Evaluate the Precipitable Water by GPS Satellite Signals – a Case Study of Summer Monsoon in Southwest of Taiwan

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Abstract

Retardation caused by Global Positioning System（GPS） satellite signals while penetrating through the troposphere gives an indication of the density of water vapour within the troposphere on the path of signal transmission. With the Global Navigation Satellite System at MIT(GAMIT) procedures for the reversal evolutional processes upon the tropospheric retardation effect, and with the three-dimensional variational method（3DVAR）of weather research and forecasting（WRF）system, the preliminary estimation on precipitable water vapor（PWV）may be assessed via the WRF-assimilated PWV. Hence, the accuracy, the near field, and the instantaneous rainstorm forecasting can be improved. Rainstorm events for July to September of 2010 in Tainan, a southern state of Taiwan, were adopted for this study. It was shown that the temporal and spatial distributions of assimilated PWV were apparently correlated, as well as the significant improvement in estimation of rainfall intensity via the WRF-assimilated PWV. It reflects the specific characters of summer monsoon and regionalized rainfall patterns; especially, the similarity between the maximum PWV and the maximum rainfall occurrence for geographically near-sited areas.

Keywords: GPS, Precipitable Water Vapor, GAMIT, 3DVAR

1. Introduction

The geographic location of Taiwan falls between the tropic and the sub-tropic weather zones. Hence, during the summer, the afternoon mesoscale rainfalls were often being developed; due to the plenty of water vapor supply. Within 2~3 hours, such kind of afternoon rainstorms can be quickly formed, and pour in few tens to few hundred millimeters of rainfall.

It is very important that the loss of traffics, agricultures and geological hazards accompanying the rainstorms may be greatly reduced; if the intensity of the precipitation can be accurately estimated in advance. However, with the traditional ground-based metrological observatories, the metrological information can only be temporally and spatially limited in sampling the regional weather data. Namely, it becomes obviously more important that with the temporal continuity and wideregional coverage, especially with the characteristics of being disturbed while propagating through the troposphere, the GPS satellite signals can provide the regionalized weather information approximately 1~2 hours in advance before the development of the afternoon rainstorms.

Purpose of this study was set to adapt the retardation characteristics for GPS satellite signals penetrating the troposphere, with the Global Navigation Satellite System at MIT(GAMIT) procedures for the reversal evolutional processes upon the tropospheric retardation effect, and with the three-dimensional variational method（3DVAR）of weather research and forecasting（WRF）system, the preliminary estimation on precipitable water vapor（PWV）may be assessed via the WRF-assimilated PWV. Hence, the accuracy, the near field, and the instantaneous rainstorm forecasting can be improved.

Rainstorm events for July to September of 2010 in Tainan, a southern state of Taiwan, were adopted for this study.

2. Methodologies

2.1 The Physical Characteristics of Troposphere

Delays caused by the atmospheric refraction within the non-ionosphere is called the Neutral Delay. However, about 80% of this part of delay concentrates mainly in the troposphere; therefore it was also called the Tropospheric Delay. The propagation velocity of electromagnetic wave within this atmospheric layer is essentially affected by changes of the atmospheric factors; i.e., pressure, temperature and water vapor. These factors cause the refractive index changes on the propagation path. This effect is called Tropospheric Refraction Error. In addition, the terrain and the height of where the receiver is located will also affect the changes of refractive index.

Generally, influences caused by the refractive index can be explained by the following two points:

（1）The velocity delay: the refractive index is greater within the troposphere than within the vacuum environment; thus, slows the electromagnetic waves propagate through the troposphere.

（2）The path curvature delay: since the refractive index varies with the height of the atmosphere, the propagating path of the electromagnetic wave is curved rather than straight lines; while transmitting through the atmosphere, which elongates the signal traveling path. Usually, the delay is no more than 1 cm, when the elevation angle is greater than 15 degrees（Bevis et al, 1992）such that it has often been ignored during the computation for errors.

The delay, caused by the refraction effect, at the zenith direction can be expressed as follows（Bauersima, 1983）:

$$\Delta L^z = \int (n-1) ds = 10^{-6} \int N ds \quad (1)$$

where, the z LΔ is the delay at the zenith direction due to the tropospheric refraction effect; n is the coefficient of refraction for the air media along the wave propagating path; N is the refractive index of the air.

The delay caused by the tropospheric refraction effect may be divided into two components:（1）the Hydrostatic Delay, which is due to the dry air, also called the Dry Delay, and（2）the Wet Delay, which is caused by molecules of water vapor. The influences due to the hydrostatic delay are originated from the atmospheric pressure and the absolute temperature; which are less affected by the environment. The hydrostatic delay is about 90% of the total delay（Rocken, 1995）. The effect of wet delay is correlated to the partial pressure of the water vapor. Although the wet delay is only 10% of the total delay, it is affected dominantly by the weather factors; of which, the variation may be as large as several times. Thayer（1974）gives the formulas for calculating the refractive index:

$$N = N_d + N_w = k_1 \frac{P_d}{T} + (k_2 + \frac{k_3}{T}) \frac{P_w}{T} \quad (2)$$

where, the refractive indices for air, dry air and wet air are shown as N, Nd and Nw, respectively. The Pd and Pw are representing the partial pressures of the dry air and the wet air. T is the absolute temperature. k1, k2 and k3 are the constants of refractions.

Namely, delays caused by refraction effects of the dry and the wet air, respectively, can be expressed as the following:

$$\Delta L_d^z = 10^{-6} \int N_d ds = 10^{-6} \int k_1 \frac{P_d}{T} ds \quad (3)$$

$$\Delta L_w^z = 10^{-6} \int N_w ds = 10^{-6} \int (k_2 + \frac{k_3}{T}) \frac{P_w}{T} ds \quad (4)$$

where z dLΔ and z wLΔ are delays caused by the dry air and the wet air refraction effect, respectively.

The liquid state water, ice, and condensations in the air will only cause a very little effect on the transmission of GPS signals. Many theoretical studies have proved that even a thick and dense cloud that would only cause a maximum delay of 7.5 mm, approximately（Duan, 1996; Busings, 1996）. However, the influence of water vapor on the transmission of electromagnetic wave is significantly sensitive. The refractive index of wet air with one mole of water vapor is approximately 17 times of that of the dry air（Busings, 1996）. Hence, even though the atmospheric air consists only 0.1～4％ of water vapor, the delay caused by the water vapor is as much as 10% of the total atmospheric delay. Besides, the wet delay caused by the water vapor may have more than 20 mm change within an hour. It hence causes a great difficulty to sufficiently estimate the wet delay produced by water vapor, as well it becomes a hard removable error source for pinpointing the GPS position.

For climate, the water vapor is an extremely important physical measurement. It is not only because of the water vapor, cloud and precipitation are strongly correlated among each other, but also the phase change of water vapor can produce voluminous latent heat for phase transition. Namely, the water vapor affects the atmospheric steadiness, the structure and development of the tropic cyclone, as well as the equilibrium of earth interior energy radiation. In addition, the water vapor is also the key greenhouse gas for global climate system. Therefore, with the inversion of such error source for positioning the GPS, the water vapor may be evaluated; the mechanism for part of weather system evolution may also be analyzed. The aspect of GPS positioning was then become an additional scientific and meteorological application.

2.2 GAMIT

GAMIT is a computer program for solving the wet air moisture content and amount of precipitable water. GAMIT uses observation theories of the two frequencies and the carrier wave phases. Except the whole cycle undetermined value N, the error generated by signals between GPS satellite and ground receiver can be eliminated. For instance, the virtual observation value（Φ）is the summation of the true distance（R）from the GPS satellite to the receiver, the clock error of the receiver（dt）, the clock error of the satellite（dT）, the Ionosphere delay error（Ion）, the troposphere delay error（Trop）, the noise of the virtual distance observation（λ）, and the residual error（ε）of multiple path effect; with wave propagating velocity under vacuum condition（c）, the equation may be written as:

$$\phi = R + c(dt - dT) + Trop + Ion + N\lambda + \varepsilon \qquad (5)$$

The delay error caused by troposphere may be eliminated by the two frequency observations. The error between the receiver clock and satellite clock can be eliminated by the first order error and second order error of carrier wave phase observations; therefore, the error caused by the delay of troposphere became the primary error of the observations made.

This study implements the corresponding position of the GPS carrier wave phase to solve the tropospheric delay at the zenith direction（ZTD）; then, uses the Saastamoinen model to solve the dry air delay at the zenith direction（ZDD）. The wet air delay at the zenith direction（ZWD）may be solved by subtracting the ZDD from the ZTD.

$$ZWD = ZTD - ZDD \qquad (6)$$

Computation of ZTD is primarily the first step for solving the wet air moisture content and the amount of precipitable water. Besides the above mentioned steps such as implementation of the two frequency observations and the second order error, a mapping function has to be implemented for GPS signals were not all zenith direction oriented. Namely, a transference on to the zenith direction via mapping function is needed for those signals traveling in an oblique path, so as to make signals from all other path may be transferred into zenith direction oriented. Niell mapping function was the model adopted to process the tropospheric delay; which is formulated as following:

$$m(\theta)=\frac{1+\frac{a}{1+\frac{b}{1+c}}}{\sin(\theta)+\frac{a}{\sin(\theta)+\frac{b}{\sin(\theta)+c}}} \quad (7)$$

The following step is to solve the ZDD by using Saastamoinen empirical model:

$$ZDD=10^{-6}\frac{k_1RP}{g_mM_d}=10^{-6}\frac{k_1R_dP_s}{g_m}=\frac{2.2767P_s}{f(\varphi,h_0)} \quad (8)$$

where, ZDD is the dry air delay at the zenith direction（mm）; Ps is the atmospheric pressure（hPa）; R = 8.31434 J/（mol•K）is the ideal gas constant; M_d =28.9644 g/mol is the molar mass of the dry air; $R_d =R/M_d$; g_m=9.784/ $f(\varphi,h_0)$ is the gravitational acceleration of the center of mass for the vertical atmospheric column; $f(\varphi,h_0)$ is a function of the latitude and the elevation of the observatory.

The ZWD can then be found by subtracting the ZDD（obtained by using Saastamoinen empirical model）from the ZTD. The relation between the ZWD and PWV（Precipitable Water Vapor）may be formed as the following（Bevis et al., 1992, 1994）:

$$PWV=\Pi\times ZWD \quad (9)$$

with

$$\Pi=\frac{10^6}{\rho R_w\left(k_2'+k_3'/T_m\right)} \quad (10)$$

where, Π is the transformation factor; k2 ' and k3 ' are 22.1±2.2 Kmb-1 and（3.739±0.012）×105K2mb-1 , respectively; Tm is the weighted mean temperature of the partial pressure for water vapor within the atmosphere. Parameters of this study all referrers to Liou et al.（2000）; the regression coefficients of 20-year statistic of 14610 air survey data for Taiwan area via radiometer and balloon-sonde.

3. Results and Discussion

Two specific events of afternoon rainstorm in Tainan within the period of July ~ September were adopted for the case study. The cases were selected due to the general weather condition such that to exclude the influences of cyclones or typhoons as well as no large-scale climatic system affecting the regional weather. The first case dated on July 21, with cumulative rainfall of 82 mm; maximum hourly intensity 60.5 mm; case 202. The second case dated on August 15, with cumulative rainfall 62.5 mm; maximum hourly intensity 20.5 mm; case 227.

Figure（2）shows the distribution of GPS observatories, weather stations with automated rain gauge around the studied area. Table（1a）shows the basic data for the Central Weather Bureau（CWB）owned observatories and automated weather stations. Table（1b）shows the basic date for GPS observatories adopted for this study.

According to GPS information and the rainfall data of the weather stations, comparison of delays for the GPS/PWV of case 202 and case 227 were done. Figure（3a, 3b）shows the relative coincidence for the changes of PWV; namely, correlation coefficients for PWV among the observatories were obtained. Figure 3. PWV hydrograph of Tainan region:（a）July 20~22,（b）Aug. 14~16, 2010.

According to the relation between the PWV and the precipitation, it is shown that the PWV sharply increased before the occurrence of precipitation; namely, the vapor cumulates before the precipitation. Besides, it shows that the significant accumulation of precipitation occurs following the high PWV gives the high correlations with the site elevations of observatories.

4. Conclustions

The GPS observations of July and August, 2010 were adopted for this study. According to the results of GPSPWV correlation, an obvious continuously increasing change of water vapor had occurred several hours before the rainfall. This phenomena indicates that it is a favourable condition for water vapor accumulation in a mesoscale system. However, when the precipitation starts, the temperature and the amount of precipitable water vapor dropped. It shows that the condensation of saturated water vapor from its gaseous state transforming into the liquid state. It indeed indicates that a condition of higher amount of precipitable water vapor in the atmosphere is essential.

According to the statistics, higher positive correlations for PWV vs. Time changes were observed at the same latitude or the adjacent regions of similar topographic conditions. Thus, for an objective forecasting by using GPS-PWV, it needs simply to adopt the observation stations according to the topographic conditions. The result has also shown that the time-lag between the maximum PWV and the most intense rainfall are 60 min in the plain region, and 120 min in the topographically higher regions; because the convective rainfall is significantly affected by the topography.

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6. Charts

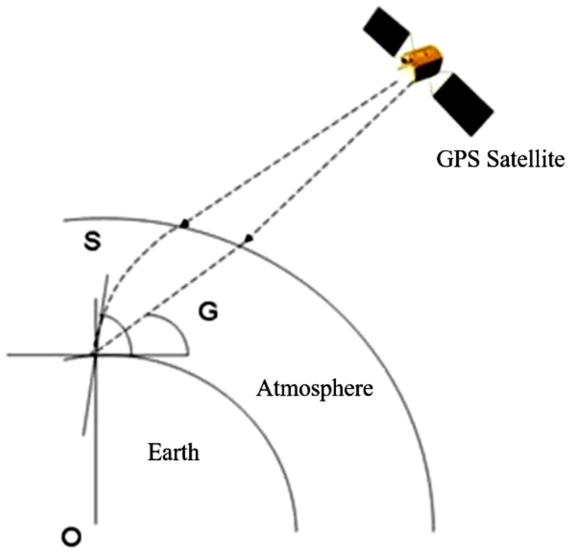


Figure 1. Schematic diagram for tropospheric delay.

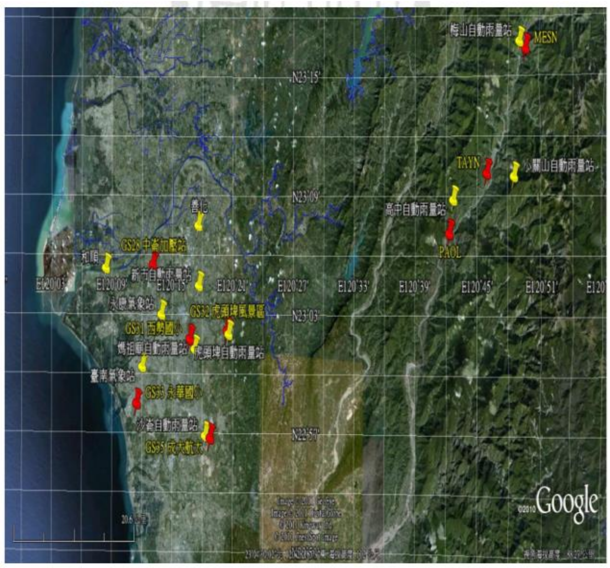


Figure 2. Distribution of GPS observatories (red tag) , weather stations with automated rain gauges (yellow tag) .

Table 1. Basic data for（a）CWB owned observatories and automated weather stations,（b）GPS observatories.

(a)

Code	Station	Elevation(m)
467410	Tainan	13.8
467420	Yongkang	8.1
C1O95	Heshun	4
C1O82	Zuozhen	30
C1O97	Hutoupi	60
C1O99	Matsu Temple	23
C1O96	Sakitop	80
C1N00	Sharon	25
C1O98	Singshi	76
C0O90	Shanhua	64
C1V23	Gaochong	760
C1V22	Xiaoguanshan	1781
C1V20	Meishan	860

(b)

No.	Code	Station	Elevation(m)	Owner
1	GS28	Zhonglun	26	CGS MOEA*1
2	GS31	Xishi	44	CGS MOEA
3	GS32	Hutoupi	57	CGS MOEA
4	GS33	Yonghua	25	CGS MOEA
5	GS35	NCKU	51	CGS MOEA
6	PAOL	Bora	431	IES AS*2
7	TAYN	Taoyuan	645	IES AS
8	MESN	Meishan	925	NLSC,MOI*3

*1 CGS MOEA：Central Geological Aurvey, MOEA

*2 IES AS：Institute of Earth Sciences, Academia Sinica

*3 NLSC,MOI：National Land Surveying and Mapping Center, Ministry of Interior

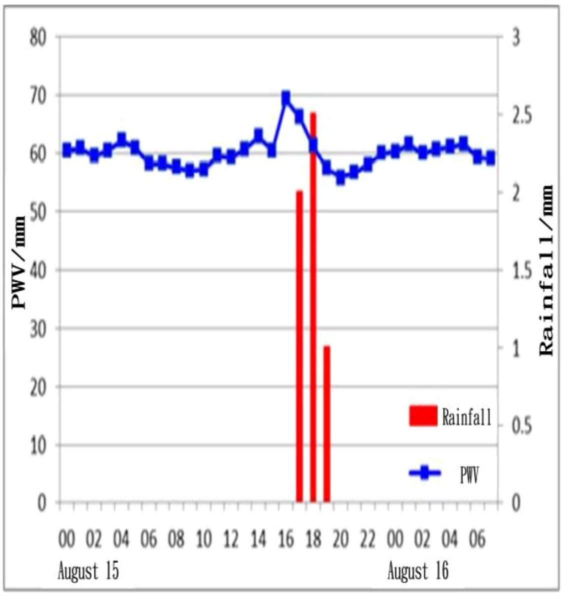
(a)

	GS28	GS31	GS32	GS33	GS35	PAOL	TAYN	MESN
GS28	1	0.88	0.92	0.90	0.85	0.66	0.62	0.42
GS31	0.89	1	0.96	0.94	0.97	0.75	0.79	0.55
GS32	0.92	0.96	1	0.93	0.93	0.74	0.75	0.49
GS33	0.90	0.94	0.93	1	0.90	0.75	0.77	0.50
GS35	0.85	0.97	0.93	0.90	1	0.73	0.77	0.55
PAOL	0.66	0.75	0.74	0.75	0.73	1	0.95	0.88
TAYN	0.62	0.79	0.75	0.77	0.77	0.95	1	0.82
MESN	0.42	0.55	0.49	0.50	0.55	0.88	0.82	1

(b)

	GS28	GS31	GS32	GS33	GS35	PAOL	TAYN	MESN
GS28	1	0.94	0.91	0.90	0.90	0.17	0.10	-0.03
GS31	0.94	1	0.93	0.90	0.93	0.15	0.10	-0.02
GS32	0.91	0.93	1	0.81	0.93	0.25	0.23	0.11
GS33	0.90	0.90	0.81	1	0.83	0.16	0.10	-0.02
GS35	0.90	0.93	0.93	0.83	1	0.25	0.24	0.11
PAOL	0.17	0.15	0.25	0.16	0.25	1	0.94	0.71
TAYN	0.10	0.10	0.23	0.10	0.24	0.94	1	0.77
MESN	-0.03	-0.02	0.11	-0.02	0.11	0.71	0.77	1

(a)



(b)

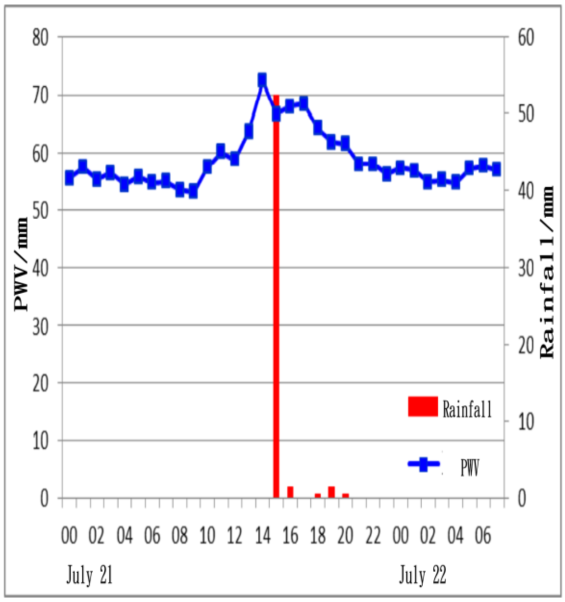


Figure 3. The PWV hydrograph and hyetograph for（a）Hutoubei（GS32）,（b）NCKU（GS35）GPS observatory.

利用 GPS 衛星信號估算降水量-以臺灣夏季西南地區為例

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摘要

藉由全球定位系統（Global Positioning System，GPS）衛星訊號穿透對流層時所產生的訊號延遲量，可表示該訊號傳輸路徑中對流層水氣的含量，本研究藉 GAMIT（GNSS at MIT）反演衛星訊號中的大氣可降水量（Precipitable Water Vapor，PWV），並利用天氣研究與預報模式（Weather Research and Forecasting，WRF）的三維變分方法（the three-dimensional variational method，3DVAR），將大氣可降水量進行數值同化，可有效提高暴雨預報的準確性及即時性。

本研究以 2010 年 7 月至 9 月臺南市的暴雨事件為例，結果顯示 PWV 的時空分布與降水明顯相關，並且通過 WRF 同化的 PWV 對降雨強度的估計有了顯著的改善，GPS-PWV 反應了夏季午後對流的特徵和區域性降雨模式，尤其是最大大氣可降水量發生位置與最大降雨量發生地區之間的相關性。

關鍵詞：全球定位系統、大氣可降水量、GAMIT、三維變分方法