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An Investigation of Real-time GNSS Precipitable Water Vapor Retrievals

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Abstract

Water vapor, the content of which can be measured by precipitable water vapor (PWV), is a greenhouse gas in the troposphere, a carrier of atmospheric energy exchange, and a material basis of weather changes. When the signals of Global Navigation Satellite Systems (GNSS) propagate through the troposphere, the tropospheric delay, as a major error source of GNSS positioning, occurs resulting from both the dry component and water vapor in the troposphere. As a result, the water vapor information is embedded in the GNSS signals, and all-weather high-accuracy tropospheric delay and PWV products can be obtained from GNSS data processing for weather and climate change research, which is low-cost compared to other water vapor monitoring techniques.

For the purpose of time-critical extreme weather prediction, GNSS real-time precise point positioning (PPP) has become a powerful technique for the determination of the zenith tropospheric delay (ZTD) over a GNSS station of interest, and the subsequent high-accuracy retrieval of PWV. This paper mainly focuses on the high-accuracy atmospheric modeling, development of real-time PPP software and the assessment of accuracy of the resulted ZTD, refinement of ZHD interpolation method for obtaining high-accuracy ZHD (zenith hydrostatic delay) from VMF1/VMF3 forecasting grids, ZWD (zenith wet delay)-PWV conversion model and the accuracy of PWV resulting from the VMF1/VMF3-based ZHD and the conversion model, and the relation between the real-time GNSS-PWV and weather changes. The details are as follows:

(1) In most of the empirical models, atmospheric pressure at the user site is typically obtained from atmospheric pressure at a reference height combined with an atmospheric pressure vertical reduction model. If the reference height largely differs from the height of the user site, the quality of the predicted atmospheric pressure is usually poor due to the simple reduction model used. In this study, a voxel-based atmospheric pressure model, named PVoxel, was developed for obtaining better accuracy atmospheric pressures using sample data of 10-year ERA5 monthly mean data, totaling 120 monthly mean values in the temporal domain. Each monthly mean atmospheric pressure and virtual temperature at each of the four selected reference heights over all globally distributed grid points (horizontal resolution: 1°×1°), i.e., at the nodes of the 3D voxels, were determined. Then the characteristics of the annual and semi-annual variation in both atmospheric pressure and virtual temperature in the temporal domain for each node were modeled. The PVoxel model developed is 4-dimensional, thus it can be used to predict atmospheric pressure at a given geographic position and any altitude, and any time. The model was evaluated by comparing the atmospheric pressures predicted for the sites of all globally distributed radiosonde stations against their corresponding radiosonde data of the sites. The model predicted results were also compared with that of the

widely used models like GPT3, UNB3m et al. and the comparison results showed that PVoxel outperformed these models, especially at high altitudes. The significant performance improvement of the new model is promising for an improvement in its resultant ZHD, which is significant for obtaining more accurate position (especially the height component) and zenith tropospheric delay.

(2) A modified BNC software (BNC_MET) was developed for real-time retrieval of GNSS-PWV. Compared to the original open-source BNC software, the error correction, quality control and parameter estimation modules were significantly improved in the new development. Two experiments were designed for the evaluation of real-time ZTD estimated by the modified BNC software. Firstly, the accuracy of ZTD resulting from four different real-time service (RTS) products were evaluated using GPS-only and GPS+GLONASS real-time PPP. Compared to the IGS final tropospheric products, the mean RMSE of ZTD resulting from GPS-only and GPS+GLONASS PPP using CNES RTS products were 8.4 mm and 8.1 mm, respectively, while the corresponding RMSEs were 7.4 mm and 7.0 mm compared to the CODE tropospheric products. High accuracy ZTD (but slightly worse than the CNES ones) were also obtained from PPP using GFZ and WHU products, and the IGS03 performed the worst. Secondly, the accuracy of ZTD estimated by BDS-only PPP and GPS+BDS PPP were also evaluated using GFZ RTS products. The results showed that the accuracy of BDS-only PPP-resulted ZTD was slightly worse than that of GPS-only ones, and the GPS+BDS scheme performed better than GPS-only and BDS-only schemes.

(3) Refinement of ZHD interpolation method for VMF1/VMF3 forecasting grids. VMF1 and VMF3 forecasting grids provide ZHD, ZWD and mapping function coefficients at globally distributed grid points. However, a unified atmospheric pressure vertical correction coefficient was adopted by the official code provided by the data-provider. As a result, large ZHD prediction errors were obtained in some places. The ZHD vertical correction part during the interpolation was improved by two new methods. Firstly, atmospheric pressure vertical correction coefficient at each of the grid point were fitted and modeled for the vertical correction of VMF-based ZHD. Secondly, 3D-voxel based atmospheric temperature model from the above-mentioned PVoxel model were used for the ZHD vertical correction. The newly proposed methods were evaluated by surface atmospheric pressure observations from 2019 to 2021 at 404 radiosonde stations. For the first method, the mean RMSE of ZHD interpolated from VMF1, VMF3(5°×5°) and VMF3(1°×1°) forecasting grids were reduced from 5.5 mm, 4.9 mm and 3.9 mm to 3.7 mm, 4.2 mm and 3.6mm, respectively, while the maximum RMSE were reduced from 4.01 cm, 4.24 cm and 1.95 cm to 1.63 cm, 2.38 cm and 1.83 cm, accordingly. For the second method, the mean RMSEs were reduced to 3.6, 4.3 and 3.7 mm, respectively, and maximum ones were reduced to 1.64, 2.38 and 1.83 cm, respectively. Both the two newly proposed methods outperformed the traditional method. In addition, three horizontal interpolation methods were also evaluated, and the bilinear interpolation performed the best.

(4) A new weighted mean temperature (T_m) model, named GGNTm, considering the nonlinear variation of T_m in the vertical direction was established using 10-year long ERA5 monthly-mean reanalysis data. A three-order polynomial function was utilized to fit the vertical nonlinear variation in T_m at the grid points, and the temporal variation in each of the four coefficients in the T_m fitting function was also modeled with the variables of the mean, annual, and semi-annual amplitudes of the 10-year time series coefficients. The performance of the new model was evaluated using its predicted T_m values in 2018 to compare with the following two references in the same year: (1) Tm from ERA5 hourly reanalysis with the horizontal resolution of 5°×5°; (2) T_m from atmospheric profiles from 428 globally distributed radiosonde stations. Compared to the first reference, the mean RMSEs of the model-predicted T_m values over all global grid points at the 950 and 500 hPa pressure levels were 3.35 and 3.94 K, respectively. Compared to the second reference, the mean bias and

mean RMSE of the model-predicted T_m values over the 428 radiosonde stations at the surface level were 0.34 and 3.89 K, respectively; the mean bias and mean RMSE of the model's T_m values over all pressure levels in the height range from the surface to 10 km altitude were 0.16 and 4.20 K, respectively. Results indicated that significant improvements made by the new model were at high-altitude pressure levels.

(5) The accuracy of the GNSS-retrieved real-time PWV using ZHD from VMF forecasting grid and T_m from GGNTm was also investigated. GPS observations from 41 IGS stations that have co-located radiosonde stations during the period of the first half of 2020 were used to test the quality of GPS-PWV. The results showed that mean RMSE of the PWVs resulting from GPS-PPP was smaller than 2mm compared to reference PWVs from collocated radiosonde data, which is accurate enough for meteorological applications.

(6) The correlation between real-time GNSS-PWV and weather change was analyzed using 20-day-long real-time PWV obtained from 11 CORS stations in Hong Kong. The atmospheric pressures measured by co-located meteorological sensors were used for the calculation of ZHD and GGNTm model was used for the conversion of ZWD to PWV. By comparing the real-time PWV to the weather records provided by Hong Kong Observatory, it can be concluded that the real-time PWVs are tightly correlated to weather change.

The accuracy of real-time PWV can be improved by implementing the above-mentioned research, which may make significant contributions to weather forecasting and the time-critical severe weather monitoring.

This dissertation includes 56 figures, 23 tables and 203 references.

Keywords: zenith tropospheric delay; precise point positioning; zenith hydrostatic delay; weighted mean temperature; precipitable water vapor