INTERNATIONAL RESEARCH JOURNAL IN ADVANCED ENGINEERING AND TECHNOLOGY (IRJAET) www.irjaet.com

ISSN (PRINT) : 2454-4744 | ISSN (ONLINE): 2454-4752

Vol. 1, Issue 4, pp.309 - 314, November, 2015

REAL-TIME GPS TRACKING -BASED PERCEPTIBLE WATER VAPOR AND RAINFALL MONITORING USING EMBEDDED SYSTEM

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ARTICLE INFO

Article History:

Received 1st Dec, 2015

Received in revised form 3rd Dec,2015

Accepted 4th Dec, 2015

Published online 6th Dec, 2015

Keywords:

Perceptible water vapor (PWV)

rainfall monitoring and forecasting

real-time orbit and clock correction

real-time precise point positioning (PPP).

ABSTRACT

GPS-based precipitable water vapor (PWV) estimation has been proven as a cost-effective approach for numerical weather prediction. Most previous efforts focus on the performance evaluation of post-processed GPS-derived PWV estimates using International GNSS Service (IGS) satellite products with at least 3–9-h latency. This becomes the focus of this paper, which investigates real-time GPS precise point positioning (PPP)-based PWV estimation and its potential for rainfall monitoring and forecasting. This paper first evaluates the accuracy of IGS CLK90 real-time orbit and clock products. Root-mean-square (RMS) errors of < 5 cm and 0.6 ns are revealed for real-time orbit and clock products, respectively, during July 4–10, 2013. Second, the real-time GPS PPP-derived PWV values obtained at IGS station WUHN are compared with the post-processed counterparts. The RMS difference of 2.4 mm has been identified with a correlation coefficient of 0.99. Third, two case studies, including a severe rainfall event and a series of moderate rainfall events, have been presented. The agreement between the real-time GPS PPP-derived PWV and ground rainfall records indicates the feasibility of real-time GPS PPP-derived PWV for rainfall monitoring. Moreover, the significantly reduced latency demonstrates a promising perspective of real-time GPS PPP-based PWV estimation as an enhancement to existing forecasting systems for rainfall forecasting.

1. INTRODUCTION

GPS has been recognized as a cost-effective approach to determine precipitable water vapor contents. Along with other meteorological sensors, GPS is able to provide PWV estimates with 1–3-mm root-mean square accuracy with respect to traditional atmosphere sensing techniques such as the radiosonde and the microwave radiometer.

With the rapid deployment of GPS monitoring stations in local, regional, and global scales in recent years, ground-based GPS meteorology can offer much improved spatial and temporal resolutions for local or regional water vapor variations than the traditional techniques based on MWR and radiosonde observations. Most GPS-based PWV systems to date rely on double difference processing of GPS observations, There are some limitations for double difference methods, such as they require the distance between GPS stations not less than 500 km and an absolute PWV value at one station in order to obtain the absolute PWV values at the other stations. GPS PWV systems based on the processing of GPS undifferenced observations, known as precise point positioning (PPP), have been widely used in recent years since they can estimate absolute PWV with a single receiver. Although GPS PPP has the ability to provide high-precision PWV estimates, how to reduce the latency of GPS PPP-based PWV estimation remains a challenge. Several local and regional GPS networks have been employed to conduct near real time PWV estimation using the International Global Navigation Satellite System. To overcome the latency issue, IGS initiated the real-time pilot project with the infrastructure of real-time GNSS data streams on a global basis in 2007. This becomes the focus of this paper, which

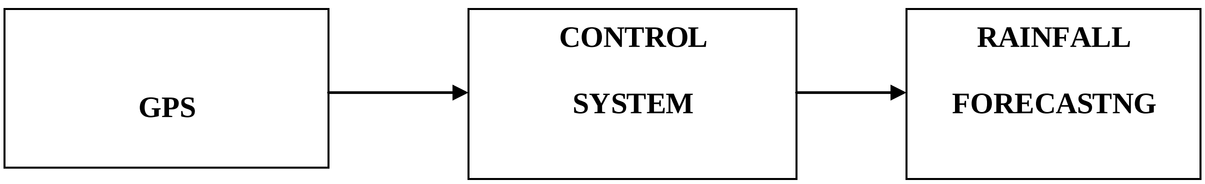

Fig.1. General block diagram for rainfall forecasting using GPS

investigates the potential of real-time GPS PPP-based PWV estimation using real-time orbit and clock products for rainfall monitoring.

2. PWV RETRIEVAL

The troposphere delay effect on GPS signals can be divided into a hydrostatic part and a wet part by,

$$ZTD = ZHD + ZWD$$

where ZTD is the zenith total delay, ZHD is the zenith hydrostatic delay, and ZWD is the zenith wet delay. On the contrary, there is no simple way to precisely model the ZWD. The usual approach is to estimate the ZWD in the PPP function model together with other parameters. PWV is related to ZWD via a conversion factor by,

$$PWV = \Pi * ZWD$$

$$\Pi = \frac{10^6}{\rho_w R_v \left[\left(\frac{k_3}{T_m} \right) + k_2' \right]}$$

where Π is the conversion factor; *ρw* is the density constant of liquid water; *Rv* is the gas constant for water vapor; *k*2 and *k*3 are the atmospheric refractivity constants and *Tm* is the weighted mean temperature of the atmosphere.

Tm can be calculated using an integral formula with vapor pressure and temperature profile information along the zenith direction over the stations, which can be expressed as,

$$T_m = \frac{\int (e/T)\, dz}{\int (e/T^2)\, dz}$$

where *e* is the vapor pressure, *T* is the absolute temperature, and *dz* is the integral path.

3. RESULTS AND DISCUSSION

A. REAL-TIME SATELLITE ORBIT AND CLOCK CORRECTIONS

Currently, the IGS RTS provides combined orbit and clock corrections estimated in both single-epoch and Kalman filter approaches. Moreover, several participating IGS agencies are also disseminating their own orbit and clock corrections for various applications. For example, GFZ has been hosting a realtime PPP project with local reference network augmentation CNES has been developing a real-time zero-difference PPP integer ambiguity resolution demonstrator. Therefore, real-time PPP users can choose the proper correction stream to match their specific application. The accuracy assessment of IGS CLK90 real-time orbit and clock products is conducted based on one-week consecutive corrections from July 4 to 10, 2013. IGS final orbit and clock products with nominal accuracy values of 2.5 cm and 0.075 ns, respectively, are selected as the reference. The orbit accuracy for each satellite is calculated as the RMS error of the differences between the real time satellite coordinates and the reference coordinates. As to the clock accuracy, one reference satellite should be selected to make a single difference with the other satellites in order to remove the clock datum inconsistency between the real-time and final clock products. In this paper, the GPS satellite with pseudorandom noise is chosen as the reference satellite. The satellite

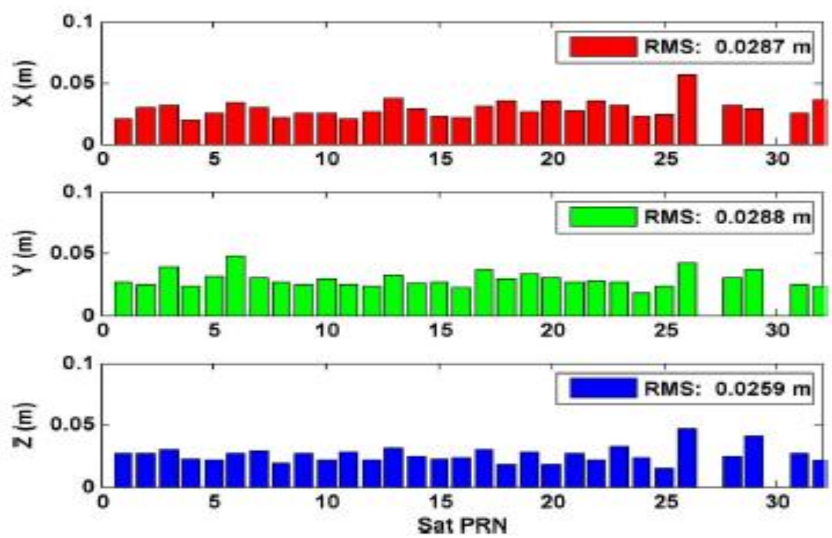

Fig.2. Accuracy values of IGS CLK90 real-time orbit product with respect to IGS final orbit product from July 2013.

clock accuracy is calculated as the RMS error of the differences between the real time single-differenced clock errors and the reference clock errors.

B. COMPARISON BETWEEN THE REAL-TIME AND POST-PROCESSED GPS PPP-DERIVED PWV TIME SERIES

In this section, the real-time GPS PPP-derived PWV time series are analyzed with respect to the PPP-derived PWV time series using the IGS final products. One-week GPS observations of IGS station WUHN collected at a sampling rate of 30 s from July 4 to 10, 2013, are processed. The absolute phase center correction model is utilized to correct the antenna phase center offset and variation. The pressure and temperature data are computed by the GPT model, and the ZHD is calculated using the Saasta moinen model. The troposphere mapping function is the global mapping function. The ZWD is estimated in a random walk pattern with an initial standard deviation of 10−2 m and a spectral density of 10−6 m2/s. The scatter plot of the PPP-derived PWV time series using real-time and final products is shown in Fig. 3. The PPP-derived PWV time series are resampled at the interval of 1 h, thus generating 168 PWV pairs during seven consecutive days.

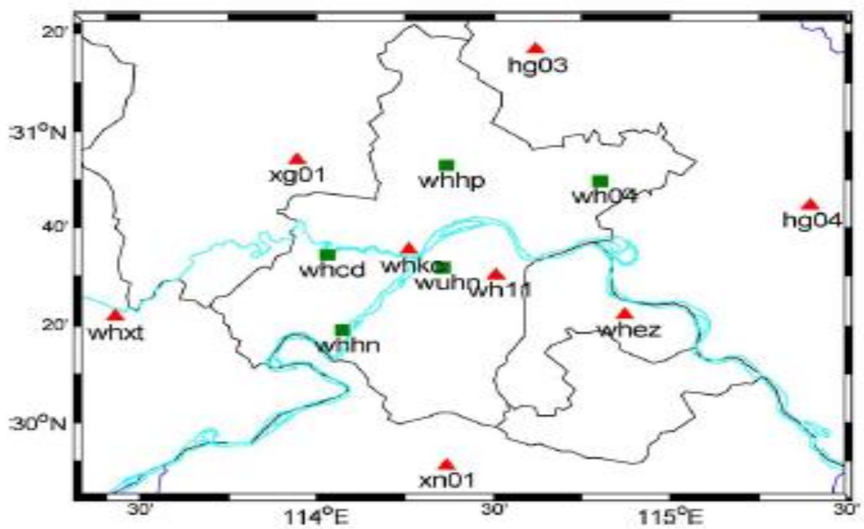

Fig.3. Network of 13 GPS stations. Five stations marked as green rectangles are colocated with rainfall record instruments, whereas the other nine stations without rainfall records are marked as red triangles.

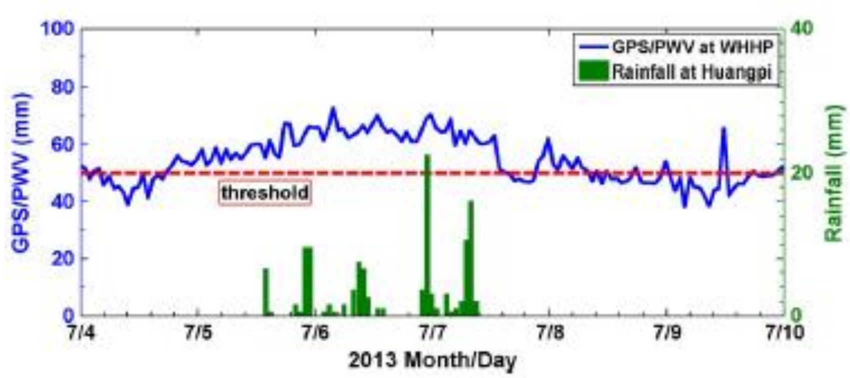

Fig.4. Real-time GPS PPP-derived PWV time series at WHHP and the rainfall record at Huangpi during a heavy rainfall event in Wuhan from July 4 to 10, 2013.

The average value and the RMS error are calculated for the PWV differences between the two PWV time series. The rule is applied to exclude PWV pairs with the difference larger than three-time RMS errors, which results in

160 PWV pairs for comparison. With respect to the PPP-derived PWV time series using IGS final products, the real-time PPP-derived PWV time series show an average value of −1.5 mm and an RMS error of 2.4 mm. On the other hand, the correlation coefficient of 0.99 is identified, which demonstrates that the real-time PPPderived PWV time series have good consistency with the post processed PPP-derived PWV series. Therefore, it is possible to use the real-time GPS PPP-derived PWV series for rainfall monitoring and forecasting.

CONCLUSION

This paper has investigated the performance of real-time GPS PPP-based PWV estimation and its potential for rainfall monitoring and forecasting with IGS CLK90 real-time orbit and clock. As regard the period of July 4–10, 2013, the orbit accuracy of < 5 cm and the clock accuracy of 0.6 ns have been identified for the IGS CLK90 real-time products. The corresponding real-time GPS PPP-derived PWV time series show an RMS error of 2.4 mm and a bias of −1.5 mm with respect to the post-processed GPS PPP-derived PWV time series using the IGS final products. Furthermore, a correlation coefficient of 0.99 is identified between the real-time and post processed PPP-derived PWV time series based on one-week observations at IGS station WUHN. By introducing the real-time GPS PPP-derived PWV values into the existing assimilation and forecasting system, it is expected that the forecasting capability would be improved, particularly for short-term rainstorm warning.

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