Generation and propagation of ionospheric disturbances studied by ground and space based GPS techniques

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Abstract

To gain a more comprehensive view of the powerful and dynamic plasma processes occurring during ionospheric storms, GPS TEC ground-based measurements from the Polar and European regions together with global space-based GPS observations performed onboard low earth orbiting satellites have been analyzed. Presented here are case and statistical studies of ionospheric storms that clearly show the generation and development of ionospheric disturbances. Discussed also are the capabilities of various techniques for routinely monitoring these ionospheric disturbances. It is concluded that the permanent monitoring of the ionosphere-plasmasphere system can play a significant role in mitigating adverse space weather effects on GNSS positioning.

Introduction

Ionospheric storms, being extreme forms of space weather, can have significant adverse effects on the performance of present-day technological systems. For example, one very important factor determining the performance of the GNSS reference network services is the time required to solve the phase ambiguities. Presented here is a case during the severely disturbed day of November 21, 2003 (Fig.1). Frequent occurrence of relatively long fixing times has been observed, particularly in the first half of the day, when the fixing times occasionally lasted more than 800 seconds. Reported are also cases of even longer fixing times during storms and extreme cases of failures in resolving the ambiguities (Jakowski et al., 2004). Prolonged and/or frequent increases of the fixing times may have adverse impact on GNSS positioning and safety-critical applications.

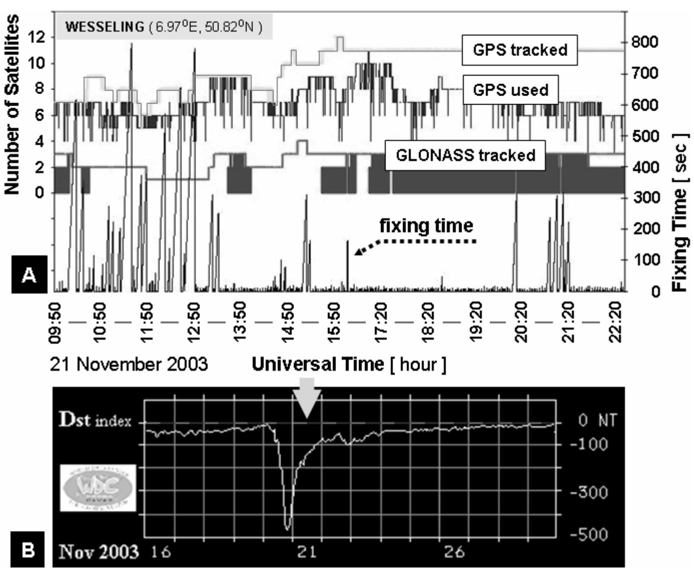

Fig.1. Ambiguity fixing time, as monitored on November 21, 2003. The severe geomagnetic storm started on November 20, with Dst values dropping far below the -400 mark in the evening hours (Panel B). Frequent occurrences of increased ambiguity fixing time (occasionally exceeding 800 seconds) are observed the following day of November 21 (Panel A). Notice also the decreased number of tracked and used GPS satellites. Dst provided by WDC-2 Kyoto.

Another important parameter to watch is the number of tracked/used GNSS satellites. For each particular ground receiving station, it is necessary to track as many GNSS satellites as possible. Some of these 'tracked' satellites cannot be used due to restrictions imposed on the satellite elevation angle (elevation cut-off criterion), signal-to-noise ratio (SNR criterion), etc. The remaining satellites are used in the processing software for fixing the ambiguities. Since further restrictions are imposed on the solution, such as limitation on error magnitude and stability of solution, the number of these 'processed' satellites however should not be less than five to ensure that the services are reliable.

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Now, as it is obvious that strong ionospheric perturbations affect the determination of phase ambiguities, it becomes important to find ways to mitigate associated problems in GNSS applications. Therefore, it is important to understand the mechanisms behind the ionospheric perturbations, examine their spatial development/propagation patterns, identify the whole spectrum of possible adverse effects, monitor the space weather and ionosphere characteristics, and ultimately - try to predict the effects of those perturbations. To obtain some more insight into the storm mechanisms we have also studied the slab thickness behavior at several ionosonde locations in Europe. Reported is wide variability of this parameter during storms, suggesting that significant vertical redistributions of plasma take place in such periods. Presented also are case and statistical studies of ionosphere storms by using ionospheric radio occultation measurements. The results show more frequent occurrences of small and medium scale irregularities, which are known to cause problems in various GPS applications.

In order to better research the above-mentioned issues, the German Aerospace Centre (DLR) established a specific ionosphere/space-weather monitoring system. This novel operational system collects various types of information on the past, actual and predicted state of the ionosphere and plasmasphere, process it immediately, and deliver real-time data products, such as TEC maps, TEC spatial and temporal gradients maps, cycle slip number, geophysical condition warnings, etc. Briefly described is the service which is offered to consortium members, scientific and industry users, educational and general public structures.

Ground-based GNSS measurements

Space weather-induced disturbances in the ionosphere are characterized by strong variations in the vertical and horizontal electron density distribution. Ground-based GNSS measurements can effectively be used to estimate the horizontal distribution of TEC on regional and global scale. DLR have been operating, since 1995, a system for regularly processing ground based GPS data and producing maps of the integrated electron content over the European and Polar regions (Jakowski et al. 2002a). The GPS data, obtained mainly from the International GPS Service (IGS) member stations, allow for the determination of slant TEC values along numerous satellite-receiver links. After calibration, the slant TEC data are mapped to the vertical by utilizing a mapping function based on a single layer approximation at h=400 km. Afterwards, the measurements are assimilated into a regional model, NTCM (Neustrelitz TEC Model), ensuring that the final map provides real values at/near the points of measurements and model values over the areas without measurements. Vertical TEC values are computed for a grid consisting of 768 grid points within the latitude range between 50°N and 90°N enabling the imaging of large scale perturbations in the polar/auroral zone.

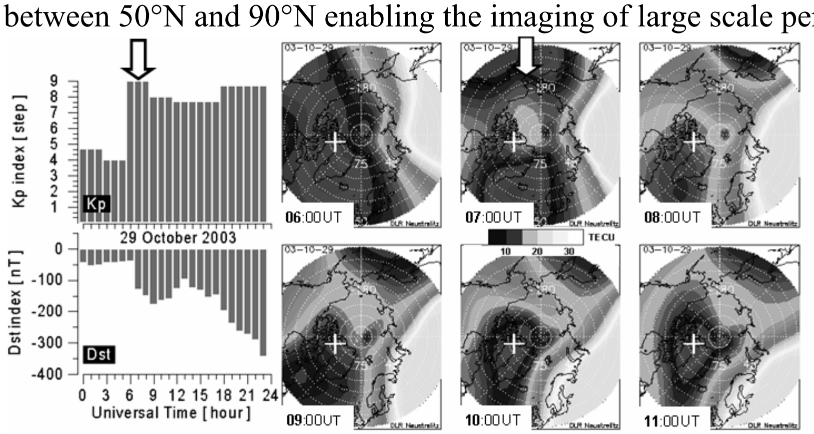

Fig.2. Ground-based GPS TEC observation of the north pole region on Oct. 29, 2003. The geomagnetic pole marked with a cross.

Enhanced space weather impact is expected first on the high-latitude ionosphere because the latter is much stronger coupled with the magnetosphere and the solar wind. For example, on the background of already increased TEC, a patch of even higher ionization was detected in the plots of the polar region during the onset of the storm on October 29, 2003 (Fig.2); the patch grew in size and moved southward over both the day and night-time hemispheres. High-latitude electric fields, precipitation of energetic particles, and plasma convection, are reportedly the most powerful driving forces for the highly dynamic and complex processes in this region. During storms, enhancements in the solar wind energy cause large perturbations in the high-latitude ionosphere and thermosphere resulting in significant variability of the plasma density, which propagate towards lower latitudes. Therefore, the regular monitoring of the total ionization in this region can significantly improve our understanding of the complex coupling processes between the solar wind, magnetosphere, ionosphere and thermosphere and ultimately, on the generation of the ionosphere disturbances.

In general, the ionospheric storms go through an initial 'positive' phase, when the electron density and the electron content are greater than the normal median values, followed by the main 'negative' phase when the above quantities are reduced below their normal pre-event values. At high latitudes, the negative phase is attributed to increased molecular concentrations of the thermosphere, enhancing the recombination processes and reducing the electron density. An established explanation for the negative phase at middle and low latitudes, supported also by our observations, is the enhanced equatorward wind system causing the modified thermospheric composition to advect to lower latitudes. Our results also demonstrate that both the extent and speed of the equatorward penetration of ionospheric disturbances depend strongly on local time and season. The time-delayed ionospheric response and the propagation velocity of the perturbations are only few of the important storm phenomena/characteristics that can be investigated in this way (Foerster and Jakowski, 2000; Stankov, 2002). For example, the propagation velocity is estimated to be in the order of 400-900[m/s]. Theoretically, due to the reduced ion drag on the night side, the propagation should be much faster on the night side than on the day side. To investigate the propagation, a very useful quantity is the relative deviation of TEC from the median, $\Delta TEC=(TEC-TEC_{med})/TEC_{med}$. The ratio enhances the perturbation effects and thus facilitates the interpretation. Presented next are results from two recent storms - in July and November 2004.

The last 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^{-th}, -150 nT on 25^{-th}, and -167 nT on 27^{-th}. The IMF and geomagnetic fields were seriously disturbed and several problems were reported by GNSS users. The observed increase of relative TEC between 0600 and 1400UT (Fig.3, left panels) indicates the action of an eastward directed electric field which penetrates from high towards lower latitudes and lifts up the plasma by $E\times B$ drift resulting in a reduced loss rate, i.e., in a positive ΔTEC response. As a natural consequence of the high latitude heating and expansion, equatorward directed neutral winds are generated that lift up the plasma along geomagnetic field lines. Since this process is most effective near 45º geomagnetic inclination, the observed ionization enhancement peaks (seen on maps) in the 45ºN latitude region supports this interpretation quite well. Furthermore, a neutral wind induced plasma uplifting process is characterized by a delayed response in lower latitudes compared with high latitudes (Foerster and Jakowski, 2000).

Indications of an upcoming storm are clearly seen on the polar maps as early as 1200UT on November 7, 2004. As the European ΔTEC maps show (Fig.3, right panels), an area of higher ionization appeared in the North before 1600UT which expanded and propagated towards lower latitudes and notably increased the TEC over the entire continent. The peak however didn't propagate far below 50 degree latitude, suggesting the occurrence of some resistance forces at these latitudes. Here we should point out some seasonal differences in the storm behavior. There exist significant differences in the temporal variation between summer and winter storms, at least over the European sector. The different average behavior can be explained by thermospheric winds blowing preferentially from the summer to the winter hemisphere and so being in phase (summer) or anti-phase (winter) with the equatorward blowing perturbation induced winds. It should be stressed however, that ionospheric storm effects are mainly controlled by geomagnetic activity and that local time variations have only a secondary modulating effect.

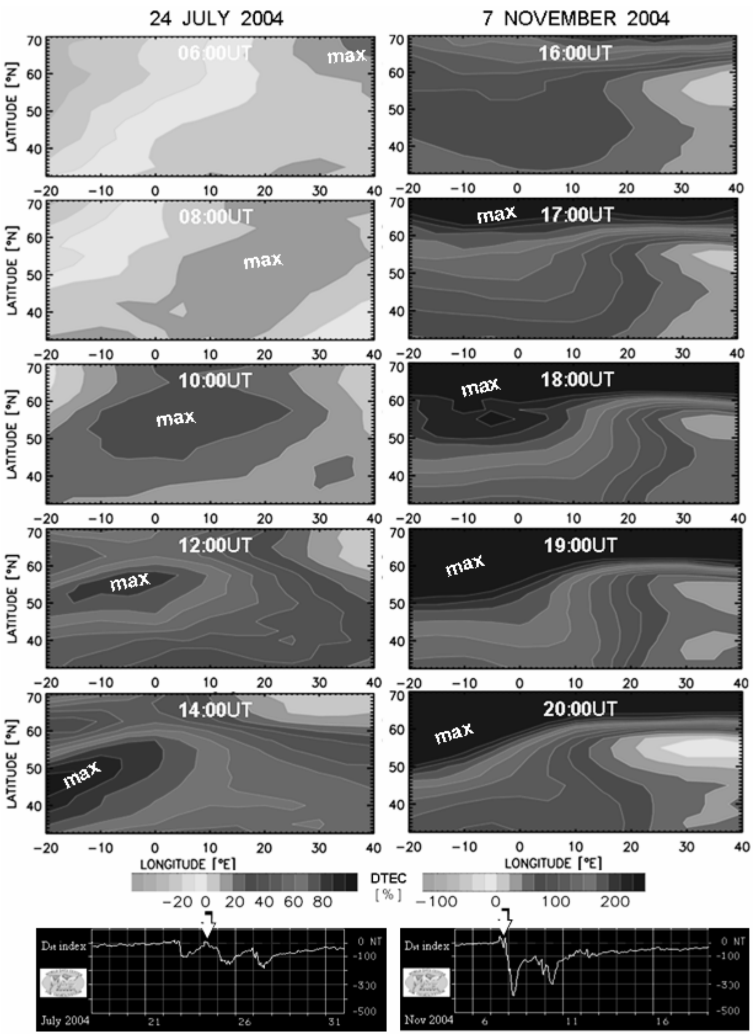

Fig.3. Relative TEC on July 24, 2004 (left panels) and November 7, 2004 (right panels). Dst values provided by WDC-2 Kyoto.

Since the storm development is well observed with ionosonde measurements of the F2 layer's density and height, we have established a system to operationally monitor those parameters at station Juliusruh (13.4ºE, 54.6ºN). Having also GPS TEC measurements, we complemented the monitoring with ionospheric slab thickness observations as well. As the slab thickness τ (TEC/NmF2) contains information on the neutral and ion gas temperature, and because it includes additional information from TEC observations which is not readily deducible from foF2 observations alone, it therefore delivers crucial information on both the top-side and bottom-side ionosphere behavior during ionospheric storms. As an example, presented are results from the ionospheric storm that started on November 7, 2004 (Fig.4). The positive phase, beginning in the early afternoon, is well seen in the foF2 measurement plot (Fig.4, top panel), when the percentage deviations from medians surges up to 80%. Similar behavior is detected in TEC as well, and as a result, only a slight increase is observed in the slab thickness values in the afternoon (Fig.4, middle panel). The thickness however rises sharply in the evening, due to decreasing foF2 values and longer-lasting TEC positive phase. In theory, increasing TEC values accompanied by constant or decreasing foF2 values (i.e. growing slab thickness) indicate a process of plasma uplifting. In such cases, the perturbation of the vertical electron density structure is localized mainly in the topside ionosphere. High slab thickness values during night-time may also indicate enhanced plasma fluxes from the plasmasphere, e.g. due to compression of the geomagnetic field during the onset phase of a storm. The following couple of days, November 8 and 9, are characterized with seriously perturbed and depleted ionosphere resulting in lower than average foF2 values. Another storm began on 9 November, causing a very strong TEC surge, exceeding 22 TECU (1 TECU=$10^{16}m^{-2}$) and not matched by concurrent foF2 increase, resulting in a strong enhancement in the slab thickness. An interesting surge in the slab thickness is observed in the early morning hours of November 7 before the nominal start of the storm. Although the pre-dawn increase in τ is a well known feature, and the day-to-day variability also known to be large, it is still difficult to explain this two-fold increase compared with previous quiet time increases. Is this a potential storm precursor? Whatever the answer, it is clear that the slab thickness measurements, if available in real time and for several suitable locations (for example, at several latitudes along a meridian), can be successfully used for monitoring (eventually predicting) the propagation of ionospheric disturbances.

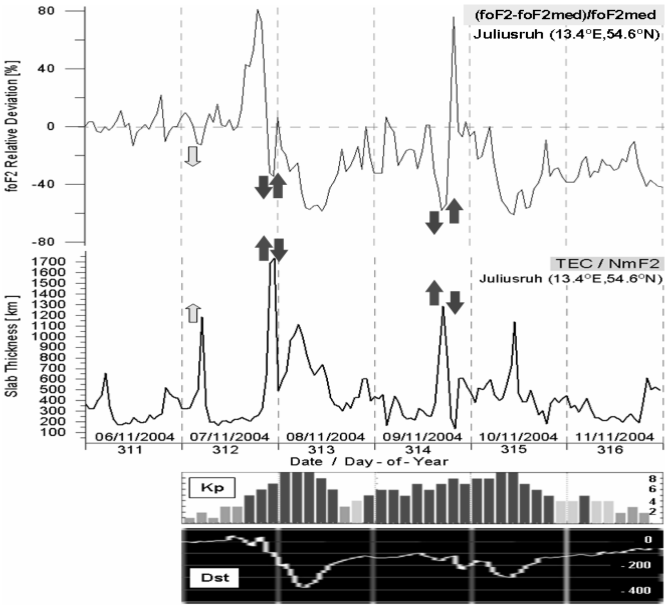

Fig.4. Operational monitoring of the F2 critical frequency and slab thickness at Juliusruh (13.4ºE, 54.6ºN) for the period 6-11 November 2004. Estimated Kp and Dst values provided by the NOAA Space Environment Center and WDC-2 Kyoto.

Space-based GNSS measurements

The GPS data measured onboard CHAMP are received at the DLR Remote Sensing Data Centre Neustrelitz and subsequently processed at DLR by an operational data processing system. Thus, the electron density profiles retrieved from the Ionospheric Radio Occultation (IRO) measurements (Jakowski et al., 2002b) are available within 3 hours after each data dump. In addition to the IRO measurements, high resolution 10 sec sampled navigation data measured with the zenith viewing antenna can also be used for probing the ionosphere (Heise et al., 2002; Stankov et al., 2003).

Valuable information about geomagnetic storms have been supplied by the GPS radio occultation experiment onboard the CHAMP satellite. When a GPS satellite crosses the Earth limb and is seen from CHAMP through ionospheric layers, the GPS receiver measures differences between signal phases and pseudo ranges on two frequencies of the GPS signal. These differences arise because of the dependency of the wave's phase and group speed on the ionospheric plasma density and can be used to determine the slant TEC value, i.e. the integral of the electron density along the line of sight between the GPS transmitter and the CHAMP receiver. Profiles of differential TEC versus occultation time are shown (Fig.5) together with the corresponding vertical profiles of electron density derived from the occultation TEC data using the Abel inversion method. The occultation sites (the sites, where the CHAMP-GPS ray touched the Earth surface) were located over, or close to, the Scandinavian region. During the first occultation (top panel), performed before the storm, no irregular features were seen while, after the storm started, the TEC plots show irregularities in the electron density. Our study indicates that such irregularities are common in the auroral oval zone but at latitudes of 65 degrees or less they are observed only if the ionospheric activity is very high.

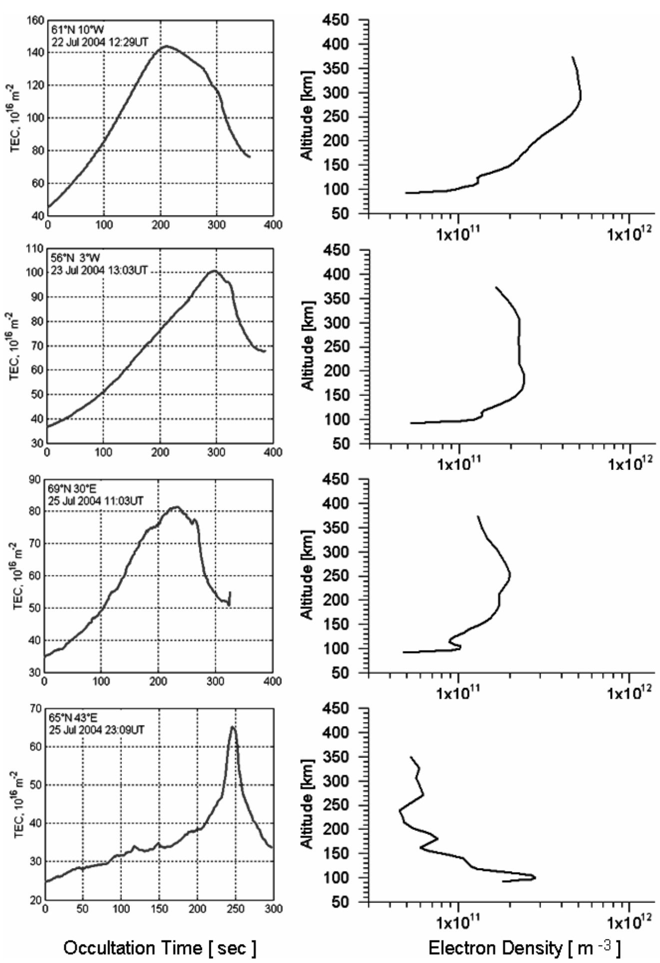

Fig.5. IRO measurements of the differential TEC along the occultation raypath (left panels) as used for electron profiles inversion (right panels); obtained before (top panels) and during the storm period of July 23-25, 2004.

One very important application of the IRO measurements is the detection of ionospheric irregularities on a global scale. In order to estimate the level of these irregularities we have applied an efficient procedure which calculates the RMS of all TEC gradients observed in each region covered during an occultation event. Thus, each RMS estimate serves as a generic measure of the ionospheric irregularity in the corresponding region of occultation. The algorithm was successfully applied to the CHAMP IRO measurements available so far. Results show the global distribution of ionospheric irregularities. In general, the occurrence frequency is higher during the day and lower during the night. Also, the intensity of the ionospheric irregularities increases sharply during winter (Fig.6). Such pronounced activity at higher latitudes in winter possibly indicates the tracing of atmospheric gravity waves (AGW) coming from lower atmosphere layers; the lower temperatures in winter may modify the atmospheric filter function in such a way that AGWs may penetrate more favorably in winter than in summer.

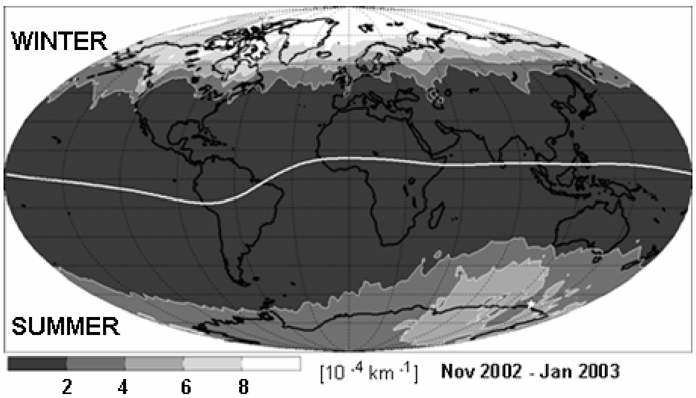

Fig.6. Intensity of ionospheric irregularities obtained via CHAMP IRO measurements from November 2002 to January 2003. Clearly visible is the increased intensity of these irregularities over the polar areas, particularly during winter.

Besides monitoring the irregular behavior of the ionospheric ionization, the IRO measurements also enable studies of the occurrence of the sporadic E layer and traveling ionospheric disturbances (TIDs). Although vertical and horizontal structures may not be separated without additional information, the capability to detect TIDs (and their relationship to other phenomena) proves again the IRO technique potential to enlighten the issues of generation and propagation of disturbances.

Operational monitoring of the space weather impact on GNSS-based positioning

Fig.7. Outline of the DLR Space Weather Operational System.

Motivated by the several problems experienced by GNSS users, the German Aerospace Center established an operational space-weather monitoring service aimed at improving GNSS positioning applications (Fig.7). Real-time data products (TEC value, spatial and temporal TEC gradient maps, cycle slip number, space weather alerts, etc.) are offered to consortium members, designated users, and general public. The products, based on information on the actual and predicted state of the ionosphere-plasmasphere system, deliver only such information which reference network operators need in order to help them deliver a more reliable, precise and secure positioning service and to eventually reduce the operational (and other business) costs. Relevant information and support are exchanged with members of the Space Weather European Network (SWENET).

The Network Model Integrity (NMI) is an important operational parameter used in the reference network software to control the integrity and quality of the satellite positioning services. NMI describes the non-linear error in the generated data. It is estimated in the following manner. First, 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 calculation of the ionospheric influence on the surrounding station and 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 estimated. The plots (Fig.8, panel A) show the remaining error at different stations located in different areas. As it is not possible to calculate the correction over Germany with one server only, the calculation is distributed between several subnets covering different areas with approximately 40 stations each. The remaining error of a subnet is the average of the errors at the subnet stations. The x-axis shows the hour of the day (universal time), while the y-axis shows the error measured in meters. Experience teaches that it is hardly possible to obtain precise and accurate results when the error is larger than 8 cm. If the error is between 4 and 8 cm, the user has to accept longer times to fix ambiguities. The network performs well if the error is less than 4 cm. NMI results are plotted for July 25, 2004 (Fig.8, panel A). 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). In the early afternoon, higher-than-usual values can be seen in the eastern areas and later, the influence is detected in the western areas as well.

Demonstrated next is how an operational space weather monitoring service can help. By generating high-resolution maps of the TEC spatial and temporal gradients (Fig.8, panel B), the sharp increase in TEC in the North East region and its propagation in south/westward direction becomes obvious. As the front of the detected disturbances moves through Europe, it reduces the reference network integrity. What is important to mention here is that the large-scale IGS TEC maps do not always provide clear and early indications of ongoing storm conditions; such are possible only if high resolution spatial and temporal resolution mapping is achieved. The 1 deg spatial and 5 min temporal resolution achieved at DLR so far indicates that this is already a good basis for developing a reliable nowcast service. The next challenge is to reliably forecast the effects of the ionospheric disturbances.

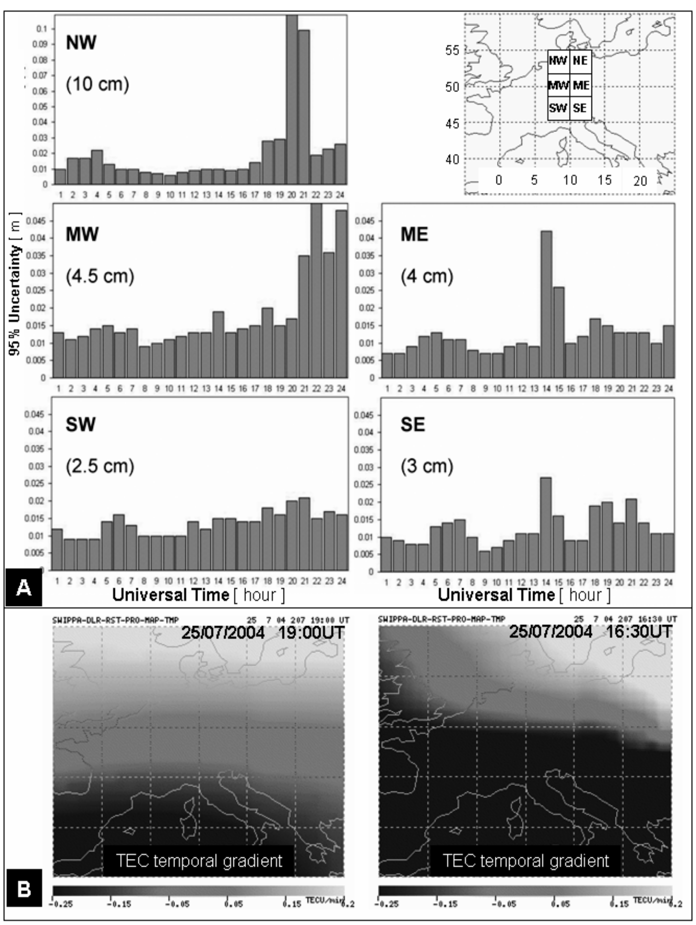

Fig.8. Adverse space weather effects on the operational quality of reference networks: operational NMI (panel A) and TEC time gradient (panel B) monitoring of Europe at 1630UT (right) and 1900UT (left) on July 25, 2004.

Discussion and conclusion

Presented were results from studying the generation and development of the ionospheric disturbances by utilizing the capabilities of several modern-day techniques for routine measurements. It has been shown that the ionospheric disturbances affect the performance of the GNSS reference networks. On the other hand, the growing number and densification of the GNSS reference networks together with the increased availability of spaced based GNSS measurements onboard LEO satellites will provide opportunities for more comprehensive monitoring of the ionosphere-plasmasphere system, especially if several complementary methods are combined and focused on certain important phenomena and effects. Since the space weather induced irregular spatial and temporal gradients of the electron density distribution may seriously degrade the performance of communication/navigation systems, a GNSS-based TEC monitoring service obviously has a big potential to help mitigating the space weather impact on various GNSS applications, provided that such a service is of high resolution and quality, faces the challenge of developing and delivering reliable forecast, and is oriented towards the professional user needs.

Acknowledgements

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