An Analysis of Spatio-Temporal Water Vapor Variation in the East Java using Ground Based GPS Receivers

Susilo1* and E Y Handoko2

1Geospatial Information Agency, Jalan Raya Jakarta Bogor KM. 46, Cibinong, West Java, 16911
2Department of Geomatics, Institut Teknologi Sepuluh Nopember, Kampus ITS Sukolilo, Surabaya 60111 Indonesia

E-mail: susilosarimun@gmail.com

Abstract. Water vapor plays a critical role in the global/regional scale of weather and climate changes. Traditionally, the water vapor measurement uses radiosonde balloons which are very sparse in the distribution. The utilization of GPS as a new method for studying water vapor has been studied in several publications. This research analyzed the precipitable water vapor (PWV) based on ground-based GPS receivers in the East Java region. In the first part, the datasets are compared. The Zenith Total Delay (ZTD) from GPS processing will be compared with the Zenith Path Delay from the International GNSS Service (IGS) results. The comparison of ZTD and ZPD shows a good agreement. The comparison of GPS PWV and Radiosonde shows a good agreement. The spatio-temporal of GPS PWV is correlated with the Monsoon Asian-Australian cycles that affect weather and climate in Indonesia. The result indicates that GPS data provide valuable information in meteorology and climatology.

1. Introduction

Water vapor is a significant component of the atmosphere's thermodynamics and is involved in cloud condensation. Due to the high variability of water vapor concentrations, it is difficult to observe accurately using traditional meteorological observation techniques (radiosonde balloon, water vapor radiometric), both spatially and temporally limited. The spatial resolution of the radiosonde data is very sparse. The distance nearest radiosonde stations are 100-200 km, and the temporal resolution observed twice or fourth a day is insufficient to monitor the spatio-temporal variation of the water vapor.

GPS has become a standard technique for measuring PWV since the 1990s [1]. GPS can provide Precipitable Water Vapor (PWV) with some advantages over radiosondes such as high accuracy, high sampling rate (5 min to 1 or 2 h, depending exclusively on data processing choices), operations in all weather conditions, and low cost allowing for a high spatial sampling [2].

The use of GPS/GNSS data in meteorology, hereafter called GPS meteorology, has been introduced. Many applications of GPS meteorology, such as tracking hurricanes/cyclones [3], observing water vapor during a typhoon [4], meteorology forecasting [5],[6],[7]. In this research, we use twenty-three GPS stations from Indonesian Continuously Operating Stations (Ina-CORS) located in East Java to study the spatio-temporal variation of water vapor during 2020.
2. Methodology

2.1. GPS Data Processing
Twenty-three (23) GPS stations in East Java registered to Indonesian Continuously Operating Stations (Ina-CORS) were used in this research. Ina-CORS is maintenance by the Indonesian Geospatial Information Agency (BIG). The distribution of twenty-three GPS stations in East Java is included in this research to be representative of a more tropical climate. The distribution of GPS stations is displayed in Figure 1. We included several Ina-CORS stations located near radiosonde stations.

![Figure 1. The distribution of GPS stations and Radiosonde stations in this research.](image)

The GPS data were processed with GAMIT software package version 10.71 [8]. The GPS data were processed in the double-difference mode in 24 h observing data within 12 stations of the International GNSS Services (IGS) regional network. The ITRF2014 coordinates [9] were used to tightly constrain the 12 coordinates of the IGS regional networks stations. We apply absolute receiver and satellite antenna models as recommended by IERS and tightly constrained the satellite orbit to the IGS combined final orbit. The Zenith Total Delay is estimated every 0.5 hours and split into Zenith Wet Delay (ZWD) and Zenith Hydrostatic Delay (ZHD). We corrected ZHD using the formula [10]:

$$ZHD = (2.27900 \pm 0.0024) \frac{P_S}{f(\lambda, h)}$$

where \(f(\lambda, h)\) are accounted for the gravitational acceleration in the latitude \(\lambda\) and the ellipsoid height \(h\) in kilometres, \(P_S\) is the surface air in hPa, and ZHD is in mm. We use the Global Pressure and Temperature 50 (GPT2) model [11] for the surface air pressure value. We use The Global Mapping Function (GMF) [12] for mapping ZHD and ZWD into the slant path directions of the GPS satellites at each epoch. The ocean tide loading effects were corrected at the observation level using the FES2004 model [13]. We adopted the IERS 2010 model [14] for the earth tides model and corrected any
atmospheric loading effect. We compared our ZTD estimates to the official IGS tropospheric product (Zenith Path Delay / ZPD) [15] at two IGS GPS stations in 2020.

2.2. GPS PWV Calculation
When an accurate ZWD is calculated by subtracting the ZHD from ZTD, the PWV is then obtained by conversion from ZWD [16]:

\[
PWV = \frac{10^6}{(k_2' + \frac{k_3}{T_m})R_\omega \rho}
\]

where \( k_2' = 16.48 K. hPa^{-1} \) and \( k_3 = (3.776 \pm 0.014) \times 10^5 K^2 hPa^{-1} \) are constants, \( R_\omega = 461 (J. kg^{-1}. K^{-1}) \) is the ideal gas constant for water vapor, \( \rho \) is the water vapor density, \( T_m \) is mean weight temperature. \( T_m \) is calculated using the observed surface temperature based on the empirical model constrained by sufficient radiosonde or reanalysis data [16]. We use \( T_m \) from [1].

2.3. Spatio-temporal Analysis
The spatial pattern was analyzed by calculating the correlation coefficient between GPS PWV and Radiosonde PWV for each GPS station. Then the correlation coefficient was plotted based on the distance and height different from the radiosonde station. The temporal pattern was analyzed by visual inspection to GPS PWV time series.

3. Results and Discussions

This section presents the ZTD and ZPD comparison, GPS PWV and Radiosonde PWV comparison, and analysis of spatio-temporal of East Java PWV.

3.1. Comparison of ZTD and ZPD
Before we analyze the spatio-temporal of PWV, first, we show the ZTD comparison for two IGS stations. For the comparison, we choose BAKO and DARW IGS stations located in Cibinong, Bogor, and Darwin, Australia. The comparison between our ZTD results and the official IGS tropospheric product [15] is shown in Figures 2 and 3.

Figure 2. ZTD and ZPD plot of BAKO IGS station. (a) time series ZPD and ZTD; (b) scatter plot of ZPD and ZTD.
Figure 3. ZTD and ZPD plot of DARW IGS station. (a) time series ZPD and ZTD; (b) scatter plot of ZPD and ZTD.

Figures 2 and 3 show the comparison plot of ZPD and ZTD from BAKO and DARW IGS stations, respectively. Overall, the time series ZTD and ZWD have a similar pattern. The statistic of this comparison shows in Table 1. We found a mean bias of about 3.98 and 4.55 mm. The standard deviation of the bias is 11.6 and 6.6 mm for the BAKO and DARW GPS stations, respectively. The agreement result is excellent and consistent with the previous studies [17],[18],[19],[20].

| Site  | # data | Mean bias (mm) | Std bias (mm) | R²   |
|-------|--------|----------------|---------------|------|
| BAKO  | 16896  | 3.98           | 11.6          | 0.97 |
| DARW  | 17331  | 4.55           | 6.6           | 1    |

3.2. PWV from GPS and Radiosonde

Figure 4, Figure 5, and Figure 6 show the time series PWV from GPS and radiosonde data. The PWV radiosonde was downloaded from http://weather.uwyo.edu/upperair/sounding.html. We compare PWV GPS with the PWV radiosonde at three GPS stations which are located close to the radiosonde stations. The three stations are CSBY (Surabaya), CTGR (Tangerang) and DARW (Darwin). The statistical comparison of PWV using three GPS stations with the nearest radiosonde sites is shown in Table 2.

Figure 4. PWV from GPS and radiosonde data for CSBY GPS station. (a) time series PWV; (b) scatter plot PWV GPS and Radiosonde.
Figure 5. PWV from GPS and radiosonde data for CTGR GPS station. (a) time series PWV; (b) scatter plot PWV GPS and Radiosonde.

Figure 6. PWV from GPS and radiosonde data for DARW GPS station. (a) time series PWV; (b) scatter plot PWV GPS and Radiosonde.

| Site   | # data | Mean bias (mm) | Std bias (mm) | R²   |
|--------|--------|----------------|---------------|------|
| CSBY   | 486    | -2.72          | 2.8           | 0.96 |
| CTGR   | 476    | 1.53           | 2.8           | 0.93 |
| DARW   | 7.16   | -2.06          | 2.8           | 0.98 |

3.3. Spatio-Temporal GPS PWV results of gridding method and coastline generation

The time series of GPS PWV for all stations and PWV Radiosonde from Juanda airport is shown in Figure 7. The GPS PWV time series in Figure 7 is started plot with the nearest distance the GPS stations to Radiosonde station. The temporal pattern of all GPS PWV has a similar pattern with the PWV radiosonde. It is indicated that our result has a good temporal pattern as a radiosonde result. There are several PWV anomaly patterns: from January to the end of February, middle April to middle May, middle June to end of July, and October to November 2020. Our suggestion for those anomalies is correlated with the precipitation or climate in East Java. Overall, PWV in April to middle October have a smaller value compared with the other months period.

The analysis of the spatial pattern of the PWV shows by the correlation coefficient for each GPS PWV to Radiosonde PWV (Figure 8). The coefficient shows that the PWV from the nearest GPS station strongly correlates with the radiosonde PWV. The lowest coefficient correlation at the CBLR GPS station is about 0.24. We suggest that the GPS station has a higher multipath environment. Figure 9 shows the plot of coefficient correlation with the radiosonde distance and excludes the CBLR station. The coefficient correlation shows that the increasing GPS stations distance will be decreasing the coefficient correlation value.
Figure 7. Time series PWV. (a) Time series GPS PWV with color represent the distance from Radiosonde site. (b) Time series Radiosonde PWV (WSRJ).

Figure 8. Spatial coefficient correlation between GPS PWV and RPWV. The color bar represent the coefficient correlation value.
Figure 9. Coefficient correlation value with the distance of GPS stations to radiosonde sites. Red line represents the direction of decreasing coefficient value with the increasing the distance from radiosonde site.

4. Conclusions
This research investigated spatio-temporal PWV using ground-based GPS stations in East Java. The consistency between the datasets has been assessed based on ZTD and PWV. The comparison between the ZTD and ZPD, GPS PWV, and Radiosonde PWV have a good agreement and strongly correlated with the coefficient correlation value 0.97 - 1.00 and 0.93 - 0.98, respectively. From our result, the temporal GPS PWV shows several anomalies, and our suggestion is correlated with the Monsoon Asian-Australian cycles that affect weather and climate in Indonesia. The spatial variation PWV shows a similar pattern for all stations. The spatial pattern of GPS PWV correlated with the distance to the radiosonde site. The nearest GPS site has a higher coefficient correlation and decreases with the increasing distance to the radiosonde site.

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5. References
[1] Bevis M, Businger S, Herring T A, Rocken C, Anthes R A and Ware R H 1992 GPS meteorology: Remote sensing of atmospheric water vapor using the global positioning system J. Geophys. Res. Atmos. 97 15787–801
[2] Koulali A, Ouazar D, Bock O and Fadil A 2012 Study of seasonal-scale atmospheric water cycle with ground-based GPS receivers, radiosondes and NWP models over Morocco Atmos. Res. 104–105 273–91
[3] Ejigu Y G, Teferle F N, Klos A, Bogusz J and Hunegnaw A 2021 Monitoring and prediction of hurricane tracks using GPS tropospheric products GPS Solut. 2021 25 1–15
[4] Zhu M, Liu Z and Hu W 2020 Observing Water Vapor Variability During Three Super Typhoon Events in Hong Kong Based on GPS Water Vapor Tomographic Modeling Technique J. Geophys. Res. Atmos. 125 e2019JD032318
[5] Zhao Q, Yao Y and Yao W 2018 GPS-based PWV for precipitation forecasting and its application to a typhoon event J. Atmos. Solar-Terrestrial Phys. 167 124–33
[6] Baker H C, Dodson A H, Penna N T, Higgins M and Offiler D 2001 Ground-based GPS water vapour estimation: potential for meteorological forecasting J. Atmos. Solar-Terrestrial Phys. 63 1305–14
[7] Shi J, Xu C, Guo J and Gao Y 2015 Real-Time GPS precise point positioning-based precipitable water vapor estimation for rainfall monitoring and forecasting IEEE Trans. Geosci. Remote Sens. 53 3452–9
[8] Herring T A, King R W, Floyd M A and McClusky S C 2018 GAMIT Reference Manual (Massachusetts Institute of Technology) 1-168

[9] Altamimi Z, Rebischung P, Métivier L and Collilieux X 2016 ITRF2014: A new release of the International Terrestrial Reference Frame modeling nonlinear station motions J. Geophys. Res. Solid Earth 121 6109–31

[10] Saastamoinen J 1972 Atmospheric Correction for the Troposphere and Stratosphere in Radio Ranging Satellites 247–51

[11] Lagler K, Schindelegger M, Böhm J, Krásná H and Nilsson T 2013 GPT2: Empirical slant delay model for radio space geodetic techniques Geophys. Res. Lett. 40 1069–73

[12] Boehm J, Niell A, Tregoning P and Schuh H 2006 Global Mapping Function (GMF): A new empirical mapping function based on numerical weather model data Geophys. Res. Lett. 33

[13] Lyard F, Lefevre F, Letellier T and Francis O 2006 Modelling the global ocean tides: modern insights from FES2004 Ocean Dyn. 2006 565 394–415

[14] Gérard P and Luzum B 2010 IERS Conventions (2010) Bur. Int. Des Poids Mes. Sevres 1–179

[15] Byun S H and Bar-Sever Y E 2009 A new type of troposphere zenith path delay product of the international GNSS service J. Geod. 2008 833 83 1–7

[16] Bevis M 1994 GPS meteorology: mapping zenith wet delays onto precipitable water J. Appl. Meteorol. 33 379–86

[17] Haase J, Ge M, Vedel H and Calais E 2003 Accuracy and Variability of GPS Tropospheric Delay Measurements of Water Vapor in the Western Mediterranean J. Appl. Meteorol. 42 1547–68

[18] Hagemann S, Bengtsson L and Gendt G 2003 On the determination of atmospheric water vapor from GPS measurements J. Geophys. Res. Atmos. 108 4678

[19] Bock O, Keil C, Richard E, Flamant C and Bouin M 2005 Validation of precipitable water from ECMWF model analyses with GPS and radiosonde data during the MAP SOP Q. J. R. Meteorol. Soc. 131 3013–36

[20] Bock O, Bouin M-N, Walpersdorf A, Lafore J P, Janicot S, Guichard F and Agusti-Panareda A 2007 Comparison of ground-based GPS precipitable water vapour to independent observations and NWP model reanalyses over Africa Q. J. R. Meteorol. Soc. 133 2011–27

[21] Wessel P, Smith W H F, Scharroo R, Luis J and Wobbe F 2013 Generic Mapping Tools: Improved Version Released Eos, Trans. Am. Geophys. Union 94 409–10