Journal of Global Positioning Systems (2025)

Vol. 21, Issue 2: 165-167

Research on the method and key technologies of timely water vapor monitoring with low-cost BDS/GNSS terminals

PhD Candidate: Luohong Li
Supervisor: Yuan Yunbin
Graduate Program: Innovation Academy for Precision Measurement Science and Technology
Institution: University of Chinese Academy of Sciences
Date: June 2025

Abstract

Atmospheric water vapor is an important greenhouse gas that plays a key role in atmospheric energy exchange, the formation and evolution of weather events such as clouds, rain, and lightning, the global water cycle, and the energy balance of the Earth-atmosphere system. With global climate warming, extreme weather events are becoming more frequent and intense, such as extreme heavy rainfall, typhoons, and floods, which pose significant threats to human production and daily life. As an important index for characterizing extreme weather and climate change, high spatiotemporal resolution and high-timeliness monitoring of atmospheric water vapor is of great significance for the forecasting and early warning of disaster weather and climate change research.

Currently, existing real-time water vapor monitoring systems rely on high-cost geodetic GNSS (Global Navigation Satellite System) terminals and meteorological equipment, which are expensive to construct and maintain and difficult to expand in the short term. Low-cost BDS (BeiDou Navigation Satellite System)/GNSS terminals, with advantages of low cost and high accuracy, have potential for densifying the existing water vapor monitoring network, but there are still research limitations and application bottlenecks in real-time water vapor monitoring. To achieve high-density, high-precision, and high-timeliness water vapor monitoring, this study focuses on low-cost BDS/GNSS terminal equipment and explores methods for real-time tropospheric estimation, auxiliary parameter models for real-time water vapor retrieval, as well as low-cost and high-timeliness water vapor monitoring method and application in complex environments.

The main research work and innovations are summarized as follows:

1. **A relative PCV estimation method based on ultra-short baselines is proposed, and the characteristics of low-cost antenna PCV and its impact on ZTD estimation are explored. The real-time ZTD estimation quality of low-cost equipment was analyzed, along with its performance under disturbed weather conditions.**

High-precision zenith total delay (ZTD) estimates are the basis for obtaining high-precision water vapor data using low-cost BDS/GNSS devices. To improve the accuracy and consistency of ZTD estimation with low-cost devices, the impact of low-cost antenna PCV (Phase Center Variation) corrections on ZTD estimation is analyzed, and quantitative results of the bias are provided. A method for calculating relative antenna PCV differences based on ultra-short

baseline relative positioning is proposed, and the PCV characteristics and regularities of low-cost antennas are analyzed. To investigate the accuracy and reliability of ZTD estimation, two independent groups of co-located GNSS arrays were deployed for a two-week real-time experiment. The ZTD estimation quality of low-cost equipment in both post-processing and real-time modes was compared with that of geodetic-grade equipment. The real-time ZTD estimation performance of low-cost equipment was further investigated during a heavy rainfall event in Wuhan, where significant tropospheric disturbances occurred. The results show that low-cost equipment can achieve tropospheric delay estimates of better than 6.3 mm in post-processing and better than 10 mm in real-time, with stable performance under approximately 224 mm of tropospheric disturbance. Seasonally, the ZTD estimation accuracy in the cold season is slightly better than in the warm season. A comparison between low-cost and geodetic equipment's ZTD differences in both post-processing and real-time modes reveals that the primary factor causing real-time ZTD accuracy loss is the real-time precision product and processing strategy. However, the ZTD estimates from low-cost equipment are comparable to those of co-located geodetic equipment, offering a cost-effective advantage for real-time high-precision tropospheric monitoring. During heavy rainfall events with precipitation intensity exceeding 33 mm/h, low-cost equipment suffers from deviations and noises caused by weather disturbances, but its real-time ZTD estimation accurately captures the trend of ZTD changes, demonstrating high timeliness and time resolution advantages for tropospheric monitoring and significant application potential in water vapor retrieval for extreme weather events.

2. **A numerical weather prediction model-based auxiliary parameters (ZHD and Tm) model for real-time water vapor retrieval is proposed and named HDTM. The corresponding application methods and service models of HDTM are established.**

Zenith hydrostatic delay (ZHD) and weighted mean temperature (Tm) are two key parameters in the water vapor retrieval process. Its timely access is a prerequisite for retrieving real-time water vapor without co-located meteorological equipment. To solve the problem of acquiring high-precision ZHD and Tm in real-time water vapor retrieval, this study uses two typical numerical weather prediction (NWP) models, including NCEP-GFS and ECMWF-IFS, to develop an auxiliary parameter model (HDTM), which is suitable for real-time water vapor retrieval. The application methods and service models are established to provide reliable ZHD and Tm parameters for GNSS stations without co-located meteorological sensors. To explore the application accuracy of the HDTM model in the China region, experiments comparing the HDTM model with ERA5, radiosonde data, and actual atmospheric pressure measurements are designed. The modeled accuracy of ZHD and Tm is verified, and the performance in representing parameter diurnal variations and short-term disturbances are discussed. Finally, by referring to water vapor products from the GNSS/MET network covering China, the study analyzes the PWV (Precipitable Water Vapor) retrieval errors caused by the HDTM model's ZHD and Tm parameters and their consistency with water vapor retrieval results based on measured meteorological parameters. The results show that using ERA5 as a reference, the ZHD and Tm accuracy at grid points in the HDTM model is better than 2.7 mm and 1.2 K, respectively. Using measurements as a reference, the sites accuracy of ZHD and Tm is better than 3.2 mm and 1.5 K, respectively. Referring to GNSS/MET water vapor products from 953 stations, the average error in PWV caused by ZHD and Tm parameters from HDTM model is around 2.1 mm. Moreover, the HDTM model with a 1-hour time interval can accurately reflect short-term parameter variations. Comparing the HDTM-Tm model with the Bevis model shows a 40% improvement in root mean square error (RMSE), while the HDTM-ZHD model's RMSE is about 50% smaller than that of the VMF3-FC ZHD. These results fully demonstrate that the HDTM model has advantages in high timeliness and high time resolution, capable of providing ZHD and Tm parameters for stations without co-located meteorological equipment, assisting in real-time water vapor retrieval with differences of less than 2.1 mm.

3. **A new real-time water vapor retrieval method that does not rely on observed meteorological parameters and a low-cost BDS/GNSS real-time water vapor monitoring terminal are proposed and verified for their application in dynamic oceanic and extreme weather environments.**

To address the bottleneck in applying high-timeliness water vapor retrieval methods in complex environments, this study proposes a water vapor retrieval method and service model based on the HDTM model, which does not rely on measured meteorological parameters. The application advantages of the new GNSS water vapor monitoring model are demonstrated from hardware platforms, application scenarios, and extreme weather response perspectives. First, the proposed water vapor retrieval method is validated through two extreme weather events: heavy rainfall in Wuhan and Typhoon "Sanba". The results show that the new method can eliminate the reliance on measured meteorological parameters, and the retrieved PWV matches the reference results well. Compared with TUW-PWV with a 6-hour resolution and reference results, the new method can reflect the water vapor accumulation and decay processes in detail with higher time resolution, accurately capturing the PWV peak during precipitation events, proving its reliability under disturbed weather conditions. Then, a low-cost and high-timeliness water vapor monitoring method was developed in this study, which is suitable for dynamic marine observations. ZTD was derived from GNSS observations obtained by low-cost terminals, and the HDTM model was employed to provide auxiliary parameters for water vapor retrieval at dynamic terminal positions. The results show that the ZTD estimation of two sets of low-cost buoys is 9.6 mm and 10.4 mm, respectively. The accuracy of retrieved PWV is 1.6 mm. For shipborne low-cost terminals in dynamic environments, the ZTD accuracy is better than 6.0 mm, and the ZHD accuracy provided by the HDTM model is 1.8 mm. The retrieved PWV differs from traditional methods by only 0.8 mm. These results demonstrate that the proposed new method significantly improves the convenience of acquiring oceanic water vapor data and can be combined with PPP-B2b for high-precision, high-timeliness, low-cost oceanic water vapor monitoring services in the future. Finally, a low-cost real-time GNSS water vapor monitoring terminal was developed, operating without requiring measured temperature and pressure observations. With an approximate cost of 1,500 RMB, this represents only about 1% of the expense of geodetic-grade GNSS equipment currently deployed in existing monitoring networks. Long-term real-time validation of the low-cost terminal at the Wuhan meteorological station for about 50 days shows that the PWV retrieved by the low-cost terminal differs by 2.0 mm from radiosonde observations and 0.5 mm from meteorological parameter-based retrievals, with no significant accuracy loss during precipitation events. These results fully demonstrate that the proposed water vapor monitoring method and terminal in this study can meet the accuracy requirements for high-precision water vapor applications under complex weather conditions and dynamic marine scenarios, providing valuable references for developing high-timeliness water vapor monitoring applications.