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Estimation Precipitable Water Vapor Using (PWV) The Permanent Single GPS Station in Makasar and Bitung, Indonesia

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Abstract
In this study, it is confirmed that single-station GPS meteorology is feasible where there is no possibility for the development of a sophisticated and reliable GPS network. Since 2009 GPS stations have been installed in Makassar and Bitung by the Indonesian Geospatial Information Agency, where meteorological sensors have also been installed at the stations. The method used is to extract Rinex data collected every 30 seconds from GPS stations and processed to estimate the total zenith delay (ZTD) of GPS signals in the troposphere. The ZTD estimate is then automatically converted to stored water vapor (PWV) with the calculations and algorithms of the goGPS software. The results obtained from this goGPS calculation are then validated. Two types of validation were applied to the PWV estimation. They all prove the validity of GPS results: (1) PWV was measured using radiosondes in Makassar and Bitung with almost the same climate regime, showing 96.5 and 83.0% correlation with GPS PWV time series, respectively. (2) the global reanalysis data set showed a correlation of 60.1 and 75.3%, respectively, with GPS results. The results of both validations employing this comparison show that a permanent GPS network can be an alternative to obtain more detailed and temporally accurate meteorological data with lower costs and time-saving operations.

Keywords: PWV, GPS, Meteorology, Radiosonde, goGPS

1. Introduction

Water vapor content in low atmospheric cycles is one of the most important parameters for water vapor monitoring and rainfall forecasts. However, its rapid rate of change makes it difficult to monitor (Li et al., 2012); However, acceptable water content is a prerequisite for any precipitation event. The occurrence of large rainfall concentrations will cause flooding, with the risk to lives and livelihoods. Besides, rainfall is also one of many regions' most critical water sources. Therefore, monitoring short-term rainfall forecasts and services, especially for high-intensity rainfall, is critical to reducing risks to life and property and increasing the utilization of water resources (Chiang et al., 2009).

Traditional water vapor observation methods cannot monitor and predict rainfall events because of the limited temporal-spatial resolution. Examples of traditional water vapor observations are that the radiosonde of adjacent distances is around 200-300 km. Balloons are launched twice per day: such spatial and temporal resolution is insufficient for monitoring and forecasting needed on a small scale of a mesoscale. Microwave radiometer price is costly and can not be used on a rainy day, so its use is less valuable in practice (Michael Bevis et al. 1994). When Bevis et al. (1992) proposed the concept of GPS meteorology, ground-based GNSS gradually became one of the most important means for obtaining integrated water vapor data (IWV) and analyzing rainfall events.

The Global Satellite Navigation System (GNSS) has been developing for more than twenty years; many cities have formed their own Continuously Operating Reference Station (CORS) network. For example, in Japan, more than a thousand ground-based GNSS stations continue to operate that are distributed evenly, which is sufficient to meet the requirements of water vapor analysis on a small scale and mesoscale. At present, GNSS-based PWV is mainly derived from two techniques, and one is the exact precise positioning point (PPP) technique based on observations that are no different; another method is the calculation of the basis or network based on double-differenced observations (Zumberge et al. 1997)

Compared to the latest conditions, the PPP technique can be used without introducing a base station of more than 500 km, the resolution of a single station based on practical and time-saving PPP techniques. Previous research has shown that it is no different about the accuracy of PWVs originating from GPS is comparable in precision with the classical measurements of water vapor radiometers, radiosondes, or radars ((M Bevis et al. 1992); (Rocken et al. 1993)). (Li et al., 2012) used ZTD, and the increase, for the now-casting rainstorm. (Benevides, Catalao, and Miranda 2015) It has proposed a simple algorithm that can estimate rain within 6 hours after a significant increase in GPS PWV at one station.

The purpose of this study is to analyze PWV derived from PPP techniques using permanent GPS single data and relevant rainfall information to explore the relationship between PWV and rainfall and provide helpful information for short-time and real-time forecasting. Rainfall data per day for experimental deposition stations is collected from April 2015 to March 2016, and hourly PWV data for GPS stations in Makassar and Bitung is processed using the open-source PPP software, namely goGPS. According to the correlation between PWV and rainfall events, a new rainfall forecast model is proposed and tested using data from other regions.

2. Methods and Dataset

For an overview of the dataset as shown in this table 1

Data set	Name station/Type of data
GPS	Standart ZTD Test : JOG2 and BAKO/Rinex
GPS	Meteorology study : CBIT and CMAK/Rinex
Radiosonde	WAAA and WAAM/PWV
BMKG	Dayli Rainfall
ECMWF	PWV Global dataset

table 1 data set

GPS data for meteorological studies were collected from two stations on Sulawesi Island, Indonesia. Two GPS stations are Makassar Observatory (CMAK), and Bitung (CBIT). Data from meteorological sensors are used for each GPS station — all GPS stations record carrier phase at 30-second intervals. We use the BAKO and JOG2 station as a standardized test of ZTD values compared to ZTD from International GNSS Services (IGS), whether the process of obtaining them with goGPS software is correct or not.

Figure 1. left is CBIT station and right is CMAK station

For validation, we chose radiosonde data for 2015/2016, which is near the GPS station. Radiosonde near CMAK is called WAAA at a distance of 18 km, and Radiosonde near CBIT is 31.3 km, whose name is WAAM. Subsequent validation uses PWV from the global reanalysis dataset from the European Center for Medium-Range Weather Forecast (ECMWF). As an application for rain events, we also use daily rainfall data in Makassar and Bitung from the Indonesian Meteorology and Climatology Agency (BMKG).

The data processing software used for GNSS observation is goGPS. goGPS is an open-source software application developed by (Realini et al. 2012) in 2007 at the Geomatics Laboratory of the Politecnico in Milano, Como Campus. Initially, it was developed in MATLAB but was recently converted to Java to expand its users, and they were started to provide it as a service through the web. This process obtains zenith troposphere delay (ZTD) at the station with high accuracy. ZTD is obtained using a mapping function that projects slant path delay to zenith at the station, which generally consists of zenith hydrostatic delay (ZHD) and zenith wet delay (ZWD). The main contribution to ZTD (about 90% of ZTD at sea level), determined by the station's height and surface pressure, is called ZHD and can be obtained precisely using an empirical model. Another contribution is ZWD (about 2-20% of ZTD), which occurs at different signal frequencies and is mainly influenced by the dipolar moment of the water vapor molecule, which causes a delay in signal propagation.

Besides, a few hours before the rainfall event, signal propagation was also influenced by delays in the hydrometeor peak (ZHMD, around 0–3% of ZTD), which showed relatively high variability before, and after precipitation. ZHD, whose position is above the station, can be calculated precisely using the surface pressure observed based on the Saastamoinen model (To and Computation 1966)

$$ZHD = \frac{0.002277 \cdot P_s}{1 - 0.00266 \cdot \cos(2\varphi) - 0.00028 \cdot H} \quad (1)$$

Where Ps is the surface pressure (unit: hPa), φ is the latitude, and H is the geodetic height (unit: km). ZHD represents a function of surface pressure after a station is determined. The increased surface pressure of 1 hPa only causes an error of about 0.2 mm ZHD (Tregoning and Herring 2006). Usually, ZWD is extracted accurately from ZTD by reducing ZHD, and PWV is then obtained by conversion from ZWD (Michael Bevis et al. 1994).

$$PWV = \frac{10^6}{\left(\mathrm{k'}_2 + \frac{\mathrm{k}_3}{\mathrm{T}_m}\right) R_v \cdot \rho} .ZWD \quad (2)$$

Where, k'2 = 16.48K hPa-1 and k3 = (3.776 ± 0.014) x 105K2 hPa-1 are constants, Rv = 461(Jkg-1·K-1) represents the ideal gas constant for water vapor, ρ is the density of water vapor density, Tm is a mean temperature of the atmospheric column. To get the Tm value, we calculated using observed surface temperatures based on empirical models constrained by reanalysis data (i.e., ECMWF data) (Michael Bevis et al. 1994).

PWV is the total moisture content of the unit in the atmosphere round column (unit: kg / m2), which is the same as the liquid water content at the same height (unit: mm) and is related to the integrated wet profile above the station (Benevides, Catalao, and Miranda 2015). After ZWD above the station is determined, PWV only correlates with Tm: an experiment has been carried out by Bevis to validate that the error is caused by Eq. (2) is 1% -2% (Michael Bevis et al. 1994). (Brenot et al. 2006) also found that PWV errors are less than 0.3 mm (based on Equation (2)), which is more accurate than PWVs that come from direct meteorological observations.

3. Result and Discussion

3.1. Troposphere Zenith Delay

BAKO Station is one of the oldest CORS stations owned by the Indonesian Geospatial Information Agency. The first time our validation was to validate the process of getting ZTD values with the goGPS software using the BAKO station. To validate this process, we use DOY 1 to 7 or January 1 - 7 of 2016.

From Bako station, standard deviation, and the correlation between the ZTD estimate obtained from goGPS software with PPP processing and ZTD from IGS for the stations over the one week. The difference between the two processing methods is less than -3.77 mm, while the standard deviation is 13.58 mm, and the correlation is 0.87; this shows a good agreement results in ZTD goGPS with ZTD from IGS.

The ZTD estimates for the BAKO station from the IGS and our solution are compared in Fig.1. Both results are consistent, and the deviations between the two solutions are well within the level of 1–2 cm. These results conform to the findings in (M Bevis et al. 1992) (Gao and Chen 2004), (Gendt, Reigber, and Dick 2001), and (Rocken et al. 1993). An error of 1–2 cm in ZTD equals an error of 1–3 mm in PWV, which is considered insignificant for this study. Therefore, unless stated otherwise, we use this PPP solution in the following analysis.

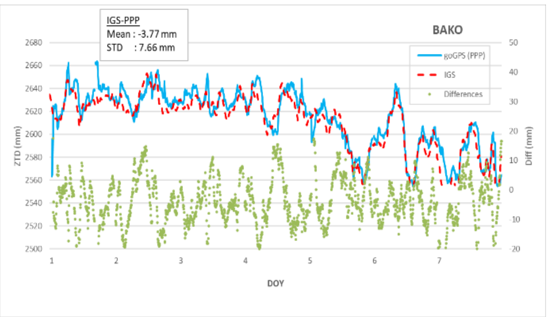

Figure 2. One-week comparison between the IGS final tropospheric product with PPP processing solutions at BAKO GPS station

Next, we calculate data BAKO and JOG2 stations from 22 to 25 January 2018. The data period that we process is every 5 minutes, so the amount of data for one day (24 hours) there are 288 data. We get the most minor, most significant, and average values from the amount of data, as presented in Figure 2.

We carried out the same process from 18 to 21 August 2018. We present the results in Figure 3 ZTD values from 22 to 25 January 2018 in the BAKO station range tend to be higher than the range of ZTD values from 18 to 21 August 2018. Likewise, at the JOG2 station, ZTD range values from 22 to 25 January 2018 also show a higher average than ZTD range values are from 18 to 21 August 2018

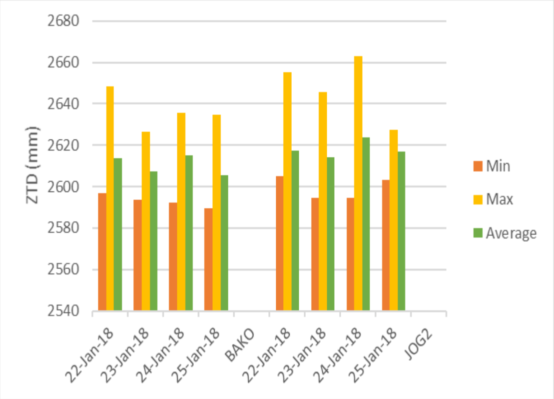

Figure 3. Min, max, and average values for 22-25 Jan 2018 at BAKO and JOG2 stations

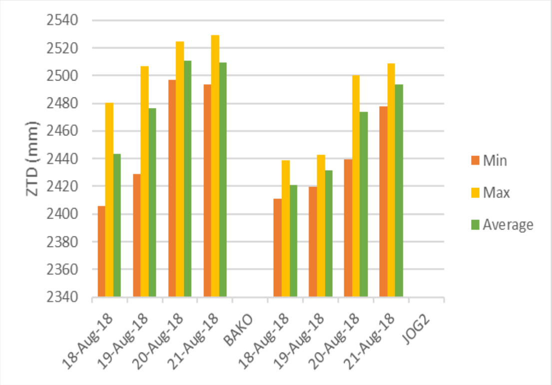

Figure 4. Min, max, and average values for 18-21 Aug 2018 at BAKO and JOG2 stations

Figure 2 and Figure 3 show that there are differences in the value of ZTD depending on different time conditions. This time difference is based on differences in seasons that exist in Indonesia, namely the rainy season and the dry season.

After the validation process, goGPS can be an alternative determination of ZTD values. Then we carry out a whole month ZTD estimation process to better see the relationship of ZTD values with differences in the January season representing the rainy season and August representing the dry season. Compared to each in a separate Bako station and Jog2 station in January and August. The results are as in figures 4 and 5.

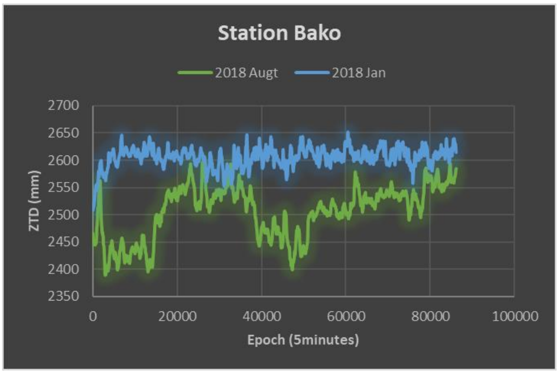

Figure 5. ZTD Jan and Augt 2018 at BAKO stations

The figure shows that the tendency of ZTD value in January is higher than that of ZTD in August for Bako and Jog2 stations, with an average difference of 99,632mm and 142,602mm, respectively.

The condition of the ZTD value during January was relatively constant compared to August, when there was a fluctuation in the value of the ZTD. This is seen in the standard deviation in August being greater due to fluctuations than January, which was relatively stable. For the BAKO station, the station is January 18,025 mm, and August is 48,118 mm. As for the JOG2 station, it was 22,986 mm in January and 42,988 mm in August.

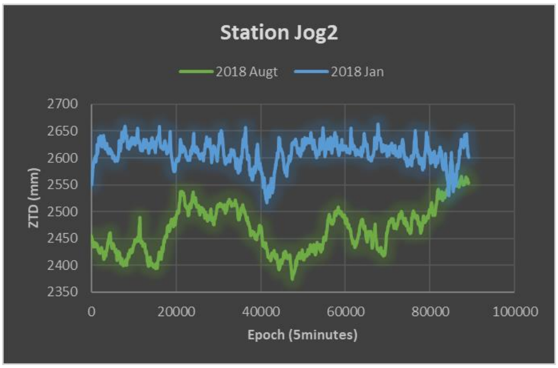

Figure 6. ZTD Jan and Augt 2018 at JOG2 stations

This means that in the rainy season, the value of ZTD is higher than in the dry season, which shows that ZTD is an indication of conformity to the conditions of the rainy season and dry season; hopefully, this phenomenon can be more beneficial for meteorological purposes.

3.2. Validation of ground-based GPS-PWV with radiosondes

After validating the process of getting the ZTD and PWV values, we continue to validate the PWV results obtained using the PWV values from Radiosonde observations. The PWV value of this radiosonde is obtained twice a day by releasing balloons into the air at 12.00 am and 12.00 pm.

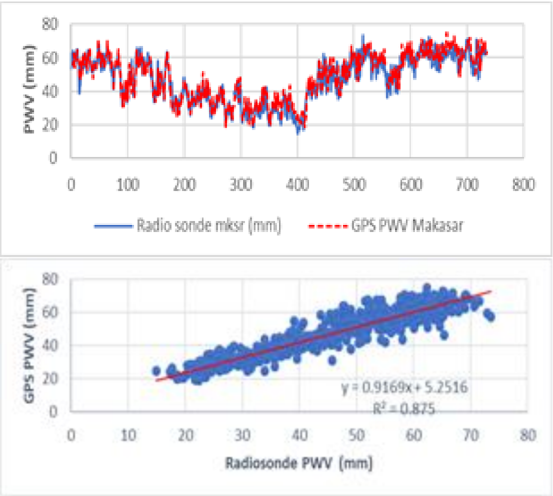

Figure 7. Comparison of GPS PWV (CMAK) and radiosonde (WAAA) twice a day, from April 2015 to March 2016 in Makassar, the relationship shows a positive correlation

To validate the estimated PWV values obtained from GPS, we first compared the PWV values from Radiosonde observation data, with a twice-daily period from April 2015 to March 2016, as in Figure 6. for Makassar Figured 7. for Bitung. The results of the PWV correlation from GPS and PWV from radiosonde for Makassar and Bitung were 96.5 and 83.0%, respectively, and the bias values were -0.299 and -5.431. This means that the relationship between the PWV from GPS and Radiosonde is perfect, despite the distance. So the PWV GPS values selected twice a day, both in Makassar and Bitung, can complement each other from the PWV values observed from the radiosonde.

We hope that the PWV obtained from GPS can be helpful for meteorological purposes because there are currently only 22 radio stations in Indonesia, and the operation is quite expensive and takes a long time. While there are 200 GPS stations, data is automatically recorded every 30 seconds.

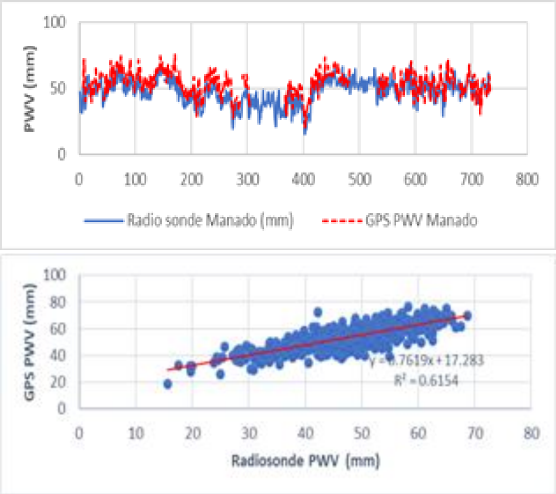

Figure 8. Comparison of GPS PWV (CBIT) and radiosonde (WAAM) twice a day, from April 2015 to March 2016 in Bitung, the relationship shows a positive correlation

Next, we want to show that the PWV data from GPS is against the radiosonde PWV value because the temporal resolution is quite dense, which is 30 seconds compared to twice a day. Furthermore, the comparison of GPS PWV values every 30 seconds and PWV radiosonde twice a day, during July 2015 in the Makassar and Bitung regions is shown in Figure 8. It shows a good agreement between the two data sets, specifically in CMAK-WAAA for Makassar and CBIT-WAAM for the pair of Bitung stations where the GPS receiving station and radio station is installed. The correlations and biases of Makassar and Bitung, respectively, are 0.876; 5.439 and 0.917; 6,597.

From figure 8, it appears that the radiosonde value for a whole month has a gap that is quite tenuous a day. With data from GPS, it can close the tenuous hose and becomes more accurate in meteorological measurements. So if this GPS is used for meteorological purposes, it will be beneficial in detail and precision in terms of weather prediction and climate applications. Moreover, we think it needs further research to be sure.

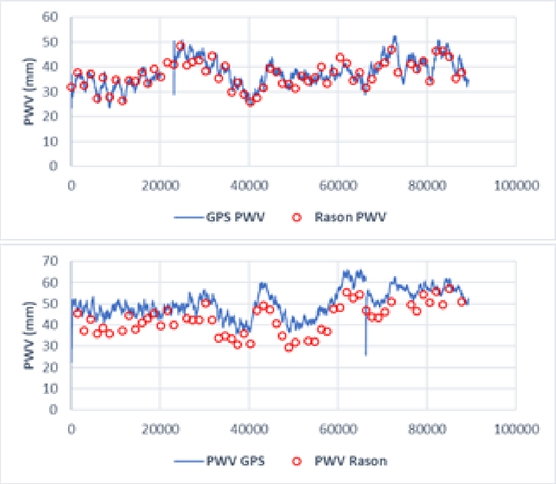

Figure 9. Comparison of GPS PWV every 30 seconds and radiosonde twice a day, July 2015, the relationship shows a positive correlation. Draw the section above Makassar and below Bitung

For the validation with the global reanalysis of the dataset from the ECMWF, we use ten days of the year from GNSS data, from 355 to 365 or the same as December 21-30, 2015, both in CMAK and CBIT, the results are as shown in Figure 9. Each -The correlations of Makassar and Bitung are 0.601 and 0.753. This means that on a global scale, PWV from GPS also shows a positive correlation. Hence, PWV obtained from GPS can be an alternative for monitoring and analysis related to meteorology, as the link is here, https://apps.ecmwf.int/datasets/data/interim-full-daily/levtype=sfc/.

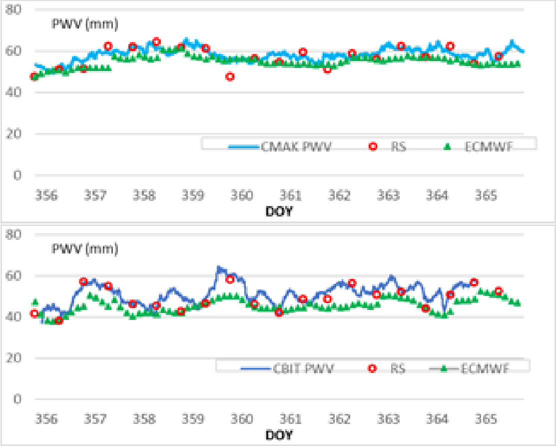

Figure 10. Comparison of GPS PWV every 30 seconds, radiosonde twice a day, and PWV ECMWF every three hours on December 21-30, 2015. The relationship shows a positive correlation, the section above Makassar and below Bitung

3.3 PWV GPS application with rainfall

1) After validating the GPS PWV value from April 2015 to March 2016, we try to apply it to the rain conditions in Sulawesi. As we know, the season in Sulawesi is a rainy season between October to March and the dry season around April to September. Therefore the application approach is based on the seasons in Sulawesi. The results are shown in Figures 10 for the rainy season and Figure 7 for the dry season.

2) In the dry season, PWV shows a declining trend, which means that when the rain starts, there is no PWV also begins to decrease, this condition occurs in Makassar and Bitung, but in Makassar, the pattern of decline is more precise.

3) In the rainy season, the trend of PWV values appears to be rising, both in Makassar and in Bitung, and the rise in Makassar is steeper than in Bitung. It may be that the conditions were arid before long or not raining, then suddenly it rained heavily.

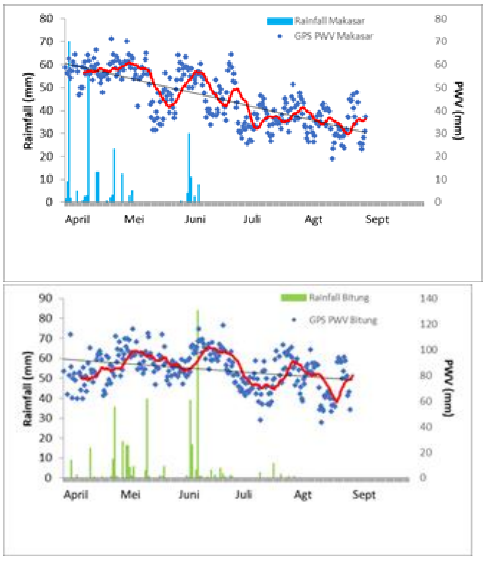

Figure 11. Comparison of daily PWV GPS with daily rainfall for six months April-Sept 2015 (dry season). The PWV trend is decreasing.

Figures 10 and 11 show that the PWV value of GPS has a significant influence on seasonal changes. In this case, during the dry season and rainy season. This means that the dynamics of the PWV change is enough to determine whether it is raining or not, and it requires quite a lot of data to study this phenomenon further

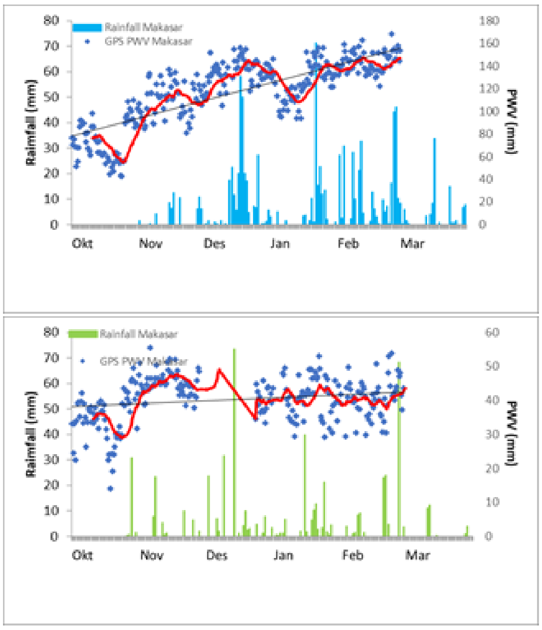

Figure 12. Comparison of daily PWV GPS with daily rainfall for six months Oct 2015-March 2016 (rainy season). The PWV trend is increasing.

GPS, which so far has only been used to measure mapping surveys and studies of the dynamics of earth movement or deformation, with our study, can be used for other purposes, namely GPS meteorology. With the study area in Sulawesi, we chose two stations, namely Makasar and Bitung, because, in these two places, there is a radiosonde station as a comparison and validation. So our results show a significant correlation between PWV from GPS and PWV from the radiosonde. So GPS in Indonesia, with a number that is still limited, can be used for purposes meteorology, even more detailed and accurate, and cheaper. Of course, many things need to be deepened in this study, such as examples of more data and natural phenomena that require more anticipation, such as heavy rains, storms, and other disasters.

4. Conclusion

GPS, which so far has only been used to measure mapping surveys and studies of the dynamics of earth movement or deformation, with our study, can be used for other purposes, namely GPS meteorology. With the study area in Sulawesi, we chose two stations, namely Makasar and Bitung, because, in these two places, there is a radiosonde station as a comparison and validation. So our results show a significant correlation between PWV from GPS and PWV from the radiosonde. So GPS in Indonesia, with a number that is still limited, can be used for purposes meteorology, even more detailed and accurate, and cheaper. Of course, many things need to be deepened in this study, such as examples of more data and natural phenomena that require more anticipation, such as heavy rains, storms, and other disasters.

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