R_d \frac{P_s}{g_m} \quad (10)$$

where k_1 and R_d have been defined in (2) and (4), respectively; P_s is the atmospheric pressure at the surface (unit: hPa); g_m is the gravity acceleration at the centroid of the vertical atmosphere column (unit: $\text{m} \cdot \text{s}^{-2}$). Substituting the gas constant $R_d=287.053 \text{ J} \cdot \text{K}^{-1} \cdot \text{kg}^{-1}$ and the constant k_1 given in Table I into (10), we can rewrite the ZHD as

$$\Delta L_h = 0.0223009 \cdot \frac{P_s}{g_m} \quad (11)$$

It can be noted that the hydrostatic delay is a function of surface pressure P_s and the gravity acceleration g_m . The surface pressure can be measured by using barometer with a high accuracy. Thus, most of ZHD models mainly focus on the accurate modeling of gravity acceleration g_m .

Meanwhile, a large number of tropospheric wet delay models have also been developed in past decades. ZHD can be modeled with a reasonably good accuracy using surface meteorological data (to be shown in section V), nevertheless the ZWD is often difficult to be modeled accurately even using surface meteorological parameters [9]. This is attributed to the nature of atmospheric water vapor that is highly variable in both space and time domains. Because of this, a comprehensive evaluation of the performance of ZWD models becomes even more crucial than the ZHD models. In the following sections, the 9 ZHD and 18 ZWD models to be evaluated in this study are described. From section III(A) to III(H), the models can be used to calculate ZHD and ZWD. However, models described in sections III(I) to III(M) can only be used to compute ZWD. Please note that in some sections, more than one model is described.

A. Saastamoinen Model

For the ZHD calculation formula in (11), Saastamoinen found that the g_m can be approximately determined using the expressions as follows [32],

$$g_m = 9.784 \cdot f(\varphi, H) \quad (12)$$

$$f(\varphi, H) = 1 - 0.0026 \cdot \cos(2\varphi) - 2.8 \times 10^{-7} \cdot H \quad (13)$$

where φ is the station latitude (unit: radian) and H is the height of the station above sea level (unit: m). Equation (11) can be rewritten by considering (12) and (13)

$$\Delta L_h = 0.0022793 \cdot \frac{P_s}{f(\varphi, H)} \quad (14)$$

In the derivation of the ZWD model, Saastamoinen assumed that the variation of water vapor pressure e can be described by the following expression [34]:

$$e = e_s \cdot \left(\frac{T}{T_s} \right)^{\frac{v \cdot g}{R_d \cdot \alpha}} \quad (15)$$

where e_s is the water vapor pressure at the surface level (unit: hPa); T is the temperature (unit: K); T_s is the surface temperature (unit: K); v is a numerical coefficient to be determined from local observations (unitless); g is gravity acceleration (unit: $\text{m} \cdot \text{s}^{-2}$); R_d is the same defined in (4); α refers to the temperature lapse rate (unit: K/km) with a standard temperature lapse rate of 6.5 K/km. Combining (15) and (6) and integrating with respect height, the Saastamoinen ZWD model is obtained:

$$\Delta L_w = 0.002277 \cdot \left(\frac{1255}{T_s} + 0.05 \right) \cdot e_s \quad (16)$$

B. Baby Model

Considering that gravity acceleration decreases with altitude, Baby et al. derived the g_m as below [35]:

$$g_m = \frac{g_s}{1 + 2T_s/[r_s \alpha (\mu + 1)]} \quad (17)$$

where g_s is the surface gravity acceleration at the station (unit: $\text{m} \cdot \text{s}^{-2}$); T_s is the surface temperature (unit: K); r_s is the distance from the center of the earth to station (unit: m); α has been

defined in (15). μ is calculated using the following expression [35]:

$$\mu = \frac{g_s r_s}{R_d(r_s \alpha - 2T_s)} \quad (18)$$

Integrating equations (11), (17), and (18), we can obtain:

$$\Delta L_h = 0.0223009 \frac{P_s}{g_s} \cdot \left[1 + \frac{2T_s R_d(r_s \alpha - 2T_s)}{r_s \alpha [g_s r_s + R_d(r_s \alpha - 2T_s)]} \right] \quad (19)$$

For the ZWD model, Baby et al. assumed that the relative humidity RH is constant up to a height H_m where it decreases to zero [35]. Based on this assumption, the saturation water vapor pressure P_{wvs} is expressed in the following form [35]:

$$P_{wvs} = \exp \left(A - \frac{B(T)}{T} \right) \quad (20)$$

where A and B are coefficients. They obtained that $A=21.3195$ and $B(T)=5327.1157$ when $T > 273.15^\circ \text{ K}$, and $A=24.3702$ and $B(T)=6162.3496$ when $T \leq 273.15^\circ \text{ K}$. Assuming that the temperature T decreases with height at a constant rate α , Baby et al. obtained the following close-form formula for the ΔL_w [35]

$$\Delta L_w = 3.81 \cdot \frac{RH}{\alpha} \cdot \left[\frac{P_{wvs}(T_s)}{B(T_s)} - \frac{P_{wvs}(T_m)}{B(T_m)} \right] \quad (21)$$

where $B(T_s)$ is the value of B corresponding to temperature measured at ground surface, denoted as T_s ; $B(T_m)$ is the value of B corresponding to temperature at height H_m , denoted as T_m .

Baby et al. also proposed a semi-empirical model for the wet delay to replace the theoretical model given above. This semi-empirical model is suitable for regions where water vapor experiences larger variations [35]. The general expression for the semi-empirical model of the wet delay is

$$\Delta L_w = v \cdot 10^{\gamma(T_s - 273.15)} \cdot RH \quad (22)$$

where v and γ are empirical coefficients that could be estimated using local meteorological observations.

C. Hopfield Model

Hopfield developed another strategy to derive the theoretical formula for hydrostatic delay calculation [36]. In this model, the hydrostatic refractivity profile was assumed to be expressed by the quartic function of height [36]:

$$N_h = N_{hs} \left(\frac{H_d - H}{H_d} \right)^4 \quad (23)$$

where N_{hs} is the hydrostatic refractivity at the surface level (unitless); H_d (unit: m) represents the equivalent height which is defined as the height above the station where the hydrostatic refractivity is zero. Substituting (23) into (1) and integrating with respect to height, we can obtain:

$$\Delta L_h = 10^{-6} \cdot N_{hs} \cdot \frac{H_d}{5} \quad (24)$$

Hopfield demonstrated that the equivalent height H_d is a linear function of surface temperature T_s [37]. The coefficients between H_d and T_s can be fitted using local meteorological data provided by radiosonde.

Hopfield also assumed that the wet refractivity profile follows the quartic distribution [36], [37]. Following the same approach that is utilized to derive the ZHD, Hopfield got the ZWD expression [36], [37]:

$$\Delta L_w = 10^{-6} \cdot N_{ws} \cdot \frac{H_w}{5} \quad (25)$$

where N_{ws} represents the surface wet refractivity (unitless); H_w (unit: m) is the wet equivalent height at which the wet

refractivity is zero and the definitions of other variables are same as before.

D. Black Model

Based on the Hopfield model, Black developed a more convenient method in the integration of the refractivity, the simple analytical form for the ZHD is [38]:

$$\Delta L_h = 2.315 \times 10^{-3} P_s \cdot \frac{T_s - 4.12}{T_s} \quad (26)$$

Considering the fact that it is difficult to model the variation of atmospheric water vapor with respect to height, Black simply recommended several ZWD correction values under different conditions [38]. He recommended $\Delta L_w = 0.28 \text{ m}$ for summer in tropic or mid-latitude regions; $\Delta L_w = 0.20 \text{ m}$ for spring or autumn in mid-latitudes; $\Delta L_w = 0.12 \text{ m}$ for winter in maritime mid-latitudes; $\Delta L_w = 0.06 \text{ m}$ for winter in continental mid-latitudes; and $\Delta L_w = 0.05 \text{ m}$ for polar regions [38].

E. Goad and Goodman Model

Also utilizing the Hopfield quartic refractivity model, Goad and Goodman suggested using the length of position vector instead of height [39]. The hydrostatic refractivity model of Hopfield can thus be rewritten as [39]:

$$N_h = N_{hs} \left(\frac{r_d - r}{r_d - R_E} \right)^4 \quad (27)$$

where r_d is the distance from Earth center to the equivalent height of the hydrostatic refractivity (unit: m); r is the distance from Earth center to a given height (unit: m); R_E is the Earth radius (unit: m). They gave the final modified Hopfield model in the following form [39]:

$$\Delta L_h = 10^{-6} \cdot N_{hs} \cdot \left[\sum_{k=1}^9 \frac{\alpha_k}{k} \cdot R^k \right] \quad (28)$$

where $R = r_d - R_E$ and the α_k are represented as

$$\begin{aligned} \alpha_1 &= 1 & \alpha_2 &= 4a & \alpha_3 &= 6a^2 + 4b & \alpha_4 &= 4a(a^2 + 3b) \\ \alpha_5 &= a^4 + 12a^2b + 6b^2 & \alpha_6 &= 4ab(a^2 + 3b) \\ \alpha_7 &= b^2(6a^2 + 4b) & \alpha_8 &= 4ab^3 & \alpha_9 &= b^4 \end{aligned}$$

where $a = -\frac{\sin ele}{H_d}$, $b = -\frac{\cos^2 ele}{2H_d R_E}$, ele (unit: radian) is the elevation angle of the ray path, H_d has been defined in (23).

Following the procedure in deriving the ZHD model, Goad and Goodman derived the ZWD model [39]:

$$\Delta L_w = 10^{-6} \cdot N_{ws} \cdot \left[\sum_{k=1}^9 \frac{\alpha_k}{k} \cdot R^k \right] \quad (29)$$

where $R = r_w - R_E$, r_w (unit: m) is distance from Earth center to the equivalent height of the wet refractivity. Other variables are same as those in (28) except replacing H_d with H_w in the calculation of a and b .

F. UNB3 and EGNOS Models

In the ZHD and ZWD calculations using the models described above, the surface meteorological observation data such as pressure and temperature are required. In UNB3 model, empirical meteorological data are used and they are predicted from the U.S. Standard Atmosphere Supplements, 1966 [40], [41]. The ZHD is calculated as [42]:

$$\Delta L_h = z_d \cdot \left[1 - \frac{\alpha \cdot H}{T_0} \right]^{\frac{q}{R_d \alpha}} \quad (30)$$

where α represents the temperature lapse rate (unit: K/km); H is the height of the station above mean sea level (unit: m); T_0 is

the temperature at mean sea level (unit: K); g is the surface acceleration of gravity (unit: $\text{m}\cdot\text{s}^{-2}$); R_d has been defined in (4); z_d is the ZHD at mean sea level (unit: m) and is computed by [42]:

$$z_d = \frac{10^{-6}k_1 \cdot R_d \cdot p_0}{g_m} \quad (31)$$

where k_1 has been defined in (2); p_0 is the atmospheric pressure at mean sea level (unit: hPa); g_m can be computed from (12). For a certain station and specified date, p_0 , T_0 , and α can be computed using the following formula:

$$\xi(\phi, D) = \xi_0(\phi) - \Delta\xi(\phi) \cdot \cos\left[\frac{2\pi(D-D_{min})}{365.25}\right] \quad (32)$$

where ξ_0 and $\Delta\xi$ are the annual average and seasonal variation, respectively, for a certain parameter at a station with latitude ϕ ; D is the day-of-year for which the computation is performed; $D_{min}=28$ in the northern hemisphere and $D_{min}=211$ in the southern hemisphere. The annual average values and seasonal variations for the meteorological parameters were derived from North American meteorological data and they are given in Table II. The expression of the EGNOS ZHD model is almost identical to the UNB3 ZHD model. The only slight difference between the two models is that g and g_m are set as constant values in EGNOS model and their values are $9.80665 \text{ m}\cdot\text{s}^{-2}$ and $9.784 \text{ m}\cdot\text{s}^{-2}$, respectively [42].

In UNB3 model, the ZWD is computed using [42]:

$$\Delta L_w = z_w \cdot \left[1 - \frac{\alpha \cdot H}{T_0}\right]^{\frac{(\lambda+1) \cdot g}{R_d \cdot \alpha} - 1} \quad (33)$$

where λ is the water vapor lapse rate (unitless); z_w is the ZWD at mean sea level (unit: m) and it is calculated using the following formula:

$$z_w = \frac{10^{-6}(T_m k'_2 + k_3) R_d}{g_m (\lambda+1) - \beta \cdot R_d} \cdot \frac{e_0}{T_0} \quad (34)$$

where $k'_2 = k_2 - k_1 \cdot R_d/R_w$ and T_m is the mean temperature (unit: K) that can be calculated from

$$T_m = T_s \cdot \left(1 - \frac{\alpha \cdot R_d}{(\lambda+1) \cdot g_m}\right) \quad (35)$$

The parameters T_0 , β , and λ can also be computed using the expression in (32). The annual average values and seasonal variations for these parameters are given in Table II. In the original version of UNB3, water vapor pressure e_0 is directly obtained using the same method as p_0 from the look-up Table II. Later Leandro et al. found that RH calculated from e_0 is greater than 100% in some cases [43]. Thus, they modified the UNB3 model to avoid the problematic values of RH . In the modified model, RH is first predicted from the look-up table. Then water vapor pressure e_0 is computed from (3). For the EGNOS ZWD model, its expression is also almost identical to UNB3 except that $T_m k'_2 + k_3$ is simply set as $382000 \text{ K}^2/\text{hPa}$ and e_0 is directly obtained from Table II [42].

TABLE II
ANNUAL AVERAGE VALUES AND SEASONAL VARIATION VALUES OF THE
METEOROLOGICAL PARAMETERS USED IN THE UNB3/EGNOS MODEL

Latitude (°)	Average					
	P_0 (hPa)	T_0 (K)	e_0 (hPa)	α (K/km)	λ	RH (%)
≤ 15	1013.25	299.65	26.31	6.30	2.77	75.0
30	1017.25	294.15	21.79	6.05	3.15	80.0
45	1015.75	283.15	11.66	5.58	2.57	76.0
60	1011.75	272.15	6.78	5.39	1.81	77.5

	≥ 75	1013.00	263.65	4.11	4.53	1.55	82.5
Seasonal Variation							
Latitude (°)	ΔP_0 (hPa)	ΔT_0 (K)	Δe_0 (hPa)	$\Delta \alpha$ (K/km)	$\Delta \lambda$	ΔRH (%)	
≤ 15	0.00	0.00	0.00	0.00	0.00	0.0	
30	-3.75	7.00	8.85	0.25	0.33	0.0	
45	-2.25	11.00	7.24	0.32	0.46	-1.0	
60	-1.75	15.00	5.36	0.81	0.74	-2.5	
≥ 75	-0.50	14.50	3.39	0.62	0.30	2.5	

G. GPT2 model

Based on the spherical harmonics, Boehm et al. developed an empirical GPT model (Global Pressure and Temperature) that can provide pressure and temperature at any location in the vicinity of the Earth's surface [44]. Lagler et al improved this model and a new version called GPT2 is now available [45]. Besides the pressure and temperature, the refined GPT2 model also outputs parameters such as water vapor pressure, water vapor lapse rate and temperature lapse rate. The GPT2 model can be accessible at the International Earth Rotation and Reference Systems Service (IERS) Conventions Product Center (<http://62.161.69.131/iers/convupdt/convupdt.html>).

H. ECMWF model

The European Center for Medium-Range Weather Forecasts (ECMWF) provides a set of global analysis and reanalysis data of the atmosphere. Based on atmospheric physical models, meteorological data from in-situ observations (e.g. surface weather stations, ships, buoys, radiosonde stations and aircraft) and remote sensing observations are assimilated into the atmospheric models to generate the analysis and reanalysis data (http://old.ecmwf.int/products/forecasts/guide/user_guide.pdf). In this study, we use the latest global atmospheric reanalysis product ERA-Interim [46] to produce the ZHD and ZWD. The data have a horizontal resolution of $0.5^\circ \times 0.5^\circ$ and a vertical resolution of 37 isobaric levels extending from 1000 hPa to 1 hPa. For a certain site, meteorological parameters are derived using bilinear interpolation of the ECMWF data at four surrounding grid points. Finally, ZHD and ZWD can be calculated using (8) and (9), respectively.

I. Berman Models

In the section III(A) to III(H), formulas for the estimation of both ZHD and ZWD have been developed in each model. From this section III(I) on, only the formula for ZWD calculation is developed. Under the assumption of linear temperature lapse, constant relative humidity and wet refractivity reducing to zero at the tropopause, Berman obtained the "Berman 70" ZWD model [47]:

$$\Delta L_w = \frac{373}{\alpha(B-A \cdot C)} \cdot \left(1 - \frac{c}{T_s}\right)^2 \cdot e_s \quad (36)$$

where A , B , and C are hygrometric constants, and their values are 17.1485, 4684.1, and 38.45, respectively. Berman also derived other three improved models, i.e. "Berman 74", "Berman (TMOD)" and "Berman (D/N)" models. The general expression of these models is written as:

$$\Delta L_w = 10.946 \cdot K \cdot \frac{e_s}{T_s} \quad (37)$$

In the “Berman 74” model K is set as 0.3224 and in the “Berman (TMOD)” model K is set as 0.3281. By analyzing the meteorological parameter profiles separately for day and night cases, Berman developed a “Berman (D/N)” model, in which $K = 0.2896$ for day case and $K = 0.3773$ for night case.

J. Callahan Model

Callahan assumed that the water vapor pressure distribution could be empirically expressed in the following form [48]:

$$e = e_s \cdot \exp(-2.88 \times 10^{-4} \cdot H - 4.8 \times 10^{-8} \cdot H^2) \quad (38)$$

where e_s is the surface water vapor pressure; H is the height above the ground surface level (unit: m). A complete derivation of the Callahan model is very complicated. By using a set of nominal values, the simplified final form is given below [9]:

$$\Delta L_w = \frac{1035 \cdot e_s}{T_s^2} \quad (39)$$

K. Chao Model

The ZWD model developed by Chao assumes that water vapor obeys the hydrostatic law and adopts the adiabatic approximation to the water vapor [49]. The model’s final form is given as:

$$\Delta L_w = 1.63 \cdot \frac{e_s^{1.23}}{T_s^2} + 2.05 \cdot \alpha \cdot \frac{e_s^{1.46}}{T_s^3} \quad (40)$$

In this model, the ΔL_w is not very sensitive to the temperature lapse rate α . The use of a mean value of α (e.g. 6.5 K/km) can lead to an adequate accuracy for the model. To enhance the model’s performance, α could be estimated using local meteorological observations.

L. Ifadis Model

Ifadis developed a global ZWD model considering a linear relationship between the ZWD and the surface meteorological data [9]. The formula of this model is given below [9]:

$$\Delta L_w = 0.00554 - 0.880 \times 10^{-4} \cdot (P_s - 1000.0) + 0.272 \times 10^{-4} \cdot e_s + 2.771 \cdot \frac{e_s}{T_s} \quad (41)$$

where P_s , e_s and T_s are the atmospheric pressure, water vapor pressure and temperature at the surface, respectively.

M. Askne and Nordius Model

Under the assumption that water vapor pressure decreases with height in the same way as the total pressure, the water vapor pressure can be expressed in the form [27]

$$e = e_s \cdot \left(\frac{P}{P_s}\right)^{\omega+1} \quad (42)$$

where, e_s and P_s are the water vapor pressure and atmospheric pressure at the surface, respectively; P is the atmospheric pressure; ω is a parameter associated with seasonal and latitudinal variations (unitless). ω should be determined using local atmospheric profiles. Substituting (42) into the last term of (7) and after some integrals and calculations, the following is obtained:

$$\Delta L_w = 10^{-6} \cdot (k'_2 + k_3/T_m) \cdot \frac{R_d}{(\omega+1) \cdot g_m} \cdot e_s \quad (43)$$

where T_m is calculated by:

$$T_m = T_s \cdot \left(1 - \frac{\alpha \cdot R_d}{(\omega+1) \cdot g_m}\right) \quad (44)$$

IV. RADIOSONDE MEASUREMENT AND ITS ACCURACY

A. Data description

Based on the balloon-borne platform, radiosonde can directly measure the meteorological parameters such as atmospheric pressure, temperature and relative humidity at different altitudes from the ground surface to a height of up to over 30 km [50]. Thus, according to (5) and (6), the hydrostatic and wet refractivity profiles can be determined. Finally, the zenith hydrostatic and wet delays could be easily calculated according to (8) and (9). Due to the high accuracy of radiosonde data, radiosonde-derived results are usually adopted as reference for other instruments/models [51]. In this paper, the zenith hydrostatic and wet delays derived from radiosonde are also adopted as reference data to assess the accuracy of each tropospheric delay model. It should be noted that the radiosonde balloon usually could not reach the height where air pressure is zero. This can usually result in an error varying from 2 to 6 cm for the ZHD measurement [35]. For some cases, if the radiosonde balloons fail to reach a high enough altitude, it can cause an error up to 1 m [35]. Therefore, to ensure the quality of ZHD derived from radiosonde, only radiosonde data that contain complete meteorological parameter profiles up to the height with a pressure equals to or less than 30 hPa are used in our study [37]. In order to compensate the hydrostatic delay between 30 hPa (or less than 30 hPa) and zero pressure that cannot be measured by radiosonde, we use (14) to calculate a small correction. This correction is added to the hydrostatic delay computed from (8) [35]. In this way, the calculated ZHD approaches the true value as much as possible [35].

In order to achieve a statistically meaningful conclusion, a large volume of radiosonde observations collected from a total of 92 stations in China over a 10-year period from 2003 to 2012 are utilized to evaluate the performance of different tropospheric delay models. Fig. 1 presents the geographic distribution of 92 radiosonde stations. Before 2006, 80 radiosonde stations were equipped with CHINA GZZ-2 sensors, 10 radiosonde stations were equipped with CHINA GTS1 sensors and two radiosonde stations were equipped with Vaisala RS80 sensors. After 2006, 52 radiosonde stations equipped with CHINA GZZ-2 were replaced by CHINA GTS1. In addition, the two radiosonde stations equipped with Vaisala RS80 were replaced by Vaisala RS92. Thus after 2006, there are 28 radiosonde stations equipped with CHINA GZZ-2 and the number of radiosonde stations equipped with CHINA GTS1 increases to 62. Radiosonde instruments of the rest two stations are Vaisala RS92. Several studies showed that the Chinese made radiosonde CHINA GZZ-2 and CHINA GTS1 can achieve comparable performance with the Vaisala radiosonde [52]–[54].

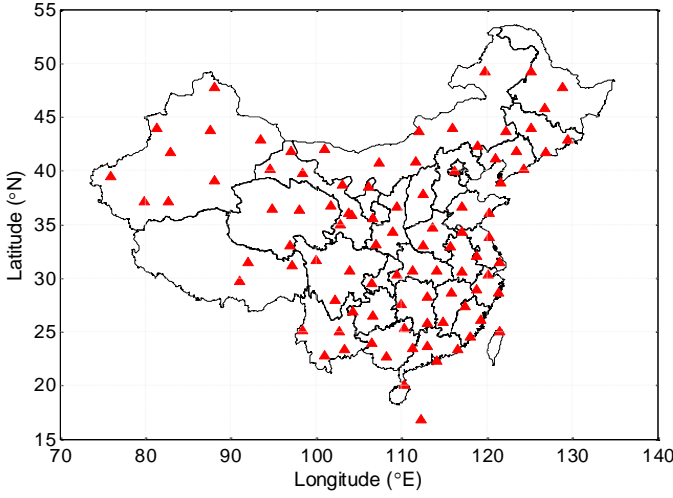


Fig. 1. The geographic distribution of 92 radiosonde stations (red solid triangles) in China

B. Accuracy of the radiosonde derived zenith hydrostatic and wet delay

In order to evaluate the accuracy of the ZHD derived from the radiosonde, we first differentiate (8)

$$d_{\Delta L_h} = 10^{-6} \left(\sum A_{i+1} d_{N_{h_{i+1}}} - \sum A_i d_{N_{h_i}} \right) \quad (45)$$

where A_{i+1} and A_i are defined as:

$$A_{i+1} = (H_i - H_{i+1}) \cdot \left(\ln N_{h_i} - \ln N_{h_{i+1}} + \frac{N_{h_{i+1}} - N_{h_i}}{N_{h_{i+1}}} \right) / (\ln N_{h_i} - \ln N_{h_{i+1}})^2 \quad (46)$$

$$A_i = (H_i - H_{i+1}) \cdot \left(\ln N_{h_i} - \ln N_{h_{i+1}} + \frac{N_{h_{i+1}} - N_{h_i}}{N_{h_i}} \right) / (\ln N_{h_i} - \ln N_{h_{i+1}})^2 \quad (47)$$

Then (5) can be differentiated as

$$d_{N_h} = \frac{k_1}{T} d_{P_d} + \frac{k_1 \cdot R_d}{T \cdot R_w} d_e - k_1 \cdot \left(\frac{P_d}{T^2} + \frac{e \cdot R_d}{T^2 \cdot R_w} \right) d_T \quad (48)$$

where d_e can be derived from (3)

$$d_e = Q \cdot d_P + R \cdot d_T + S \cdot d_{RH} \quad (49)$$

where Q , R and S represent

$$\begin{aligned} Q &= 21.147866 \times 10^{-6} \cdot RH \cdot e^\theta \\ R &= 6.1121 \times RH(1.0007 + 3.46 \times 10^{-6} \cdot P) \cdot e^\theta \cdot \frac{18.729 - 2 \times (T - 273.15) / 227.3 - \theta}{T - 15.28} \\ S &= 6.1121 \times (1.0007 + 3.46 \times 10^{-6} \cdot P) \cdot e^\theta \\ \theta &= \frac{[18.729 - (T - 273.15) / 227.3] \cdot (T - 273.15)}{T - 15.28} \end{aligned}$$

Considering the total atmospheric pressure P equals to the sum of P_d and e , we rewrite (48) as

$$d_{N_h} = \left[\frac{k_1}{T} + \left(\frac{k_1 \cdot R_d}{T \cdot R_w} - \frac{k_1}{T} \right) \cdot Q \right] \cdot d_P + \left[\left(\frac{k_1 \cdot R_d}{T \cdot R_w} - \frac{k_1}{T} \right) \cdot R - k_1 \left(\frac{P_d}{T^2} - \frac{e \cdot R_d}{T^2 \cdot R_w} \right) \right] \cdot d_T + \left(\frac{k_1 \cdot R_d}{T \cdot R_w} - \frac{k_1}{T} \right) \cdot S \cdot d_{RH} \quad (50)$$

Substituting (50) into (45) and assuming that the measurements of pressure, temperature and relative humidity are uncorrelated, we can derive the uncertainty of ZHD, denoted as $\sigma_{\Delta L_h}$ by utilizing the error propagation law:

$$\sigma_{\Delta L_h} = 10^{-6} \cdot \sqrt{B_1 \cdot \sigma_P^2 + B_2 \cdot \sigma_T^2 + B_3 \cdot \sigma_{RH}^2} \quad (51)$$

where σ_P , σ_T and σ_{RH} are the uncertainties of the total pressure, temperature and relative humidity measurements, respectively. In addition, the coefficients B_1 , B_2 and B_3 are defined as:

$$\begin{aligned} B_1 &= \sum \left\{ A_{i+1}^2 \cdot \left[\frac{k_1}{T_{i+1}} + \left(\frac{k_1 \cdot R_d}{T_{i+1} \cdot R_w} - \frac{k_1}{T_{i+1}} \right) \cdot Q_{i+1} \right]^2 + A_i^2 \cdot \left[\frac{k_1}{T_i} + \left(\frac{k_1 \cdot R_d}{T_i \cdot R_w} - \frac{k_1}{T_i} \right) \cdot Q_i \right]^2 \right\} \\ B_2 &= \sum \left\{ A_{i+1}^2 \cdot \left[\left(\frac{k_1 \cdot R_d}{T_{i+1} \cdot R_w} - \frac{k_1}{T_{i+1}} \right) \cdot R_{i+1} - k_1 \cdot \left(\frac{P_{d_{i+1}}}{T_{i+1}^2} + \frac{R_d \cdot e_{i+1}}{R_w \cdot T_{i+1}^2} \right) \right]^2 + A_i^2 \cdot \left[\left(\frac{k_1 \cdot R_d}{T_i \cdot R_w} - \frac{k_1}{T_i} \right) \cdot R_i - k_1 \cdot \left(\frac{P_{d_i}}{T_i^2} + \frac{R_d \cdot e_i}{R_w \cdot T_i^2} \right) \right]^2 \right\} \\ B_3 &= \sum \left\{ (A_{i+1} \cdot S_{i+1})^2 \cdot \left(\frac{k_1 \cdot R_d}{T_{i+1} \cdot R_w} - \frac{k_1}{T_{i+1}} \right)^2 + (A_i \cdot S_i)^2 \cdot \left(\frac{k_1 \cdot R_d}{T_i \cdot R_w} - \frac{k_1}{T_i} \right)^2 \right\} \end{aligned}$$

Following the same procedure, we can derive the uncertainty of the ZWD, denoted as $\sigma_{\Delta L_w}$:

$$\sigma_{\Delta L_w} = 10^{-6} \cdot \sqrt{D_1 \cdot \sigma_P^2 + D_2 \cdot \sigma_T^2 + D_3 \cdot \sigma_{RH}^2} \quad (52)$$

where

$$\begin{aligned} D_1 &= \sum \left[(C_{i+1} \cdot Q_{i+1})^2 \cdot \left(\frac{k_2'}{T_{i+1}} + \frac{k_3}{T_{i+1}^2} \right)^2 + (C_i \cdot Q_i)^2 \cdot \left(\frac{k_2'}{T_i} + \frac{k_3}{T_i^2} \right)^2 \right] \\ D_2 &= \sum \left[C_{i+1}^2 \cdot \left[\left(\frac{k_2'}{T_{i+1}} + \frac{k_3}{T_{i+1}^2} \right) \cdot R_{i+1} - \left(\frac{k_2' \cdot e_{i+1}}{T_{i+1}^2} + \frac{2 \cdot k_3 \cdot e_{i+1}}{T_{i+1}^3} \right) \right]^2 + C_i^2 \cdot \left[\left(\frac{k_2'}{T_i} + \frac{k_3}{T_i^2} \right) \cdot R_i - \left(\frac{k_2' \cdot e_i}{T_i^2} + \frac{2 \cdot k_3 \cdot e_i}{T_i^3} \right) \right]^2 \right] \\ D_3 &= \sum \left[(C_{i+1} \cdot S_{i+1})^2 \cdot \left(\frac{k_2'}{T_{i+1}} + \frac{k_3}{T_{i+1}^2} \right)^2 + (C_i \cdot S_i)^2 \cdot \left(\frac{k_2'}{T_i} + \frac{k_3}{T_i^2} \right)^2 \right] \\ C_{i+1} &= (H_i - H_{i+1}) \cdot \left(\ln N_{w_i} - \ln N_{w_{i+1}} + \frac{N_{w_{i+1}} - N_{w_i}}{N_{w_{i+1}}} \right) / (\ln N_{w_i} - \ln N_{w_{i+1}})^2 \\ C_i &= (H_i - H_{i+1}) \cdot \left(\ln N_{w_i} - \ln N_{w_{i+1}} + \frac{N_{w_{i+1}} - N_{w_i}}{N_{w_i}} \right) / (\ln N_{w_i} - \ln N_{w_{i+1}})^2 \end{aligned}$$

By utilizing the 10-year radiosonde data of the 92 stations, we calculated the empirical values of B_1 , B_2 , B_3 , D_1 , D_2 and D_3 for each station. Here, we only give their maximum, minimum and mean values in Table III. According to [55], Chinese-made radiosonde can fully meet the accuracy requirements for upper-air meteorological measurements in the CIMO (Commission for Instruments and Methods of Observations) Guide [50]. Thus, we used the standard errors established in CIMO Guide to derive the uncertainties of ZHD and ZWD. The specified pressure, temperature and RH accuracies for radiosonde instrumentation are $\sigma_P = 1$ hPa, $\sigma_T = 0.5$ K and $\sigma_{RH} = 0.05$, respectively. Substituting these values and those in Table III into (51) and (52), the corresponding $\sigma_{\Delta L_h}$ and $\sigma_{\Delta L_w}$ are obtained and given in the last two rows of Table III. Results show that the mean accuracies (standard deviation) of ZHD and ZWD derived from the radiosonde are 2.4 mm and 4.4 mm, respectively. Thus, radiosonde data can be adopted as accuracy standard to evaluate the performance of the tropospheric delay models.

TABLE III
UNCERTAINTY VALUES ESTIMATED FROM THE RADIOSONDE MEASUREMENTS

	Maximum	Minimum	Mean
B_1	5.51×10^6	7.47×10^5	3.19×10^6
B_2	6.66×10^7	8.42×10^5	1.02×10^7
B_3	1.40×10^7	7.93×10^3	3.09×10^6
D_1	1.66×10^{-1}	2.13×10^{-5}	2.48×10^{-2}
D_2	5.70×10^7	1.00×10^4	7.62×10^6
D_3	2.83×10^{10}	1.89×10^7	6.96×10^9
$\sigma_{\Delta L_h}$	4.71 mm	0.98 mm	2.40 mm
$\sigma_{\Delta L_w}$	9.22 mm	0.22 mm	4.39 mm

V. TROPOSPHERIC MODEL ASSESSMENT

In the model evaluation, all the models are used to calculate the tropospheric hydrostatic and wet delays for the geographic locations of each radiosonde site (site's latitude, longitude and height are known). This ensures the delays observed from radiosonde and calculated from the models can be directly compared. In the model computation, all the models except UNB3, EGNOS, GPT2 and ECMWF need surface meteorological parameters and they are extracted from radiosonde observations. In order to evaluate the GPT2 model, we exploit the Baby ZHD model and Askne ZWD model to calculate the ZHD and ZWD, respectively, using the empirical meteorological parameters provided by GPT2 model. This is because in section V(A) we find that Baby model is the most accurate one among all the ZHD models if their meteorological parameters can be obtained from the GPT2. In the same way, we choose the Askne ZWD model to compute the ZWD by using meteorological parameters from GPT2 model. For the sake of convenience, each model is abbreviated with a code as listed Table IV. In addition, we may notice that the calculation of some models needs some other parameters in addition to surface observations (see Table IV). The parameters in hydrostatic models include α (in BA_ZH) and H_d (e.g. HO_ZH and GG_ZH) and the parameters in wet models include H_w (in HO_ZW, GG_ZW and BA_ZW), α (in AN_ZW, BA_ZW, B70_ZW, and CH_ZW), ω (in AN_ZW), v and γ (in BAS_ZW). In this study, the values of all these parameters are fitted from radiosonde observations for each site in order to enhance the modeling performance. Specifically, according to each model's expression, radiosonde derived ZHDs/ZWDs are exploited to estimate the parameters in this model by performing a Least-Squares fitting method. Accuracies of the models will be assessed in terms of mean bias, standard deviation (STD) and root mean squares (RMS) error against the radiosonde derived hydrostatic and wet delays.

TABLE IV
ZHD AND ZWD MODELS AND THEIR ABBREVIATION CODES AND INPUT PARAMETERS

No.	Model Name	ZHD Model Code (input parameters)	ZWD Model Code (input parameters)
1	Askne and Nordius	--	AN_ZW (e_s, T_s, ω, α)
2	Baby semi-empirical	--	BAS_ZW (T_s, RH, v, γ)
3	Baby theoretical	BA_ZH (P_s, T_s, α)	BA_ZW (T_s, RH, α, H_w)
4	Berman70	--	B70_ZW (e_s, T_s, α)
5	Berman74	--	B74_ZW (e_s, T_s)
6	Berman D/N	--	BDN_ZW (e_s, T_s)
7	Berman TMOD	--	BTM_ZW (e_s, T_s)
8	Black	BL_ZH (P_s, T_s)	BL_ZW (--)
9	Callahan	--	CA_ZW (e_s, T_s)

10	Chao	--	CH_ZW (e_s, T_s, α)
11	ECMWF	EC_ZH (--)	EC_ZW (--)
12	EGNOS	EG_ZH (--)	EG_ZW (--)
13	Goald and Goodman	GG_ZH (P_s, T_s, H_d)	GG_ZW (e_s, T_s, H_w)
14	GPT2	GP_ZH (--)	GP_ZW (--)
15	Hopfield	HO_ZH (P_s, T_s, H_d)	HO_ZW (e_s, T_s, H_w)
16	Ifadis	--	IF_ZW (P_s, e_s, T_s)
17	Saastamoinen	SA_ZH (P_s)	SA_ZW (e_s, T_s)
18	UNB3	UN_ZH (--)	UN_ZW (--)

A. Assessment of ZHD Models with Radiosonde

1) Overall Performance of the ZHD Models

Using the measurements recorded during the 10-year period at 92 radiosonde stations as references, the overall performance of the 9 ZHD models are evaluated. Table V lists the means, STD and RMS errors of the differences between ZHD derived from radiosonde measurements and empirical models. Fig. 2 shows the ranking of the ZHD models by the size of RMS errors. As shown in Table V and Fig. 2, we can find that EC_ZH achieves the best performance with an accuracy of 2.8 mm and UN_ZH performs the worst with an RMS error of 19.1 mm. It is not surprising that the EC_ZH model has a good agreement with the radiosonde data since the radiosonde observations have also been employed to generate the ECMWF reanalysis data. BA_ZH, HO_ZH and GG_ZH have very similar performance though they are not as good as EC_ZH. In addition, we notice that HO_ZH and GG_ZH actually have the identical performance. This is because GG_ZH is a modified model from HO_ZH and its expression is the same as HO_ZH in the zenith mode. BL_ZH and SA_ZH models also show good performance with an accuracy of about 8 mm. It is interesting to see that GP_ZH achieved an accuracy of 11.6 mm. Also using the empirical meteorological parameters, EG_ZH and UN_ZH show similar performance with RMS errors of 17.9 mm and 19.1 mm, respectively. Therefore, it is better to employ GP_ZH rather than EG_ZH or UN_ZH to provide the ZHD corrections when surface meteorological parameters are unavailable or a quick tropospheric correction with modest precision is needed.

TABLE V
STATISTICAL RESULTS OF THE DIFFERENCES BETWEEN ZHD DERIVED FROM EMPIRICAL MODELS AND ZHD FROM 10 YEARS (2003-2012) OF OBSERVATIONS AT 92 RADIOSONDE STATIONS (UNIT: MM)

Model	Mean	STD	RMS
BA_ZH	-1.3	5.8	6.0
BL_ZH	-5.1	6.0	7.8
EC_ZH	0.9	2.6	2.8
EG_ZH	-5.3	17.1	17.9
GG_ZH	-0.7	6.0	6.1
GP_ZH	1.4	11.5	11.6
HO_ZH	-0.7	6.0	6.1
SA_ZH	-6.0	5.9	8.4
UN_ZH	-0.8	17.4	19.1

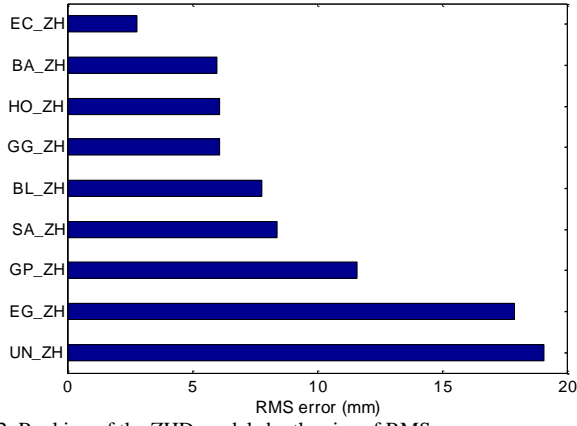


Fig. 2 Ranking of the ZHD models by the size of RMS errors

2) Seasonal Performance of the ZHD Models

Table VI presents the performance of the 9 ZHD models for different seasons. For the best accuracy model EC_ZH, we can notice that there are no significant differences among the four seasons. Similarly, BA_ZH, BL_ZH, GG_ZH, GP_ZH, HO_ZH and SA_ZH are very consistent over the seasons and no significant variations have been observed in their RMS errors from spring to winter. However, the EG_ZH and UN_ZH show significant seasonal variations. In terms of temporal performance over seasons, it can be seen that the EC_ZH is the best model, which is consistent with the results in Fig. 2.

TABLE VI

SEASONAL STATISTICS OF DIFFERENCES BETWEEN ZHD DERIVED FROM EMPIRICAL MODELS AND ZHD FROM 10 YEARS (2003-2012) OF OBSERVATIONS AT 92 RADIOSONDE STATIONS (UNIT: MM)

Model		Spring	Summer	Autumn	Winter
BA_ZH	Mean	-1.4	-1.9	-1.3	-0.6
	STD	5.8	5.8	5.9	5.8
	RMS	6.0	6.1	6.1	5.8
BL_ZH	Mean	-5.2	-6.8	-5.2	-3.0
	STD	5.8	5.7	6.0	5.8
	RMS	7.8	8.9	8.0	6.5
EC_ZH	Mean	0.7	1.2	0.7	1.2
	STD	2.6	2.4	2.4	3.0
	RMS	2.7	2.6	2.6	3.2
EG_ZH	Mean	-8.7	-21.3	-0.1	8.4
	STD	14.6	9.6	12.7	15.1
	RMS	17.0	23.3	12.7	17.2
GG_ZH	Mean	-2.3	-1.9	-1.3	-1.0
	STD	5.8	5.6	5.6	6.3
	RMS	6.3	5.9	5.7	6.4
GP_ZH	Mean	1.2	0.2	1.3	2.9
	STD	12.6	9.0	10.5	13.3
	RMS	12.7	9.0	10.6	13.6
HO_ZH	Mean	-2.3	-1.9	-1.3	-1.0
	STD	5.8	5.6	5.6	6.3
	RMS	6.3	5.9	5.7	6.4
SA_ZH	Mean	-6.1	-6.5	-6.1	-5.3
	STD	5.8	5.8	6.0	5.8
	RMS	8.4	8.8	8.5	7.9
UN_ZH	Mean	-11.3	-23.8	-2.7	5.7
	STD	14.9	9.8	13.2	15.7
	RMS	18.7	25.8	13.5	16.7

3) Assessment of the ZHD Models at Different Latitudinal Regions

In addition to the overall and seasonal performance, we also investigate the performance of the ZHD models at different latitudinal regions in China. China covers the region from 15°N to 55°N in latitude. The ZHD model performance in four regions 15~25°N, 25~35°N, 35~45°N, and 45~55°N are studied. As seen in Table VII, the performance of the models vary with latitudes and EC_ZH performs best in all the four regions. For BA_ZH, BL_ZH, GG_ZH, HO_ZH and SA_ZH, their accuracies in 35~55°N are higher than those in 15~35°N. However for the EG_ZH and GP_ZH, their accuracies in 35~55°N are lower than in 15~35°N latitude zones. It is worthwhile to note that GP_ZH also utilizes the BA_ZH to compute the ZHD but they show opposite performance. In other words, this perhaps reveals the GPT2 can provide better predictions of the meteorological parameters in low latitude regions in China.

TABLE VII

STATISTICS OF DIFFERENCES BETWEEN ZHD DERIVED FROM EMPIRICAL MODELS AND ZHD FROM 10 YEARS (2003-2012) OF OBSERVATIONS AT 92 RADIOSONDE STATIONS AT DIFFERENT LATITUDINAL REGIONS (UNIT: MM)

Model		Latitudinal Regions (°N)			
		15~25	25~35	35~45	45~55
BA_ZH	Mean	-3.9	-2.2	-1.0	2.1
	STD	3.3	5.7	3.3	2.6
	RMS	5.1	6.1	3.4	3.4
BL_ZH	Mean	-7.1	-5.6	-4.8	-3.4
	STD	3.5	5.8	4.3	3.8
	RMS	7.9	8.1	6.4	5.1
EC_ZH	Mean	0.4	0.7	1.4	1.3
	STD	2.1	2.6	2.7	2.5
	RMS	2.1	2.7	3.0	2.8
EG_ZH	Mean	-10.7	-7.2	-1.8	-2.9
	STD	12.9	16.0	17.8	20.3
	RMS	16.7	17.6	17.9	20.5
GG_ZH	Mean	0.2	-1.0	-0.8	-1.2
	STD	6.8	6.0	5.9	4.3
	RMS	6.9	6.1	5.9	4.4
GP_ZH	Mean	-0.9	-0.1	4.0	1.1
	STD	8.6	10.5	11.9	14.3
	RMS	8.6	10.5	12.6	14.4
HO_ZH	Mean	0.2	-1.0	-0.8	-1.2
	STD	6.8	6.0	5.9	4.3
	RMS	6.9	6.1	5.9	4.4
SA_ZH	Mean	-8.8	-6.9	-5.5	-2.8
	STD	3.3	5.7	3.4	2.5
	RMS	9.4	9.0	6.4	3.8
UN_ZH	Mean	-15.2	-10.6	-3.5	-2.5
	STD	12.9	16.1	17.8	20.3
	RMS	19.9	19.3	18.1	20.5

B. Assessment of ZWD Models with Radiosonde

1) Overall Performance of the ZWD Models

Table VIII summarizes the detailed statistics of ZWD differences between radiosonde measurements and various ZWD models. In Fig. 3, the performance of all the 18 ZWD models is ranked in terms of their RMS errors.

It can be seen that the best and worst ZWD models are EC_ZW and BL_ZW, respectively. As highlighted in shadow in Table VIII, their RMS errors are 21.4 mm and 110.4 mm, respectively. The reason for the rather poor performance of BL_ZW can be explained by the fact that only several crude

piecewise constant values are used to model the ZWD in BL_ZW (see section III(D)). In general, we can see that all the models are incompetent to model the ZWD with a high accuracy. Though the size of ZWD usually is only $\sim 10\%$ of ZHD, the RMS error of the best ZWD model (EC_ZW, 21.4 mm) is 7.6 times larger than that of the best ZHD model (EC_ZH, 2.8 mm). This clearly illustrates the difficulty of modeling the highly variable ZWD with high accuracy. As shown in Fig. 3, we can also observe that the 7 models BAS_ZW, HO_ZW, GG_ZW, AN_ZW, SA_ZW, CA_ZW and B74_ZW (categorized as group 1) show very similar levels of accuracy. The 7 models IF_ZW, BTM_ZW, CH_ZW, B70_ZW, GP_ZW, BA_ZW and BDN_ZW (categorized as group 2) present similar performance with RMS errors vary from 40.2 mm to 46.2 mm. The rest 3 models EG_ZW, UN_ZW, and BL_ZW (categorized as group 3) show considerably worse accuracy than the other two groups. The performance of UN_ZW is better than EG_ZW, which demonstrates the improvement in the water vapor pressure prediction in the UN_ZW model. It is worth mentioning that the GP_ZW model in group 2, which requires no actual meteorological observation data, has mean, STD and RMS error of -12.4 mm, 43.5 mm and 45.2 mm, respectively. It performs better than BA_ZW and BDN_ZW models, both of which need actual meteorological observation data in calculation.

Though the EC_ZW achieves the best accuracy in wet delay modeling, it is not suitable for real-time applications because its data could not be obtained in real time. In addition, the use of BAS_ZW (the 2nd highest accuracy), HO_ZW (or GG_ZW, the 3rd highest accuracy) or AN_ZW (the 4th highest accuracy) models for ZWD modeling is not strongly recommended in practical applications. This is because several parameters in these models (i.e. v and γ in BAS_ZW; H_w in HO_ZW and GG_ZW, α and ω in AN_ZW) need to be estimated using local meteorological observations to achieve a better modeling performance. The lack of suitable information on these parameters is a major hindrance in using these models in practice. Instead, the SA_ZW (the 6th highest accuracy), CA_ZW (the 7th highest accuracy) or B74_ZW (the 8th highest accuracy) models are good choices since they require only data of ground surface temperature and water vapor pressure in their modeling.

TABLE VIII
STATISTICAL RESULTS OF DIFFERENCES BETWEEN ZWD DERIVED FROM
EMPIRICAL MODELS AND ZWD FROM 10 YEARS (2003-2012) OF
OBSERVATIONS AT 92 RADIOSONDE STATIONS (UNIT: MM)

Model	Mean	STD	RMS	Model	Mean	STD	RMS
AN_ZW	5.8	35.3	35.8	CH_ZW	-9.6	40.3	41.5
BA_ZW	-21.2	40.5	45.7	EC_ZW	-11.1	18.3	21.4
BAS_ZW	-1.9	33.2	33.2	EG_ZW	-21.2	65.1	68.4
B70_ZW	-19.4	39.6	44.1	GG_ZW	-6.9	34.0	34.7
B74_ZW	-14.3	36.3	39.0	GP_ZW	-12.4	43.5	45.2
BDN_ZW	-17.3	42.9	46.2	HO_ZW	-6.9	34.0	34.7
BTM_ZW	-16.6	36.7	40.3	IF_ZW	1.6	40.2	40.2
BL_ZW	-60.4	92.4	110.4	SA_ZW	8.9	37.1	38.2
CA_ZW	-15.1	36.0	39.0	UN_ZW	-10.1	62.0	62.8

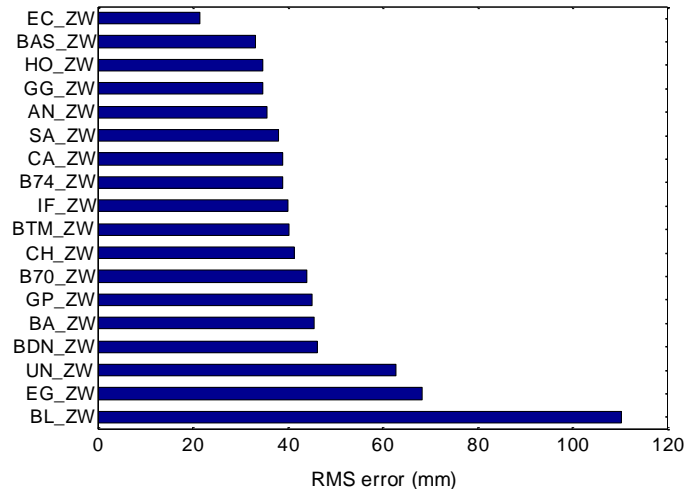


Fig. 3 Ranking of the ZWD models by the size of RMS errors

2) Seasonal Performance of the ZWD Models

China region covers a large landmass and each radiosonde station experiences considerable seasonal variations. Thus the radiosonde data can be used to evaluate the seasonal performance of the 18 ZWD models. It can be clearly seen in Table IX that the RMS errors of the empirical models in winter are significantly smaller than other seasons. All the models show that the RMS errors in summer are the largest in four seasons. This can be explained that summer and winter are usually the most and least humid season of the year, respectively. In addition, it is noted that in China region the performance of ZWD models in spring are very similar to those in autumn, with a slightly better accuracy in spring. We can also notice that EC_ZW achieves the best accuracy in all the four seasons, as highlighted in shadow. In spring, summer and autumn, the poorest accuracies are yielded by BL_ZW. However, EG_ZW performs the worst in winter among all the 18 models.

3) Assessment of the ZWD Models at Different Latitudinal Regions

The performance evaluation results of the 18 ZWD models in four different latitude zones are presented in Table X. Except the BL_ZW, the RMS errors of ZWD models decrease with latitude increasing. This is consistent with the water distribution fact that northern China (higher latitude regions) is much drier than southern China (lower latitude regions) [56]. The drier atmosphere contains less variable water vapor thus it is not a surprise all the ZWD models (except BL_ZW) consistently have better modeling accuracies in drier atmosphere. For each latitude region, the ZWD models with the highest and lowest accuracies are highlighted in shadow.

Among the 18 ZWD models, EC_ZW achieves the best performance again in all the latitude regions. The second best model belongs to BAS_ZW in the latitude regions from 15°N to 45°N. Instead, the SA_ZW model performs the second best in the latitudinal region of 45°~55°N with a RMS error of 17.5 mm. In addition, AN_ZW, GG_ZW, GP_ZW, HO_ZW and IF_ZW models also show comparable performance with the BAS_ZW and SA_ZW models. The two empirical models EG_ZW and

UN_ZW show unsatisfactory performance in all the four regions, with RMS errors all larger than 40 mm.

By taking account of both the accuracy and simplicity (using fewer meteorological parameters) of the models for the whole China region (15~55°N), SA_ZW is the first choices to model the zenith wet delay in China. BAS_ZW has the better accuracy than SA_ZW for most part of China (15~45°N), however it

requires much more meteorological parameters than the SA_ZW model. In addition, if surface meteorological observations are difficult to be obtained, we recommend AN_ZW be exploited to calculate the ZWD corrections with the use of meteorological parameters predicted from the GPT2 model.

TABLE IX
SEASONAL STATISTICS OF DIFFERENCES BETWEEN ZWD DERIVED FROM EMPIRICAL MODELS AND ZWD FROM 10 YEARS (2003-2012) OF OBSERVATIONS AT 92 RADIOSONDE STATIONS (UNIT: MM)

Model		Spring	Summer	Autumn	Winter	Model		Spring	Summer	Autumn	Winter
AN_ZW	Mean	4.7	12.7	4.2	2.9	CH_ZW	Mean	-5.2	-27.6	-12.9	4.2
	STD	34.7	44.5	37.9	22.0		STD	38.2	51.2	41.1	24.6
	RMS	35.0	46.3	38.1	22.2		RMS	38.5	58.1	43.0	25.0
BA_ZW	Mean	-18.9	-37.2	-25.5	-5.5	EC_ZW	Mean	-12.3	-14.2	-10.9	-7.3
	STD	38.7	49.9	41.4	26.2		STD	17.9	22.8	18.5	12.1
	RMS	43.0	62.3	48.6	26.8		RMS	21.7	26.9	21.4	14.1
BAS_ZW	Mean	-2.9	7.8	-4.6	-5.8	EG_ZW	Mean	-31.7	29.6	-29.5	-50.2
	STD	32.0	41.4	35.2	21.4		STD	57.2	69.1	64.9	35.0
	RMS	32.1	42.1	35.5	22.2		RMS	65.4	75.1	71.3	61.2
B70_ZW	Mean	-17.1	-34.4	-23.4	-5.6	GG_ZW	Mean	-7.8	-2.0	-11.2	-5.7
	STD	38.2	49.6	40.6	25.1		STD	33.0	42.7	35.8	22.8
	RMS	41.8	60.3	46.9	25.7		RMS	33.9	42.8	37.5	23.5
B74_ZW	Mean	-13.2	-19.6	-18.3	-6.3	GP_ZW	Mean	-13.6	-13.6	-12.1	-11.0
	STD	35.8	44.8	38.0	24.4		STD	43.6	51.8	47.6	28.3
	RMS	38.1	48.9	42.3	25.2		RMS	45.6	53.6	49.2	30.4
BDN_ZW	Mean	-15.7	-23.6	-22.3	-8.0	HO_ZW	Mean	-7.8	-2.0	-11.2	-5.7
	STD	40.8	54.9	44.8	27.6		STD	33.0	42.7	35.8	22.8
	RMS	43.8	59.8	50.0	28.7		RMS	33.9	42.8	37.5	23.5
BTM_ZW	Mean	-15.2	-23.6	-21.0	-7.4	IF_ZW	Mean	-1.2	14.5	-0.8	-4.3
	STD	36.1	45.0	38.3	24.8		STD	39.1	50.1	41.3	26.4
	RMS	39.2	50.8	43.7	25.8		RMS	39.1	52.1	41.4	26.7
BL_ZW	Mean	-91.7	-69.1	-68.3	-13.2	SA_ZW	Mean	7.0	19.8	6.2	4.4
	STD	87.5	107.4	93.9	47.3		STD	36.2	47.0	38.8	22.8
	RMS	126.8	127.7	116.2	49.1		RMS	36.9	51.0	39.3	23.3
CA_ZW	Mean	-14.5	-16.5	-19.8	-9.4	UN_ZW	Mean	-17.0	35.9	-15.4	-41.5
	STD	35.5	44.5	37.9	24.5		STD	54.5	67.2	61.1	33.4
	RMS	38.4	47.5	42.7	26.3		RMS	57.0	76.2	63.0	53.3

C. Validation by GPS Precise Point Positioning (PPP)

In the assessments presented above, tropospheric delays derived from the radiosonde were used as benchmarks to evaluate the accuracies of the ZHD and ZWD models. However, from the discussion in section IV(B) we can notice that radiosonde data are not error free. Thus the model assessment performed above is actually dependent on the accuracy of radiosonde measurements. In order to perform an absolute accuracy assessment for all the tropospheric models, we further evaluate the performance of the models using GPS PPP technique. The PPP is a good method for tropospheric model evaluation since results obtained for each station are independent [57].

The Positioning And Navigation Data Analyst (PANDA) software package developed by the Wuhan University is used to conduct the PPP experiment in this study [58]. In GPS PPP, all the errors including the tropospheric delay are required to be

precisely determined to achieve high accuracy positioning. In GPS PPP mode the tropospheric delay can be corrected by two strategies: (1) tropospheric delay is estimated based on a priori model in the data processing; (2) tropospheric delay is directly corrected using an external model [57]. For the first strategy, a common practice is to use an empirical model to directly compute the ZHD. At the same time, the ZWD is parameterized and estimated in the data processing. The PANDA software itself, by default, adopts the first strategy to estimate tropospheric delay. However in our tests we did not use the default strategy, instead, we adopted the second strategy. Tropospheric wet delays are no longer estimated with the position coordinates but directly corrected by the tropospheric models. Specifically, the BA_ZH model is used to correct the hydrostatic delay and the 18 ZWD models are applied to correct the wet delays. This is because (1) the ZHD is a relatively stable quantity and can be modeled with a high accuracy; (2) as shown in Fig. 4, the BA_ZH model is the 2nd

TABLE X
STATISTICS OF DIFFERENCES BETWEEN ZWD DERIVED FROM EMPIRICAL MODELS AND ZWD FROM 10 YEARS (2003-2012) OF OBSERVATIONS AT 92 RADIOSONDE STATIONS FOR DIFFERENT LATITUDINAL REGIONS (UNIT: MM)

Latitudinal Regions (°N)						Latitudinal Regions (°N)					
Model		15~25	25~35	35~45	45~55	Model		15~25	25~35	35~45	45~55
AN_ZW	Mean	15.6	12.0	-1.3	-6.9	CH_ZW	Mean	-36.8	11.7	-1.0	-1.1
	STD	45.8	42.5	20.9	18.3		STD	61.3	46.3	23.6	21.8

	RMS	48.4	44.2	21.0	19.6		RMS	71.5	47.7	23.6	21.8
BA_ZW	Mean	-42.5	-26.8	-10.4	-9.7	EC_ZW	Mean	-11.2	-12.9	-9.2	-9.4
	STD	54.6	46.9	25.6	24.8		STD	25.1	19.8	14.3	12.6
	RMS	69.2	54.0	27.6	26.7		RMS	27.5	23.6	17.0	15.7
BAS_ZW	Mean	-7.2	-0.7	-1.8	-1.5	EG_ZW	Mean	6.5	-10.2	-39.9	-42.3
	STD	47.1	40.7	19.8	17.7		STD	75.6	75.0	41.1	36.7
	RMS	47.6	40.7	19.9	17.8		RMS	75.9	75.6	57.3	56.0
B70_ZW	Mean	-39.2	-24.2	-10.1	-9.3	GG_ZW	Mean	-15.8	-6.2	-5.6	-5.1
	STD	54.6	46.5	24.3	22.8		STD	48.2	41.0	21.1	18.5
	RMS	67.2	52.4	26.3	24.6		RMS	50.7	41.5	21.8	19.2
B74_ZW	Mean	-24.4	-14.0	-11.9	-10.9	GP_ZW	Mean	-14.4	-15.5	-9.6	-7.9
	STD	51.3	42.9	23.3	21.9		STD	51.6	52.8	30.0	28.6
	RMS	56.8	45.1	26.1	24.5		RMS	53.6	55.0	31.5	29.7
BDN_ZW	Mean	-29.4	-17.8	-12.8	-12.7	HO_ZW	Mean	-15.8	-6.2	-5.6	-5.1
	STD	63.6	50.3	26.3	25.5		STD	48.2	41.0	21.1	18.5
	RMS	70.0	53.4	29.7	28.5		RMS	50.7	41.5	21.8	19.2
BTM_ZW	Mean	-28.7	-16.9	-13.2	-12.3	IF_ZW	Mean	20.4	9.2	-11.6	-3.8
	STD	51.7	43.1	23.8	22.8		STD	50.9	48.7	21.2	17.6
	RMS	59.2	46.3	27.2	25.9		RMS	54.9	49.6	24.1	18.0
BL_ZW	Mean	17.7	-28.0	-116.1	-116.9	SA_ZW	Mean	19.2	15.2	0.7	2.4
	STD	78.3	87.6	65.8	58.7		STD	50.0	45.2	20.3	17.3
	RMS	80.3	91.9	133.5	130.8		RMS	53.6	47.7	20.3	17.5
CA_ZW	Mean	-22.1	-14.6	-13.5	-12.9	UN_ZW	Mean	14.7	-0.5	-27.1	-27.1
	STD	50.3	42.7	23.2	21.8		STD	73.8	72.4	37.4	33.0
	RMS	54.9	45.2	26.9	25.4		RMS	75.3	72.4	46.2	42.7
URUM		43.5900	87.6300	856.1000							
WUHN		30.5317	114.3573	28.2000							

best ZHD model after EC_ZH. However the EC_ZH model is not suitable for real-time GPS positioning due to the unavailability of real-time input data. GPS data from 6 stations (Table XI) for one month period, i.e. July 2013, are processed in kinematic mode with the tropospheric delays calculated by the models. For the 5 IGS stations (BJFS, LHAZ, TWTF, URUM and WUHN), the kinematic solutions are assessed by the IGS provided precise coordinates. In addition, static PPP solutions from the PANDA are used as a reference to evaluate the accuracy of the kinematic solutions for HKST station.

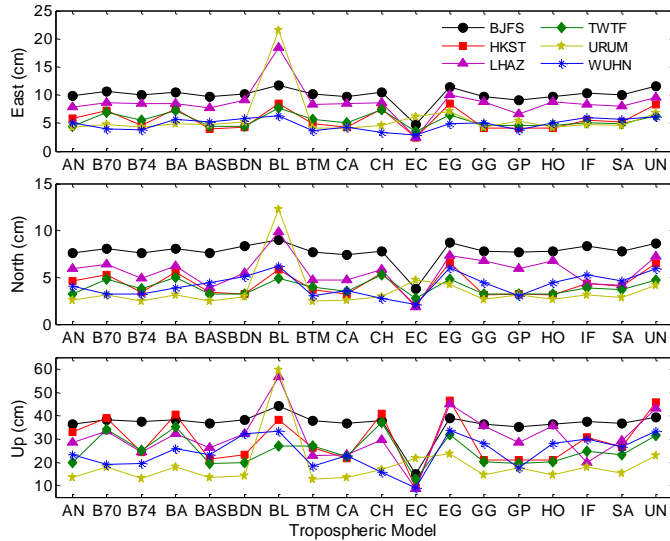


Fig. 4. RMS of PPP kinematic positioning errors

TABLE XI
THE LOCATION OF THE 6 GPS STATIONS

Station name	Latitude (°N)	Longitude (°E)	Height (m)
BJFS	39.6086	115.8925	87.4130
HKST	22.3952	114.1842	258.6894
LHAZ	29.6573	91.1040	3622.0000
TWTF	24.9536	121.1645	203.1220

Fig. 4 illustrates the RMS of the kinematic PPP positioning errors for the 6 stations. The abscissa shows the abbreviation code of the 18 ZWD models. The three sub-graphs show the RMS values for the east, north and up components, respectively. With the use of tropospheric model, the kinematic PPP accuracy is approximately 5~10 cm in the horizontal and 10~50 cm in up direction for the tested 6 stations. As seen in Fig. 4, generally kinematic PPP solutions using the EC_ZW (ECMWF) and BL_ZW (Black) models have the best and worst performance, respectively. This is in consistency with the assessment presented in the last section. In addition, it is not a surprise that the performance of EG_ZW (EGNOS) or UN_ZW (UNB3) model is not as good as other models since these two models use predicted meteorological parameters. Among the 6 stations, URUM station gets the highest positioning accuracies. This can be explained that URUM station is located at Urumqi, a region with semi-arid climate. Thus, water vapor induced wet delay is not as much as that at the other stations.

In last section, we classified the 18 ZWD models into three groups according to their accuracy. It is interesting to find that the performance of the 18 models basically match with that classification. The PPP kinematic positioning solutions using ZWD models of group 1 generally have better accuracies than those using ZWD models of group 2. This is true for the results obtained from using ZWD models of group 2 and group 3. Nevertheless, there are some exceptional cases. For instance, GP_ZW model does not show a good ranking in the assessment presented in section IV(B) (see Fig. 3). However, its performance in kinematic PPP is comparable with BAS_ZW that is ranked as the second best ZWD model in the last section IV(B) (see Fig. 3). Moreover, for different stations the performance of some models vary greatly. These discrepancies are explicable by this reason. In the GPS positioning, the zenith delays need to be projected to the line-of-sight direction of GPS satellite signals with a mapping function (Global Mapping

Function (GMF[44]) is adopted in PANDA software). The mapping function cannot account for the non-isotropic distribution of the atmospheric delay because the water vapor distribution at different azimuths overhead each station is different.

VI. CONCLUSION

In space geodetic techniques particularly in today's GNSS applications, it is always scientifically significant and practically important to accurately correct the tropospheric delay to achieve the best possible solutions. The optimal way to correct tropospheric delays is to make observations of atmospheric profiles. However, it is impossible to deploy a large number of instruments such as radiosonde to obtain atmospheric profiles. In some applications, tropospheric delays with an accuracy of several centimeters are allowed. Based on this realistic consideration, many tropospheric delay models using surface meteorological measurements (including pressure, temperature and relative humidity) have been developed. In this study, a comprehensive assessment and analysis of the performance of 9 ZHD models and 18 ZWD models is performed using the benchmark values derived from 10 years (2003-2012) of observations at 92 radiosonde stations in China.

Our studies show that the ZHD model with the best overall accuracy is EC_ZH with RMS error of 2.8 mm. The BA_ZH, GG_ZH, HO_ZH, BL_ZH and SA_ZH models also achieve good performance with RMS errors ranging from 6.0 mm to 8.4 mm. For seasonal temporal performance, EC_ZH, BA_ZH, GG_ZH, HO_ZH, BL_ZH and SA_ZH consistently show good modeling accuracy in all the four seasons. We also examine the spatial performance of the models in different latitudinal zones in China. We find that most of the models perform better in high latitude regions than in low latitude regions. Though the EC_ZH achieves the highest accuracy, it is only the best choice for post-mission applications. This is because the ECMWF reanalysis data cannot be available in real-time and the ECMWF forecasts are very difficult to access. For real-time applications, considering the performance and complexity of all the models, we recommend SA_ZD be used to model the ZHD in China region since it is the simplest one that needs only the surface pressure data. However, if both surface pressure and temperature data are available, the BA_ZH model is recommended. When neither pressure nor temperature data are available or only cm-level accuracy is required, GP_ZH is a good choice as we have shown that GP_ZH can achieve an overall accuracy of 11.6 mm in China.

The highly variable nature of water vapor content in the atmosphere results in the difficulty of modeling the wet delay as well as the hydrostatic delay. The model with best overall performance is EC_ZW, with RMS error of 21.4 mm. The BAS_ZW, HO_ZW, GG_ZW, AN_ZW and SA_ZW also show relatively good performance with RMS errors less than 40 mm. From the perspective of seasonal performance, all the ZWD models perform better in winter than in summer in China region. Models in spring show similar performance to those in autumn. In addition, basically higher accuracy of ZWD

modeling can be obtained in high latitudes than in low latitudes. The EC_ZW, BAS_ZW, SA_ZW, AN_ZW, GG_ZW, GP_ZW, HO_ZW and IF_ZW exhibit relatively good accuracy in all the four latitude zones in China.

In addition to the assessment by radiosonde, we also tested the 18 ZWD models in the kinematic PPP mode with the ZHD calculated by the BA_ZH model. The performance of the 18 models generally in good agreement with the accuracy assessment results that use radiosonde as benchmarks. Generally, ZWD models in group 1 have better performance than those in group 2, and similarly for ZWD models in group 2 and group 3. Based on our results, we conclude that: 1) For post-mission applications, EC_ZW can provide the highest accuracy of ZWD; 2) For real-time applications, a possibility is to use EC_ZW forecasts, however, for most of the users this kind of data are very difficult to access. Therefore, we recommend SA_ZW as the optimal ZWD model for the China region due to its simplicity and good performance; 3) If there are radiosonde data available, it is recommended to use the radiosonde data to establish a semi-empirical Baby model for this region; 4) If no surface meteorological observation is available, the best choice is to employ AN_ZW to compute the ZWD with meteorological parameters provided by the GPT2 model. However when a more accurate estimate of tropospheric wet delay is required, other techniques such as radiosonde, water vapor radiometer (WVR) and GNSS may be considered.

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