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Quantitative assessment of meteorological and tropospheric Zenith Hydrostatic Delay models

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Abstract

Tropospheric delay has always been an important issue in GNSS/DORIS/VLBI/InSAR processing. Most commonly used empirical models for the determination of tropospheric Zenith Hydrostatic Delay (ZHD), including three meteorological models and two empirical ZHD models, are carefully analyzed in this paper. Meteorological models refer to UNB3m, GPT2 and GPT2w, while ZHD models include Hopfield and Saastamoinen. By reference to in-situ meteorological measurements and ray-traced ZHD values of 91 globally distributed radiosonde sites, over a four-years period from 2010 to 2013, it is found that there is strong correlation between errors of model-derived values and latitudes. Specifically, the Saastamoinen model shows a systematic error of about −3 mm. Therefore a modified Saastamoinen model is developed based on the "best average" refractivity constant, and is validated by radiosonde data. Among different models, the GPT2w and the modified Saastamoinen model perform the best. ZHD values derived from their combination have a mean bias of −0.1 mm and a mean RMS of 13.9 mm. Limitations of the present models are discussed and suggestions for further improvements are given.

Keywords: Zenith Hydrostatic Delay; Radiosonde; UNB3m; GPT2/GPT2w; Saastamoinen; Hopfield

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1. Introduction

Nowadays, radio signals are widely used in space geodetic techniques, such as Global Navigation Satellite Systems (GNSS), Doppler Orbitography Radiopositioning Integrated by Satellite (DORIS), Very Long Baseline Interferometry (VLBI) and Interferometric Synthetic Aperture Radar (InSAR). When the radio signals travel through the troposphere, both the speed and the path of radio waves is changed significantly. Such effects are called tropospheric delay. Unlike the ionospheric delay, the tropospheric delay cannot be eliminated by multi-frequency combination. More specifically, the tropospheric delay observed at the Earth surface generally exceeds 2 m at zenith, and about 20 m at an elevation of 5 degree. Hence, the tropospheric delay has been recognized as a major error source for many space geodetic applications (Boehm and Schuh, 2013; Eriksson et al., 2014; Majumder et al., 2015; Shi et al., 2015; Willis et al., 2014; Yao et al., 2014).

In general, the tropospheric delay can be divided into two components: a hydrostatic component mainly caused by dry gases of the air, and a non-hydrostatic (wet) component due to water vapor (Davis et al., 1985). Zenith Hydrostatic Delay (ZHD) contributes 90% to the Zenith Total Delay (ZTD), and can be calculated by in-situ surface

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meteorological observation fed into empirical models, with accuracy from millimeter to sub-millimeter (Mendes, 1999). However, the water vapor is inhomogeneous in the atmosphere, so the highly variable non-hydrostatic component is difficult to be modeled. Since the ZHD can be modeled precisely, the zenith non-hydrostatic (wet) delay (ZWD) are then estimated as unknown parameters (Brunner and McCluskey, 1991; Dach et al., 2015; Herring et al., 2015; Rózsa, 2014). A normal ZWD accuracy of <1 cm were reported with respect to the Water Vapor Radiometer (WVR) observations (Ghoddousi-Fard, 2009; Kuehn et al., 1993). This is especially useful and necessary for meteorology studies (Bevis et al., 1992; Bock et al., 2014; Fang et al., 1998; Rohm et al., 2014). Apparently, the accuracy of estimated ZWD depends on the accuracy of ZHD to a large extent. Furthermore, a priori ZHD errors can cause height errors of up to 10 mm amplitude (Tregoning and Herring, 2006). Therefore, it is necessary to study how to achieve a priori ZHD with high accuracy.

The accuracy of a priori ZHD highly depends upon the accuracy of the surface meteorological measurements, as well as the selected ZHD model. If in-situ surface pressure and temperature measurements are not available, we may retrieve those data from a Numerical Weather Model (NWM), e.g. the European Centre for Medium-Range Weather Forecasts (ECMWF) (Dee et al., 2011), or alternatively, use the empirical meteorological models.

So far, the most famous meteorological models include the UNB series (Leandro et al., 2006, 2008) and the GPT series (Böhm et al., 2015, 2007; Lagler et al., 2013). The two most commonly used ZHD models were proposed and then named by Hopfield (1969) and Saastamoinen (1972), respectively. Tuka and El-Mowafy (2013) studied the performance of different ZHD models, with comparison between various models carried out by using Saastamoinen model as a reference. Yao et al. (2015) analyzed the accuracy of GPT2 on a global scale. However, the meteorological data from ECMWF used as the reference, is also the data source of GPT2. Consequently, it would be more objective to use in-situ meteorological observations to evaluate the corresponding model. In this study, we use radiosonde measurements and ZHD values computed from those data as the external reference, which approach has been adopted by Mendes (1999), Liu et al. (2000), Singh et al. (2012), and Eriksson et al. (2014). Furthermore, we also aim to find some possible weakness of the existing models and to provide suggestions for the future research.

We organize the rest of the paper as follows. In Section 2, we introduce the most commonly used meteorological and ZHD models, the radiosonde data, and the methodology of our analysis. In Section 3, we show the error analysis of the models mentioned previously, by reference to radiosonde-derived values. Finally, in Section 4, we summarize the analysis conclusion.

2. Models and methodology

2.1. Meteorological models

UNB3m, developed by researchers of the University of New Brunswick, is the advanced version of the UNB series models and has been adopted by the Wide Area Augmentation System (WAAS) (Leandro et al., 2006). Its algorithm is based on the prediction of meteorological values for a specified location and day of year, in which a look-up table for meteorological parameters is used. This look-up table is derived from U.S. Standard Atmosphere Supplements 1966 (COESA, 1966). The annual mean value and amplitude of a cosine function is used (phase fixed to 28 January) as equation below,

$$A = a_0 + a_1 \cos\left((\mathrm{doy} - 28)\frac{2\pi}{365.25}\right) \tag{1}$$

where A stands for the meteorological parameter value, a_0 is the annual average, and a_1 stands for the annual amplitude.

GPT2w (Böhm et al., 2015) and GPT2 (Lagler et al., 2013) are improved from the Global Pressure and Temperature (GPT) (Boehm et al., 2007), which two models are both based on 10 years (from 2001 to 2010) of monthly mean profiles for pressure, temperature and specific humidity (37 pressure levels and 1° × 1° global grids) from the ECMWF Re-Analysis (ERA-Interim), with mean values, annual and semi-annual variations, as shown in Eq. (2). The main difference between GP2w and GPT2 is the spatial resolution, which is 1° for the former, and 5° for the later. The International Earth Rotation and Reference Systems Service (IERS) recommended GPT2 for radio techniques (Petit and Luzum, 2013).

$$A = A_0 + A_1 \cos\left(\frac{\mathrm{doy}\cdot 2\pi}{365.25}\right) + B_1 \sin\left(\frac{\mathrm{doy}\cdot 2\pi}{365.25}\right) + A_2 \cos\left(\frac{\mathrm{doy}\cdot 4\pi}{365.25}\right) + B_2 \sin\left(\frac{\mathrm{doy}\cdot 4\pi}{365.25}\right) \tag{2}$$

where A_0 is the average value, A_1, B_1 stand for the annual amplitude, and A_2, B_2 stand for the semi-annual amplitude.

2.2. Radiosonde data

Radiosonde is an instrument carried by a balloon through the atmosphere, equipped with devices to measure pressure, temperature, humidity, etc., and provided with a radio transmitter for sending this information to the observing station (WMO, 2008). Radiosonde provides the most reliable source of information on the profile of the atmosphere, which has been the backbone for operational forecasting and a key data source for climate analysis. However, due to its high cost, radiosonde data is only available twice a day (at 00:00 and 12:00 UTC) for most stations.