Development of products for GNSS users at the Belgian Solar-Terrestrial Centre of Excellence

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Nowadays, GNSS are used to measure positions in the frame of many different types of applications. The positioning accuracy which usually ranges from a few mm to about 20 m depends on the type of observables (code or phase measurements), on the positioning mode (absolute or differential) or on the fact that positions are computed in real time or in post-processing. The effects of the ionosphere remain one of the main factors which limit the precision of many applications. The Total Electron Content (TEC) is the key parameter for the mitigation of the ionospheric error but the way the ionosphere influences GNSS data processing techniques depends very much on the type of application. Ionospheric effects are also an important limitation to the reliability of GNSS applications: when mitigation techniques fail, the "nominal" precision level is not reached; in this case, users are not necessarily aware about the fact that their results are "out of tolerance". This is an issue which is crucial for European positioning system Galileo which is supposed to give certified precision levels to its customers. The best precisions can be reached in differential mode using phase measurements. In differential mode, mobile users improve their positioning precision thanks to "differential corrections" provided by a reference station. For example, the so-called Real Time Kinematic technique (RTK) allows to measure positions in real time with a precision usually better than a decimeter when the distance between the reference station and the user is smaller than 20 km. As differential applications are based on the assumption that the measurements made by the reference station and by the mobile user are affected in the same way by the ionospheric effects, these applications are affected by gradients in TEC between the reference station and the user. For this reason, local variability in the ionospheric plasma can be the origin of strong degradations in positioning precision: during severe geomagnetic storms, RTK positioning error can reach several meters.

The Royal Meteorological Institute of Belgium (RMI) started the development of products and services for GNSS users in the frame of the Solar Influences Data Centre (SIDC) Space Weather Pilot Project (2003-2005). This project was created in response to an ESA announcement of opportunity of which the goal was to promote the development of Space Weather related services dedicated to any interested user community (customers). The role of the RMI team was to develop services to assess in real time and to forecast a few hours in advance Space Weather effects on different GNSS applications. From October 2006 to July 2008, the RMI has been the Coordinator of a project called GALOCAD. This project has been selected in the frame of Galileo Joint Undertaking call 2423. GALOCAD stands for "Development of a GAlileo LOcal Component for the nowcasting and forecasting of Atmospheric Disturbances affecting the integrity of high precision Galileo applications". Based on a dense network of

GNSS stations in Belgium, the goal of GALOCAD was to study the possibility to create a prototype Galileo Local Component (in Belgium) that would assess in real time and forecast a few hours in advance the effects of the atmosphere (ionosphere and neutral atmosphere) on Galileo high accuracy real time positioning. In addition, during Minister Council of 22 March 2006, the Belgian Government has decided to create the Solar Terrestrial Centre of Excellence (STCE) which involves the Royal Meteorological Institute of Belgium, the Royal Observatory of Belgium and the Belgian Institute for Space Aeronomy. The STCE is a new (long-term) project which aims at creating an international expert centre in the frame of Solar Terrestrial Relations. The STCE involves both research and operational services. In this project, the role of the RMI team is to monitor, to model and to forecast the ionospheric activity and its effects on real time GNSS applications.

In the frame of these activities, the strategy used by the RMI is based on 3 steps:

- Step 1: monitoring, modeling and forecasting Space Weather activity "parameters" which have an influence on the performances of GNSS applications (electron concentration, Total Electron Content (TEC), geomagnetic activity, …)
- Step 2: development of products and services for GNSS users; these products and services are based on the information obtained about Space Weather activity during step 1.
- Step 3: "publication" of data (from step 1), products and services (from step 2) through dynamic web pages and warning messages (e-mail, SMS, …)

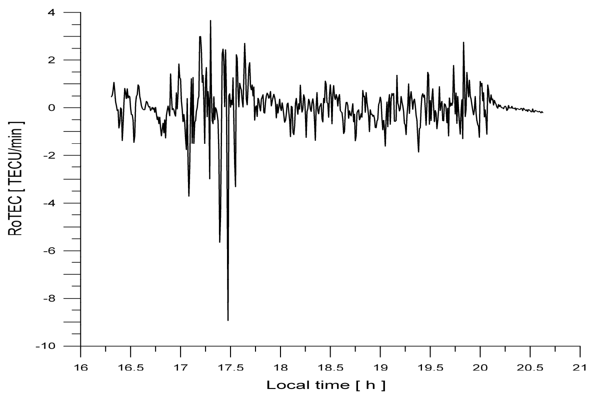

Fig. 1. Ionospheric variability (TECU/min) at Brussels on 20 November 2003 (satellite 2)

Qualitative assessment of ionosphere influence on real time high precision GNSS positioning

At the present time, the RMI is mainly involved in the development of products and services for users of high precision real time GNSS applications like the RTK positioning technique. As already mentioned, local variability (few km) in the TEC is the origin of degraded positioning conditions for GNSS differential applications. Therefore, in a first step, we developed a technique allowing to detect the occurrence of local variability in TEC. In practice, GNSS carrier phase measurements can be used to monitor local TEC variability: small-scale ionospheric structures can be detected by monitoring the Rate of TEC (RoTEC) at a single station; as ionospheric disturbances are moving, we can expect that such structures will induce

TEC temporal variability which can be detected at a single station (Warnant and Pottiaux, 2000; Warnant et al., 2007a and b). Based on the amplitude of the detected RoTEC, a scale which ranges from 1 to 9 measures the "intensity" of the ionospheric disturbance. This method (called "single-station" method) has been validated using the GPS data collected at the permanent (mid-latitude) station of Brussels from 1993 to 2008. The largest RoTEC detected at Brussels were observed during severe geomagnetic storms. Figure 1 shows the ionospheric variability detected by the single station method during the severe geomagnetic storm of 20 November 2003. This is the second largest RoTEC value observed on the period 1993-2008 at Brussels; the largest RoTEC observed on this 15-year period was 9.839 TECU/min during the severe geomagnetic storm of 30 October 2003.

The single station method offers a tool to develop a "qualitative" service for GNSS users. Indeed, this method can detect the occurrence of local variability in TEC which degrades high precision real time differential applications. In practice, depending on the level of variability detected during a period of one hour, our product assesses its probable influence on real time positions using a qualitative color scale: green (no problem), orange (small degradations possible), red (strong degradations are expected), black (high precision real time positioning is impossible). Figure 2 shows this (hourly) product on 20 November 2003 during a severe geomagnetic storm.

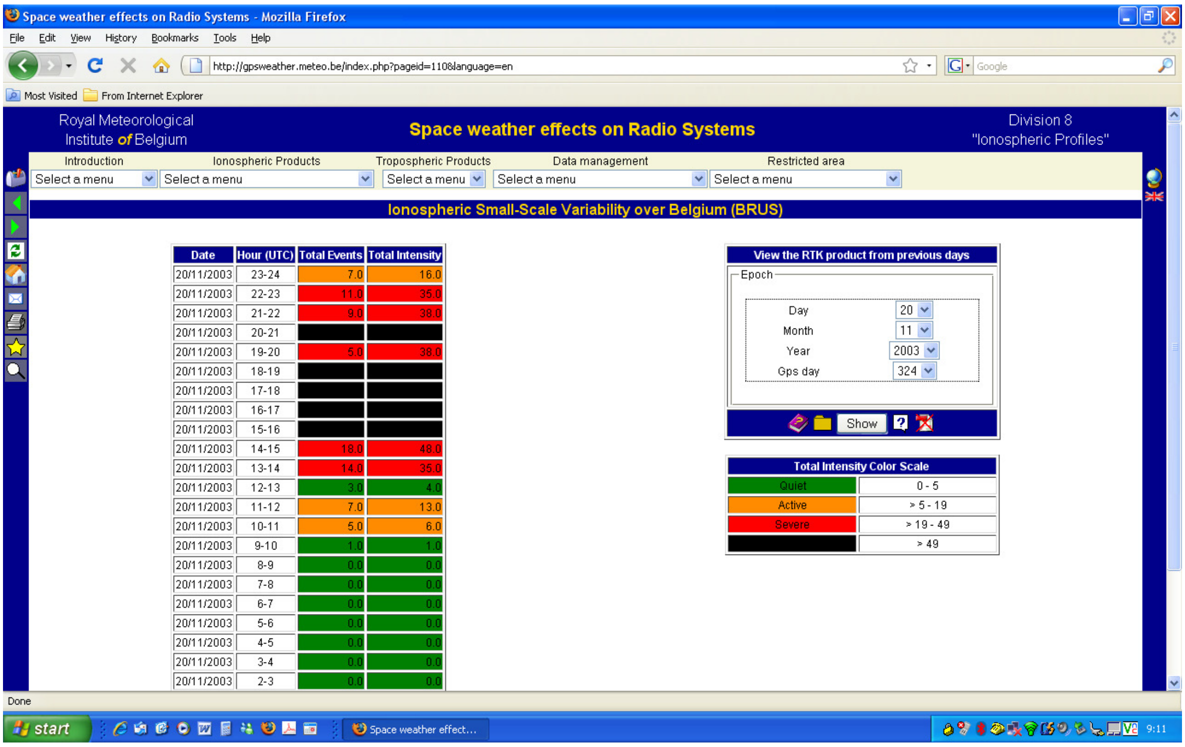

Fig. 2. GNSS product based on the single station method on 20 November 2003.

When red or black conditions are detected, warnings are sent to registered users by email.

Nowcasting and forecasting geomagnetic activity

By analyzing the period 1993-2008, we found that severe geomagnetic storms are the main drivers of strong variability in TEC. In other words, if we would be able to forecast the occurrence of severe geomagnetic storms, this would enable us to send warnings to GNSS users when we expect that the forecast geomagnetic activity could be the origin of degradations in GNSS positions during the next few hours. For this reason, we implemented the so-called MAK model which allows forecasting K index at the geomagnetic observatory of Dourbes (Belgium) based on solar wind data (Andonov et al., 2004). This model will be replaced soon by an "hybrid" model which allows to nowcast and forecast Dourbes K based on both solar wind and Dourbes magnetometer real time measurements (Kutiev et al., 2008). Figure 3 shows the forecasts given by the MAK model on 21 January 2005.

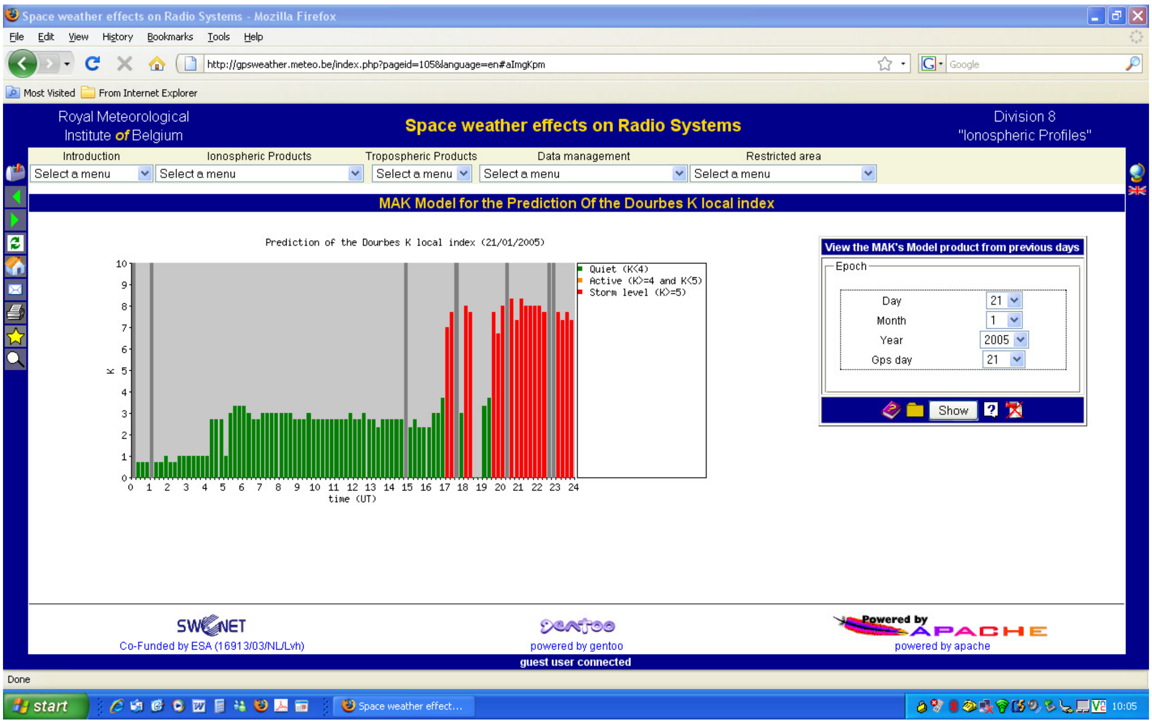

Fig. 3. MAK forecasts for 21 January 2005.

Towards a quantitative assessment of the positioning error

The RMI continues to perform studies in order to develop products which are able to provide users with a more "quantitative" assessment of ionospheric effects. Indeed, GNSS users are usually not interested ionosphere physics, TEC maps, TEC variability, … They would like to be directly informed about the positioning error in centimeters. In the frame of the above mentioned GALOCAD project, the RMI developed software which allows assessing the positioning error experienced by RTK users on the field (Lejeune and Warnant, 2008). This software which uses permanent station data has been validated with success on a few test cases representing "typical ionospheric conditions" (including a severe magnetic storm). It needs to be further automated and further validated before being able to produce an operational assessment of ionospheric effects. Before the end of 2009, a prototype service based on this software will be implemented for a 20 km region around Brussels.

Outlook: new web site and real time corrections

We have been using the site http://gpsweather.meteo.be during several years to publish our GNSS products. The maintenance of this site will be soon abandoned to switch to a new web site developed in the frame of the Belgian Solar-Terrestrial Centre of Excellence. This new site which will become operational at the beginning of 2009 will contain information about ionospheric activity (Dourbes Digisonde data, GPS TEC, local variability in TEC, TEC from ionosphere models, …), geomagnetic activity (Dourbes K nowcast and forecast using the Hybrid model), cosmic rays (Dourbes neutron monitor), ionospheric effects on GNSS (qualitative product using the single station method over Europe, prototype quantitative product at the end of 2009), etc.

In parallel to the research towards the assessment of ionospheric effects on positions, the RMI is also considering to provide GNSS users with real time ionospheric corrections. In particular, the RMI is developing an improved TEC reconstruction technique based on triple frequency measurements which are available from Galileo (GIOVE A and B) or which will be available from the modernized GPS constellation (Spits and Warnant, 2008). This method should improve TEC reconstruction by one order of magnitude what will allow us to develop more precise ionospheric corrections in the frame of different types of GNSS applications. The 3D reconstruction of electron concentration based on the combined use of GNSS and Digisonde data is also under study.

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