GPT2: An improved model for tropospheric slant delays in VLBI and GNSS analysis

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***Abstract*—GPT2 is an improved empirical model for the determination of tropospheric delays to be used in high-precision global analyses of space geodetic observations at microwave frequencies, such as Global Navigation Satellite Systems (GNSS) and Very Long Baseline Interferometry (VLBI). It provides pressure, temperature, temperature lapse rate, water vapor pressure values, as well as hydrostatic and wet mapping functions coefficients. The underlying horizontal resolution is 5 degrees, and the parameters contain annual and semiannual variations. We show results of geodetic VLBI which demonstrate the improvement with GPT2 compared to earlier empirical models for the tropospheric delays. Future extensions of GPT2 will contain an improved parameterization for the calculation of zenith wet delays.**

BIOGRAPHIES

Johannes Böhm is Professor for Space Geodetic Techniques at the Vienna University of Technology. In his PhD studies and thereafter, he dealt with tropospheric path delays and developed tropospheric models for the analysis of observations from space geodetic techniques. His main interests now are atmospheric effects in space geodesy in general and the determination of global terrestrial and celestial reference frames from VLBI observations.

Klemens Lagler is Research and Teaching Assistant at the ETH Zurich. As the main part of his master thesis at the Vienna University of Technology he developed the new tropospheric model GPT2 and evaluated it with other existing models. Now he is doing his PhD at the Institute of Geodesy and Photogrammetry at the ETH Zurich.

Michael Schindelegger is PhD student at the Department of Geodesy and Geoinformation with a research focus on modeling atmospheric and non-tidal oceanic effects on Earth rotation on different time scales. He has good experience in processing meteorological data from numerical weather models as needed for various geodetic purposes.

Hana Krásná is a PostDoc scientist, working in the research group Advanced Geodesy at the Vienna University of Technology. Her PhD thesis focused on the determination of geodynamic parameters from VLBI, such as complex frequency-dependent Love and Shida numbers of solid Earth tides and parameters of Free Core Nutation. Hana Krásná is member of the VLBI group and one of the main developers of the Vienna VLBI Software VieVS.

Robert Weber is associate professor at the Department of Geodesy and Geoinformation, Vienna University of Technology, Austria. His main fields of research are Global Navigation Satellite Systems, geodetic reference systems, active GNSS reference station networks and applications of GNSS for geodynamics and meteorology. Robert Weber served within several activity fields of the IGS, e.g. as the former chair of the GNSS Working Group. He teaches courses in satellite navigation and gravity field modeling at TU Vienna and is involved in several projects setting up regional GNSS reference networks, Network-RTK, Real-Time-PPP as well as GNSS Atmosphere Monitoring.

Gregor Möller is a second year PhD student at Vienna University of Technology. In his Master thesis he analysed a real-time GNSS network concerning quality and stability. His current research focuses on GNSS signal analysis and tropospheric delay modelling - especially in terms of meteorology and navigation application. Since 2011, Gregor Möller is a member of the IGS Troposphere Working Group.

I. INTRODUCTION

Tropospheric delay modeling is the major error source in the analysis of observations from space geodetic techniques, such as Global Navigation Satellite Systems (GNSS) or geodetic Very Long Baseline Interferometry (VLBI). For global applications aiming at highest precision, such as geodynamical studies (cf. Tesmer et al., 2011 [12]) or reference frame solutions (cf. Tesmer et al., 2007 [11]), tropospheric delays ΔL are usually modeled as sum of hydrostatic and wet delays (see Equation 1). Herein, the zenith hydrostatic delays ΔL_h^z are very accurately determined from pressure values at the site applying the model by Saastamoinen (1972 [10]) as refined by Davis et al. (1985 [5]). Those values are then mapped down to the elevation of the observation with the hydrostatic mapping function $mf_h(e)$. On the other hand, the zenith wet delays ΔL_w^z are estimated, e.g. as piecewise linear offsets every 30 minutes, with the wet mapping functions $mf_w(e)$ as partial derivatives.

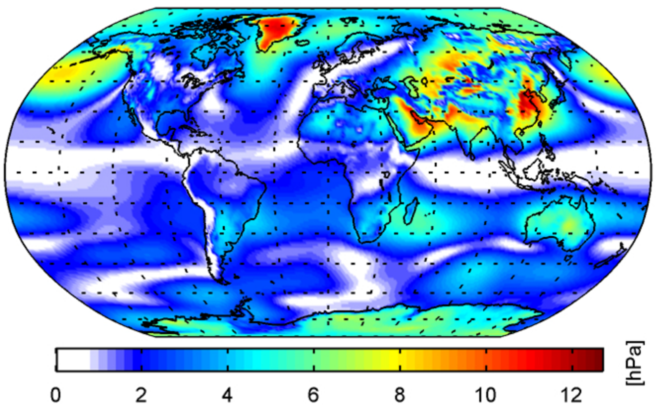

Figure 1: Amplitudes of annual pressure variations in hPa as provided with GPT2

$$\Delta L = \Delta L_h^z \cdot mf_h(e) + \Delta L_w^z \cdot mf_w(e) \qquad (1)$$

The Conventions of the International Earth Rotation and Reference Systems Service 2010 (IERS Conventions 2010; Petit and Luzum, 2010 [8]) and their electronic updates recommend using pressure values recorded at the sites and the Vienna Mapping Functions 1 (VMF1; Böhm et al., 2006a [1]). If those values are not available, the analyst is advised to apply the empirical model GPT2 (Lagler et al., 2013 [7]) or the earlier Global Pressure and Temperature model (GPT; Böhm et al., 2007 [3]) and the Global Mapping Functions (GMF; Böhm et al., 2006b [2]).

In Section II we review some properties of GPT2. We discuss its application in VLBI analysis in Section III and finally provide an outlook in Section IV, describing the potential application of GPT2 for navigation purposes.

II. Properties of GPT2

The development and validation of GPT2 as well as the comparison with GPT/GMF have been described in detail by Lagler et al. (2013 [7]). The output parameters of GPT2 are pressure, temperature, temperature lapse rate, water vapor pressure, as well as hydrostatic and wet mapping function coefficients. These mapping function coefficients have to be used with VMF1 subroutines. GPT2 is an empirical (blind) model based on grids with a horizontal resolution of 5 degrees, and every parameter is represented by annual and semiannual amplitudes and phases. In earlier models like GPT, GMF, or the ESA blind model (Krüger et al., 2004), there is no semiannual term and with GPT and GMF the phase of the annual term is fixed to January 28. For example, Figures 1 and 2 show the amplitudes of the annual pressure variations and the month of the annual pressure maximum. It is interesting to note that the largest annual pressure variations occur in Asia. However, the corresponding maxima and minima are not always clearly allocated to the end of January or July. Similar plots are provided for the temperature (Figures 3 and 4) and the specific humidity (Figures 5 and 6) where the distribution of amplitudes and phases is less varied but follows a clear annual pattern.

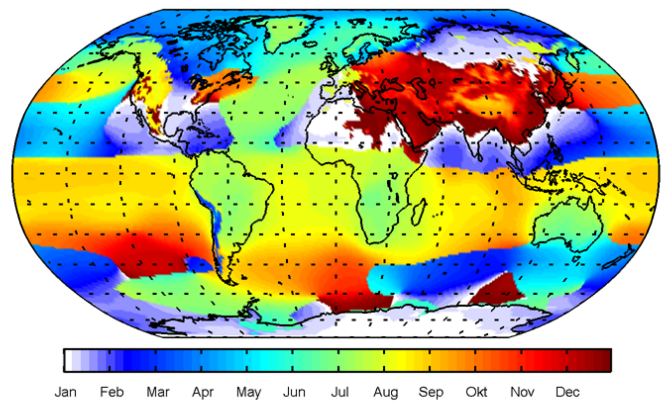

Figure 2: Month of maximum of the annual pressure variation in GPT2

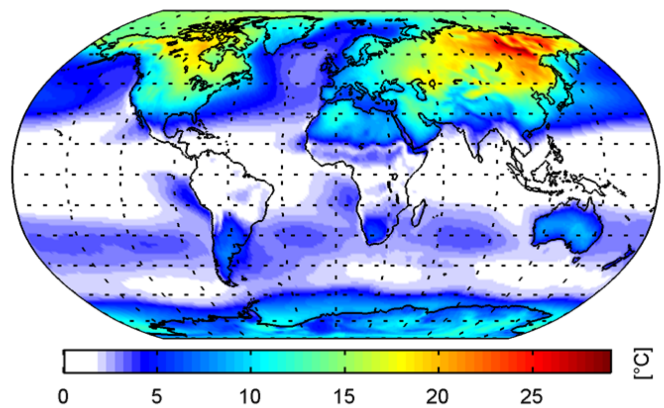

Figure 3: Amplitudes of annual temperature variations in ^{o}C as provided with GPT2

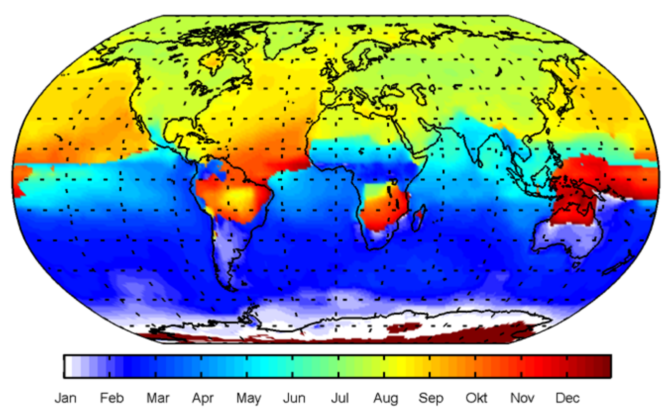

Figure 4: Month of maximum of the annual temperature variation in GPT2

In Figures 7, 8, and 9, we show zenith hydrostatic delays, hydrostatic mapping functions, and wet mapping functions at station Tsukuba in Japan from 2010.0 to 2012.0. In particular we show the values from GPT/GMF, GPT2, and from the Vienna Mapping Functions 1. Together with the mapping function coefficients of the VMF1, also zenith hydrostatic and wet delays are provided which are determined from ray-tracing through pressure level data of the European Centre for Medium-

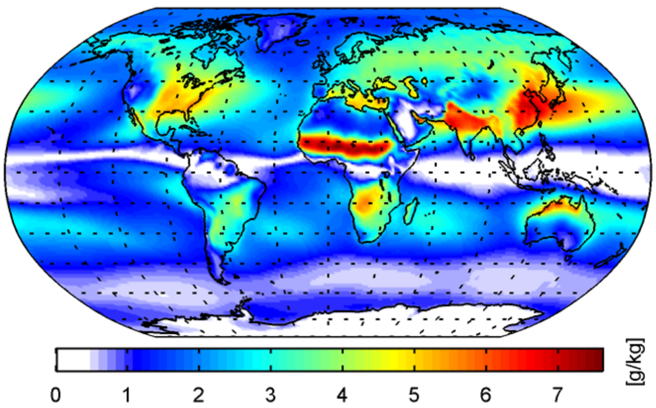

Figure 5: Amplitudes of annual specific humidity variations in g/kg as provided with GPT2

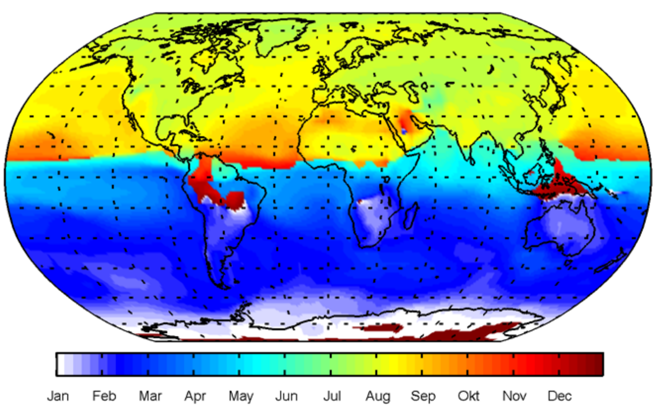

Figure 6: Month of maximum of the annual specific humidity variation in GPT2

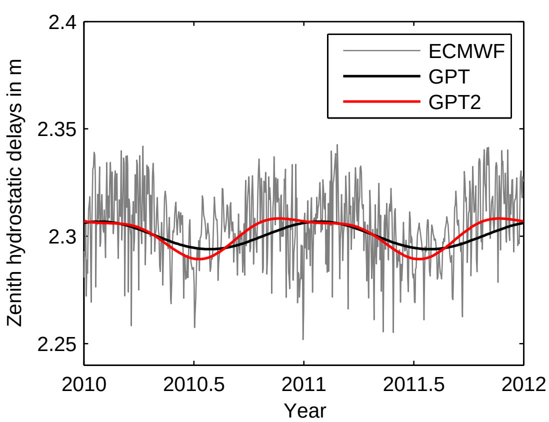

Figure 7: Zenith hydrostatic delays at Tsukuba, Japan

Range Weather Forecasts (ECMWF). We find a good agreement of all three models. We can also note that the additional semiannual term and the flexible phase of the annual variation support an even better agreement of GPT2 with VMF1. Of course – as GPT/GMF and GPT2 are blind models – they cannot account for the daily and weekly variations as available with the VMF1.

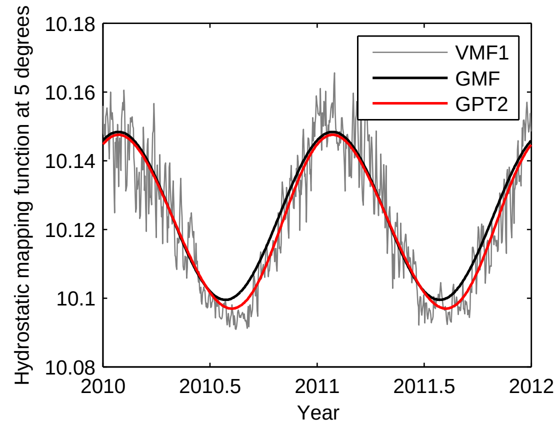

Figure 8: Hydrostatic mapping functions at Tsukuba, Japan at 5 degrees elevation

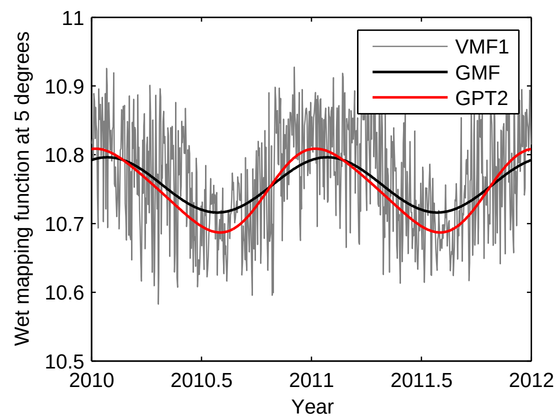

Figure 9: Wet mapping functions at Tsukuba, Japan at 5 degrees elevation

III. Application in VLBI analysis

We ran three global VLBI solutions with all observations from 1984.0 to 2012.5 using the Vienna VLBI Software (VieVS; Böhm et al., 2012 [4]). We applied VMF1 with pressure values recorded at the sites, GPT/GMF, and GPT2 for the three solutions. We followed the IERS Conventions 2010 (Petit and Luzum, 2010 [8]), apart from the fact that we also applied non-tidal atmospheric loading corrections as provided by the NASA Goddard Group (Petrov and Boy, 2004 [9]). This procedure is important for studies of tropospheric delay models, because otherwise there would be a destructive effect between zenith hydrostatic delays and atmospheric loading (Tregoning and Herring, 2006 [13]). We determined the annual and semiannual station height differences of the solutions with GPT/GMF and GPT2 with respect to the solution with VMF1 and local pressure values. We found an average improvement of 40% for the annual and the semiannual height differences (see Figure 10) with GPT2 compared to GPT/GMF.

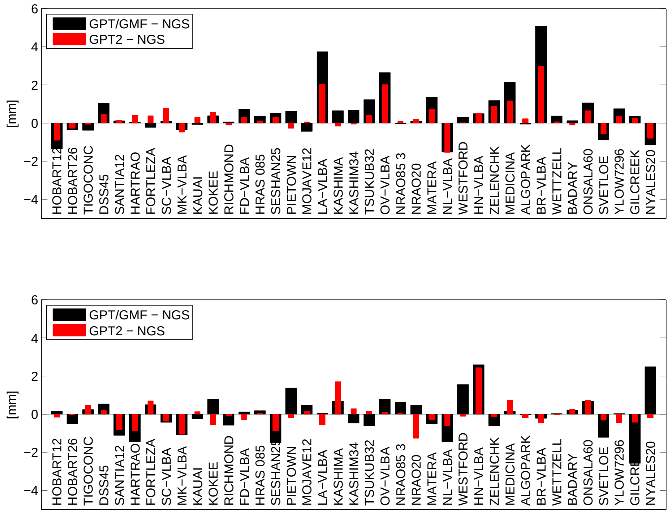

Figure 10: Difference in annual (upper plots) and semiannual (lower plot) height amplitudes at stations included in more than 50 sessions with GPT2 and GPT/GMF compared to VMF1 and pressure values recorded at the sites ("NGS")

IV. Outlook

We plan to equip GPT2 with an improved capability for calculating zenith wet delays. In its present version, GPT2 only provides pressure, temperature, temperature lapse rate, and water vapor pressure values, so that we could use the model by Saastamoinen (1972 [10]) (see Equation 2) to determine zenith wet delays. In Equation 2 the zenith wet delay ΔL_w^z is in meters, the water vapor pressure e in hPa, and the temperature T in Kelvin. Figure 11 shows the zenith wet delays at station Tsukuba as determined from GPT2 and as derived from ray-tracing through pressure level data from the ECMWF.

$$\Delta L_w^z = 0.002277 \cdot ((1255/T + 0.05) \cdot e) \tag{2}$$

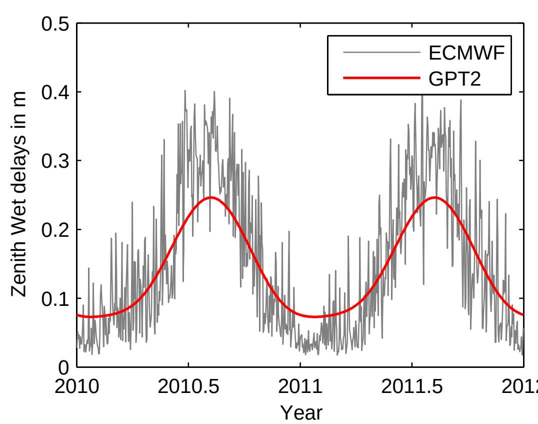

Figure 11: Zenith wet delay at Tsukuba, Japan

In future, water vapor lapse rate and mean temperature should also be added as output parameters, because then more sophisticated models could be applied for the zenith wet delays (see Krüger et al., 2004 [6]). For the sake of improved zenith wet delays, we probably have to use a higher grid resolution than 5 degrees.

Acknowledgment

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