ADVERSE SPACE WEATHER EFFECTS ON PRECISE POSITIONING – CASE STUDIES

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INTRODUCTION

The ionospheric plasma can significantly influence the propagation of radio waves. Ionospheric disturbances can cause range errors, rapid phase and amplitude fluctuations (radio scintillations) of satellite signals leading to degradation of the system performance, its accuracy and reliability. The cause of such disturbances should be sought in the processes originating from the Sun and the space weather. Numerous studies on this subject have been already carried out internationally in order to measure the space weather induced effects, to understand and mitigate the impact of the space weather on the technological systems, and ultimately - to forecast these space weather effects [1,3, 4, 5, 6].

Since the trans-ionospheric propagation errors are major error sources in satellite navigation and positioning, Global Navigation Satellite System (GNSS) users have to apply appropriate mitigation techniques such as corrections by the use of dual frequency techniques, model corrections, local/global augmentation systems. Strong gradients in the horizontal Total Electron Content (TEC) structure as well as small-scale structures of the ionospheric plasma may seriously complicate or even prevent the resolution of phase ambiguities in precise geodetic or surveying networks. In the reference networks, the ionospheric corrections degrade with increasing spatial de-correlation of propagation terms, particularly during severe ionospheric storms. Whereas medium scale variations in time and space such as Traveling Ionospheric Disturbances (TIDs) mainly impact reference networks, local small scale irregularities may cause radio scintillations inducing severe signal degradation and even loss of lock. Amplitude scintillations and phase fluctuations are produced by refractive and diffractive scattering by ionospheric plasma-density irregularities, especially at equatorial and polar latitudes.

Reported here are adverse space weather effects on precise positioning, observed during two recent strong ionospheric storms, 29 October 2003 and 25 July 2004. The analysis is focused on the ionosphere perturbations impact on positioning - the increased time required to fix GNSS signal phase ambiguities; discrepancies between the number of tracked, processed and solved GNSS satellites; strong phase and amplitude fluctuations, etc. Detailed also are the observations of the geophysical conditions during these two storms and the means to mitigate the adverse effects [4,7].

THE OCTOBER 2003 IONOSPHERIC STORM

Solar region 486 is the largest sunspot group of the current 23-th solar cycle, which produced one of the most powerful proton flares of this solar cycle peaking at 11:10UT on 28 October 2003. This massive coronal mass ejection (CME), observed on SOHO/LASCO imagery, impacted the Earth's magnetic field at 06:11UT on 29 October 2003. Thus, the transit time was about 19 hours making this CME one of the fastest ever, with a speed of near 2000 km/s. A second CME peeled off the Sun at 20:49UT on 29 October 2003 and charged particles from the ejection started arriving at the Earth around 16:00UT on 30 October 2003. This is yet another remarkable transit from Sun to Earth; this second blast was moving -- at an estimated speed of 8.4 million km an hour -- even faster than the first one did and particles from the first lingered even as the second onslaught started. These two consecutive CMEs caused severe disturbances of the interplanetary (IMF) and geomagnetic fields resulting in persistent severe storms (Kp reaching its maximum value of 9). The first CME was characterized with strong southward IMF Bz and initiated severe storming at middle and high latitudes in the 06:00-09:00UT period on 29 October. Immediately after that, in the 09:00-18:00UT period, northward Bz prevailed; however, the major (to severe) storming persisted. Later, a sharp southward turn in the Bz occurred (at 18:00UT), thus ending the period with severe storming again (Kp=9). The second CME was also powerful, the GOES-10, -11, and -12 geosynchronous satellites (Fig.1, top panels) have experienced magnetopause crossings and in fact they have been outside the magnetopause for much of the time since the onset of the storms. IMF Bz sustained southward values, in the -15 to –30 nT range, assuring a severe response. The geomagnetic field was at predominantly severe-storm levels (Fig.1, bottom panel).

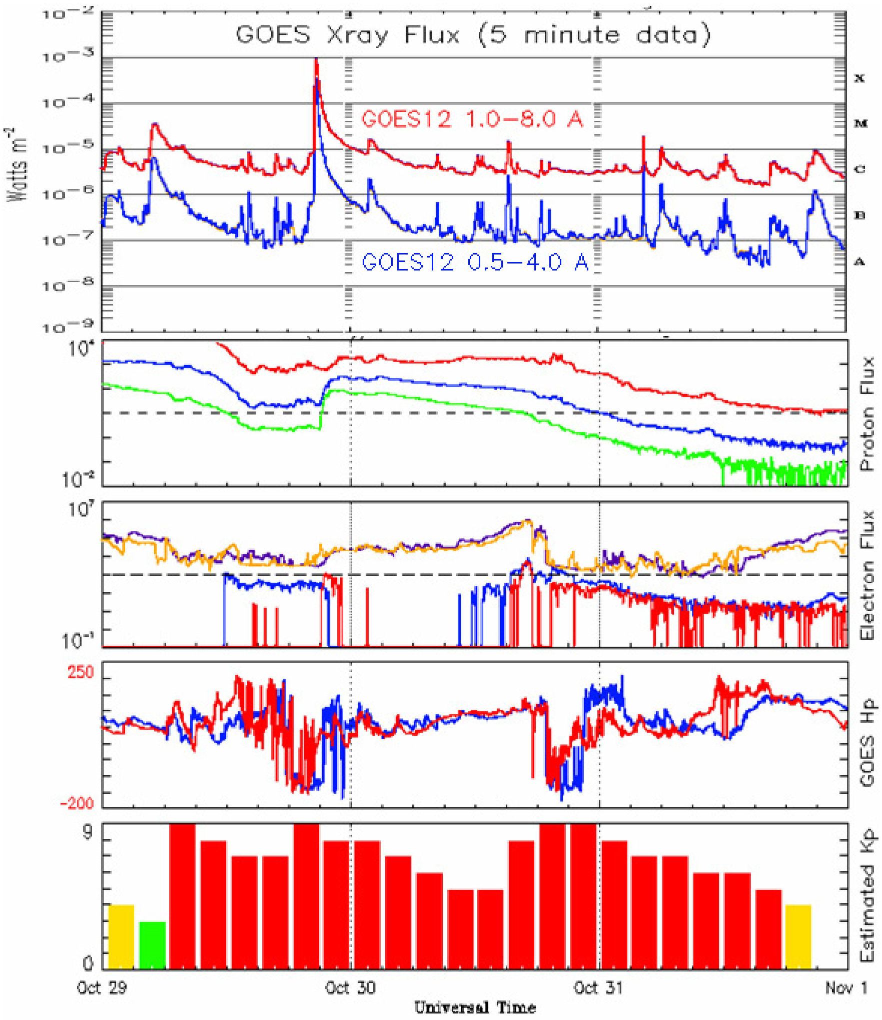

Fig.1. Space environment observations for the 29-31/10/2003 storm period. Presented are plots of the 5-min solar X-ray flux values measured on the GOES satellites (top panel), proton flux, electron flux, Hp, and estimated Kp values. Courtesy of NOAA/SEC Boulder, USA.

There were several problems -- experienced and reported by GNSS users -- undoubtedly linked to the above described adverse space weather conditions. For example, several GPS receiver outages have been reported and the Wide Area Augmentation System (WAAS) service was interrupted. The permanent TEC monitoring over both the North and South poles indicated strong perturbations - probably due to active particle precipitation and electromagnetic plasma convection across the poles. Enhanced scintillation level was also detected. On the user side, heavy problems occurred in differential GPS applications. GPS reference networks were not reliable during the storm. Next, we will describe two of the most frequently observed effects – the increased time required to fix GNSS signal phase ambiguities and the observed discrepancies between the number of tracked, processed and solved GNSS satellites.

Increased time required to fix GNSS signal phase ambiguities

Since the trans-ionospheric propagation errors are a major source of positioning errors in satellite-based navigation, the users of satellite navigation systems have to apply appropriate mitigation techniques such as: corrections based on dual frequency techniques, model-assisted corrections, local and/or global augmentation systems. With the help of transmitted GNSS corrections, a positioning with accuracy of a few centimeters is already achievable in GPS reference networks. One very important factor determining the performance of any GNSS reference network service is the time required to solve the phase ambiguities. The strong variability of the ionosphere obviously affects the determination of phase ambiguities. Presented here (Fig. 2, top panel) is a case when difficulties arise and at a certain stage it becomes even impossible to fix ambiguities. At 12:32UT real problems occurred: the time to fix the ambiguities extended too much and it became impossible to get a fixed solution. It is very difficult during such periods to model the error influences and therefore the user cannot receive a precise positioning. Certainly, the GNSS users can benefit a lot if reliable nowcast and forecast of the ionosphere disturbances are available to them.

Discrepancies between the number of tracked, processed and solved GNSS satellites

Another exemplary situation is presented here. Special computer programs are used for 'solving' phase ambiguities. To maintain a regular and reliable service, it is necessary to ensure that, at any given moment in time, the signal phase ambiguities are 'solved' for at least five GNSS satellites. For this purpose (to ensure this minimum number of 'solved' satellites), for each particular ground receiving station, as many GPS and GLONASS satellites as possible are tracked. Some of these 'tracked' satellites cannot be used due to restrictions imposed on the satellite elevation angle (elevation cutoff criterium), the signal-to-noise ratio (SNR criterium), etc. The remaining satellites are being 'processed', i.e. their signals are used in the processing software for fixing the ambiguities. Criteria also exist when trying to solve the ambiguities, for example the errors should be small and the solution stable. Therefore, due to the 'solving criteria' some of the 'processed' satellites cannot be used. Thus, the number of satellites, for which the ambiguities have been fixed (solved), are called 'solved' satellites and their number is equal to or less than the number of processed satellites. To maintain a regular and reliable service, five 'solved' satellites are needed at any moment in time. Under normal conditions, the number of 'processed' satellites should equal the number of 'solved' satellites. This is exactly the situation between 00:00UT and 06:00UT on 29 October 2003 when the numbers are equal and varying between 11 and 6 satellites (Fig. 2, bottom panel).

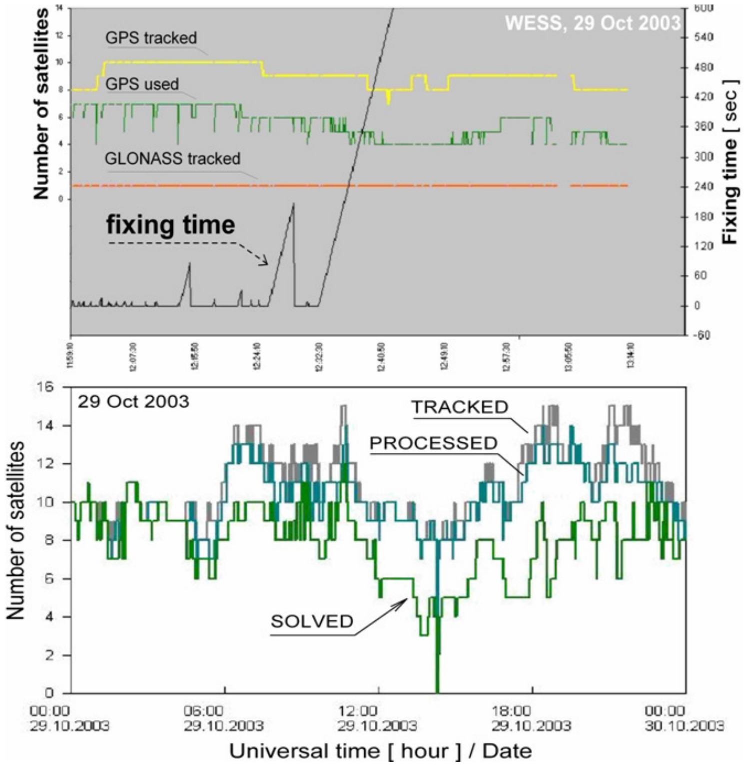

Fig.2. Space weather's adverse effects during the 29/10/2003 ionospheric storm. Top panel: Time required to fix ambiguities; notice the long fixing time (more than 3 minutes) at 12:24UT and the breakdown at 12:32UT. Bottom panel: Number of tracked, processed and solved satellites; normally, the number of processed satellites should equal the number of solved satellites.

The strong ionospheric perturbation leading to performance degradation of the reference network, particularly on 29 October in the afternoon, was already indicated by large scale perturbations of the ionospheric plasma at the Northern polar region (Fig.3). When the solar wind energy, measured by the Northern hemispherical power index [2], couples into the magnetosphere, strong convection electric fields are generated which may be accompanied by direct particle precipitation producing additional ionization mainly in the bottomside ionosphere. The action of a strong convection electric field is directly visible in the polar TEC maps in particular from 0700 -1200 UT where a significant horizontal plasma transport from the day-side towards the night-side ionosphere takes place probably via $\mathbf{E}\times\mathbf{B}$ drift. This observation clearly indicates that the polar ionosphere is a kind of "space weather kitchen" where subsequent perturbation processes propagating towards lower latitudes are prepared. This gives a unique chance to warn or even to predict severe ionospheric perturbations expected to occur in mid-latitudes after a certain time delay. Unfortunately very little is known so far about such propagation processes [1]. A careful analysis of these observations will contribute to improve our understanding of large scale perturbation processes and their propagation towards lower latitudes which obviously arrived in this case over Germany shortly after the noon. A second event of enhanced perturbation activity is seen in the polar TEC maps around 21:00 and 22:00 UT which is more significant at the South Pole.

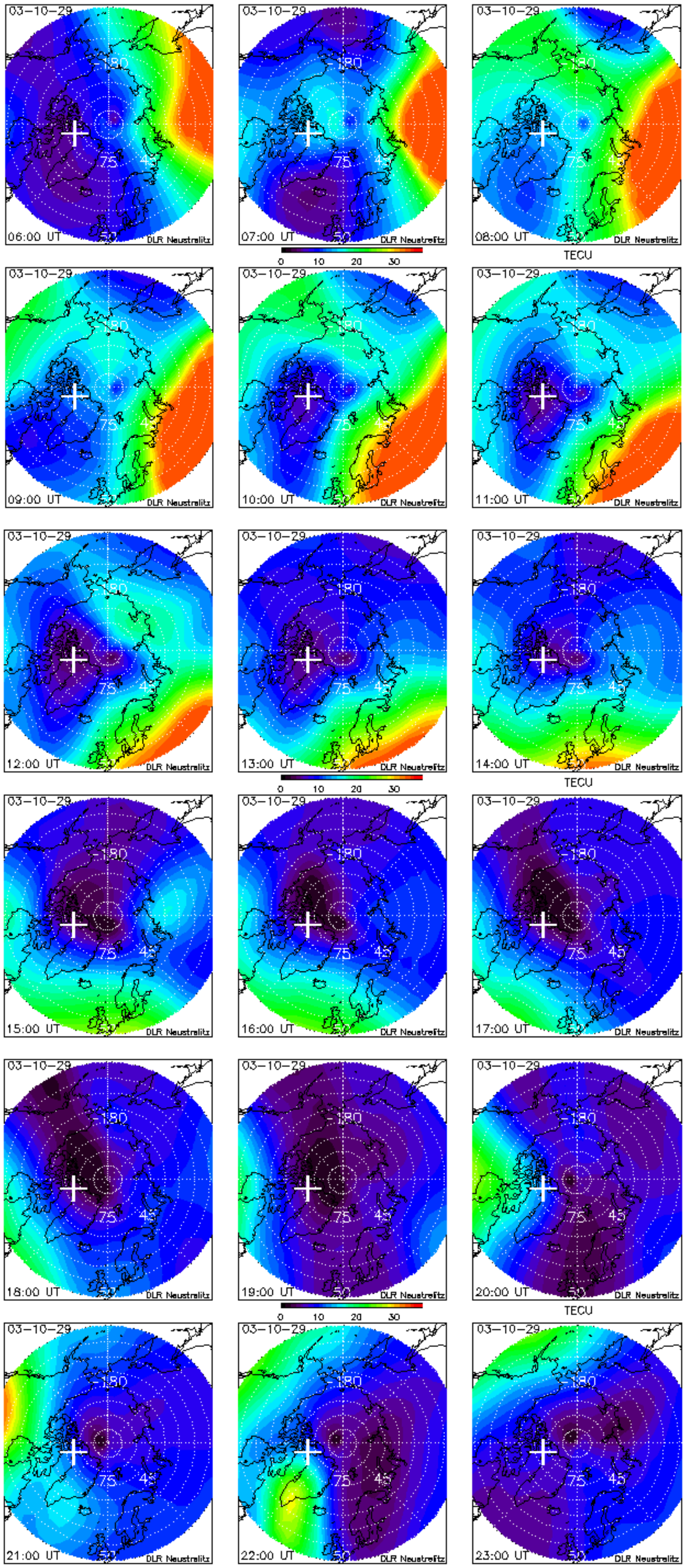

Fig.3. Ground-based GPS TEC observations over the North Pole region in the 06:00–23:00UT period on 29/10/2003. Courtesy of DLR/IKN Neustrelitz (http://www.kn.nz.dlr.de/).

THE JULY 2004 IONOSPHERIC STORM

The last 10 days of July 2004 were remarkably active period considering the approaching solar minimum of the current cycle. Three major storm events occurred, with Dst index reaching -104 nT on $23^{\text{-th}}$, -150 nT on $25^{\text{-th}}$, and -167 nT on $27^{\text{-th}}$ of July. The IMF and geomagnetic fields were seriously disturbed (Fig.4). Again, several problems were reported by GNSS users but here we will take a closer look at the reference network model integrity.

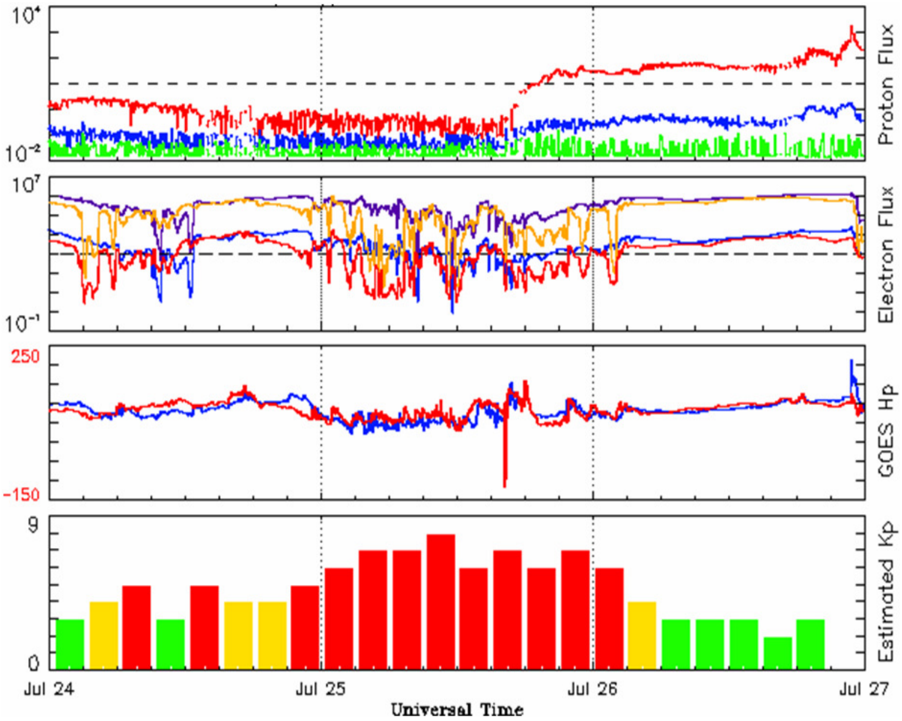

Fig.4. Space environment parameters observed during the storm on 25/07/2004. Presented are plots of the proton flux, electron flux, Hp, and estimated Kp values.
Courtesy of SEC/NOAA Boulder, USA.

Decreased network model integrity

The Network Model Integrity module is used within the software of the *ascos satellite positioning services* reference network (http://ascos.ruhrgas.de/). First, the ionospheric influence on GNSS signals is determined and then the software removes the linear parts of these effects 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. An associated problem is that, during periods of disturbed ionosphere, the ionospheric residuals cannot be considered as linear. The module is used to describe the non-linear error in the generated data. This error is determined by omitting one station from the calculation of the ionospheric influence. Then, the surrounding stations are used to predict the ionospheric influence for the site of the omitted station. Finally, the predicted error is compared with measured values and the ionospheric and geometric errors are shown separately.

The graphs show the remaining error at different stations located in different areas. As it is not possible to calculate correction data all over Germany with one server only, *ascos* has split the calculation for the network onto several servers covering different areas with approximately 40 stations each. The remaining error of a single subnet is then plotted with an average value. The x-axis shows the hour of the day (universal time), while the y-axis shows the amount of the error in metres. Recent experiences teach that it is hardly possible to obtain precise and accurate results while the error is larger than 8 cm. If the error is between 4 and 8 cm, the reference network user has to accept longer times to fix ambiguities. Smaller values represent a quiet ionosphere.

The graphs show the results of the network model integrity tool for 25 July 2004. The plots of the different subnets are shown according to the area they cover in Germany (NW – North West, NE - North East, MW – Mid West, ME – Mid East, SW - South West, SE – South East). Around noon, higher-than-usual values can be seen in the eastern areas. Later, the influence is detected in the western areas as well.

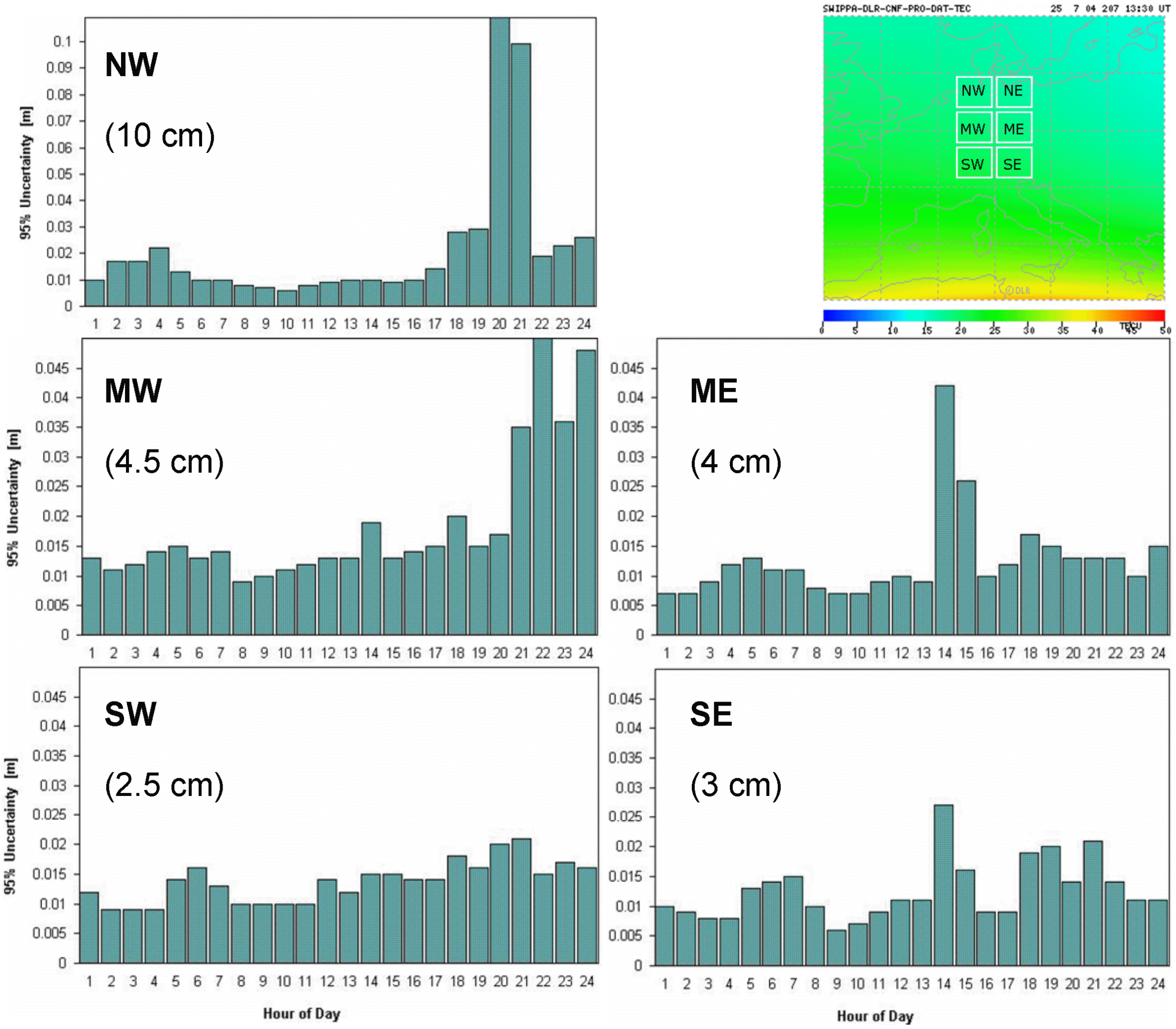

Fig.5. Space weather's adverse effects on the operational quality of reference networks. The *ascos* network model integrity on 25/07/2004 for the NW, MW, SW, ME, SE areas of Germany (cf. the TEC map in the upper right corner).

OPERATIONAL SERVICE FOR MONITORING THE SPACE WEATHER IMPACT

Motivated by the several problems experienced by GNSS users, after analysing these problems and considering the research and operational monitoring experience, the German Aerospace Centre (DLR) team initiated a project SWIPPA (Space Weather Impact on Precise Positioning Applications) aiming at establishing and operating a specific space-weather monitoring service for improving current Global Navigation Satellite System (GNSS) applications (http://www.kn.nz.dlr.de/swippa/index.htm). Within this project, real-time data products and services (TEC maps, TEC spatial and temporal gradients maps, cycle slips number, geophysical conditions warnings, etc.) are offered to the consortium members, designated users, and general public. These products, based on information of the actual and predicted state of the ionosphere-plasmasphere system, provide only the type of space weather information which GNSS users really need for the execution of their day-to-day tasks. As an example, it is demonstrated here how SWIPPA products and services can really help. By generating high-resolution maps of the TEC spatial and temporal gradients (Fig.6), the sharp increase in TEC in the North-East region during the 25 July 2004 storm becomes quite obvious and its propagation in south- and west-ward direction clear. As the front of the detected disturbances moves through Europe, it causes various problems, including the decrease in the network model integrity (Fig.5).

What is important to mention here is that, in this case, probably due to the exhaustion of the ionosphere during the persisting storm conditions from the previous days, the large-scale TEC maps of the polar and European regions did not provide clear and early indications for the developing storm conditions at lower latitudes. Such clear and advanced indications have been successfully delivered by the new, direct, high-resolution, and frequent mapping of the TEC values and TEC spatial/temporal gradients deduced from the *ascos* network (Fig. 6).

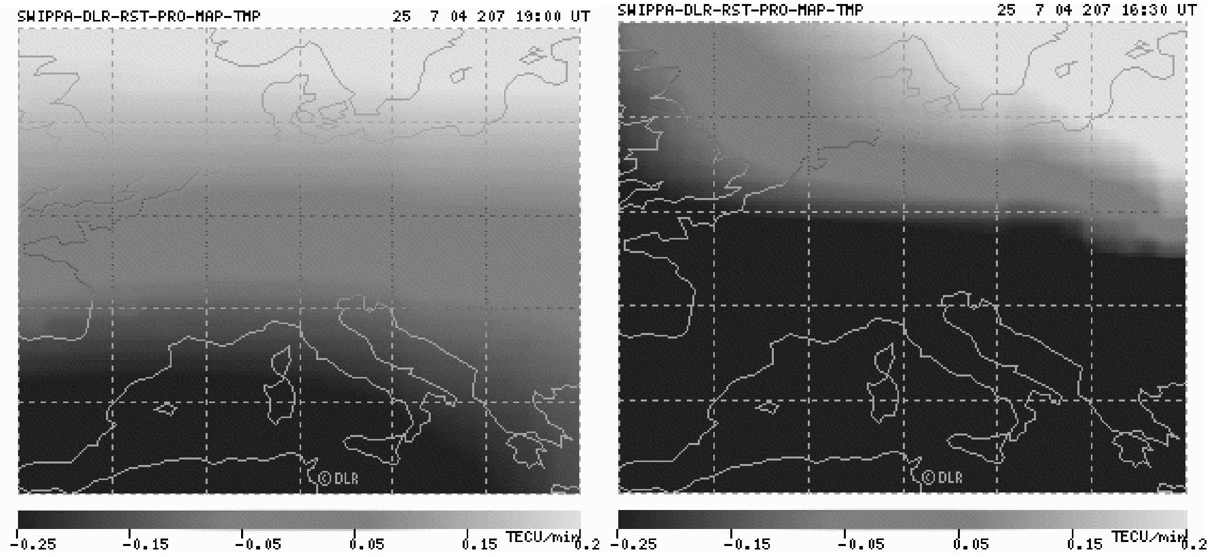

Fig.6. TEC temporal gradients maps over the European area, for 16:30 UT (right panel) and 19:00UT (left panel) on 25/07/2004. Courtesy of DLR/IKN via SWIPPA (http://www.kn.nz.dlr.de/swippa/index.htm).

DLR participates actively in the European Space Weather Programme; SWIPPA is a substantial contribution to this program and is partly sponsored by the European Space Agency (ESA) via the Space Weather Pilot Project (http://www.estec.esa.nl/wmwww/wma/spweather/esa_initiatives/pilotproject/pilotproject.html). Recently, the Space Weather European Network (SWENET) has been established. SWENET aims at federating existing and newly created space weather services, assisting in the development of a common network, developing associated software infrastructure, providing support to service development activities, encouraging common development, undertaking public outreach activities, assessing user requirements, etc.

SUMMARY AND OUTLOOK

Presented were several cases of adverse space weather effects on precise positioning observed during the ionospheric storms on 29 October 2003 and 25 July 2004. The focus was on the increased fixing time, the discrepancies between processed and solved satellites, and the decreased reference network reliability. Demonstrated was also the necessity of an operational nowcast and forecast service using real-time space weather observations.

In relation to the above-mentioned problems and necessity of space-weather monitoring service, outlined was the SWIPPA project. This project utilises specific space weather information in reference networks in order to help GNSS specialists to deliver a more reliable, precise and secure positioning service and to eventually reduce the operation, production, and other business costs. Another major task of the project is to regularly provide relevant information and support to the SWENET community.

The benefits of the operational space-weather service will be independently evaluated and recommendations for improvements will be given. However, in line with the increased sophistication of present-day technological systems, expected is a growing market for navigational and precise positioning applications in Europe, particularly when GALILEO becomes operational.

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