Near Real-Time Tropospheric Signal Delay from EPN and German Permanent GPS Sites

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Abstract

A near real-time processing of GPS observations has been established at the University of the Bundeswehr Munich. Tropospheric signal propagation delay is estimated for almost all EPN stations which provide GPS observations on an hourly basis. Within 45 minutes after the full hour the results are available for further modelling. The quality of the solution has been tested in comparison to (1) the reprocessed data using final IGS orbits, (2) the EUREF troposphere combination product, (3) measurements of a Water Vapour Radiometer and (4) radiosonde data. Details of the network of ground stations, the processing strategy and the quality of the product are presented.

1 Introduction

Water vapour is one of the most weather influencing gases in the atmosphere and simultaneously one of the worst known parameters in weather modelling and forecasting. Moisture measurements of the upper atmosphere are only available from radiosonde launches, which have poor coverage in space and time. During the last years many experiments showed that the Global Positioning System (GPS) could be an additional technique to provide water vapour distribution over large scale areas (van der Marel et al., 2003). The estimated tropospheric signal propagation delay of the GPS signals depends strongly on the amount of moisture in the atmosphere. In the parameter adjustment the delay is set up as a random walk parameter which is piece-wise constant for a specific time span of typically a few minutes up to two hours. By use of a suitable mapping function the zenith total delays (ZTD) for the selected time intervals are estimated for each station. Using meteorological measurements this delay can be converted into integrated precipitable water vapour (IPWV), which is used in numerical weather models (NWM). In recent studies the flexibility of NWM has been improved, which allows the assimilation of the total zenith delay directly, see e. g. Ridal & Gustafsson (2003). To take advantage of GPS measurements for weather modelling zenith total delays have to be available with short time delays. A common interval for updating meteorological measurements is one hour. Thus, a scheme for processing GPS observations in near real-time hourly batches has been established at the Institute of Geodesy at the University of the Bundeswehr Munich (UBW) in cooperation with the German Federal Agency of Cartography and Geodesy (BKG) with the final goal to launch an operational service at BKG.

2 Project Description

Since autumn last year a cooperation between BKG and UBW is ongoing to set up a near real-time GPS processing. BKG is the main provider of basic geomatic information for the whole of Germany. Hence, it is always interested in establishing and offering permanent high quality long term services to its customers. Since the beginning of measurement campaigns for the European Reference Frame (EUREF) and the installation of European Permanent GPS Network (EPN) BKG was one of the main GPS contributors for Europe.

The aim of the cooperation between BKG and UBW is to offer a near real-time product of an extensive GPS network, namely the EPN, including some additional sites. The main intension for this service is to provide zenith total delay estimations with a continental coverage for numerical weather modelling. Thus, the product is mainly designed for the requirements of the weather service, which are summarized below:

1. The accuracy of the parameters should be at least at the level of 2 mm IPWV, which corresponds to approximately 10 mm of ZTD.
2. The observation network should include important weather-influencing regions, namely the north-western part of Europe as well as the North Atlantic.
3. The coverage of the observations should meet the coverage for weather modelling. A large and homogeneous network is better suited than a small

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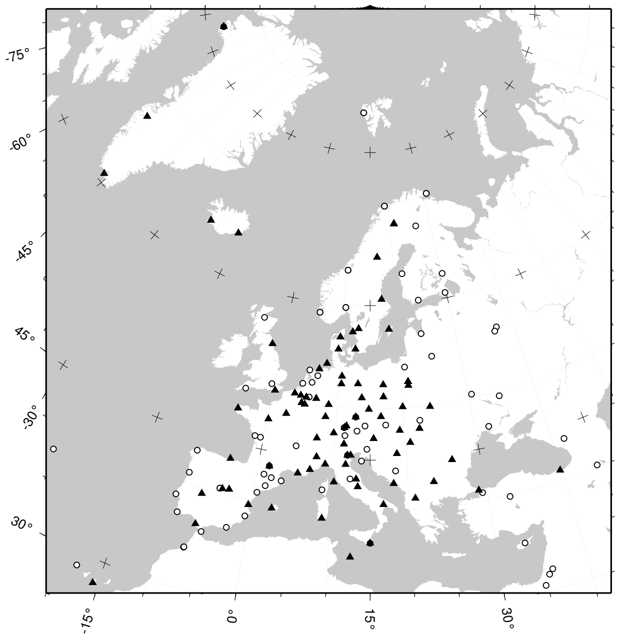

Figure 1: All stations of EPN. Stations marked by a triangle provide hourly observations and are included in the processing.

and dense one. Thus, a European observation network with a moderate densification in Germany is anticipated.

4. The time limit for updating the NWM defines the deadline for delivery of the results to 45 minutes past every full hour.

To meet these requirements we focus on stations of EPN. More than 50 % of them provide observations every hour (see Figure 1). The inclusion of additional German sites which do not belong to the EPN is planned for the operational phase. Currently, an extensive quality checking phase is ongoing to guarantee the best accuracy level, which meets the first requirement.

3 Processing Strategies and Schedule

Precise GPS processing can hardly be done in near real-time. Many important input parameters which can only be derived from a long term analysis are not or are only approximately known, in particular orbits, manoeuvres, and clock-errors of the satellite, sudden displacements of sites or ionospheric influences. For a validation of the near real-time GPS solution (NRT) it is therefore advisable to re-process the whole solution using final – highly precise – input parameters. Therefore our near real-time solution is post processed using the same strategy after the precise IGS-orbits are available. For all the GPS processings the Bernese GPS Software is used (Hugentobler et al., 2001). The outlines of the strategies are given in Table 1. Differences of both processing types occur due to the use of different IGS products and the session length. They are indicated in Table 2.

Table 1: Summary of important parameters for both NRT and final processing.

Cut-off angle	10°
Ambiguity resolution	QIF strategy
Tropospheric model	no
Mapping function	Dry-Niell
ZTD parameter constraining	loose constraints (5 m)
Type of solution	L3-fixed
Constraining of coordinates	Heavily constrained by 0.1 mm to the ITRF2000 coordinates of 8 main EUREF core stations
ZTD estimation	1 tropospheric parameter per hour and station
Coordinate estimation	1 set of coordinates session

Table 2: Difference between NRT and final processing.

Step	NRT	Final
Obs. input	moving 8-hour window	daily files
Orbits	IGS ultra-rapid	IGS precise
Ionosphere model	(currently) no model	CODE model
Processing time	15 to 20 min	about 1 hour
Processing delay	20 min	2–3 weeks

To ensure the delivery of the results in due time the near real-time processing is quite time critical. Therefore the hourly data transfer has been optimized for getting as much observations as possible in the fastest way. Firstly we check if any requested data is already on the local disc and does not need to be transferred. Secondly all data centres are requested simultaneously for available observations. Data centres which do not respond now are not contacted any more during the current processing batch. Thirdly the needed observation files are allocated to the transfer list of the different data centres and transfer is started – again in parallel sessions. To avoid delays due to slow network connection, a strict time-out criteria is applied, which ensures a maximum transfer time of less than 3 minutes.

The hourly schedule for the near real-time processing is similar as presented by Brockmann & Troller (2002) and given in the following:

Min. 05: Transfer of old observation data to fill possible gaps during the processing window in case one station delivers its data too late for the previous processing.
Min. 10: Checking and transferring of most recent orbit file.
Min. 15: First transfer of the most recent observation files. At this time observations of the majority of the stations are already available.
Min. 20: Second data transfer to get observations possibly delivered belatedly. Start of the processing immediately after the transfer is complete.
Min. 45: ZTD estimations are ready for delivery.

4 Network Results

For a basic quality monitoring the NRT solution is compared to the final solution. To optimize processing strategies a two weeks test campaign was processed with exactly the same observation input for different analyses. The results were compared to the EUREF troposphere combination product, which is a combination of the solution of all 16 EUREF analysis centres provided by the BKG. The combination on EUREF level is submitted to IGS for further combination on a global scale. GPS stations of EPN are processed by at least three analysis centres. The majority uses the Bernese GPS Software with similar processing strategies (Söhne & Weber, 2002).

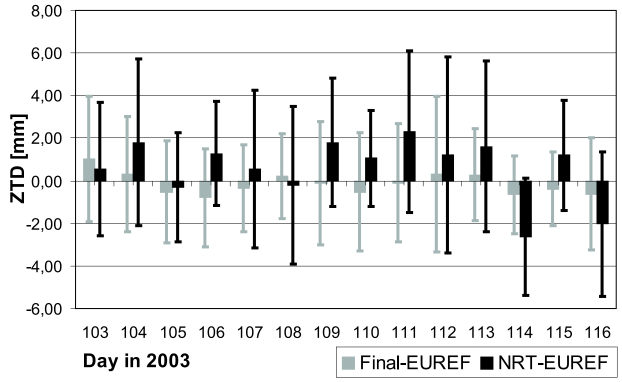

Figure 2: Daily bias and RMS of NRT and final solution versus the EUREF combination.

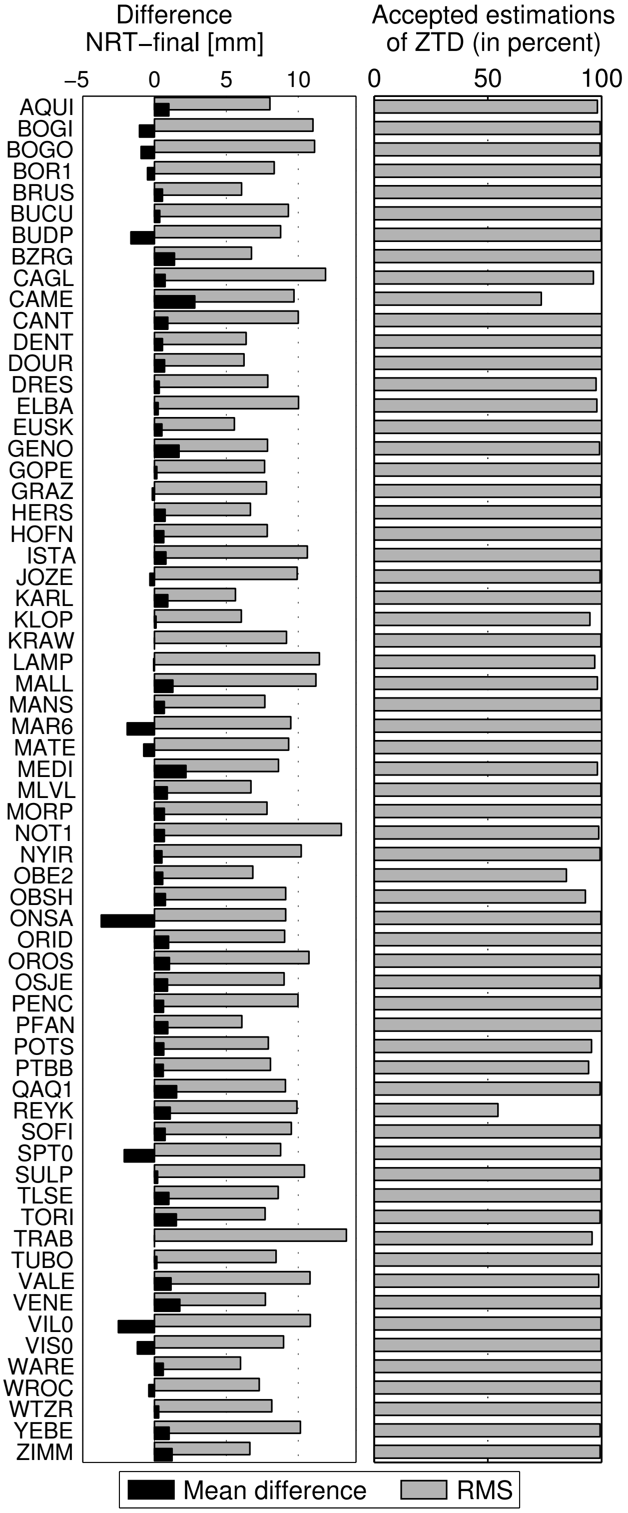

Figure 3: Station specific biases and RMS of NRT versus final solution. Stations with less than 30 % of accepted estimations / observations have been excluded.

The comparison of our solution to the troposphere combination is done epoch-wise for the ZTD estimations of all stations and summarized to one value per day. Figure 2 shows the time-series of differences of both the NRT and the final solution during the test campaign. The consistency of final solution and EUREF combination is rather good. This meets our expectations because of the similar processing strategies. On the average there is a difference of 0.1 mm±2.5 mm. For the NRT solution the difference is only slightly greater:

−0.6 mm±3.3 mm. The estimated RMS of the bias may be too optimistic because only daily mean values are compared. For a more realistic comparison Figure 3 shows the specific differences between the NRT and our final solution for each site. The left part in Figure 3 shows the mean difference and the scattering. In general the bias is very small. The RMS for the majority of the stations is at a sufficient level of 6 to 10 mm, which is almost the accuracy reached by other groups (Douša, 2002; Gendt et al., 2002). The average bias for all stations is 0.4 mm ± 8.7 mm. The right part of Figure 3 shows the percentage of reasonable ZTD estimations during the test campaign. Missing data occur not only because of missing observations but also due to a basic outlier rejection in the comparison, which should also be applied before assimilating the data to weather models.

Despite the fact that the accuracy is at the desired level of < 2 mm IPWV there is still potential for optimizing the processing and decreasing the differences – especially the scattering. Thus, extensive testing of different strategies is ongoing using the example data set mentioned above. Additionally, to get more realistic information about the accuracy independent techniques are involved as described in the next section.

5 Comparison of GPS with WVR and RAOB

For validation and evaluation of the GPS results, a new station has been set up in March 2003 in Oberschleißheim (OBSH, near Munich) at the German Weather Service (DWD). This station collocates three different techniques which can be used to derive the atmospheric water vapour: GPS, Water Vapour Radiometry (WVR) and Radiosondes (RAOB).

In Oberschleißheim radiosondes are launched twice per day and the DWD contributes the measurements to the global network of World Meteorological Organisation (WMO). The radiosonde data are available online (see e. g. `http://raob.fsl.noaa.gov/`). For München/Oberschleißheim the WMO Station ID is 10868. The ZWD is obtained by integrating the humidity along the profile of the ascending radiosonde (Elliott & Gaffen, 1991).

The Radiometer installed at this station has been developed by the Radiometrics Corporation, Boulder, USA (Radiometrics, 2002). It is a dual-frequency-receiver, that measures the sky brightness temperature (the microwave radiation) at 23.8 GHz and 31.4 GHz. Different modes of operation offer the measurement in zenith direction, in a specified azimuth and elevation grid, or in the line of sight to the GPS satellites. As a meteorological sensor is attached to the instrument, pressure, temperature and relative humidity at the station are recorded simultaneously at each measurement epoch.

Observations in OBSH are taken in a 5° to 20° elevation and a 45° azimuth grid over all of the unobstructed sky with a cut off elevation of 25°. The measured sky brightness temperature is converted into the tropospheric wet delay in the line of sight by the use of three station specific regression coefficients. The delay is mapped into the zenith direction using the Niell Wet Mapping Function. With site-specific pressure values the hydrostatic delay (ZHD) is computed using Saastamoinen's model. ZWD and ZHD sum up to the zenith total delay, which can finally be compared to the GPS results. For a reasonable comparison the radiometer results are decimated to the GPS ZTD estimation intervals.

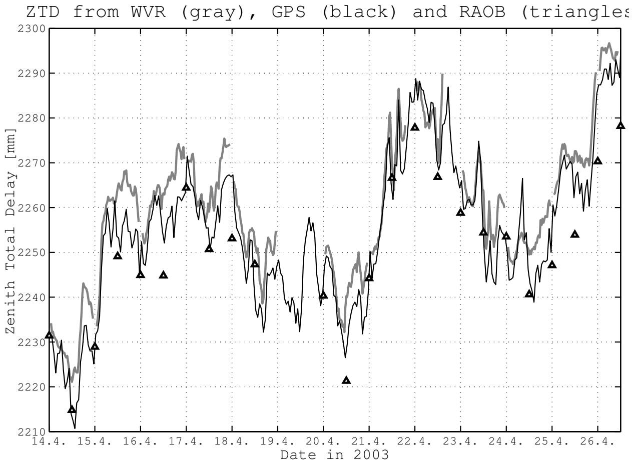

Figure 4: Comparison of zenith total delay

The GPS results of the two weeks test campaign in April 2003 are compared to the ZTD derived from RAOB and WVR in the respective time (see Figure 4). In general the consistency of all three techniques is fairly good. Nevertheless, different mean levels and short term inconsistencies are obvious. In average the results from RAOB are on the lowest, from GPS on the middle and from WVR on the highest level. The fact that GPS derived delay are mostly enclosed by RAOB and WVR results – the two most important techniques for off ground water vapour observations – proves the quality of the GPS processing. The mean bias between GPS and RAOB is 3.4±5.8 mm and between WVR and GPS 5.2 ± 4.3 mm. For WVR and RAOB the difference is on a higher level of 9.9 ± 8.4 mm. However, it should be mentioned that the confidence of comparisons with RAOB data is limited due to the very low number of measurements of 24 within the two weeks campaign. In terms of IPWV the difference of GPS results to RAOB and WVR amounts to 0.5 mm and 1 mm respectively.

For WVR and RAOB the time span of co-located measurements and tropospheric delay estimations covers the period from middle of March to beginning of May 2003 (see Figure 5). Approximately 100 common epochs allow a more realistic comparison of the zenith wet delay — the addition of the consistently modelled ZHD was only necessary for comparisons with GPS results in the former paragraph and has no influence to the comparison. The bias of 9.9 mm derived from all epochs confirms the first result. The decreased standard deviation of 5.2 mm reflects the long term stability and good fit of WVR and RAOB measurements. For further studies of annual bias-variations co-located observations in different seasons are needed, which are not yet available. As demonstrated in Pottiaux et al. (2003) for an other experiment the differences in ZWD show an annual variation: In cold months the bias is clearly less (about 10 mm) than in warmer months (about 25 mm). This effect leads to the assumption, that there is an unmodelled temperature dependency in the radiometer observations, which needs to be confirmed for different measurement conditions.

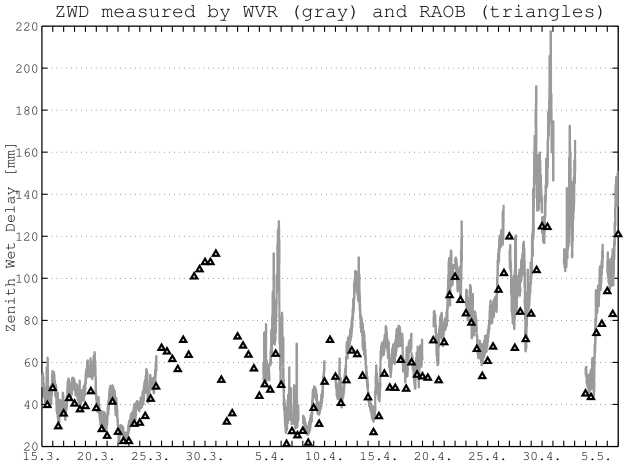

Figure 5: Comparison of zenith wet delays derived from WVR and radiosondes.

6 Conclusions

An hourly near real-time GPS processing was set up at the Institute of Geodesy at the University of the Bundeswehr Munich. It was designed under the special aspects to deliver atmospheric zenith total delay estimations as additional data for weather modelling. We showed that the product meets the basic requirements it is designed for. Nevertheless, proving a sufficient accuracy and objective quality monitoring only by use of GPS results is hardly possible. Thus, different external data were used as additional reference. Inter-GPS comparisons – especially with the EUREF combination product – show a satisfactory consistency, which is mainly the consequence of similar processing conditions. The near real-time results show a higher scattering of the results due to the non-uniform quality of the input data. Larger differences occur on very few stations. These special problems need further studies. Inter-technique comparisons prove that GPS is as appropriate as WVR and radiosondes to derive atmospheric water vapour. After removing an almost constant bias the consistency is at the level of 4 mm and 6 mm ZTD respectively. The task for the near future is to get a more uniform quality of ZTD estimations for all of the analysed stations.

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