Mapping functions for atmospheric delay modelling in GNSS analysis

J. Boehm[1], A.E. Niell[2], H. Schuh[1], V. Tesmer[3], and P. Tregoning[4]

Abstract

Comparisons with radiosonde data and the application in GPS and VLBI analyses show that the Vienna Mapping Function 1 (VMF1) is currently the most accurate mapping function that is available globally for the whole history of VLBI and GNSS observations. VMF1, as derived from data of the European Centre for Medium-Range Weather Forecasts (ECMWF), is provided with a time resolution of six hours for selected sites as well as on a global 2° by 2.5° grid (http://www.hg.tuwien.ac.at/~ecmwf1). Additionally, the Global Mapping Function (GMF) has been developed as an empirical, spherical harmonic model which is consistent with VMF1. GMF depends only on the station coordinates and the day of the year and thus can easily be implemented in existing software packages. Together, the mapping functions derived from numerical weather models are more accurate than the NMF and produce significant improvements in the analysis of GNSS data.

1 Introduction

In recent years, mapping functions for the neutral atmosphere delays have been developed which are based on data from numerical weather models. Unlike prior mapping functions, they use information about the vertical distribution of the refractivity and thus can assess the ‘thickness’ of the troposphere which is a measure for the value of the mapping functions (Niell, 1996).
Niell (2001) developed the Isobaric Mapping Function (IMF) whose hydrostatic part, IMFh, is based on the height of the 200 hPa pressure level and whose wet part, IMFw, is determined from a non-rigorous raytrace at 3° elevation. Boehm et al. (2006a) used the rigorous raytrace at 3° elevation for both components, i.e. hydrostatic and wet Vienna Mapping Function 1 (VMF1). IMF and VMF1 are available with the temporal resolution of the underlying numerical weather models, currently 6 hours.
Although these new mapping functions have been available for some years now, many analysts still use the Niell Mapping Function (NMF) (Niell, 1996) because it depends only on the station latitude, height and the day of the year and thus can be easily implemented. However, comparisons with the more recent mapping functions (IMF, VMF1) showed that NMF has not only deficiencies in the temporal behaviour, but also large static (systematic) deficiencies in certain areas; thus, the Global Mapping Function (GMF) was developed (Boehm et al., 2006b). Similar to NMF, GMF is an empirical mapping function that can be determined from station latitude, longitude and height and day of the year. GMF, which is based on spherical harmonics up to degree and order 9, has been developed with the goal to be more consistent with VMF1 (‘averaged VMF1’) than the empirical NMF. For example, Figure 1 shows all four mapping functions (NMF, IMF, VMF1, GMF) for station O’Higgins in the Antarctica during 2005.

[1] Vienna University of Technology, [2] MIT Haystack Observatory, [3] Deutsches Geodätisches Forschungsinstitut,
[4] Research School of Earth Sciences, The Australian National University

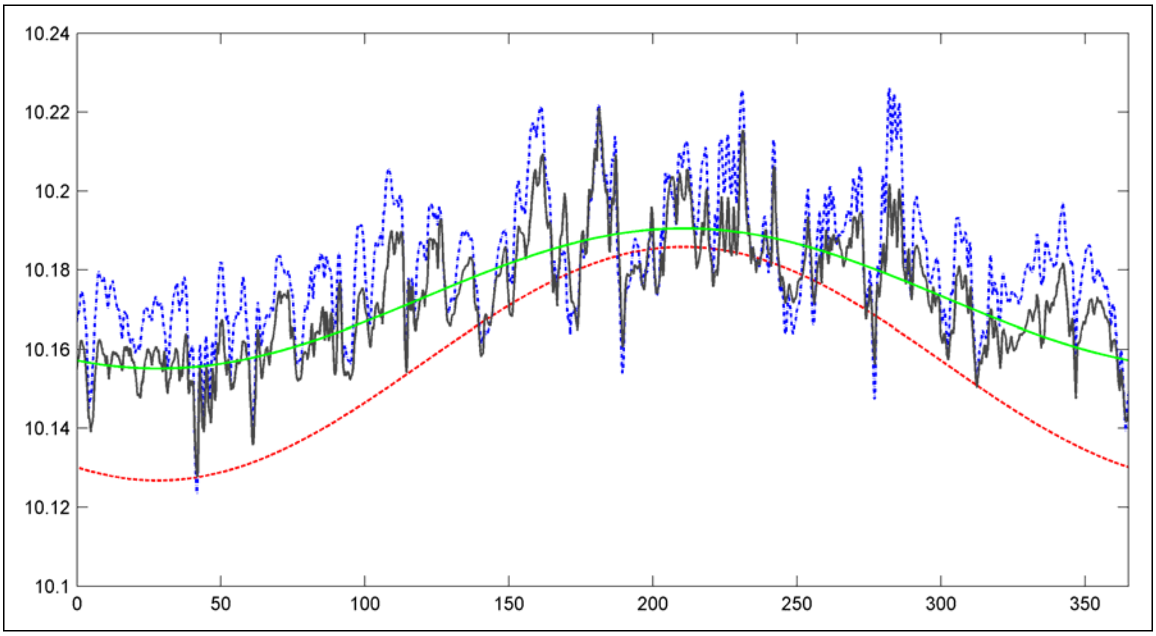

Figure 1. Hydrostatic mapping functions of NMF (red, dash-dash), IMF (blue, dash-dot), VMF1 (black, solid) and GMF (green, solid) at 5° elevation at station O'Higgins in the Antarctica during 2005. Especially around January, the NMFh is significantly smaller than the other mapping functions, which is the reason for lower station heights obtained with NMF at this station.

Niell (2006) compared mapping functions derived from radiosonde data in 1992 with the four mapping functions mentioned above. Figure 2 (taken from Niell (2006)) expresses the standard deviations of the differences of the hydrostatic (left plot) and wet (right plot) mapping functions in terms of station heights using a rule of thumb (see e.g. Boehm et al. (2006a)). The standard deviations for the hydrostatic mapping functions are increasing with increasing latitude, caused by the fact that the variability of the pressure fields is larger towards the poles. The standard deviations for the wet mapping functions are largest around the equator because the wet zenith delays are at a maximum in these regions. VMF1 performs best for the hydrostatic as well as for the wet mapping functions, and the standard deviation is about half the magnitude of that for IMF. GMF and NMF have larger standard deviations because they contain only a seasonal term and thus cannot reproduce the short-term variations sampled by VMF1 and IMF which have 6 hour temporal resolution. These figures show that the wet mapping functions are less critical than the hydrostatic mapping functions for the precision of geodetic results. Niell (2006) also shows that the error is reduced to about 60% at 7.5° elevation and to less than about 20% at 15° elevation.

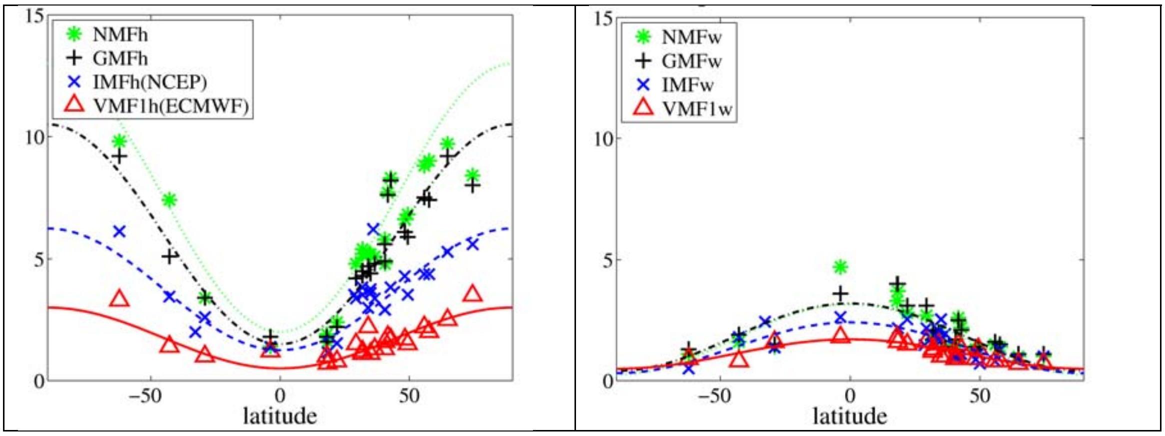

Figure 2 (from Niell (2006)). Standard deviation of station heights in mm from radiosonde comparisons in 1992 for the hydrostatic mapping functions (left plot) and the wet mapping functions (right plot). VMF1 has the smallest standard deviation, followed by IMF with a standard deviation that is about twice as large as that of VMF1. GMF is slightly better than NMF, but both empirical mapping functions cannot perform better since they contain only a seasonal term.

The influence of the new mapping functions on geodetic results has been described in previous publications, in particular by Boehm et al. (2006c) for one year of GPS analysis and by Tesmer et al. (2006) for a global VLBI re-analysis from 1984 to 2005. Readers are referred to these references for a description of the analysis strategy and results. The most important findings are summarized in Sections 2 and 3.

2 Mean station height changes

Changes in the mapping functions primarily cause changes of the station heights, and these changes can very well be predicted by a rule of thumb (Boehm et al, 2006a). Figures 3a and 3b show these predicted station height changes as determined on a global 15° by 15° grid as provided by the European Centre for Medium-Range Weather Forecasts (ECMWF). These plots illustrate that there are rather large station height changes of sometimes more than 1 cm when using VMF1 instead of NMF, but rather small changes between using VMF1 and GMF, which is a consequence of the fact that for this plot the same grid data were actually used for the derivation of both mapping functions.

The corresponding lower plots (Figure 3c and 3d) show the estimated station height changes determined from the analysis of one year of global GPS observations (Boehm et al., 2006c). The agreement between simulation and estimation is very good, thus allowing for a reliable assessment of NMF and GMF at regions where no GNSS data have been analysed. The good agreement is also confirmed with results determined from VLBI observations (Tesmer et al., 2006).

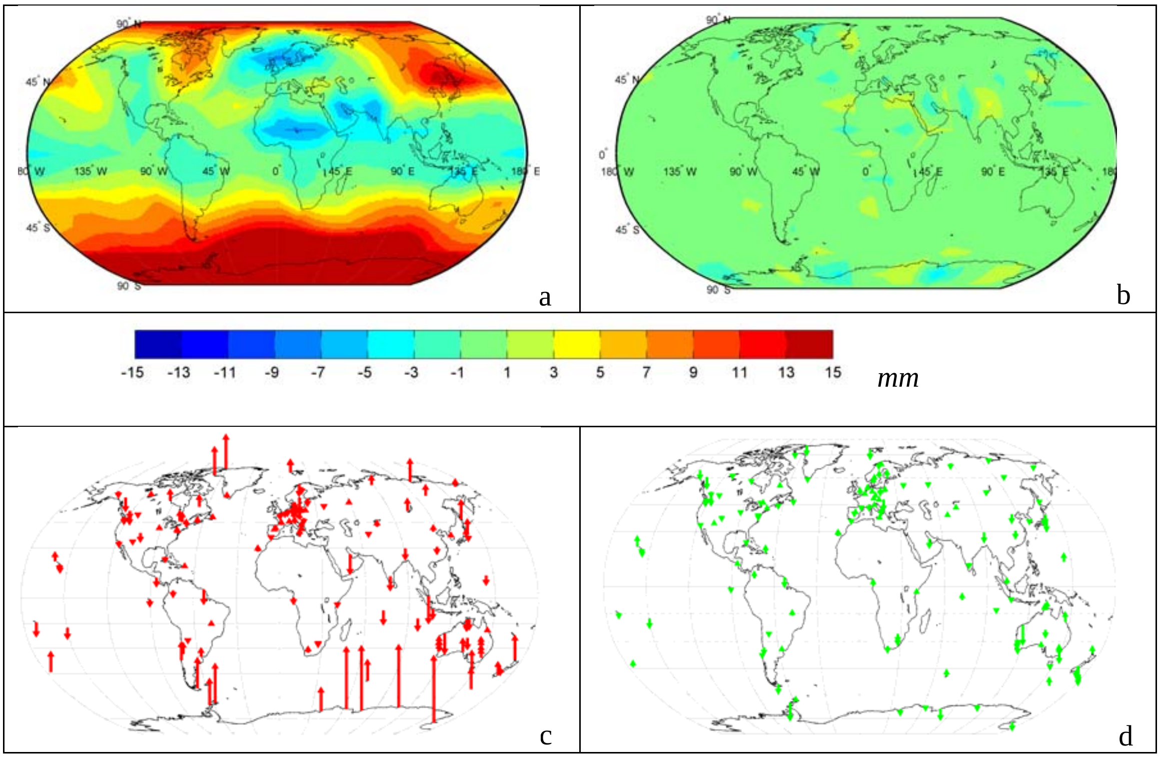

Figure 3. Predicted and estimated station height changes when using VMF1 instead of NMF or GMF. Figure 3a: Predicted station height changes when using VMF1h instead of NMFh. There are station height changes larger than 1 cm south of 45° S latitude, around Japan, and towards the North Pole. Figure 3c: These predicted station height changes are confirmed by estimated station height changes using one year of global GPS data. The maximum station height changes occur at the coast of the Antarctica with 1.3 cm. Figure 3b: Predicted station height changes when using VMF1 instead of GMF. The changes are close to zero all over the globe because this dataset of VMF1 was used to determine GMF. Figure 3d: Estimated station height changes when using VMF1 instead of GMF. The largest height change occurs for a site in Australia with 3 mm, but generally the height changes are at the 1 mm level or smaller and there are no biases between the results.

3 Repeatability of station coordinates

Tesmer et al. (2006) evaluated the effect of the new mapping functions on VLBI results by analysing global VLBI solutions from 1984 to 2005. For these investigations the cutoff elevation angle was set to 5° and no down-weighting of low observations was applied. Figure 4 shows the NMF/VMF1, GMF/VMF1 and IMF/VMF1 ratios for the weighted RMS of daily latitude, longitude, and height estimates after removing an annual signal. It is clear that VMF1 solutions have the best repeatabilities, especially for the height component (7% improvement compared to NMF).

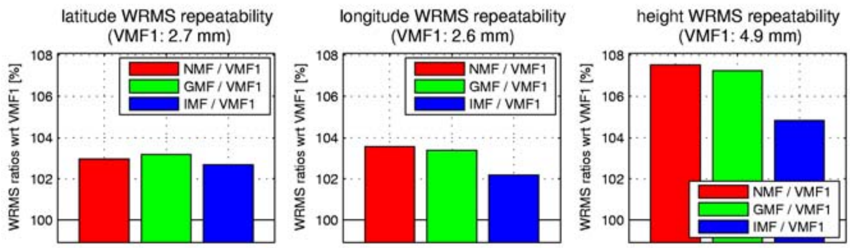

Figure 4 (from Tesmer et al. (2006)). Weighted RMS of VLBI station coordinates after removing the annual term for the latitude (left), longitude (middle), and height component (right). The repeatability with VMF1 is used as reference (horizontal line at 100%). The improvement in precision with VMF1 is about 3% for the horizontal components compared to NMF, GMF, and IMF, and about 7% and 5% for the height components.

Boehm et al. (2006c) determined the standard deviation of station heights for one year of global GPS data. For this dedicated analysis, the cutoff elevation angle was set to 7° and no down-weighting of low observations was applied. The standard deviation using VMF1 is smaller at 117 of the 133 stations with an average relative improvement of 6% compared to the analysis using NMF.

In GPS analyses, low elevation observations are usually down-weighted (if not eliminated) due to problems with multi-path and/or antenna phase centre variations. With such an approach the shortcomings of the older mapping functions will be mitigated but they will not disappear completely. Low elevation observations with precisely modelled atmospheric delays are important to de-correlate the tropospheric delay, station height, and clock parameters. For VLBI, Niell (2006) recommended using observations down to 5° elevation in combination with VMF1.

4 Availability of the VMF1

At the webpage http://www.hg.tuwien.ac.at/~ecmwf1 the coefficients of VMF1 are provided for selected GPS sites from 1 January 2005 as well as on global grids from 1 January 1994. At the selected sites (primarily the IGS stations) the highest resolution refractivity profiles are used (0.25°) from the ECMWF archives. However, a further extension of the list of stations is limited because the extraction of the profiles is very time-consuming. On the other hand, the coefficients of VMF1 are also provided on global 2.0° by 2.5° grids, allowing the determination of VMF1 for any site on the globe.

First comparisons between VMF1 for selected sites and the corresponding VMF1 interpolated from the grids indicate that the differences (expressed as standard deviations of stations heights using the rule of thumb as above) are about 0.5 mm and 1 mm for the hydrostatic and wet delays, respectively. The larger differences in the wet part are due to the higher variability (in space) of the wet part of the atmosphere. However, significant differences will only become visible in regions with small-scale structure of the wet atmosphere and a high number of meteorological sensors to capture these structures for the numerical weather model.

Together with the coefficients of VMF1, the hydrostatic zenith delays as derived from the numerical weather model are provided at the webpage given above, because the influence of the a priori hydrostatic zenith delays is critical for the precision as well as for the accuracy of geodetic results (Boehm et al., 2006a).

5 Recommendations

Comparisons with radiosonde data and the application in GPS and VLBI analysis have shown that VMF1 is currently the most accurate mapping function that is available globally for the whole history of VLBI and GPS observations. Furthermore, it is planned to use forecasting data to provide VMF1 in real time. Thus, it is recommended to use VMF1 for any global applications such as the determination of the terrestrial reference frame and Earth orientation parameters. Alternatively, it is recommended to use GMF, rather than NMF, which is consistent ('bias-free') with VMF1 and can be implemented in software packages easily.

Acknowledgements

J. Boehm and H. Schuh would like to thank the Zentralanstalt für Meteorologie und Geodynamik, Wien for providing access to the ECMWF data.

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