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Research on the Key Technologies in Water Vapor Retrieval Using Ground-based GNSS

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ABSTRACT

As the most abundant greenhouse gas in the earth atmosphere, water vapor plays an important role in maintaining livable temperature environment and contributes much to the global warming. The content of water vapor in the atmosphere is pretty variable in both temporal and spatial domain, which greatly affects the climate and weather system. The phase change of water vapor is accompanied by the absorption and release of heat, which has a significant influence on the vertical stability of the atmosphere and the formation of the severe convection weather. Its dramatic change in a short time always leads to destructive weathers. Therefore, monitoring the content and distribution of water vapor in the atmosphere and a good understanding of the spatial and temporal change of water vapor are of great significance to the research of climate change, the short-term weather forecasts, and the severe weather warning.

Ground-based GNSS can be used to retrieve water vapor based on the signal delays passing through the atmosphere. Compared to the traditional methods, the GNSS technique has the advantages of continuous operation, low cost, all weather conditions, high accuracy and high temporal resolution. By using this technique, not only the two-dimensional content of the precipitable water vapor can be retrieved, but also the three-dimensional distribution of the water vapor density can be reconstructed by the water vapor tomography. This thesis describes in detail the principles of precipitable water vapor retrieval using ground-based GNSS as well as the methods of obtaining the water vapor density by water vapor tomography, analyses the influences of different modeling factors on the accuracy of the global temperature and pressure model, discusses the accuracy of ZHD models based on the estimated meteorological parameters, proposes new models for improving the accuracy of precipitable water vapor retrieval and new solutions for optimizing the PWV interpolation, establishes an advanced water vapor tomography method based on a genetic algorithm, conducts experiments in urban areas, and obtains some interesting conclusions. The main research work and related contributions of this thesis are as follows:

1. The empirical global temperature and pressure models can provide necessary parameters for ZHD estimation to overcome the lack of meteorological observations located at most of the GNSS stations. This thesis evaluates the influences of different modelling factors on the accuracy of modeling, including the model forms, the temporal and spatial

resolution of the data sources. It can be concluded by analyzing the results that there no obvious daily cycles existed in temperature lapse rate and specific humidity, the daily cycle needs to be considered in the construction of the temperature and pressure model, the adoption of sophisticated models (multiple model coefficients) did not necessarily improve the accuracy of the temperature and pressure, only the performance of model based on time-segmented idea is improved as increasing the temporal resolution of the data sources, increasing the spatial resolution of the data sources can significantly improve the performance of each model. This thesis also discusses the accuracy of the three most commonly used ZHD models without measured temperature and pressure, the Saastamoinen model achieves the best performance, for some certain regions however, the Saastamoinen model should be further refined and more attention should be paid for the selection of ZHD model.

2. The global weighted mean temperature lapse rate in different height ranges are obtained and analyzed for the first time, the Tm lapse rate from the surface to a height less than 2 km above the surface is determined to perform the time-series analysis. This thesis achieves the mean value, annual and semiannual amplitudes for Tm lapse rate on a regular 1° grid, and establishes the GPT2wh model. The numerical results with ECMWF data show that the improvement is 0.03 K at the height level with an average altitude difference of 54 m and the improvement becomes 7.36 K as the average altitude difference increases to 1994 m. In comparison with the radiosonde data, the average RMSE and Bias of the GPT2wh model are 3.83 K and -0.32 K, respectively, which are 8% and 66% better than the existing model. The proposed model can effectively reduce the lack of elevation correction in the Tm estimation and improve the Tm accuracy at the sites with large altitude difference.

3. This thesis analyzes the linear relationship between the surface temperature and the weighted mean temperature globally, shows that the results of the linear regression are not only location-dependent, but also change with seasons. Resting upon a global 2.5°×2° grid of coefficients of Tm-Ts linear function, a new Tm model called GGTm-Ts model is proposed, which can provide Tm with high accuracy at any site in two modes, one for the case with measured Ts provided and the other for the case without measured Ts. Taking the Tm derived from GGOS Atmosphere and radiosonde data as the true value, the comparison shows that the accuracy of Tm estimated by the GGTm-Ts model is 46.9%/15.3% higher than the Bevis formula, and 37.8%/19.5% higher than the GPT2w model when the measured Ts exists, the improvement over the GPT2w model becomes 7.2%/5.4% while there is no measured Ts.

4. The influence of Tm estimated by Bevis formula, GPT2w model, GPT2wh model and GGTm-Ts model on GNSS-PWV is discussed in this thesis. Comparison with IGS data shows that the GGTm-Ts model is the first choice for GNSS-PWV when the measured Ts can be obtained in real time, and the accuracy of PWV converted by the GPT2wh model and the GGTm-Ts model in mode #2 is comparable in the case of no measured Ts. The GPT2wh model could be used widely since its ability to estimate a variety of meteorological parameters. Considering that the spatial resolution of the GGTm-Ts model and the GPT2wh model are 2.5°×2° and 1°×1°, respectively, the GGTm-Ts model has more room for expansion.

5. This thesis proposes a GNSS-PWV interpolation scheme based on the idea of remove-interpolate-restore. The proposed GPT2wh model is used to calculate the PWV estimates, the existing interpolation algorithms are adopted to interpolate the PWV residuals, and then restore the PWV information for the stations to be calculated. The proposed interpolation scheme requires no meteorological data at an interpolation station and no regression analysis of the observation data. The station cross-validation and grid data validation conducted in SatRef show that the differences of PWV interpolation under different weather conditions have little relationship with the interpolation algorithm, and mainly depends on the stability of the PWV in the research region during the experimental period, the

introduction of the elevation factor multiple times during the interpolation may bring additional errors, the reference stations have no ability to provide sufficient and reliable interpolation information in elevation correction by using the existing interpolation algorithms when the elevation of the sites to be calculated is far from the elevation range of reference stations. These deficiencies can be compensated by the proposed interpolation scheme, which also effectively improves the spatial resolution and interpolation accuracy of PWV, realizes the possibility of obtaining accurate PWV at the location without GNSS receivers.

6. This thesis proposes the usage of grayscale graph to study the matrix ill-condition of the tomographic observation equations, sets the thresholds to determine whether a voxel is passed through by sufficient signal rays. The fitness function is constructed by the observation equations and the inversion problem is transformed into an optimization problem, a new water vapor tomography method based on a genetic algorithm is proposed, which no longer depends on excessive constraints, a priori information and external meteorological data. The experiments conducted in SatRef under different weather conditions show that the water vapor tomographic results based on the genetic algorithm are in good agreement with the radiosonde profiles, the water vapor distribution derived from ECMWF data and the tomographic results obtained by the least squares method, the proposed method can provide reliable and accurate water vapor density.