Tropospheric Delay Estimations in a Regional Network of EUREF Stations. Quality Assessment Using Water Vapour Radiometer and Radiosonde Observations

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Abstract

Nowadays, the propagation delay induced by the atmospheric water vapour (WV) on GPS satellite signals remains the main accuracy-limiting factor for high precision GPS positioning. The behaviour of the water vapour in the atmosphere can be studied using three independent observation techniques: namely Global Positioning System (GPS), Water Vapour Radiometers (WVR) and Radiosondes (RS). In the paper, we briefly describe the processing strategies chosen to process the three sources of observations (GPS, RS and WVR). Then, we assess the quality of our GPS zenith wet delays (ZWD) estimates by comparing them to ZWD time series measured by Water Vapour Radiometers and Radiosondes. Finally, we compare our results to the CODE and EUREF tropospheric products.

1. Introduction

Nowadays, the propagation delay of GPS signals induced by the water vapour (WV) in the atmosphere remains the main accuracy-limiting factor for high precision GPS positioning. For this reason, the Royal Observatory of Belgium (ROB) decided to set up a research program on the wet component of the tropospheric error affecting GPS observations.

The basics of this research program, is to study the behaviour of the water vapour in the atmosphere using three independent techniques of observation: namely, the Global Positioning System (GPS), Water Vapour Radiometers (WVR) and Radiosondes (RS). GPS and Radiosonde equipments were already present on the ROB-site of Brussels. Therefore, we set up in 2001 a Water Vapour Radiometer to have the collocation of the three observation techniques.

In order to carry out these comparisons, we decided to process a network of GPS stations located around the site of Brussels. In the paper, we give an overview of the main characteristics of this network. Then, we dedicate a section to the processing strategies chosen to process GPS, RS and WVR observations. Finally, in section 4, we evaluate the quality of our GPS estimations. The evaluation is achieved in two steps. In the first step (described in sections 4.0.1 and 4.0.2), we compare our estimations to those made using the two other techniques. In the second step (described in sections 4.0.3 and 4.0.4), we compare them to the tropospheric products computed by two analysis centers: namely, CODE and EUREF.

2. Network of stations

For the purposes of our study, we have selected a network of 7 EUREF stations located in Western Europe. As shown in the figure 1, the stations of the network are distributed around the sites of Brussels and Wettzell which present the advantage of having collocation of GPS receivers and Water Vapour Radiometers. In addition, the Royal Meteorological Institute of Belgium provided us Radiosonde observations for the site of Brussels. Therefore, we mainly focus on the results of Brussels where the three techniques are available.

The observation set is composed of almost one year of continuos observations for all instruments except for the WVR of Wettzell for which only 6 months of data were processed. Table 1 summarizes the data availability for all the instruments. Table 2 summarizes the availability of the techniques for each site of the network.

Table 1: Data availability for each instrument

GPS Sites	From	To
All Sites	01/01/2001	31/12/2001
WVR Sites	From	To
Brussels	01/02/2001	31/10/2001
Wettzell	01/01/2001	29/06/2001
RS Site	From	To
Brussels	01/01/2001	31/12/2001

Table 2: Summary of the techniques availability for each site of the network

Site Name	GPS	WVR	RS
Brussels	yes	yes	yes
Dentergem	yes	no	no
Kootwijk	yes	no	no
Potsdam	yes	no	no
Waremme	yes	no	no
Wettzell	yes	yes	no
Zimmerwald	yes	no	no

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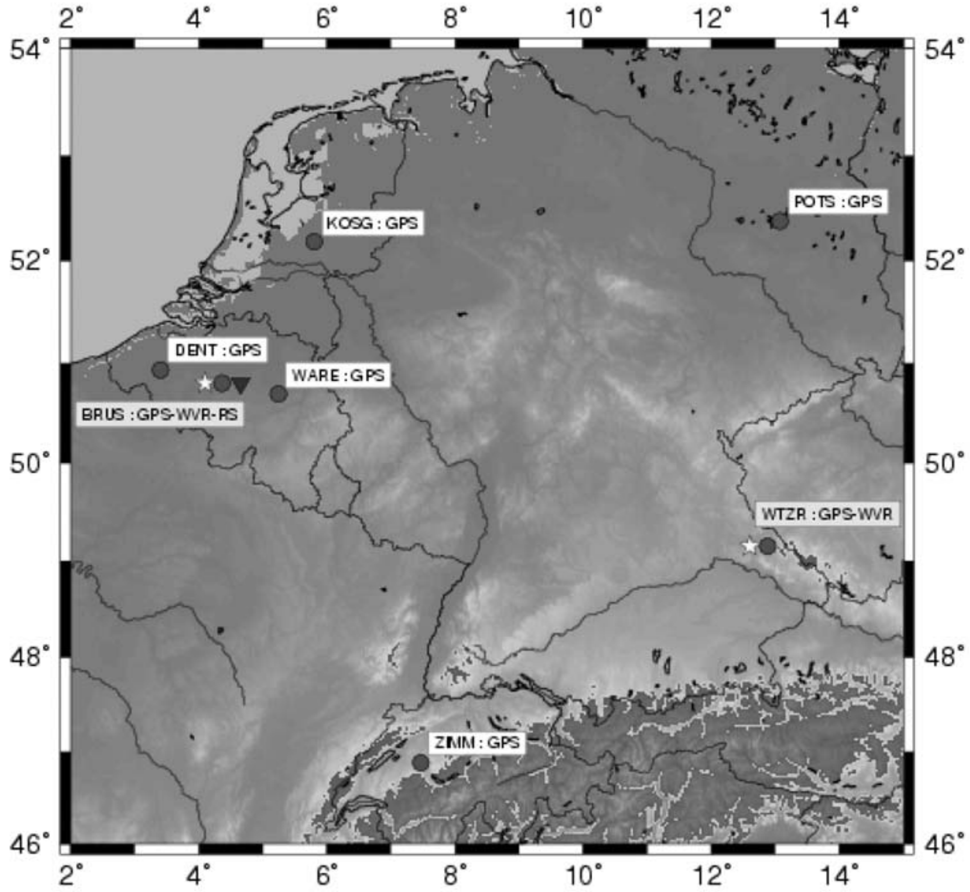

Figure 1: Map of the regional network of EUREF stations used in this study. Red circles indicate GPS observation sites, yellow stars Water Vapour Radiometer sites and blue triangles Radiosonde sites.

3. Processing strategies

The study presented in this paper is mainly based on the comparison scheme shown in figure 2. The basic principle is to assess the quality of our GPS ZWD estimations using external and independent sources of informations: namely, Radiosonde and Water Vapour Radiometer observations. In this section, we describe the strategies used to derive estimations of the zenith wet tropospheric delay (ZWD) from the different techniques.

3.1 Processing GPS observations

GPS tropospheric delays has been estimated using a standard processing strategy based on the Bernese Software version 4.2. The main characteristics of the processing strategy are:

- IGS precise orbits, clocks and eop's,
- 24 hours sessions,
- 30 seconds decimated RINEX files,
- QIF Ambiguity resolution,
- 12 or 24 tropospheric parameters estimated per session during an ionosphere free run,
- mapping function : Dry Niell,
- no a-priori tropospheric gradient estimation,
- elevation cut off angle at 10 degree,
- the Bernese TRP files were used for the comparison with the other techniques.

Figure 3 shows the time series of zenith total delays estimated using GPS observations at Brussels.

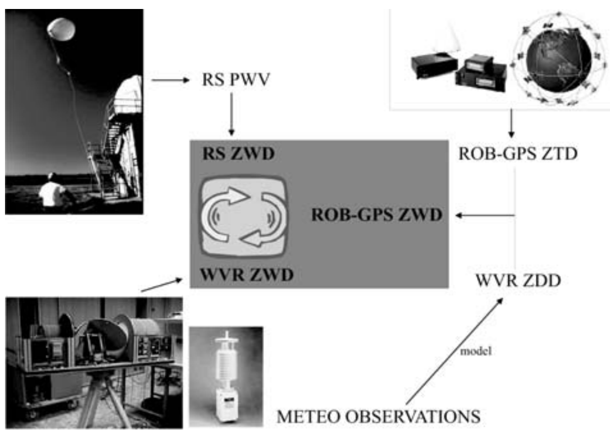

Figure 2: Comparison scheme used to assess the quality of our GPS zenith wet delay estimates

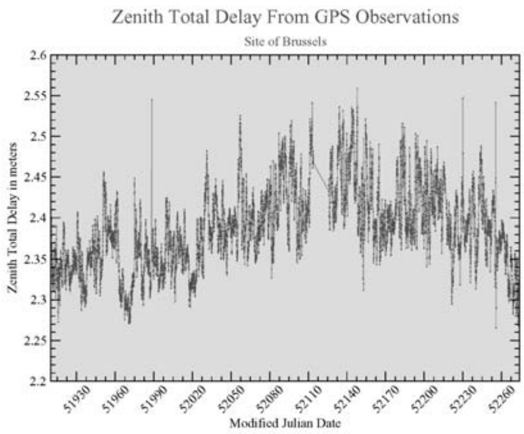

Figure 3: Zenith total tropospheric delays estimated using GPS observations at Brussels for the year 2001

3.2 Processing WVR observations

Water Vapour Radiometer observations have been processed using a standard processing scheme based on the Elgered method for reprieving the zenith wet delays. More details on this method can be found in (Wu, 1978) and (ELGERED, 1993). Moreover, details on the radiometers used in this study can be found in (POTTIAUX, 2002). The reader can also refer to this paper for details on the so-called standard WVR processing strategy. At the end of the processing, Bernese meteorological files of type 3 and 5 are output for comparison with the other techniques. These files contains estimations of the tropospheric delay every 15 minutes. Figure 4 shows the time series of the zenith wet tropospheric delays estimated using the Water Vapour Radiometer observations at Brussels.

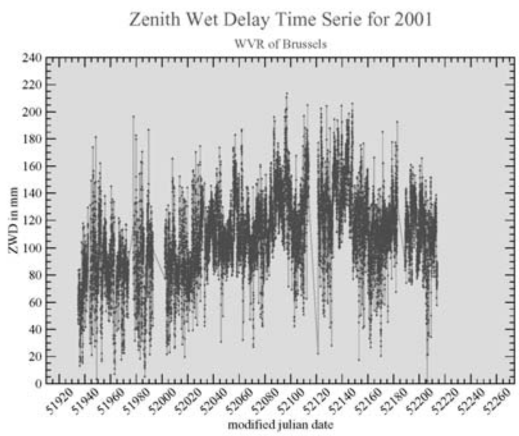

Figure 4: Zenith wet tropospheric delay estimated using Water Vapour Radiometer observations for the site of Brussels

3.2 Processing RS observations

The Royal Meteorological Institute of Belgium provided us one year of continuous Radiosonde observations for the year 2001. We have developed a dedicated software in order to estimate an integrated precipitable water vapour (IPWV) from the Radiosonde profiles. This software is based on the integration of the water vapour density Dv along the ray path. The following equation expresses the IPWV in terms of the water vapour density Dv:

$$IPWV = mD_v(z)\partial gz \tag{1}$$

Then we need to express the water vapour density in terms of radiosonde observables:

$$IPWV = \int \left\{ U(z) \times e_s(z) \times \frac{1}{R_v \times T(z)} \right\} \cdot dz \tag{2}$$

where U is the relative humidity, T the temperature, es the saturation water vapour pressure and Rv the specific gas constant for water vapour.

Using the Clapeyron-Clausius equation, we can finally express the equation (2) in terms of the raw observations of the Radiosonde. Applying a numerical integration method we can compute the IPWV. In the geodetic community, results are often express in terms of zenith wet delay. The following equation allows the conversion from IPWV to ZWD:

$$ZWD = K\ x\ IPWV \tag{3}$$

where the dimension-less constant K is about 6.5. Radiosonde balloons are launched twice a day at Brussels and figure 5 shows the time series of the estimated IPWV over the year 2001.

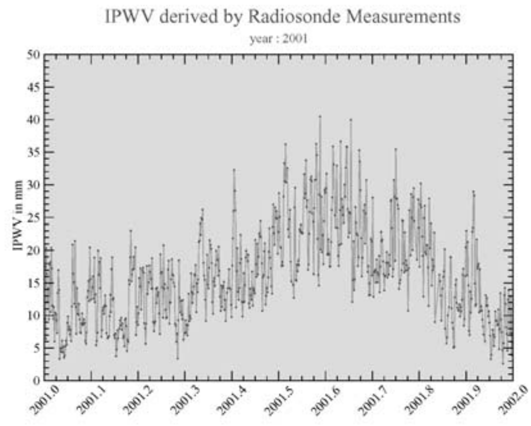

Figure 5: Precipitable water vapour estimated using Radiosonde observations for the site of Brussels over the year 2001

4. Quality assessment of the GPS-ZWD

The next step in the study is to assess the quality of our GPS zenith wet delay estimates using the different sources of informations. Therefore, we compare {\sl ROB-GPS ZWDs to the following ZWDs:

- *RS ZWDs*, the zenith wet delays computed using Radiosonde observations (section 4.0.1),
- *WVR ZWDs*, the zenith wet delays computed using Water Vapour Radiometer observations (section 4.0.2),
- *CODE-GPS ZWDs*, the zenith wet delays computed by the CODE analysis center using GPS observations (section 4.0.3),
- *EUREF-GPS ZWDs*, the zenith wet delays computed by the EUREF analysis center using GPS observations (section 4.0.4).

4.0.1 Comparison of ROB-GPS estimations with Radiosonde observations

The first step in order to assess *ROB-GPS ZWD* estimates is to compare them to *RS ZWD* estimates. We carry out this analysis for the site of Brussels where Radiosonde observations are available. In order to be coherent with the comparison between GPS and WVR we decided to consider only periods when all the techniques are available. Figure 6 shows the differences between *RS ZWD* and *ROB-GPS ZWD*. The two techniques agree very well with a mean bias of 0.82 mm and a standard deviation of about 4.40 mm of ZWD.

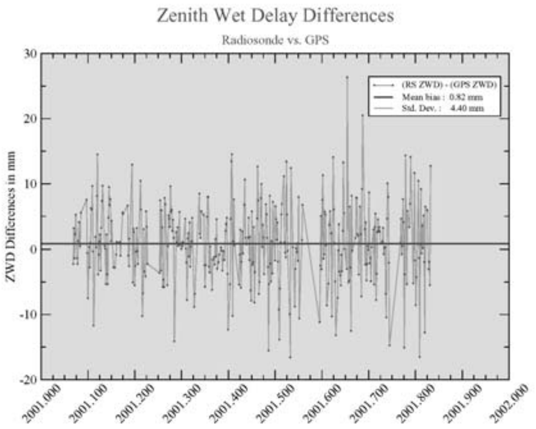

Figure 6: Zenith wet tropospheric delay differences between ROB-GPS and Radiosonde estimations for the site of Brussels over 2001

4.0.2 Comparison of ROB-GPS estimations with Water Vapour Radiometer observations

The second step in the quality assessment is to compare our *ROB-GPS ZWD* estimates to *WVR ZWD* estimates. Figure 7 shows the ZWD differences between WVR and GPS estimates for the site of Brussels.

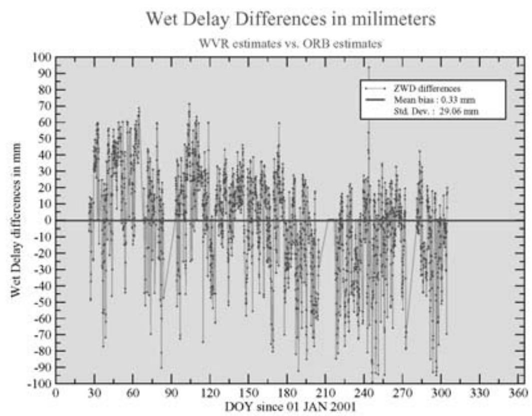

Figure 7: Zenith wet tropospheric delay differences between ROB-GPS and WVR estimations for the site of Brussels

For the site of Brussels, ZWD differences have a mean bias of 0.33 mm and a standard deviation of 29.06 mm. The same analysis has been done for the site of Wettzell. It shows a mean bias of -4.78 mm and a standard deviation of 10.60 mm.

The Brussels's WVR agrees very well with the ROB-GPS ZWD estimations. Nevertheless, this instrument presents much more variability than the one located in Wettzell. Further studies need to be done to explain this difference in variability. Nevertheless, we can already push forward some hypothesis that could explain partially this difference. The first hypothesis is that Wettzell has more continental weather and benefits therefore of more stable weather conditions. The second hypothesis is that the WVR of Brussels could have a "higher instrumental noise level" in the determination of the ZWDs than the WVR of Wettzell. Indeed, these two WVRs have a completely different design. Therefore, new investigations in that domain is required and will be partially achieved through a "WVR calibration campaign" in Wettzell during the summer of 2002.

4.0.3 Comparison of ROB-GPS estimations with the CODE-GPS estimations

After having compared the {\sl ROB-GPS ZWD estimates with the two other independent techniques, we have compared them to GPS estimates done by the CODE analysis center. Figure 8 shows the time series of ZWD differences between the ROB and the CODE estimates. Both estimates agree with a mean bias of -1.56 mm and a standard deviation of 7.55 mm for the site of Brussels.

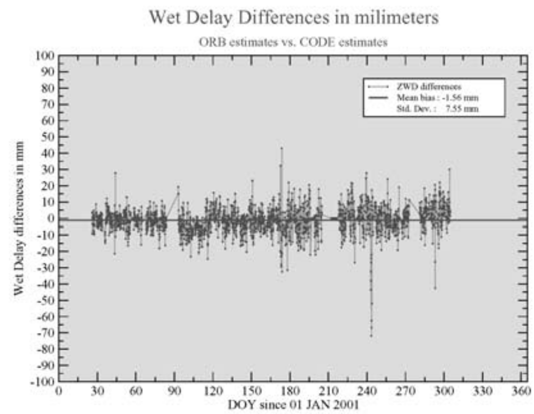

Figure 8: Zenith wet tropospheric delay differences between ROB-GPS and ROB-CODE estimations for the site of Brussels

Table 3. Summary of the comparisons between ROB and CODE zenith total delay estimates. Dentergem and Waremme are not processed by the CODE analysis center and therefore are not listed in the table

Station	*Mean Bias*	*Std. Dev.*
Brussels	*-0.76 mm*	*6.66 mm*
Kootwijk	*-1.76 mm*	*6.59 mm*
Potsdam	*-1.02 mm*	*6.43 mm*
Wettzell	*-1.87 mm*	*6.60 mm*
Zimmerwald	*+5.06 mm*	*6.80 mm*

The same analysis has been done for each station processed by the CODE analysis center. The results of this analysis can be found in the table 3 for other stations of the network. All the station within the network present similar results except the site of Zimmerwald. This site presents a mean bias of 5 mm.

4.0.4 Comparison of ROB-GPS estimations with the EUREF-GPS estimations

Finally, we have compared our ROB-GPS estimates with the EUREF estimates combined by the Bundesamt für Kartographie und Geodäsie (BKG). For the comparison we have used the SINEX troposphere files of the EUREF data center.

We have divided the data collection into two subsets. The first one starts at DOY 105 and ends at DOY 244 of 2001. The second starts at DOY 245 and spends until the end of 2001. The reason of this subdivision is due to a change in the estimation strategy of the EUREF CB. Figures 9 and 10 show the Brussels time series of the ZWD differences for both subsets. Tables 4 and 5 summarize the corresponding statistics for each network's site.

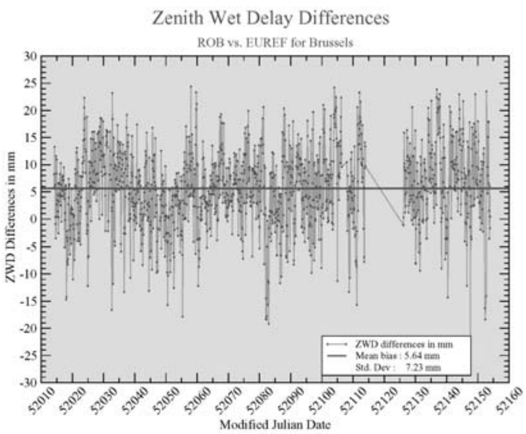

Figure 9: Zenith wet tropospheric delay differences between ROB-GPS and ROB-EUREF estimations for the site of Brussels (from DOY 105 to DOY 244)

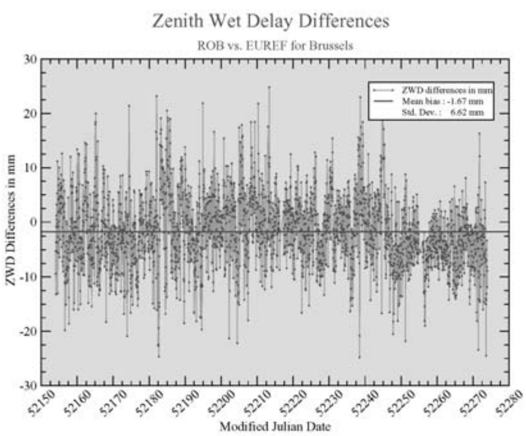

Figure 10: Zenith wet tropospheric delay differences between ROB-GPS and ROB-EUREF estimations for the site of Brussels (from DOY 245 to DOY 365)

Table 4: Summary of the comparisons between ROB and EUREF ZWD estimates (from DOY 105 to DOY 244) for each station within the network

Station	Mean Bias	Std. Dev.
Brussels	5.64 mm	7.23 mm
Dentergem	6.25 mm	6.69 mm
Kootwijk	3.54 mm	6.48 mm
Potsdam	3.99 mm	6.83 mm
Waremme	9.28 mm	6.89 mm
Wettzell	3.40 mm	6.79 mm
Zimmerwald	9.77 mm	6.57 mm

Table 5: Summary of the comparisons between ROB and EUREF ZWD estimates (from DOY 245 to DOY 365) for each station within the network

Station	Mean Bias	Std. Dev.
Brussels	-1.67 mm	6.62 mm
Dentergem	-0.55 mm	6.14 mm
Kootwijk	-1.52 mm	5.81 mm
Potsdam	-2.67 mm	6.18 mm
Waremme	+0.73 mm	6.16 mm
Wettzell	-2.04 mm	6.44 mm
Zimmerwald	+6.02 mm	6.60 mm

Table 6: Statistics summary of the comparisons for Brussels

Brussels	Mean Bias	Std. Dev.
ROB vs. RS	+0.82 mm	4.40 mm
ROB vs. WVR	+0.33 mm	29.06 mm
ROB vs. CODE	-1.56 mm	7.55 mm

Table 6: Statistics summary of the comparisons for Wettzell

Wettzell	Mean Bias	Std. Dev.
ROB vs. WVR	-4.78 mm	10.60 mm
ROB vs. CODE	-3.28 mm	6.02 mm

5. Conclusions

In this paper, we compare the zenith wet delays computed using three independent techniques of observations: namely, GPS, Radiosonde and Water Vapour Radiometers. We show that zenith wet delays computed from Radiosonde and GPS at Brussels agree very well with mean bias of 0.82 mm. We also give evidences that the ZWDs estimated using our GPS processing strategy agree with the WVR ZWDs with a mean bias of 0.33 mm at Brussels. Finally, we show that ZWDs estimated at the ROB agree with ZWDs estimated by CODE and EUREF analysis centers within the two millimeters of ZWD.

Acknowledgment

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