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研究论文

利用地基 GPS 技术反演武汉地区大气可降水分

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摘要：利用武汉地区的探空资料和 GPS 实测数据，对对流层干分量延迟、对流层加权平均温度进行了检验分析。结果表明，对于武汉地区而言，常用的大气干分量延迟模型 (SAAS, Hopfield and Black) 存在着 1~2 cm 的系统误差，这在利用 GPS 资料估算大气可降水分 (PWV) 时会引入 2~3 mm 的误差；对流层加权平均温度与常用的 Bevis 公式也存在着一定的差异，但这种差异对 PWV 结果影响很小。为此，提出了校正对流层干分量延迟的方法，并利用实测数据对该方法进行了检验。实践证明，这种校正方法基本上可以消除常用干分量模型的系统误差。

关　键　词：天体测量学；GPS；大气可降水分；对流层加权平均温度；干分量延迟；探空气球

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Remote Sensing of PWV Using Ground-Based GPS Data in Wuhan Region

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Abstract: Since early nineties last century, ground based GPS meteorology has been getting great progress in the world. Many countries including China have been constructing continuous GPS network for the purpose of research and application of this new technology. The results

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from these networks are encouraging and then near real-time estimation of Precipitable Water Vapor (PWV) are undergoing to build a perfect system in some countries too. Despite of these, one fundamental element is usually neglected, which was found by analyzing the radiosonde data collected in Wuhan Observatory to prepare for the incoming ground-based GPS meteorology application in Wuhan. That is the accurate model of Dry air Zenith Delay (DZD) in certain region. Usually, three most popular Dry air Zenith Delay models —— Saastamoinen (SAAS), Hopfield and Black are believed to be accurate in several millimeters and then are thought to be almost no influence on the estimation of PWV. In practice, due to the relationship between DZD and the temperature and pressure profile above site, DZD models in different regions may be a little different from each other. To reduce the influence of DZD model errors on the estimation of PWV, DZD models accuracy should be investigated so that a precise model suitable to this region is obtained. This paper is trying to do some work on this aspect using radiosonde data in Wuhan region. The following results indicate that there is a systematic error which can be up to more than 16 mm in the three popular DZD models, which will introduce more than 2 mm into the result of PWV. Therefore, a bias and some scale parameters are introduced in these models to eliminate the systematic errors. The parameters are estimated using the Least Squares method and are shown in Table 3 below. To validate these models after calibration, a set of data was analyzed. The results show that the influence of DZD on PWV is less than 1 mm after calibration in Wuhan. On the other hand, the same case occurs on another fundamental element —— the weighted mean tropospheric temperature. With the same way as Bevis used, more than 40 days' radiosonde data were processed and it was found that there was a good linear relationship between the mean tropospheric temperature and the surface temperature in Wuhan area while linear regression was involved in analysis. Moreover, the linear equation resulted from those radiosonde data is so close to Bevis' formula that the equation owns the influence of 1 mm on the estimation of PWV in Wuhan compared with Bevis'.

Key words: astrometry; GPS; Precipitable Water Vapor (PWV); weighted mean temperature of troposphere; Dry air Zenith Delay (DZD); Radiosonde

1 Introduction

In the last decade there was considerable research into the use of ground based static GPS data for the meteorology application which was known as Ground-based GPS meteorology whose main objective is to derive the Precipitable Water Vapor (PWV) content in troposphere. Studies during this period indicated that PWV derived from GPS data is comparable with that from radiosonde in 1−2 mm [1−3], which can improve short-term weather forecast accuracy by 20 percent while it was assimilated into Numerical Weather Prediction (NWP) model [4,5]. Also, GPS owns higher temporal and spatial coverage and lower cost compared with traditional water vapor sensing technologies such as Water Vapor Radiometer (WVR). Nowadays the determination of PWV using ground-based GPS data is quite popular in many countries.

In China, the first permanent GPS continuously operating network for meteorology research and application purpose was completed in the Yangtse River Delta including Shanghai region and other cities around it in Aug., 2002. Also, there are still other cities such as Shenzhen (being constructing by our GPS Center), Beijing (by Beijing) are under construction of multi-functional continuously operating GPS network including GPS meteorology application. Hubei Province including Wuhan region plans to construct similar network in the following two years too (one project of the Tenth 5-year Plan of Hubei Weather Bureau). To prepare for the future GPS Meteorology (GPS/MET) application in Wuhan Region, studies have been carried out to evaluate the technology application efficiency at present. This article has the objective of presenting the first results of studies that came about when compared to the values of PWV obtained by launching of radiosondes at Wuhan Observatory accomplished in the fall of 2002.

As the determination of PWV using GPS is based on the separation of Dry air Zenith Delay (DZD), which can be obtained by certain empirical models, such as Saastamoinen (SAAS), Hopfield, and Black model, using surface temperature, pressure, from Total Zenith Delay(TZD) to gain Wet air Zenith Delay (WZD), and the profile of the tropospheric mean temperature, which can be obtained by superficial temperature too, to get the value of mapping scale factor so that WZD can be converted to PWV. However, DZD from empirical models shows a little systematic error compared with that from radiosonde as shown in Figure 1. Also, there is still difference between these empirical models as shown in Figure 1. Then, selecting a good model or calibrating an empirical model using radiosondes for certain region is necessary for the accurate estimation of PWV in this region. On the other hand, the value of the weighted mean tropospheric temperature

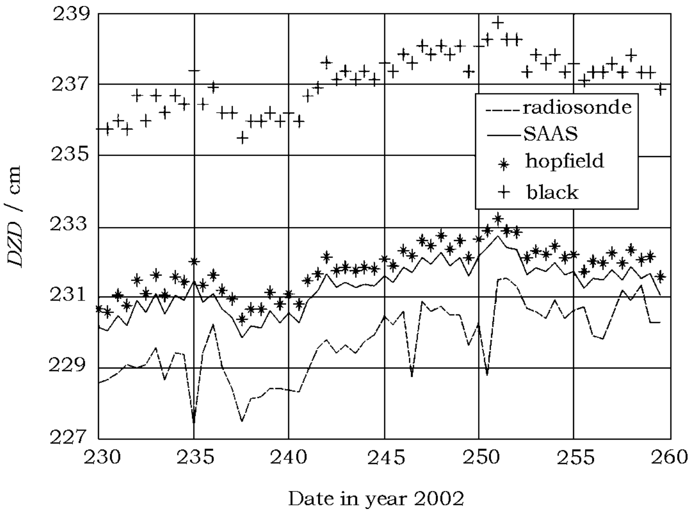

Fig.1 DZDs calculated from the radiosonde data and three models from Aug. 18 to Sept. 16, 2002

modeled from surface meteorological observations depends on the place. Then it is still necessary to develop a linear regression among those amounts from radiosondes launched in Wuhan Observatory to fit the application of GPS/MET in this area. This paper will focus on these two aspects to find a good model for the accurate estimation of DZD in Wuhan region and a fine linear equation for the determination of the weighted mean tropospheric temperature in this region too.

2 Data Set and Applied Method

The GPS data were collected simultaneously at the site of releasing radiosonde in Wuhan Observatory at the interval of 30 s, accomplished by Hubei Weather Bureau and Wuhan Observatory in the period of Sept. 17 to 27, 2002, corresponding to the 260 – 270 d of the same year. The GPS antenna used is Trimble brand, TRIMBLE TR GEOD L1/L2 GP model, and the receiver is Trimble 4000SSI model. To construct a large-scale campaign so that the correlation at two ends of one baseline is small enough to get accurate estimation of troposphere zenith delay at Wuhan Observatory, data at other four sites were collected simultaneously too. One is GBG0, which is one site of Dongting Lake Vertical Deformation campaign (a project of SGG, Wuhan University) observed during this period whose sites are about 200 km from Wuhan. Other three sites are IGS permanent tracking stations —— WUHN, SHAO, BJFS, whose data were download from ftp://garner.ucsd.edu. The radiosonde used is GZZ2 model with 701-radar tracking and receiving data collected when sounding balloon is ascending at the speed of 7 m/s. It collects data 5 – 8 times per minute and can reach about 31 km above surface where air pressure is about 10 hpa during August and September in Wuhan.

For the determination of the Zenithal Tropospheric Delay (ZTD) of GPS signals, the GPS data were processed with the GAMIT GPS Analysis Software version10.06 developed at MIT using ionosphere-free combination LC observable and double differences method involved, with 30-second processing interval and the application of 15° minimum elevation angle. The mapping function used was of Niell [6]. The satellite orbits used in the processing were the final orbit products of IGS and downloaded from ftp://137.79.24.21. The method used to estimate ZTD is the approximation of the stochastic method —— piecewise linear method [7,8]. ZTD was estimated once every two hours when these GPS data were processed in J2000 inertial frame with WUHN constrained strongly and others loosed.

For the meteorological data recorded by radiosondes, they were processed for two purposes. The first was to estimate DZD and the second was to gain the weighted mean tropospheric temperature.

The DZD can be written as [9]

$$d = 10^{-6} \int_H N_\mathrm{d} \mathrm{d}h \ , \qquad (1)$$

where N_d is the dry air refractivity. The dry air refractivity can be calculated from the meteorological measurements using a precise empirical formula by Thayer [10] as:

$$N_{\mathrm{d}} = 77.6\frac{P_{\mathrm{d}}}{T}\left(1 + P_{\mathrm{d}}\cdot\left(57.90\times10^{-8}\times\left(1+\frac{0.52}{T}\right) - 9.4611\times10^{-4}\times\frac{t}{T^2}\right)\right) \ , \tag{2}$$

where P_{d} is the partial pressure of dry air in mbar, T is the temperature in Kelvin, and t is temperature in Celsius. The dry partial pressure and temperature along the vertical path should be known to calculate the dry air refractivity along the vertical path, which can be provided by the radiosonde measurements. This information can then be used to convert the upper dry air refractivity into the dry delay in the vertical direction using the following expression:

$$d_{\mathrm{R}} = 10^{-6}\sum_i (h_{i+1} - h_i)\frac{N_{\mathrm{d}_{i+1}} + N_{\mathrm{d}_i}}{2} \ , \tag{3}$$

where the quantities with subscript i and $i+1$ denote their values at the top and bottom of every layer respectively, h is height in km and N_{d} is dry air refractivity.

The weighted mean temperature of troposphere T_{m} is defined as [11]

$$T_{\mathrm{m}} = \frac{\int (e/T)\cdot \mathrm{d}h}{\int (e/T^2)\cdot \mathrm{d}h} \ , \tag{4}$$

where e is the partial pressure of water vapor in mbar. In practice, the upper-air sounding can provide a series of discrete temperature and relative humidity measurements while a balloon is rising. In the formula above, water vapor pressure is needed. Then we first convert the relative humidity profile into the profile of water vapor pressure. Actually, the discrete observations in a profile separate the troposphere into many layers. If we assume temperature and water vapor pressure variations in each layer are linear, then the formula above can be written as [8]

$$T_{\mathrm{m}} = \frac{\sum (e/T)\cdot (h_{i+1} - h_i)}{\sum (e/T^2)\cdot (h_{i+1} - h_i)} \ . \tag{5}$$

In the above expression, h is the height above the mean sea level in meter, e and T are the average water vapor pressure and temperature for the corresponding layer.

3 Calibration of DZD in Wuhan

The DZD is usually calculated using an empirical model that makes use of surface meteorological measurements. The most popular and famous models belong to SAAS, Hopfield and Black. Three models for DZD are expressed as [8]

$$\mathrm{d}_{\mathrm{S}} = 0.2277\cdot\frac{P}{F(\varphi, H)} \ ,$$

$$F(\varphi, H) \equiv 1 - 0.0026\cdot\cos(2\varphi) - 0.00028\cdot H \ ,$$

$$d_{\mathrm{Hop}} = 1.552\cdot(h - H)\cdot\frac{P}{T} \ ,$$

$$h \equiv 40.082 + 0.14898 \cdot (T - 273.16),$$

$$d_{\mathrm{B}} = 0.2343 \cdot (T - 4.12) \cdot \frac{P}{T} .$$

In the above expression φ is the latitude of station in radian, H is the leveling height of the station in km, and P is the total surface air pressure measurement in mbar. T is the absolute temperature in Kelvin, and h denotes the height of upper edge troposphere in km. The delays with subscript S, Hop and B are denoted the SAAS, Hopfield and Black models respectively. The unit of DZD is centimeter.

To analyze how much these models are suitable for Wuhan region, one month radiosonde data, from Aug.18 to Sept.16, 2002, were processed to compare the result from three models mentioned above and formula (3) as shown in Figure 1. The results show that there is a systematic offset between the delays computed from the radiosonde data and the models. The offset is clearly revealed in Figure 2, which is constructed using the differences between delays computed from radiosonde data and other three models. Statistics for the differences between the radiosonde results and the three models (Table 1) shows that the average offsets are about 15.9, 21.0, 71.3 mm for SAAS, Hopfield and Black respectively. These results mean that SAAS and Hopfield models are more suitable to Wuhan region than Black model. But systematic errors have to be calibrated so that PWV offset affected by DZD model is less than 1 mm.

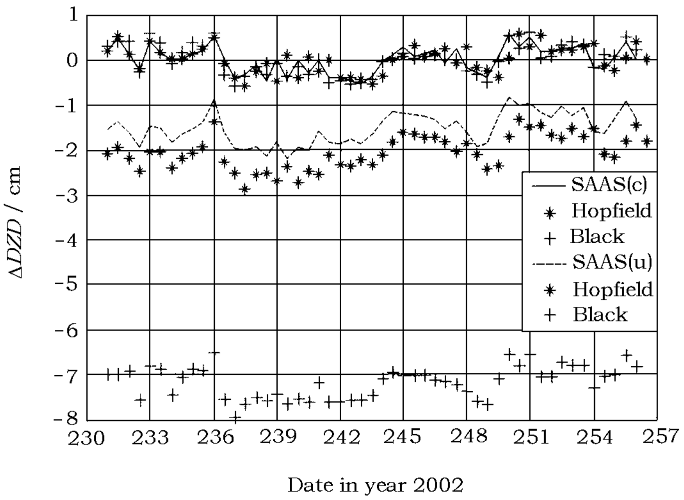

Fig.2 Differences of DZD (radiosonde-model) before and after the calibration

In this figure, c denotes the results after calibrating, u before calibration.

Table 1 Statistics on the Deviations Between Radiosonde and Three Models

	Max	Min	Mean	rms
radiosonde – SAAS	−0.18	−4.11	1.59 ± 0.64	1.71
radiosonde – Hopfield	−0.67	−4.72	2.10 ± 0.66	2.20
radiosonde – Black	−2.30	−9.33	7.13 ± 0.80	7.19

Since DZD is related to the hydrostatic refractivity, which is a function of the ratio of dry air pressure to the absolute temperature. We also adopt similar expression in the following calibration model.

$$d_{\mathrm{R}} - d_{\mathrm{M}} = \delta + \mu \frac{P_{\mathrm{d}}}{T} + \varepsilon \ .$$

Here, the left-hand side of the equation is the difference between the DZDs computed from radiosonde data and those from a model. δ represents the bias (constant part of the systematic differences) in cm, μ is a calibration scale factor in cm Kelvin mbar^{-1}, and ε random error.

Using radiosonde data collected twice daily (at UTC 23:15 and 11:15 everyday) by the Wuhan Observatory, the parameters δ and μ are estimated for three models using the Least Squares technique. The results are shown in Table 2.

Table 2　Estimated Calibration Parameters

Model	δ/cm	$\mu/\mathrm{cm}\cdot\mathrm{K}\cdot\mathrm{h}^{-1}\cdot\mathrm{Pa}^{-1}$
SAAS	-11.14 ± 0.21	2.860 ± 0.062
Hopfield	-13.52 ± 0.21	3.420 ± 0.063
Black	-12.81 ± 0.24	1.670 ± 0.071

The small uncertainties of the estimated bias and scale parameters indicate that the calibration parameters are significant. The adjusted differences compared to the result of uncalibrated models as plotted in Figure 2 show that the systematic offset is eliminated. The Black model obtains a similar result as other two models after calibration, compared with the big difference shown in Figure 1.

4　Determination of Weighted Mean Troposhperic Temperature in Wuhan

There are many methods for the estimation of the weighted mean temperature of troposphere. One often mentioned by many published papers is Bevis method, which was based on a large number of radiosonde data in the United States, whose form is described as follows:

$$T_{\mathrm{m}} = 70.2 + 0.72 \cdot T_0 \ , \tag{6}$$

where T_0 is the surface temperature of site in Kelvin, T_{m} denotes the linear estimate of the weighted mean temperature of troposphere.

From formula (5), T_{m} relates to the water vapor pressure and temperature profile above site, which is variable for different areas. On the other hand, the accuracy of T_{m} will influence the conversion from WZD to PWV through mapping scale factor directly. The influence on PWV can be up to 1 mm if the uncertainty of T_{m} is 3.4 K as indicated by Table 3 [8]. For this reason, formula (6) may be not suitable for Wuhan region. Then a precise model of T_{m} will be needed for certain region so that its influence can be reduced as more as possible.

Here, we take the similar method as Bevis by using 44 d radiosonde data, from Aug.18 to Sept.30, 2002, to construct a useful formula for Wuhan.

Using water vapor pressure (e) and temperature (T) of these 88 radiosondes profiles above Wuhan Observatory, through a numerical integration via equation (5), the values of weighted mean temperature of troposphere were obtained. Starting from these values of $T_{\rm m}$ and the surface temperature at the moment of launching of each radiosonde, the linear regression parameters were adjusted, obtaining the following expression:

$$T_{\rm B} = 265.31 + 0.79 \cdot t_0 \ , \tag{7}$$

where $T_{\rm B}$ is given in Kelvin while t_0 should be in Celsius.

Figure 3 shows the values of the weighted mean temperatures of troposphere as a function of surface temperature, using the data collected from 88 radiosondes. The continuous line represents the linear regression given by equation (7).

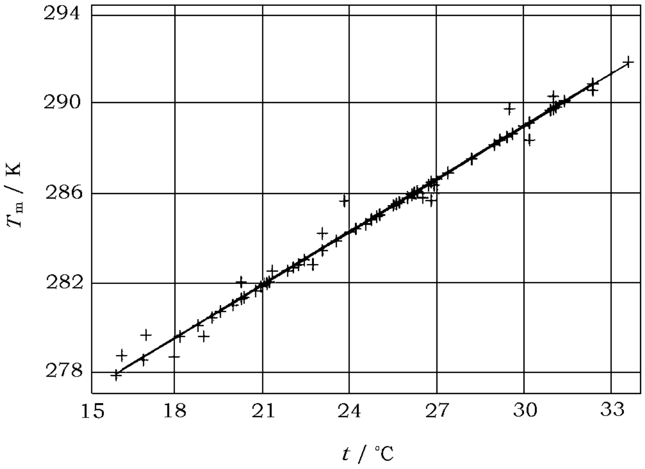

Fig.3 Values of mean tropospheric temperature from 88 radiosondes launched in Wuhan Observatory

As Figure 3 shows, there is a good linear relationship between the surface temperature and the weighted mean tropospheric temperature in Wuhan. The residuals of the weighted mean tropospheric temperatures estimated from radiosonde data compared with those from equation (7) are very small and the RMS is 0.3581.

Figure 4 shows the difference of $T_{\rm m}$ between the result from Bevis formula and that from radiosonde data.

As shown, Bevis formula also expresses the good linear relationship between the surface temperature and the weighted mean tropospheric temperature in Wuhan during these 44 days. The RMS is 0.4224 which is a little larger than 0.3581. According to the accuracy of weighted mean tropospheric temperature on the estimation of PWV described in Table 3, formula (7) and

Bevis' formula own the same accuracy on the estimation of PWV on the level of less than 0.45 mm for these 44 days.

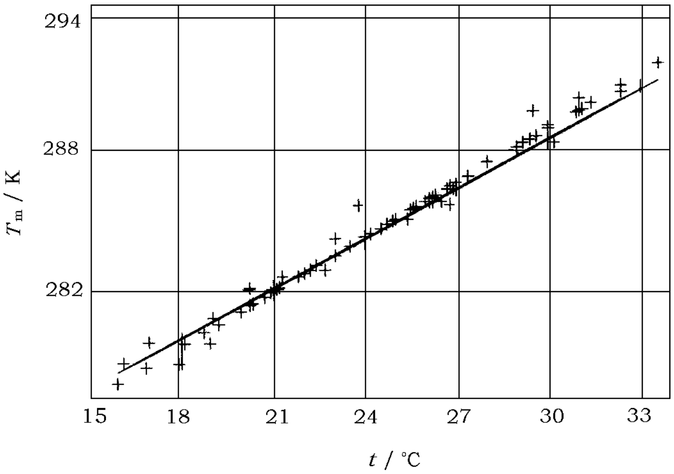

Fig.4 Values of mean tropospheric temperature from 88 radiosondes launched in Wuhan Observatory

Table 3 The Uncertainty of F as Function of σ_T

	σ_T/K			
	1.0	2.0	3.0	4.0
σ_F	0.0009	0.0014	0.0020	0.0026
PWV/mm	0.45	0.7	1.0	1.3

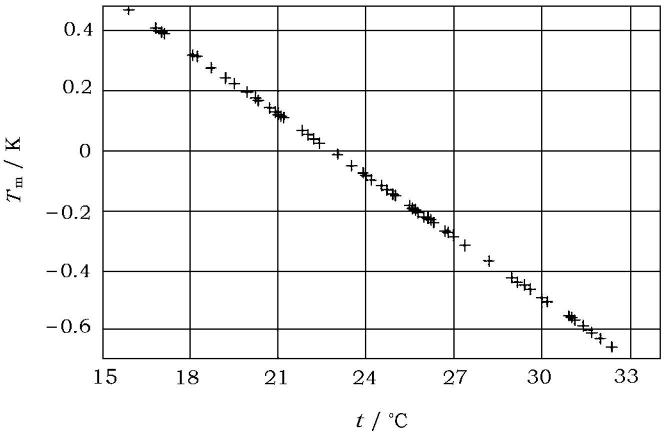

Fig.5 The difference of the weighted mean tropospheric temperature between the results from Bevis formula (6) and equation (7)

Figure 5 shows the difference of the weighted mean tropospheric temperature between the results from Bevis formula (6) and equation (7) whose absolute values are less than 0.7°C which would own influence less than 0.40 mm on the estimation of PWV. But, there is a trend shown in Figure 5 that the absolute values of differences of T_{m} will rise when temperature is going up or down at the turn point of 22°C. Then in winter when temperature is below 0°C, the difference will be up to 2°C, which would introduce 0.7 mm into PWV.

Therefore, Bevis' formula agrees with formula (7) on the level of 0.7 mm on PWV, considering the climate in Wuhan region. If the influence of the weighted mean tropospheric temperature on PWV less than 0.5 mm is needed for application to Wuhan region, then equation (7) is recommended.

5 Validation and Analysis

As discussed above, three calibrated DZD models for Wuhan region from the most popular models are obtained with the birth of the linear equation for the estimation of the weighted mean tropospheric temperature using over a month radiosonde data. To validate the three calibrated models and the linear equation, 11 d GPS data were processed according to what was described in section two to get PWV while SAAS model is used to get DZD, equation (7) is used to obtain T_{m}. Also the DZD of 14 d from Sept.17 to 30, 2002 are computed with formula (3) using the profiles above Wuhan Observatory provided by radiosondes. The differences of DZD using two methods are shown in Figure 6.

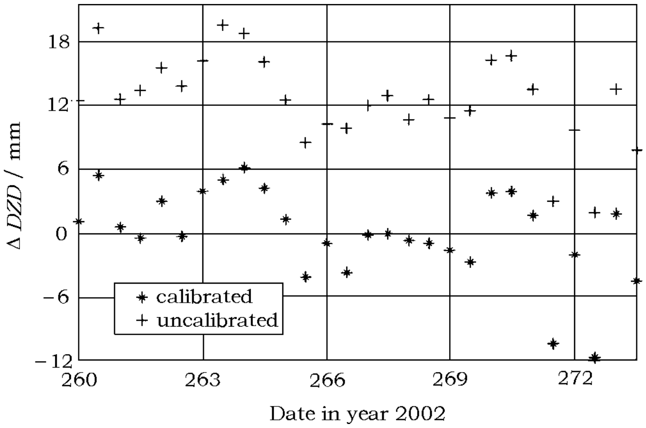

Fig.6 The differences between DZD from calibrated and uncalibrated SAAS models and radiosondes launched during Sept.17 to 30, 2002

As shown in Figure 6, the differences after calibration are usually fluctuating from −6 mm to 6 mm except two cases around day 272 which are up to −10.42 mm and −11.86 mm that are still less than the mean difference 12.55 mm before calibration. This means that the SAAS model after calibration eliminates the systematic error, which could introduce more than 2 mm error into PWV. However, there are two cases occurred at day 271.5 and 272.5 where the differences of DZD from uncalibrated SAAS model are closer to that from radiosondes than after calibration. This may be caused by the bad records stayed in radiosonde data which were not corrected effectually when 701 radar receiving data. Taking out these two cases, the three calibrated models are recommended to Wuhan region considering the consistency of these three calibrated models in Figure 2.

The weighted mean tropospheric temperatures derived from radiosondes during this period were used to get equation (7) and the RMS of values in Figure 3 is 0.3513. According to Table 3 and the formula deduced by Liu [8], their influences on PWV are very small and can be neglected.

6 Conclusions

This work describes the first experiences in the estimation of PWV using GPS in Wuhan region. Three calibrated DZD models for Wuhan are presented here with a bias parameter δ and a scale parameter μ introduced into the most popular DZD models. Also a linear equation for the estimation of the weighted mean tropospheric temperature for Wuhan was obtained using a linear regression method to analyze more than 40 d radiosonde data if the influence of the weighted mean tropospheric temperature on PWV less than 0.5 mm is needed for application to Wuhan region. The result of validation using 11 days' GPS and radiosonde data shows that the calibrated DZD models and equation (7) work well in the separation of PWV from TZD.

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