Ionospheric impact on the performance of GNSS reference networks

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ABSTRACT

The ionospheric influence on reference networks has been proven at daily and longer-term levels and can be a significant error factor. The impact is noticeably stronger during ionospheric perturbations and storms, which raises the question about reliability of GNSS reference networks during such unfavourable conditions.

Addressed here are potential problems of present day GNSS reference network concepts, particularly problems that can be related to ionospheric interference. Presented also are case studies of adverse space weather effects on positioning. Analysed are the feasibility and effectivity of a space weather operational service for mitigation purposes.

INTRODUCTION

Multiple studies have already proved that the space weather (OFCMS, 1995) can have adverse effects on the Earth's ionosphere-plasmasphere system (Jakowski, 1996; Jakowski et al., 1998, 1999, 2002a, 2002b; Stankov, 2002). Since the trans-ionospheric propagation is a major source of error in the positioning based on Global Navigation Satellite Systems (GNSS), the GNSS users need to apply appropriate mitigation techniques, such as: corrections based on dual frequency techniques, model-assisted corrections, local and/or global augmentation systems (Klaehn et al., 2003).

One very important factor determining the performance of a GNSS reference network service is the time required to solve the phase ambiguities, the so called Ambiguity Fixing Time (AFT). Although not the only cause, the geomagnetic/ionospheric disturbances can lead to increased AFT and more frequent occurrence of increased AFTs (**Fig.1**).

Another important operational factor is the number of 'solved' GNSS satellites (a 'solved' satellite is a tracked satellite for which the phase ambiguities have been successfully fixed). To maintain a regular and reliable service, it is necessary to ensure that, at any moment, the signal phase ambiguities are 'solved' for at least five GNSS satellites. Reported are cases during ionospheric storms when the number of solved satellites falls below this threshold number (Jakowski et al., 2004).

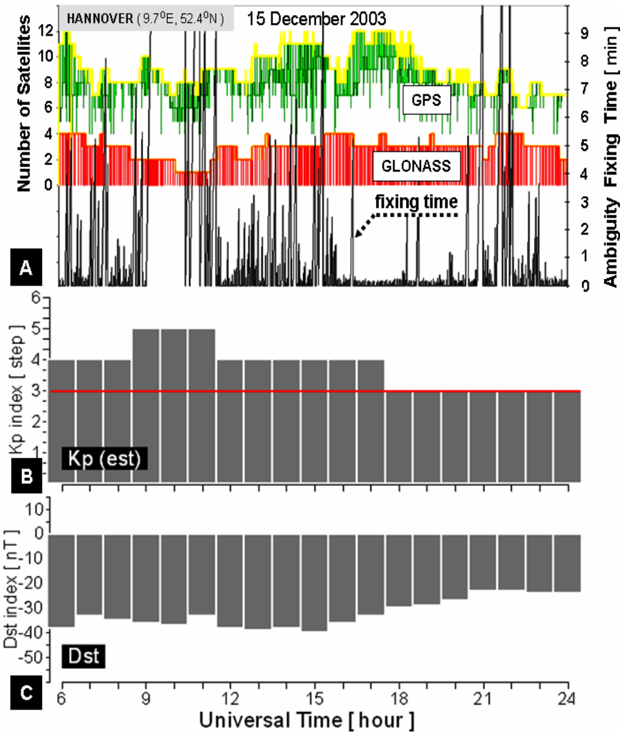

Fig.1. Frequent occurrence of increased ambiguity fixing time observed during the disturbed ionospheric conditions on 15 December 2003 (panel A). Notice the prolonged AFT between 0900 and 1030UT coinciding with the peak in the geomagnetic activity (panel B).

It is clear that the GNSS reference networks need permanent monitoring to ensure that they maintain their nominal accuracy (Wanninger, 1999, 2002, 2004). For the purpose, a Network Model Integrity (NMI) module has been developed and used within the GNSS reference network software to describe the non-linear error in the generated data (Chen, 2003). If the error exceeds a certain threshold (specific for each network) than the user should expect longer times for fixing the ambiguities and should be aware of increased inaccuracies. In extreme cases, fixing the ambiguities may not be possible at all. Developments that can help the network performance include: single-solution devices, higher density networks, and better nowcast and forecast of the ionospheric behaviour.

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SPACE WEATHER OPERATIONAL SERVICE

Motivated by the several problems experienced by GNSS users, the German Aerospace Centre (DLR) established an operational space-weather monitoring service aimed at improving GNSS positioning applications. The operational system processes data from ascos® (http://ascos.ruhrgas.de/) and SAPOS® (http://www.sapos.de/) reference networks and generates near real-time products which are immediately forwarded to consortium members, designated users, and general public (**Fig.2**). These products include Total Electron Content (TEC) maps, spatial and temporal TEC gradient maps, space weather alerts, etc. Relevant information and support are exchanged with members of the Space Weather European Network (SWENET).

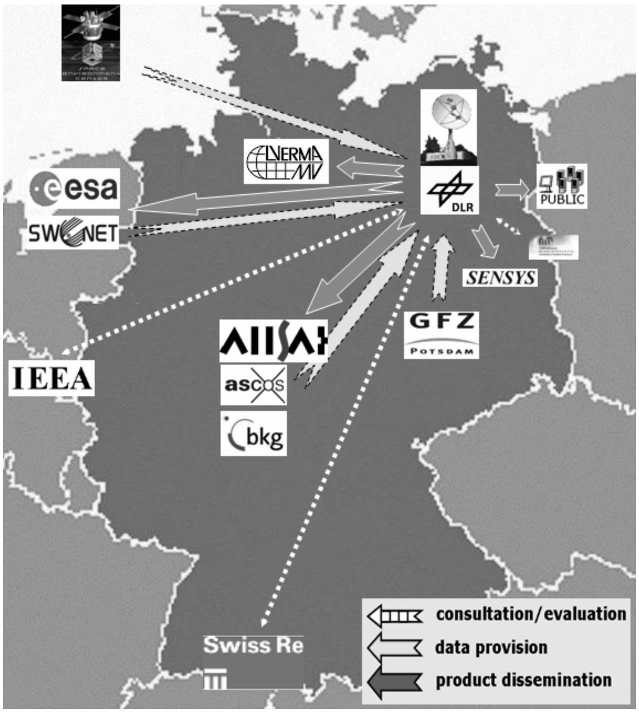

Fig.2. DLR Space Weather Operational System (http://www.kn.nz.dlr.de/swippa/index.htm)

The mapping resolution (**Fig.3**) is very high - both spatially (1 deg) and temporally (5 min); all maps produced with a latency of less than a minute. By generating such high-resolution maps of TEC and the TEC spatial and temporal gradients, the propagation of ionospheric disturbances becomes quite obvious (Stankov et al., 2005). As the front of the detected disturbances advances, it may negatively affect the performance of the reference networks. What is important to mention here is that large-scale TEC maps do not always provide clear and early indications of ongoing storm conditions, besides, such maps do not 'catch' small scale phenomena known also to cause problems. The high spatial and temporal mapping resolution achieved at DLR indicates that such resolution is already a good basis for developing a reliable nowcast service.

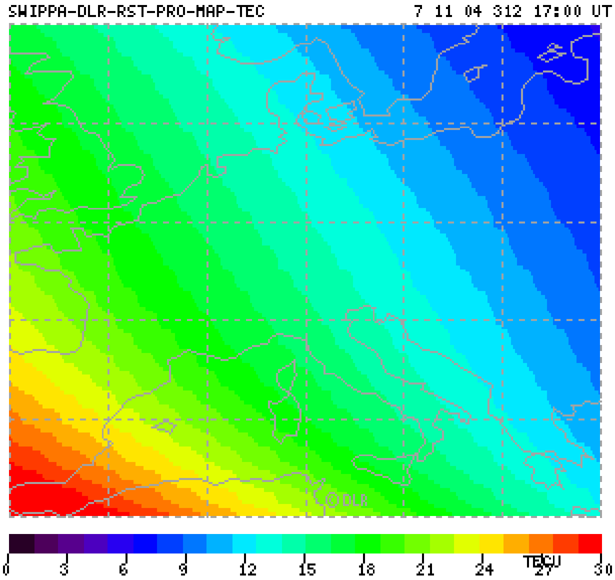

Fig.3. SWIPPA TEC map for 1700UT on 7 Nov 2004.

Generated also are TEC forecast maps based on prediction of the TEC 'quite-time behaviour' and subsequent correction deduced from measured TEC relative deviations from its quiet-time values (Stankov et al., 2001, 2002). Upon analysing and synthesising various types of real-time space weather observations, appropriate alerts are synthesised and forwarded to the users, warning them about ongoing and oncoming ionospheric disturbances. The next challenge is to reliably forecast the effects of the ionospheric disturbances.

IONOSPHERIC IMPACT ON GNSS REFERENCE NETWORK PERFORMANCE

To investigate the propagation of ionospheric disturbances, a very useful quantity is the relative deviation (ΔTEC) of the TEC current measurements from their corresponding monthly median, i.e. $\Delta TEC=(TEC-TECmed)/TECmed$. The ΔTEC ratio enhances the perturbation effects and thus facilitates the interpretation. For example, during the ionospheric storm on 7 November 2004, the European ΔTEC maps (**Fig.4**) show an area of higher ionization appearing in the North before 1600UT which expands and propagates towards lower latitudes and noticeably increases the total ionisation (Stankov et al., 2005). It must be underlined that significant differences exist between the winter and summer storm-time behaviour of both the TEC and the propagation of disturbances. Therefore, the impact on the GNSS reference network performance can vary.

The Network Model Integrity (NMI) is an important operational parameter used in the GNSS reference network software to control both, the integrity and quality of the satellite positioning services. In fact, the NMI module is used to describe the potential non-linear residual errors in the generated data transmitted to the user.

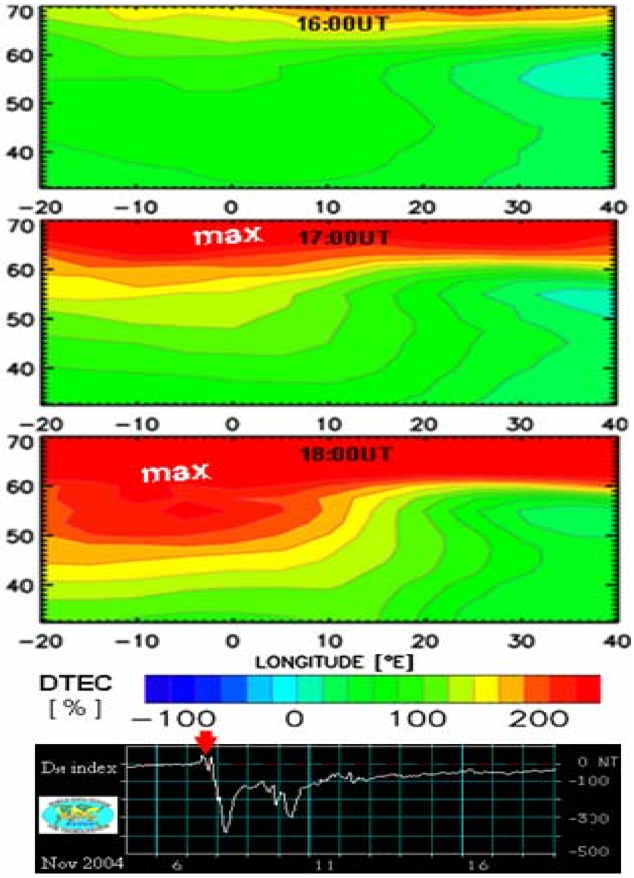

Fig.4. ΔTEC monitoring over Europe during the storm on 7 Nov 2004; notice the propagation of ionospheric disturbances in south/southwest direction.

The non-linear error is estimated in the following manner. Initially, the ionospheric influence on GNSS signals is determined and then the linear parts of these effects are removed by applying ionospheric and geometric corrections to the raw data. The influence on the user position is interpolated from the influence determined on the surrounding reference stations. During periods of disturbed ionosphere however, the ionospheric residuals cannot be considered linear even locally. The non-linear error is determined by omitting one station from the interpolation, comparing the interpolation results for all satellites at that station with the real measurements, then computing the weighted RMS over all satellites at one epoch, and accumulating these weighted RMS over one hour to obtain a 95% distribution. As mentioned before, if the residual error is large, the user may experience longer times for fixing the ambiguities and increased inaccuracies. An NMI plot shows the averaged error over an entire reference network (or if the network is too large – over a sub-network), i.e. the average of the errors estimated at each individual network station. The x-axis shows the hour of the day (universal time), while the y-axis shows the error. NMI results, for a South-East (SE) German reference network, are plotted for the storm day of 7 November 2004 (**Fig.5**).

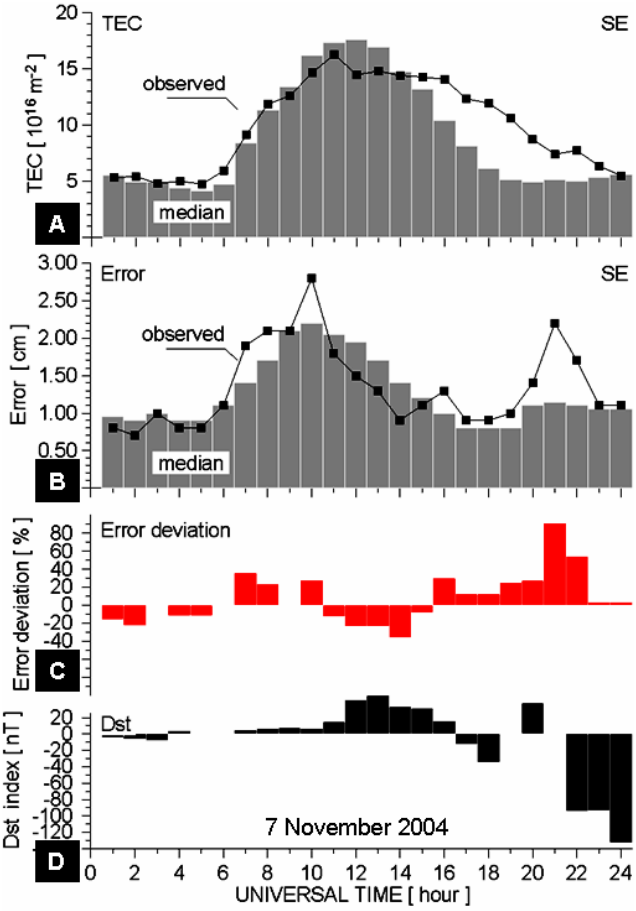

Fig.5. Network Model Integrity (NMI) during the storm on 7 November 2004. Panel A: observed and median TEC. Panel B: observed and median residual error. Panel C: Relative deviation of the error from its median values; notice the strong increase (up to 80%) of the residual error after 1800UT, during the main storm phase. Panel D: the Dst geomagnetic index.

It must be noted that the median behaviour of TEC and NMI correlate quite well which indicates that the network performance is linked to the total ionospheric ionisation. However, to prove the above correlation, more data from various seasons and solar activity levels are needed. Also, further work is required to better quantify the possible relationship between NMI and the ionospheric behaviour. Knowing these relationships, the GNSS reference network performance can than be easier to estimate from real-time ionospheric space weather data.

SUMMARY AND OUTLOOK

The SWIPPA project focuses on the concrete use of space weather information in operational GNSS reference networks for purposes of precise positioning. GNSS users are provided with warnings, nowcast and forecast of the ionospheric status, based on information of the actual and predicted state of the ionosphere, in order to deliver a precise and secure positioning service and to reduce the operation, production, and other business costs.

The benefits of the space weather service are being evaluated and recommendations for improving the service are expected. Expected also is that the market for GNSS based precise positioning and navigation applications will grow in near future, particularly when GALILEO becomes operational.

Development of forecast products and further improvement of the nowcast products, addressing the ionospheric space weather effects on GNSS applications, are some of the objectives of the new project SWACI (Space Weather Apllication Centre – Ionosphere).

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REFERENCES

Chen, X., H. Landau, U. Vollath (2003): New Tools for Network RTK Integrity Monitoring. Proc ION GNSS 2003, 9-12 Sep 2003, Portland OR USA.

Jakowski, N. (1996): TEC Monitoring by Using Satellite Positioning Systems. Modern Ionospheric Science (Eds. H. Kohl, R. Rüster, K. Schlegel), EGS, 371-390.

Jakowski, N., K. Hocke, S. Schlueter, S. Heise (1998): Space Weather Effects Detected by GPS Based TEC Monitoring. Proc. ESA Workshop on Space Weather, 11-13 November 1998, ESTEC, WP-155, 241-243.

Jakowski, N., S. Schlueter, E. Sardon (1999): Total Electron Content of the ionosphere during the geomagnetic storm on January 10, 1997. Journal of Atmospheric and Solar-Terrestrial Physics, 61, 299-307.

Jakowski, N., S. Heise, A. Wehrenpfennig, S. Schlueter, R. Reimer (2002a): GPS/GLONASS - based TEC measurements as a contributor for space weather. Journal of Atmospheric and Solar-Terrestrial Physics, 64, 729-735.

Jakowski, N., A. Wehrenpfennig, S. Heise, I. Kutiev (2002b): Space weather effects on trans-ionospheric radio wave propagation on 6 April 2000, Acta Geodaetica et Geophysica Hungarica, 37(2-3), 213-220.

Jakowski, N., S.M. Stankov, D. Klaehn, S. Schlueter, Y. Beniguel, J. Rueffer (2004): Operational service for monitoring and evaluating the space weather impact on precise positioning. Proc. European Navigation Conference GNSS 2004, 16-19 May 2004, Rotterdam, The Netherlands.

Klaehn, D., S. Schlueter, A. Jungstand (2003): On the implementation and performance of the ESTB ionospheric corrector processor. Proc. European Navigation Conference GNSS 2003, 22-25 April 2003, Graz Austria.

OFCMS - Office of the Federal Co-ordinator for Meteorological Services (1995): "National Space Weather Program Strategic Plan", Report FCM-P30-1995, August 1995, Washington D.C., USA.

Stankov, S. M. (2002): Ionosphere-plasmasphere system behaviour at disturbed and extreme magnetic conditions. OSTC Final Scientific Report, Royal Meteorological Institute of Belgium, Brussels, Belgium.

Stankov, S. M., I. Kutiev, N. Jakowski, A. Wehrenpfennig (2001): A new method for total electron content forecasting using Global Positioning System measurements. Proc. ESA Space Weather Workshop, 169-172, 17-19 December 2001, Noordwijk, The Netherlands.

Stankov, S.M., N. Jakowski, A. Wehrenpfennig, R. Warnant (2002): Index of local response to geomagnetic activity for use in the short-term ionospheric forecast. in: Ionospheric Modelling and Variability Studies for Telecommunication Applications (Proceedings of the EU COST-271 workshop, 1-5 October 2002, Faro, Portugal).

Stankov, S.M., N. Jakowski, V. Wilken, K.Tsybulya (2005): Generation and propagation of ionospheric disturbances studied by ground and space based GPS techniques. Proc. Ionospheric Effects Symposium (IES), 3-5 May 2005, Alexandria VA USA, Paper No. A064/9B2.

Wanninger, L. (1999): The Performance of Virtual Reference Stations in Active Geodetic GPS networks under Solar Maximum Conditions. Proc. ION GPS 1999, Nashville TN USA, 1419-1427.

Wanninger, L. (2002): Die Bedeutung der Ionosphaere fuer Referenzstationsnetze. Proc. SAPOS Symposium, 21-23 May 2002, Hannover Germany.

Wanninger, L. (2004): Ionospheric Disturbance Indices for RTK and Network RTK Positioning. Proc. ION GNSS 2004, Long Beach CA USA, 2849-2854.