First Experiences with a Water Vapor Radiometer at the Royal Observatory of Belgium

E. POTTIAUX, R. WARNANT[1]

Abstract

In 1998, the Royal Observatory of Belgium decided to set up a reasearch program on the wet component of the troposheric error affecting GPS observations. In the frame of this study a Water Vapor Radiometer has been installed at Brussels. The paper describes our first experiences with this instrument.

1. Introduction

In 1998, the Royal Observatory of Belgium (ROB) decided to set up a research program on the wet component of the tropospheric error affecting GPS observations. In the frame of this study, a Water Vapor Radiometer (WVR) jointly built by the Swiss Federal Institute of Technology in Zurich (ETHZ) and the CAPTEC GmbH has been installed at Brussels in February 2001.

This instrument measures the sky brightness temperature at two radio frequencies - namely 23.8 Ghz and 31.5 Ghz - characteristic of the Water Vapor (WVR) and Liquid Water (LW) emission lines. Precipitable Water Vapor (PWV) can be retrieved from these sky brightness temperatures applying radiative transfer methods. A meteorological logger is attached to the radiometer and provides surface observations of pressure, temperature and humidity. Using these meteorological observations and a suitable mapping function, Zenith Wet Delay (ZWD) and Zenith Total Delay (ZTD) can be retrieved from pointed PWV. The Figure 1 shows the WVR of Brussels.

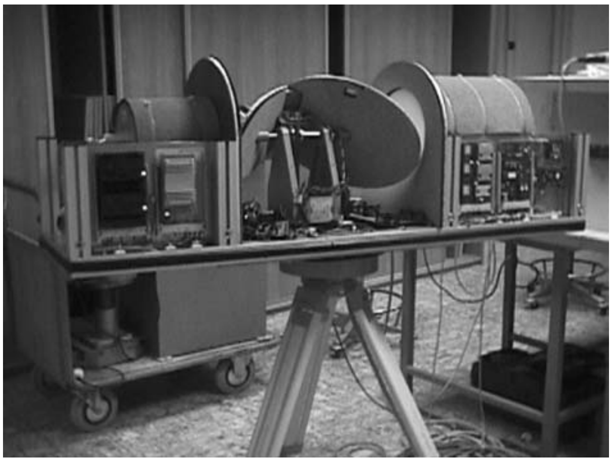

Figure 1: Picture of the generation III Water Vapor Radiometer jointly built by the Swiss Federal Institute of Technology and the CAPTEC GmbH.

The paper describes first results obtained at Brussels with this instrument. We cover different topics such as the fundamentals of WVR observation (section 2.1) and the description of raw observations (section 2.2). We also devote a part of the paper to the sensitive problem of the data quality (section 3). Finally we briefly describes first results obtained with the Water Vapor Radiometer of Brussels.

2. Principe of a Water Vapor Radiometer

In this section we describe the fundamentals of WVR observation. The first paragraph (section 1) will cover observation principle and answer the question *"What does a WVR observe?"*. Then in the next paragraph, we answer the questions *"What kind of observable do we really have?"*, *"What are the raw observables of a WVR?"*. Finally, in the section 2.3 we describe how to compute the Path Delays (PDL) from the raw observables.

2.2 Fundamentals of observation: The Sky Brightness Temperatures

The Water Vapor contained in the atmosphere behaves as a black body in term of electromagnetic emissions. The observation principle of a WVR is therefore based on the radiative transfer methods as explained in [SOLHEIM, 1993]. The main Water Vapor molecular emission line is located at 22.235 Ghz. Nevertheless the atmospheric presure and the presence of Liquid Water also affect microwave emission at this frequency. Observing at 23.8 Ghz can minimize the pressure dependency and a second observation at 31.5 Ghz allows compensation for liquid water emissions. Therefore, the WVR measures the atmospheric Sky Brightness Temperature at these two frequencies. From the observation of the Sky Brightness Temperature at both frequencies, it is possible to compute the Integrated Water Vapor Content (IPWV) above the observation site.

2.2 Raw observations and reference signals

From the technical point of view, the WVR has two antennae which measure the Sky Brightness Temperature at these two frequencies. These antennae output electric signals (voltages) corresponding to our observables (i.e. the Sky Brightness Temperature at both frequencies). Nevertheless, to analyse these signals, the WVR needs to tune its antenna measurements to reference signals: the so-called Calibration Targets (CT). These Calibration Targets (one per channel) have an emission power spectrum similar to a black body and can be settled in two different states called "cold" and "hot" corresponding to two different brightness temperatures

[1] Eric Pottiaux, René Warnant, Royal Observatory of Belgium, Eric.Pottiaux@oma.be, R.Warnant@oma.be

(namely 300 K and 700 K). These Calibration Targets allow to normalize the voltages output by the antennae in order to get rid of a number of environmental influences.

However, it is important to point out that he ambient temperature largely influences the signals in the High Frequency Parts of a WVR, in particular, the signals coming out of the Calibration Targets. The technical design of a WVR must handle this aspect and minimize the influence of the ambient temperature on the High Frequency Parts of the WVR. Therefore, a heating plate and its controller minimize the temperature variations inside the Brussels radiometer. The Figure 2 shows the basic technical design of the Brussels Radiometer. The grey left boxes represent the High Frequency Parts and everything inside the left yellow box is temperature stabilized.

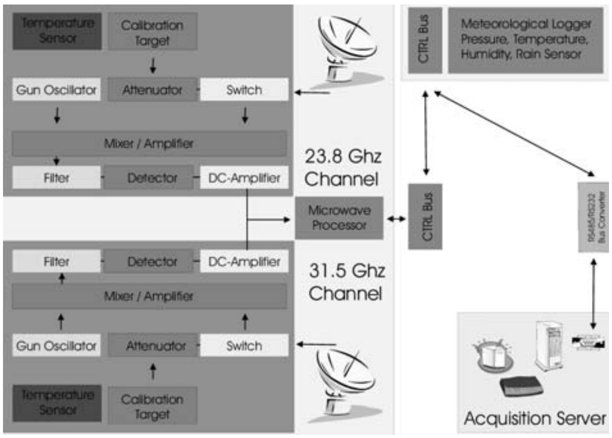

Figure 2: Technical design of the WVR of Brussels. The grey boxes represents the two High Frequency Parts of the WVR. Everything inside the left yellow box is temperature stabilized.

From the technical design of the radiometer shown in the Figure \ref{technical design} we can express the raw observations (for one epoch) of the entire system as follows:

- the antenna voltage of the 23.8 Ghz channel ($P_{a,23.8}$ in volts),
- the antenna voltage of the 31.5 Ghz channel ($P_{a,31.5}$ in volts),
- the calibration target voltage of the 23.8 Ghz channel in "cold" state ($P_{c,23.8}$ in volts),
- the calibration target voltage of the 31.5 Ghz channel in "cold" state ($P_{c,31.5}$ in volts),
- the calibration target voltage of the 23.8 Ghz channel in "hot" state ($P_{h,23.8}$ in volts),
- the calibration target voltage of the 31.5 Ghz channel in "hot" state ($P_{h,31.5}$ in volts),
- the ambient temperature around the calibration target of the 23.8 Ghz channel ($T_{23.8}$ in Kelvin),
- the ambient temperature around the calibration target of the 31.5 Ghz channel ($T_{31.5}$ in Kelvin),
- the ambient temperature of the heating plate (T_{base} in Kelvin).

In addition, the following meteorological measurements are taken:

- the ground pressure (*P_r* in mbar),
- the ground temperature (*T* in Kelvin),
- the reading of rain sensor.

Using these raw observations and the methods explained in the next section a Path Delay (PDL) estimate can be computed for each azimuth-elevation couple of angles.

2.3 Path Delay Computation

The processing of the raw observations in order to compute Wet Path Delays is achieved through 4 basic steps : the Filtering, the Tipping Curves Analysis, the Path Delay Computation, and finally the Path Delay Smoothing. We will now briefly describe each step.

Step 1: Filtering of the raw observations. The first step in the data processing is the filtering of the raw observations. During this step outliers are identified and rejected from the processing. Also specific azimuth-elevation couple of angles can be removed from the data set. This is particularly usefull if environmental influences are identified in particular directions (for example influence of observational dome or trees). Finally the Calibration Targets and Antennae Measurements can be smoothed before being processed.

Step 2: The Tipping Curves Analysis. As already said, to analyse the signal collected by the antennae, the WVR needs to tune its measurements to reference signals: the Calibration Targets. The "hot" state of the Calibration Targets plays a decisive role in the determination of the Antennae Brightness Temperatures. But since they have no constant noise temperatures and even are not known accurately, the hot load temperatures have to be computed (calibrated) with an independent method: the method of the Tipping Curves. More details on this method can be found in: [ELGERED, 1993] and [WU, 1978].

Step 3: Path Delay Computation. After having applied the Tipping Curves method, the voltages output by each antenna (T_{ant}) can be converted into Sky Brightness Temperatures using the Calibration Targets as references:

$$T_{ant} = \frac{(P_a - P_c)}{(P_h - P_c)}(T_h - T_c) + T_c \tag{1}$$

where *P_c*, *P_h* are the voltages of the calibration target in "cold" and "hot" position, *P_a* the voltage of the antenna and *T_c*, *T_h* the recorded temperatures of the Calibration Targets in "cold" and "hot" position respectively. Such an equation can be written for each channel of the WVR (T_{ant1}, T_{ant2}).

Then the Sky Brightness Temperatures are used to compute a Wet Path Delay (WPD) using the following equation:

$$WetDelay = K_0 + K_1 T^*_{ant1} + K_2 T^*_{ant2} \tag{2}$$

where the symbol "*" means that the Sky Brightness Temperatures are linearized and where the empirical coefficients *K_i* depend on the site considered. For more details on this subject, we refers to the following papers: [WU, 1979] and [ELGERED, 1993].

This procedure is applied to each azimuth-elevation couple of angles in order to compute pointed Wet Path Delay. A suitable mapping function is then applied to compute the corresponding zenithal values using the ground meteorological measurements.

Step 4: Path Delay Smoothing. As final step, a smoothing of the Zenith Wet Delay is applied by averaging the time series using a moving window in the time domain. Two successive smoothing are applied (*median* and *mean* smoothing) with specific length of the moving window. At the end of this step, Bernese meteorological files of type 3 and 5 are produced and can directly be used in the Bernese software.

3. Quality of Raw Observations

Before processing the radiometer observations in order to determine Zenith Wet Delay Estimates, we have investigated the quality of the WVR data. Indeed, this kind of instrument is very sensitive to environmental influences (ambient temperature, electromagnetic interferences, condensation, rain fall, obstruction of the field of view, etc.) - especially at low elevation angles. Therefore, a particular attention must be given to the quality and the monitoring of the data.

In that direction, we have developed at the ROB a dedicated software named {\sl WVR Real-Time Monitoring Software} (RTM) in order to monitor in quasi real time the quality of the raw observations, the influence of the environment and the status of the radiometer.

After processing almost one year of data, this software has not shown any significant influence of the surrounding environment (trees, observation domes, electromagnetic interferences, etc.). The Table \ref{outliers in the raw data} shows some results of this software for the whole data collection.

Table 1: Number and percentage of outliers on the main observables for the whole data collection over the year 2001.

Category	Channel	Number	Percentage
Cold CT	31.5 Ghz	3386	0.54
Cold CT	23.8 Ghz	256	0.02
Hot CT	31.5 Ghz	3391	0.54
Hot CT	23.8 Ghz	1404	0.09
Antenna	31.5 Ghz	10281	0.67
Antenna	23.8 Ghz	3961	0.25

Nevertheless, several problems and limitations has been identified in the hardware and in the software of the WVR. These problems will be studied in the near future in order to be fixed.

4. Time Serie of Zenith Wet Delay with the WVR of Brussels

After almost one year of observations, we are able to process the first long time series of Zenith Wet Delay with the WVR of Brussels. The results were obtained using the last version of the processing software delivered with WVR (namely *version 4.0*) and the results are shown in the Figure 3.

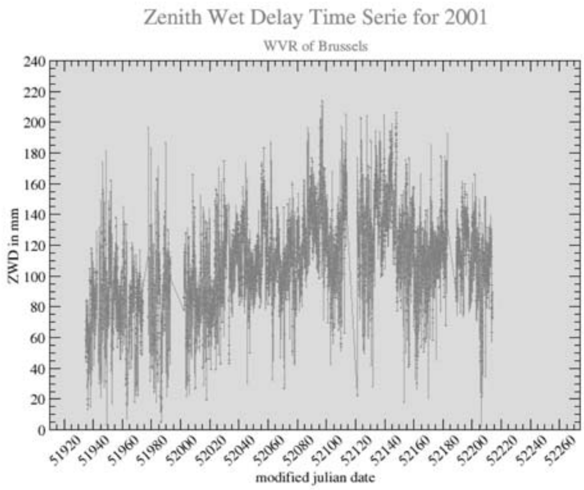

Figure: 3: Zenith Wet Delay time serie for 2001 obtained from the WVR of Brussels.

Also, comparisons of PWV retrieval using WVR and GPS have been presented at the EUREF symposium of Ponta Delgada in 2002. The mean difference between both techniques are on the submilimeter level of Zenith Wet Delay as shown in the Table 2. For more details on this subject we refer the reader to [POTTIAUX, 2002].

Table 2: Comparison WVR and GPS Zenith Wet Delay Estimation

Zenith Wet Delay Differences	*WVR-GPS*
Mean Bias:	+0.33 mm
Standard Deviation:	29.06 mm

5. Conclusions and Future Developments

In this paper, we have assessed the quality of the WVR observations in Brussels over almost one year of continuous data. The raw data present only few significant outliers and the measurement noise is at the level of the noise of the Calibration Targets. This allows to compute Precipitable Water Vapor and Zenith Wet Delay Estimates of good quality.

Nevertheless, during this period we also have identified several hardware and software troubles that need to be fixed. Therefore, further studies will be done in the near future in order to fix these problems.

Bibliography

ELGERED G.: *Tropospheric Radio-Path Delay from Ground-based Microwave Radiometry*. Atmospheric Remote Sensing by Microwave Radiometry, edited by Janssen, M.A., John Wiley & Sons, 1993.

POTTIAUX E., WARNANT R.: *Tropospheric Delay Estimations in a Regional Network of EUREF stations*. Quality Assessment Using Water Vapor Radiometer and Radiosonde Observations. EUREF Proceedings of the EUREF 2002 symposium in Ponta Delgada (Azorian Islands), this vol.

SOLHEIM F.S.: *Use of pointed water vapor radiometer observations to improve vertical GPS surveying accuracy*. Thesis submitted to the Faculty of Graduate School of the University of Colorado, 1993.

WU S.C., CLAFIN E.S., RESCH G.M.: *Microwave Radiometer Measurement of Water Vapor Path Delay: Data Reduction Techniques*. DSN Progress Report, 42-48, Jet Propulsion Laboratory, Passadena, CA, pp. 22-30, Sept./Oct. 1978.

WU S.C.: *Optimum Frequency of passive Microwave Radiometer for Tropospheric Path Length Correction*. IEEE Transactions on Antenna and Propagation, Vol. AP-27, No. 2, March 1979.