The impact of tropospheric mapping functions based on numerical weather models on the determination of geodetic parameters

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Abstract. Since troposphere modeling is one of the major error sources in the analysis of Global Positioning System (GPS) and Very Long Baseline Interferometry (VLBI) observations, mapping functions have been developed in the last years which are based on data from numerical weather models. Boehm and Schuh (2004) show that the application of the Vienna Mapping Functions (VMF) instead of the Niell Mapping Functions (NMF) in VLBI analysis improves the repeatability of baseline lengths and significantly changes the terrestrial reference frame. This paper presents the first results with the VMF implemented in a GPS software package (GAMIT/GLOBK). The analysis of a global GPS network from April 2004 until March 2005 with VMF and NMF shows that station heights can change by more than 10 mm, in particular from December to January in the Antarctic, Japan, the northern part of Europe and the western part of Canada, and Alaska. The application of the VMF (instead of NMF) also improves the precision of the geodetic results and reveals seasonal signals in the station height time series more clearly.

Keywords: troposphere modeling, GPS, numerical weather model

1 Introduction

One of the major error sources in the analyses of Global Positioning System (GPS) and Very Long Baseline Interferometry (VLBI) observations is modelling path delays in the neutral atmosphere of microwave signals emitted by satellites or radio sources. The common concept of troposphere modelling is based on the separation of the path delay, ΔL, into a hydrostatic and a wet part (Davis et al. 1985).

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

In Equation 1, the total delays $\Delta L(e)$ at an elevation angle e are made up of a hydrostatic (index h) and a wet (index w) part, and each of these terms is the product of the zenith delay ($\Delta L_h{}^z$ or $\Delta L_w{}^z$) and the corresponding mapping function mf_h or mf_w. These mapping functions, which are independent of the azimuth of the observation, have been determined for the hydrostatic and the wet part separately by fitting the coefficients a, b, and c of a continued fraction form (Marini 1972) to standard atmospheres (e.g., Chao 1974), to radiosonde data (Niell 1996), or recently to numerical weather models (NWMs) (Niell 2000, Boehm and Schuh 2004). Whereas the hydrostatic zenith delays $\Delta L_h{}^z$, which can be determined from the total pressure p in hPa and the station coordinates at a site (Saastamoinen 1973), and the hydrostatic and wet mapping functions are assumed to be known exactly, the wet zenith delays $\Delta L_w{}^z$ are estimated within the least-squares adjustment of the GPS or VLBI observations.

The Vienna Mapping Functions (VMF), as introduced by Boehm and Schuh (2004), are based on exact raytracing through the NWMs at an initial elevation angle of 3.3°. It has been shown for VLBI analyses (Boehm et al. 2005) that VMF yields significantly better results in terms of baseline length repeatabilities than the Niell Mapping Functions (NMF) (Niell 1996) (which uses an empirical function dependent on only the day of year and station latitude and height) and that its application will influence the terrestrial reference frame (TRF). The investigations presented here show the first GPS results with the Vienna Mapping

Functions implemented in a GPS software package (GAMIT/GLOBK) (King and Bock, 2005).

Several investigations (e.g., Boehm et al. 2005) have shown that there is no significant station height change resulting from differences between the VMF and NMF wet mapping functions. In contrast, there are significant differences between the hydrostatic mapping functions at low elevations which cause apparent station height changes. There exists a "rule of thumb" to estimate the approximate height change from a difference in the hydrostatic mapping function (Niell et al. 2001): “*The change of the station height is approximately one third of the tropospheric delay difference at the lowest elevation included in the analysis. (Station heights increase with increasing mapping functions.)*” This rule of thumb shall be illustrated by one example: Figures 1 and 2 show the hydrostatic delays at 7° elevation calculated using the NMF and VMF for station Casey, Antarctica, and the corresponding station heights obtained from GPS analysis, respectively. In January, when the difference between VMF and NMF is at a maximum (45 mm), differences of the station heights are also at a maximum (15 mm).

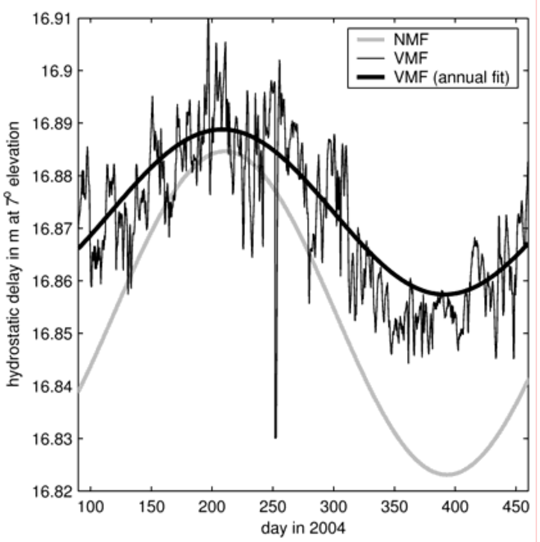

Fig. 1. Hydrostatic delays at 7° elevation determined with NMF and VMF at station CAS1 (Casey), Antarctica. The annual variation is plotted for the VMF to illustrate its seasonal behaviour. There is good agreement between the mapping functions in July and August, but the disagreement reaches ~ 45 mm at 7° elevation in the Antarctic summer (from December through to February).

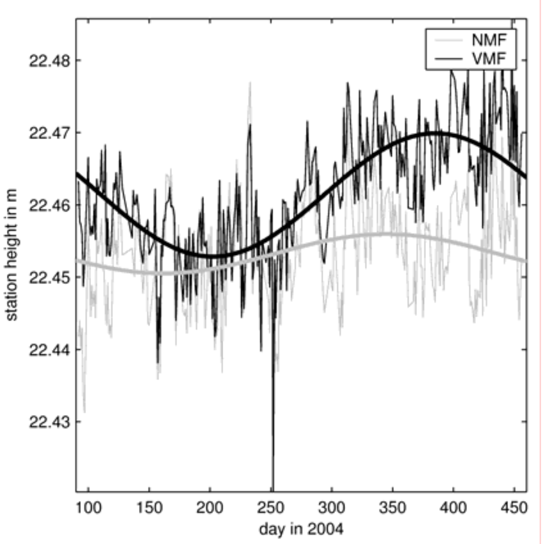

Fig. 2: Station heights of CAS1 determined from GPS with NMF or VMF with an elevation cutoff angle of 7°. The annual variation is plotted for both time series. The differences of the hydrostatic delays (Figure 1) are mirrored in the station height differences. The station height difference in January 2005 is about 15 mm, which is approximately one third of the hydrostatic delay difference at 7° elevation. The amplitude of the annual variation becomes significantly larger when using VMF instead of NMF.

2 Simulation studies

Based on monthly mean values from 40 years Re-Analysis data (ERA40) provided by the European Centre for Medium-Range Weather Forecasts (ECMWF) in 2001, differences between the two hydrostatic mapping functions, NMF and VMF, have been determined on a global grid (30° in longitude by 15° in latitude) for an elevation angle of 7°. Multiplied by the hydrostatic zenith delay which is taken from the ERA40 data, the hydrostatic delay differences at 7° can be applied to assess the apparent station height changes when using VMF instead of NMF with the rule of thumb mentioned above. Figure 3a shows these simulated station height changes (VMF minus NMF) for January 2001 (0 UT) with large positive values for stations south of -45° latitude and also for those in Japan and north-eastern China. On the other hand, the changes are negative over the northern part of Europe, the western part of Canada, and Alaska. In contrast, there are hardly any differences in June through August (Figure 3b), indicating that there is a much better agreement between NMF and VMF at that time. Since there is a clear annual signal in the

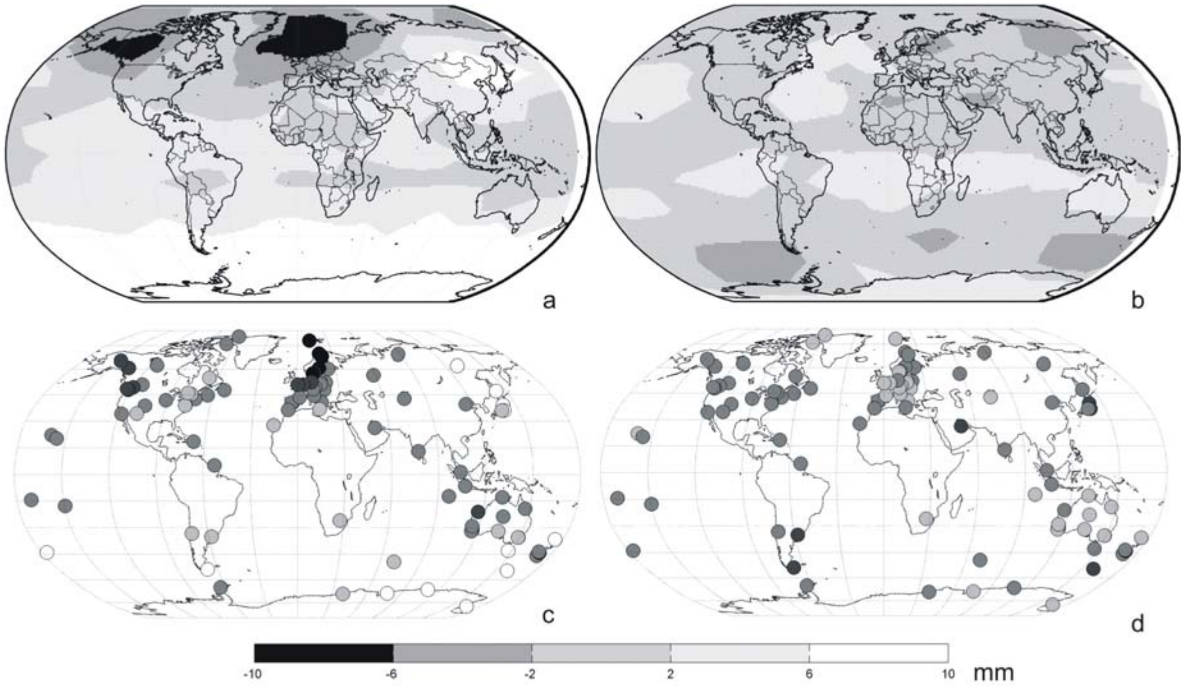

Fig. 3a. GPS station height changes (in mm) simulated from ERA40 data for January 2001 when using VMF instead of NMF. From these simulations, large positive station height changes (~10 mm) can be expected for Antarctica and around Japan and negative height changes can be expected for the northern part of Europe, the western part of Canada, and Alaska. **Fig. 3b**. GPS station height changes (in mm) simulated from ERA40 data for July 2001 when using VMF instead of NMF. In July 2001, there are only relatively small height changes which can be expected in other years, too. **Fig. 3c**. Station height differences from GPS analysis using either NMF or VMF for January 2005. It is evident that these analysis data confirm the simulations from ERA40 data for January 2001 (Figure 3a), i.e. positive station height changes can be found in the southern hemisphere and around Japan, and negative station height changes occur at stations in northern Europe, the western part of Canada, and Alaska. **Fig. 3d**. Station height differences from GPS analysis using either NMF or VMF for July 2005. Clearly, these analyses confirm the simulations from ERA40 data for July 2001 (Figure 3b), i.e. the estimated station height changes are moderate compared to January (see Figure 3c). Nevertheless, even the two lows at high southern latitudes are revealed by the GPS analysis.

differences of the mapping functions, it can be expected that the apparent station height changes for 2001 would be very similar in other years. In other words, Figures 3a and 3b show the errors that have been introduced into the estimates of GPS or VLBI station heights that have been obtained previously when using the NMF based on a common assumption for the global weather.

3 Vienna Mapping Functions in GAMIT/GLOBK

A global network of more than 100 GPS stations was analysed with the software package GAMIT/GLOBK (King and Bock, 2005) applying both the NMF and VMF mapping functions. By taking observations from April 2004 until March 2005 a full year of daily estimates for the station coordinates was available. In the GPS analysis presented here the elevation cutoff angle was set to 7° and no downweighting of low observations was applied. Atmosphere loading (tidal and non-tidal) (Tregoning and van Dam, 2005) was applied as well as other effects described in the IERS Conventions (2003). For the investigations described below the time series of estimated station heights at 97 sites were used, being sites with more than 300 daily height estimates. The site distribution is shown in Figure 3c.

Amplitudes and phases of annual periodic signals were estimated by least-squares for all station height time series from NMF and VMF (see Figure 2). Then these sinusoidal functions were used to calculate the station height differences on 1 January 2005 and 1 July 2004, respectively (Figures 3c and 3d). A comparison of the estimated height differences from GPS with those predicted from the NWMs shows a very high correlation (cf. Figures 3a/3c and Figures 3b/3d). This confirms that the NMF has temporal deficiencies, with a maximum around January, especially at high southern latitudes, for Japan, the northern part of Europe, the western part of Canada, and Alaska.

Figure 4 shows the amplitudes and phases for all 97 GPS stations. Generally, there is no significant reduction of the amplitudes when using VMF instead of NMF. Moreover, at particular stations (e.g. CAS1 in the Antarctica, compare Figure 2), VMF clearly increases the amplitudes of the seasonal signals. Analysing all 97 stations, there is a larger amplitude at 56 stations when using VMF compared to NMF (by 0.5 mm ± 1.9 mm) whereas only at 41 stations do the amplitudes of the annual variations get smaller. At first sight, this result is surprising since we would expect to remove apparent seasonal signals with improved mapping functions. The standard deviation of the station heights with respect to the sinusoidal functions clearly decreases for almost all stations using the VMF compared to NMF (Figure 5). This suggests that VMF reveals existing seasonal signals more clearly which either stem from other deficiencies of the GPS analysis (e.g. multipath or phase center variations) or are of geophysical origin (e.g. mismodeling of loading effects). The agreement between the amplitudes and phases when changing from NMF to VMF is good; however, at some stations, especially in the southern hemisphere and in northern Europe, large discrepancies occur. This may be due to the short time series that has been used in this analysis (only one year). If significant, these changes in amplitudes of annual signals might influence the determination of normal modes of the Earth according to Blewitt (2003).

The standard deviation of the daily station heights with regard to the annual signal is smaller for 82 of the 97 stations (see Figure 5), and the average relative improvement is about 6%. Thus, using the VMF not only changes the terrestrial reference frame but it also improves considerably the precision of the GPS analysis.

The progression from the old NMF to the new mapping functions based on NWMs influences the terrestrial reference frame by changing the heights of some stations - in particular, in Japan and in some regions of the northern hemisphere (Figure 6). Thus, there will be a distortion of the whole frame and rather likely a general shift along the z-axis. As radio-wave techniques play an important role in the realization of the International Terrestrial Reference Frame (ITRF), a significant influence on the next ITRF can be expected if weather-based mapping functions are used in the analysis of the GPS and VLBI observations.

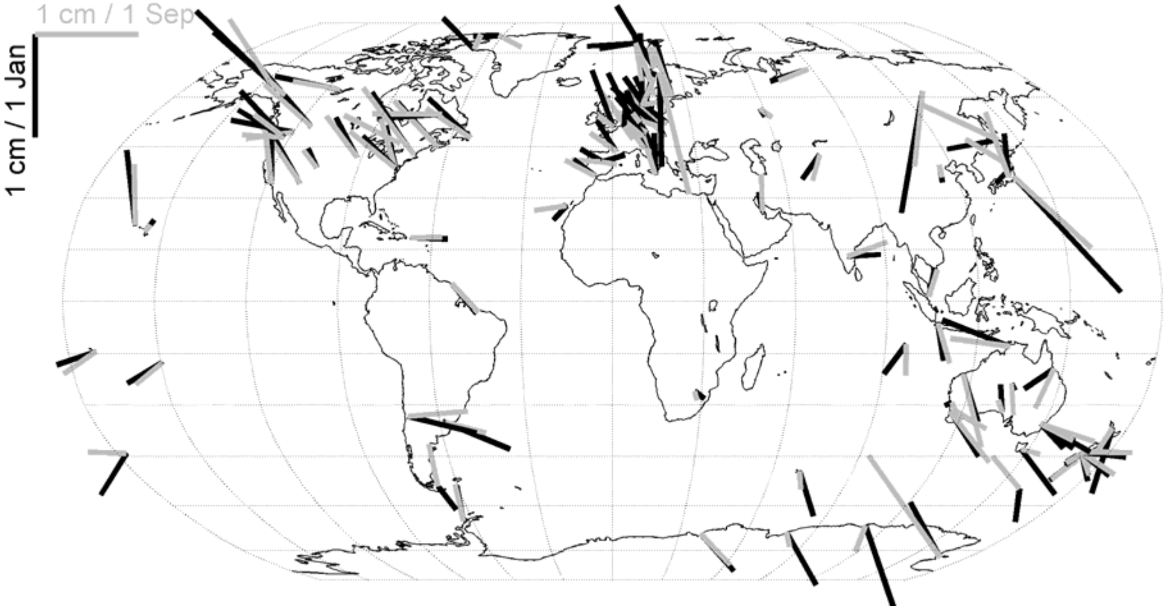

Fig. 4. Amplitudes and phases of annual variation in the station height time series determined from GPS analyses using NMF or VMF. The grey bars correspond to NMF, the black bars to VMF.

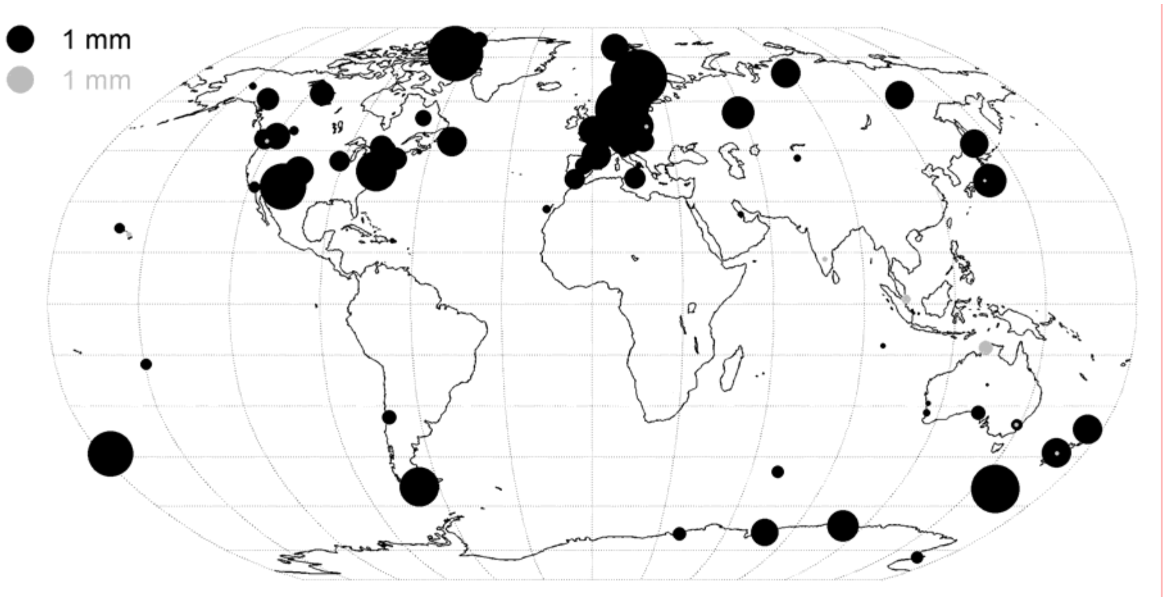

Fig. 5. Difference of standard deviations of the station height time series after removing the annual signal. A clear improvement of the residual station heights is evident when using VMF instead of NMF. Black circles indicate improvement with VMF, grey circles with NMF. The radius of the circles corresponds to the magnitude of the change.

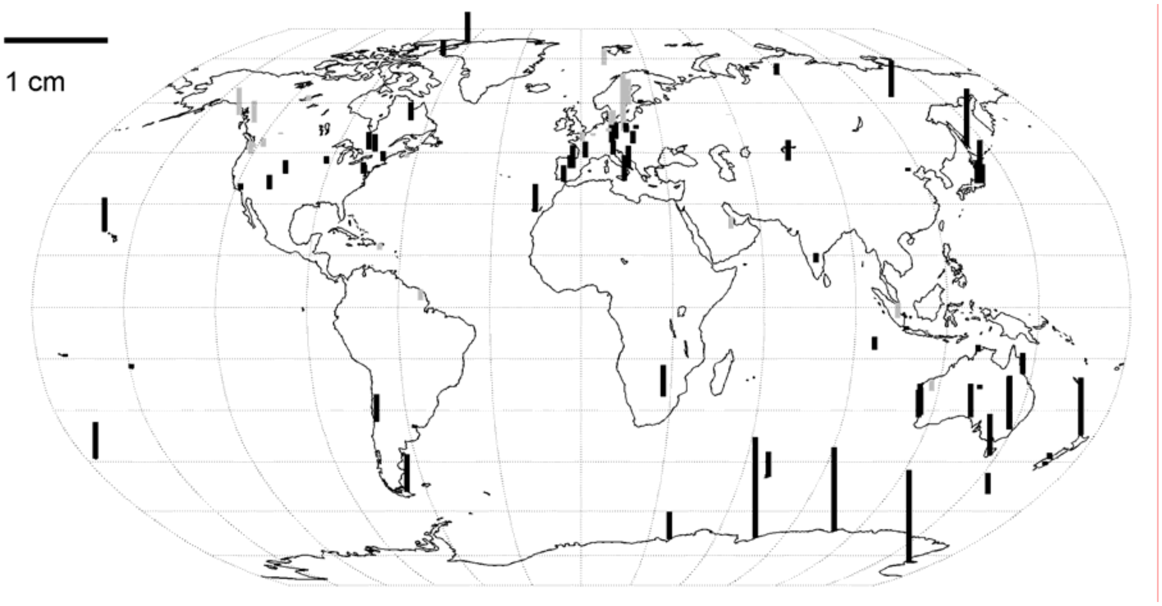

Fig. 6. Station height changes when using VMF instead of NMF. Black lines indicate increases of station heights, grey lines indicate decrease.

4 Conclusions

For the first time, the Vienna Mapping Functions (VMF) based on data from a numerical weather model have been applied in global GPS analysis. Significant improvements in the precision of geodetic results are found compared to using the Niell Mapping Function (NMF) based on a very general assumption about the global weather. After removing an annual signal, the standard deviation of the residual station heights decreases for more than 80% of the stations, and the average relative improvement is about 6% compared to NMF with values as high as 20% at some stations. Thus, the VMF helps to reveal signals which either stem from other deficiencies of the GPS analysis (e.g. multipath, phase center variations, mismodelled tidal signals) or are of geophysical origin (e.g. mismodeling loading effects). Furthermore, the application of the Vienna Mapping Functions will change the terrestrial reference frame by changing station heights. The maximum station height differences when changing from the NMF to VMF occur in January, especially in Antarctica (Casey: +15 mm), Japan, the northern part of Europe (Tromsoe -8.8 mm), the western part of Canada, and Alaska.

The results presented here are derived from analyses where no elevation-dependent weighting of the observations has been performed. Very similar results are obtained when such weighting is used, although the influence of the more accurate tropospheric mapping functions is reduced.

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