# Homogeneous Zenith Total Delay Parameter Estimation from European Permanent GNSS Sites

*Wolfgang Soehne, Bundesamt für Kartographie und Geodäsie, wolfgang.soehne@bkg.bund.de*
*Mariusz Figurski, Military University of Technology, mfigurski@wat.edu.pl*
*Karolina Szafranek, Military University of Technology, kszafranek@wat.edu.pl*

## Abstract

*Starting in 2001 the EUREF Permanent Network (EPN) Local Analysis Centres (LAC) are delivering Zenith Total Delay (ZTD) parameters which were combined at the BKG (Bundesamt fuer Kartographie und Geodaesie, Germany) combination facility. The results have been step-by-step improved, depending on several changes of the processing scheme, leading to an internal precision of 2-3 mm ZTD.*

*The availability of a set of homogeneously processed GPS satellite orbits, clocks and Earth Rotation Parameters (ERP) covering a period of more than a decade (the so-called Potsdam-Dresden reprocessing) motivated MUT (Military University of Technology, Poland) to the all-in-one processing of the EPN stations for the same period. The applied strategy thereby followed the guidelines for EPN processing.*

*While the improvement in coordinate estimation has been recently demonstrated, this paper investigates the quality of the ZTD parameters estimated together with the coordinates. Comparisons with the existing EUREF combined solution, with IGS solutions and with radiosonde data will be presented to evaluate the possible improvement in ZTD estimation by reprocessing activities.*

*Keywords: EUREF Permanent Network, GPS, troposphere, reprocessing, zenith total delay*

## 1. Introduction

Since June 2001 (GPS week 1108, [Soehne and Weber, 2002]) the EUREF Permanent Network Local Analysis Centres are delivering the estimated Zenith Total Delay parameters to the BKG data centre for combination, in daily files using the so-called SINEX TRO format [IGS, 1997]. Several changes have been introduced to the processing scheme of the contributing solutions (reference frame realization, software versions, processing options, etc.) as well as in the combination scheme (bias estimation, outlier detection, etc.). The results have been step by step improved, leading to an internal precision of 2-3 mm ZTD. In 2008, the EUREF Special Project “Troposphere Parameter Estimation” was closed and the ZTD processing and the combination moved towards routine operation.

The availability of a set of homogeneously processed GPS satellite orbits, clocks, and ERPs covering a period of more than a decade (the so-called Potsdam-Dresden reprocessing [Steigenberger et al., 2006]) in 2005 motivated MUT to the all-in-one processing of the EPN stations for the period 1996 to 2007. The applied strategy thereby followed the guidelines for EPN processing.

While the improvement in coordinate estimation has been shown recently [Kenyeres et al., 2008], this paper investigates the quality of the ZTD parameters estimated together with the coordinates. Comparisons with the existing EUREF combined solution, with IGS solutions and with non-GPS solutions (VLBI, radiosonde data) will be presented to demonstrate the possible improvement in ZTD estimation by reprocessing activities.

# 2. The MUT reprocessing

The main purpose of a reprocessing (i.e. repetition of a processing of GNSS data gathered by permanent stations during long period using the newest strategy, models, software and products) of a regional network as EPN is to obtain stable and homogenous coordinates time series. Since 1996, when EPN was set-up, analysis strategies, software packages, models etc. have been changed and improved causing some inhomogeneities in the solutions, especially coordinates time series. Nowadays, there exist more precise products, especially Earth Rotation Parameters and GPS satellite orbits which let us to reprocess regional networks. Reprocessing tests of the whole EPN were done simultaneously by two centres [Kenyeres et al., 2008]: Royal Observatory of Belgium (where global IGS stations were taken into consideration) and Military University of Technology from Poland (where new orbits from the so-called Potsdam-Dresden IGS reprocessing are used). The analysis of both tests should give conclusions for the planned official EPN reprocessing [Voelksen, 2009].

Daily and weekly coordinate time series were obtained from the EPN reprocessing. The estimation of the coordinates was improved as described in [Kenyeres et al., 2008]. The time series after the reprocessing were more stable and homogeneous; the number of discontinuities was decreased, as well as the weighted rms values: while for the EPN combined solution the weighted rms values decreased from 2 mm to 1 mm for the horizontal and from 6 mm to 3 mm for the up component over the time span 1996 to 2007, the values were almost stable on the 1 mm (2D) and 3 mm (up) level for the MUT reprocessed solution over the whole time span. The comparison of Helmert transformation parameters between each consecutive solution and the cumulative solution from EPN and MUT reprocessed solutions also showed significant improvement (e.g., no discontinuity at GPS week 1400, less drifts in the time series).

In addition to the coordinates, standard troposphere solutions are also outcome of this activity. This paper involves comparisons of different troposphere solutions with the estimated ZTD parameters obtained as a result of the EPN reprocessing test by MUT.

The MUT reprocessing covered the period 1996-2007 (GPS weeks 834-1459). The applied strategy was similar to the guidelines for EPN processing. The data were processed using Bernese GPS software version 5.0 [Beutler et al., 2007]. Absolute models of ground and satellite antenna phase center calibrations were implemented (for those stations on which they were available; otherwise receiver antenna corrections converted from relative antenna calibrations or copied from the same antenna type without radome were used).

Daily RINEX observation files containing less than 50% of possible observation epochs were ignored. To eliminate outliers the two-step pre-processing method was applied. Rejection criterion of L3 outliers was set up as 0.0020 m (normalized L1 zero-difference zenith value). Satellite clock corrections were not estimated, but biases were eliminated by forming double differences. Receiver clock corrections were estimated as a part of the biases pre-processing using code measurements and finally were eliminated, also by forming double differences. Method of ambiguity determination depended on the length of a baseline. For baselines up to 1300 km length the QIF (quasi ionosphere free) strategy in a baseline processing mode using CODE (The Centre for Orbit Determination in Europe) global ionosphere models was used. For baseline lengths shorter than 200 km the L5/L3 approach was employed and for baselines shorter than 20 km the L1/L2 approach [Beutler et al., 2007].

GPS satellite orbits and Earth Rotation Parameters were taken from the International GNSS Service (IGS) as a result of IGS network 'Potsdam-Dresden' reprocessing [Steigenberger et al., 2006].

For the final adjustment, ionosphere was cancelled out due to ionosphere free linear combination usage, but CODE global ionospheric models helped to increase the number of resolved ambiguities in the ambiguity resolution.

Troposphere parameters are a product of the reprocessing but troposphere model is also an input to GNSS processing. ZTD is divided into two components: dry (hydrostatic) part – Zenith Hydrostatic Delay (ZHD) and wet part – Zenith Wet Delay (ZWD). About 90% of tropospheric delay is connected with the dry part of the atmosphere and it is easy to be described by a model [Saastamoinen, 1973]. The wet part depends on the water vapor content in the atmosphere, so it is hard to model it. Troposphere delay $\Delta\rho$ is a function of zenith distance $z$:

$$\Delta\rho = m(z)\cdot ZTD \tag{1}$$

The mapping function *m(z)* enables the determination of the delay value for any direction. During the data processing Saastamoinen-based dry component mapped with the Dry-Niell mapping function was used as a priori model. The Wet-Niell mapping function was employed to map the wet component (without any a priori model). The estimation of zenith delay corrections was made at 1-hour intervals for each station. Horizontal gradient parameters were estimated for each station per day with no a priori constraints [Bar-Sever et al., 1998]. Daily SINEX TRO files were computed on a weekly basis, i.e., the weekly coordinate solutions estimated in the first step are used as input and are fixed – as it is done in the regular EPN processing.

# 3. Intra-technique comparison

A comparison of the MUT solution with existing GNSS ZTD solutions can give an impression of the improvement which can be achieved by a homogeneous processing. However, it has to be discussed within such an intra-technique comparison which solution could serve as a reference for the other one. Usually, the one with the higher precision (if quantities are known) is assumed as the reference. In the following sections, the differences are referred to the MUT solution (section 3.1), to the network solutions (section 3.2), and to the GNSS solutions (section 4).

## 3.1. Comparison with IGS and EPN combined solutions

Both within IGS as well as within EUREF, the analysis centres (ACs) are delivering troposphere solutions for a long time. The IGS was starting to combine ZTD solutions in 1997 (GPS week 0890) in the frame of the troposphere working group. Between 4 and 7 ACs were sending solutions with a time resolution of two hours. Some of the key characteristics of IGS were that the ACs are using different software packages and that most of the solutions cover large networks of 100+ stations. Therefore, most of the stations were analysed by at least three or more ACs. Since GPS week 1203 the EUREF combined solution was included in the IGS combination what is clearly visible in the right plot of Figure 1. With GPS week 1400 the troposphere combination of IGS was stopped and replaced by the station-wise solution, see section 3.2.

The EPN troposphere combination started in June 2001 (GPS week 1108) with four LACs. With the participation growing steadily, since GPS week 1185 all 16 EPN LACs are continuously contributing. In GPS week 1130, some analysis options were modified, e.g. change from 2 hours to 1 hour troposphere parameter resolution.

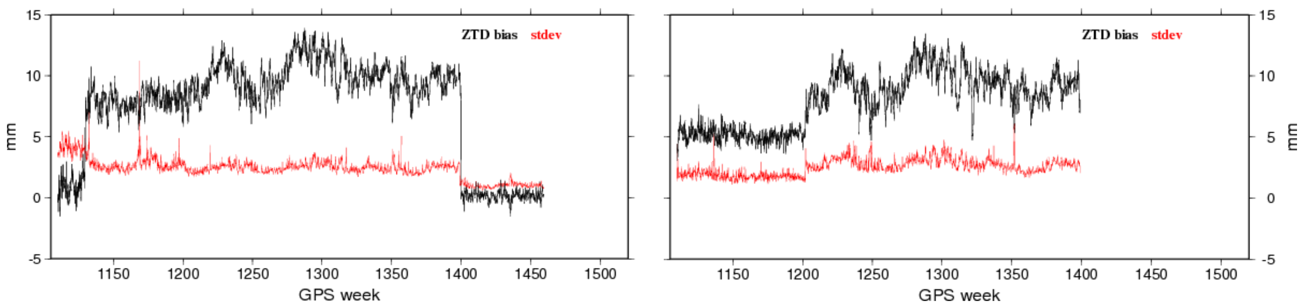


*Figure 1: Weekly mean ZTD bias and its standard deviation between MUT reprocessed solution and EPN combined solution (on the left) and IGS combined solution (on the right). Note that a) IGS combination stopped with GPS week 1399 and b) EPN combined solution contributed to IGS combination since GPS week 1203.*

## 3.2. Comparison with IGS PPP solution

Beside the troposphere combination product based on network solutions (section 3.1) a station-wise troposphere solution has been established in the IGS. It is computed by JPL (Jet Propulsion Laboratory) using the precise point positioning (PPP) approach [Zumberge et al., 1997]. The ZTD resolution is five minutes for each station. It could be expected that such a solution had a considerable higher noise level than a solution with a mean value over one hour as it comes from a network solution. This is exemplarily shown in figure 2 for the EPN stations Borowiec (BOR1) in Poland and San Fernando (SFER) in Spain. The MUT reprocessed solution is compared to the EPN combined solution (EUR) and to the IGS PPP solution (JPL), respectively. Again, concerning the EUREF solution the jump in GPS week 1400 can be seen clearly. Moreover, the scattering between MUT and EUR solution is significantly reduced below 2 mm ZTD. This gives the level of precision which could be expected by a homogeneous reprocessing of the whole network.

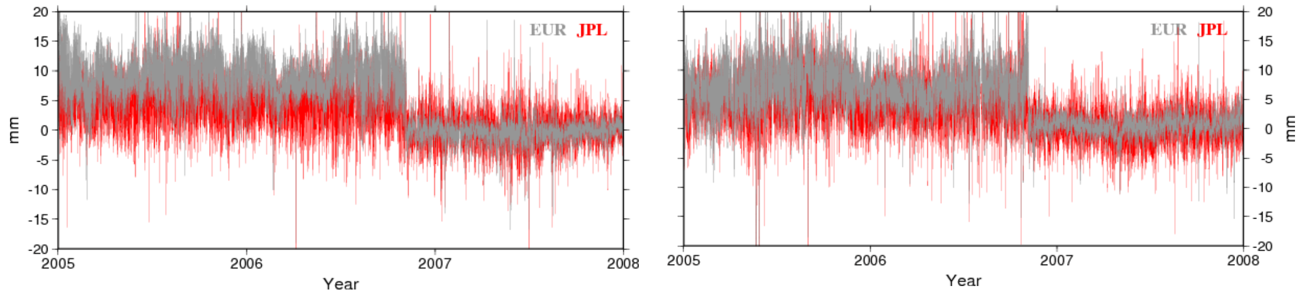


*Figure 2: ZTD differences between MUT solution and EPN combined solution (in gray) and IGS PPP solution (in red) for the stations BOR1 (left) and SFER (right).*

# 4. Inter-technique comparison

Beside the possibility to check the reprocessed GNSS results with other existing GNSS solutions it is interesting to compare the GNSS results with results derived from other techniques. We carried out two comparisons, one with another geodetic technique as VLBI (Very Long Baseline Interferometry) and the other one with a non-geodetic but meteorological data.

## 4.1. Comparison with IVS combined solution

Like GNSS, it is possible to estimate the ZTD using VLBI. One advantage of this technique is the relatively long time series of more than 25 years which are available meanwhile. Repeated reprocessing covering the complete time span, e.g. to introduce new mapping functions like Vienna Mapping Function (VMF, [Boehm and Schuh, 2004]) or Global Mapping Function (GMF, [Boehm et al., 2006]), seems to be possible within a relatively short time. One disadvantage is the sparse network of about 30 stations worldwide. Moreover, the temporal coverage is not optimal since the processing of observation is organized in 24 hour sessions, not continuous as in IGS or EUREF. The VLBI community is organized in the International VLBI Service (IVS). Setting up a pilot project “Tropospheric Parameters” in April 2002, IVS is producing a combined ZTD solution starting with GPS week 1147, similar to the GNSS combination within the IGS [Heinkelmann, 2008]. Eight ACs are contributing to this product which has a time resolution of one hour.

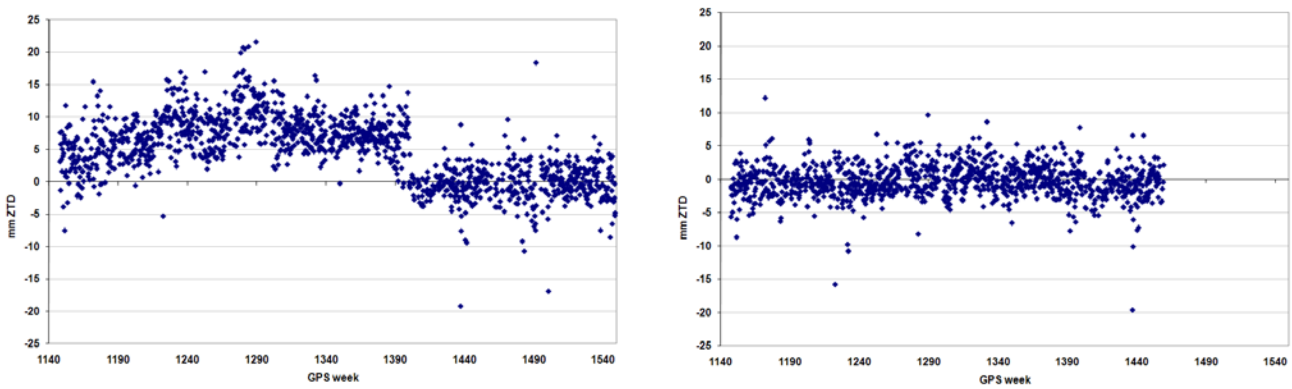


*Figure 3: Daily ZTD biases between IVS combined solution and EPN combined solution (left) as well as MUT solution (right) for site Wettzell.*

Before the comparison of VLBI and GNSS ZTD solutions is carried out, differences in time and height have to be accounted for. The IVS combined solution has a time stamp to the full hour (minute ‘00’). The IGS combined solution has also a time stamp to the full hour but covers two hours of resolution. Finally, the EUREF combined solution covers one hour but with a time mark to the half hour (minute '30'). If necessary, an interpolation was carried out to fit the IVS time stamp. As described in [Heinkelmann, 2008], these different intervals could lead to a higher standard deviation of the difference in the comparison as within the solutions themselves. The height difference between the GNSS and VLBI reference points leads to an additional (artificial) difference in ZTD. In this paper, this is accounted for following the rule of thumb [Saastamoinen, 1973], [Schmid et al., 2005]:

$$\Delta ZTD \approx \kappa * \Delta H \qquad (2)$$

with $\kappa \cong -0.3$ mm difference in ZTD per 1 m height difference. Figure 3 shows the difference between the IVS combination and the EPN combined solution on the left and the MUT reprocessing on the right. Site Wettzell was used because it has the most contributions to the IVS combined product. Before GPS week 1400 there was a significant bias between EPN and IVS solution. From the reprocessing it can now be concluded that this bias came from the GPS part and it was mainly due to the ground antenna relative phase center values used so far. After GPS week 1400 there is almost no visible bias. Table 1 summarizes the differences for the six co-located stations which are part of EPN. For reason of comparison, also the MUT reprocessing is divided in two sections. It can be seen that the results, mean difference and its standard deviation, after GPS week 1400 are in a good agreement between current combination and reprocessing.

*Table 1: Mean biases and standard deviations of the differences between the GPS-based and VLBI-based ZTD for European co-located stations. Because of the important changes with GPS week 1400 two sections before and after the change are considered. Before GPS week 1400, the GPS-based ZTD are wetter than the VLBI results. After GPS week 1400, the results are very similar although the solutions with respect to MUT have slightly smaller standard deviation. Note that the difference in height between both sensors is accounted for following (2). '#' gives the number of samples used for the comparison.*

| | EUR minus IVS | | | | | | MUT minus IVS | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1147-1399 | | | 1400-1548 | | | 1147-1399 | | | 1400-1459 | | |
| SITE | Mean (mm) | Stdev. (mm) | # | Mean (mm) | Stdev. (mm) | # | Mean (mm) | Stdev. (mm) | # | Mean (mm) | Stdev. (mm) | # |
| Matera | 6.3 | 6.1 | 331 | -2.5 | 3.8 | 209 | -1.3 | 3.5 | 331 | -2.9 | 3.3 | 82 |
| Medicina | 9.1 | 3.8 | 77 | -4.3 | 3.2 | 72 | -2.1 | 2.2 | 78 | -4.3 | 3.1 | 21 |
| Ny Alesund | 5.6 | 2.6 | 463 | 0.2 | 3.2 | 257 | -0.5 | 2.5 | 470 | 0.2 | 2.3 | 108 |
| Onsala | 4.4 | 3.0 | 80 | -1.8 | 1.8 | 33 | -2.2 | 2.5 | 80 | -1.3 | 1.7 | 7 |
| Svetloe | 6.5 | 6.0 | 2 | -1.5 | 3.2 | 100 | 0.4 | 5.9 | 4 | n/a | n/a | 0 |
| Wettzell | 6.5 | 3.6 | 902 | -1.2 | 3.0 | 475 | -1.0 | 2.5 | 903 | -1.9 | 2.7 | 185 |

## 4.2. Comparison with radiosonde data

Radiosondes are a powerful instrumentation to register various meteorological parameters. The tropospheric delay cannot be measured directly, but it can be computed. In Europe, the density of radiosonde launch sites is comparable to the EPN. Thanks to the EUREF-EUMETNET Memorandum of Understanding [Vedel, 2007] the download of radiosonde data is provided on a regular basis. Moreover, a program for ZTD computation from radiosonde observations is also provided [Haase et al., 2003]. [Pottiaux et al., 2008] give a detailed description on the procedure. One disadvantage of radiosondes is the poor temporal resolution with in general two launches per day. Concerning the comparison with GPS, the geographical distance between the two stations has to be taken into consideration.

Figure 4 shows the ZTD difference between the two GPS solutions for the twin stations in Borowa Gora, Poland, and results of radiosonde number 12374 (Legionowo) which is located approximately 9 km in south-west direction. The EPN stations BOGI and BOGO are processed by a different subset of LACs. BOGI is processed by OLG, SUT, and WUT, BOGO by COE, GOP, and WUT (see http://www.epncb.oma.be → Data & Products → Products → Analysis Centres for details about the individual LACs). The height difference between both stations (BOGI minus BOGO) is about minus 10 m. Whereas this height difference is clearly reflected in the ZTD differences for the EPN combination before GPS week 1400 (left plots) it diminished afterwards. Finally, a higher scattering of the differences during summer is visible. It points to the higher variability of the atmosphere during summer. Due to the spatial difference between the sensors the higher variability reflects in the differences of the ZTD values.

Comparisons of the EPN ZTD combined solution and radiosonde results on a regular basis can be found on the EPN webpage, http://www.epncb.oma.be → Data & Products → Products → Site Zenith Path Delays.

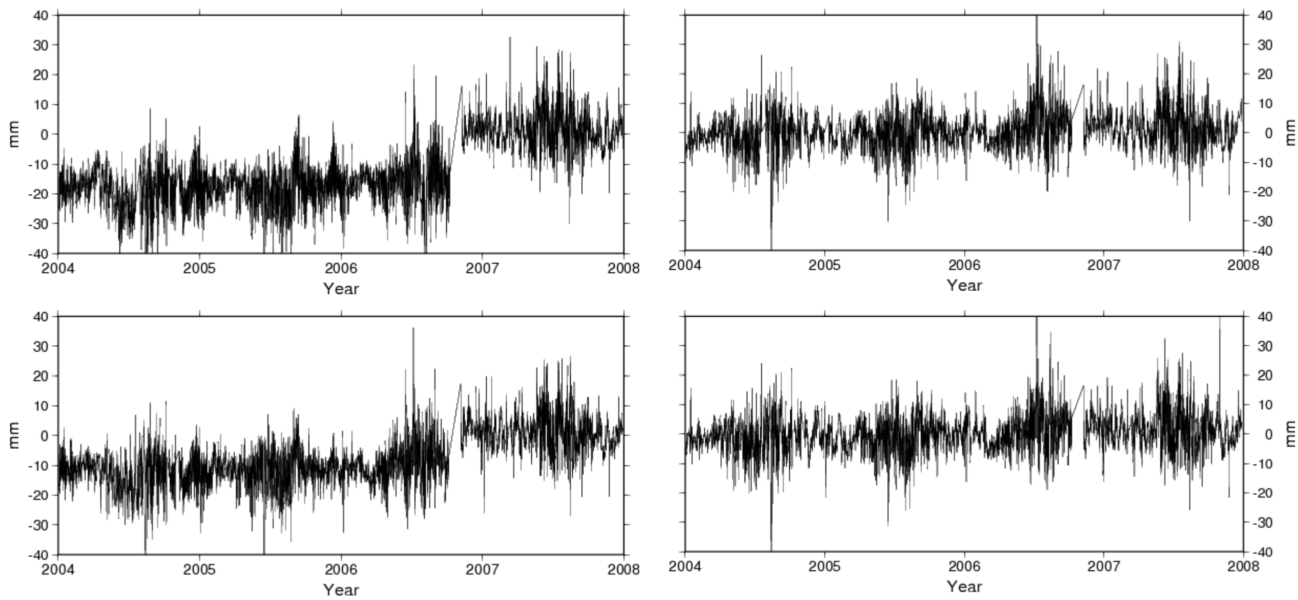


*Figure 4: Time series of ZTD differences between radiosonde and EPN combined solution (left) as well as MUT reprocessing solution (right) for site Borowa Gora, Poland, with co-located stations BOGI (upper part) and BOGO (lower part).*

## 5. Conclusions

In this paper we investigated the quality of zenith total delay parameter time series on some EUREF sites. MUTs reprocessing of the complete EPN with a homogeneous set of satellite orbits, clocks and Earth Rotation Parameters was leading to a homogeneous time series of zenith total delay parameters, covering the period 1996 to 2007.

Within comparisons with other GNSS results the reprocessing can serve as a reference to identify jumps, coming from, e.g., parameter or model changes, or periodic signals, coming from the analysis.

The comparison with external results from, e.g. VLBI or radiosondes can serve for investigations about temporal variations of each sensor as well as biases between the different sensors.

The results of this test reprocessing are promising with respect to the upcoming coordinated re-processing activities of the EPN [Voelksen, 2009].

## 6. Acknowledgements

The research of Mariusz Figurski and Karolina Szafranek was supported by the grant PBG 12-231 of Polish Ministry of Science and Higher Education.

The authors would like to thank Peter Steigenberger and his colleagues from GeoForschungsZentrum Potsdam and Technical Universities (TU) of Dresden and Munich for the provision of reprocessed IGS products.

The authors would like to thank particularly Henrik Vedel from the Danish Meteorological Institute for providing them with the radiosonde observation processing program and Robert Heinkelmann (Deutsches Geodätisches Forschungsinstitut Munich, formerly TU Vienna) for the co-operation concerning the IVS results.

# 7. References

[Bar-Sever et al., 1998], Bar-Sever, Y. E., P. M. Kroger, and J. A. Borjesson, "*Estimating horizontal gradients of tropospheric delay with a single GPS receiver*" J. Geophys. Res., vol. 103 (B3), pp 5019–5035, 1998

[Beutler et al., 2007], Beutler, G., and many colleagues, „*User manual of the Bernese GPS Software Version 5.0*", edited by R. Dach, U. Hugentobler, P. Fridez, M. Meindl, Astronomical Institute, University of Bern, 2007

[Boehm and Schuh, 2004], Boehm, J. and H. Schuh, *"Vienna Mapping Functions in VLBI analyses"*, Geophys. Res. Lett., vol. 31, L01603, doi:10.1029/2003GL018984, 2004

[Boehm et al., 2006], Boehm, J., A. Niell, P. Tregoning, and H. Schuh, *"The Global Mapping Function (GMF): A new empirical mapping function based on numerical weather model data"*, Geophys. Res. Lett., vol. 33, L07304, doi:10.1029/2005GL025546, 2006

[IGS, 1997], ftp://igscb.jpl.nasa.gov/igscb/data/format/sinex_tropo.txt

[Haase et al., 2003], Haase J., M. Ge, H. Vedel, and E. Calais, *"Accuracy and Variability of GPS Tropospheric Delay Measurements of Water Vapor in the Western Mediterranean"*, J. Appl. Meteor., 42, pp 1547-1568

[Heinkelmann, 2008], Heinkelmann, R. „*Bestimmung des atmosphärischen Wasserdampfes mittels VLBI als Beitrag zur Klimaforschung*", Geowissenschaftliche Mitteilungen TU Wien, Nr. 82, 2008 (in German)

[Kenyeres et al., 2008], Kenyeres, A., J. Legrand, M. Figurski, C. Bruyninx, P. Kaminski, and H. Habrich, "*Homogeneous Reprocessing of the EPN: First Experiences and Comparisons*", Bollettino di Geodesia e Scienze Affini, vol. LXVIII, no. 3, pp. 207-218, 2009

[Pottiaux et al., 2008], Pottiaux, E., E. Brockmann, W. Söhne, and C. Bruyninx, "*The EUREF - EUMETNET Collaboration: First Experiences and Potential Benefits*", Bollettino di Geodesia e Scienze Affini, vol. LXVIII, no. 3, pp. 269-278, 2009

[Saastamoinen, 1973], Saastamoinen, J., "*Contribution to the theory of Atmospheric Refraction"*, Bull. Géod., 107, pp 13-34, 1973

[Schmid et al., 2005], Schmid, R., M. Rothacher, D. Thaller, and P. Steigenberger, *"Absolute phase center corrections of satellite and receiver antennas. Impact on GPS solutions and estimation of azimuthal phase center variations of the satellite antenna"*, GPS Solutions, 9, 4, 283-293, doi: 10.1007/s10291-005-0134-x, 2005

[Soehne and Weber, 2002], Soehne, W. and G. Weber, *"EUREF Permanent Network Special Project - Status Report"*, Report on the Symposium of the IAG sub-commission for Europe (EUREF), Ponta Delgada, 05-08 June 2002, Mitteilungen des Bundesamtes für Kartographie und Geodäsie, Band 29 (EUREF publication No. 12), pp. 85-90

[Steigenberger et al., 2006], Steigenberger, P., M. Rothacher, R. Dietrich, M. Fritsche, A. Rülke, and S. Vey, "*Reprocessing of a global GPS network*", J. Geophys. Res., vol. 111 (B5), B05402, doi:10.1029/2005JB003747, 2006

[Vedel, 2007], Vedel, H., "*EUREF / EGVAP MoU and Status of EGVAP*", Report on the Symposium of the IAG Sub-commission for Europe (EUREF), held in London, 06-09 June 2007, Mitteilungen des Bundesamtes für Kartographie und Geodäsie (in print)

[Voelksen, 2009], Voelksen, C., "*EPN Reprocessing – a new EPN Project: Current Status*", Report on the Symposium of the IAG Sub-commission for Europe (EUREF), held in Florence, 27-30 May 2009, Mitteilungen des Bundesamtes für Kartographie und Geodäsie (in print)

[Zumberge et al., 1997], Zumberge, J. F., M. B. Heflin, D. C. Jefferson, M. M. Watkins, and F. H. Webb, *"Precise point positioning for the efficient and robust analysis of GPS data from large networks"*, J. Geophys. Res., vol. 102(B3), 5005–5017, 1997