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Determining the precipitable water vapor with ground-based GPS and comparing its yearly variation to rainfall over Taiwan

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Abstract

Water vapor plays an important role in weather prediction. Thus, it would be helpful to use precipitable water vapor (PWV) data from Global Positioning System (GPS) signals to understand weather phenomena. Approximately 100 ground GPS stations that cooperate with approximately 500 ground weather stations were used in this study. The relationship between the PWV and rainfall was investigated by analyzing the amplitude and phase that resulted from harmonic analyses. The results indicated that the maximum PWV amplitudes were between 10.98 and 13.10 mm and always occurred at the end of July. The magnitudes of the PWV growth rate were between 0.65 and 0.81 mm/yr. These rates increased from 9.2% to 13.0% between 2006 and 2011. The largest peak PWV amplitude occurred in the Western region. However, the largest rainfall amplitude occurred in the Southern region. The presented peak rainfall time agreed with the peak PWV time in the Western, Southern, and Central Mountain regions. Although rainfall decreased with time in Taiwan, this decrease was not large. The greatest rainfall consistently occurred during the months in which typhoons occurred, and the greatest PWV values occurred at the end of July. Although the end of July had the greatest monthly average PWV values, the rainfall magnitude during this period was smaller than that during the typhoons, which only occurred for a few days; the PWV also increased during typhoons. Because this effect was short-term, it did not significantly contribute to the PWV monthly average.

Keywords: GPS; Precipitable water vapor; Rainfall; Yearly variation; Taiwan

1. Introduction

The troposphere medium is non-dispersive, the velocity of electromagnetic waves in the troposphere is only related to its temperature, pressure and humidity at a frequency of less than 30 GHz. The frequencies of Global Positioning System (GPS) signals are approximately 1.2 and 1.5 GHz. The path delay of GPS signals is affected by tropospheric parameters, including water vapor. Water vapor plays an important role in predicting and monitoring weather. Thus, it is helpful to evaluate variations in weather systems by observing the water vapor distribution. In addition, water vapor observations may help understand special weather phenomena. Water vapor may be determined by calculating the path delay of GPS signals in the atmosphere, and this method is significant for weather research.

The change of the dry air density is consistently influenced by surface pressure. Thus, the estimated dry delay can be predicted within an accuracy of millimeters, and the observed temperature, relative humidity and pressure can be determined with an atmospheric model. However,

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due to the variable distribution of water vapor, no accurate model exists for estimating the wet delay based on the measured partial pressure of water vapor. In general, the wet delay can reach approximately 35 cm in a wet and humid area in the zenith direction (Bevis et al., 1992). Theoretically, the greatest zenith tropospheric effect on the GPS signal can be resolved with the hydrostatic zenith delay formula (Saastamoinen, 1973). Under the assumption that the Earth's atmosphere is spherically symmetric, well distributed and layered, the slant of the tropospheric path delay can be derived from the zenith delay with a mapping function (Niell, 1996). However, the above assumptions regarding Earth's atmosphere are not true. For example, the distribution of the atmosphere is thinner in the polar areas than at the equator. The Azimuthal asymmetry model is used in data processing to correct the horizontal gradient problem. With this model, the tropospheric path delay can be obtained within an accuracy of cm (Gardner, 1977).

Because ground-based GPS is inexpensive, it can be densely distributed. GPS technology can provide in near real-time, highly precise, and continuously varying precipitable water vapor (PWV) data across a wide coverage area (Liou et al., 2001). This ability is very important for improving the short-term weather forecast capability, especially in terms of thunderstorm forecasting and numerical weather forecast models. Moreover, Liou et al. (2000) also suggest that the most accurate GPS estimates of PWV were achieved when the GPS analysis contains station separations of more than 2000 km when using differential GPS data processing. Currently, the ground-based GPS network of the National Oceanic and Atmospheric Administration (NOAA) of the United States can automatically estimate the variation of PWV above the network surface every 30 min (Smith et al., 2007). In a study of Sweden and Finland, the differences between Water Vapor Radiometer (WVR) and GPS observations of the PWV are on the order of 1–2 mm based on three-month field measurements (Emardson et al., 1998). The accuracy of absolute PWV has also been estimated from GPS observations (Tregoning et al., 1998). They found that GPS, radiosonde, and WVR estimates of PWV differ by 1.4 mm between any two types of observations with a bias of 0.2 mm. When it comes to the comparison of the ZTD from GPS and VLBI, the difference is around 3.8 mm with correlation coefficients of higher than 0.87 (Wei et al., 2012). Furthermore, data from Haase et al. (2003) are compared with independent equivalent values derived from radiosonde profiles; the difference between radiosonde and GPS zenith total delay (ZTD) has a standard deviation of 12 mm of delay and a bias of 7 mm of delay. Basili et al. (2004) use the Special Sensor Microwave/imager and the radiosonde observations over the Mediterranean area to validate the accuracy of the PWV retrieved by ground-based GPS. Moreover, Li et al. (2008) performed composite analysis of diurnal cycle of GPS-PWV in central Japan during calm summer days, and found that the diurnal variation of PWV seemed to be strongly affected by the local thermal circulations. Jin et al. (2010) utilize the residual-based stochastic model which is proposed to use in scientific software packages, e.g., Bernese, GAMIT and GIPSY, to improve the precision of GPS baseline and ZTD estimation. In addition, several studies (Iwabuchi et al., 2000; Mzany et al., 2002; Wang et al., 2013; Pérez-Ramírez et al., 2014) investigated the applications of ground-based GPS remote sensing for measurement of atmospheric water vapor indifferent areas.

With regard to PWV seasonal variations and trends, continuous GPS observations in China for 2004–2007 were used to produce PWV where strong seasonal cycles were found, the summer with maximum water vapor, and the winter with minimum water vapor (Jin et al., 2008). Moreover, the PWV diurnal cycle determined by Wang et al. (2009) has an annual mean, peak-to-peak amplitude of 0.66, 0.53 and 1.11 mm for the globe, Northern Hemisphere, and Southern Hemisphere, respectively. Furthermore, the higher amplitudes of annual PWV variations are located in middle latitudes, and the lower amplitudes are found in high latitudes and the equatorial areas. The larger differences of mean PWV between the summer and winter are located in middle latitudes with about 10–30 mm, particularly in the Northern Hemisphere. The semiannual variation amplitudes are relatively weaker with about 0.5 ± 0.2 mm (Jin and Luo, 2009). On the other hand, Chen and Li (2013) find the PWV variation amplitude in weak radiation days is larger than that in strong radiation days. The variation of the PWV is obviously related to the global solar radiation. Seco et al. (2011) focus in the relationship between rain occurrence, atmospheric pressure and water vapor content using nine years data. Roman et al. (2012) also utilize ground-based GPS to retrieve the PWV in the U.S. Great Plains and Midwest and to detect a 1 mm/yr PWV trend from 2000–2009. When it comes to the weather forecaster, Choy et al. (2013) utilize GPS sensing of PWV to analyze the March 2010 Melbourne storm, they find strong correlation between ground-based GPS-PWV estimates and storm passage. In America, National Weather Service Forecasters use GPS-PWV for enhanced situational awareness during the Southern California summer monsoon (Moore et al., 2015).

In the data-processing procedure, the individual ZTD for each GPS station can be obtained after resolving the ambiguity with the least-squares method, which uses the double-difference strategy with GPS carrier phase measurements. By analyzing the hydrostatic zenith delay formula, the zenith hydrostatic delay and zenith wet delay (ZWD) are separated from the ZTD (Chen et al., 2011). A relationship exists between the PWV and the ZWD. Thus, ZWD can be converted into PWV using a transfer factor. Moreover, the 1–2 mm accuracy of PWV values that were derived from GPS observations in this study was previously validated against Water Vapor Radiometers (Yeh et al., 2014). In this study, approximately 100 ground-based GPS stations that cooperated with approximately