Journal of Atmospheric and Solar-Terrestrial Physics 69 (2007) 485–499
Journal of ATMOSPHERIC AND SOLAR-TERRESTRIAL PHYSICS
www.elsevier.com/locate/jastp

Ionospheric effects on GNSS reference network integrity

S.M. Stankov*, N. Jakowski

German Aerospace Center (DLR), Institute of Communications and Navigation, D-17235 Neustrelitz, Germany

Received 29 May 2005; received in revised form 6 August 2006; accepted 29 August 2006
Available online 14 November 2006

Abstract

Global navigation satellite system (GNSS) positioning techniques are based on precise but ambiguous carrier phase observations. The ambiguities can be resolved by properly modelling the ionospheric influence. However, under perturbed ionospheric conditions, the ionospheric modelling may become inaccurate and thus lead to degraded network performance. Generally, the ionospheric impact is noticeably stronger during ionospheric storms and perturbations, which raises the question of how the GNSS reference networks perform, in terms of integrity and reliability, during such unfavourable conditions. For the purpose, potential problems of reference network concepts that can be attributed to ionospheric interference are addressed here. In particular, the ionospheric impact on the residual error in reference networks is analysed, and some preliminary results are presented. Case studies of ionospheric storms clearly show the development/propagation of ionospheric disturbances and associated effects on positioning inaccuracies. Also studied is the feasibility of operational space weather monitoring services for mitigating the ionospheric impact and improving the performance of reference networks.

Keywords: GNSS; Reference networks; Ionospheric disturbances

1. Introduction

The subject of this paper is the impact of ionospheric disturbances on the performance of the GNSS reference networks. It is very important for GNSS-based positioning applications (particularly for those operating in real time) to know the current ionospheric state and development because the ionospheric disturbances are responsible for the largest unknown term in the GNSS observation equation (Datta-Barua, 2004). Due to its dispersive nature, the ionosphere causes phase shifts in the transmitted electromagnetic signals, whereas the (code) message encoded in the signal experiences a delay. The magnitude of both effects is largely determined by the ionospheric conditions, therefore, high-precision positioning is impossible without accurately modelling the 'ionospheric error term'. Various concepts/techniques, currently utilised for mitigating the ionospheric effects, require permanent monitoring of both the ionospheric conditions and the effects to ensure that the GNSS reference networks maintain the nominal accuracy (Vollath et al., 2002; Wanninger, 1999, 2002, 2004). In order to successfully apply these mitigation techniques, it is also crucial to monitor both, the source and the environment of these effects, i.e., the solar and ionospheric conditions, and to do it on a permanent

*Corresponding author. Tel.: +49 3981 480 113; fax: +49 3981 480 123.
E-mail address: Stanimir.Stankov@dlr.de (S.M. Stankov).

1364-6826/$ - see front matter
doi:10.1016/j.jastp.2006.08.008

basis. At the moment, however, it is still not possible for the industry alone to perform comprehensive ionospheric/space weather monitoring and to completely and successfully mitigate the ionospheric effects.

The objective of this paper is twofold: first, to help bridging the current knowledge of ionospheric disturbances (ionospheric behaviour in general) and the (expected) performance of GNSS reference networks, and second, to show the importance of the permanent ionospheric monitoring for understanding and mitigating the ionospheric effects.

There are several key characteristics of the GNSS reference network performance: the time needed to solve the phase ambiguities, the number of available/used GNSS satellites, the GNSS reference network integrity, and others.

Although not the only source of increased ambiguity fixing time (AFT), the ionospheric conditions certainly contribute to the occurrence of this phenomenon. For example, a case is presented here during the storm on 15 December 2003 (Fig. 1). Frequent occurrences of relatively long AFTs (exceeding 5 min) have been observed, on one occasion lasting more than an hour. Other cases of long fixing times during storms and even failures in resolving the ambiguities have been reported elsewhere (Jakowski et al., 2004). Prolonged AFTs may have adverse impact on GNSS positioning and safety-critical applications. It is interesting to mention that, although three (even four) frequency ambiguity resolution will do better than a dual frequency system, the ionospheric activity will remain a significant factor in the ambiguity fixing performance (Chen et al., 2004).

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 because of restrictions imposed on the satellite elevation angle (elevation cut-off criterion), signal-to-noise ratio

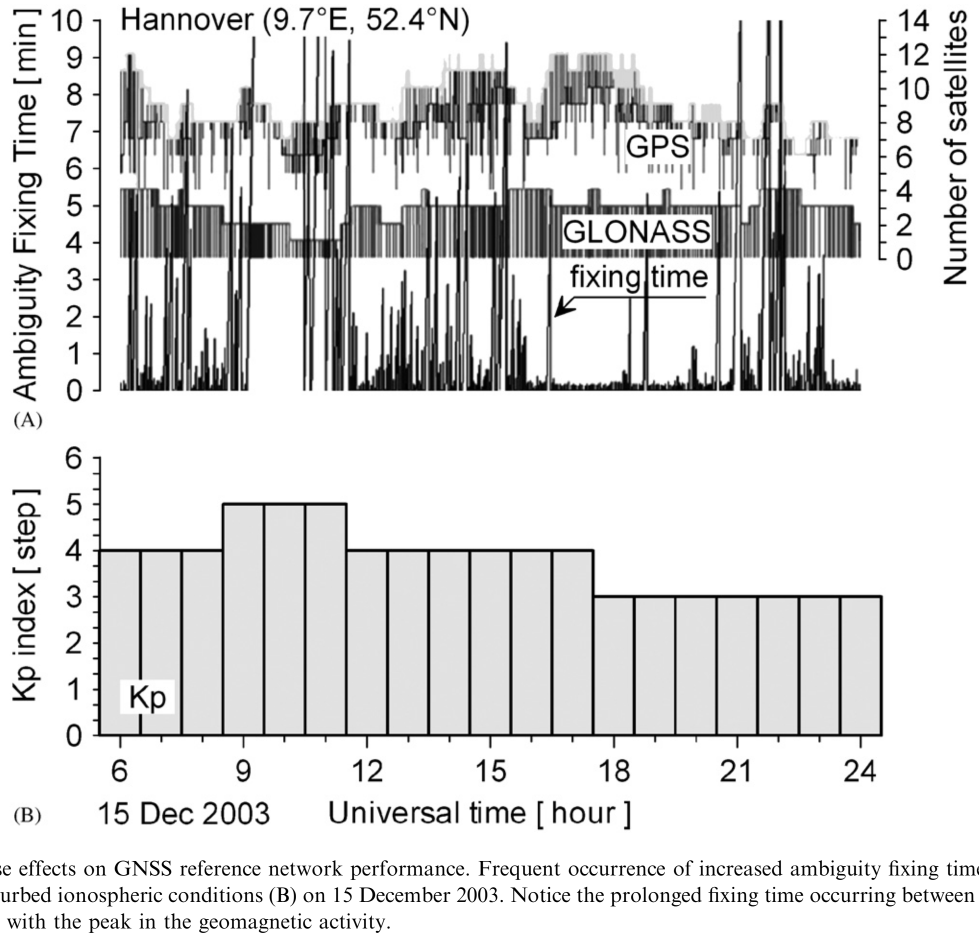

Fig. 1. Adverse effects on GNSS reference network performance. Frequent occurrence of increased ambiguity fixing time (A) observed during the disturbed ionospheric conditions (B) on 15 December 2003. Notice the prolonged fixing time occurring between 0900 and 1030 UT coinciding with the peak in the geomagnetic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

(SNR criterion), etc. Data from the remaining satellites are used by the processing software to resolve the ambiguities. Since further restrictions are imposed on the solution, such as limitation on the error magnitude and stability of solution, the number of these 'processed' satellites should not be less than five to ensure that the services are reliable (Trimble Navigation, 2005).

GNSS reference network integrity is monitored by operationally estimating the non-linear error in the output data (Chen et al., 2003). If the error exceeds a certain threshold (specific for each network), the user should expect longer AFT and should be aware of increased inaccuracies. In extreme cases, solving the ambiguities may not be possible at all. Just to demonstrate the residual error variability, a case is presented here during the storm on 20 November 2004 (Fig. 2). The residual error increases significantly during this ionospheric storm, with pronounced peaks formed at 0900 and 1500 UT when the error is several times larger than the monthly median error. The plot also shows that observing the geomagnetic activity alone is not very helpful when trying to estimate the error—the Kp values do not necessarily suggest when and how strong the error will be. Obviously, there are additional factors influencing the error magnitude, and it is important to find them if willing to predict this error. Such a task is not easy, so there are some developments that the industry implements in its efforts to mitigate the ionospheric effects, including: sensor fusion, building higher-density networks, multi-carrier processing, and modelling the ionospheric behaviour. Since it is obvious that strong ionospheric perturbations do affect the determination of phase ambiguities and the performance of the network, it becomes important to understand the spatial development/propagation patterns of the ionospheric perturbations, to identify the possible adverse effects, to operationally monitor key ionospheric characteristics, and ultimately, to predict effects of those perturbations.

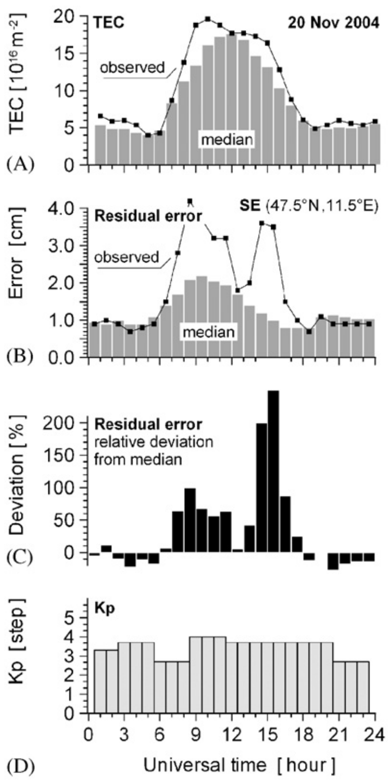

Fig. 2. Adverse effects on GNSS reference network performance. Increased ionospheric residual error (B) and relative error deviation from monthly medians (C) observed during the disturbed geomagnetic conditions (D) on 20 November 2004. Notice the correlation between the TEC (A) and IRE (B) behaviour.

2. GNSS reference network integrity

In GNSS-based reference networks, the differential residual error between the reference station and the rover is a major error contributor. Since the ionospheric effects increase with the baseline length, the reference stations must be deployed in a dense enough pattern to allow for modelling the distance-dependent errors to an acceptable accuracy. A large portion of the differential ionospheric biases can be modelled and removed successfully by using observations of a network of reference stations, provided the stations are not more than 50–80 km apart (Wanninger, 2004). Nevertheless, during storms and/or in the presence of small and medium scale ionospheric disturbances, large ionospheric residuals remain. Therefore, a significant part of the GNSS network integrity monitoring is in fact controlling the ionospheric residual error (IRE).

Integrity monitoring (for residual interpolation and ambiguity resolution) is crucial for the operational quality of network real time kinematics (RTK) systems. The network model integrity (NMI) module (Trimble Navigation, 2005) is developed and utilised in GNSS reference networks for estimation of the potential non-linear residual errors in the generated data transmitted to the user. At the same time, it is also a very useful tool for prediction of the rover performance. To estimate the non-linear residual error, the NMI module omits one reference station from the interpolation procedure (using adjacent stations instead) and then compares the interpolation results for that omitted station with the real measurements. It computes the interpolation error and a weighted root-mean-square (RMS) value over all satellites. The RMS values of all network stations are accumulated for each hour, and the I_{95} index (Wanninger, 2004) is calculated. Actually, the I_{95} index is a statistical figure, obtained from dual frequency ambiguity–fixed carrier phase observations, providing information on the amount of differential ionospheric biases. The index value is the 95% margin of all $\left(\Delta I_{\mathrm{LAT}}^2 + \Delta I_{\mathrm{LON}}^2\right)^{1/2}$ quantities accumulated in a predefined time period (usually, 1 h), where ΔI_{LAT} and ΔI_{LON} are the differential ionospheric biases in south–north and west–east directions, respectively. The highest value for the respective hour is the required error estimate used by the NMI module. During periods of disturbed ionosphere however, the ionospheric residuals cannot be considered linear even locally. Since it is not possible to calculate the correction over large areas with one server only, the calculation is distributed between several sub-networks covering different areas with approximately 40 stations each. The remaining error of a given sub-network is the average of all errors at all stations. The abscissa shows the hour of the day (universal time), while the ordinate shows the absolute value of the error (Fig. 2). The network performs well when the error is small; higher the error, higher the probability of long fixing times and inaccuracies in the output.

In order to investigate the GNSS reference network integrity and its dependence on the ionospheric activity, GNSS and NMI data from a German reference network have been collected and processed. The network covers approximately the area from 45°N to 55°N in latitude and from 5°E to 15°E in longitude. To better analyse the spatial effects on the residual error, three sub-networks have been used, with their approximate centre points located along a meridian: NE(53.5°N, 11.5°E), ME(50.5°N, 11.5°E) and SE(47.5°N, 11.5°E). The NMI module is a recent development, so regular NMI data are available for users since October 2004, therefore represent low solar activity conditions only. It must be noted that even in such limited database, there are occasional data gaps, so it is too early to draw firm conclusions on certain phenomena.

Since residual errors seem always to exist in the network output, a clear separation should be made between the average/median error and the storm–time error. In essence, the median behaviour is the 'background' level of the error under normal, regular ionospheric conditions. The storm-time behaviour is highly volatile, much more complex than the median behaviour, and crucial for the real-time operation/application of the GNSS reference networks.

2.1. Median behaviour

To obtain the average diurnal variations of the IRE, all available values (from October 2004 to December 2005) have been binned according to hour of day (UT), month of year, and location (sub-network). After that, the corresponding monthly medians were calculated and this provided a preliminary insight into the error's diurnal behaviour and its dependence on season, latitude, and even on solar activity.

The collection of diurnal variation plots for each month of year 2005 reveals (Fig. 3) that there are three distinct types of diurnal behaviour, depending largely on season. In the winter months (November, December, January and February) the residual error is more than 100% higher during the day, with peak values occurring between 0900 and 1200 LT. In summer (June, July and August) the daytime error values remain rather low and unchanged at a level of around 1 cm, while a pronounced increase is observed during night, highest in the evening hours between 1900 and 2200 LT. The largest error increase of about 100% is recorded in the month of June. The plots of May and October show a mixed diurnal behaviour with slight increases both during day and night. In the remaining (near equinoctial) months (March, April and September) the error variability is small and is around the 'background' level of 1 cm throughout day and night.

The latitudinal behaviour of the error is characterised by an increase in poleward direction, particularly during winter and summer (Fig. 4). The most pronounced increase is observed in the winter month of February (137%); however, considering the unsettled geomagnetic conditions during this month, the large errors observed during the day suggest that there is a correlation between the geomagnetic/ionospheric disturbances and the increased residual error. The February data also

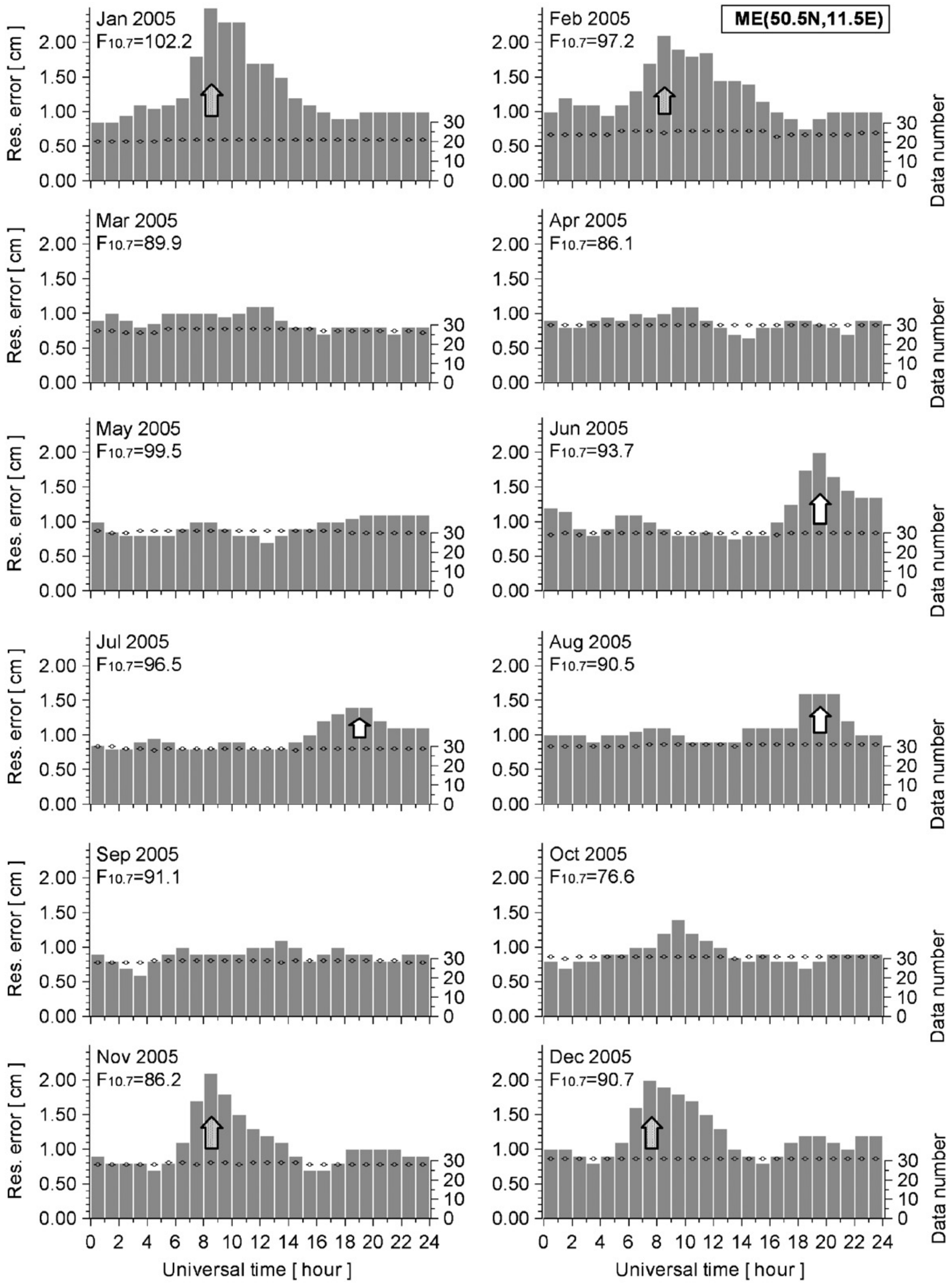

Fig. 3. Annual behaviour of the ionospheric residual error as estimated at ME(50.5°N,11.5°E). For each UT hour, the monthly median value of the residual error is presented with a vertical bar (ref. to the left axis), while the number of data used for calculating the median value is indicated with a circle (ref. to the right axis).

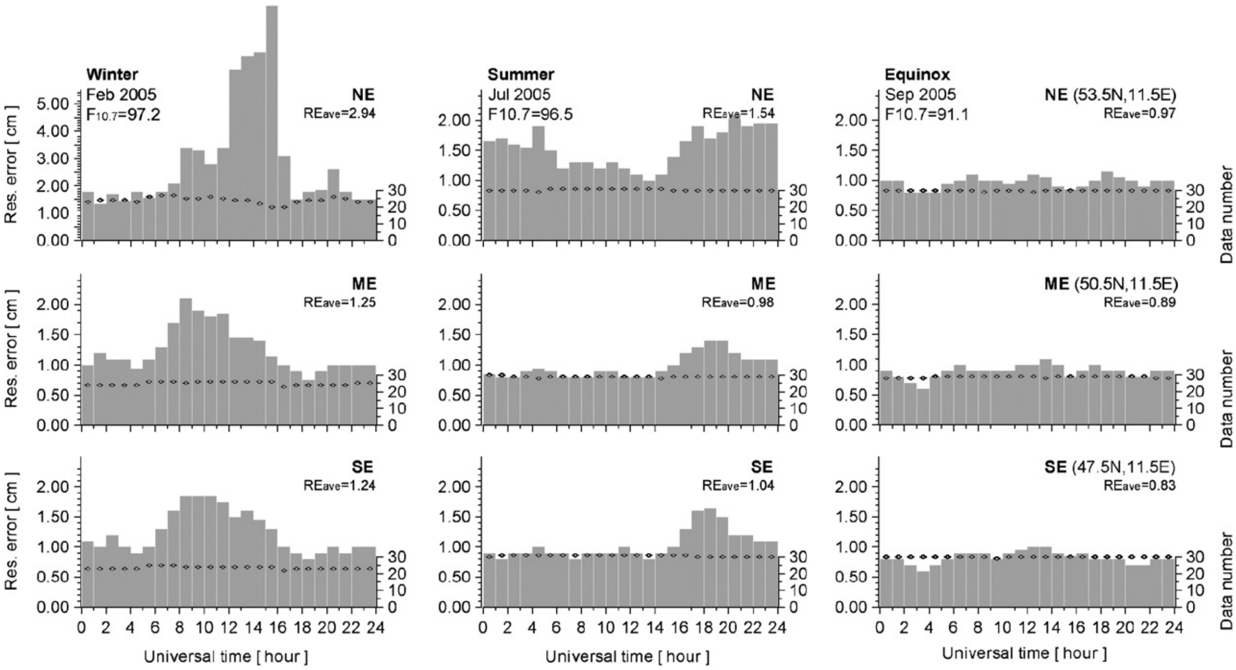

Fig. 4. Latitudinal dependence of the ionospheric residual error as estimated at 53.5°N (top panels), 50.5°N (middle panels) and 47.5°N (bottom panels), during winter (left panels) and summer (right panels). For each UT hour, the monthly median value of the residual error is presented with a vertical bar (ref. to the left axis), while the number of data used for calculating the median value is indicated with a circle (ref. to the right axis). The average median value of the residual error (REave) is also provided.

suggest that the ionospheric effects on positioning can be quite strong at higher latitudes. To further highlight the latitudinal variations, the monthly median values of the error were averaged over all 24 h and plotted for the northern (NE) and southern (SE) sub-networks (Fig. 5). The latitudinal difference is relatively small (only 6° between the approximate centres of the sub-networks) but the differences in the error magnitude are already discernible. Thus, the higher latitude values are about 17–21% larger during the equinoxes and even higher in summer (50%) and winter (30% in December, 137% in February).

Given the well-known dependence of the ionospheric state on the level of solar activity, a correlation between the solar activity and the ionospheric effects on GNSS reference network performance should also be expected. The majority of residual error observations are from year 2005 when the solar activity was low, monthly F10.7 ranging between 75 and 100 units. Having also the NMI data from October 2004 and November 2004, when the solar activity was slightly higher, it would be interesting to see whether such dependence on solar activity does really exist. Indeed, although the

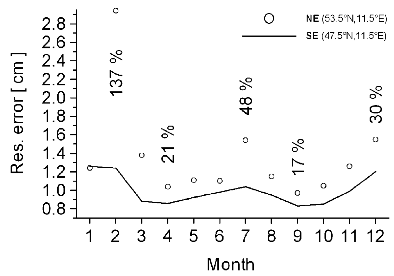

Fig. 5. Latitudinal dependence of the ionospheric residual error at low solar activity (year 2005): average annual variations as estimated at 53.5°N (open circles) and 47.5°N (solid line). In spite of the relatively small latitudinal difference, the average error increase in poleward direction can be up to about 50% in summer (June), 17–21% in equinox (September, April), and 30–137% in winter (December, February). For the northern sub-network, the residual error measurements are rather scarce in January 2005 and no real dependence on latitude is detected, nevertheless, the 137% upsurge in February suggests that the winter increase can be quite significant particularly at higher latitudes.

pattern of the diurnal variations does not seem to be affected, it is obvious that the decrease in solar activity (about 25%) leads to a similar decrease in the average residual error (Fig. 6). It seems that the peak values during day are less affected than the remaining values. Although the correlation seems obvious, longer time series of residual error observations are needed for a detailed statistical analysis.

2.2. Storm-time behaviour

The performance of GNSS reference networks under disturbed ionospheric conditions is particularly important if real-time and/or high precision applications are planned. It is expected that the residual error increases during periods of ionospheric disturbances/storms. To better analyse the IRE variability during storms, the relative deviations from monthly medians have been calculated, $IRE_{rel} = (IRE_{obs}–IRE_{med})/IRE_{med}$. An obvious advantage in using a dimensionless quantity like IRE_{rel} is the opportunity it offers for comparison of results from different locations/times and for comparison of the error behaviour with that of key ionospheric characteristics, such as the total electron content (TEC).

Several cases during winter, summer and equinox storms (Fig. 7) are presented, showing that the IRE increases significantly (more than 300%) during the main phase of the summer and winter storms. This type of behaviour is consistent with the positive deviations detected in TEC measurements (Proelss, 1995; Foerster and Jakowski, 2000; Jodogne and Stankov, 2002; Jakowski et al., 2002, 2005). It is interesting that there is no such increase during the equinox storm on 4 April 2005. Actually, the error increases, but it is not occurring during the main phase on 4 April 2005, it is observed on the following day, 5 April 2005, during the recovery phase. A similar behaviour is recorded during another storm event on 11 April 2005 (Fig. 8). The lack of error increase during the main phase, when the storm and the ionospheric perturbations are in full swing, is quite difficult to explain. There are probably some specific conditions that exist during equinox storms or in the local ionosphere, technical reasons also not excluded. On the other hand, the increase on the following day/evening can mean that the ionospheric perturbations during the recovery phase of the storm can induce significant residual errors comparable in magnitude to those occurring during the main phase of winter and summer storms. In addition, intensified ionospheric irregularities can also be responsible for such errors.

It is also not clear why the IRE magnitude varies even when the geomagnetic activity is consistently high. A possible explanation is that, under disturbed geomagnetic conditions, the ionospheric plasma

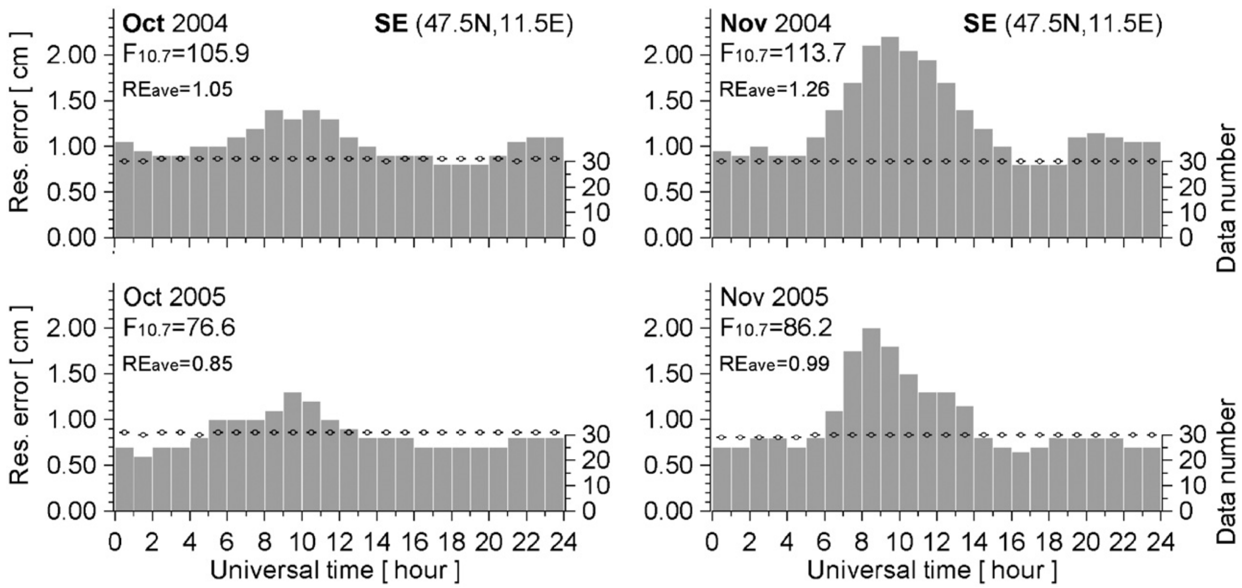

Fig. 6. Solar activity dependence of the ionospheric residual error as estimated for higher solar activity (year 2004, top) and lower solar activity (year 2005, bottom) for October (left) and November (right). For each UT hour, the monthly median value of the residual error is presented with a vertical bar (ref. to the left axis), while the number of data used for calculating the median value is indicated with a circle (ref. to the right axis). Notice that the average median value of the residual error (REave) decreases from 1.05 (October 2004) to 0.85 (October 2005) and from 1.26 (November 2004) to 0.99 (November 2005).

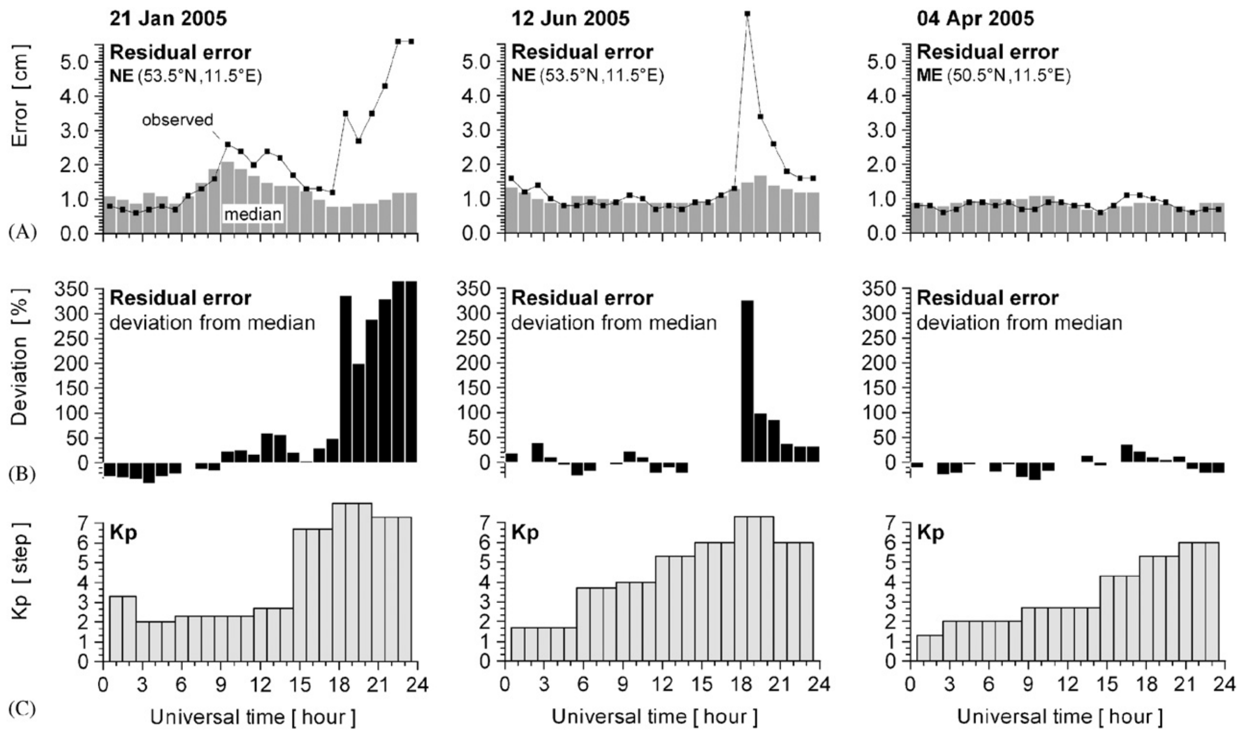

Fig. 7. Storm-time variations of the ionospheric residual error during winter (21 January 2005, left panels), summer (12 June 2005, middle panels), and equinox (4 April 2005, right panels). (A): Instant and median observations of the ionospheric residual error. (B): Residual error deviations from monthly medians. (C): Kp index.

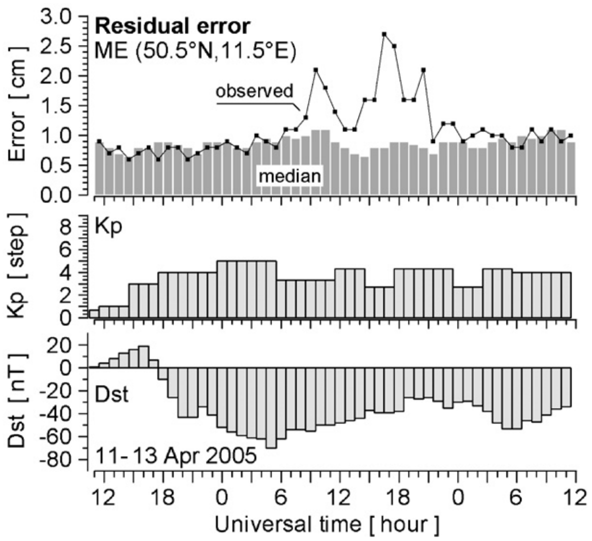

Fig. 8. Storm-time variations of the ionospheric residual error (top panel) during equinox (11–13 April 2005). Notice the error's delayed increase occurring during the recovery phase of the geomagnetic storm.

dynamics—in the form of strong spatial and temporal plasma density gradients—plays a more important role in the residual error's occurrence and magnitude than the high geomagnetic activity alone. The presence of strong ionospheric gradients indicates the development of highly dynamic processes in the Earth's ionosphere–plasmasphere system with the potential of having degrading effect on positioning/navigation. For example, both wide area augmentation system (WAAS) and local area augmentation system (LAAS) receivers utilize carrier–smoothing filters to reduce the effects of multipath and thermal noise at the aircraft. By applying such filters, users can ultimately improve accuracy. However, the presence of significant ionospheric gradients can introduce a bias into this filter's output; if unmitigated, this bias can grow to be much larger than the noise and multipath effects the filter is supposed to reduce (Walter et al., 2004). The irregular variations in the error magnitude can be explained also with the inevitable averaging over a number of satellite-to-receiver links when calculating the residual error. Due to the different location of the GNSS network receivers and the ever-changing visibility of GNSS satellites, the signal ray paths traversing the ionosphere change their direction over time and thus, the residual error for a network of receiving stations is in fact an average value over different locations. Different ray paths may cross ionospheric regions that are affected in different ways by the storms. Also, some ray paths may cross regions of ionospheric irregularities while others may not. Therefore, for higher precision estimates of the IRE in GNSS reference networks, it will be necessary to take into account the exact position of receiving stations, the direction and movement of signal ray paths.

3. Importance of ionospheric monitoring for GNSS applications

There are several important topics that should be highlighted in search of possible explanation of the residual error behaviour and efficient ways of mitigating the ionospheric impact: local ionospheric reaction to geomagnetic activity, propagation of ionospheric disturbances, ionospheric irregularities, and the operational ionospheric/space weather services. Since the TEC is a key ionospheric parameter that proved to be quite efficient in monitoring the ionospheric state (Jakowski, 1996; Jakowski et al., 2002), it is also believed that TEC monitoring can be further utilised for predicting the GNSS reference network performance in the part that depends on ionospheric influence (Jakowski et al., 2004, 2005; Stankov et al., 2005).

3.1. GNSS measurements

Considering the importance of the GNSS TEC measurements for monitoring/investigating the above-mentioned issues, a brief overview of the ground- and space-based techniques is provided next.

A system for regularly processing ground-based GPS measurements from the international GPS service (IGS) and producing TEC maps over the European region (-20°E$\leqslant$longitude$\leqslant 40^\circ$E; 32.5°N $\leqslant$latitude$\leqslant 70^\circ$N) has been operating at DLR since 1995 (Jakowski, 1996). The GPS data allow the determination of slant TEC values along numerous satellite–receiver links with 30 s time resolution. The instrumental biases are separated from the observations by assuming a second-order polynomial approximation for TEC variations over the observing GPS ground station. Both the TEC and the instrumental satellite–receiver biases are estimated simultaneously by Kalman filtering. The calibrated slant TEC data are then mapped onto the vertical by applying a mapping function which is based on a single layer approximation at $h_{sp} = 400$ km. To provide a value for each grid point and to ensure higher reliability of the maps, particularly in cases of sparse measurements in certain areas, the available TEC measurements are combined with values from an empirical model (Jakowski et al., 1998). The advantage of applying such assimilation is that even in cases of low numbers of measurements, plausible ionospheric corrections can still be delivered to the user.

Satellite missions, such as the low earth orbit (LEO) Challenging Minisatellite Payload (CHAMP) carrying a dual frequency GPS receiver onboard, offer good opportunities to derive vertical electron density profiles by using the radio limb sounding technique. This technique has proved to be a powerful tool for remote sensing the Earth's neutral atmosphere and ionosphere by analysing GPS radio occultation data. To obtain information on the spatial and temporal electron density distribution above the CHAMP orbit height, the 0.1 Hz sampled dual frequency navigation measurements are used to derive the TEC along the ray paths between the CHAMP and GPS satellites. After assimilating these integral measurements into a parameterised ionospheric model of local electron density it is possible to reconstruct the spatial electron density distribution close to the CHAMP orbit plane (Heise et al., 2002).

3.2. Local ionospheric reaction to geomagnetic activity

It is well known that the ionospheric behaviour changes both spatially and temporarily, and consequently, the ionospheric impact should also vary from location to location and time to time. When considering GNSS applications, it is important to concentrate on monitoring and understanding the local ionospheric behaviour and effects (e.g., the local ionospheric response to geomagnetic activity) rather than on the global features. In order to better analyse the TEC variations, particularly those supposedly induced by the geomagnetic activity, it is preferable to use the TEC relative deviation, $\mathrm{TEC_{rel}} = (\mathrm{TEC_{obs}} - \mathrm{TEC_{med}})/\mathrm{TEC_{med}}$. The general $\mathrm{TEC_{rel}}$ dependence on geomagnetic activity during different seasons and latitudes has been first investigated by analysing GPS TEC data from year 1995 to 2001 (Stankov and Jakowski, 2006). It has been found that $\mathrm{TEC_{rel}}$ increases steadily with the increase of the geomagnetic index Kp. The strength of this positive response is particularly pronounced in the winter months and is increasing in poleward direction. A slight positive response is also observed in the summer months of June and July. Opposite to the solstice periods, pronounced decreases in relative TEC are observed during the equinox periods April–May and September–October. This finding is in concordance with previous research that positive storms prevail in winter, while it is unlikely to observe positive storms in May and September (Proelss, 1995; Fuller-Rowell et al., 1994, 1996). Since the error increase is more probable during the onset/main phase of the storm, our special attention should be on the positive TEC variations. Typical examples of the relation between observed positive TEC_{rel} and increased IRE_{rel} have been provided for winter and summer conditions (Fig. 7). However, a more detailed analysis is needed to explain the delayed IRE_{rel} increase during the April 2005 events (Fig. 8). It appears that the TEC_{rel} variations are strongly influenced by the storm-time, i.e., time elapsed from the storm onset. Although each storm has its individual characteristics, some common features should be visible in a detailed statistical analysis. Thus, to derive this storm-time pattern in the TEC_{rel} behaviour, a superposed epoch analysis was carried out on the TEC values during selected storm periods in summer (May, June, July, August) and winter (November, December, January, February) from years 1995 to 2004. Only storms with clear and rapid onset have been considered. Practically, it has been done in the following manner. A nominal start of the storm (0 ST) was assigned to the middle of any 2-h-period in which a sufficiently large positive increase of D_{st} was observed, i.e., $D_{st}(+1\,h)-D_{st}(-1\,h)>10nT$. In addition, the D_{st} value should have been higher than $-25\,nT$ for the previous 24 h and should have fallen below the $-50\,nT$ mark at least once in the 24 h period following the onset. Upon fulfilling the above conditions, the storm is selected and all observations are rearranged according to this new storm-time scale. The average TEC_{rel} at each latitude and ST hour have been calculated (Fig. 9). The positive phase of the summer storm is most pronounced at middle latitudes and lasts on average 12–24 h around the nominal onset of the storm. In contrast, the positive phase in winter is most pronounced at high latitudes, may start earlier and last much longer. The negative phase lasts from 48 to 72 h, both in summer and winter, but it starts earlier and is more pronounced during summer at high latitudes. Prolonged positive storm phases suggest that increases in the ionospheric error can be expected long after the beginning of an ionospheric

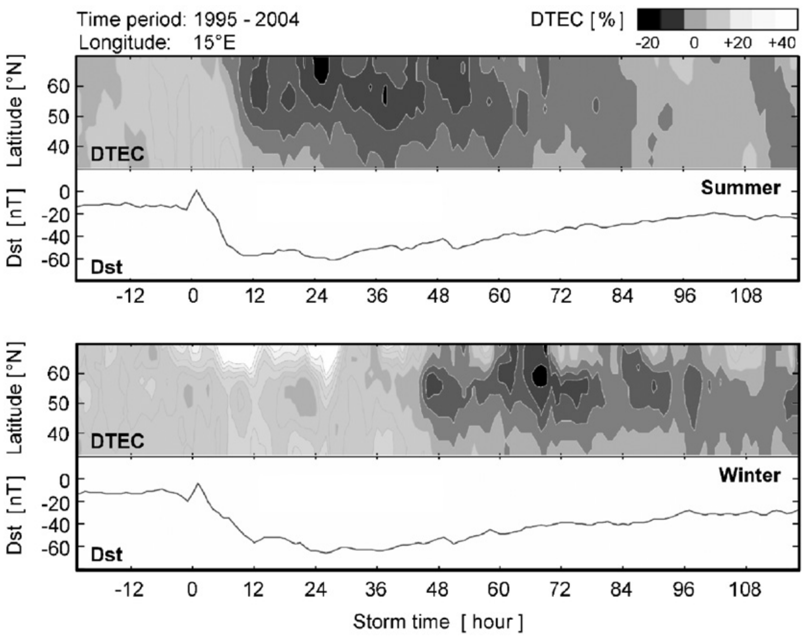

Fig. 9. Average storm-time behaviour of the GPS TEC percentage deviations from monthly medians (DTEC) at 15°E longitude and 30–70°N latitudes during summer (May, June, July, August) and winter (November, December, January, February) from years 1995 to 2004.

storm. Moreover, at middle latitudes, the TEC_{rel} increase is significantly delayed—it occurs at about the 12 ST h for storms that start during night and at the 24 ST h for storms that start during day (Foerster and Jakowski, 2000). It means that positive storm effects are more often during the day but their occurrence during night cannot be excluded (Belehaki and Tsagouri, 2001). The influence of the negative storm phase and the seriously depleted ionosphere on the ionospheric error remains to be investigated.

3.3. Propagation of ionospheric disturbances

Enhanced space weather impact is expected first on the high-latitude ionosphere because the latter is more strongly coupled with the magnetosphere and the solar wind. The high-latitude electric field, 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 (Fig. 10). In this example from the storm that started on 7 November 2004, an area of higher ionization appearing in the North at around 1600 UT, expanded towards lower latitudes, noticeably increasing the TEC over the entire continent. The peak, however, did not propagate far below 50°

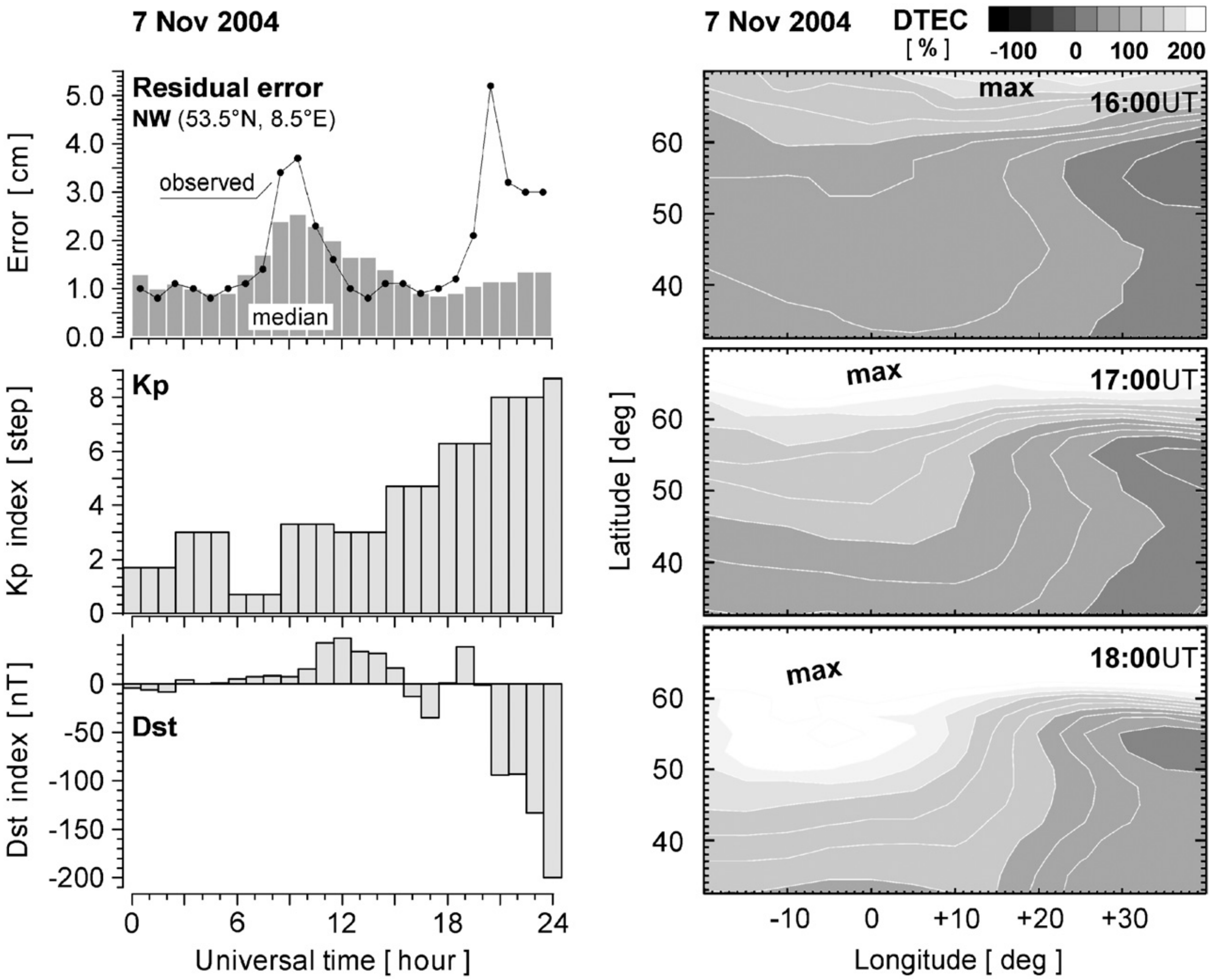

Fig. 10. Monitoring of (top left panel) the residual error and (right panels) the differential TEC (DTEC) over Europe during the storm on 7 November 2004. Notice the propagation of ionospheric disturbances in south/southwest direction coinciding with the pronounced IRE increase in evening hours.

latitude, suggesting the occurrence of resistance forces at these latitudes. In fact, both the extent and the speed of equatorward penetration of ionospheric disturbances depend strongly on local time and season. 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. Also, there are significant differences in the temporal variation between summer and winter storms; the different average behaviour 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 (Foerster and Jakowski, 2000; Stankov et al., 2005). The increase of the residual error in reference networks correlates quite well with the propagation of ionospheric disturbances monitored by the differential TEC. It shows again the capability that the TEC monitoring offers for predicting the IRE.

3.4. Ionospheric irregularities

Apart from the large-scale ionospheric gradients/processes caused by the ionospheric storms and/or the changes in solar activity, local time, and season, the medium- and small-scale ionospheric irregularities (Tsybulya and Jakowski, 2005) are also known to influence the radiowave propagation and communications. The small-scale irregularities in particular can cause diffraction and scattering of the trans-ionospheric radio signals. Upon receival of these signals, random temporal fluctuations (known as scintillations) occur in both amplitude and phase. Therefore, the ionospheric irregularities are expected to influence the GNSS-based positioning, particularly in certain seasons and latitudes. For example, the relatively large residual errors in summer nights can be attributed to such irregularities (Fig. 3). In general, the irregularities characterised by longer wavelengths (medium, 100–250 km) dominate at low/equatorial latitudes while the irregularities with shorter wavelengths (small, 25–50 km) are more intense at high latitudes. The latter can contribute to the general increase of residual errors in poleward direction (see Figs. 4 and 5). The occurrence frequency of ionospheric irregularities is higher during periods of high magnetic and auroral activity, e.g., during ionospheric storms.

3.5. Operational ionospheric monitoring service for GNSS positioning applications

Building on the previous experience of ionosphere/space–weather observations (Jakowski, 1996; Jakowski et al., 2002, 2004, 2005; Stankov et al., 2003, 2005), DLR established a novel operational space–weather monitoring service as a part of the Space Weather Application Centre Ionosphere (SWACI) project. The objective is to provide a permanent service, based on GNSS and space weather observations, that generates and distributes specific products to operators of GNSS-based reference networks in order to help them deliver more reliable, precise and secure positioning services and to eventually reduce the operation, production and other business costs. The objective is achieved by permanently monitoring the ionosphere/space weather, operationally providing ionospheric/space weather observations, pre-processing and calibration of GNSS data, generation of value-added products such as TEC maps and derivative products covering the European and Polar regions, post-processing and analysis of ionospheric/space weather information, analysis of ionospheric/space weather effects, user benefit analysis, etc. The mapping resolution is very high (Fig. 11), both spatially (1 deg) and temporally (5 min); all maps produced with a latency of less than a minute. A novel in-house procedure has been developed for monitoring the TEC mapping quality by estimating the so-called grid ionospheric vertical delay and the grid ionospheric vertical error (Klaehn et al., 2003). Also monitored and available during the generation of the TEC map is the distribution of the ionospheric piercing points (IPP) over the area covered by this map; the IPP is the intersection of the ray path with the idealised ionospheric layer at 400 km altitude.

By generating high-resolution maps of the TEC value and the TEC spatial and temporal gradients, the propagation of ionospheric disturbances becomes obvious. As the front of the detected disturbances advances, it may negatively affect the performance of the reference networks. However, it should be mentioned that the TEC mapping alone does not always provide clear and early indications of ongoing storm conditions, TEC gradients mapping is also needed. The production of TEC gradient maps is based on the calculation of temporal and spatial gradients at each grid point in the European region (optimally, 1° spatial

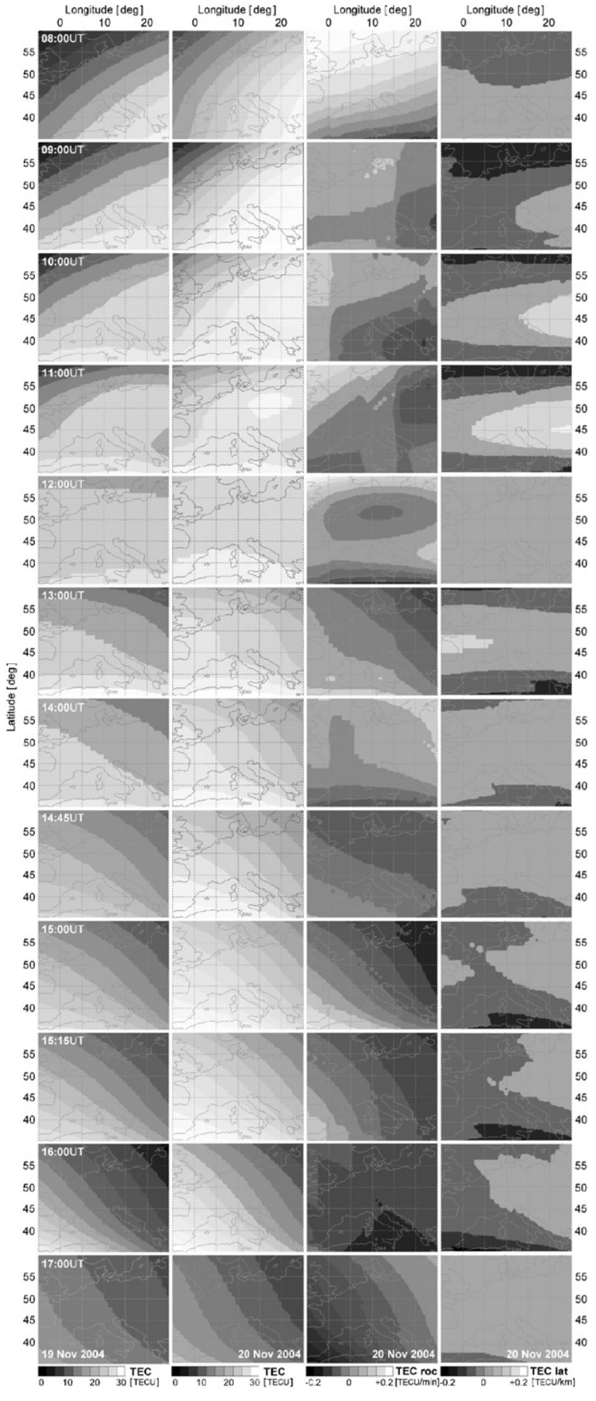

Fig. 11. SWACI Operational service. European maps of the GNSS TEC value (columns 1 and 2, TECU = $10^{16}/m^2$), TEC rate of change (column 3, TECU/min), and TEC latitudinal gradients (column 4, TECU/km) during the storm on 20 November 2004. For comparison, the corresponding TEC maps from 19 November 2004 are also provided. The ionospheric perturbations, particularly around 0900UT and 1500UT, are easily detected on the TEC gradients maps.

resolution). Three types of gradient maps are generated–temporal (rate of change), latitudinal and longitudinal gradients maps. Latitudinal (north–south) gradients (right side map) show how and to what extent the disturbances propagate toward lower latitudes. Longitudinal (east–west) gradients show how the disturbances move between different local-time sectors which can be helpful in the same way as the latitudinal gradients, particularly during sunrise and sunset conditions. The existence of quick and strong TEC changes in time (the so-called TEC rate of change, or TEC temporal gradients) indicates that there are highly dynamic ionosphere–plasmasphere processes taking place at that moment. The regions of such enhanced ionospheric dynamics can easily be detected on the maps of the temporal gradients. In relation to this, assessed is the feasibility of implementing a new ionospheric perturbation index that is more closely related to the ionospheric effects and oriented towards the GNSS user needs for high precision positioning. This new perturbation index, provisionally named regional ionosphere disturbances index (RIDX), has several formulations in order to better address the nature of perturbation phenomena (Jakowski et al., 2006).

The high spatial and temporal mapping resolution achieved at DLR is a good basis for developing a reliable nowcast service. A preliminary forecast service is also offered by generating TEC maps based on prediction of the TEC 'quite-time behaviour' and subsequent correction deduced from the measured TEC relative deviations from its quiet-time values (Stankov et al., 2004).

4. Conclusion

A preliminary analysis of the ionospheric impact on GNSS reference networks was presented, clearly showing that the ionospheric disturbances, and the ionospheric conditions in general, do influence the integrity and the overall performance of the GNSS reference networks. Important network performance characteristics, such as the AFT and the IRE, seem to be particularly affected.

Even with the use of ionospheric models implemented in the network software, residual errors due to the ionospheric influence, are still observed. There are several diurnal patterns in the error behaviour that are largely dependent on season. In winter, the residual error increases during day and decreases during night, the opposite behaviour is observed in summer, and no significant error variability is detected in equinox.

It has been found that the ionospheric impact is noticeably stronger during ionospheric storms. Several case studies show that, in the majority of cases, the residual error increases significantly during the onset and main phases of the storm. However, increases during the recovery phase are also observed, which prompts the investigation of other ionospheric phenomena that might be responsible, such as the ionospheric irregularities.

The occurrence and/or propagation of ionospheric perturbations, due to their complex interaction with the thermosphere and magnetosphere, cannot be sufficiently well described by using planetary geomagnetic activity indices only. Neither can the ionospheric effects on GNSS applications be accurately determined/predicted. Therefore, new ionospheric perturbation indices are needed to quantitatively describe the ionospheric perturbations and more importantly, the ionospheric effects. For example, it is possible to define an index based on the standard deviation of TEC measurements from some non-perturbed values, empirically modelled or monthly median values.

The increasing number and densification of GNSS reference networks, combined with the increased availability of ground-based and spaced-based GNSS measurements worldwide, will definitely provide more opportunities for comprehensive monitoring of the entire ionosphere–plasmasphere system. At the same time, higher quality will be demanded of the GNSS-based services. In this perspective, specialised ionosphere/space weather services that operationally generate and deliver nowcast/forecast information to professional GNSS users will be crucial for the mitigation of ionospheric effects, especially if high precision and safety critical applications are envisaged.

Acknowledgements

This research has been funded by the German Aerospace Center (DLR), the German State Government of Mecklenburg under grant V230-630-08-TIFA-334, and the European Space Agency (ESA) under contract ESTEC 16952/02/NL/LvH. Thanks are also due to the German Federal Agency for Cartography and Geodesy (BKG), E.ON Ruhrgas AG, Allsat network and services GmbH, International GPS Service (IGS), NOAA Space Environment Center (SEC), for providing data needed for this work.

References

Belehaki, A., Tsagouri, I., 2001. Study of the thermospheric–ionospheric response to intense geomagnetic storms at middle latitudes. Phys. Chem. Earth C 26 (5), 309–313.

Chen, X., Landau, H., Vollath, U., 2003. New tools for network RTK integrity monitoring. In: Proceedings of the ION GNSS 2003, 9–12 September 2003, Portland OR, USA, pp. 1355–1360.

Chen, X., Vollath, U., Landau, H., Sauer, K., 2004. Will Galileo/modernised GPS obsolete network RTK? In: Proceedings of the European Navigation Conference, 17–19 May 2004, Rotterdam, The Netherlands.

Datta-Barua, S., 2004. Ionospheric threats to space-based augmentation system development. In: Proceedings of the ION GNSS 2004. Long Beach, CA, USA.

Foerster, M., Jakowski, N., 2000. Geomagnetic storm effects on the topside ionosphere and plasmasphere: a compact tutorial and new results. Surv. Geophys. 21 (1), 47–87.

Fuller-Rowell, T.J., Codrescu, M.V., Moffett, R.J., Quegan, S., 1994. Response of the thermosphere and ionosphere to geomagnetic storms. J. Geophys. Res. 99 (A3), 3893–3914.

Fuller-Rowell, T.J., Codrescu, M.V., Rishbeth, H., Moffett, R.J., Quegan, S., 1996. On the seasonal response of the thermosphere and ionosphere to geomagnetic storms. J. Geophys. Res. 101 (A2), 2343–2354.

Heise, S., Jakowski, N., Wehrenpfennig, A., Reigber, C., Luehr, H., 2002. Sounding of the topside ionosphere/plasmasphere based on GPS measurements from CHAMP: initial results. Geophys. Res. Lett. 29 (14), 1699.

Jakowski, N., 1996. TEC monitoring by using satellite positioning systems. In: Kohl, H., Ruester, R., Schlegel, K. (Eds.), Modern Ionospheric Science. European Geophysical Society, Katlenburg-Lindau, pp. 371–390.

Jakowski, N., Sardon, E., Schlueter, S., 1998. GPS-based TEC observations in comparison with IRI95 and the European TEC model NTCM2. Adv. Space Res. 22 (6), 803–806.

Jakowski, N., Heise, S., Wehrenpfennig, A., Schlueter, S., Reimer, R., 2002. GPS/GLONASS based TEC measurements as a contributor for space weather forecast. J. Atmos. Solar–Terrestrial Phys. 64 (5–6), 729–735.

Jakowski, N., Stankov, S.M., Klaehn, D., Beniguel, Y., Rueffer, J., 2004. Operational service for monitoring and evaluating the space weather impact on precise positioning applications of GNSS. In: Proceedings of the European Navigation Conference, 17–19 May 2004, Rotterdam, The Netherlands, Paper No. ENC-GNSS2004–119.

Jakowski, N., Stankov, S.M., Klaehn, D., Rueffer, J., Huck, B., Rietdorf, A., 2005. Ionospheric impact on the performance of GNSS reference networks. In: Proceedings of the European Navigation Conference, 19–22 July 2005, Munich, Germany, Paper No. ENC-GNSS2005–527a.

Jakowski, N., Stankov, S.M., Schlueter, S., Klaehn, D., 2006. On developing a new ionospheric perturbation index for space weather operations. Adv. Space Res. in press.

Jodogne, J.C., Stankov, S.M., 2002. Ionosphere–plasmasphere response to geomagnetic storms studied with the RMI–

Dourbes comprehensive database. Ann. Geophys. 45 (5), 629–647.

Klaehn, D., Schlueter, S., Jungstand, A., 2003. On the implementation and performance of the ESTB ionospheric corrections processor. In: Proceedings of the European Navigation Conference, 22–25 April 2003, Graz.

Proelss, G.W., 1995. Ionospheric F-region storms. In: Volland, H. (Ed.), Handbook of Atmospheric Electrodinamics, 2. CRC Press, Boca Raton, FL, USA, pp. 195–248.

Stankov, S.M., Jakowski, N., Heise, S., Muhtarov, P., Kutiev, I., Warnant, R., 2003. A new method for reconstruction of the vertical electron density distribution in the upper ionosphere and plasmasphere. J. Geophys. Res. 108 (A5), 1164.

Stankov, S.M., Kutiev, I.S., Jakowski, N., Wehrenpfennig, A., 2004. GPS TEC forecasting based on auto-correlation analysis. Acta Geod. Geophys. Hung. 39 (1), 1–14.

Stankov, S.M., Jakowski, N., Wilken, V., Tsybulya, K., 2005. Generation and propagation of ionospheric disturbances studied by ground and space based GPS techniques. In: Proceedings of the Ionospheric Effects Symposium (IES 2005), 3–5 May 2005, Alexandria, VA, USA, Paper No. A064/9B2, 807–814.

Stankov, S.M., Jakowski, N., 2006. Indexing the local ionospheric response to magnetic activity by using total electron content measurements. Acta Geod. Geophys. Hung. 41 (1), 1–15.

Trimble Navigation Ltd., 2005. GPSNet^{TM} User Guide, Version 2.40, Revision A, Part Number 48596-24-ENG, Trimble Navigation Ltd., 512.

Tsybulya, K., Jakowski, N., 2005. Medium- and small-scale ionospheric irregularities detected by GPS radio occultation method. Geophys. Res. Lett. 32, L09103.

Vollath, U., Landau, H., Chen, X., 2002. Network RTK concept and performance. In: Proceedings of the International Symposium on GPS/GNSS, 6–8 November 2002, Wuhan, China.

Wanninger, L., 1999. The performance of virtual reference stations in active geodetic GPS networks under solar maximum conditions. In: Proceedings of the ION GPS 1999. Nashville, TN, USA, 1419–1427.

Wanninger, L., 2002. Die Bedeutung der Ionosphaere fuer Referenzstationsnetze. In: Proceedings of the SAPOS Symposium, 21–23 May 2002. Hannover, Germany.

Wanninger, L., 2004. Ionospheric Disturbance Indices for RTK and Network RTK Positioning. Proceedings ION GNSS 2004. Long Beach, CA, USA, pp. 2849–2854.

Walter, T., Datta-Barua, S., Blanch, J., Enge, P., 2004. The effects of large ionospheric gradients on single frequency airborne smoothing filters for WAAS and LAAS. In: Proceedings of the ION NTM 2004, 26–28 January 2004, San Diego, CA, USA, pp. 103–109.