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RELIABILITY OF THE TEC COMPUTED USING GPS MEASUREMENTS — THE PROBLEM OF HARDWARE BIASES

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In this paper, we outline the procedure used at the Royal Observatory of Belgium in order to compute the TEC using GPS measurements with a precision of 2–3 TECU. This procedure requires the determination of the so-called receiver and satellite *differential group delays.* The combined biases (receiver + satellite) are determined on a daily basis (i.e. one solution a day) using the geometry-free combination of code observations. The method is applied to a network of 7 permanently operating Turbo Rogue receivers; the reliability of these computed biases is discussed.

Keywords: hardware biases; GPS; ionosphere; total electron content, TEC

1. Introduction

The Global Positioning System has already proved to be a very useful tool to study the ionosphere. Indeed, GPS code and carrier phase measurements can be processed in order to determine the Total Electron Content (Lanyi and Roth 1988, Warnant 1996). In practice, the TEC can obtained from:

1. The so-called geometry-free combination of dual frequency code measurements, $P^i_{p,GF}$;

$$P^i_{p,GF} = P^i_{p,L1} - P^i_{p,L2}\,. \tag{1}$$

This equation can be rewritten in function of the Total Electron Content, TEC^i_p:

$$P^i_{p,GF} = -1.05 \cdot 10^{-17} TEC^i_p + (DG_p - DG^i) \tag{2}$$

with

TEC^i_p slant TEC measured along the path going from satellite i to receiver p;

DG^i, DG_p the satellite i and receiver p differential group delays;

$P^i_{p,L1}$, $P^i_{p,L2}$ the $L1$, $L2$ P-code measurements made by receiver p on satellite i.

When the Anti-spoofing is active (it is the case since January 31, 1994), the code observations have a precision ranging from a few decimeters to more than one metre. These measurements are not ambiguous but contain biases called receiver and satellite differential group delays. The existence of these biases is due to the fact that the two GPS frequencies undergo different propagation delays inside the receiver and satellite hardware.

2. The geometry-free combination of dual frequency phase measurements $\Phi^i_{p,GF}$;

$$\Phi^i_{p,GF} = \Phi^i_{p,L1} - \frac{f_{L1}}{f_{L2}} \Phi^i_{p,L2} \tag{3}$$

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or rewritten in function of the TEC:

$$\Phi^i_{p,GF} = -5.52 \cdot 10^{-17} TEC^i_p + N^i_{p,GF} \tag{4}$$

with

f_{L1}, f_{L2} the frequency of the $L1$, $L2$ carriers;

$\Phi^i_{p,L1}$, $\Phi^i_{p,L2}$ the $L1$, $L2$ carrier phase measurements made by receiver p on satellite i;

$N^i_{P,GF}$ a real ambiguity.

Phase measurements have a precision better than one millimetre but contain an initial ambiguity which is real in the case of the geometry-free combination. In the absence of cycle slips, $N^i_{P,GF}$ has to be solved for every satellite pass.

3. A combination of geometry-free code and phase measurements.

$$P^i_{p,GF} - \lambda_{L1}\Phi^i_{p,GF} = (DG_p - DG^i) - \lambda_{L1} N^i_{p,GF} \tag{5}$$

with λ_{L1} the $L1$ carrier wavelength.

This combination is used to solve the ambiguity $N^i_{P,GF}$ which is introduced in Eq. (4) in order to determine the TEC. This third method allows to combine the advantages of both measurement types: the TEC is obtained from the precise phase measurements but the information contained in the code observations is used to solve the ambiguity. Nevertheless, the procedure requires the determination of the receiver and satellite differential group delays. In most of the cases, these biases have to be computed:

the satellite biases: they are measured by the manufacturer before the satellites are launched but these values are not valid any more when they are on their orbit (see, for example, Wilson and Mannucci 1993, Wanninger et al. 1994, Warnant 1996).

— the receiver biases: in the past, the old Rogue receivers (the so-called Big-Rogue and Mini-Rogue) had an auto-calibration function allowing to measure the receiver bias. Unfortunately, this function does not exist any more on the Turbo Rogue receiver. To our knowledge, no other receiver has this capability.

2. Computation of the biases

The Royal Observatory of Belgium has a network of 7 permanent GPS stations (Fig. 1). The station of Brussels is in continuous operation since April 1993. Dentergem, Dourbes and Waremme were installed in January 1994. In this section, we outline the method we have developed to study the hardware biases. The method has been applied to our Turbo Rogue network.

In fact, the error made in the determination of the differential group delays is the largest error source when computing the TEC using GPS measurements. It is clear that these biases cannot be neglected: for example the bias of one of our receivers (serial number 238) is +5.33 ns. The fact to neglect it would give an error of 16 TECU on the computed TEC.

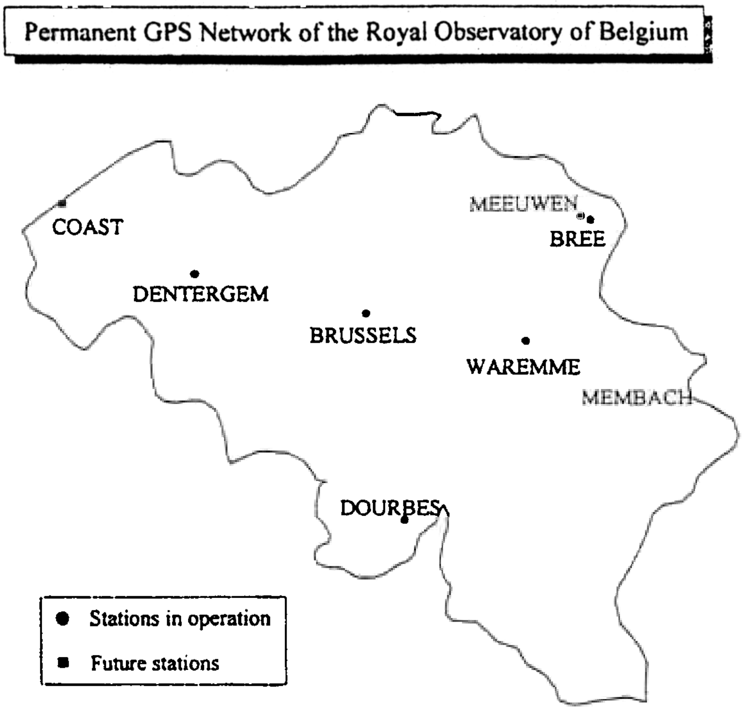

Fig. 1. The permanent network of the Royal Observatory of Belgium

In practice, the combined biases (receiver + satellite) are determined using Eq. (1) where the ionosphere is modelled by means of a simple polynomial in latitude and local time. Every model (i.e. polynomial) is computed using periods of about 6 hours of data. During this procedure, the "usual" assumptions are made:

— the ionosphere is concentrated in a spherical shell of infinitesimal thickness located at a height of 350 km; the intersection between this layer and the satellite line of sight is called the *ionospheric point*;

— "static" behaviour of the ionosphere on short periods (6 hours): the TEC only depends on latitude and local time;

— the receiver and satellite biases are constant on short periods. In the case of the Turbo Rogue biases, we have verified this assumption: during a period of a few hours, the biases remain constant within 0.2 ns (Warnant and Wanninger 1994, Warnant 1996).

The combined biases are determined on a daily basis (i.e. one solution a day). We only process night-time observations with an elevation mask of 20°: in most of the cases, the ionosphere is "quieter" during the night. This procedure which has been applied to our 7 Turbo Rogue GPS receivers has allowed us to study the long-term behaviour of the computed biases. The main results obtained with this network can be summarized as follows:

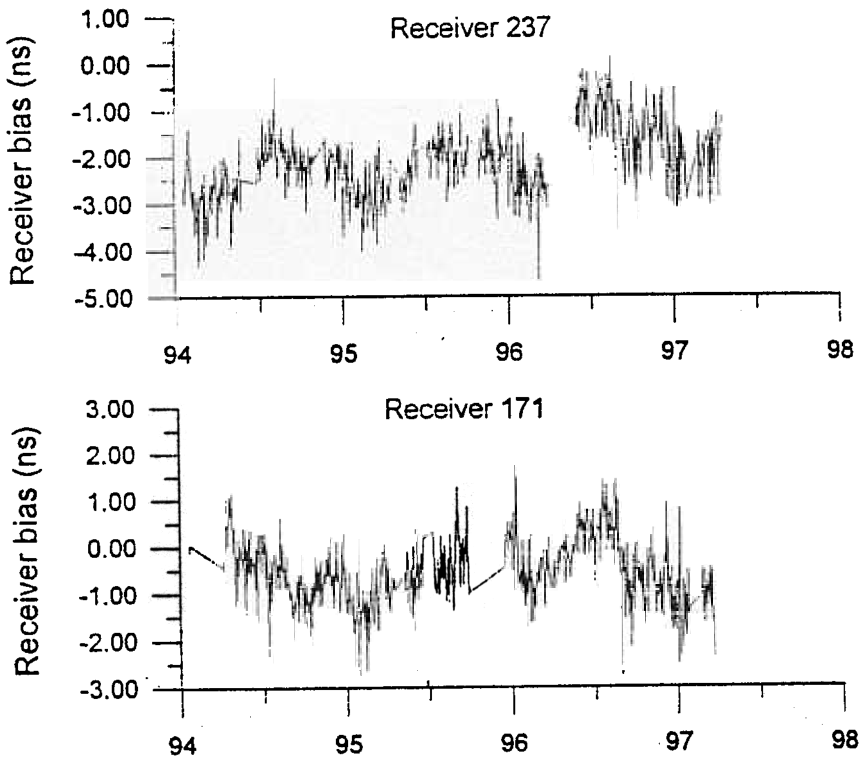

Fig. 2. Computed biases for Turbo Rogue receivers 237 and 171

- the Turbo Rogue bias changes as the Anti-Spoofing is activated or not: we have observed that, in most of the cases, the difference between the two values (i.e with Anti-Spoofing on or off) is about ±0.5 ns. Since January 31, 1994, the Anti-spoofing is activated but sometimes, it is turned off on a few or all the satellites;

- the biases of two "identical" receivers even with two consecutive serial numbers can be very different from each other: for example, the biases of receivers 237 and 238 are respectively −2.37 ns and +5.33 ns;

the bias depends on the temperature; the effect is visible during hot summer days;

Figure 2 shows the computed differential group delays for 2 receivers (serial numbers 237 and 171) in a period of about 3 years. By looking at this figure, it can be seen that the bias changes (sometimes much) as soon as in the hardware is changed a little (after a repair, for example): in June 1996, we have replaced the microprocessor of receiver 237: you can see very clearly a jump in the computed biases after this change; a similar replacement has been made receiver 171 in December 1995 and a repair has been performed in September 1996.

In addition, the computed biases have a (short-term) day-to-day variability of about 1 ns and have a periodic (seasonal) behaviour. Which is the origin of these variations in the *computed* biases? There are 2 possible explanations: the variations are due to a real change of the receiver bias or they are due to the fact that the use of our simple polynomial to model the ionosphere gives rise to residual errors which vary from day to day, from season to season, ... as in the case of the ionosphere. If this last explanation is true, then we would expect that the residual errors would be similar for the different receivers: from Fig. 1, it is clear that the seasonal behaviours of receivers 171 and 237 are very similar; it is also the case of the other receivers. If these seasonal variations were real changes of the biases, the effect would be different for the different receivers. It could be argued that this seasonal trend could be due to the environmental parameters in which the receivers are placed: the external temperature also depends on the season. Nevertheless, in our case, this explanation cannot be true: the receiver installed at Brussels which is placed in a room where the temperature remains constant within 2 or 3°K undergoes the same seasonal variations as the other receivers.

For these reasons, the value of the bias adopted to determine the TEC is obtained by computing the mean of all the daily solutions in a period the duration of which depends on data availability: it ranges from one month to more than one year. This technique has the advantage that it reduces the influence of the ionospheric residual errors: most of the effects are cancelled in the mean.

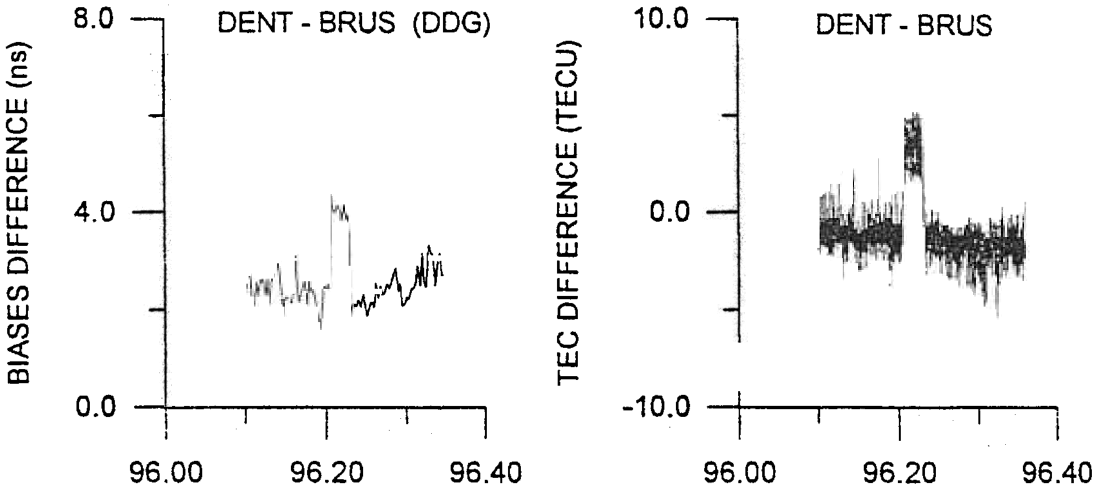

Fig. 3. Difference between the biases (left) and the TEC (right) computed for the receivers installed at Dentergem (sn 238) and Brussels (sn 321)

3. Determination of the TEC

When the biases have been determined, the TEC is computed as a function of latitude and local time (or longitude) of the ionospheric point. For example, the data collected at Brussels (latitude = 50.8°N, longitude = 4.4°E) allow to compute the TEC from about 35°N to 60°N in latitude and from −20°W to 25°E in longitude.

To obtain TEC profiles representative of the ionosphere above the observing station, we apply the following procedure:

— we select all the TEC values corresponding to an ionospheric latitude, L_{iono}, given by:

$$L_{\mathrm{sta}} - 1.5° \leq L_{\mathrm{iono}} \leq L_{\mathrm{sta}} + 1.5°$$

where L_{sta} is the latitude of the observing station;

— we compute the mean of these TEC values in 15 minute periods.

Figure 4 shows the TEC profile above Brussels on October 30 1994 obtained by this method. The procedure outlined here above has been applied to a data set covering a period of more than 8 years: since May 1989, GPS measurements have been regularly performed at Brussels. Since April 1993, the measurements are continuous. Three additional permanent stations are in operation since January 1994 (Dentergem, Dourbes and Waremme); 3 new stations (Bree, Meeuwen and Membach) have been installed in 1997.

Figure 5 shows, as example, the results obtained at Brussels for two months (January 1994 and January 1997): in this figure, all the TEC profiles corresponding to the same month are represented on the same graph.

To verify the reliability (precision and accuracy) of the TEC determined by the method developed at ROB, two experiments have been performed:

1. *Precision*: we have compared the TEC obtained at Brussels with the TEC computed at Dentergem, Dourbes and Waremme (the typical distance between stations is about 70 km) during a period of more than 3 years: in most of the cases, the difference between the TEC at Brussels and the TEC in the other Belgian stations remains within 2–3 TECU (Fig. 6).

2. *Accuracy*: at Dourbes, an ionosonde which is the property of the Belgian Meteorological Institute is collocated with our GPS station. GPS and ionosonde de-

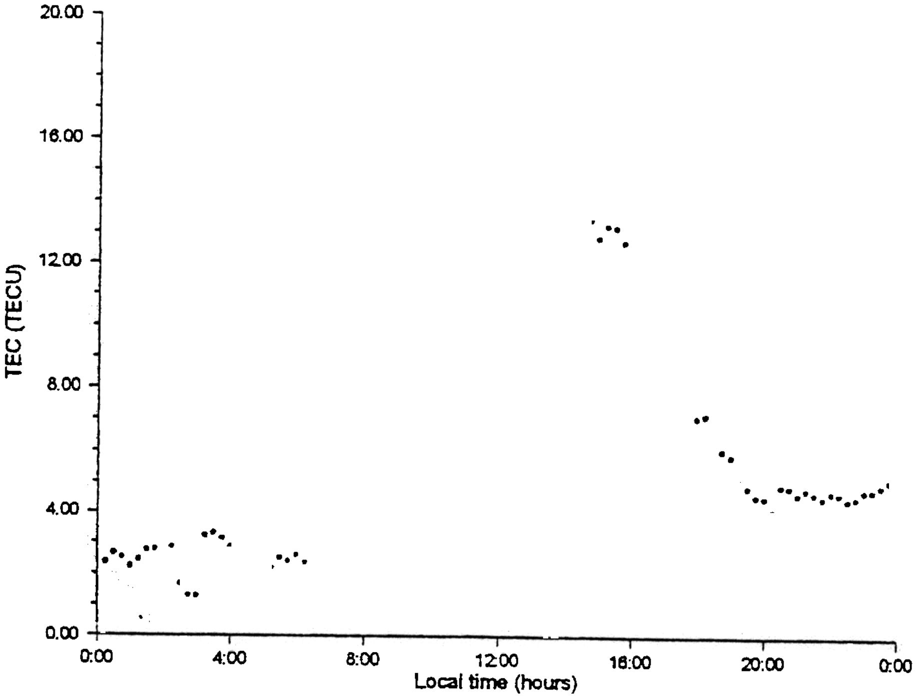

Fig. 4. TEC at Brussels on October 30 1994

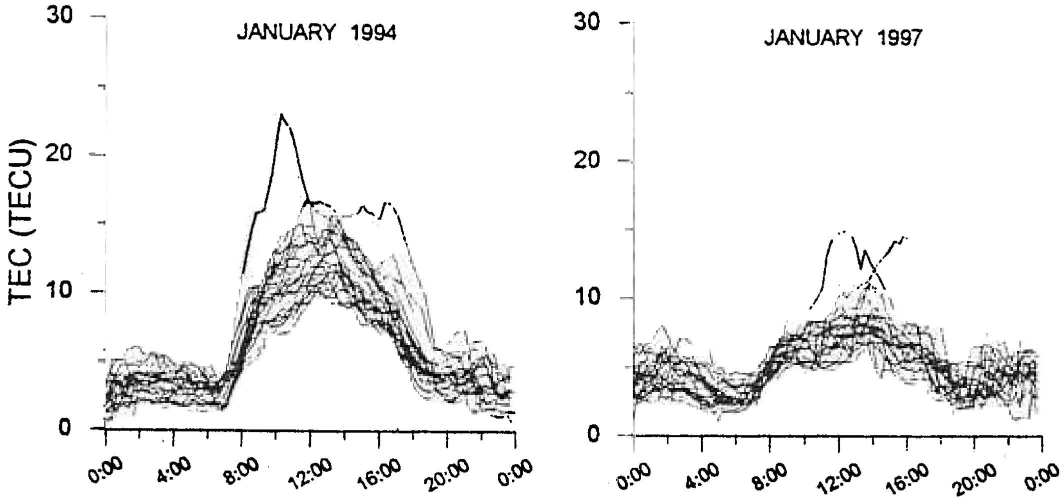

Fig. 5. TEC at Brussels during 2 month (January 1994 and January 1997)

rived TEC have been compared on a period of 2 years (Warnant and Jodogne 1997). Again, the two methods are in agreement within 2–3 TECU.

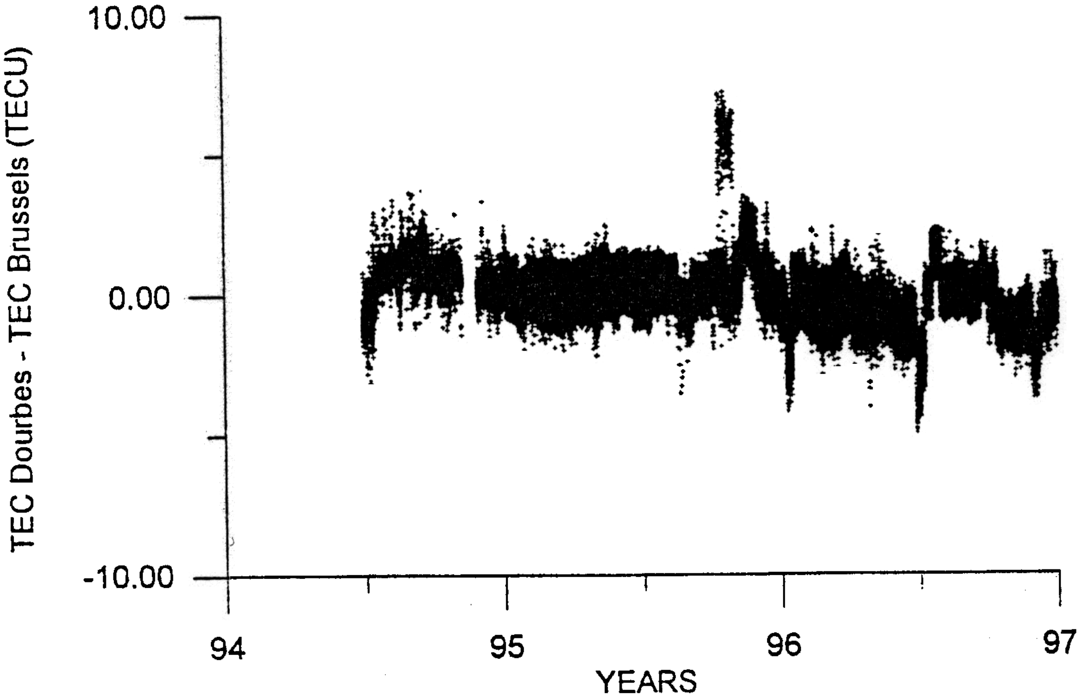

Fig. 6. Difference between the value of the TEC computed at Dourbes and Brussels

4. Conclusion

The paper has outlined the method developed at the Royal Observatory of Belgium in order to compute the Total Electron Content. This method requires the determination of the receiver and satellite differential group delays. The combined biases (receiver + satellite) are obtained on a daily basis from the geometry-free combination of code observations. The computed biases undergo day-to-day and seasonal variations; in most of the cases these variations are "artificial": they are due to ionospheric residual errors. For this reason, we adopt the mean value of all the computed biases on a long period to reduce the influence of these errors. Nevertheless, the biases also undergo "real" changes: they are sometimes due to the temperature (during hot summer days) but we have not been able to explain all these variations. For this reason, the receiver bias has to be regularly controlled. In addition, the consistency (precision) of our method has been verified: the TEC computed at Brussels has been compared to the TEC obtained at Dentergem, Dourbes and Waremme: they agree within 2–3 TECU.

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