Application of Water Vapor Retrieval Data Acquired by BDS in Analysis of Typhoon

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Abstract. In the paper, the data observed by the Beidou navigation satellite system (BDS), which is based on the continuously operating reference stations (CORS) of Nanning, is processed and analyzed by GAMIT 10.6 software. Also, the inverse distance weighted method (IDW) has been employed to simplify the analysis of data. Besides, the meteorological observation data of the radiosonde station in Nanning is used as an inspection standard to verify the computational accuracy and reliability of the data processing of BDS. Furthermore, combined with both the meteorological observation data of the radiosonde station and the actual rainfall, more emphases are placed on the analysis of time-series changes in precipitable water vapor (PWV) in this paper. Finally, the results show that the PWV obtained by the data inversion of BDS has good consistency with that acquired from the meteorological observation data of the radiosonde station. The overall variation trend of the PWV, which is acquired by the data inversion of BDS, not only can basically keep up with the actual rainfall before and after the typhoon passes through the territory, but also can be better applied in the early warning of extreme weather.

1. Introduction

The construction project of Guangxi Beidou ground-based augmentation system was approved in 2015, and all construction work was accomplished by the end of December 2017. Based on the dual-satellite data processing of the original CORS, the reference station system, data control center, communication network, and user system was upgraded and rebuilt to provide multi-system (including GPS, BDS and GLONASS) high-precision navigation and positioning services for Guangxi users. A total of 102 reference stations of BDS and one data center were upgraded throughout the region. The average distance between the reference stations is 45 km, and all reference stations can cover 236,700 km² of the whole area[1]. Since the BDS-related applications have gradually served the public in Guangxi, it is necessary to analyze the performance and accuracy of BDS and its observed data[2].

This paper studies the changes of PWV in Nanning from September 15 to 18, 2018 before and after the No. 22 super typhoon Mangkhut passed through the territory. Combined with the meteorological observation data of the radiosonde station in Nanning, this paper focuses on analyzing the time-series variation characteristics of PWV. The analysis of the reliability and accuracy of PWV (called BDS/PWV) obtained through the inversion of data, which was observed by the high-precision reference stations of BDS, has been implemented. Also, the IDW has been employed to simplify the analysis of data[3]. On this basis, the correlation between the PWV (called Radio/PWV) acquired from the meteorological observation data of the radiosonde station and the BDS/PWV has been
investigated.

2. Calculation of PWV

2.1 Data sources
In accordance with the time of the typhoon Mangkhut passing through the territory, the experimental time was selected from September 10 to 26, 2018, and the target area was located in Nanning. There are 7 CORS in the experimental areas that included Shuangqiao, Dawangtan, Lingli, Taiping of Qinzhou, Binyang, Pingguo and Quli. The locations of stations are shown in Figure 1, where △ means CORS and ○ represents the radiosonde station [4]. The GAMIT software is employed to process experimental data, and the appropriate number of IGS stations is used as the auxiliary stations to improve the accuracy of the solution. The calculation of the data of the radiosonde station, which is implemented based on multiple parameters such as air pressure, temperature and humidity, mainly depends on the high-altitude meteorological observation data that the radiosonde balloon brings back twice in one day.

![Figure 1. Distribution map of CORS stations and radiosonde stations used in the experiment.](image)

2.2 PWV obtained by the data inversion of BDS
The inversion of the PWV based on the Beidou ground-based augmentation system includes the following steps. (1) The original observation data is processed by the high-precision data processing software GAMIT 10.6, and the zenith total delay (ZTD) of each station is calculated. (2) The zenith hydrostatic delay (ZHD) is obtained according to the meteorological observation data and the zenith hydrostatic delay model. (3) The zenith wet delay (ZWD) is acquired by subtracting the ZHD from the ZTD, i.e., ZWD=ZTD-ZHD. (4) The error parameters such as the weighted mean atmospheric temperature model in the target area are optimized, and the water vapor conversion coefficient (Π) is calculated, and the ZWD is converted into the PWV [5].

In the calculation of precipitable water vapor, the conversion of wet delay is closely related to the temperature of troposphere [6]. The average temperature of water vapor weight in the troposphere needs to be introduced in the calculation process, namely, the weighted average atmosphere temperature, which is expressed by $T_m$, with the unit of K.

$$PWV = \left( \frac{k}{\rho_w} \right) \cdot \Delta s = \frac{10^6}{\rho_w R_s \left( k_2 + k_3 / T_m \right)} \cdot \Delta s = \Pi \cdot \Delta s$$  \hspace{1cm} (1)
\[
\Pi = \frac{10^6}{\rho_w R_e \left( k_3 + k_4 / T_m \right)}
\]  

(2)

\[
PWV = \Pi \cdot ZWD
\]  

(3)

In the formula above, \( \rho \) is the density of liquid water; \( \Pi \) can be regarded as a dimensionless constant, namely, the conversion coefficient between ZWD and PWV, which represents the conversion ratio between wet delay and precipitable water. The dimensionless constant is 0.15 according to experience. That is to say, 1mm PWV will cause a signal delay of 6.4 or 6.5 mm \(^7\). Formula (1) shows a linear relationship between the two, which can be simplified as Formula (3).

3. Case analysis

3.1 Precision analysis

3.1.1 Comparative analysis between BDS/PWV and Radio/PWV. The data of the radiosonde station is mainly collected by the radiosonde balloon released twice a day (0:00 and 12:00, UTC). The observation height of the radiosonde balloon under different environmental conditions is 25-38 km according to international practice. However, the water vapor in the atmosphere is mainly distributed below 8 km. Therefore, the height fluctuation of the radiosonde balloon has no effect on the accuracy of the acquired PWV. Since it is the most common means of detecting atmospheric data in the meteorological department, it is often used as an inspection standard for new methods of water vapor detection\(^8\).

![Figure 2. Comparison between time-series changes of BDS/PWV and Radio/PWV](image)

In order to analyze and verify the calculation accuracy of BDS/PWV, the analysis of change trend between BDS/PWV and Radio/PWV is needed, as shown in Figure 2. It can be seen from the overall trend that the two kinds of computed results are accordant, and the points in time corresponding to the peaks are also consistent, indicating that the inversion results of the data obtained by BDS have certain reference value.

Data statistics of BDS/PWV and Radio/PWV are carried out, and the correlation between the two is acquired, which is shown in Table 1.
| Region  | Station | MEAN /mm | MAX/mm | MIN/m m | STD (standard deviation)/mm | RMS (root-mean-square value) /mm | R(correlation coefficient) |
|---------|---------|----------|--------|---------|----------------------------|---------------------------------|---------------------------|
| NanNing | JZ02    | -0.293   | 7.512  | -11.870 | 4.403                      | 4.414                           | 0.874                     |
|         | JZ04    | 0.284    | 7.301  | -15.159 | 4.710                      | 4.718                           | 0.827                     |
|         | JZ05    | 0.408    | 7.957  | -13.021 | 4.048                      | 4.084                           | 0.895                     |
|         | JZ14    | 0.631    | 9.705  | -18.519 | 5.417                      | 5.556                           | 0.801                     |
|         | JZ28    | 0.614    | 8.167  | -17.641 | 5.016                      | 5.044                           | 0.824                     |
|         | JZ57    | 1.521    | 8.021  | -17.029 | 4.625                      | 4.964                           | 0.854                     |
|         | JZ60    | 0.539    | 9.156  | -14.753 | 4.435                      | 4.484                           | 0.866                     |
| Mean value |        | 0.27     |        |         |                            |                                 |                           |

It can be seen from Table 1 that the correlation coefficient $R$ between any two of the 7 CORS is greater than 0.8, and the maximum value is 0.895, which indicates that the BDS/PWV is in alignment with the Radio/PWV. MEAN represents the average of the difference values between BDS/PWV and Radio/PWV for each reference station, and its maximum value is 1.521 mm. Besides, the average MEAN for all base stations throughout the region is 0.27 mm, which shows that the calculated BDS/PWV has very high reliability and can be applied to the analysis of PWV in Nanning.

The standard deviation (STD) in Table 1 is basically between 4.0 and 5.5 mm, indicating that the dispersion degree of data between the reference stations is generally consistent, and the degree of deviation is not large. Besides, the root mean square (RMS) is also distributed between 4.0 and 5.6 mm. Furthermore, it can be noted that the maximum values of STD and RMS occur in the JZ14 station, and the JZ14 is also a reference station with the weakest correlation. Based on the geographical location of the reference stations, it is found that the JZ14 is closest to the sea. Therefore, it can be inferred that the JZ14 is affected by other factors during the inversion, resulting in the fact that the inversion accuracy of JZ14 is not as good as that of other reference stations far from the sea.

Through the above-mentioned analysis, it can be demonstrated that the BDS/PWV calculated in this experiment is equipped with a better accuracy, and the dispersion degree of data between the reference stations is generally consistent, and there is a good correlation between BDS/PWV and Radio/PWV.

### 3.1.2 Analysis of results obtained by applying IDW
Owing to the large number and wide distribution of CORS selected for experimentation in various regions, the specific data analysis cannot be implemented well. In order to make the analysis results clearer and more intuitive, and to further verify the calculation accuracy of BDS/PWV, the IDW has been applied in this paper. The inversion data of multiple CORS around the radiosonde station is effectively normalized to the vicinity of the radiosonde station. In other words, the BW/PWV is used to estimate the PWV of the radiosonde station, and then compared with the Radio/PWV.
The statistical analysis of the calculated PWV (called IDW/PWV) based on the IDW has been accomplished. Combined with the data of the radiosonde station, the change trend of IDW/PWV is given in Figure 3. It can be seen from Figure 4 that the change trends of IDW/PWV and Radio/PWV are accordant, and the points in time of the peaks are also highly consistent, showing that the IDW/PWV provides a better reference and can reflect the variation characteristics of the corresponding PWV.

To verify the accuracy of IDW/PWV, a statistical analysis of the difference values between IDW/PWV and Radio/PWV is carried out, which is shown in Table 2.

| Region | MEAN/mm | MAX/mm | MIN/mm | STD (standard deviation)/mm | RMS (root-mean-square value) /mm | R (correlation coefficient) |
|--------|---------|--------|--------|-----------------------------|-----------------------------------|---------------------------|
| NanNing | -0.1423 | 5.0671 | -4.0020 | 4.2485                      | 4.2571                           | 0.8976                    |

Combined with Table 1, it can be shown from the analysis of Table 2 that the correlation coefficient between IDW/PWV and Radio/PWV in Nanning is very close to 0.9, which is slightly better than that between BDS/PWV and Radio/PWV. In other words, the consistency between IDW/PWV and Radio/PWV is better than that between BDS/PWV and Radio/PWV.

The difference values between IDW/PWV and Radio/PWV in Nanning are presented in Figure 4.
As can be seen from Figure 4, the difference values between IDW/PWV and Radio/PWV are basically between -4 and 5 mm. Compared with the difference values between BDS/PWV and Radio/PWV, those between IDW/PWV and Radio/PWV have been significantly improved. The average (MEAN) of the difference values between IDW/PWV and Radio/PWV is -0.14 mm, which is much smaller than the MEAN (0.27 mm) of the difference values between BDS/PWV and Radio/PWV. Compared with the BDS/PWV, the IDW/PWV is closer to the Radio/PWV. In terms of other accuracy index shown in Table 1, such as maximum difference, minimum difference, STD, RMS, etc., there are some improvements in Table 2, which shows that the PWV calculated by the IDW is reliable. Moreover, in the field of difference values, MEAN, correlation, etc., the accuracy of IDW/PWV is better than that of BDS/PWV.

3.2 Analysis of both PWV and evolution of the rainstorm’s development process in Nanning

The accuracy verification of probability theory and statistics proves that the accuracy of PWV obtained from the inversion of 7 CORS is relatively reliable in all respects, reflecting the change process of water vapor in Nanning. Combined with the development process of the rainstorm resulted from the typhoon, the analysis of the change trend of PWV in August in Nanning has been completed. Subsequently, the differences between BDS/PWV at different reference stations are further explored. The time-series changes in the PWV at 7 CORS are presented in Figure 5.

Figure 5. Change trend of PWV in Nanning.
It can be known from Figure 6 that the values of PWV obtained from the inversion of 7 CORS are basically consistent in the overall trend. Besides, the PWV has a large fluctuation between the 13th and the 17th, and the variation is more than 40mm, which coincides with the time of the typhoon Mangkhut passing through the territory.

The change trend of PWV has been analyzed based on the meteorological observation data in Nanning and the time of the typhoon Mangkhut passing through the territory. The PWV continued to decline throughout Nanning from the 12th. Then, the PWV reached a minimum value of about 35 mm until 21:00 on the 15nd. Subsequently, the PWV rose sharply in the next 12 hours. The PWV in Nanning had remained at a relatively high level of more than 65 mm since 8:00 on the 16rd, which was caused by the typhoon that was passing through the territory of Guangdong. At this time, the typhoon had an unprecedented impact on the entire South China region, and Nanning was also within the scope of influence.

The PWV dropped sharply for the first time in the early morning of the 24th, but did not fall below 60 mm. Since the typhoon had entered Nanning at that time and brought high-intensity rainfall to Nanning, there would be a drop in the PWV. Moreover, the PWV did not completely fall down due to the existence of the typhoon. Instead, it began to rise at 12:00 on the 24th. The typhoon gradually disappeared in the white area at 17:00 on the 24th. Without the influence of the typhoon, the PWV began to drop rapidly to a minimum. Therefore, there was another rain in the Nanning.

The actual rainfall process is basically in line with the above-mentioned changes. It shows that the PWV calculated from the CORS does not have a large error and is consistent with the actual rainfall. Furthermore, it also indicates that the PWV calculated from the CORS can be applied to the actual business or used as the original data for short-term PWV forecasting.

4. Conclusions
Based on the processing of the meteorological observation data of 7 CORS and radiosonde stations in Nanning, the paper draws the following conclusions:

(1) Although the difference values between BDS/PWV and Radio/PWV are large at a few points in time, the two have good consistency in terms of overall trends and peaks.

(2) There is also a high consistency and correlation between IDW/PWV and Radio/PWV. Compared with the BDS/PWV, the IDW/PWV is equipped with a smaller error and MEAN, as well as a better correlation. Another large advantage of IDW is that it can reflect the time-series variation characteristics of PWV more clearly and directly.

(3) Both the BDS/PWV and the IDW/PWV are highly consistent with the Radio/PWV in overall trends and peaks. What’s more, in practical applications, the sudden changes in the peak values of PWV can be well correlated with both the changes in extreme weather and the heavy rainfall, indicating that the PWV obtained by the data inversion of BDS has a high reference value for monitoring and forecasting of extreme weather.

Fund projects
Guangxi Natural Science Foundation (2018GXNSFAA138168); science and technology projects of Guangxi surveying and Mapping Bureau (2016-E-01; 2018-E-0); science and technology projects of Guangxi Normal University (0819-2016L11).

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