GPS positioning errors during the space weather event of October 2003

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Abstract

Due to the configuration of the Earth's magnetic field and its reconnection with the Interplanetary Magnetic Field (IMF), the high latitudes ionosphere is directly connected with outer space and, consequently, highly sensitive to the enhancement of the electromagnetic radiation and energetic particles coming from the Sun. Under such conditions the ionosphere may show the presence of small-scale structures or irregularities imbedded in the large-scale ambient plasma. These irregularities can produce short term phase and amplitude fluctuations in the carrier frequency of the radio waves which pass through them, commonly called ionospheric phase and amplitude scintillations. Since September 2003 a GPS Ionospheric Scintillation and TEC Monitor (GISTM) receiver has been deployed at the Italian Arctic station "Dirigibile Italia" in Ny Alesund (79.9° N, 11.9° E, Svalbard, Norway), in the frame of the ISACCO (Ionospheric Scintillations Arctic Campaign Coordinated Observation) project. The receiver computes and records GPS phase and amplitude scintillation parameters, as well as TEC (Total Electron Content). The measurements made by ISACCO during the superstorm of October 2003 have been here used to assess the positioning errors affecting GNSS (Global Navigation Satellite Systems, such as GPS and the European Galileo) users and their correlation with the occurrence of observed levels of scintillation.

The ISACCO Project

ISACCO (Ionospheric Scintillations Arctic Campaign Coordinated Observation) was born in September 2003 when the first GISTM receiver was installed at Ny Alesund (79.9° N, 11.9° E, Svalbard, Norway) (De Franceschi et al., 2006). In 2004 a second receiver was located about 1 km far from the first one, with the final goal, to be achieved after the forthcoming third installation, to remove possible geometric ambiguity from the measurements.

During the last Italian Antarctic Campaign in January 2006, another GISTM was installed at the Italian station "Mario Zucchelli", Terra Nova Bay (74.7° S, 164.1° E, Antarctica). The possibility of installing another receiver at the Italian-French Antarctic station of Concordia at DomeC, on the Antarctic plateau, is under evaluation.

The GISTM system consists of a NovAtel OEM4 dual-frequency receiver with special firmware and a stable ovenized crystal oscillator (OCXO), comprising the major component of a GPS signal monitor, specifically configured to measure amplitude and phase scintillation from the L1 frequency GPS signals, and ionospheric TEC (Total Electron Content) from the L1 and L2 frequency GPS signals.

The principal features of GISTM are the followings:

- Tracks and reports scintillation and TEC measurements from up to 11 GPS satellites in view.
- A 25 Hz raw signal intensity noise bandwidth and a 15 Hz phase noise bandwidth to insure that all the spectral components of both amplitude and phase scintillations are measured. Phase data and amplitude data are sampled at a 50 Hz rate.
- Single frequency (L1) satellite carrier phase is compared against a stable ovenized crystal oscillator (OCXO) to insure that all phase scintillation effects are recorded, not merely the 1/f refractive component measured by dual-frequency differential systems.
- Software is included in the GISTM to automatically compute and log the amplitude scintillation index, S4, and phase scintillation index, σ_ϕ, the latter computed over 1, 3, 10, 30 and 60 seconds. In addition, TEC and TEC rate are each logged every 15 seconds. Phase and amplitude data, either in raw form or detrended (to remove systematic variations), can also be logged at 50-Hz.

All scintillation and TEC data are stored locally and transmitted to a data server in quasi-real time (every hour). The 50 Hz raw data are transmitted to the data server and become readily available for post-processing analysis.

The amplitude scintillation is traditionally monitored by the S4 index, which is the standard deviation of the received power normalized by its mean value derived from the detrended received signal intensity. A high-pass filter is used for detrending the raw amplitude measurements. A fixed choice of a 0.1 Hz 3-dB cutoff frequency for both phase and amplitude filtering is used (Van Dierendonck et al., 1993, and references therein). Crucially for the analyses discussed in this article, the GISTM can also log carrier and code phase range data from both the L1 and L2 signal frequencies, so that these can be converted to the RINEX (Receiver Independent Exchange) format using a NovAtel proprietary software, therefore allowing manipulation and processing using different positioning techniques.

The typical GISTM configuration adopted in the ISACCO project is given in figure 1.

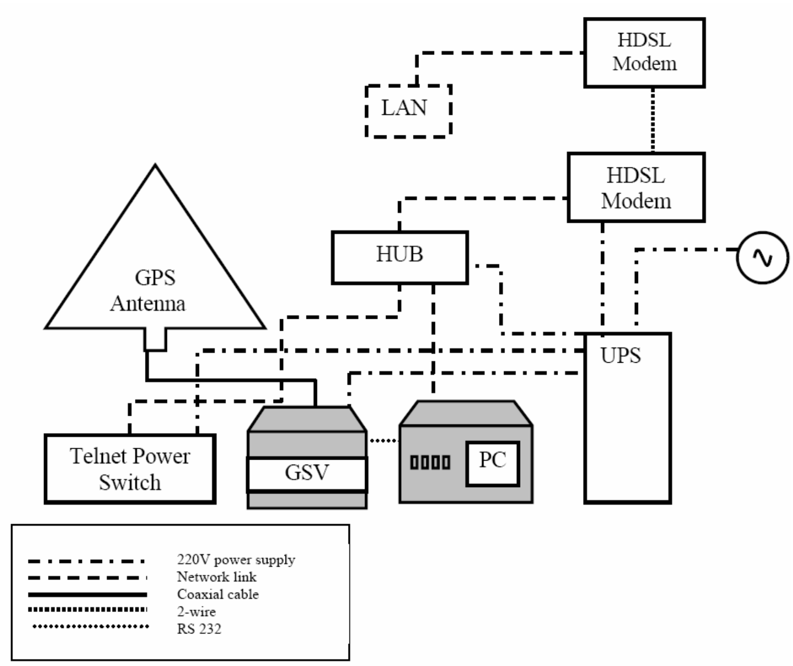


Figure 1: A scheme of a typical GISTM unit configuration adopted in the ISACCO project.

The TEC and scintillations data acquired by ISACCO are currently available via ftp, but a database to visualize, download, and plot scintillation and TEC data is under construction. The database, called electronic Space Weather (eSW), will host all the INGV upper atmosphere data collected by vertical and oblique ionospheric soundings, riometers (Relative Ionospheric Opacity meter) and ISACCO receivers.

The scintillation events of October 2003

The event, known as the Halloween storm, occurred in late October 2003 when an extremely large solar eruption, the biggest for decades, on 28 October 2003 caused an intense geomagnetic storm. A second solar eruption on the 29th of October resulted in a reintensification of the storm about a day later (fig.2; for a general overview see Gopalswamy et al., 2005). The observations recorded by ISACCO over Ny Alesund and by four similar receivers managed by the Institute of Engineering Surveying and Space Geodesy (IESSG), of the University of Nottingham, located in Northern Europe at latitudes between 53° and 70° N are at the base of recent papers (Aquino et al, 2005, De Franceschi et al., 2006) addressed to the understanding of the general movement of the ionospheric plasma during such a severe storm. In that case the physical mechanism, responsible for the majority of the scintillation events, seems to be the gradient drift instability as indicated by the coincidence of the enhancement of S4 and σ_ϕ with the edges of steep TEC gradients, for example observed in the link to PRN 31 from Ny Alesund (fig.3). In figure 3, Phi60 indicates the 60 seconds version of the σ_ϕ index, which has been frequently used by researchers to measure phase scintillation occurrence on the GPS L1 signal (e.g. Doherty et al, 2000). Further evidence of this physical mechanism being dominant during the October 2003 event was observed at the other stations forming the INGV/IESSG network (Aquino et al, 2005).

Effects on GPS positioning errors

In this article we describe experiments carried out to assess the impact of the October 2003 events on GPS user positioning errors, in particular when the L1 and L2 carrier phase data are used in a static network solution. Such GPS dual-frequency carrier phase based techniques are aimed at high accuracy (at least sub-centimeter level)applications, therefore the need to investigate whether and to what extent these could be affected, giving users a measure of potential impact. Similar analyses had been previously carried out using the IESSG network of receivers (e.g. Aquino et al., 2006), however this is the first such type of assessment at the arctic latitude of Ny Alesund.

For this purpose the RINEX data of the Ny Alesund GISTM for the days 30th and 31st October 2003 were split into 2-hour sessions for processing, so that possible effects could be correlated with temporal variations in the scintillation parameters, in particular the phase scintillation index σ_ϕ. As stated above, for the analyses presented herein we used the 60 seconds version of this index, referred here as Phi60. These 2-hour sessions were processed independently in a network approach to ensure the best possible accuracy, using available data from IGS (International GPS Service) permanent stations in the region, all of which with very accurate, known coordinates. The observable was the ionosphere corrected L1 double difference carrier phase, also referred to as the double difference ionospheric-free L1 carrier phase. Precise IGS orbits were also used in the processing scheme. The processing strategy was to fix the IGS stations to their known coordinates, the solution being obtained for the Ny Alesund station. Ground truth coordinates for this station were previously determined using the same approach, however from 'ionospherically quiet' data to avoid any corresponding accuracy degradation due to scintillation.

Figures 4 and 5 show the results of these experiments. The 3D errors computed for the Ny Alesund station in each of the 2-hour sessions and the RMS residuals are plotted for the two respective days being analysed and are represented by the bar graphs at the top and middle of each figure. Correspondingly, also presented are the values of the Phi60 index (in radians) for all satellites in view during the same two days, respectively (bottom plot in each figure), as observed by the Ny Alesund GISTM. It can be clearly seen that expected levels of accuracy corresponding to the positioning technique used are only achieved on sessions where the levels of recorded phase scintillation were the lowest. For example, in the sessions when the overall measured phase scintillation levels were below 0.3 radians the 3D errors fell mostly within a few milimeters. This can be seen quite markedly in particular on the 31st October (figure 5) after 12:00 UT. In contrast, when the levels of scintillation were the highest, as for example during the late sessions of the 30th October, the positioning errors increase correspondingly, with a clear correlation between errors and phase scintillation levels observed throughout the whole of the two days. A similar correlation between observed phase scintillation and the RMS residuals of the corresponding 2-hour sessions demonstrate the level of degradation imposed on the actual measurements by the occurrence of high levels of phase scintillation. The main conclusion here is that users relying on data collected during the periods of high phase scintillation occurrence would therefore be disappointed that their results would not meet the expected level of accuracy when post-processing the corresponding data.

Finally, it is worth mentioning that the storm occurred on 30th October 2003 was so intense that its effects were detected also at mid latitude over Nottingham (53^{o}N), as shown by the 3D error analysis carried out using the IESSG GISTM receiver (figure 6). In this case again a similar network approach was used and processing was performed as in the previous analyses, demonstrating that under such severe ionospheric conditions even users at mid latitudes may be affected.

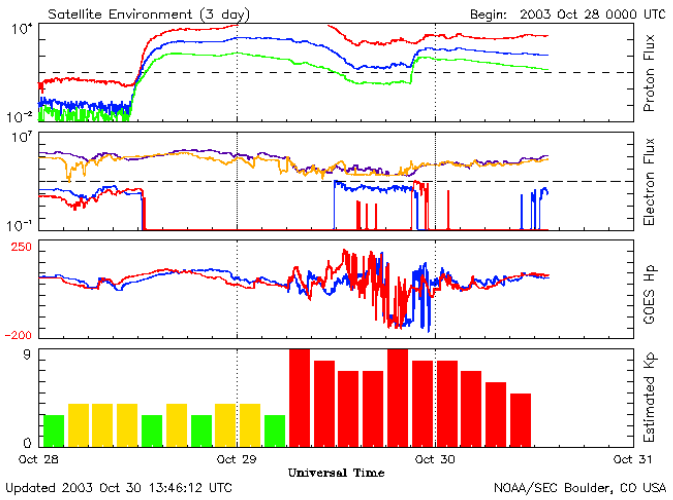


Figure 2. External conditions recorded by the GOES satellites during late October 2003.

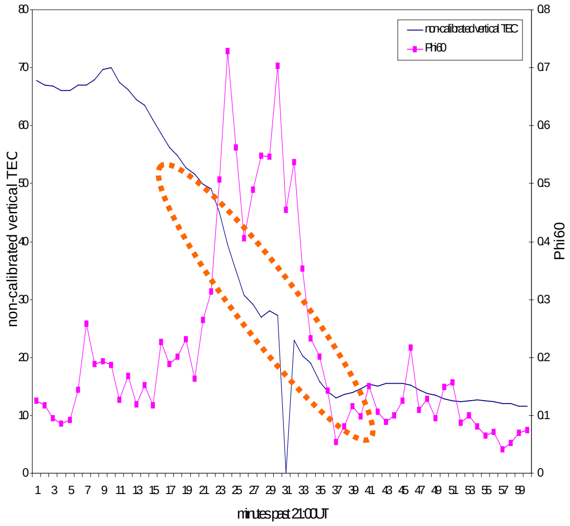
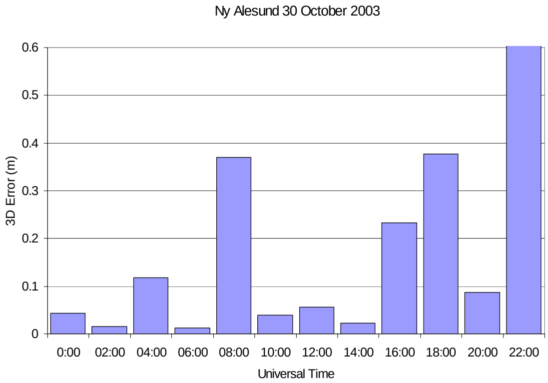
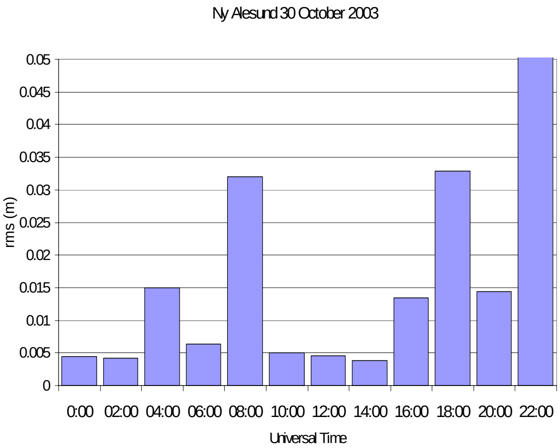


Figure 3. Temporal behaviour of the TEC and 60 seconds σ_ϕ (Phi60) recorded at Ny Alesund (link to PRN 31) between 21 and 22 UT on October 30, 2003.





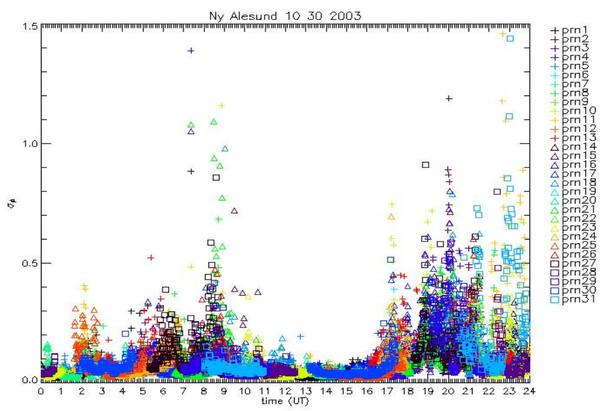


Figure 4. Correlation of 3D errors and RMS residuals (top and middle) with phase scintillation occurrence (bottom) at Ny Alesund on 30th October 2003 (see text for discussion)

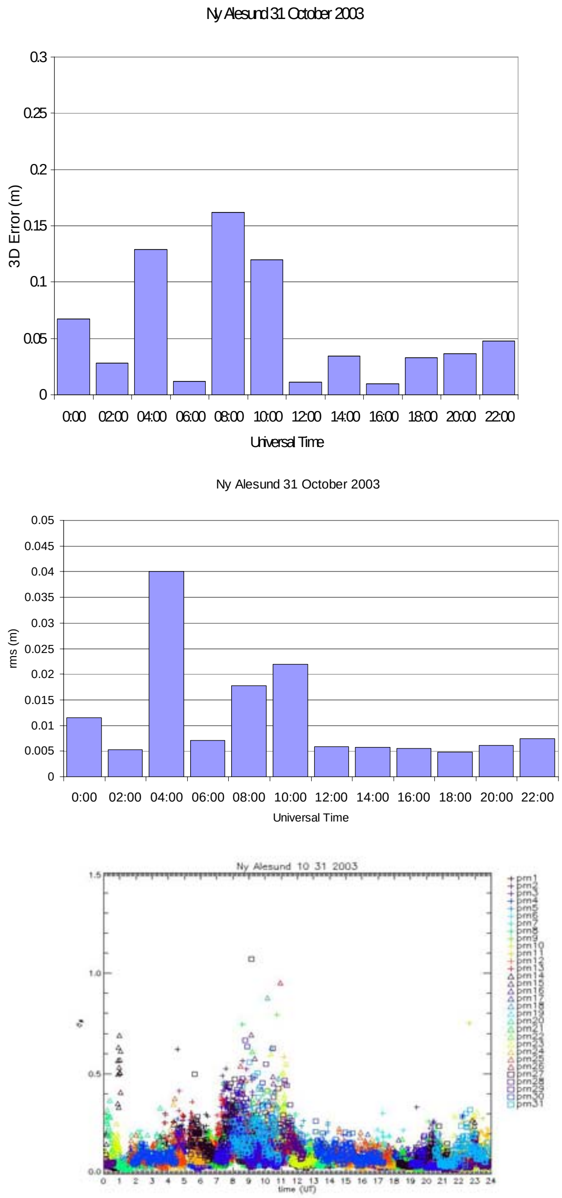


Figure 5. Correlation of 3D errors and RMS residuals (top and middle) with phase scintillation occurrence (bottom) at Ny Alesund on 31st October 2003 (see text for discussion)

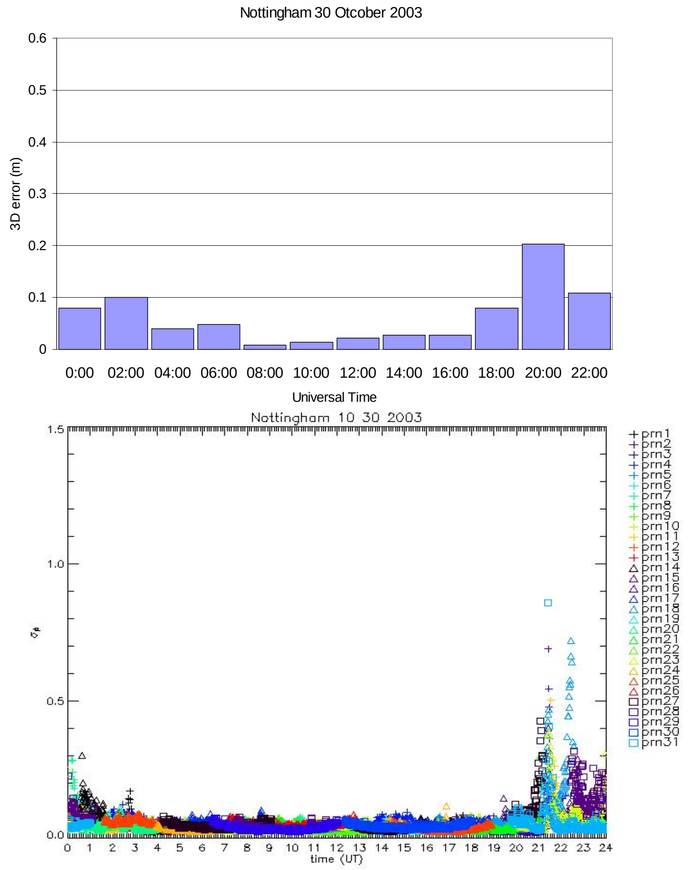


Figure 6. Correlation of 3D errors (top) and phase scintillation occurrence (bottom) at Nottingham on 30th October 2003 (see text for discussion)

Summary and discussions

The case study of October 2003 presented in this paper highlights the need for a continuous and systematic monitoring of the ionosphere to understand the physical mechanisms causing scintillations and, at the same time, to collect useful information to build and develop nowcasting and forecasting tools. These techniques, in turn, will contribute to the investigation and potential mitigation of the impact of the scintillations on the navigation, positioning and communication systems.

To achieve this goal it is important to create a scintillation database with a good spatial/temporal coverage. Given the scarceness of polar observations of ionospheric scintillations, the ISACCO project could offer a good opportunity to the users/scientific community, in terms of:

- Scientific aims, such as the understanding of the physical mechanism producing scintillations, the understanding of the general dynamics of the ionosphere during scintillation events, the understanding of the most favourable external conditions (solar disturbances, particle precipitations, geomagnetic storms) for the occurrence of scintillation events;
- Spectral analysis to validate and/or to improve the existing irregularities/scintillations models;
- Spectral analysis to create algorithms useful to create novel nowcasting and forecasting tools;

- Collaboration with international networks of permanent stations, as already done for IPY(http://www.ipy.org/development/eoi/details.php?id=551) and for the European COST296 Action (2005-2008; www.cost296.rl.ac.uk);
- Statistical studies on the positioning errors useful to quantify the impact on GNSS users;
- Participation to international projects addressed to the impact of ionospheric scintillation on the EGNOS (European Geostationary Navigation Overlay System) and on the new European GALILEO Satellite Navigation System.

Acknowledgments

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