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Performance Analysis of Mapping Functions and Mean Temperature Equations for GNSS Precipitable Water Vapor in the Korean Peninsula

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ABSTRACT

The performance of up-to-date mapping functions and various mean temperature equations were analyzed to derive optimal mapping function and mean temperature equation when GNSS precipitable water vapor (PWV) was investigated in the Korean Peninsula. Bernese GNSS Software 5.2, which can perform high precision GNSS data processing, was used for accurate analysis, and zenith total delay (ZTD) required to calculate PWV was estimated via the Precise Point Positioning (PPP) method. GNSS, radiosonde, and meteorological data from 2009 to 2014 were acquired from Sokcho Observatory and used. ZTDs estimated by applying the global mapping function (GMF) and Vienna mapping function 1 (VMF1) were compared with each other in order to evaluate the performance of the mapping functions. To assess the performance of mean temperature equations, GNSS PWV was calculated by using six mean temperature equations and a difference with radiosonde PWV was investigated. Conclusively, accuracy of data processing was improved more when using VMF1 than using GMF. A mean temperature equation proposed by Wu (2003) had the smallest difference with that in the radiosonde in the analysis including all seasons. In summer, a mean temperature equation proposed by Song & Grejner-Brzezinska (2009) had the closest results with that of radiosonde. In winter, a mean temperature equation proposed by Song (2009) showed the closest results with that of radiosonde.

Keywords: GNSS, precipitable water vapor, mean temperature equation, mapping function

1. INTRODUCTION

The precipitable water vapor (PWV) in the atmosphere can be measured through radiosonde or microwave radiometer (MWR). However, these methods have many limitations to measure PWV. When using radiosonde, two or four observations occur in a day in general, its temporal resolution is low and new equipment has to be used in every observation, it is disadvantageous in terms of cost. The MWR is difficult to measure PWV accurately during rainy days and very expensive therefore it cannot be operated in many places.

The Global Navigation Satellite System (GNSS) estimates a zenith total delay (ZTD) of signals due to the troposphere during the GNSS data processing procedure. GNSS PWV is retrieved from the ZTD. This method does not measure PWV in the atmosphere directly as in the radiosonde or MWR but the PWV is obtained with nearly the same accuracy as in the existing methods (Bevis et al. 1992).

The estimation on PWV using the GNSS has many advantages compared to existing PWV measurement methods. First, it can obtain PWV for all around the year. It is not affected by the weather and continuous estimation with a short interval such as less than 10 min is possible. Second, the GNSS receiver is relatively inexpensive and easily movable as well as low cost of operation and maintenance. It can also employ GNSS infrastructure

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already developed around Korea and the world freely or at low cost. Third, it can obtain GNSS PWV at near real time due to the development of real-time or near real-time data processing technology. Accordingly, it can be utilized in weather forecasting via numerical weather prediction models (Lee et al. 2007).

Research on PWV using the GNSS has started from the late 1990s in South Korea (Moon 1998). In 2000s, a variety of methods that improve estimation accuracy of PWV were proposed and many studies on verification of the GNSS PWV have been conducted. Furthermore, various mean temperature equations have been developed for regions in the Korean Peninsula (Wu 2003, Song & Yun 2004, Ha et al. 2006, Ha & Park 2008, Song & Grejner-Brzezinska 2009, Song 2009). Since 2010, many studies on practical weather or utilization, such as climate analysis using the GNSS PWV, have been carried out. For example, Song (2012) analyzed a correlation between heavy snow in Gangwon in 2011 and GPS PWV. Kim & Bae (2015) analyzed a correlation between meteorological factor and PWV through analysis on PWV pattern before and after the heavy snow. Nam & Song (2015) analyzed a correlation between GPS PWV and amount of snowfall and other meteorological factors during the heavy snow period in Gangwon in 2014. Won & Kim (2015) presented analysis on spatiotemporal changes in PWV in the path of typhoon Ewiniar.

In the present study, performances of mapping function and mean temperature equation that are closely related to the reliability of the GNSS PWV are analyzed and optimal mapping function and mean temperature equation are derived in relation to the Korean Peninsula. High precision GNSS data processing is performed using precise point positioning (PPP) method via Bernese GNSS Software 5.2. For observation data, data at Sokcho Observatory from 2009 to 2014 where GNSS observation and radiosonde observations have been conducted simultaneously were acquired. In this study, effects of mapping function on data processing accuracy were analyzed using up-to-date mapping functions and GNSS PWV was calculated using six different mean temperature equations. Also, a PWV difference between radiosonde and GNSS was analyzed to select the most appropriate mean temperature equation in the Korean Peninsula.

The present paper is organized as follows: In Chapter 2, a method of GNSS data processing is briefly introduced and a method of conversion into PWV from data processing result is described. In Chapter 3, up-to-date mapping functions and mean temperature equations used in this study are explained. In Chapter 4, analysis strategies about mapping function and mean temperature equation are introduced and their results are described. Finally, the conclusion of this study is presented in Chapter 5.

2. RESEARCH METHODOLOGY

A signal delay due to the troposphere shall be estimated in the GNSS data processing procedure in order to acquire PWV from the GNSS. Thus, acquiring accurate PWV starts from high precision data processing. Next, estimated signal delay is recovered into GNSS PWV using meteorological data and mean temperature equation. In Chapter 2, a method used in this study for high precision data processing and a method that converts ZTD obtained via data processing into PWV are explained.

2.1 GNSS Data Processing

High precision data processing is needed foremost to calculate PWV accurately. In this study, Bernese GNSS Software 5.2 (Dach et al. 2007) developed by the University of Bern, Switzerland was used for data processing and the Precise Point Positioning (PPP) strategy was taken for the data processing method (Zumberge et al. 1997). The PPP provides a fast processing speed for single GNSS station and sufficient precision in the PWV calculation (Park et al. 2014).

Table 1 lists detailed setup information applied to the GNSS data processing. The final product of the Center for Orbit Determination in Europe (CODE) was used for precise ephemeris and clocks. The mask angle value was set to 5 degrees. Intervals of sampling and ZTD parameter were set to 5 min and 10 min. Finally, Global Mapping Function (GMF) and Vienna Mapping Function 1 (VMF1) were employed and the effect of mapping function on the accuracy of data processing was analyzed.

2.2 GNSS precipitable water vapor

The GNSS signal is delayed as it is passed through the troposphere and refracted. With the advancement of GNSS technology, this delay is now estimated at several mm level of accuracy through high precision data processing (Bevis

Table 1. GNSS data processing configuration.

Item	Setup
Processing engine	Bernese GNSS software 5.2
Data processing strategy	Precise point positioning
Satellite ephemeris/Clocks	CODE final
Elevation cutoff angle	5 degree
Sample interval	300 sec
Temporal resolution for ZTD	10 min
A priori tropospheric model/Mapping function	GMF / VMF1

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et al. 1992). ZTD is a parameter that refers to signal delay in the zenith direction, is divided into Zenith Hydrostatic Delay (ZHD) due to dry gas component and Zenith Wet Delay (ZWD) (Baek et al. 2007). That is,

$$ZTD = ZHD + ZWD \quad (1)$$

where, ZHD is calculated through the below process using barometric pressure information at the observatory region and the Saastamoinen hydrostatic model (Schuler 2001).

$$ZHD = 10^{-6}\int_{H_0}^{\infty} N_{HYD}\,dH = 0.022275\left[\frac{m^2}{s^2\cdot hPa}\right]\cdot\frac{p_0}{g_m} \quad (2)$$

where, H_0 means an altitude of the observatory, H is an altitude, p_0 is an atmospheric pressure in the observatory, g_m is a weight mean gravity acceleration, and N_{HYD} is a refractive index in the hydrostatic atmosphere. N_{HYD} is expressed as follows:

$$N_{HYD} = -k_1 R_d \frac{1}{g_m}\frac{dp}{dH} \quad (3)$$

where, k_1 is a hydrostatic refractive constant, R_d is a dry atmospheric gas constant, and p is a pressure. g_m is calculated via the following equation.

$$g_m = 9.784\left[\frac{m}{s^2}\right]\left(1 - 0.00266\cos 2\varphi - 0.00028\left[\frac{1}{km}\right]h\right) \quad (4)$$

where, φ means an altitude and h is a latitude. By substituting Eq. (4) into Eq. (2) and arranging the equation, the following equation is produced.

$$ZHD = \frac{0.022275\left[\frac{m^2}{s^2\cdot hPa}\right]p_0}{9.784\left[\frac{m}{s^2}\right]\left(1-0.00266\cos 2\varphi-0.00028\left[\frac{1}{km}\right]h\right)} = \frac{0.0022767\left[\frac{m}{hPa}\right]p_0}{1-0.00266\cos 2\varphi-0.00028\left[\frac{1}{km}\right]h} \quad (5)$$

Conclusively, ZTD in Eq. (1) is a value that is estimated during the data processing procedure and ZHD is calculated through the model so that the remaining ZWD can be known.

Then, ZWD is converted into PWV by the following correlation equation (Schuler 2001).

$$ZWD = 10^{-6}\left(k_2' + \frac{k_3}{T_m}\right)\frac{R_w}{\rho_{LW}}PWV \quad (6)$$

Here, k_2' and k_3 are refractive index constants, R_w means gas constant of water vapor, ρ_{LW} refers to density of water vapor, and T_m is a mean temperature in the troposphere. All variables except for T_m are constants and already known values. T_m is calculated using mean temperature equation and surface temperature.

3. MAPPING FUNCTIONS AND MEAN TEMPERATURE EQUATIONS

3.1 Mapping Functions

A mapping function is a correlation equation of delay in the zenith direction and delay in the slant direction, which is expressed as shown in Eq. (7). Here, zenith hydrostatic delay (ZHD) and zenith wet delay (ZWD) can be converted into slant total delay (STD) by the dry mapping function m_h and wet mapping function m_w. Note that e means the elevation angle of a GNSS satellite at the observation point.

$$STD = m_h(e)ZHD + m_w(e)ZWD \quad (7)$$

A mapping function that represents a correlation equation of delay in the zenith direction and delay in the slant direction was proposed by Saastamoinen (1972) and Marini (1972) for the first time. Since then, it was complemented and in 2000s, Niell mapping function (NMF) (Niell 1996) was most widely used. Boehm et al. (2006) proposed two mapping function models: GMF and VMF1 based on numerical weather forecast model of the European Centre for Medium-Range Weather Forecasts (ECMWF). The GMF model is an empirical mapping function that produces a mean value of the VMF1 model, which can be used by inputting latitude, longitude, altitude, and day of year.

Since NMF and GMF are approximate models to observation data or numerical model results, which calculate atmospheric delay using a determined coefficient, they can be used independently. However, they produce average values only, which are limited to simulate the ever-changing atmosphere. On the other hand, since VMF1 calculates delay around the world using numerical forecasting model every time, it simulates real atmospheric condition better. Instead, it is required to receive VMF1 data through the Internet in advance.

As described in the above, VMF1 is up-to-date mapping function model based on numerical forecasting model of the ECMWF, which has been known as the most accurate model that represents the real atmospheric conditions. The VMF1 model provides a service with four different versions: VMF1 Grid, VMF1-FC Grid, VMF1 Site, and VMF1-FC Site versions. VMF1 Site version provides a model value of the corresponding specific site location (e.g., the IGS sites). VMF1 Grid model, the most generally used model, provides

ZHD and ZWD values around the Earth with a resolution of 2°×2.5° (latitude × longitude). The VMF1-FC Grid model is a model that can be applied in order to use the VMF1 Grid model in real time. The VMF1 model is updated in every six hour four times a day.

3.2 Mean Temperature Equations

A mean temperature equation is a correlation equation of mean temperature in the atmosphere and surface temperature, which is expressed as a linear equation in general as follows:

$$T_m = a \cdot T_s + b \tag{8}$$

Here, T_m refers to a mean temperature in the atmosphere (unit K), T_s is a surface temperature (unit K), and a and b are coefficients. A mean temperature equation proposed by Bevis et al. (1992) is the most widely known equation and the Mendes model (Mendes 1999) is the world-wide model. As mentioned in the introduction, many mean temperature equations have also been developed in Korea in 2000s. Next, mean temperature equations developed for the Korean Peninsula are discussed and their characteristics are explained.

3.2.1 Mean temperature equations for the Korean Peninsula

Since a mean temperature equation that represented the climate characteristics in the Korean Peninsula was developed by Wu (2003) for the first time, it was developed by a few researchers. Wu (2003) developed a mean temperature equation using data collected from 1998 to 2001 for four years at six radiosonde observatories (Gwangju, Baengnyeongdo, Sokcho, Osan, Jeju, and Pohang).

$$T_m = 0.968T_s + 1.056 \tag{9}$$

Song & Yun (2004) also developed a mean temperature equation using data collected in 2003 for one year at six radiosonde observatories (Gwangju, Baengnyeongdo, Sokcho, Osan, Jeju, and Pohang).

$$T_m = 0.94T_s + 16.7 \tag{10}$$

Ha et al. (2006) developed the following mean temperature equation by analyzing data at six radiosonde observatories (Jeju, Gwangju, Sokcho, Osan, Pohang, and Heuksando) from 1998 to 2005 for eight years.

Table 2. Summaries of mean temperature equations.

Model	a	b	Observatory	Data collection period
Bevis et al. (1992)	0.72	70.2	USA	1989-1991 (Three years)
Mendes (1999)	0.789	50.4	Worldwide	1992 (One year)
Wu (2003)	0.968	1.056	Six in Korea	1998-2001(Four years)
Song & Yun (2004)	0.94	16.70	Six in Korea	2003 (One year)
Ha et al. Since (2006)	0.907	16.5	Six in Korea	1998-2005 (Eight years)
Song & G.-Brzezinska (2009)	1.01	-12.35	Song (2004) Improved version	
Ha & Park (2008)	0.884	23.4	Ha (2006) Improved version	
Song (2009)	0.98	6.21	Six in Korea	2003-2005 (Three years)
	0.76	72.91		
	0.92	22.49		
	0.97	8.67		

$$T_m = 0.907T_s + 16.5 \tag{11}$$

Song & Grejner-Brzezinska (2009) and Ha & Park (2008) re-introduced their mean temperature equations with better performance as follows respectively:

$$T_m = 1.01T_s - 12.35 \tag{12}$$
$$T_m = 0.884T_s + 23.4 \tag{13}$$

In addition, Ha (2014) proposed a mean temperature equation that can be calculated by time function and Song (2009) developed a seasonal mean temperature equation as below:

$$T_m = 0.98T_s + 6.21, \text{(Spring)} \tag{14}$$
$$T_m = 0.76T_s + 72.91, \text{(Summer)} \tag{15}$$
$$T_m = 0.92T_s + 22.49, \text{(Fall)} \tag{16}$$
$$T_m = 0.97T_s + 8.67, \text{(Winter)} \tag{17}$$

In Table 2, characteristics of above-mentioned mean temperature equations for the Korean Peninsula and internationally renowned mean temperature equations are summarized.

3.2.2 Comparison of mean temperature equations

Atmospheric mean temperature graph was produced by substituting a surface temperature from –20℃ to 40℃ in the mean temperature equations used in the PWV reliability analysis. As shown in Fig. 1, nearly all models were crossed over at a place around 12℃ of surface temperature. This temperature corresponds to a temperature in spring and fall in the Korean Peninsula. On the other hand, a difference between the mean temperature equations became larger at 20℃ or temperatures below freezing. The histogram in Fig. 1 shows a temperature distribution at the surface in summer (June, July, and August) and winter (December, January, and February) at Sokcho Observatory from 2009 to 2014. The surface temperatures in summer and winter

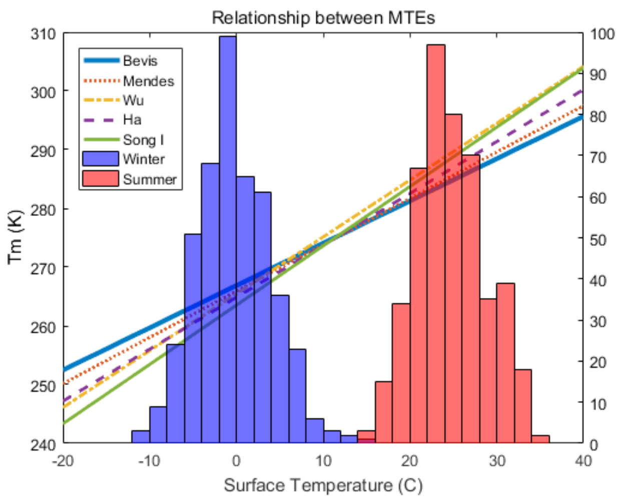

Fig. 1. Comparison of mean temperature equations and histogram of surface temperature.

are frequently distributed at a place where a difference of mean temperature is increased. Thus, there is no significant change in PWV regardless of which means temperature equation used in spring and fall, whereas the values of PWV should be changed according to mean temperature equation in summer and winter.

4. RESULTS

4.1 Mapping Function

As mentioned in the above, data processing should be done accurately first in order to acquire accurate precipitable water vapor. The performance of data processing is related to many factors. Thus, this study aims to verify the effect of each model on precision of data processing focusing on mapping function, in particular, up-to-date mapping functions. To achieve this goal, data processing was conducted using each of GMF and VMF1 with regard to data at Sokcho Observatory in 2014 for one year. The estimated ZTD formal accuracy and discontinuity of boundary values at the data processing results of daily were analyzed.

4.1.1 Formal accuracy

The formal error of ZTD estimated during the GNSS data processing procedure was analyzed. This is calculated by a square root of the covariance value related to the ZTD parameter. This refers to an estimated error of ZTD so that accuracy of data processing can be assessed by comparing formal errors.

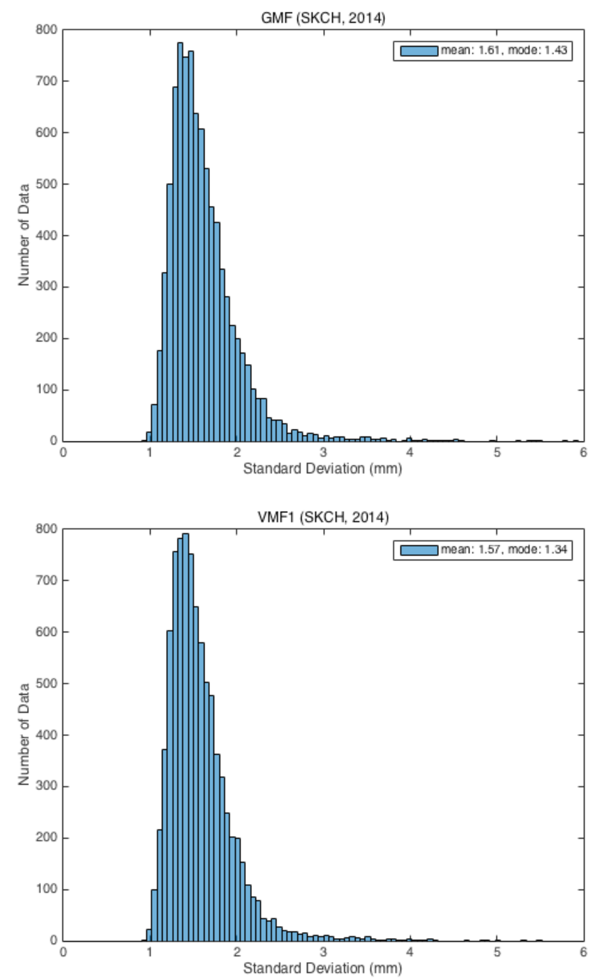

Fig. 2. Histogram of the formal errors for GMF (top) and VMF1 (bottom).

The histogram analysis results on formal errors of ZTD showed that smaller formal errors were revealed when using VMF1 than using GMF. The above graph in Fig. 2 shows the result using GMF and the below one shows the result using VMF1. For GMF, a mean of the formal errors was 1.61 mm and a mode was 1.43 mm. On the other hand, for VMF1, a mean was 1.57 mm and a mode was 1.34 mm, indicating a mean of formal errors in VMF1 was 0.04 mm smaller than that of GMF as well as a mode of VMF1 was 0.09 mm smaller than that of GMF. It is not a significant difference but using VMF1 can process data more accurately than using GMF.

4.1.2 Discontinuity

Second, discontinuity of ZTD value at the boundary of daily data processing was investigated. The daily estimated ZTD value has the lowest precision at the both ends and values at both ends should have continuity with the last or first ZTD estimated value of the adjacent days. However,

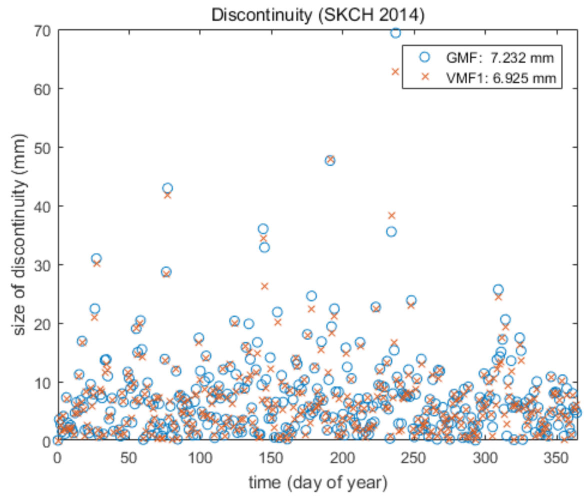

Fig. 3. Discontinuity of ZTD values at the boundaries.

real estimation results are not so. Thus, the reliability of the estimated value can be judged by checking this difference.

Fig. 3 shows a size of discontinuity at the boundaries in the daily data processing results at Sokcho Observatory in 2014. A size of discontinuity in both of GMF and VMF1 was mostly less than 20 mm and a mean size of discontinuity was 7.232 mm when using GMF and 6.925 mm when using VMF1. If this number is converted to PWV, it is a level of around 1 mm. When comparing GMF and VMF1, a size of VMF1 was approximately 0.3 mm smaller than that of GMF. In Fig. 3, a smaller size of discontinuity was also found when using VMF1 overall. This means that the reliability of ZTD estimation is increased when using VMF1.

In the above, histogram analysis on formal errors of ZTD parameters and evaluation on discontinuity at the boundaries were conducted to analyze performances of data processing according to mapping function. For ZTD parameter formal errors, a mean of formal errors using VMF1 was approximately 2.5% smaller than that of GMF. Moreover, a size of discontinuity using VMF1 was approximately 4.2% smaller than that of GMF on average. Based on the above analysis results, we can conclude that using VMF1 improved reliability of data processing more than using GMF.

4.2 Mean Temperature Equation

Since we cannot know the true value of PWV, it is difficult to evaluate the reliability. Therefore, the reliability of the GNSS PWV is evaluated by comparing PWV obtained from radiosonde, which measure PWV using a completely independent method. In contrast with the GNSS, radiosonde is a method that measures PWV directly so although it is not a true value, it is widely utilized as a reference PWV (Joh et al. 2001, Kwon et al. 2007, Park et al. 2009).

4.2.1 Strategy for PWV reliability analysis

The reliability of the GNSS PWV was verified by comparing and analyzing the radiosonde PWV and GNSS PWV from June 1 2009 to April 30 2014 at Sokcho Observatory. Since Sokcho Observatory performs radiosonde observation, GNSS observation, and meteorological data measurement at one place, it is appropriate for research on PWV. The analysis period was set by considering a period that radiosonde observation equipment was replaced. Note that RS92-SGP model of Vaisala from Finland was used from June 1 2009 to March 6 2011 followed by RSG-20A model of Jinyang Industrial Co. Ltd. in Korea until April 30 2013. After this, M2K2-DC model of MODEM in France was used up to April 30 2014.

If radiosonde device is replaced, its PWV is also changed discontinuously. This is because every device has different deflection. This deflection should be compensated in order to have accurate analysis. However, since we cannot know the true value, only a relative deflection between devices was compensated.

The data processing method used to calculate the GNSS PWV is summarized in Table 1 and VMF1 was used as a mapping function. When PWV is calculated using ZTD after data processing, two foreign mean temperature equations and four mean temperature equations in Korea were selected and used as a mean temperature equation among the models introduced in Table 2. Song & Grejner-Brzezinska (2009) and Ha & Park (2008) are revised version of mean temperature equations proposed by Song & Yun (2004) and Ha et al. (2006), which are improved version of the previous models. Therefore, previous mean temperature equations were excluded from this analysis. In summary, six mean temperature equations used in the analysis are Bevis (Bevis et al. 1992), Mendes (Mendes 1999), Wu (Wu 2003), Ha (Ha & Park 2008), Song I (Song & Grejner-Brzezinska 2009), and Song II (Song 2009).

By applying the six mean temperature equations, each of GNSS PWV was calculated and a bias of differences and root mean square error (RMSE) were calculated compared to those in the radiosonde PWV. Finally, the most suitable mean temperature equation for the Korean Peninsula was derived by comparing and analyzing the results between the mean temperature equations.

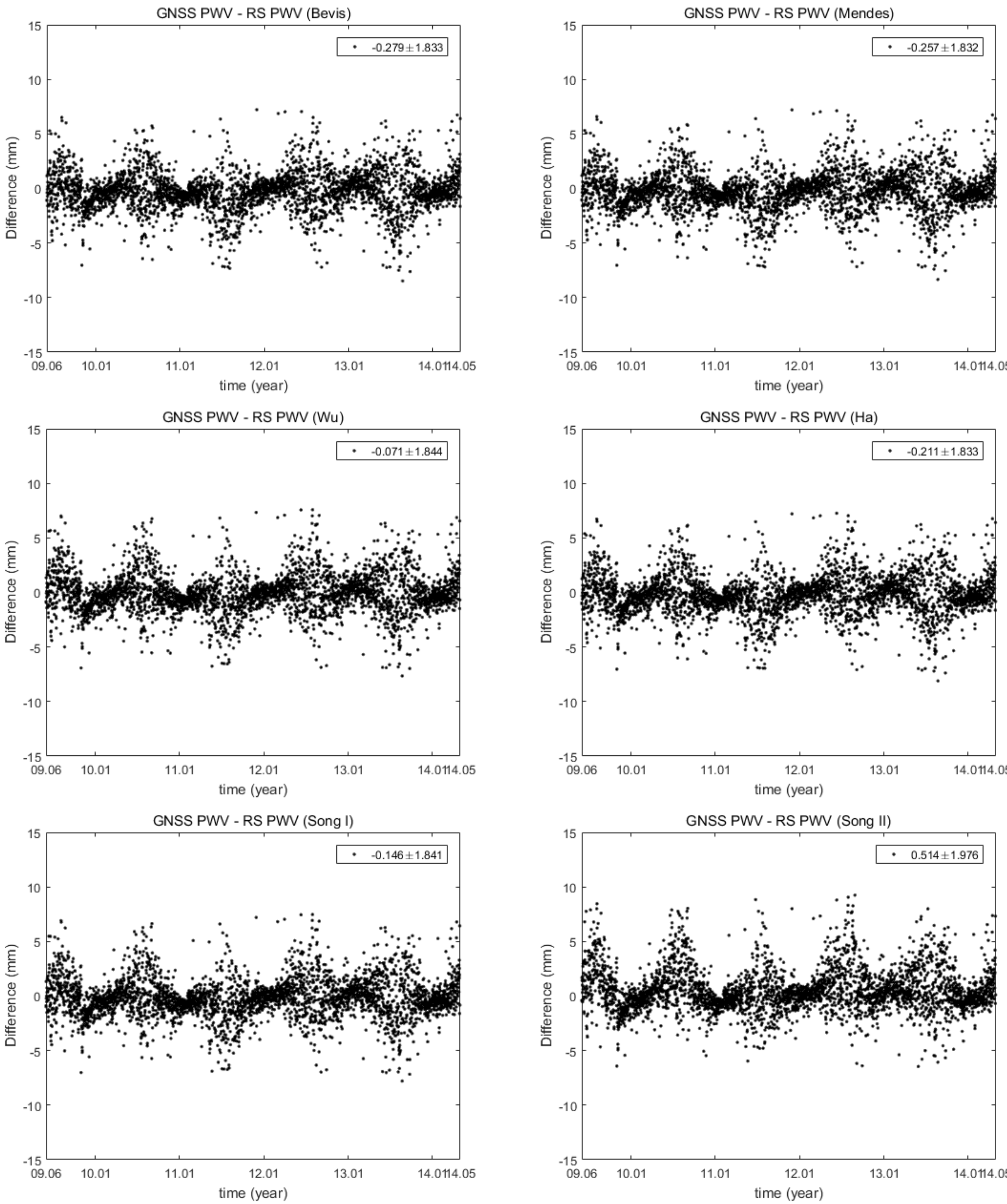

Fig. 4. Difference between GNSS PWV and radiosonde PWV for respective MTEs.

4.2.2 Comparison between GNSS PWV and radiosonde PWV

The GNSS PWV and radiosonde PWV at Sokcho Observatory from June 2009 to April 2014 for four years and 11 months were compared and analyzed. Fig. 4 shows values of PWV calculated using the six mean temperature equations subtracted by the radiosonde PWV in which radiosonde device deviation was compensated. As shown

Table 3. Summary of comparative analysis results for the MTEs.

	Bevis	Mendes	Wu	Ha	Song I	Song II
Bias (mm)	-0.279	-0.257	-0.071	-0.211	-0.146	0.514
STD. (mm)	1.833	1.832	1.844	1.833	1.841	1.976
RMSE (mm)	1.854	1.850	1.845	1.845	1.847	2.041

in Fig. 4, an overall trend was similar regardless of which mean temperature equation used. As shown in the figure, it was repeated that in summer, a deviation between GNSS PWV and radiosonde PWV was large whereas it was small in winter. In order to analyze a detailed difference according to mean temperature equation used, bias, standard deviation, and RMSE were calculated, which are summarized in Table 3.

As shown in Table 3, a difference due to mean temperature equation was not significant. Except for Song II model, all RMSEs were within 2 mm, indicating a consistent result with radiosonde PWV. The PWV calculated using completely independent method showed minimal difference, which means that the observation results of GNSS PWV or radiosonde PWV are reliable. Song II had relatively worse result because it used different equation in every season for one year analysis overall.

The characteristics of mean temperature equations revealed that mean temperature equations in Korea (except for Song II) had less bias but slightly larger standard deviation than those in foreign mean temperature equations. With regard to RMSE, models in Korea whose bias was smaller than foreign models showed slightly better result. In particular, both models of Wu and Ha had the least RMSE value. Among the six mean temperature equations, Wu model showed the least bias (-0.071 mm) and RMSE (1.845 mm), which was found as the most suitable model for the Korean Peninsula in the long term when calculating PWV using the GNSS.

4.2.3 Comparison between GNSS PWV and radiosonde PWV with the seasons

For the climate of the Korean Peninsula which has distinctive four seasons, it is necessary to evaluate a performance of mean temperature equation by season. As shown in Fig. 1, no significant difference is found between the models at temperatures that correspond to spring or fall. However, there are large deviations between the models at temperatures that correspond to summer (June, July, and August) or winter (December, January, and February). Thus, GNSS PWV and radiosonde PWV were compared and analyzed only for corresponding periods of each of summer and winter.

Table 4. Summary of comparative analysis results with the seasons for the MTEs.

		Bevis	Mendes	Wu	Ha	Song I	Song II
Summer	Bias (mm)	-0.474	-0.379	0.147	-0.213	0.017	1.547
	STD. (mm)	2.625	2.627	2.637	2.631	2.639	2.671
	RMSE (mm)	2.666	2.653	2.640	2.638	2.638	3.085
Winter	Bias (mm)	-0.322	-0.336	-0.340	-0.352	-0.372	-0.199
	STD. (mm)	0.962	0.960	0.958	0.957	0.953	0.987
	RMSE (mm)	1.014	1.017	1.016	1.019	1.023	1.006

In Fig. 5, red-colored points refer to the result during the summer and blue-colored points mean the result during the winter. It is clearly distinctive that a deviation is large in the summer and small in the winter. In order to analyze an in-depth difference according to mean temperature equation used, bias, standard deviation, and RMSE were summarized in Table 4.

Except for Song II model, when mean temperature equations in Korea were used, a difference with radiosonde was smaller than using foreign mean temperature equations in summer. In particular, the models in Korea reduced a bias significantly and although the foreign models had better standard deviation, its difference was not that significant. For RMSEs, Ha and Song I models were the best among all mean temperature equations. In particular, Song I model was the least bias (0.017 mm) and its RMSE was also relatively small. Thus, Song I was found as the most optimum model in summer for the Korean Peninsula.

On the other hand, the winter showed the opposite trend from that of the summer. The foreign models had smaller bias and larger standard deviation compared to local models except for Song II. Song II showed the least bias among all mean temperature equations as well as the least RMSE, which was analyzed as the most suitable model in winter for the Korean Peninsula.

5. CONCLUSIONS

In this study, performance analysis on mapping function and mean temperature equation was conducted to acquire the optimum result when calculating the GNSS PWV in the Korean Peninsula. Bernese GNSS software 5.2 was used for high precision data processing and ZTD was estimated using the PPP method. For mapping function, two of GMF and VMF1 were applied and data processing was conducted in 2014 for one year with data at Sokcho Observatory. The result showed that when VMF1 was used, a formal error of ZTD was reduced by 2.5% and a size of ZTD discontinuity by 4.2% compared to using GMF. Thus, VMF1 showed more accurate data processing result. In order to select the most suitable mean temperature equation for the Korean

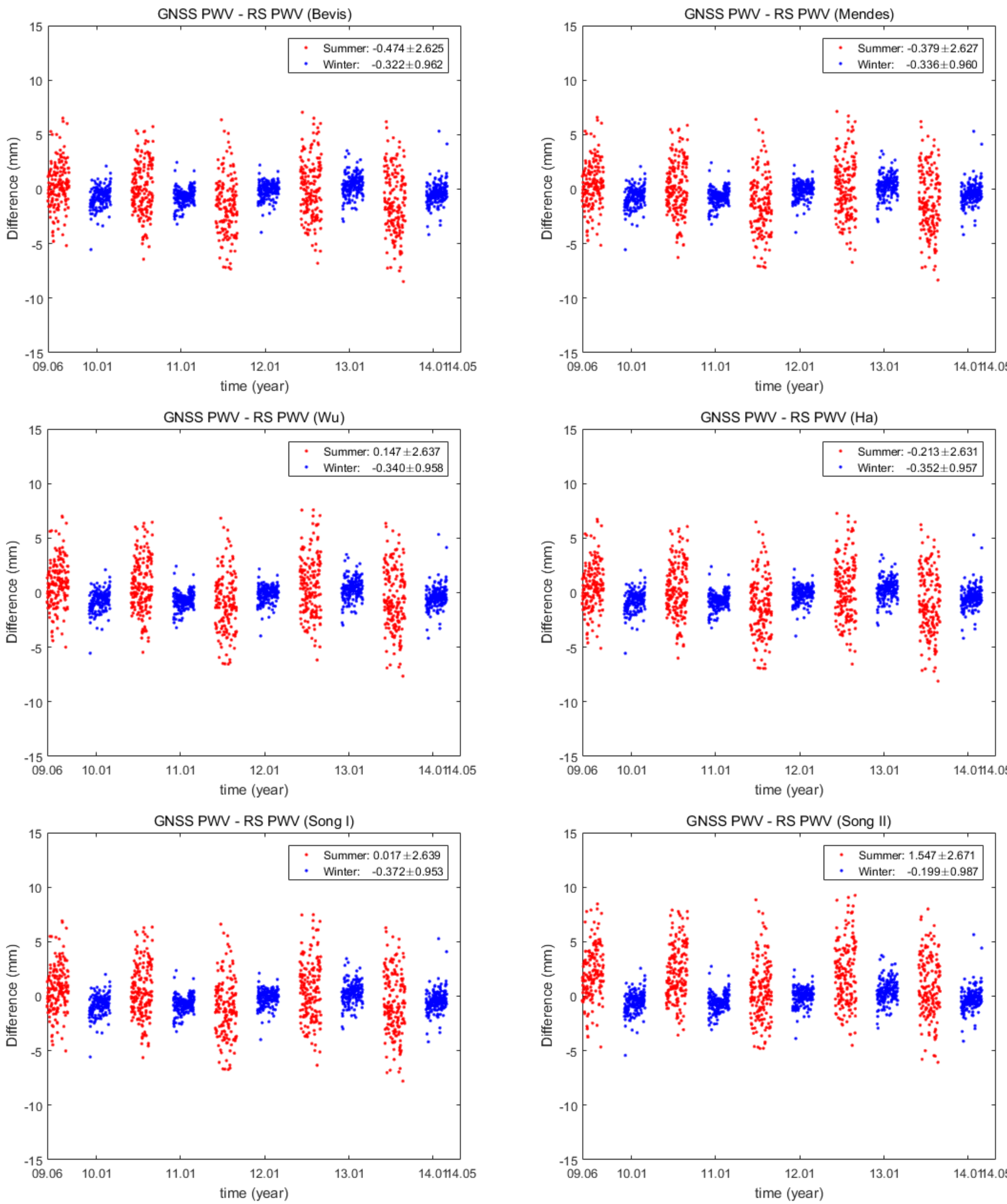

Fig. 5. Difference between GNSS PWV and radiosonde PWV with the seasons for respective MTEs.

Peninsula, GNSS PWV was calculated from June 1 2009 to April 30 2014 for about five years at Sokcho Observatory using six mean temperature equations. When compared with radiosonde observation results during the same period at the same location, a mean temperature equation of Wu revealed the least difference compared to radiosonde result for the period including all seasons. In addition, each mean temperature equation of Song I and Song II was slightly closer to the radiosonde observation result in summer (June, July, and August) and winter (December, January, and February). However, their difference was only a sub-millimeter compared to other local mean temperature equations indicating that similar performance can be achieved regardless of which mean temperature equation selected.

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REFERENCES

Baek, J.-H., Lee, J.-W., Choi, B.-K., & Cho, J.-H. 2007, Processing Strategy for near real time GPS precipitable water vapor retrieval, JASS, 24, 275-284. http://dx.doi.org/10.5140/JASS.2007.24.4.275

Bevis, M., Businger, S., Herring, T. A., Rocken, C., Anthes, R. A., et al. 1992, GPS meteorology: remote sensing of atmospheric water vapor using the global positioning system, JGR, 97, 15787-15801. http://dx.doi.org/10.1029/92JD01517

Boehm, J., Niell, A., Tregoning, P., & Schuh, H. 2006, Global mapping function (GMF): A new empirical mapping function based on numerical weather model data, GRL, 33, L07304. http://dx.doi.org/10.1029/2005GL025546

Dach, R., Hugentobler, U., Fridez, P., & Meindl, M. 2007, Bernese GPS Software Version 5.0. User manual (Bern: Stampfli publications)

Ha, J. 2014, Development of time-dependent mean temperature equations for GPS meteorology, JPNT, 3, 143-147. http://dx.doi.org/10.11003/JPNT.2014.3.4.143

Ha, J.-H. & Park, K.-D. 2008, Comparison of Local Mean Temperature Equations for GPS-based Precipitable Water Vapor Determination, JASS, 25, 425-434. http://dx.doi.org/10.5140/JASS.2008.25.4.425

Ha, J.-H., Park, K.-D., & Heo, B.-H. 2006, Development of a local mean temperature equation for GPS-based precipitable water vapor over the Korean Peninsula, JASS, 23, 373-384. http://dx.doi.org/10.5140/JASS.2006.23.4.373

Joh, J.-H., Pak, P.-H., Park, J.-U., Lim, H.-C., Kim, S.-C., et al. 2001, Proof of Measurement Precision for Precipitable Water using GPS, Asia-Pacific Journal of Atmospheric Sciences, 37, 557-565

Kim, J. S. & Bae, T.-S. 2015, Comparative Analysis of GNSS Precipitable Water Vapor and Meteorological Factors, Journal of the Korean Society of Surveying, Geodesy, Photogrammetry and Cartography, 33, 317-324. http://dx.doi.org/10.7848/ksgpc.2015.33.4.317

Kwon, H.-T., Iwabuchi, T., & Lim, G.-H. 2007, Comparison of Precipitable Water Derived from Ground-based GPS Measurements with Radiosonde Observations over the Korean Peninsula, Journal of the Meteorological Society of Japan, 85, 733-746. http://dx.doi.org/10.2151/jmsj.85.733

Lee, J.-W., Cho, J.-H., Baek, J.-H., & Park, J.-U. 2007, Analysis on GPS PWV effects as an initial input data of NWP model, JASS, 24, 285-296. http://dx.doi.org/10.5140/JASS.2007.24.4.285

Marini, J. W. 1972, Correction of Satellite Tracking Data for an Arbitrary Tropospheric Profile, Radio Science, 7, 223-231. http://dx.doi.org/10.1029/RS007i002p00223

Mendes, V. B. 1999, Modeling the neutral-atmospheric propagation delay in radiometric space techniques, UNB Geodesy and Geomatics Engineering Technical Report, No.199. http://www2.unb.ca/gge/Pubs/TR199.pdf

Moon, Y. 1998, Estimation of Precipitable Water Vapor in Troposphere using Global Positioning System, Master's Degree, Yonsei University, South Korea

Nam, J. Y. & Song, D. S. 2015, Remote Sensing of GPS Precipitable Water Vapor during 2014 Heavy Snowfall in Gangwon Province, Journal of the Korean Society of Surveying, Geodesy, Photogrammetry and Cartography, 33, 305-316. http://dx.doi.org/10.7848/ksgpc.2015.33.4.305

Niell, A. E. 1996, Global mapping functions for the atmosphere delay at radio wavelengths, JGR, 101, 3227-3246. http://dx.doi.org/10.1029/95JB03048

Park, C.-G., Baek, J.-H., & Cho, J.-H. 2009, Comparison of Precipitable Water Vapor Observations by GPS, Radiosonde and NWP Simulation, JASS, 26, 555-566. http://dx.doi.org/10.5140/JASS.2009.26.4.555

Park, H.-E., Roh, K. M., Yoo, S.-M., Choi, B.-K., Chung, J.-K., et al. 2014, Quality Assessment of Tropospheric Delay Estimated by Precise Point Positioning in the Korean Peninsula, JPNT, 3, 131-141. http://dx.doi.org/10.11003/JPNT.2014.3.4.131

Saastamoinen, J. 1972, Atmospheric Correction for the Troposphere and Stratosphere in Radio Ranging of Satellites, The Use of Artificial Satellites for Geodesy, Geophysics Monograph Series, vol. 15, eds. S. W. Henriksen, A. Mancini, B. H. Chovitz (Washington, DC: American Geophysical Union), pp.247-251

Schuler, T. 2001, On ground-based GPS tropospheric delay estimation, PhD Dissertation, Universitat der Bundeswehr, Munchen, Germany

Song, D. S. 2009, GPS water vapor estimation modeling with high accuracy by consideration of seasonal characteristics on Korea, Journal of the Korean Society of Surveying, Geodesy, Photogrammetry and Cartography, 27, 565-574

Song, D. S. 2012, Correlation Analysis between GPS Precipitable Water Vapor and Heavy Snowfall on Gangwon Province in Early 2011, Journal of the Korean Society of Surveying, Geodesy, Photogrammetry and Cartography, 30, 97-104. http://dx.doi.org/10.7848/ksgpc.2012.30.1.097

Song, D.-S. & Grejner-Brzezinska, D. A. 2009, Remote sensing of atmospheric water variation from GPS measurements during a severe weather event, EPS, 61, 1117-1125. http://dx.doi.org/10.1186/BF03352964

Song, D. S. & Yun, H. S. 2004, Determination of Weighted Mean Temperature for the GPS Precipitable Water Vapor Estimation, Journal of the Korean Society of Surveying, Geodesy, Photogrammetry and Cartography, 22, 323-329

Won, J. & Kim, D. 2015, Analysis of Temporal and Spatial Variation of Precipitable Water Vapor According to Path of Typhoon EWINIAR using GPS Permanent Stations, JPNT, 4, 87-95. http://dx.doi.org/10.11003/JPNT.2015.4.2.087

Wu, S. 2003, Adjustment of meteorological variables for the accurate estimation of GPS PWV, Master's Degree, Seoul University, South Korea

Zumberge, J. F., Heflin, M. B., Jefferson, D. C., Watkins, M. M., & Webb, F. H. 1997, Precise point positioning for the efficient and robust analysis of GPS data from large networks, Journal of Geophysical Research, 102, 5005-5017. http://dx.doi.org/10.1029/96JB03860

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