The retrieval of atmospheric water vapor based on Beidou Ultra-rapid precise ephemeris using different mapping functions

Qiuying Guo, Jianhui Hou* and Xuxiang Wu
School of Surveying and Geo-Informatics, Shandong Jianzhu University, Jinan, Shandong Province, 250101, China
*Corresponding author’s e-mail: jhuihou@163.com

Abstract. The atmospheric mapping function is an important model to convert the total tropospheric delay on the slant path of satellite signal into the zenith tropospheric delay. It is important to choose the appropriate mapping function to improve the accuracy of water vapor estimation. Beidou observation data in different seasons from 6 MGEX stations were processed using GAMIT 10.7 software. Three mapping functions (NMF/GMF/VMF1) were used in the estimating the atmospheric precipitable water vapor (PWV) based on Beidou Ultra-rapid precise ephemeris. The results of PWV/BDS were compared with the PWV/GPS. The experiments showed that the average bias between PWV/BDS and PWV/GPS is about 1-5 mm. The GMF mapping function is slightly better than NMF and VMF1 in the retrieval of atmospheric water vapor.

1. Introduction
Water vapor is an important component of the earth’s atmosphere, which is mainly distributed at the bottom of the troposphere. There is little water vapor in the atmosphere, but water vapor is a highly variable atmospheric constituent and remains one of the most poorly characterized meteorological parameters [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].

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 [3].

Therefore, it is of great significance to select a proper tropospheric mapping function for retrieving atmospheric water vapor. The famous mapping functions are the Niell Mapping Function (NMF), Vienna Mapping Function 1 (VMF1) and Global Mapping Function (GMF). The differences between the mapping functions are mainly reflected in the differences of the coefficients a, b and c.

The above three mapping functions are used for retrieving PWV based on Beidou system (BDS) using 6 MGEX stations in this paper. The results of PWV based on BDS were compared with the PWV based on GPS.
2. Mapping function

In 1972, Marrini first put forward a method of constructing mapping function by continued fractions [4]. The general expression of the mapping function is the equation (1).

\[
mf(e) = \frac{1 + \frac{a}{b}}{1 + \frac{1 + c}{a \sin(e) + \frac{b}{\sin(e) + c}}}
\]

In the equation (1), \(e\) is elevation angle of satellite; \(a\), \(b\) and \(c\) are coefficients of the mapping function. The coefficients dry and wet mapping functions are adopted with different parameters. The coefficients of the mapping function can be a constant or a expression.

2.1. NMF (Niell mapping function)

NMF is a global atmospheric delay mapping function established by Niell using the data of 26 balloon stations around the world [5]. NMF mapping function adopts formula (1). The dry mapping coefficient \(a_h\) is calculated as follows:

\[
a_h(\varphi, t) = a_{avg}(\varphi) + a_{amp} \cos \left(\frac{2\pi(t-28)}{365.25}\right)
\]

In the equation (2), \(\varphi\) is the station latitude; \(t\) is the day of year; \(a_{avg}\) and \(a_{amp}\) are obtained by interpolating linearly closest to the station latitude provided by the NMF coefficients table. The dry mapping coefficient \(b_h\), \(c_h\) and the wet mapping coefficient \(a_w\), \(b_w\), \(c_w\) are also obtained by interpolating linearly according to the NMF coefficients table.

2.2. VMF1 (Vienna mapping function 1)

Boehm and Schuh of Vienna University of Technology proposed the atmospheric delay mapping function VMF1 in 2004 [6]. Then the mapping function coefficients \(b\) and \(c\) of VMF model are corrected and VMF1 was developed. VMF1 uses 40-year observation data from the European Centre for Medium-Range Weather Forecasts (ECMWF), while the coefficient \(a\) is obtained by interpolating 2°×2.5° grid list files generated by the real measured data and 34 hours delay.

2.3. GMF (Global mapping function)

The VMF1 is provided only at discrete locations and there is a delay problem of the coefficient \(a\). Therefore, Boehm et al proposed GMF based on data from the global ECMWF numerical weather model [7]. The coefficients of the GMF were obtained from an expansion of the VMF1 parameters into spherical harmonics on a global grid. The values of the coefficients require only the station coordinates and the day of year as input parameters. The coefficients \(a_h\) and \(a_w\) of the GMF were determined for the period September 1999 to August 2002 using 15°×15° global grid of monthly mean profiles for pressure, temperature, and humidity from the ECMWF 40 years reanalysis data [7]. The coefficients \(b\) and \(c\) value are the same as VMF1 model.

The coefficient \(a\) can be determined as follows:

\[
a = a_0 + A \cos \left(\frac{doy - 28}{365} \cdot 2\pi\right)
\]
Then, the global grid of the mean values $a_0$ and that of the amplitudes $A$ were expanded into spatial spherical harmonic coefficients up to degree and order 9 (according to Equation (4) for $a_0$).

$$a_0 = \sum_{n=0}^{9} \sum_{m=0}^{n} P_{nm} (\sin \phi) \cdot [A_{nm} \cos (m \cdot \lambda) + B_{nm} \sin (m \cdot \lambda)]$$

(4)

3. Data processing and analysis

3.1. Experimental data and processing strategies

In order to analyze the performance of PWV retrieval based on the three mapping functions (NMF, VMF1 and GMF), 6 Multi-GNSS Experiment (MGEX) stations (CUT0, CUUT, GMSD, HKWS, LHAZ and PIMO) were selected. The distribution of the 6 MGEX stations is shown in Figure 1. All the selected MGEX stations have BDS and GPS observations. Beidou and GPS observation data in different seasons in 2018 were processed by GAMIT 10.7 software. The observation data in January-February and in June-August are selected considering that different moisture content may lead to different precision of retrieved PWV. The sampling time of observation data is 30s. The data processing models and strategies are shown in Table 1. The 6 MGEX stations are located in the Asia Pacific Region, and the number of Beidou satellites visible at each station is above 7.

![Figure 1. Geographical location of the 6 MGEX stations used in this study.](image)

Table 1. Data processing models and strategies.

| Item                          | MODELS and STRATEGIES                      |
|-------------------------------|--------------------------------------------|
| Choice of Experiment          | BASELINE                                   |
| Choice of Observable          | LC_AUTCLN                                  |
| Elevation cutoff              | 10°                                        |
| A-Priori value for ZTD        | Saastamoinen                               |
| Zenith Model                  | PWL (piecewise linear)                     |
| Mapping function              | NMF/VMF1/GMF                               |
| Atmospheric load model        | atmdisp_cm.2018                            |
| Ocean tidal model             | otl_FES2004.grid                           |
| Orbit and Clock Products      | WHU Ultra-rapid precise ephemeris          |
3.2. Analysis of PWV estimates based on NMF/VMF1/GMF mapping functions

Beidou and GPS observation data in different seasons in 2018 were processed by GAMIT 10.7 and data processing models and strategies in Table 1. Reliable, precise baseline solution results are the basis of retrieving PWV by GAMIT software. Normalized Root Mean Square (NRMS) and baseline repeatability are important indexes to measure the quality of GAMIT baseline solutions [8]. The NRMS value is generally considered to be less than 0.3. If the NRMS value is about 0.25, the baseline solution is considered to be successful. Calculation statistics show that the NRMS values of GPS are less than 0.25 and the NRMS values of BDS are less than 0.23 using the above 6 MGEX stations. And the baseline relative accuracy based on BDS and GPS are all 10⁻⁸ level. The results of precise baseline solutions lay a foundation for the retrieval of PWV.

The PWV estimation results based on BDS were compared with the PWV estimation results based on GPS. The Bias, root mean square error (RMSE) of the PWV/BDS with PWV/GPS as reference values were calculated. And the correlation coefficients between the PWV/BDS and the PWV/GPS were also calculated. Table 2 shows the statistical results of the Bias and RMSE of PWV/BDS using the three mapping functions. Figure 2 shows the comparisons of the PWV/BDS with the PWV/GPS using NMF/VMF1/GMF mapping functions of the 6 stations in different seasons respectively.

| Statistics | January-February | June-August |
|------------|------------------|-------------|
| Bias       | NMF  | VMF1 | GMF  | NMF  | VMF1 | GMF  |
| RMSE       | 0.05 | 0.14 | 0.10 | 0.75 | 0.82 | 0.58 |
|            | 2.17 | 2.03 | 2.00 | 2.61 | 2.60 | 2.57 |
Table 2 shows that: the average Bias of the PWV/BDS compared with the PWV/GPS in January-February and June-August are about 0.10mm and 0.72mm respectively; and the RMSE are about 2.07mm and 2.59mm respectively.

Figure 2 shows that the PWV/BDS has good consistency with the PWV/GPS. There are average differences about 1-2mm between PWV estimations based on BDS or GPS in January-February. There are obvious difference between the PWV/BDS and the PWV/GPS in June-August and the average bias between the PWV results of the two systems is about 2-3mm. Also there are differences about 1-2mm between PWV estimations using the NMF/VMF1/GMF mapping functions based on BDS or GPS.

4. Conclusions
(1) The accuracy of atmospheric water vapor retrieval based on Beidou Ultra-rapid precise ephemeris can basically meet the requirements of atmospheric observation and international meteorology.

(2) The retrieval results of PWV based on BDS in dry and wet seasons are very consistent with PWV based on GPS. The average bias and RMSE between the PWV results of the two systems is less than 1mm and 2.6mm respectively.

(3) There are differences about 1-2mm between PWV estimations using different mapping functions (NMF/VMF1/GMF) based on BDS or GPS.

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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] Bevis M., Businger S., Chiswell S. (1994) GPS meteorology: mapping zenith wet delays onto precipitable water. Journal of Applied Meteorology, 33 (3): 379-386.
[4] Saastamoinen, J., 1972. Atmospheric correction for the troposphere and stratosphere in radio ranging satellites. The Use of Artificial Satellites for Geodesy. 15, 247-251.
[5] Marini J. (1972) Correction of satellite tracking data for an arbitrary troposphere profile. Radio Science, 7(2): 223-231.
[6] Niell A. (1996) Global mapping functions for the atmosphere delay at radio wavelengths. Journal of Geophysical Research, 1996, 101(2): 3227-3246.
[7] Boehm J., Schuh H. (2004) Vienna mapping functions in VLBI analyses. Geophysical Research Letters, 31: L01603.
[8] Boehm J., Niell A., Tregoning P., Schuh H. (2006) The Global Mapping Function (GMF): A new empirical mapping function based on numerical weather model data. Geophysical Research Letters, 33:1-4.
[9] Liu Y., Dang Y., Xu C. (2019) Beidou baseline solution based on GAMIT for national GNSS stations. Engineering of Surveying and Mapping, 28(3): 25-29.