A Preliminary study for real-time estimation of precipitable water vapor using GNSS precise point positioning in Thailand

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ABSTRACT The amount of precipitable water vapor (PWV) is an important variable in monitoring climate change, weather forecasting, and the greenhouse effect. The PWV is normally measured by meteorological instruments, such as radiosondes, microwave radiometers or meteorological satellites. On the other hand, the use of the Global Navigation Satellite System (GNSS) in meteorology known as GNSS-Meteorology is an alternative way to estimate the PWV values, which is less data processing load and cost-effective. Moreover, it has the advantages in high spatio-temporal resolution. In the last two decades, several studies have shown that the estimated PWV values derived from ground-based GNSS receivers are nearly proportional to the amount of PWV from the meteorological instruments. Thus it confirms that GNSS data can be used for the atmospheric water vapor sensing or meteorological applications. In this study, a preliminary study of real-time PWV using GNSS Precise Point Positioning (PPP) processing is conducted. The Federal Agency for Cartography and Geodesy (BKG) NTRIP Client (BNC) version 2.12.3 software platform, which use the Ionosphere-free combinations together with Extended Kalman Filter (EKF) techniques to estimate the zenith tropospheric delay (ZTD), is used to process the GNSS observation data. The CLK91 real-time orbit and clock products generated to the broadcast ephemeris based on the International GNSS Service (IGS) network by BKG through a NTRIP caster are adopted in the data processing step. The GNSS observations in three months (April-June, 2017) from the 22 permanent stations in Thailand are used for this investigation. The real-time ZTD estimated are compared with PPP post-processing from Position and Navigation Data Analyst (PANDA) software. In order to accurately transform the zenith tropospheric delay (ZTD) into the PWV, the meteorological data and the local mean tropospheric temperature model (Tm) are evaluated for this study.

1. Introduction

The application of the Global Navigation Satellite System (GNSS) in meteorology known as GNSS-Meteorology have been intensively studied more than two decades (Bevis et al., 1992);(Bevis et al., 1994);(Elgered et al., 1991). Ground-based GNSS receivers could provide the estimated tropospheric Zenith Total Delay (ZTD) or Precipitable Water Vapor (PWV) values with an accuracy comparable to the meteorological instruments such as radiosondes and microwave radiometers (Hagemann et al., 2002; Yuan et al., 2014); (X. Li et al., 2015). Compared to the conventional meteorological instruments, GNSS-Meteorology shows various advantages, for instance, less data processing load, cost-effective, all-weather availability, and spatio-temporal resolution. Various tests have been conducted to evaluate GPS-PWV in post-processing and near-real-time technique. An assessment on GPS-PWV using International Global Navigation Satellite Systems Service (IGS) ultra-rapid orbit data were conducted by (Satirapod et al., 2011). The results addressed the potential use of ultra-rapid orbits for a near-real-time estimation of PWV. Near-real-time GPS-PWV was applied in numerical weather prediction and showed 2% improvement for the relative humidity in a 12-hour forecast (Gendt et al., 2004). Assimilation of GPS-ZTD observations have been shown to give some improvements in the forecasting of cloud (Bennitt et al., 2012).

In order to estimate GNSS ZTD/PWV, there are two data processing techniques: the baseline/network (Elgered et al., 1991) approach and Precise Point Positioning (PPP) (Zumberge et al., 1997) approach. The baseline/network approach is complex in terms of selection of baseline and the data processing load when the number of stations has increased. The PPP approach is based on Un-Differenced (UD) observations and displays its unique advantages to applications compared to the baseline/network (Yuan et al., 2014). In the PPP approach, there is no base station required; thus, data processing time is relative to the number of stations and ZTD/PWV values can be estimated epoch by epoch, which is really useful for the meteorological applications that require near-real-time or real-time ZTD/PWV values (Grinter et al., 2013; X. Li et al., 2015).

Since April 2013, the precise real-time satellite orbit and clock products have been released from the IGS Real-Time Pilot Project (IGS-RTPP) through Networked Transport of RTCM (Radio Technical Commission of Maritime Services) via Internet Protocol (NTRIP) (Weber et al., 2016). Since then, a total of ten analysis centers have provided real-time products, including BKG, CNES, DLR, ESA, GFZ, GMV, Geo++, NRCAN, TUW and WHU. Product quality and essential explanations of these products are available at the official Real-Time Service (RTS) webpage (http://rts.igs.org/). This products are highly useful opportunities and challenges for real-time PPP of estimated ZTD/PWV values for atmospheric and disaster monitoring, especially for nowcasting.

Several studies of the real-time PPP technique using GPS or GNSS data from Continuously Operating Reference Station (CORS) networks have been investigated and proven that GNSS-derived ZTD/PWV values could be shown a positive impact on NWP and applied for weather forecasting (Dousa et al., 2014; Rohm et al., 2014). Over the last 2-3 years, GNSS techniques have rapidly developed. In terms of the increasing number of satellites, GNSS CORS networks, and correction products that are used to estimate the position quickly, accurately. Those developments are vastly useful for estimated ZTD/PWV values, especially for time-critical meteorological applications (Lu et al., 2015; Shi et al., 2015). In Thailand, GNSS Real-Time-Kinematic (RTK) network infrastructure project was established in 2016 and will be completed in 2018 with about 222 CORS stations to support surveying, precise positioning, land governance and cadastral operations. There is a good opportunity to evaluate ZTD/PWV values in Thailand. Also, the variation of estimated ZTD values in this region is more challenging than other places (W. Li et al., 2012; YiBin Yao et al., 2015; Yuan et al., 2014);

In this preliminary study, the Federal Agency for Cartography and Geodesy (BKG) NTRIP Client (BNC) version 2.12.3 software platform (Weber et al., 2016), which uses the Ionosphere-free combinations together with Extended Kalman Filter (EKF) techniques to estimate the receiver position, the receiver clock bias and ZTD, is used to process the GPS data. Although GNSS observations were available, only GPS observations were processed. The CLK91 products generated from CNES to the broadcast ephemeris were adopted in the data processing step. The GPS data in three months period (April-June, 2017) from the 22 permanent stations was used for this investigation. The contribution of selected stations are shown in Figure 1. The real-time ZTDs estimated from those stations were compared with those PPP post-processing from PANDA software from Wuhan University (Jing-nan et al., 2002). In order to accurately transform ZTD values into PWV values, the meteorological data from meteorological stations and the local mean tropospheric temperature model (Tm) were evaluated for this study. The processing results were investigated to assess the quality of ZTD values derived from real-time PPP and to evaluate the data reliability from selected CORS stations.

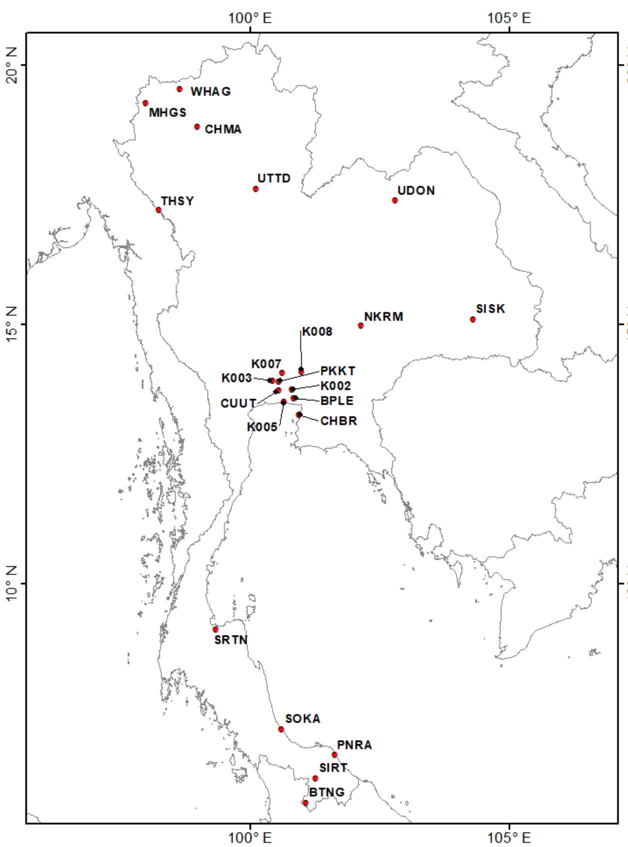

Figure 1. Location of selected GNSS CORS stations for this study (red dots). We have collected the meteorological data from meteorological stations within 60 km distance.

2. Observation Model and processing strategy

2.1 Observation equations

The GPS observation equations for PPP of single dual-frequency receiver based on carrier phase (*Φ*) and pseudorange (*P*), respectively, can be expressed as the ionosphere-free code combinations and the ionosphere-free phase combinations to eliminate the first order ionospheric effects. For cm or mm precise level, some error sources have to be cancelled or mitigated, such as antenna phase offsets and variations of satellites and receivers, phase wind-up, solid Earth tides, ocean loading, polar tides, Earth rotation parameter (ERP), and relativistic effects. If those error sources can be eliminated or accurately calculated with empirical model, the simplified observation equations for PPP are (Kouba, 2009):

$$\ell_P = \rho + c.(dt - dT) + T_r + \mathcal{E}_P \quad (1)$$

$$\ell_\Phi = \rho + c.(dt - dT) + T_r + N.\lambda + \mathcal{E}_\Phi \quad (2)$$

where ℓ_P and ℓ_Φ are the ionosphere-free combinations of pseudoranges and carrier phases, ρ is the geometrical range computed as a function of the satellite and receiver coordinates, c is the vacuum speed of light, dt and dT are the station receiver and satellite clock offsets from GPS time, T_r is the tropospheric path delay (ZPD), N is the non-integer ambiguity of the carrier-phase ionosphere-free combination, λ is the carrier-phase L3-combined wavelengths, $\mathcal{E}_P$ and $\mathcal{E}_\Phi$ are the relevant measurement noise components, include multipath.

The ZPD can donate as a function of ZTD with mapping function (M), relating the tropospheric delay to the elevation angle of the satellite, while replacing the known satellite clocks (dT) and coordinates according to the following mathematical model in the simplest form (Kouba, 2009):

$$\ell_P = \rho + c.dt + M.ZTD + \mathcal{E}_P \tag{3}$$

$$\ell_\Phi = \rho + c.dt + M.ZTD + N.\lambda + \mathcal{E}_\Phi \tag{4}$$

In this study, The Ionosphere-free linear combinations together with Extended Kalman Filter (EKF) techniques in BNC software are used to estimate the receiver coordinate, the receiver clock bias, the non-integer ambiguity and ZTD as unknown parameters where are solved for each observation epoch.

2.2 Tropospheric delay model

The troposphere is the lowest layer of the atmosphere. It has a distance above the Earth's surface of 8 km at the poles to 16 km height over the equator and consists of a dry and a wet component. About 90% of the tropospheric delay is caused by the dry or hydrostatic part, which is mainly a function of pressure (Hofmann-Wellenhof et al., 2008). The wet part depends on the water vapor, which is highly variable to the weather, climate and greenhouse effect, is difficult to model because of its high variability. The troposphere can cause path delays when radio signals propagate from GNSS satellites to the Earth's surface, regularly reaching a value of 2.3 m at the zenith and over 20 m at the low elevation angles (YiBin Yao et al., 2015). These effects depend on the real-valued refractive index (N) along a signal ray path. The ZPD can be expressed as (Hofmann-Wellenhof et al., 2008):

$$ZPD = 10^{-6} \left(\int N_{dry} ds + \int N_{wet} ds\right) \tag{5}$$

where N_{dry} is the dry refractive index, N_{wet} is the wet refractive index, the integration is taken along the signal ray path.

In GPS data processing, it is known that the ZPD is obtained from a zenith delay using proper mapping functions, which are depend on the zenith angle of the satellite. There are different atmospheric model using in mapping function, such as NMF (Niell Mapping Functions), VMF1 (Vienna Mapping Functions 1) or Ifadis (Mendes, 1998). Nonetheless, in the BNC software, the tropospheric mapping function is simplified as: (Weber et al., 2016)

$$M = f(z) = 1/\cos(z) \tag{6}$$

Where z is the zenith angle of the satellite. Consequently, the ZPD can be expressed as:

$$ZPD = ZTD * 1/\cos(z) \tag{7}$$

A priori ZTD can be obtained from the standard empirical models such as (Hopfield, 1971), (Niell, 1996), and (Saastamoinen, 1972) models. The latter one has been applied In BNC software.

$$ZPD = 0.002277\sec(z)\left[P + \left(\frac{1255}{T_s} + 0.05\right) e - B\tan^2 z\right] + \delta R \tag{8}$$

where P is the air pressure (unit: millibars), T_s is the temperature (unit: Kalvin), e is the partial pressure of water vapor (unit: millibars), B and δR are the correction terms that depend on z and the height of the station, respectively (Xu, 2007).

2.3 Converting the ZTD to the PWV

The ZTD derived from PPP can be expressed in two components as: a Zenith Hydrostatic Delay (ZHD) and a Zenith Wet Delay (ZWD). The ZHD can be derived with a good accuracy with surface meteorological data. However, the ZWD is commonly used as an estimated parameter for higher accuracy due to a high variation and can be transformed into PWV with mean temperature (T_m). The ZWD can be expressed in terms of the ZTD and ZHD (Bevis et al., 1992)

$$ZWD = ZTD - ZHD \quad (9)$$

Over the past two decades, there are several empirical ZHD models developed offering users great flexibility of choice in their application (Chen et al., 2016). In this study, ZHD with the surface air pressure at the closet meteorological station is obtained from (Saastamoinen, 1972) model as:

$$ZHD = 2.27793P / (1\text{-}0.00266\cos(2ø)\text{-}0.00028H) \quad (10)$$

where ø is the latitude of the station (unit: radius), H is the height of the station above sea level (unit: meters).

The quantity of PWV above a receiver is usually stated as the vertically integrated mass of water vapor per unit area (e.g., in kilograms per square meter) or as the height of an equivalent column of liquid water. This quantity is related to the ZWD in unit of length at the receiver (Bevis et al., 1994).

$$PWV = \prod * ZWD \quad (11)$$

where $\prod$ is the dimensionless constant of proportionality.

$$\prod = 10^6 M_w / (\rho_w R_v (k_2 - k_1 \frac{M_w}{M_d} + \frac{k_3}{T_m}) \quad (12)$$

Where ρ_w is the density of liquid water with values 10^3 kg.m^{-3}. R_v is the special gas constant of water vapor with values 461.51 JK^{-1}kg^{-1}. M_w and M_d are the molar mass of dry air and water vapor with values 0.00289644 kg.mol^{-1} and 0.018016 kg.mol^{-1}, respectively. k_1, k_2 and k_3 are the physical constant derived by several laboratories. In this study, the values 77.6900 K.hPa^{-1}, 71.2952 K.hPa^{-1}, 375463 K^2.hPa^{-1} for k_1, k_2, and k_3 are used (Yuan et al., 2014). T_m is weighted mean temperature of the atmosphere (unit: Kelvin).

$$T_m = \frac{\int \frac{e}{T} dz}{\int \frac{e}{T^2} dz} \quad (13)$$

To calculate the T_m from equation (13), both e and T are extended from the surface to the top of atmosphere which is not possible in real-time retrieval of PWV values. An alternative way is used empirical model presented by (Bevis et al., 1992), (Mendes et al., 2000), and GPT2w. Moreover, (Y. Yao et al., 2014) developed the GTm-III model to estimate T_m every location in the world. These models have been applied to several researches (Bosy et al., 2012; Yuan et al., 2014). Nevertheless, Tm determined from the empirical models is not as accurate as that directly obtained from the NWP models (Yuan et al., 2014).

In Thailand, (Suwantong et al., 2016) derived the local T_m using AIRS and AMSU for GNSS-PWV estimation. The results show that the GNSS-PWVs derived from the local T_m model have the same level of the Root Mean Square Error (RMSE), which are comparable to the global T_m. Using the local T_m can reduce the mean bias from −1.06 mm to 0.20 mm. Thus, this model is applied in this study. The local T_m model is derived for the day time as:

$$T_m = 0.6066 * T_s + 113.2914 \quad (14)$$

and for the night time as:

$$T_m = 0.7938 * T_s + 57.4856 \quad (15)$$

The surface temperature T_s can be obtained from empirical model or meteorological sensor. The later one was used in this study.

2.4 Software and Processing step

In the preliminary study, The BKG NTRIP Client (BNC), developed by BKG (Weber et al., 2016), is capable of performing PPP in real-time tool with some post processing functionality, also retrieving real-time GNSS data streams from an IP address, a serial port or the NTRIP transport protocol. When using the PPP processing, some effects are not corrected by BNC, such as satellite antenna phase center variations, ocean and atmospheric loading, and polar tide. These error sources can affect the accuracy of the GNSS-derived ZTD estimates (Ahmed et al., 2014; Kouba, 2009).

For this study, in order to obtain approximate reference coordinates of the CORS stations, 1-day batches of data are processed from the PANDA software. By using a 24-hr data set, the station coordinate accuracy within a centimeter level are used as a priori coordinate in subsequent processing (Jing-nan and Mao-rong, 2002). The BNC software are used to process real-time PPP using data streams from 22 CORS stations of code and phase observations, the broadcast ephemeris and CLK91 correction streams for satellite orbits and clocks. During the processing in BNC, these corrections from the real-time streams are applied to the broadcast ephemeris. Along with the precise position estimates, the estimated ZTD can also be obtained as one of the outputs. The ZTD values at the common epoch are compared to the PANDA-ZTD products at every 2 hr. The PWV values can be estimated by using equation (9), (10) and (11) with local mean temperature and metrological data.

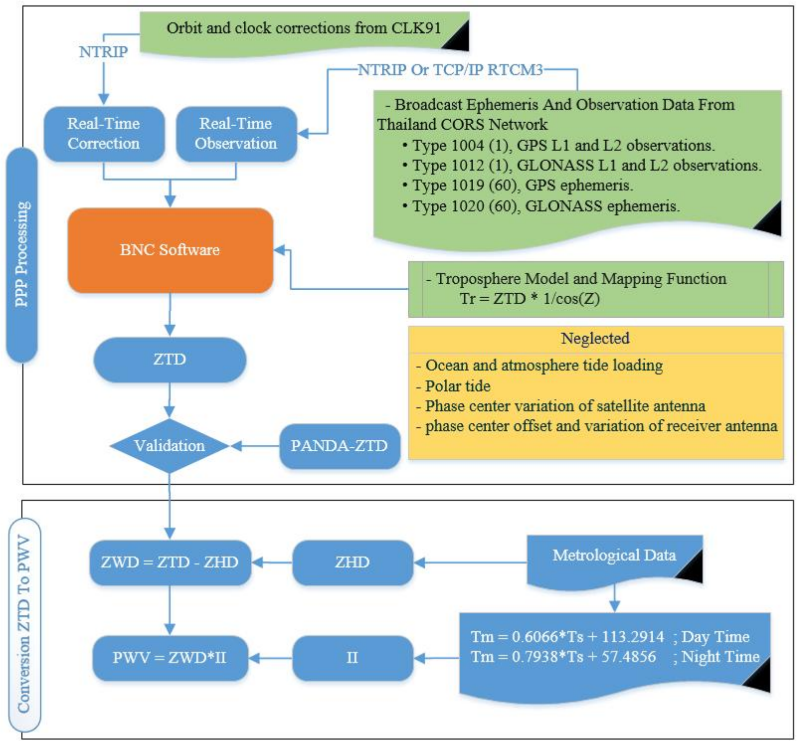

Figure 2. Data Processing Step to estimate the real-time ZTD/PWV values

Table 1 . Configuration of the BNC software is used in this study. * In the correction streams used, the satellite's position refers to its antenna, therefore, the satellite antenna PCO correction is not necessary

Configuration	Detail
Update cycle	Real-time
Output interval	1 s
GNSS used	GPS
Strategy	PPP
A Priori ZPD model	Saastamoinen
Troposphere mapping Function	1/cos(z)
Receiver PCV correction	YES
Receiver PCO correction	YES
Satellite PCV correction	No
Satellite PCO correction	No*
Solid earth tide	Yes
Ocean tide loading and Polar tide	No
Input data format	RTCM-3
Input Orbit/Clock correction format	RTCM-SSR
Input broadcast ephemeris format	RTCM-SSR
Ambiguity resolution	No

3. Results and analysis

3.1 Real-time PPP-ZTD Results and Validation

In order to assess the quality of ZTD values derived from PPP technique with the real-time correction, we processed 22 CORS stations for the period of three months between April to June in 2017. The ZTD values were validated using the ZTD values from PANDA Software including outlier rejection procedures. The real-time ZTD solution derived from GNSS is 1 second while the PANDA-ZTD is sampled every 2 hour. Consequently, only the ZTD values at the same epoch were compared. The comparisons of the ZTD values derived from the PPP float solution and the PANDA-ZTD are shown in Table 2 and Figure 3. The results showed that RMSE and mean bias of the different ZTD values vary from 8.7 to 11 millimeters and -5.6 to 0.1 millimeters, respectively. It is notable that the threshold accuracy for ZTDs as input to NWP models is 15 mm (De Haan, 2006). Thus, for all 22 stations, the estimated ZTD values were accurate enough for the operational NWP. We found that the average percentage of the different ZTD values within 20 mm are about 78% of the real-time epoch solution. We also found that seven stations (BPLE, BTNG, CUUT, K008, PKKT, PNRA and SIRT), above 80% of the real-time epoch solution, are found within the 20 mm. Consequently, we concluded that most of stations were hardly agreed with PANDA-ZTD. According to (Yuan et al., 2014) 20 mm error in ZTD will result in an error of approximately 3 mm in PWV, which is the threshold accuracy for PWV in weather nowcasting (De Haan, 2006).

Table 2. Mean Bias (mm), RMSE (mm) and Percentage of Value below 20 mm (the Threshold of Weather Nowcasting) of the Different ZTD Values between Real-Time PPP and PANDA. The underlined stations are shown the percentage of the different ZTD values over then 80%.

Station	Mean Bias	RMSE	< 20 mm	Station	Mean Bias	RMSE	< 20 mm
BPLE	-2.4	9.9	81	NKRM	-2.6	10.2	76
BTNG	-3.6	10.7	81	PKKT	-1.9	9.9	84
CHBR	-5.6	10.8	71	PNRA	-3.7	9.9	84
CHMA	-2.9	10.5	75	SIRT	-3.8	9.4	81
CUUT	-1.6	9.7	82	SISK	-4.7	10.3	73
K002	-0.3	9.3	78	SOKA	-5.4	10.6	80
K003	0.0	9.4	82	SRTN	-5.4	10.6	71
K005	-0.9	8.7	85	THSY	-2.1	10.5	68
K007	0.1	9.2	80	UDON	-3.8	10.3	77
K008	-0.4	9.5	81	UTTD	-4.8	11.0	72
MHGS	-4.1	10.2	76	WHAG	-1.0	9.9	78

The accuracy of ZTD values in our data processing are depended on the real-time corrected observations and corrections. If the data processing center is lost the internet connection to CORS station or the correction service, this will degrade the accuracy of the real-time epoch solution and cause the large variation in data processing. Especially, the CORS stations in remote area can be insufficient internet stability. In addition, the quality of observation data streaming from CORS stations also affect the accuracy of the output solution such as data gap, satellite geometry, or availability of satellites.

3.2 Precipitable Water Vapor

The PWV values derived from the real-time PPP technique using local mean temperature (equation 14-15) and meteorological data are shown in Figure 4. The results showed that the PWV values from the most stations were vary from 25 to 75 millimeters. Unlike WHAG was vary from 10 to 40 millimeter because the height of the station is about 745 meters above Mean Sea Level (MSL), while the height of other stations were average 75 meters above MSL. Figure 4 illustrates the PWV values from 22 stations during a period of three months. The PWV values were increased from about 50 to 70 millimeter between DOY 96 to DOY 130 because of changing season from dry season to rainy season and the influence of the southeast monsoon brings heavy storms.

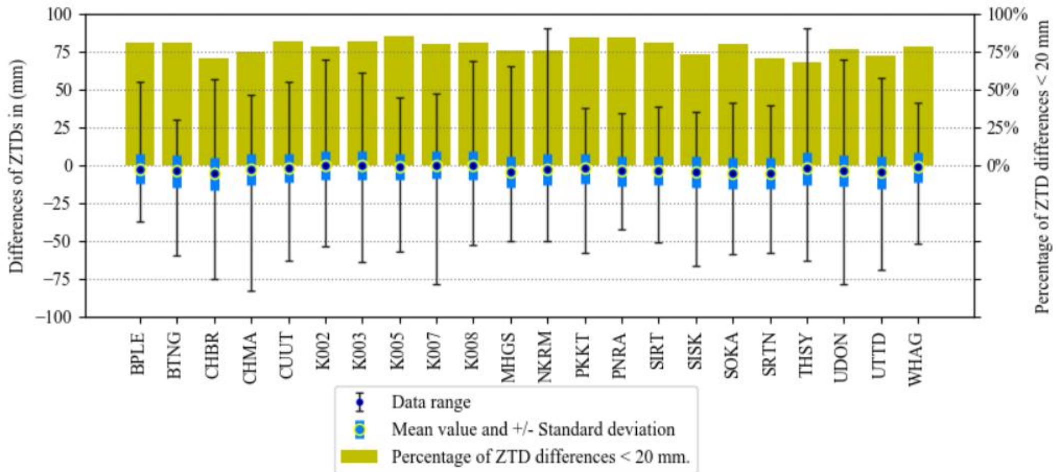

Figure 3. The comparison between the real-time ZTD and the PANDA-ZTD for 22 CORS stations, during April-June in 2017.

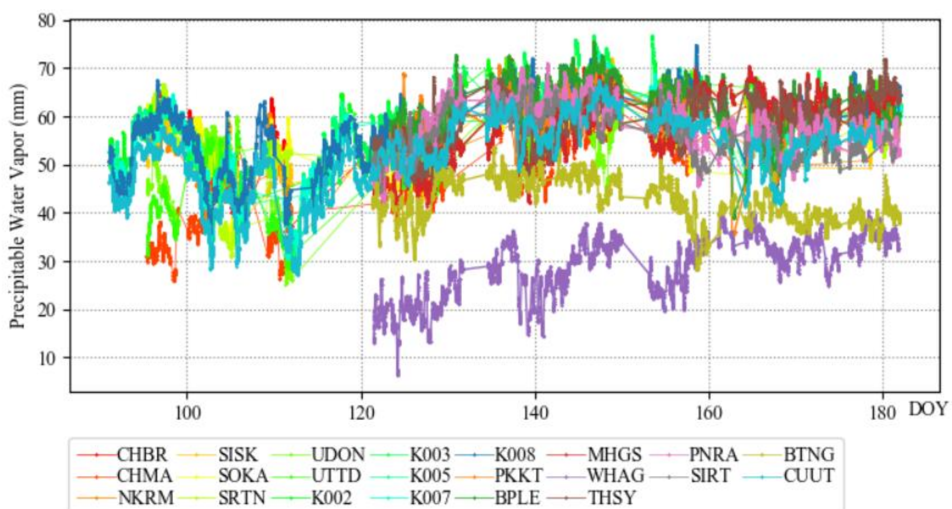

Figure 4. PPP-PWV derived from GPS using local mean temperature and local meteorological data, during April-June in 2017.

5. Conclusion

In this research, the preliminary study for real-time estimation of precipitable water vapor using GNSS precise point positioning in Thailand had been conducted. The three months of GPS observation data from selected 22 CORS stations were used in data processing together with the CLK91 real-time correction. The ZTD values can be estimated along with unknown parameter using PPP technique within BNC software. The ZTD values from 22 CORS stations had been compared by the PANDA-ZTD software as the reference values at 1 hour interval. The results showed that the average of RMSE and Mean Bias of 22 stations were about 10.02 mm and -2.7 mm, respectively. The quality of ZTD satisfied with the threshold requirements (15 mm) for the NWP. However, the different ZTD values of most station, about 78% of the real-time epoch solution, were within 20 mm. The results concluded that most of stations were hardly agreed with PANDA-ZTD. The estimated PWV over three months showed the seasonal and temporal variation in the water vapor content in the atmosphere.

In order to get high accuracy of the real-time PWV using GNSS observation data, it still remains a challenging task at a space and time resolution, due to high variation of PWV in this mid-latitudes (YiBin Yao et al., 2015; Yuan et al., 2014). In this research, the data processing strategy needs to be implemented to increase the accuracy of output solutions. Further research of a long-term PWV series will be focused on improving the real-time ZTD/PWV product, more accurate and stable for support meteorological applications.

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