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Original article

Regional Ts-Tm Relation to Improve GPS Precipitable Water Vapor Conversions

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Abstract

As the retrieval accuracy of PWV estimates from GPS measurements is proportional to the accuracy of water vapor WMT, the WMT model is a significant formulation in the conversion of PWV from the GPS ZWD. The purpose of this study is to develop a MWMT model for the retrieval of highly accurate GPS PWV using the radiosonde measurements from six upper-air observing stations in the region of Korea. The values of 1-hr PWV estimated at four GPS stations during one year are used to evaluate the validity of the MWMT model. It is compared to the PWV obtained from radiosonde data that are located in the vicinity of GPS stations. Inter-comparison of radiosonde PWVs and GPS PWVs derived using different WMT models is performed to assess the quality of our MWMT model for Korea. The result in this study indicates that the MWMT model is an effective model to retrieve the enhanced accurate GPS PWV, compared to other GPS PWV derived by Korean annual or global WMT models.

Keywords: GPS Tropospheric Delay, Precipitable Water Vapor, Monthly Weighted Mean Temperature, Radiosonde

1. Introduction

As technology advances, it becomes practicable to make comparative measurements of equivalent parameters using entirely independent methods. One such method is the ground-based GPS (Global Positioning System) meteorology technique used to observe the upper-air moisture contents. The water vapor content of the atmosphere is sometimes given as the height of an equivalent column of liquid water, which is referred to the PWV (Precipitable Water Vapor) (Bevis *et al*., 1992). Numerically, the IWV (Integrated Water Vapor) is the product of the density of liquid water ρ_w and the PWV. Both the PWV and the ZWD (Zenith Wet Delay) have typically been calculated in centimeters or millimeters, so their ratio is a dimensionless quantity, as shown in Eq. (1).

$$\mathrm{PWV} = \Pi \times \mathrm{ZWD} \tag{1}$$

where $\Pi = \frac{10^8}{\rho \cdot R_v \cdot [(k_3/T_m) + k_2']}$, ρ is the density of water (kg/m^3), R_v is the specific gas constant of water vapor, (J/kg-K), k_2' is 22.1 ± 2.2 (K/mb), k_3 is (3.739 ± 0.012)×10^5 (K^2/mb), and T_m is the weighted mean temperature of the atmosphere (K).

Davis *et al*.(1985) demonstrated that the T_m depended on both the upper air temperature profile and the vertical distribution of water vapor as follows (Ross and Rosenfeld, 1997):

$$T_m = \frac{\int_0^\infty \frac{P_w}{T} dz}{\int_0^\infty \frac{P_w}{T^2} dz} = \frac{\int_{P_s}^0 \frac{\rho_w}{\rho_0} dp}{\int_{P_s}^0 \frac{\rho_w}{\rho_0 T} dp} \tag{2}$$

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where P_w is the partial pressure of water vapor (hPa), P_s is the air pressure at the surface (hPa), and ρ_0 is the air density (kg/m^3). Eq. (2) can be rewritten using the PWV and the specific humidity (q) as:

$$T_m = \frac{\rho_0 \cdot g \cdot PWV}{\int_{P_s}^{0} \frac{q}{T} dp} = \frac{\rho_0 \cdot g}{\int_{P_s}^{0} \left(\frac{q}{PWV} \right) \frac{dp}{T}} \tag{3}$$

Eq. (3) shows that the upper air temperature profile is weighted by the fraction of the PWV in each layer of the atmosphere. The T_m varies with location, altitude, season, and weather condition. The accuracy of PWV estimates using the GPS is proportional to the relative accuracy of the T_m (Bevis *et al.*, 1994; Ross and Rosenfeld, 1997; Wang *et al.*, 2005). An uncertainty of T_m will create an ambiguity in the retrieval of PWV from the GPS ZWD. If the vertical profiles of temperature and water vapor partial pressure were known exactly, the calculation of T_m and the PWV would also be exact, from Eq. (1) and (2). Therefore, the appropriate WMT (Weighted Mean Temperature) model that can reduce biases between the actual mean temperatures in the upper-air and the estimated mean temperatures will be useful for the estimation of an accurate GPS PWV.

2. Determination of the Monthly Weighted Mean Temperature Model

The method for determining the WMT model has been used as the linear regression or more complicated relationship between the surface temperature (T_s) measured from the ground weather stations and the T_m obtained from vertical profiles (Bevis *et al.*, 1992; Wang *et al.*, 2005). The atmosphere has typically a minus temperature gradient up to the tropopause, the T_m will be the mean temperature of the atmosphere weighted by the water vapor pressure as shown in Eq. (2). Since most of the water vapor is distributed in the lower atmosphere (above 2~3 km from the surface), we can expect that the T_m would be associated with the T_s. Thus, the WMT model with a linear form can be defined as Eq. (4).

$$T_m = a \times T_s + b \tag{4}$$

where a and b are coefficients obtained from the comparison of T_m from Eq. (2) using the upper air profiles of P_w and T from the radiosonde. The surface temperatures are obtained from the ground weather observing stations such as the AWS (Automated Weather Station). Due to the spatial and temporal irregularity of water vapor pressure and temperature, the magnitude of T_m varies in different locations and

Table 1. Linear weighted mean temperature models ($T_m = a \times T_s + b$)

Nation	*a*	*b*	# of used data	RMSE (K)	Period of data
USA (Bevis *et al*., 1992)	0.720	70.2	8,718	4.74	1989~1991 (2yrs)
Global (Mendes *et al*., 1995)	0.789	50.4	32,467	3.07	1992 (1yrs)
German (Solbrig, 2000)	0.770	54.7	Derived from numerical weather fields		
Global (Schueler *et al*., 2001)	0.647	86.9	Numerical weather prediction		1999~2001 (2yrs)
Taiwan (Liou *et al*., 2001)	1.070	-31.5	586	1.67	1988~1997 (10yrs)
South Korea (Song and Grejner-Brzezinska, 2009)	1.010	-12.35	16,939	1.95	2003~2005 (3yrs)
Indian (Raju *et al*., 2007)	0.749	62.576	4,104	2.20	1995-1997 (3yrs)
China (Cao *et al*., 2008)	0.777	54.60	2,710	9.34	2004~2007 (4yrs)
Australia (Feng *et al*., 2001)	0.726	70.03	2,493	3.16	1999~2000 (2yrs)

times. Many researchers developed independent T_m using the vertical air profiles from the radiosonde for highly accurate GPS PWV retrieval (see Table 1).

In order to determine the MWMT (Monthly WMT) models, we collected and analyzed the radiosonde data from the WMO (World Meteorological Organization) as well as the surface temperature data at six sites from 2001 to 2003. Fig. 1 shows the geographic locations of the radiosonde sites, as well as the GPS stations. The radiosonde PWVs are used to evaluate retrieval accuracy of GPS PWV using the newly developed MWMT and six linear WMT models. The radiosonde profiles were integrated to retrieve the T_m using Eq. (2), which is described by Ross and Rosenfeld (1997), and the coefficients a and b of Eq. (4) were then determined by a least-squares fit of data sets per month. Table 2 lists the MWMT models and the statistical results.

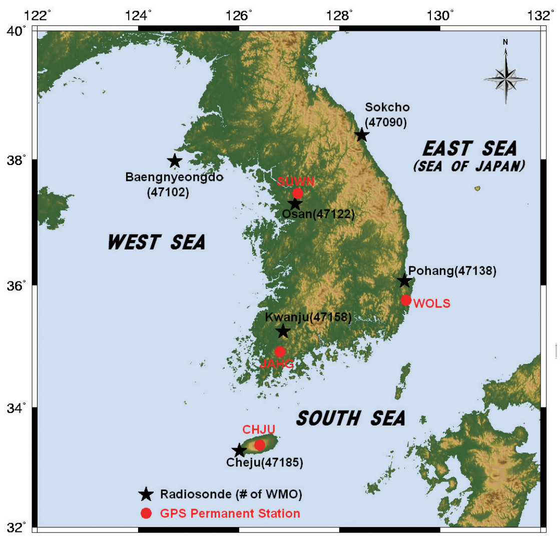


Fig. 1. Location map of radiosonde sites and GPS permanent stations

From the results of MWMT, we found that the slopes of the monthly linear equation were increased from 0.74 in July to 0.99 in February, as the monthly temperature became colder. The low RMSE (Root Mean Square Error) of each MWMT is shown in April (±2.25 K), and the large RMSE is in January (±1.55 K). The range of correlation coefficient between the T_s and the T_m for each month is distributed from 0.783 (June) ~ 0.954 (December). The mean correlation coefficient between the T_s and the T_m at all stations is revealed as 0.881.

Table 2. Coefficients (*a* and *b*) of monthly WMT models and statistical results of a regression between the surface temperatures and the upper-air temperatures in terms the RMSE (*c*) and the correlation coefficient (*D*)

Month	MWMT model ($T_m = a \times T_s + b$)	Statistical result (*c*=RMSE, *D*=correlation coefficient)
JAN	a=0.93, b=18.23	c=±1.55 K, D=0.938
FEB	a=0.99, b=03.77	c=±1.72 K, D=0.942
MAR	a=0.94, b=16.56	c=±1.92 K, D=0.927
APR	a=0.84, b=45.90	c=±2.25 K, D=0.880
MAY	a=0.76, b=71.02	c=±2.23 K, D=0.837
JUN	a=0.68, b=96.33	c=±2.08 K, D=0.783
JUL	a=0.74, b=77.89	c=±1.76 K, D=0.840
AUG	a=0.75, b=75.32	c=±1.73 K, D=0.851
SEP	a=0.75, b=73.55	c=±1.84 K, D=0.833
OCT	a=0.76, b=69.03	c=±2.07 K, D=0.858
NOV	a=0.91, b=25.82	c=±1.85 K, D=0.924
DEC	a=0.98, b=05.00	c=±1.63 K, D=0.954

3. Evaluation of the GPS PWV Retrieval Accuracy using the MWMT

High-precision GPS data processing software, such as Bernese, GAMIT/GLOBK, and GOA II (GIPSY-OASIS II), can be used to estimate the ZTD (Zenith Total Delay), after accounting for all the other contributions coming from ionospheric refraction, signal multipath and scattering by the neighborhood environment of the ground-based receiver (Jade *et al.*, 2005; Nordman *et al.*, 2009; Song and Grejner-Brzezinska, 2009). In order to evaluate retrieval accuracy of GPS PWV with the developed MWMT models, we used 12 months of data recorded at four GPS tracking stations operated by the NGII (National Geographical Information Institute) in Korea. The GOA II software developed by the JPL (Jet Propulsion Laboratory) is utilized in the GPS data processing to obtain the hourly ZTD at the

GPS station during one year (Lichten and Border, 1987; Larson and Miyazaki, 2008; Song and Yun, 2008; Song *et al*., 2008). We retrieved the GPS PWV that was calculated from the ZWD obtained from the ZTD by subtracting the ZHD (Zenith Hydrostatic Delay). The ZHD can be computed using the air-pressure and the temperature data at the surface of the GPS station in the Saastamoinen hydrostatic model (Saastamoinen, 1972), as shown in Eq. (5).

$$ZHD = \frac{(2.2779 \pm 0.0024[mm/hPa]) \cdot P_s}{1 - 0.00266 \cdot \cos 2\varphi - 0.00028\left[\frac{1}{km}\right] \cdot h} \quad (5)$$

where

P_s: total atmospheric pressure at surface/antenna site [hPa]

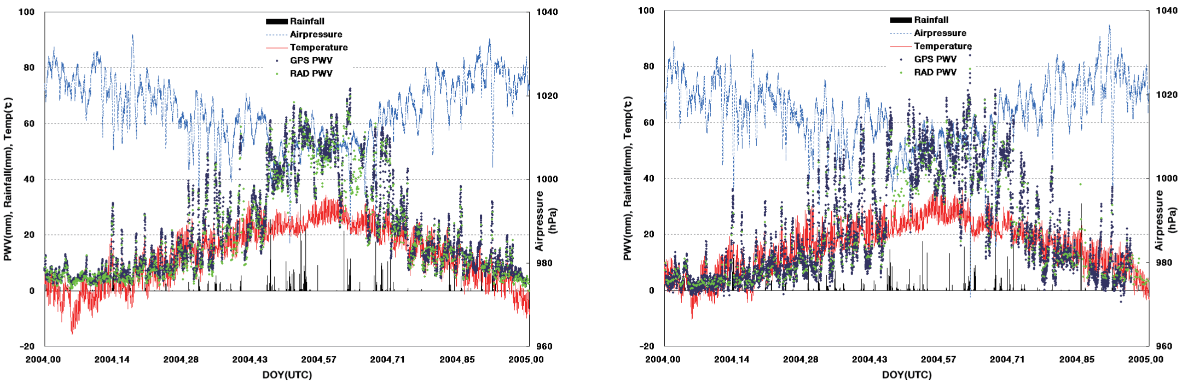
φ: geodetic latitude of the site [°]

h: ellipsoidal height [km].

Fig. 2 depicts the time series of the 1-hr estimated GPS PWV values using the MWMT, radiosonde PWV, and meteorological data at surface during 12 months. In order to properly evaluate the retrieval accuracy of GPS PWV using the MWMT, we estimated the GPS PWV using other WMT models. In other words, we again retrieved the GPS PWV in the conversion procedure from the ZWD to the PWV using the T_m values, which were calculated by other annual or global WMT models. The WMT models used are those presented by Song, Bevis, Mendes, Solbrig, Liou, and Schueler, as listed in Table 1.

Fig. 3 shows the time series graphs of hourly differences between the PWV derived from GPS and the radiosonde at the SUWN station. The GPS PWVs were derived using seven WMT models with identical weather conditions (i.e. air pressure and temperature) in all GPS PWV retrieval processes. Also, the radiosonde PWVs used in the difference calculation of both PWVs are the same in all procedures. In the analyzed results, the most enhanced RMSE (±1.770 mm) result showed in the case in which the MWMT was used.

In order to investigate the validity of MWMT in terms of GPS PWV retrieval accuracy, we classified the data set as each month, and performed a statistical analysis. Fig. 4 depicts the RMSE and the PWV offsets between the radiosonde PWV and the GPS PWV using each WMT model as well as MWMT. The GPS PWV retrieved from the adoption of MWMT models is the best fit with the PWV values derived from the radiosonde; the RMSE ranged from 1.605 mm in March to 4.348 mm in July, and the PWV offsets between these values varies from -0.133 mm in September to 1.130 mm in November. In comparison with the PWV using the other six WMT models including the result from the MWMT, the minimum RMSE at each month corresponds to the case when the MWMT is used. The worst-case scenario on an accuracy evaluation in Korea is revealed in the considered case of Taiwan's WMT model, which was developed by Liou *et al*.(2001) and was applied in this study. In general, the RMSE using the MWMT model steadily improves for all months, compared to the case in which the



(a) SUWN **(b) WOLS**

Fig. 2. Time series of GPS PWV using the MWMT, radiosonde PWV, air pressure, temperature, and rainfall at four sites

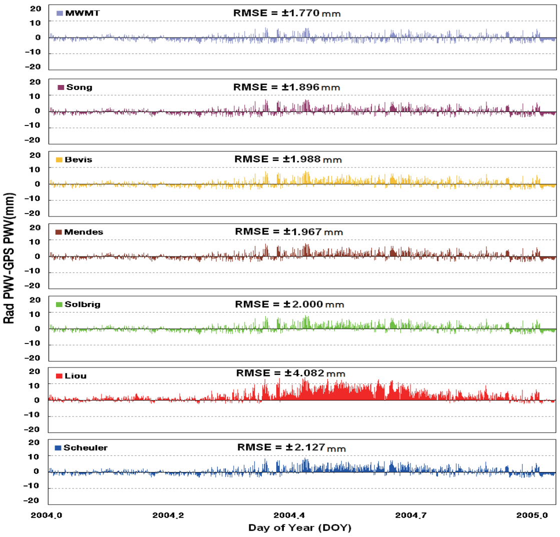


Fig. 3. Time series of hourly differences between PWV from two sensors at SUWN station

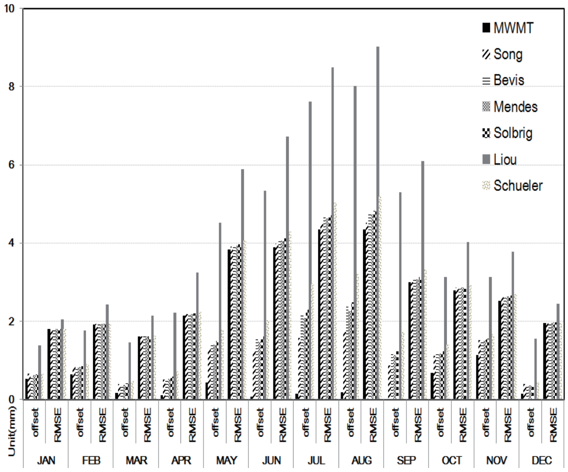


Fig. 4. Statistical results of a comparison between GPS PWV with various WMT models and radiosonde PWV in terms of the PWV offsets (radiosonde PWV – GPS PWV) and the RMSE

Korean annual WMT model (Song's model) was applied. The RMSE of PWV offset using the MWMT, compare to the Korean annual WMT model is less than about 0.006 mm (in Januany) to 0.132 mm (in November).

4. Conclusion

Since the balloon-borne radiosondes are available only twice a day at sparse locations over land, the exact T_m values obtained from upper-air profiles by radiosonde to estimate accurate GPS PWV using the real-time T_m are regularly unavailable. Therefore, the linear WMT model has been used to estimate the mean temperature of the upper air at the GPS station using the surface temperature. In this study, we retrieved the atmospheric PWV from the ground-based GPS measurements with the MWMT model for the enhanced GPS PWV retrieval with lowest biases compared with radiosonde PWV. The MWMT formula and other six WMT formulae are used to compare to the method of evaluating the validity of GPS PWV in terms of retrieval accuracy. We demonstrated that the GPS PWV using the MWMT model is in good agreement with that obtained from the radiosonde, compared to the usage of annual or global WMT models. Although the improving RMSE range from the analyzed results might be small, however, we suggest that the MWMT model would be useful for obtaining an enhanced GPS PWV. This is because we recognized that the MWMT model can reduce the biases of GPS PWV that were caused in the PWV conversion from the ZWD. An uncertainty of T_m by employing an annual or global linear T_m equation could create an uncertainty in the PWV retrieval from the GPS tropospheric delay. Thus, the weighted mean temperature is based on the MWMT considering that the monthly variation of upper-air temperature can improve the retrieval accuracy of GPS PWV. We expect that the MWMT developed in this study will be useful to the weather forecasting system in Korea, since the GPS meteorology technique is just beginning to be applied in numerical weather forecasting.

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