# Processing GPS measurements during periods of high ionospheric activity: the influence on GPS data preprocessing

R. WARNANT<sup>1</sup>, J. GREVESSE<sup>2</sup>, E. POTTIAUX<sup>1</sup>

## Abstract

Since mid-1998, the solar activity has increased and has reached 2 maxima in 2000 and 2002. During periods of high solar activity, larger TEC values, larger TEC gradients and a larger number of ionospheric disturbances (i.e. scintillations and Travelling Ionospheric Disturbances) are observed. Even if most of the processing software make use of an ionospheric free combination to obtain the final solution, the ionosphere plays an important role in several steps of the processing strategy. In the case of the BERNESE 4.2 software, the ionosphere has an impact on data preprocessing (MAUPRP) and on ambiguity resolution (QIF). In particular, several software options give a tolerance on the ionospheric variability and have therefore to be set to a value which depends on the ionospheric activity. The paper discusses the influence of the choice of the parameter MAXION on GPS data preprocessing using MAUPRP during periods of high ionospheric activity. It shows that the default value of this parameter (MAXION = 400%) is well-suited in the case of highly disturbed ionospheric conditions for midlatitude stations.

### Introduction

The ionospheric activity follows the 11-year solar activity cycle. Since the end of 1998, the ionospheric activity has increased and has reached two maxima : the first one in 2000 and the second one in 2002. During periods of high solar activity, larger TEC values (Figure 1), larger TEC gradients and a larger number of ionospheric disturbances (i.e. Travelling Ionospheric Disturbances (TIDs) and scintillations, see Figure 2) are observed (WARNANT, POTTIAUX, 2000).



Figure 1. Mean daily TEC at Brussels from 1993 to 2002.

In particular, several severe geomagnetic storms have been observed during the period 2000-2002. These geomagnetic storms are often followed by high ionospheric variability and scintillations. Even if most of GPS data processing software make use of an ionospheric free combination to obtain the final result of the adjustment, the ionosphere plays an important role in several steps of the processing strategy. In the BERNESE 4.2 software, the ionosphere has an influence on data preprocessing (using MAUPRP) and on ambiguity resolution. The goal of the paper is to assess the influence of highly disturbed ionospheric conditions at midlatitudes on data preprocessing using MAUPRP software. For this purpose, we make a case study: we assess the influence of a severe geomagnetic storm and its associated ionospheric disturbances on the results of MAUPRP.



Figure 2. Number of ionospheric disturbances observed per month at Brussels from 1993 to 2002.

## Ionosphere and geomagnetic activity

The ionosphere is usually divided in 3 regions depending on geomagnetic latitude (figure 3):

- the mid-latitude region where the TEC and its gradients are the lowest and the most regular;
- the equatorial region where the highest TEC gradients and TEC values are observed;

<sup>&</sup>lt;sup>1</sup> R. Warnant, E. Pottiaux, Observatoire Royal de Belgique, Avenue Circulaire, 3 B - 1180 Bruxelles, Belgium, R. Warnant@oma.be/Eric.Pottiaux@oma.be

<sup>&</sup>lt;sup>2</sup> J. Grevesse, Université de Liège, Unité de Géomatique, Allée du 6 août, 2 B-4000 Liège, Belgium

 the polar region where the TEC is the most variable and irregular; in this region, the TEC behaviour is strongly dependent on geomagnetic activity.

Magnetic storms are defined as periods where the Earth magnetic field becomes disturbed. The degree of instability of the Earth magnetic field is quantified by different indices; let us mention the Kp indice which measures the degree of instability of the magnetic field on 3 hour periods. It is a

planetary indice which is not characteristic of local magnetic conditions. Its values range from 0 to 9. A period of disturbed activity is defined as a magnetic storm if the Kp index is larger than a threshold value:

- Kp = 5, corresponds to minor storm conditions;
- Kp = 6, corresponds to major storm conditions;
- Kp >6, corresponds to severe storm conditions.



Figure 3. The regions of the ionosphere.

## **Principle of MAUPRP**

In the BERNESE V 4.2 software, the preprocessing of GPS phase measurements in differenced mode is performed by the MAUPRP software. The main goal of this software is to check data for outliers and cycle slips. When it is possible, the detected cycle slips are corrected. When a detected cycle slip cannot be corrected, the program sets a new ambiguity. The cycle slip detection is based on combinations of GPS observations (i.e. triple differences) which change slowly with time and where even a small cycle slip will appear as a jump. In practice, MAUPRP proceeds in 3 steps (BEUTLER et al., 2001):

1. In double difference data, it identifies segments of data where no (large) cycle slip has occurred with "utmost certainty".

2. Based on these "clean" segments, it performs a triple difference adjustment where the position of the first station is kept fixed to it's a-priori value and where the position of the second receiver is computed.

3. The residuals of this triple difference adjustment are computed: when the "combined" option is chosen by the user, the software checks if the *zero cycle slip hypothesis* is verified. Two conditions have to be met to satisfy this hypothesis:

- condition 1: No "jump" in the L1 and L2 triple difference residuals. Indeed, uncorrected cycle slips on L1 or L2 measurements will appear as jumps in these residuals; the advantage of the method is that even a small cycle slip of 1 cycle on L1 or 1 cycle on L2 will give a jump of about 20 cm in the residuals. Nevertheless, under disturbed conditions, the ionosphere can also be the origin of a jump in the L1 and L2 residuals. For this reason, the user has to supply a value of a program option called "MAXION" which gives the maximum value of a residual that could be due to the ionosphere. In most of the cases, for a regional network of mid-latitude stations, the parameter MAXION is set to 400 % of a L1 cycle (i.e. 76 cm).
- condition 2 : No "jump" in the ionospheric free (L3) combination of the L1, L2 triple difference residuals. The advantage of L3 is that it does not depend on the ionosphere.

### Case study

The influence of the ionospheric activity on MAUPRP depends on the choice of the MAXION parameter. For this reason, we verify that the choice "MAXION = 400%" is well-suited for periods of high ionospheric activity. To perform this test, we processed the data collected :

during 3 severe geomagnetic storms on the baseline Kootwijk-Wettzell (602 km): we analysed the L1,L2 triple difference residuals in order to verify if the influence of the disturbed ionosphere remains below the tolerance of 400% of L1 cycles. In practice, only a few data points were found above this tolerance. An example of such data points is shown in figure 4. For this reason, the choice of the tolerance can be considered as "realistic" and the results of the preprocessing are not much affected by the ionospheric activity. In figure 4, the geometric free combination (L4) of the L1, L2 triple difference residuals is also displayed. Indeed, in the absence of cycle slips, the ionosphere is the unique "source" which can give large outliers in the L4 combination. The comparison of the L1 and L4 outliers shows a very good correlation but they are no corresponding outliers in the L3 (ionospheric free) residuals: this fact demonstrates that the outliers are due to the ionosphere.



Figure 4. L1, L3 and L4 triple difference residuals on baseline Kootwijk -Wettzell for satellite pair 18/10 on DOY 097 in 2000.

 A 301 km baseline in the equatorial region (Mauna Kea-Honolulu) at solar maximum. In this case, ionospheric residuals larger than 760 mm are regularly observed on all satellite pairs. An example of such residuals is given in figure 5. For this reason, during the period we studied (DOY 230-300/00), a value MAXION = 500 % was more realistic.



Figure 5. L1, L3 and L4 triple difference residuals on baseline Mauna Kea-Honolulu for satellite pair 10/7 on DOY 236 in 2000.

#### The importance of "MAXION"

To assess the importance of a well-adapted choice of "MAXION", we performed the following "simulation": we re-processed the baseline Kootwijk-Wettzell (DOY 097/00) and we tested 3 values of the MAXION parameter: 100 % (too small), 400 % (well-suited) and 999 % (too large).

*Case 1:* MAXION is too small : if the ionosphere is disturbed and gives residuals larger than MAXION, the software interpretes the jump due to the ionosphere as a cycle slip but will not be able to correct it. In other words, the software is not able to verify the first condition of the zero cycle slip hypothesis. For this reason, the software introduces a new ambiguity. In addition, during the procedure, the software will mark several "good" data points as outliers (Beutler et al., 2001). If this problem regularly appears, this will result in an "abnormal" number of ambiguities (and of eliminated data points) which will affect the final result (see table 1).

*Case 2:* if MAXIONO is too large: even if a small cycle slip occurs on L1 or L2 data, the zero cycle slip hypothesis can be satisfied on the L1 and L2 residuals but in most of the cases, there will be a detectable jump in the L3 residuals. Nevertheless, there are combinations of cycle slips on L1 and L2 which only give a small L3 residual. For example, a cycle slip of 4 cycles on L1 and 5 cycles on L2 will result in a residual of -0.059 m on L3 : depending on the receiver quality, this residual is at the limit of the measurement noise. In other words, there is a small chance that a too large MAXION value will be the origin of undetected (and uncorrected) cycle slips.

Table 1. Number of eliminated data points and number of ambiguities set by MAUPRP depending on the choice of the MAXION parameter for the baseline Kootwijk-Wettzell on DOY 097 in 2000.

MAXION	100 %	400 %	999 %
Number of ambiguities	72	48	47
Number of eliminated data points	1122	1065	1065

## **Conclusions and future work**

The standard value of the MAXION parameter in MAUPRP (i.e. MAXION = 400 %) is well-suited to disturbed ionospheric conditions in mid-latitude stations. This value has to be increased in the case of equatorial stations. A too small value of MAXION would lead to an abnormal number of ambiguities to solve and to an abnormal number of eliminated measurements. On the other hand, in a few cases, a too large value of MAXION could lead to undetected cycle slips. In the future, we will investigate the use of MAUPRP in high latitude stations and the effect of the ionosphere on ambiguity resolution.

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