TROPOSPHERE DELAY MODELING BASED ON NUMERICAL WEATHER MODELS

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ABSTRACT

Modern troposphere delay models like the Vienna Mapping Functions (VMF1) are based on data from Numerical Weather Models (NWM) with a time resolution of typically 6 hours. Different from purely analytical formulations like the Global Mapping Functions, the VMF1 can account for real weather phenomena like changing high and low pressure systems and are thus more accurate. Additionally, the zenith hydrostatic delays can also be derived from NWM if pressure values recorded at the sites are not available. We compare the VMF1 and zenith delays as derived from data of the European Centre for Medium-range Weather Forecasts (ECMWF) with those parameters derived from data of the National Centers for Environmental Prediction (NCEP), and we find a good agreement between those two realizations with station height differences at the few-millimeter level.

Key words: Troposphere delay modeling; Mapping functions; Ray-tracing.

1. INTRODUCTION

Troposphere delay modeling is a major error source in the analysis of space geodetic observations at microwave frequencies, like those from the Global Navigation Satellite Systems (GNSS) or geodetic Very Long Baseline Interferometry (VLBI). The delay along the bent path and the bending effect of the signal depend on the refractivity along the path, and the latter can be determined from pressure, temperature and humidity values as available with Numerical Weather Models (NWM). Thus, NWM can be used to determine the refractivity along the path and consequently also the delays of the signals.

In the analysis of space geodetic observations the slant delay is usually divided into a hydrostatic and a wet part, and each of these parts is set up as the product of the respective zenith delay and mapping function. Whereas the zenith hydrostatic delay can be determined very accurately from the surface pressure at the station, the zenith wet delay is estimated with the wet mapping function as partial derivative. Additionally, so-called North and East gradients are estimated to account for azimuthal asymmetries of the troposphere delays around the site.

However, in GNSS or VLBI analysis we do not only estimate zenith delays but also clock values or station coordinates, e.g. the station height component. Consequently, via correlations between those parameters, errors in the mapping functions and hydrostatic zenith delays map into station height estimates. A rule of thumb by MacMillan and Ma (1994 [10]) suggests that about 1/5 of the troposphere delay error at 5 degrees elevation shows up as station height error.

2. MAPPING FUNCTIONS

The Vienna Mapping Functions 1 (VMF1; Böhm et al., 2006a [1]) are based on the continued fraction form as proposed by Herring (1992 [8]) with three coefficients a, b, and c. Whereas the b and c coefficients are represented by analytical functions of station latitude and day of the year, the a coefficient is determined by one-dimensional ray-tracing in zenith direction and at an initial elevation angle of 3.3 degrees through data from NWM, i.e., only refractivity at the site vertical is used for this type of ray-tracing and no asymmetries around the sites are considered. At the Institute of Geodesy and Geophysics (IGG) of the Vienna University of Technology, Austria, 6-hourly data from the European Centre for Medium-range Weather Forecasts (ECMWF) are applied to calculate the VMF1, and the coefficients are provided for all VLBI and selected GNSS sites, as well as on global grids at $http://ggosatm.hg.tuwien.ac.at/$.

As far as the availability is concerned, the coefficients a for 0, 6, 12, and 18 UT as determined from analysis data of the ECMWF are provided at about 8 UT on the following day, i.e., the maximum delay is 32 hours. On the other hand, IGG also provides the coefficients a as determined from forecast data of the ECMWF for real-time applications. In that case, the coefficients a at 0, 6, 12, and 18 UT are provided at about 8 UT on the previous day, and the last observation that was used for the forecast was from 0 UT on the previous day. This means that the forecast-VMF1 is predicted over up to 42 hours. Böhm et al. (2009 [4]) showed that this is not at all critical for the hydrostatic part which can be well predicted over 42 hours. For the wet part, however, the effect on station heights can be as large as 1.5 mm at equatorial regions.

Böhm et al. (2006b [2]) also determined the Global Mapping Functions (GMF), which are a kind of averaged Vienna Mapping Functions 1. These are analytical functions (spherical harmonic expansions up to degree and order 9) and they do not need external time series as input, but only station coordinates and the day of the year. Of course, they cannot describe the effect of real weather phenomena, but on average they agree very well with the VMF1 (Steigenberger et al., 2009 [15]; Fund et al., 2011 [6]).

3. ZENITH HYDROSTATIC DELAYS

The zenith hydrostatic delays can be determined very accurately from the pressure at the site (Saastamoinen, 1972 [14]; Davis et al., 1985 [5]). The optimum way would be to record pressure values continuously at all sites. However, if those values are not available, zenith hydrostatic delays can be determined from data of NWM. For example, together with the coefficients a of the VMF1, also the zenith hydrostatic delays as determined from data of the ECMWF are provided at $http://ggosatm.hg.tuwien.ac.at/$. If neither pressure values taken at the sites nor zenith hydrostatic delays from NWM are accessible, then analytical models have to be used, e.g., the Global Pressure and Temperature model (GPT; Böhm et al., 2007 [3]). On average, GPT agrees very well with the annual variation of zenith hydrostatic delays from NWM but of course it cannot account for fast weather variations like the change of high and low pressure systems.

Moreover, one has to be very careful when using an analytical model like GPT in GNSS analysis for geophysical applications. Applying a 'mean' pressure value (e.g., from GPT) instead of the true pressure for the determination of the a priori hydrostatic zenith delay has the consequence that atmosphere loading effects are partly mitigated (Steigenberger et al., 2009 [15]). For example, the true pressure at the site shall be 1020 hPa whereas the mean pressure (e.g., from GPT at the site is 1000 hPa. Then, atmosphere loading is about -8 mm using a coefficient of -0.4 mm/hPa. On the other hand, the a priori hydrostatic zenith delay is too small by 46 mm if we use GPT instead of the real pressure. This error in the zenith hydrostatic delay maps into a delay error of +28 mm at 5 degrees elevation, and - applying the rule of thumb by MacMillan and Ma (1994 [10]) - the estimated station height is too big by 5.5 mm. Consequently, most of the loading effect has been removed unintentionally by applying a mean pressure for the determination of the zenith hydrostatic delay.

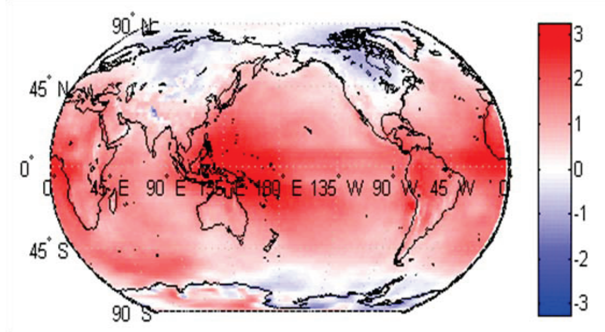

Figure 1. Simulated station height differences in mm when using VMF1-UNB instead of VMF1 as hydrostatic mapping function.

4. VMF1-UNB

Recently, the University of New Brunswick (UNB) has determined a coefficients of the VMF1 from data of the National Centers for Environmental Prediction (NCEP). They used NOAA-NCEP re-analysis data, and we will refer to this realization of the VMF1 as VMF1-UNB. Similar to the VMF1 as determined by IGG from ECMWF data, UNB provides those series with a time resolution of 6 hours and on global grids with a resolution of 2.0 and 2.5 degrees in latitude and longitude, respectively.

Comparisons for the year 2010 between VMF1 and VMF1-UNB show a good agreement between those two realizations. The overall mean biases and standard deviations for the zenith hydrostatic and wet delays are -2.4 $\pm$ 3.8 mm and -6.3 $\pm$ 14.7 mm respectively. The larger differences in the wet part are particularly pronounced at the equator; however, these differences are not critical because the wet zenith delays are usually estimated in GNSS analysis.

As for the mapping functions, the overall differences are rather small with 0.8 $\pm$ 0.9 mm and 0.4 $\pm$ 0.6 mm for the hydrostatic (see Figure 1) and wet part, respectively, if expressed as station height errors. However, there are systematic effects between the hydrostatic mapping functions. One of those effects - a systematic trend between equator and poles at the mm-level - can be explained by the use of a constant Earth radius in the ray-tracing program at IGG as compared to the more realistic Gaussian radius as applied at UNB.

When using VMF1 and VMF1-UNB in the analysis of VLBI observations of the continuous VLBI campaign CONT08 in August 2008, both mapping functions yield similar improvement in baseline length repeatabilities compared to baseline length repeatabilities from GMF (see Figure 2).

It is very important for the geodetic community to also have a realization of VMF1 other than that of IGG, because the availability of VMF1-UNB increases the robustness dramatically, and both realizations can serve

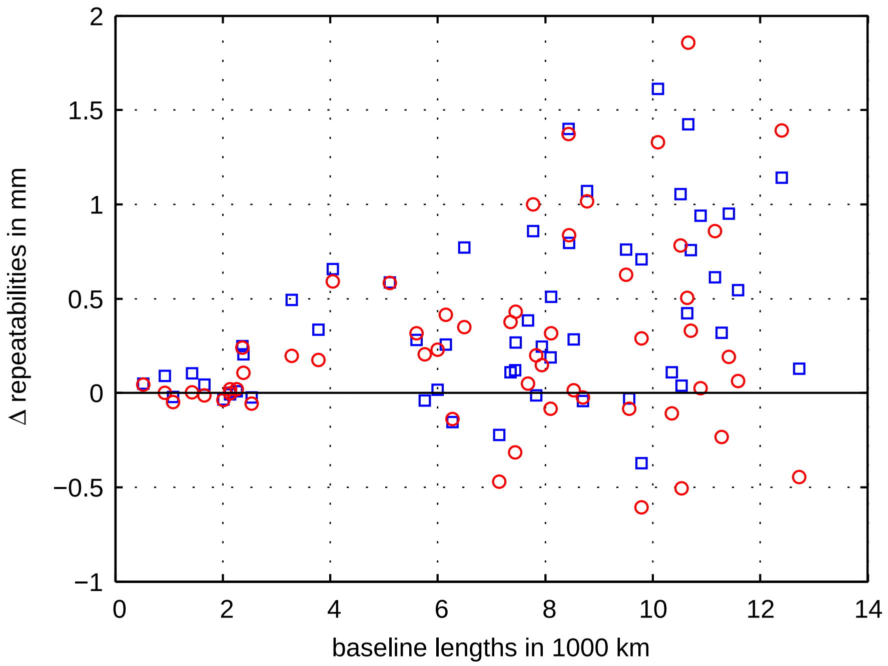

Figure 2. VLBI baseline length repeatability differences in mm for CONT08 with VMF1 (blue squares) and VMF1-UNB (red circles) with respect to baseline length repeatabilities with GMF plotted versus baseline lengths in 1000 km.

as backup in software packages if the other one is not available. Furthermore, VMF1-UNB allows consistency with models of other geophysical effects based on NCEP data, like the atmosphere loading corrections provided by Petrov and Boy (2004 [13]).

5. OUTLOOK

With the VMF1, essentially one parameter per site every 6 hours is provided to characterize the troposphere delays. However, VMF1 does not account for azimuthal asymmetries around the site. On the other hand, ray-traced delays could be calculated for every observation (Hobiger et al., 2008 [9]). This is feasible for VLBI with a limited number of observations, but it is not generally possible with GNSS with huge numbers of observations. For that case, interpolation methods have to be applied. For example Gegout et al. (2011 [7]) introduced adaptive mapping functions, i.e. extending the continued fraction form by Herring (1992 [8]) with additional parameters to account for higher orders of azimuth- and elevation-dependence, and fitting those parameters to a large number of ray-traced delays.

However, in future troposphere delay modeling will stay a limiting factor for the accuracy of space geodetic techniques observing at microwave frequencies. Pany et al. (2011 [11]) showed for VLBI2010 simulations (Petrachenko et al., 2009 [12]) that turbulence is putting a lower limit at the 1-mm level on the accuracy of VLBI positions from 24 hour solutions, depending on the atmospheric conditions at the sites.

ACKNOWLEDGMENTS

Johannes Böhm is grateful to the Austrian Weather Service (ZAMG) for granting access to the data of the ECMWF and to the Austrian Science Fund (FWF) for supporting this work under Project P20902-N10 (GGOS Atmosphere). The effort behind VMF1-UNB has been partly funded by the National Sciences and Engineering Council of Canada (NSERC).

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