Near real-time detecting of atmospheric water vapor content based on BeiDou Navigation Satellite System

Qiuying Guo1*, Jianhui Hou1, Shihai Chen2, Yingjun Sun1

1School of Surveying and Geo-Informatics, Shandong Jianzhu University, Jinan, Shandong Province, 250101, China
2Gansu Non-ferrous Metals Geological Exploration Bureau, Lanzhou, Gansu Province, 730046, China
*Corresponding author’s e-mail: qyguo@sdjzu.edu.cn

Abstract. With the improvement of Beidou navigation satellite system (BDS), real-time monitoring of atmospheric water vapor content based on BDS has become a research hotspot. BDS and GPS observation data of seven MGEX CORS stations were processed using GAMIT 10.7 software and the atmospheric precipitable water vapor (PWV) was estimated. The PWV/BDS using Beidou final precise ephemeris and ultra-rapid precise ephemeris was respectively compared with PWV/GPS using IGS final precise ephemeris. The experiment results showed that the PWV/BDS is in good agreement with the PWV/GPS. The standard deviation (Std) of the PWV/BDS based on Beidou final precise ephemeris and ultra-rapid precise ephemeris are respectively 2.91mm and 3.97mm. And the RMS of the PWV/BDS based on Beidou final precise ephemeris and ultra-rapid precise ephemeris are respectively 3.97mm and 3.85mm with the PWV/GPS as the reference value.

1. Introduction
Water vapor is an important component of the earth's atmosphere, which directly affects the weather's sunny, cloudy and precipitation. The water vapor is a highly variable atmospheric constituent and plays a key role in the formation and evolution of disastrous weather [1].

Determination of atmospheric water vapor using global navigation satellite system (GNSS) is an important application. As a new means of water vapor detection, GNSS technology has its unique advantages including all weather observation, global coverage, high precision and high spatial-temporal resolution [2].

With development of BDS, many scholars and researchers have carried out research on detecting atmospheric water vapor based on BDS. Wang Haishen etc. made comparative analysis among Beidou, GPS and sounding system, gave the preliminary results of performance and accuracy of Beidou vapor detection. The results of PWV were consistent detected by Beidou, GPS and radiosonde [3]. Shi Chuang etc. also used Beidou experimental network data, combined with the radiosonde observation, gave the results of performance and accuracy of Beidou vapor detection. The result of PWV well reflected the change regularity of PWV [4].

With the completion of Beidou-3 GNSS constellation deployment, it is of great significance to real-time detect atmospheric water vapor content based on BDS. The aim of this paper is to study the performance and accuracy of retrieving PWV using Beidou final precise ephemeris and ultra-rapid precise ephemeris.
2. Principle of atmospheric water vapor detecting based on GNSS

GNSS signals bend and delay as they pass through the troposphere. The zenith tropospheric delay (ZTD) composed of zenith hydrostatic delay (ZHD) and zenith wet delay (ZWD) is often used to represent this error. The ZTD can be obtained by the total tropospheric delay on the slant path (STD) and the corresponding mapping function [2].

ZTD can be estimated using the precise relative positioning software (GAMIT, etc) or precise point positioning software (PANDA, etc). The ZHD can be calculated accurately according to the Saastamoinen (SAAS) model using the precise surface pressure data (Saastamoinen, 1972) [5]. Then the ZTD minus the ZHD is the ZWD. The ZWD can be further converted to the precipitable water vapor (PWV) by a ratio value $\Pi$ [6]. The main formula for calculating PWV is as follows:

$$\text{ZWD} = \text{ZTD} - \text{ZHD}$$  \hspace{1cm} (1)

$$\text{ZHD} = \frac{(2.279 \pm 0.0024) P_s}{1 - 0.00266 \cos(2\lambda) - 0.00028H}$$  \hspace{1cm} (2)

$$\text{PWV} = \Pi \times \text{ZWD}$$  \hspace{1cm} (3)

$$\Pi = 10^{6\left[(k'_1 + k_3 / T_m) \times R_v\right]}$$  \hspace{1cm} (4)

Where, $P_s$ is the pressure; $k'_1$ and $k_3$ are the atmospheric refractive coefficients; $R_v$ is the constant of water vapor; $T_m$ is the weighted average temperature.

$T_m$ is an important parameter which affects the accuracy of the PWV. In the case of no measured meteorological data, the GPT2 model published by Global Geodetic Observing System (GGOS) can be used to calculate the $P_s$ and $T_m$ corresponding the time and place of the GNSS observation station.

3. Analysis of atmospheric water vapor detecting based on Beidou

3.1. Experimental data and processing strategies

In order to analyze the performance of PWV retrieval based on BeiDou final precise ephemeris and ultra-rapid precise ephemeris, seven Multi-GNSS Experiment (MGEX) stations (CMUM, HKWS, JFNG, KARR, MCHL, MIZU and PNGM) were selected. The distribution of the 7 MGEX stations is shown in Figure 1. All the selected MGEX stations have BDS and GPS observations. Beidou and GPS observation data of the 7 stations from the doy of 230 to 240 in 2018 were processed by GAMIT 10.71 software. The sampling time of observation data is 30s. The data processing models and strategies are shown in Table 1.
| Item                             | MODELS and STRATEGIES |
|---------------------------------|------------------------|
| Choice of Experiment            | BASELINE               |
| Choice of Observable            | LC_AUTCLN              |
| Elevation cutoff                | 15°                    |
| A-Priori value for ZTD          | Saastamoinen           |
| Zenith Model                    | PWL (piecewise linear) |
| Meteorological data             | RNX UFL GPT 50         |
| Mapping function                | VMF1                   |
| Atmospheric load model          | Atmdisp_cm.2018        |
| Ocean tidal model               | Otl_FES2004.grid       |
| Orbit and Clock Products        | WHU precise ephemeris  |

3.2 Performance analysis of PWV/BDS based on final and ultra-rapid precise ephemeris

Beidou and GPS observation data of the 7 stations from the day of 230 to 240 in 2018 were processed by GAMIT 10.71. The PWV/GPS based on IGS final precise ephemeris is taken as the reference value. The PWV/BDS estimation results based on Beidou final and ultra-rapid precise ephemeris (http://www.igs.gnsswhu.cn/index.php/Home/DataProduct/igs.html) were analysed and compared with the PWV/GPS respectively.

The statistical quantities used for analyzing and comparing the PWV/BDS estimates are:

\[ \text{The Standard deviation: } \text{Std} = \sqrt{\frac{\sum_{i=1}^{n} (\text{PWV}_{BDS} - \text{PWV})^2}{n-1}} \]  
\[ \text{Where, } \text{PWV}_{BDS} \text{ is the PWV estimates using Beidou final precise ephemeris or ultra-rapid precise ephemeris, } \text{PWV} \text{ is the mean of } \text{PWV}_{BDS} \text{ estimates; } \text{PWV}_{GPS} \text{ is the PWV estimates based on GPS using IGS final precise ephemeris which are taken as reference values.} \]

\[ \text{The Root Mean Square Error: } \text{RMSE} = \sqrt{\frac{\sum_{i=1}^{n} (\text{PWV}_{BDS} - \text{PWV}_{GPS})^2}{n}} \]  

Where, \( \text{PWV}_{BDS} \) is the PWV estimates using Beidou final precise ephemeris or ultra-rapid precise ephemeris, \( \text{PWV} \) is the mean of \( \text{PWV}_{BDS} \) estimates; \( \text{PWV}_{GPS} \) is the PWV estimates based on GPS using IGS final precise ephemeris which are taken as reference values.

The Std and RMSE of the PWV/BDS using Beidou final precise ephemeris or ultra-rapid precise ephemeris were calculated respectively. Table 2 shows the statistical results of the Std and RMSE of PWV/BDS using the final and ultra-rapid precise ephemeris for the 7 MGEX stations.

Figure 1 shows the comparisons of the PWV/BDS based on using Beidou final precise ephemeris with the PWV/GPS of the 7 MGEX stations. Figure 2 shows the comparisons of the PWV/BDS based on using Beidou ultra-rapid precise ephemeris with the PWV/GPS.

| Station | PWV/BDS by final precise ephemeris | PWV/BDS by ultra-rapid precise ephemeris |
|---------|-----------------------------------|------------------------------------------|
|         | Std | RMSE | Std | RMSE |
| CMUM    | 1.88 | 1.88 | 1.97 | 1.88 |
| HKWS    | 3.95 | 4.59 | 5.39 | 4.33 |
| JFNG    | 3.39 | 2.49 | 3.61 | 3.64 |
| KARR    | 2.78 | 2.83 | 4.39 | 5.05 |
| MCHL    | 1.56 | 1.57 | 3.48 | 3.52 |
| MIZU    | 5.12 | 5.13 | 5.76 | 5.12 |
| PNGM    | 1.71 | 1.79 | 3.19 | 3.39 |
| Mean value | 2.91 | 2.90 | 3.97 | 3.85 |
Figure 2. Comparison of the PWV/BDS based on using Beidou final precise ephemeris with the PWV/GPS of the 7 MGEX stations.
Table 2 shows that: the average Std of the PWV/BDS based on final precise ephemeris and ultra-rapid precise ephemeris of the 7 stations are about 2.91mm and 3.97mm respectively; and the RMSE are about 2.90mm and 3.85mm respectively. Figure 2 and Figure 3 show that the PWV/BDS has good consistency with the PWV/GPS. There are differences about 1-5mm between PWV estimations based on BDS and GPS. The difference between the PWV/BDS based on ultra-rapid precise ephemeris and the PWV/GPS is slightly larger than that of the PWV/BDS based on final precise ephemeris.
4. Conclusions
Near real-time detecting of atmospheric water vapor content based on BeiDou ultra-rapid precise ephemeris are very consistent with the GPS. And there is no obvious systematic deviation between the PWV/BDS and the PWV/GPS. The average Std of the PWV/BDS and the RMSE based on Beidou ultra-rapid precise ephemeris are about 3.97mm and 3.85mm respectively. The accuracy of atmospheric water vapor retrieval based on Beidou ultra-rapid precise ephemeris can basically meet the requirements of atmospheric observation.

Acknowledgments
The authors would like to thank WHU for providing precise Beidou precise products. This work is supported by the Shandong Provincial Natural Science Foundation, China (ZR2017MD029), Shandong Provincial Department of Housing and Urban Rural Construction Technology Project Plan (2017-R1-004) and High quality curriculum construction project of graduate education in Shandong Province (SDYKC18080). The authors greatly appreciate the Editor and the anonymous Reviewers on this manuscript.

References
[1] Rockeen C., Van Hove T., Ware R. (1997) Near real-time GPS sensing of atmospheric water vapor. Geophysical Research Letters, 24 (24): 3221-3224.
[2] Bevis M., Businger S., Chiswell S. (1994) GPS meteorology: mapping zenith wet delays onto precipitable water. Journal of Applied Meteorology, 33 (3): 379-386.
[3] Wang Haishen, Cao Yunchang, Liang Hong. Analysis on Water Vapour Detection by Beidou Satellite. Digital Communication World, 2015, (10): 13-16.
[4] Shi Chuang, Wang Haishen, Cao Yunchang, etc. Analysis on Performance of Water Vapor Detection Based on Beidou Satellite. Geomatics and Information Science of Wuhan University, 41(3):285-289.
[5] Saastamoinen, J., 1972. Atmospheric correction for the troposphere and stratosphere in radio ranging satellites. The Use of Artificial Satellites for Geodesy. 15, 247-251.
[6] Choy, S., Wang, C., Zhang, K., et al., 2013. GPS sensing of precipitable water vapour during the March 2010 Melbourne storm. Advances in Space Research. 52, 1688-1699.