Precise Tropospheric Delay Map of Thailand using GNSS Precise Point Positioning Technique

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Abstract
It is well known that the atmospheric effects are the most dominant spatially correlated errors in GNSS observations. The atmosphere causing the delay in GNSS observations consists of two main layers i.e. ionosphere and troposphere. The ionospheric delay can be mitigated using a linear combination of the two-frequency data. Unlike the ionospheric delay, the tropospheric delay cannot be removed using the same methodology. Compensation for the tropospheric delay is usually carried out using a standard tropospheric model. However, a standard tropospheric model cannot be used to completely remove the tropospheric delay in GNSS observations. With the use of GNSS Precise Point Positioning (PPP) technique, the tropospheric delay can be precisely obtained in a data processing step. Therefore, this paper focuses on an estimation of precise tropospheric delay using the GNSS PPP technique with the Positioning and Navigation Data Analyst (PANDA) software. Results obtained from the PPP technique are then compared with IGS tropospheric products and standard tropospheric models e.g. Saastamonien, modified Hopfield and simplified Hopfield. The obtained tropospheric delay shows a good agreement with the IGS product at millimeter level. It is found that the standard tropospheric models can only provide tropospheric corrections which are accurate at decimeter level in Thailand region. Finally, the same processing procedure is applied to produce precise tropospheric delays for all GNSS Continuously Operating Reference Stations (CORS) in Thailand and initial tropospheric delay results are presented in this paper.

1. Introduction

In GNSS data processing, Precise Point Positioning (PPP) technique provides cm-level absolute positioning with one dual frequency receiver. Precise Point Positioning (PPP) is popular in geodetic, geodesy, geodynamic and some applications that need high accuracy coordinate (Wang et al., 2015). This technique eliminates satellite orbit and clock errors using precise orbit and clock products from International GNSS Service (IGS) or other Analysis Center (ACs).The receiver clock error has to be determined at the user end. Usually, the receiver clock error is defined as a parameter. For atmospheric delay, Precise Point Positioning (PPP) technique uses the linear combination of two frequency data to mitigate the ionospheric delay but the tropospheric delay is eliminated by an empirical model such as Saastamonien model (Saastamoinen, 1972) or Modified Hopfield model (Hopfield, 1969) etc. However, they could not completely remove the tropospheric delay so it's define as aparameter in step of adjustment processing. After processing, the estimated tropospheric delay will be better than the empirical tropospheric delay obtained from empirical model (Kouba, 2015).

In this paper, the tropospheric delays are obtained from GNSS observation at CUSV/CUUT station that is located on the rooftop of building 4 faculty of engineering Chulalongkorn University, Bangkok, Thailand in November 2015 using PPP technique in static mode with Position and Navigation Data Analyst (PANDA) software from Wuhan University. Furthermore, we compared accuracy of the tropospheric delay which is estimated from PPP technique with IGS tropospheric product and IGS tropospheric product with standard empirical model i.e. Saastamonien, modified Hopfield and simplified Hopfield then Statistical results were then calculated to show accuracy of the tropospheric delay from PPP which was more precise than standard empirical model when they were compared with IGS tropospheric product. After it was showed that the tropospheric delay from PPP technique is accurate, the initial

ISSN 1686-6576 / © Geoinformatics International

precise tropospheric delay for Thailand was produced using GNSS observations from continuously operating reference stations (CORS) on April 2015, June 2015 and September 2015 to show the difference of tropospheric delay for each season in Thailand.

2. Precise Point Positioning (PPP)

In general, precise point postioning (PPP) uses dual frequency pseudorange and carrier phase for eliminating the first order ionospheric delay in pseudorange and carrier phase which is the one of main error source in the GNSS observations. Other errors still remain in the observation, such as: troposphere delay, satellite/receiver clock error, multipath error, etc. By using the ionosphere-free combination (for pseudorange is called PC and carrier phase is called as LC), the basic observation equation of PPP can be expressed as:

$$P^j_{i(PC)} = \rho^j_i + c(dt_i - dT^j_i) + ZTD_i \cdot M(e)^j_i + \varepsilon_{PC}$$

Equation 1

$$\varphi^j_{i(LC)}\lambda_{LC} = \rho^j_i + c(dt_i - dT^j_i) + ZTD_i \cdot M(e)^j_i + N^j_{i\,LC}\lambda_{LC} + \varepsilon_{LC}$$

Equation 2

where $P^j_{i(PC)}$ is ionosphere free combination of pseudorange observation. $\varphi^j_{i(LC)}$ is ionosphere free combination of carrier phase observation. i and j are epoch and satellite number, respectively. ρ^j_i is geometry distance between satellite and receiver. dt_i and dT^j_i are receiver clock error and satellite clock error, respectively. c is the vacuum speed of light. λ_{LC} is ionosphere free wavelength. ZTD_i is tropospheric delay in zenith direction. $M(e)^j_i$ is mapping function, which is a function of satellite elevation angle e. $N^j_{i\,LC}$ is defined as ionosphere free ambiguity. ε_{PC} and ε_{PC} are the multipath error and observation noise of ionosphere free combination observation (Li,2014). In Precise Point Positioning (PPP) processing, eliminating satellite orbit and clock error often uses final orbit and clock product from International GNSS Service (IGS) or Analysis Center (ACs). Zenith tropopheric delay (ZTD) can be divided into two parts including Zenith Hydrostatic Delay (ZHD) part and Zenith Wet Delay (ZWD) part. Zenith Hydrostatic delay (ZHD) is more stable than zenith wet delay (ZWD) Therefore, ZHD can be precisely calculated using empirical models such as the Saastamoinen model, or modified Hopfield etc. On the other hand, zenith wet delay (ZWD) need to be estimated as piece-wise constant (PWC) (Kouba, 2015).

3. Tropospheric Delay

The tropospheric is the atmospheric layer between earth surfaces. The troposphere is non-dispersive medium at GNSS carrier frequencies which mean, the effect on the GNSS signal transmission are independent from working frequency (Xu, 2007). The effect of troposphere on the GNSS signals is made an extra delay in the measurement of the signal travelling from the satellite to receiver. This delay depends on the temperature, pressure and humidity depending on station location and seasons (Xu et al., 2012). As it was already mentioned, the total delay consists of ZHD, and ZWD. Zenith hydrostatic delay (ZHD) depends on dry gases presenting in the troposphere (78% $N2$, 21% $O2$, etc.). It is effected from temperature and atmospheric pressure. This part of delay can be predicted due to the variation which is less than 1% in few hours. Unlike zenith wet delay (ZWD), this part of delay varies faster than zenith hydrostatic delay (ZHD) and in a quite random way. Zenith wet delay (ZWD) is caused by water vapour and condensed water in the form of clouds. Therefore, it depends on the weather conditions while receiving GNSS signals. Hence, it is difficult to model this part of the delay. Currently, there are several tropospheric models for mitigating the tropospheric delay such as Saastamonien model which can be expressed in equation 3.

$$\delta = \frac{0.002277}{\cos z}\left[P + \left(\frac{1255}{T} + 0.05\right)e - B\tan^2 z\right] + \delta R$$

Equation 3

Where δ is the tropospheric path delay (in meters). z is the zenith angle of the satellite, T is the temperature at the station (in units of Kelvin (K)), P is the atmospheric pressure (in units of millibars (mb)) and e is the partial pressure of water vapour (in mb). B and δR are the correction terms that depend on H and z, respectively. H is the height of the station (Xu, 2007). Another one is modified hopfield model (Hopfield, 1969) which can be summarized as:

$$\delta^{Trop}_i(E) = 10^{-6} N^{Trop}_{i,0}\left[\sum_{k=1}^{9} \frac{\alpha_{k,i}}{k} r^k_i\right], i = d, w$$

Equation 4

Subscript i is used to identifying the ZHD and ZWD components of the tropospheric delay, and

$$r_i = \sqrt{(R_e + h_i)^2 - (R_e \cos E)^2} - R_e \sin E$$

$$N_{d,0}^{Trop} = \frac{0.776x10^{-4}xP}{T} \qquad N_{w,0}^{Trop} = 0.373x\frac{e}{T^2}$$

$$\alpha_{1,i} = 1 \qquad \alpha_{6,i} = 4a_i b_i(a_i^2 + 3b_i)$$

$$\alpha_{2,i} = 4a_i \qquad \alpha_{7,i} = b_i^2(6a_i^2 + 4b_i)$$

$$\alpha_{3,i} = 6a_i^2 + 4b_i \qquad \alpha_{8,i} = 4a_i b_i^3$$

$$\alpha_{4,i} = 4a_i(a_i^2 + 3b_i) \qquad \alpha_{9,i} = b_i^4$$

$$\alpha_{5,i} = a_i^4 + 12a_i^2 b_i + 6b_i^2$$

$$a = -\frac{\sin E}{h_i} \qquad b_i = -\frac{\cos^2 E}{2h_i R_e}$$

$$h_d = 40136 + 148.72(T - 273.16) \qquad h_w = 11000$$

Where δ is the tropospheric path delay (in meters). z is the zenith angle of the satellite. T is temperature at station (Kelvin (K)). P is the atmospheric pressure (millibars (mb)). e is partial pressure of water vapour (millibars (mb)). R_e is the Earth's radius (Xu, 2007).

4. Comparison of IGS Tropospheric Delay and Initial Tropospheric Delay for Thailand

In this paper, we processed GNSS data from CUUT/CUSV station that is located at rooftop of Building 4 Faculty of Engineering Chulalongkorn University, Bangkok Thailand (13.7358N,100.5338E) for one month (1 - 30 November 2015) at a 30 second interval using PPP technique with Final orbit and clock products from GeoForschungsZentrum Postdam (GFZ) (Montenbruck, et al., 2014). PANDA software was used for obtaining zenith tropospheric delay (ZTD) every 2 hours. Therefore, we compared ZTD from PPP with ZTD from IGS product (Dow et al., 2009). Furthermore, we compared ZTD obtained from the standard empirical model such as Saastamonien, modified Hopfield, and simplified Hopfield models using global pressure temperature model (Boehm et al., 2007) with ZTD from IGS product then RMSE statistics were then calculated. Therefore, we generated initial precise ZTD from PPP technique using GNSS observations at SOKA (Songkhla province), SISK (Sisaket province), PJRK (Prajuab Kirikhan province), NKSW (Nakornsawan province), NKRM (Nakhon Ratchasima province), DPT9 (Pharam 9, Bangkok province), CHMA (Chiang Mai province), CHAN (Chantaburi province), UTTD (Uttaradit province) which are Continuous Operating Reference System station (CORS) in Thailand owned by the Department of Public Works and Town and Country Planning of Thailand (DPT). Furthermore, there is comparison in zenith total delay which is obtained from PPP with standard empirical model each CORS station in Thailand.

5. Result

5.1 Accuracy of Zenith Total Delay from PPP

According to Figure 1, zenith total delay (ZTD) which is estimated by PPP technique at CUUT/CUSV station in November 2015 difference from IGS product in millimeters level. On the other hand, zenith total delay (ZTD) which is obtained from standard empirical model delay are accurate in decimeters level.

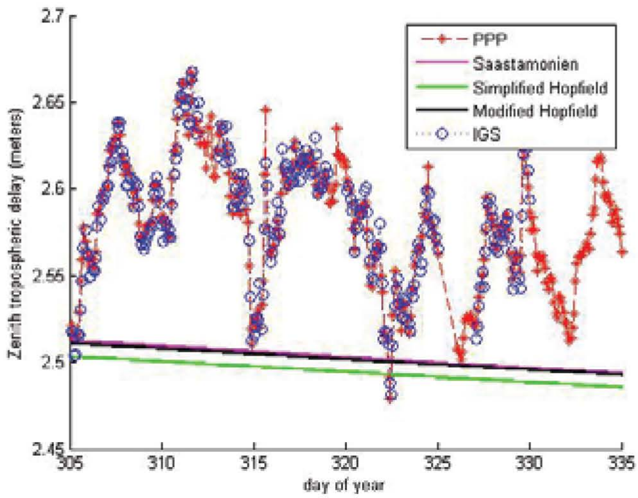

Figure 1: Comparision of tropospheric delay from PPP, Saastamonien, modified Hopfield, and simplified Hopfield

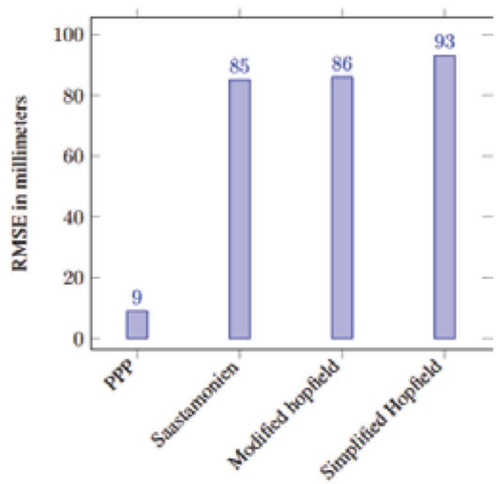

Figure 2: RMSE of ZTD from PPP, Saastamonien, modified Hopfield, and simplified Hopfield models computed by using ZTD from IGS products as references

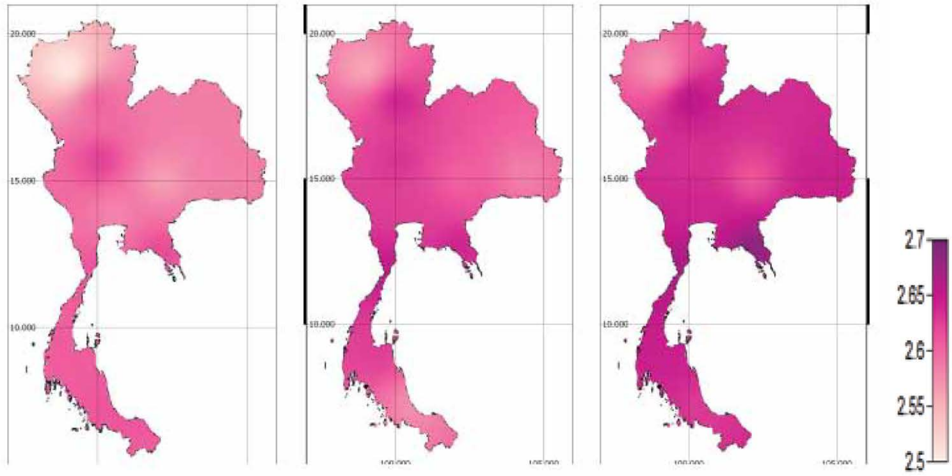

Figure 3: Precise ZTD which are generated by PPP for each time interval April (left) June (middle) September (Right) in 2015

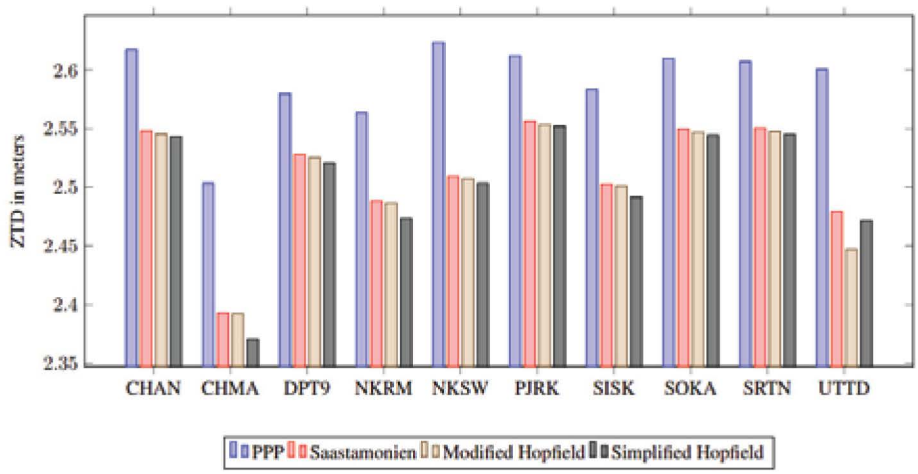

Figure 4: Comparison of ZTD from PPP, Saastamonien, modified Hopfield, and simplified Hopfield models at each CORS station in April

The accuracy of the estimated ZTD can be calculated by comparing with IGS products. Figure 2 shows that RMSE values of zenith tropospheric delay (ZTD) which is calculated from PPP technique, Saastamonien model, modified Hopfield model, simplified Hopfield model are 9, 85, 86, 93 millimeters, respectively.

5.2 Initial Precise Zenith Total Delay of Thailand

According to section 5.1, we showed the accuracy of tropospheric delay from PPP that was more accurate than standard tropospheric model. Initial zenith total delays were generated using PPP technique in April, June and September 2015 from CORS stations in Thailand. Figure 3 shows that zenith total delays were different at each period of the year because of the seasonal weather conditions. Furthermore, there was a comparison of zenith total delay (ZTD) between PPP technique and standard empirical model at each CORS station of Thailand in Figure 4.

6. Conclusion

In conclusion, zenith tropospheric (ZTD) calculated by PPP technique was more accurate than standard empirical model i.e. Saastamonien, modified Hopfield, and simplified Hopfield models by comparing with IGS tropospheric delay products. Therefore, we used PPP to created initial precise zenith tropospheric delay for Thailand from GNSS CORS stations. This initial precise zenith total delay can be used as correction terms for CORS station to produce correction term for Real Time Kinematics (RTK) processing or using as a guideline to create local tropospheric delay model for Thailand in the future.

Acknowledgements
The authors would like to thank to the Department of Public Works and Town & Country Planning (DPT) for providing the GNSS data used in this study. This paper is based on the paper presented at the 37th Asian Conference on Remote Sensing, Colombo, Sri Lanka, 17-21 October 2016.

References

Boehm, J., Heinkelmann, R. and Schuh, H., 2007, Short Note: A Global Model of Pressure and Temperature for Geodetic Applications. *Journal of Geodesy, 81*(10), 679-683. doi:10.1007/s00190-007-0135-3

Dow, J. M., Neilan, R. E. and Rizos, C., 2009, The International GNSS Service in a changing Landscape of Global Navigation Satellite Systems. *Journal of Geodesy, 83*(3), 191-198. doi:http://dx.doi.org/10.1007/s00190-008-0300-3

Hopfield, H. S., 1969, Two-Quartic Tropospheric Refractivity Profile for Correcting Satellite Data. *Journal of Geophysical Research, 74*, 4487-4499. doi:10.1029/JC074i018p04487

Kouba, J., 2015, *A Guide to Using the IGS Products.* International GNSS Service (IGS). Retrieved from http://kb.igs.org/hc/en-us/articles/201271873

Li, W., 2014, *Precise Point Positioning using PANDA Software Package.* GNSS Research Center, Wuhan University.

Montenbruck, O., Steigenberger, P., Khachikyan, R., Weber, G., Langley, R., Mervart, L. and Hugentobler, U., 2014, IGS-MGEX: Preparing the Ground for Multi-Constellation GNSS Science. *InsideGNSS, 9*(1), 42-49.

Saastamoinen, J., 1972, Atmospheric Correction for the Troposphere and Stratosphere in Radio Ranging Satellites, in The use of Artificial Satellites for Geodesy (eds S. W. Henriksen, A. Mancini and B. H. Chovitz). *American Geophysical Union, Washington, D. C.. doi: 10.1029/GM015p0247.*

Wang, F., Chen, X. and Guo, F., 2015, GPS/GLONASS Combined Precise Point Positioning with Receiver Clock Modeling. *Sensors*, 15478-15493.

Xu, G., 2007, *GPS* (2 ed.). Springer-Verlag Berlin Heidelberg. doi:10.1007/978-3-540-72715-6

Xu, Z., Xu, A., Xu, X. and Liao, J., 2012, Research on the Correlation of Troposphere Delay Parameters in GPS. *International Journal on Advances in Information Sciences and Service Sciences, 4*(22), 336-343. doi:10.4156/aiss.vol4.issue22.41