Importance of Hydrostatic Delay Models in Deriving PWV from GPS Signal Delays

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***Abstract*—Studies have shown that Precipitable Water Vapor (PWV) derived from the Global Positioning System (GPS) signal delays are useful in remote sensing applications like rainfall prediction. The GPS-PWV values are derived from the zenith Wet Delays (ZWD). The accuracy of the GPS-PWV values largely depends on the accuracy of ZWD values, which are depended on the accuracy of the Zenith Hydrostatic Delays (ZHD). In this paper, the effect of different ZHD models on the GPS-PWV values are analyzed using 1 year of data from 6 different GPS stations. It was found that the performance of the different ZHD models varies as per the location and an optimum ZHD model is suggested for the different regions.**

I. INTRODUCTION

Precipitable Water Vapor (PWV) expressed in units of length, defines the water vapor content in a vertical column of unit cross section. These PWV values are useful in applications such as rainfall prediction [1], [2]. With the rapid deployment of Global Positioning System (GPS) ground stations, GPS signal delays are extensively being used to retrieve the PWV values (GPS-PWV) with better temporal resolution under all weather conditions.

The GPS-PWV values are derived from the Zenith Wet Delays (ZWD). This delay is obtained by subtracting the Zenith Hydrostatic Delay (ZHD) from the total tropospheric signal delays (ZTD) as shown by eq. 1.

$$ZWD = ZTD - ZHD \tag{1}$$

ZWD is a function of atmospheric water vapor profile and humidity. Whereas, ZHD generally depends on the surface pressure (P_s), temperature and refractive index of the troposphere and it contributes about 90 % of the total zenith delay. The accuracy of GPS-PWV values derived using ZWD values largely depend on the accuracy of ZHD.

There are different models that can be used to derive the ZHD values. Static ZHD model is the simplest model which is based on the station height only. Saastamonien ZHD model uses an empirical equation based on temperature and pressure values from Global Pressure Temperature (GPT) and/or GPT2 models. Vienna Mapping Function 1 (VMF1) ZHD model is based on actual meteorological data. This model takes longer time to process and needs internet connection throughout to get the 6-hourly updated coefficients.

TABLE I
GPS AND RADIOSONDE DATABASE

Region	IGS Station Identifier	Rad Station Identifier	Lat (Deg)	Lon (Deg)
Tropical	NTUS	48698	01.34 N	103.89 E
	DARW	94120	12.42 S	130.89 E
Sub-Tropical	MAS1	60018	27.67 N	015.58 W
	LHAZ	55591	29.66 N	091.13 E
Temperate	HOB2	94975	42.83 S	147.50 E
	YAKT	24959	62.01 N	129.71 E

In this paper, we compute GPS-PWV values using ZHD values from these different models and compare the results to the ground-truth. We take PWV values from radiosonde (Rad-PWV) as our ground-truth.

II. DATABASE AND DATA PROCESSING

The ZWD values are processed using the GPS-Inferred Positioning System (GIPSY) simulation software. The software requires ZHD values as input. We generate 4 set of ZWD values using 4 different ZHD models. The PWV values are then calculated using these ZWD values as shown by eq. 2.

$$PWV = PI \cdot ZWD \tag{2}$$

where, PI is a dimensionless factor determined by using eq. (3), which was derived using radiosonde data from 174 stations in our previous paper [3].

$$PI = [-\text{sgn}(L_a) \cdot 1.7 \cdot 10^{-5} |L_a|^{h_{fac}} - 0.0001] \cdot \cos \frac{2\pi(DoY - 28)}{365.25} + 0.165 - 1.7 \cdot 10^{-5} |L_a|^{1.65} + f, \tag{3}$$

where, L_a is the latitude, DoY is day-of-year, $h_{fac} = 1.48$ for stations from northern hemisphere and 1.25 for stations from southern hemisphere. $f = -2.38 \cdot 10^{-6} H$, where H is the station height, which can be ignored for stations below than 1000m.

The mathematical procedures to derive the PWV values from the radiosonde data is described in [4]. It requires inputs such as water vapor pressure, temperature and relative humidity data which can be recorded from radiosondes.

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For this paper, the PWV values are processed for 6 International GNSS Service (IGS) GPS stations for year 2012. Radiosonde data for the collocated radiosonde stations are downloaded from the website of Wyoming University [5]. The respective details are given in Table. I.

III. Results and Discussions

A. Analysis of Different ZHD Models

We first analyze the GPS-PWV values calculated using different ZHD models. Fig. 1 shows the boxplot of GPS-PWV values for one station, each from different regions. For each region, there are 4 boxplots indicating the different ZHD models.

When PWV values of the three regions are compared, it can be clearly seen that the PWV values for the tropical station is the highest with a least variation followed by the sub-tropical and then by the temperate region. This is expected as the absolute temperature is high with very less variation for the tropical region. Whereas for the other regions, the temperature can go very low and has higher variation as these regions experience seasonal changes.

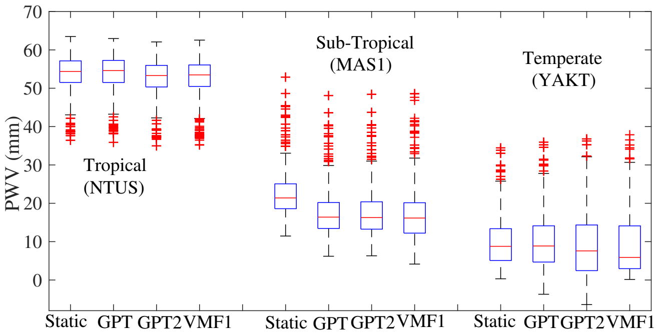

Fig. 1. Boxplot of PWV values for different regions when different ZHD models are used.

When the GPS-PWV values calculated using different ZHD models are inter-compared, no major changes are observed for the tropical region. For the sub-tropical region, PWV values for the Static model are higher compared to the others. For this sub-tropical station (MAS1), Static model might have overestimated the PWV values, as Static model is depended on height only and MAS1 is comparatively from a higher altitude. For the temperate station, it is observed that the median PWV value for the VMF1 model is the lowest compared to the rest of the models. This analysis shows that the different ZHD models have effect on the PWV values. Therefore, in the next section we compare these PWV values from different models to the ground truth values.

B. GPS-PWV Vs Rad-PWV

Table. II shows the root mean square error (mm) between the GPS-PWV values calculated using different ZHD models and the radiosonde PWV values.

TABLE II
RMSE (mm) values between Rad-PWV and GPS-PWV

Region	Station	RMSE (mm)			
		Static	GPT	GPT2	VMF1
Tropical	NTUS	**3.52**	3.58	3.83	3.67
	DARW	**5.87**	8.17	8.17	8.78
Sub-Tropical	LHAZ	5.57	**2.76**	3.36	5.50
	MAS1	5.19	**4.52**	4.49	4.49
Temperate	HOB2	4.89	4.77	4.66	**3.77**
	YAKT	4.72	4.33	3.53	**2.94**

It can be observed that for both the stations of the tropical region, Static model performs better. Since, the tropical stations do not undergo any drastic seasonal changes, the addition of temperature, pressure parameters as that of GPT, GPT2 or VMF1 model does not necessarily improve the PWV values.

Unlike for the tropical region, we observe that for the subtropical region, the GPT model performs the best. The Static model has a poor performance in the sub-tropical region; firstly because the sub-tropical region has seasonal changes which the Static model cannot capture. Secondly, as the Static model only considers height, especially for stations from higher altitude it overestimates the PWV values. Finally, it can be observed that the VMF1 model outperforms other models in case of the temperate region. Although VMF1 performs the best, it takes longer time computationally and also requires throughout internet connection to get the updated VMF1 coefficients.

IV. Conclusion and Future Works

Effect of using different ZHD models on the PWV values have been studied. It was found that the use of different ZHD models has a significant impact on the derived PWV values. The GPS-PWV values calculated using different ZHD models were compared to the radiosonde derived PWV values, and the RMSE of difference between the GPS-PWV and the Rad-PWV values were studied. It was found that the Static ZHD model, the GPT model, and the VMF1 model have the least RMSE values in the tropical, the sub-tropical, and the temperate regions respectively.

As a future work, this work will be extended by considering more stations from each region.

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