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Performance Assessment of GPS-Sensed Precipitable Water Vapor Using IGS Ultra-Rapid Orbits: a Preliminary Study in Thailand

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ABSTRACT

Precipitable Water Vapor (PWV) is a significant variable used for climate change studies. Currently PWV can be derived from the Global Positioning System (GPS) observation in addition to the specific instruments such as Radiosondes (RS), Microwave Radiometers (MWR) and Meteorological Satellites. To accurately derive PWV from GPS data, long periods of observation time in conjunction with final orbit data have to be applied in the data processing steps. This final orbit data can be acquired from the International GNSS Service (IGS) with 13 days latency, which is not practical in climate change studies or meteorological forecasting. Alternatively, real-time ultra-rapid orbits are more suitable for this application but with lower orbit accuracy. It is therefore interesting to evaluate the impact of using different orbits in the estimation of PWV. In this study, data from permanent GPS base stations in Thailand were processed using Bernese 5.0 software to derive near real-time PWV values. Ultra-rapid orbit data have been introduced in the data processing step with different time windows and compared to that using final orbit data with the 24-hr time window. The results have shown that 1.0 mm and 2.9 mm biases can be achieved using 24-hr and 12-hr time windows, respectively. These results therefore address the potential use of ultra-rapid orbits for a near real-time estimation of PWV.

KEYWORDS

GPS, Precipitable Water Vapor

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I. Introduction

Precipitable Water Vapor (PWV) is the total atmospheric water vapor contained in a vertical column of unit area, commonly expressed in terms of the height. Normally, the PWV content can be measured using specific instruments such as Radiosondes (RS), Microwave Radiometers (MWR) and Meteorological Satellites. However, these devices would only ever provide a sparse spatial coverage because of their expensive costs. Alternatively, PWV can be derived using GPS observed data. Results from previous research [1] - [7] have shown consistency of GPS-derived PWV and PWV measured from either MWR or RS. The increasing numbers of permanent GPS base stations in many countries encourage the use of GPS in meteorological studies. By utilizing data transmission and processing techniques, PWV can be derived without any additional cost. Furthermore, the highly temporal data from GPS can provide continuous measurements or even near real-time PWV around the GPS station. This enables promising active weather forecast especially for forecasting heavy rainfall. Previous studies in Thailand [8] - [10] have demonstrated a very good agreement between the GPS-derived PWV using final IGS orbits and the directly-measured PWV from the MWR. The GPS-derived PWV in Thailand is considered to be useful information to the Bureau of Royal Rainmaking and Agricultural Aviation since the PWV value is a key indicator for the success of royal rainmaking attempt. Currently, there are several GPS base stations operating in Thailand such as the Department of Public Works and Town & Country Planning (DPT) GPS base stations and the Department of Lands (DOL) GPS network. The density of these GPS stations is around a 200–600 km spacing. Although the current density is still not sufficient to model the high temporal and spatial variability of PWV, it is important to address its potential especially when more dense GPS station spacing becomes available in the near future.

To obtain the most accurate PWV estimates from GPS observations, long periods of GPS observations and precise orbit data must be employed in the data processing steps. This final orbit data can be acquired from the IGS with approximately 13 days latency. This latency is not acceptable for a near real-time weather forecast application. However, the use of real-time ultra rapid orbits is considered as an alternative for this application. Therefore, there is a need to evaluate the effect of using different orbits (final and ultra rapid IGS orbits) on the derivation of PWV. For a near real-time estimation, the computation time is one of the critical factors. An optimal observation time window used for a reliable estimation of PWV is also investigated in this study. In this paper, the GPS data and other data used are described. The data processing strategy used in the Bernese GPS software package is explained and the detailed procedures for calculating the PWV are given. Next the results are presented with some discussion followed by some concluding remarks.

II. GPS OBSERVATIONS AND OTHER USED DATA

GPS data used in this study were kindly provided by the Department of Public Works and Town & Country Planning (DPT). The DPT GPS base stations consist of 11 stations distributed over Thailand (see Figure 1). The DPT GPS base stations project was established in 1996 with 4 stations implemented at the beginning. Presently a total of 11 stations are fully operational. The DPT GPS Base Stations were designed to serve as reference stations for both real-time and post-processed positioning applications. Each station is equipped with a dual-frequency GPS receiver (Leica GRX1200) and a meteorological sensor (LeicatoMET). This configuration provides continuous L1 and L2 GPS observations and surface atmospheric pressure information which are needed for an estimation of PWV. First, the common availability period for most DPT GPS stations was checked. It was found that the period between January and July 2007 is the common period which has up to 10 GPS stations available. Hence, GPS data from a total of 10 stations (except for the Songkla station) were retrieved during that period. It should be noted that this period of time has covered all seasons (winter, summer and rainy) in Thailand. Figure 2 shows a photograph of the DPT9 GPS station.

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The final and ultra rapid orbits, spanning the same period of GPS data used, were downloaded from the International GNSS Service (IGS) (http://igscb.jpl.nasa.gov/components/prods_cb.html). Other data such as earth orientation parameters, receiver information, antenna phase center variation tables and satellite problems were downloaded from the Astronomical Institute, University of Bern (AIUB) (ftp://ftp.unibe.ch/aiub/BSWUSER50/GEN/).

Figure 1
Location of GPS Base Stations operated by DPT

Figure 2
Photograph of the DPT9 GPS station in Bangkok, Thailand

III. GPS DATA PROCESSING STRATEGY

The data processing can be divided into two steps; the establishment of reference coordinates and the estimation of Zenith Total Delay (ZTD) from GPS observations. The details are given below.

3.1 Establishment of reference coordinates

The scientific Bernese software version 5.0 [11] is selected as the main GPS data processing software to ensure accuracy and reliability of positioning results. In order to obtain accurate reference coordinates of all stations, GPS data were processed in daily batches with the IGS final orbits using standard processing settings as recommended in the software manual. The daily coordinate repeatabilities are typically ranging from 1.0 to 1.5, 1.0 to 2.0 and 3.0 to 5.0 mm for respectively the north, east and height components. The daily solutions were combined into weekly averaged solutions. The weekly averaged solutions of an individual station are then used as reference coordinates for subsequent processing.

3.2 Estimation of Zenith Total Delay (ZTD) from GPS observations

By using Bernese software, the ZTD can be reliably estimated from a 24-hr GPS observation time. To obtain the most reliable ZTD values, GPS data from all stations were re-processed with the IGS final orbits in daily batches by introducing the weekly averaged solutions as fixed coordinates. The Bernese software was configured to output the ZTD values at 3-hr intervals. The obtained ZTD values will be subsequently converted into PWV values. The details on how to convert from the ZTD to the PWV will be given in the next section. The outputs obtained from processing the GPS data with the final orbits will be used as references for subsequent comparison. Then, all GPS data were cut into segments of 3-hr, 6-hr, 8-hr, 12-hr and 24-hr respectively. This means that, for example, the 3-hr data segment from a total of 212 days (Jan-July 2007) resulted in a total of 1,696 sessions. Each data segment was separately processed using the ultra rapid orbits and the weekly averaged solutions were introduced as known coordinates in the processing steps. All processing was done in automatic mode using the Bernese Processing Engine (BPE). It should be noted that all settings were kept the same as the previous processing batch. Hence, any differences evident are due to the use of different observation lengths and orbit information. Table 1 summarizes the processing options and number of processing sessions.

	Number of processing sessions					
Month/	Final orbit	Ultra rapid orbit				
year	24-hr	24-hr	12-hr	8-hr	6-hr	3-hr
Jan’07	31	31	62	93	124	248
Feb’07	28	28	56	84	112	224
Mar’07	31	31	62	93	124	248
Apr’07	30	30	60	90	120	240
May’07	31	31	62	93	124	248
Jun’07	30	30	60	90	120	240
Jul’07	31	31	62	93	124	248
Total	212	212	424	636	848	1,696

Table 1
Processing options and number of processing sessions

IV. CONVERTING THE ZTD TO THE PWV

After obtaining the ZTD from the GPS data processing steps, the ZTD can be converted to PWV using empirical equations. As stated by [12], the ZTD can be divided in to two parts, Zenith Hydrostatic Delay (ZHD) and Zenith Wet Delay (ZWD). The relationship can be written as equation (1).

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$$\mathrm{ZTD} = \mathrm{ZHD} + \mathrm{ZWD} \quad (1)$$

As suggested in [1], the ZHD can be derived using surface pressure as described in equation (2)

$$\mathrm{ZHD} = \frac{2.2768\mathrm{P_s}}{1 - 2.66\cos(2\phi) - 2.8\times10^{-4}\mathrm{H}} \quad (2)$$

where ZHD Zenith Hydrostatic Delay (millimeter)
P_S Surface atmospheric pressure (millibar)
ϕ Latitude (Radian)
H Height above geoid (meter)

While ZWD is the integral function of partial water vapor pressure along a vertical column as shown in equation (3)

$$\mathrm{ZWD} = 10^{-6}\left(k_2' \int \frac{\mathrm{P_v}}{\mathrm{T}} dz + k_3 \int \frac{\mathrm{P_v}}{\mathrm{T}^2} dz \right) \quad (3)$$

where ZWD Zenith Wet Delay (millimeter)
Pv Partial water vapor pressure (millibar)
T Temperature (kelvin)
k'_2 Empirical constant (17 ± 10) (kelvin/millibar)
k_3 Empirical constant (3.776 ± 0.03) × 105 ($kelvin^2$/millibar)

To calculate the ZWD from equation (3), the partial water vapor pressure (Pv) is needed to be measured along a vertical path which is not possible in practice. However, the ZWD can be alternatively determined by subtracting the known ZHD from the ZTD as described in the equation (1).

[1] derived a relationship between the ZWD and the PWV as presented in the equation (4).

$$\mathrm{PWV} = \Pi \times \mathrm{ZWD} \quad (4)$$

where

$$\Pi = \frac{10^6}{\rho_l \times \mathrm{R_v}\left(k_3 / \mathrm{T_m} + k_2'\right)} \quad (5)$$

and

$$T_m = \int \frac{P_v}{T_i} dz \Big/ \int \frac{P_v}{T_i^2} dz \quad (6)$$

where ρ_l Density of water (1000 kg × m^{-3})
R_v Specific gas constant of water vapor (461.45 J × kg^{-1} × $kelvin^{-1}$)
T_m Weighted mean temperature of the atmosphere (kelvin)
T_i Partial temperature (kelvin)

Since, the Π can not be directly calculated from equation (6) due to the lack of reliable T_m information in Thailand, the empirically derived value of Π at 0.15 [1] was used to convert the ZWD to the PWV in this study.

V. RESULTS AND DISCUSSION

After processing of GPS data with the final orbit information, the obtained ZTD values at every 3-hr interval were converted into the PWV values for each individual GPS station. The obtained PWV values during January and July 2007 have been plotted in Figure 3. It can be seen from Figure 3 that for the period between January and March, the PWV values at the PRACHUAPKIRIKHAN and SURATTHANI stations are higher than PWV values from other stations. This is due to the influence of the north-east monsoon passage especially in the southern part of Thailand. For all stations, the PWV values tend to increase during May, June and July, since this period is generally known as a southwest monsoon period in Thailand. The PWV can be used to accurately identify the onset of the southwest monsoon which is very important to an agricultural sector. In addition, Long term PWV data will be useful for climate studies because the variation of PWV can be closely monitored over the Thai region.

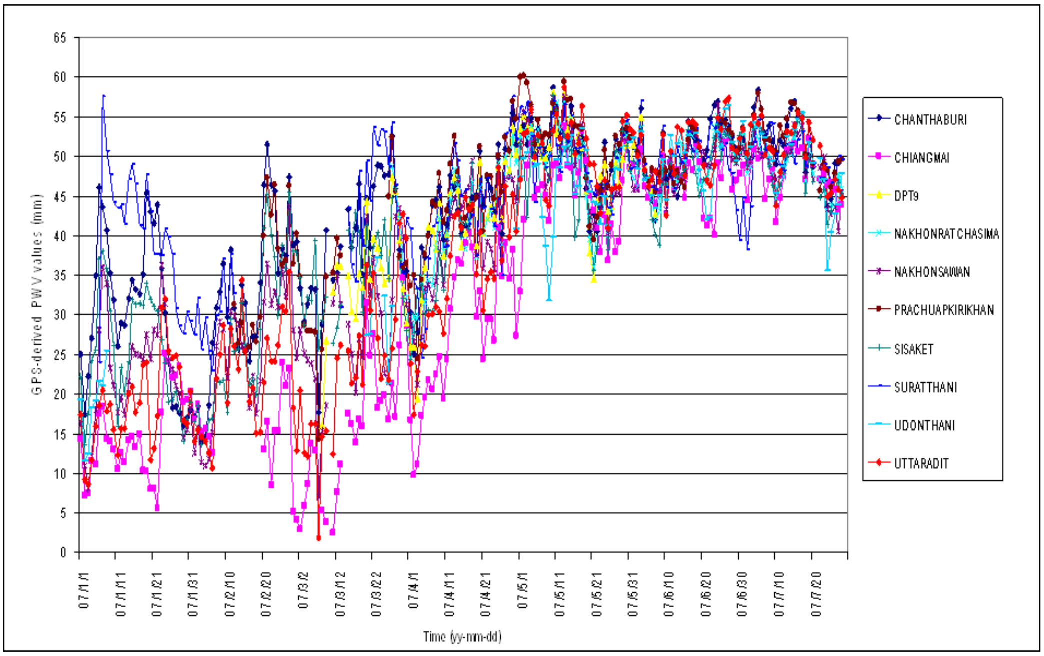

Figure 3
Plot of the GPS-derived PWV values at each Thai GPS station

The obtained PWV values as shown in Figure 3 will be used as reference values. In order to investigate the potential of using ultra rapid orbits to replace the final orbit, the PWV obtained from re-processing the same GPS data using ultra-rapid orbits with different time windows have been compared to the reference values. The averaged differences between reference PWV values and PWV values obtained from ultra-rapid orbits have been plotted in Figure 4. As expected, the 24-hr time window produces the most reliable results. It can be clearly seen from Figure 4 that the longer the observation time window, the smaller the averaged difference.

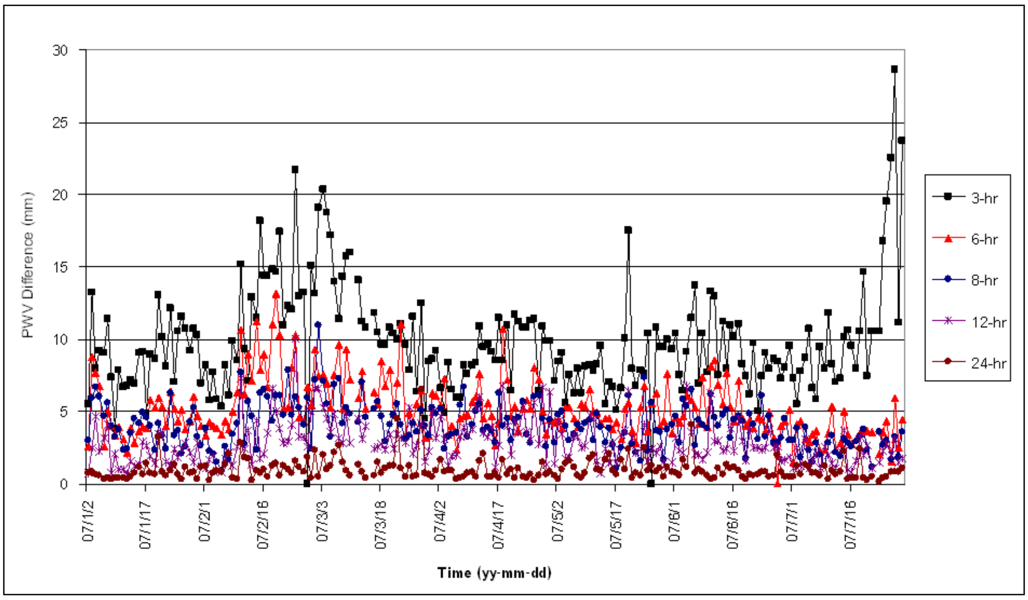

Figure 4
Plot of averaged differences between reference PWV values and PWV values obtained from ultra-rapid orbits using different time windows

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The statistical values were then calculated and presented in Table 2. The 1.0 mm and 2.9 mm averaged differences (or biases) could be achieved using 24-hr and 12-hr time windows, respectively. These results are very promising, as it addresses a possibility for using ultra-rapid orbits for a near real-time estimation of PWV values. The computation time for PWV estimation is very much dependent on the observation time window used. With respect to the computational time, the use of 24-hr and 12-hr time windows for 10 GPS stations requires approximately 15-min and 7-min processing time for 10 GPS stations. It should be noted that the processing time is based on the use of a dual-core 2.0 GHz processor with 2 GB of RAM.

Table 2
Statistics of differences between the PWV using ultra rapid orbits and final orbits (unit: mm)

Station	3-hr		6-hr		8-hr		12-hr		24-hr	
	Diff.	S.D.	Diff.	S.D.	Di	S.	Di	S.	Di	S.
CHANTHABURI	9.9	11.0	5.3	5.0	4.1	3.7	2.9	2.8	1.0	1.2
CHIANGMAI	9.9	11.8	5.2	4.8	4.1	3.7	2.9	2.8	1.0	1.3
DPT9	8.9	8.2	5.3	4.9	4.2	3.6	3.1	2.8	1.1	1.3
NAKHONRATCHASIMA	9.2	12.6	4.6	4.3	3.7	3.2	2.7	2.6	0.9	1.2
NAKHONSAWAN	9.8	11.6	5.2	4.9	4.0	3.6	2.8	2.7	1.0	1.2
PRACHUAPKIRIKHAN	10.5	13.6	5.4	5.1	4.1	3.8	3.1	2.9	1.0	1.2
SISAKET	9.9	12.1	5.3	5.1	4.1	3.7	2.8	2.7	1.0	1.2
SURATTHANI	10.1	13.0	5.2	5.0	4.0	3.5	2.8	2.7	1.1	1.4
UDONTHANI	9.5	13.2	4.6	4.5	3.7	3.4	2.6	2.5	1.0	1.4
UTTARADIT	9.9	11.8	5.3	5.0	4.1	3.7	2.9	2.8	1.0	1.2
Mean from all stations	9.8	11.9	5.1	4.9	4.0	3.6	2.9	2.	1.0	1.3

VI. CONCLUDING REMARKS

After processing of GPS data with the final orbit information, the obtained ZTD values at every 3-hr interval were converted into the PWV values for each individual GPS station. The obtained PWV values during January and July 2007 have been plotted in Figure 3. It can be seen from Figure 3 that for the period between January and March, the PWV values at the PRACHUAPKIRIKHAN and SURATTHANI stations are higher than PWV values from other stations. This is due to the influence of the north-east monsoon passage especially in the southern part of Thailand. For all stations, the PWV values tend to increase during May, June and July, since this period is generally known as a southwest monsoon period in Thailand. The PWV can be used to accurately identify the onset of the southwest monsoon which is very important to an agricultural sector. In addition, Long term PWV data will be useful for climate studies because the variation of PWV can be closely monitored over the Thai region.

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