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INDEXING THE LOCAL IONOSPHERIC RESPONSE TO MAGNETIC ACTIVITY BY USING TOTAL ELECTRON CONTENT MEASUREMENTS

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Investigated is the relationship between the level of geomagnetic activity and the GPS TEC relative deviations from the monthly medians. Detailed information on this dependence is of crucial importance for developing a new synthetic index which, by quantifying the local response of TEC to geomagnetic activity, will be able to improve the quality of autocorrelation forecast procedures.

Keywords: ionospheric disturbances; modelling and forecast; total electron content

1. Introduction

One of the ultimate aims of the ionospheric research is the reliable prediction of basic ionospheric characteristics, such as the critical frequency (f_oF2) and the total electron content (TEC). Such predictions can be used in managing and planning HF radio services, including the definition of the operating frequencies, signal strength, signal-to-noise ratio, multipath probability, etc. During the years, the focus has gradually shifted from long-term predictions to short-term forecasting based on data obtained in near real time from both, the extensive network of ionosondes and from Global Positioning System (GPS) TEC stations. The traditional way of predicting the ionospheric characteristics has been to employ previously-developed empirical and/or theoretical models of these characteristics using model inputs that are supposed to adequately represent the conditions in the prediction period. The problem is that such models are mostly climatological, i.e. they are relevant to undisturbed conditions of large-scale 'slow' dynamics and therefore are not suitable for short-term forecasting purposes. Recently, new approaches have been proposed to rectify the above-mentioned problem (Houminer and Soicher 1996, Williscroft and Poole 1996, Muhtarov and Kutiev 1999, Kutiev et al. 1999, Kutiev and Muhtarov 2001, Fuller-Rowell et al. 2002, Araujo-Pradere et al. 2002, Araujo-Pradere and Fuller-Rowell 2002, Muhtarov et al. 2002). Considering that several procedures, real-time estimates, and predictions of the fundamental geomagnetic activity indices D_{st}, K_p, and A_p (Menvielle and Berthelier 1991) are now readily available (O'Brien and McPherron 2000, Boberg et al. 2001, Takahashi and Toth 2001, De Franchesci et al. 2001), these methods will be better equipped with prediction capabilities because of the proven dependence of the ionospheric characteristics on the geomagnetic activity. Moreover, present and future space missions will help advancing the knowledge of the solar-terrestrial inter-relationship and will improve the geomagnetic storm prediction (Tsurutani and Gonzalez 1995) and associated phenomena.

A new procedure has been recently developed for TEC — based forecasting (Stankov et al. 2004), relating the forecasted TEC value much closer to the past, current and predicted space weather conditions. The TEC time series is considered as a sum of two components — periodic and random. The periodic component is non-random and describes the average behaviour (controlled mainly by the solar activity). On the other hand, the random component describes the TEC fluctuations supposedly inflicted by the geomagnetic field disturbances; moreover, it is implicitly assumed that these TEC fluctuations depend solely on the level of geomagnetic activity. Such an interpretation suggests that the TEC median behaviour is the signal and the fluctuation is the noise. The forecast is therefore performed in two main stages — first, the median prediction, i.e. extrapolation of the TEC monthly medians, and second, the short-term forecast, i.e. extrapolation of the TEC relative deviation ($\mathrm{TEC}_{\mathrm{rel}}$) from its median (extrapolation based on current and forecasted values of geomagnetic indices). For the purpose, utilised is a classical linear prediction method (Childers 1978, Muhtarov et al. 2002). Difficulties, concerning short-term forecast, arise from the fact that the average dependence of $\mathrm{TEC}_{\mathrm{rel}}$ from K_p is highly non-linear, which is clearly detected from the GPS TEC measurements (Fig. 1). The mutual correlation between two random variables is highest when these variables are linearly dependent (Childers 1978, Oppenheim and Schafer 1989). This is not so in our case, so a polynomial approximation of the mean dependence between $\mathrm{TEC}_{\mathrm{rel}}$ and K_p can perform the role of an index helping to linearise the $\mathrm{TEC}_{\mathrm{rel}}/K_p$ dependence and thus rectifying the aforementioned problem. The behaviour of the $f_o\mathrm{F2}$ relative deviations have already been analysed and used in modelling studies of the F region response to storms (Kutiev and Muhtarov 2001, Fuller-Rowell et al. 2002, Araujo-Pradere et al. 2002, Araujo-Pradere and Fuller-Rowell 2002, Muhtarov et al. 2002, and references therein).

However, significant differences are observed between the behaviour of the TEC relative deviations and the corresponding $f_o\mathrm{F2}$ relative deviations. These facts are analysed and reported here together with a further analysis of the TEC response to geomagnetic forcing. Sequentially, it becomes clear that the method of $f_o\mathrm{F2}$ forecasting cannot be directly applied to the TEC forecasting, and modifications in the strategy are needed in the latter. This paper presents also results from our

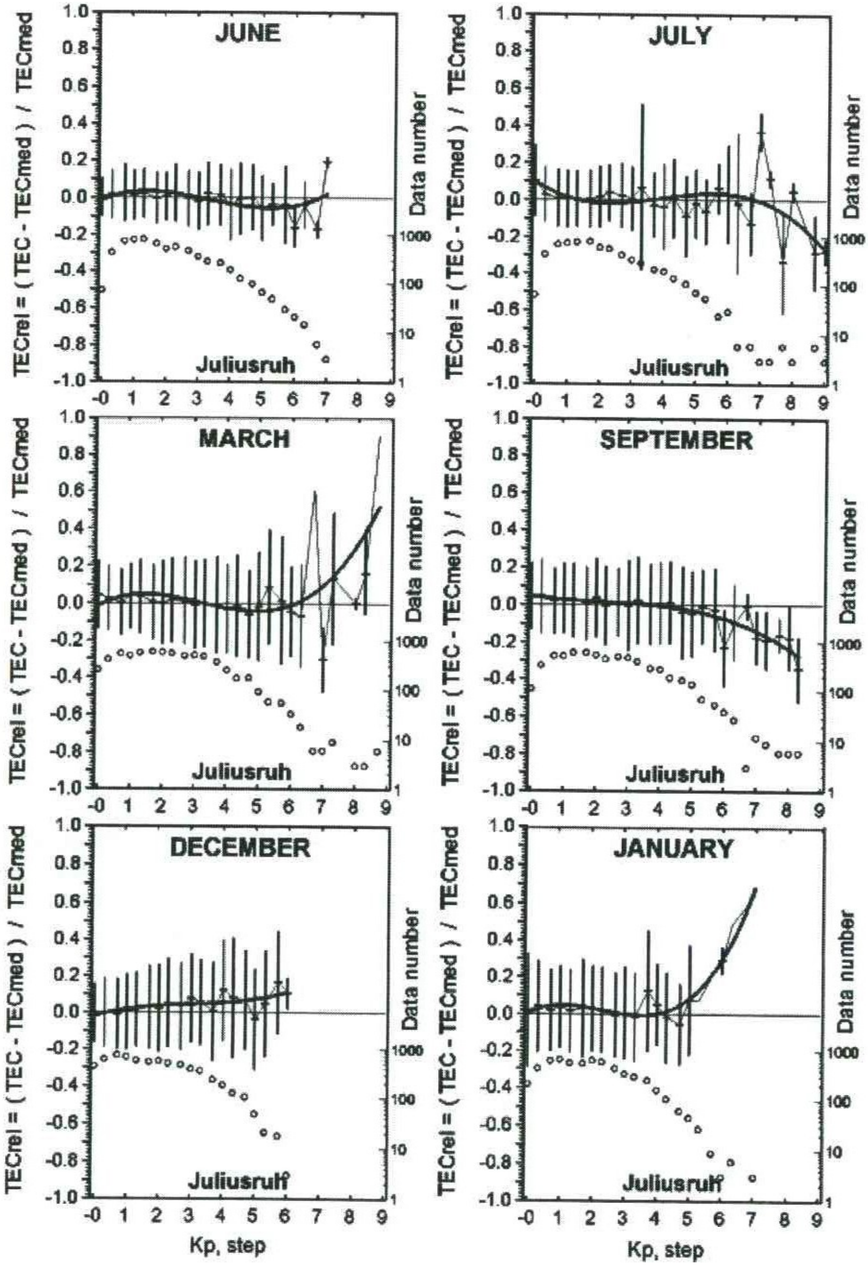

Fig. 1. TEC relative deviations from monthly medians, obtained during 1995–2001 for the site of ionosonde station Juliusruh (54.6°N, 13.4°E). The average dependence of TEC_{rel} on K_p presented with a solid line; standard deviation (vertical bar) and data number (circle) for each K_p value also provided

work towards developing an index of local ionospheric response to magnetic activity based on TEC observations only. Preliminary calculations of the index coefficients for some European stations are provided as well.

2. GPS TEC data base

Since 1995, the German Aerospace Centre (DLR) has been operating a system for regularly processing ground based GPS data and producing TEC maps over the European region ($-20°E \leq$ longitude $\leq 40°E$; $32.5°N \leq$ latitude $\leq 70°N$) using mainly measurements by the ground station network of the International GPS Service (IGS). The GPS data allow the determination of slant TEC values along numerous satellite-receiver links with 30 sec 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 a Kalman filter run over 24 hours. 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 the NTCM empirical model (Jakowski 1996). The advantage of applying such assimilation is that even in cases of low numbers of measurements, reasonable ionospheric corrections can still be delivered to the users.

3. TEC dependence on geomagnetic activity

In order to better analyse the TEC variations, particularly those supposedly induced by the geomagnetic activity, probably the best quantity to be used in such case is the TEC relative deviation ($\mathrm{TEC_{rel}}$) which is calculated by subtracting the monthly median ($\mathrm{TEC_{med}}$) from the corresponding measured TEC value and divided by the median value:

$$\mathrm{TEC_{rel}} = \frac{(\mathrm{TEC} - \mathrm{TEC_{med}})}{\mathrm{TEC_{med}}} . \tag{1}$$

In this way, diurnal, seasonal, and solar cycle variations are effectively removed. Other advantages of using a dimensionless quantity like $\mathrm{TEC_{rel}}$ is in the opportunities it offers for comparison of results from different sites (and time), and also for comparison with the behaviour of other characteristic such as $f_o\mathrm{F2}$. Previous studies involving predictions of the $f_o\mathrm{F2}$ relative deviations proved the efficiency of this approach of predicting the relative deviations instead of the absolute values (Houminer and Soicher 1996, Kutiev et al. 1999, Muhtarov et al. 2002).

The following calculations have been made to facilitate the analysis of the TEC dependence on geomagnetic activity. First, for each month of the year, the 24 hourly medians were determined. Then, the TEC relative deviations for each hour and month were then calculated by using Eq. (1). As mentioned already, we assume that the TEC fluctuations depend solely on the level of geomagnetic activity; therefore it is necessary to analyze possible relationship pattern/s between the TEC_{rel} variations and an index of geomagnetic activity (the K_p index was chosen for the purpose as it has the longest time series of observations which would facilitate a necessary comparison between TEC_{rel} and f_oF2_{rel}). After that, the available TEC_{rel} values within a given month were sorted into 28 bins corresponding to all possible values of K_p (0.00, 0.33, 0.67, 1.00, 1.33, ..., 8.67 and 9.00). Finally, for each bin (i.e. for each level of K_p) and each month, the basic statistics were calculated — mean and median values, standard deviation, scattering (twice the standard deviation), number of data in each bin, etc. Exemplary results are provided (Fig. 1) for winter, equinox, and summer months. Significant differences are detected in the TEC variability during different seasons and at different latitudes. Interestingly, differences were also observed between the GPS TEC and f_oF2 storm-time behaviour.

3.1 Seasonal and latitudinal differences in the TEC relative variations

In order to obtain more information on the seasonal and spatial differences in the TEC relative deviations, these deviations have been obtained for three European stations — Ebre (81.70°E , 43.30°N), Slough (83.72°E, 54.25°N), and Lerwick (89.14°E, 62.34°N) — conveniently situated at three different geomagnetic latitudes and within a narrow geomagnetic longitude range (Fig. 2). The plots are based on the averaged relative deviations and produced by using the Kriging method (Oliver and Webster 1990). Differences are observed in both the positive and the negative TEC variability. First (positive response), it is obvious that in the winter months of December and January the increase of TEC_{rel} during storms is quite significant: it can reach 20–25% at lower latitudes (Fig. 2, bottom panel) and exceed 35–40% at higher latitudes (Fig. 2, top panel). Therefore, the strength of the positive response is definitely increasing in poleward direction. Also, when heading North, the positive values are spreading towards the neighbouring equinox months of September and March. Positive response (although not so strong) is observed again in the summer (June and July). Second (negative response), it is clear from the figure that pronounced decreases are observed during the equinox periods April–May and September–October for high geomagnetic activity, although not as strong as in the f_oF2 case. In addition, a strong latitudinal dependence is detected: at the Northern stations the negative response is stronger and starts from lower K_p values.

3.2 Observed differences between the TEC and f_oF2 relative variations

In order to compare the GPS TEC and f_oF2 relative deviations, the full annual response of both characteristics have been calculated for the site of ionosonde station Juliusruh (13.4°E, 54.6°N). The results show (Fig. 3) that the TEC response is generally stronger and much more complex than the f_oF2 response. First, it is obvious that, for low geomagnetic activity, the dependence of the relative TEC on K_p is similar to that of the relative f_oF2. However, for higher values of K_p, significant differences are observed. It is obvious that for f_oF2 (Fig. 3, bottom

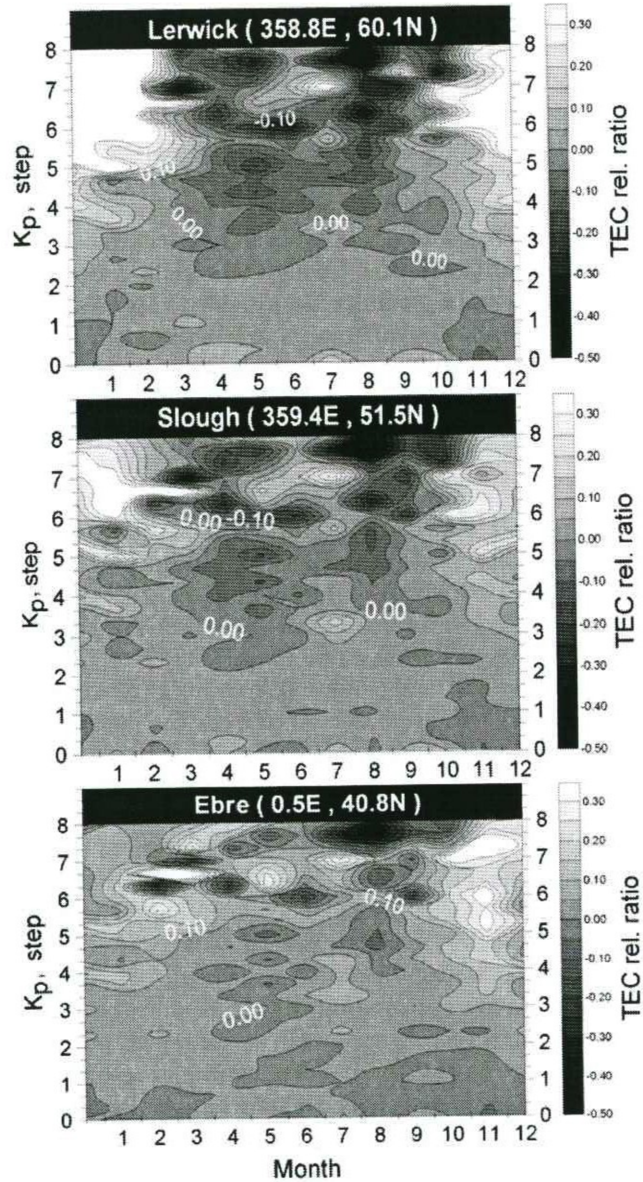

Fig. 2. Annual behaviour of the TEC relative deviations from the corresponding monthly medians, obtained during 1995–2001 for the sites of ionosonde stations Lerwick (358.8°E, 60.1°N), Slough (359.4°E, 51.5°N), and Ebre (0.5°E, 40.8°N)

panel) the relative response to increased magnetic activity is negative throughout the year. Oppositely, the TEC relative response to increased magnetic activity (Fig. 3, top panel) may be negative for some months (e.g. May and August–September) but for the rest of the year there are signs of pronounced increases. The results are similar to those obtained earlier at Dourbes (4.6°E, 50.1°N) (Stankov 2002, Jodogne and Stankov 2002). Second, let us revisit the open question of where exactly the boundary between the quiet and disturbed geomagnetic conditions lies. It is generally accepted that quite conditions exist if $K_p < 3$, unsettled conditions if $3 \leq K_p \leq 4$, and storm conditions prevail if $K_p > 4$. However, we see that such a definition is not perfect in terms of ionospheric measurements/effects. It follows from the observation that the median values of a given ionospheric characteristic are actually the upper limit of the quiet (undisturbed) conditions. Considering our assumption of sole dependency of the TEC (or f_oF2) perturbations on geomagnetic activity and $\mathrm{TEC_{rel}}$ definition (1), the median conditions should be defined as those K_p for which $\mathrm{TEC_{rel}}$ (or $f_o\mathrm{F2_{rel}}$) = 0. It should also be taken into account that the magnetic activity is ever-present which in effect leads to $\mathrm{TEC_{rel}}$ (or $f_o\mathrm{F2_{rel}}$) = 0 not at $K_p = 0$ but at higher index values. The 'zero isoline' is clearly seen in the plot of the f_oF2 variability (Fig. 3, top panel) and it is obvious that for f_oF2, the 'quiet' behaviour during winter (January and December) can be observed for K_p values even larger than 4, while during equinox — up to 3, and during summer — not more than 2.67. This fact speaks of generally higher sensitivity of the f_oF2 response to geomagnetic activity during the summer. The picture is much more complicated in the case of TEC measurements due to the entirely positive response during winter and the predominantly negative response during equinoxes. Thus far, it can be stated that the TEC variability is more diverse in its response to geomagnetic activity than that of the f_oF2.

3.3 Positive TEC deviations during increased magnetic activity

It is interesting also to analyse the positive TEC relative deviations at higher geomagnetic activity and their differences from the f_oF2 relative deviations. For this purpose, we need to look into the storm-time behaviour of TEC and provide concurrent observations of f_oF2 as well. Positive TEC relative deviations are caused by the so-called 'positive phases' of the ionospheric storms. In general, it is accepted that the positive storm phase is induced by the strong equatorward thermospheric winds in the expansion phases, reducing the ion loss and effectively increasing the ion production in the day-time hemisphere (Foerster and Jakowski 2000). The most significant consequence is the plasma uplifting effect — the strong meridional winds push the F2 layer plasma upward, leading to reduced F2 layer peak density and increased h_mF2 and TEC. This effect can be easily detected from measurements through the slab thickness shape parameter τ. There is also another possible mechanism — downwelling of molecule rich gas (after summer-to-winter hemisphere transport of composition bulge) causing recombination rate decreases and 'positive storm effect' in TEC. The latter mechanism explains also why the positive storms prevail in winter.

A well-known storm event that occurred in the period 31 March 2001 – 2 April 2001 is investigated here in more detail to demonstrate the abovementioned effects and to point out some differences between the TEC and f_oF2 reactions. GPS TEC and f_oF2 measurements at Juliusruh are provided together with the D_{st} and

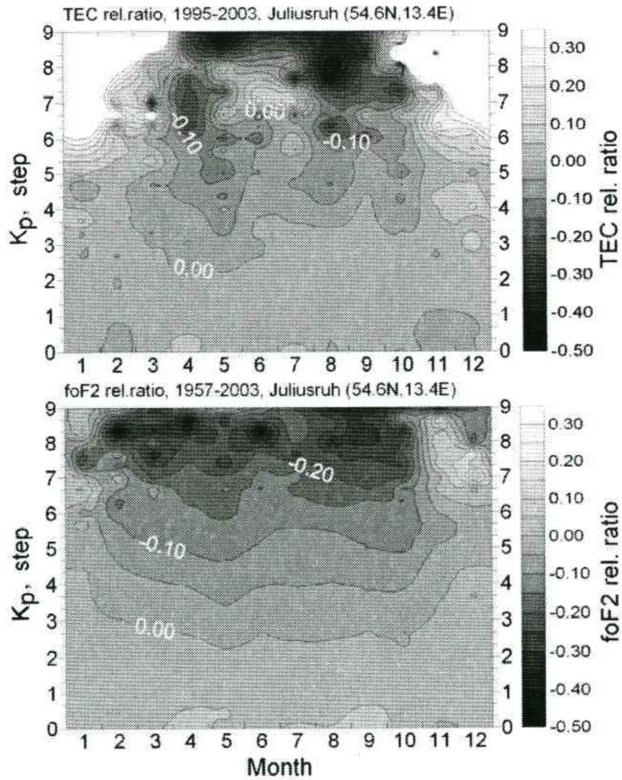

Fig. 3. Annual behaviour of the TEC and f_oF2 relative deviations from the corresponding monthly medians, obtained during 1995–2001 for the site of ionosonde station Juliusruh (54.6°N, 13.4°E)

K_p indices (Fig. 4). This storm started at 00:30UT on 31 March 2001 and very strong perturbations in the geomagnetic field components were observed: the K_p index almost reached its maximum of 9 and D_{st} sharply decreased to –358 nT at 08:00 UT on 31 March 2001. This storm was also long lasting: the main phase (–50 nT $\rightarrow D_{st}(\min)$) lasted about 3 hours and the recovery phase ($D_{st}(\min) \rightarrow -50$ nT) lingered for more than 54 hours. Both positive and negative storm effects were observed in the TEC and f_oF2 measurements. A sharp positive increase (exceeding 150%) was observed in TEC following the storm commencement and the increase lasted for about 6 hours. During this period, the K_p index rised from 6.67 to 8.67 but receded slightly to the 6.33 mark. In contrast to the TEC positive response, the f_oF2 positive response was not so pronounced and was significantly shorter. Case studies of other storms revealed similar behaviour (Stankov 2002).

It has been confirmed that it is more likely to observe positive storms in winter (Proelss 1995) and a possible explanation is the limited extent of the composition disturbance zone (Belehaki et al. 2000). Oppositely, it is unlikely to observe positive storms in May and September. Although the positive storm effects are more often during the day, night-time positive effects are also reported (Tsagouri et al. 2000,

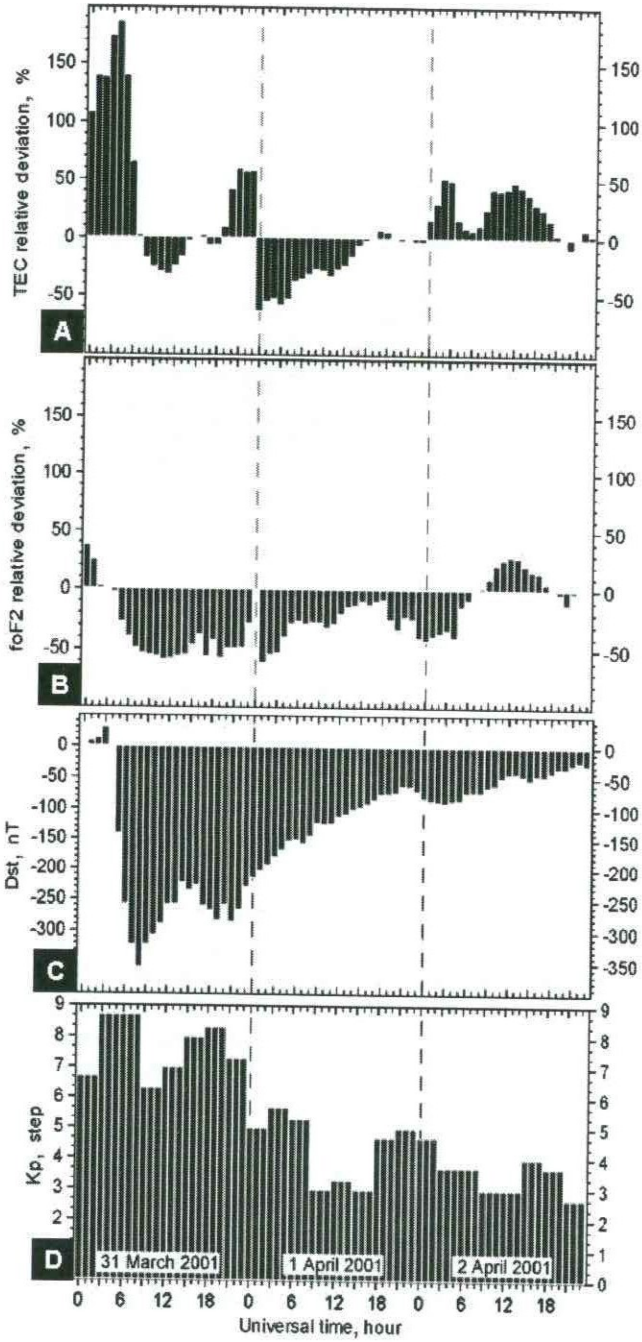

Fig. 4. GPS TEC (panel A) and f_oF2 (panel B) relative deviations from medians as observed at Juliusruh (54.6°N, 13.4°E) during the ionospheric storm 31 March – 2 April 2001. D_{st} (panel C) and K_p (panel D) observations also presented

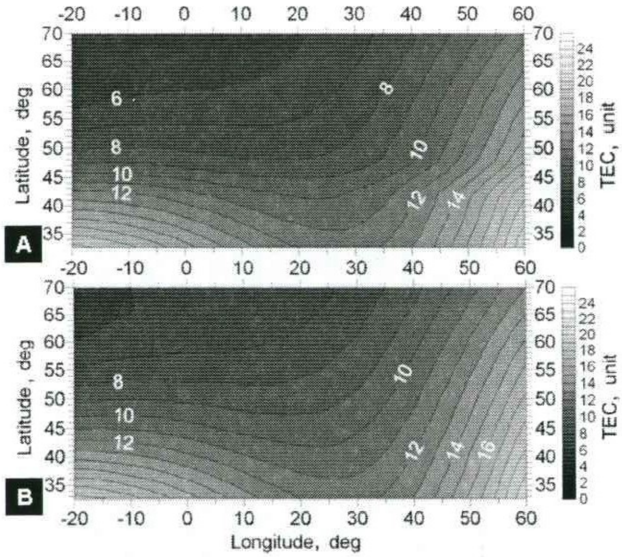

Fig. 5. Index implementation into correcting TEC maps. Comparison of the corrected map (panel A) and the corresponding NTCM model map (panel B) for 1 April 2001 0400 UT, $F_{10.7} = 257.5$, $K_p = 5.67$

Belehaki and Tsagouri 2001). Therefore, further investigation of the local time influence on TEC_{rel} is needed when a more comprehensive GPS TEC database is accumulated.

4. Indexing the local TEC response to magnetic activity

Proposed is a new index which can describe the averaged response of local ionospheric characteristics (e.g. TEC) to geomagnetic activity conditions. Essentially, the index will be an approximation of the averaged normalized behaviour of the forecasted characteristic (for example, see the solid lines in Fig. 1). Both, the accuracy and the type of approximation, are very important. On the one hand, this approximation will provide the actual index values and should be as accurate as possible because it is going to directly affect the linearisation of the TEC_{rel} to K_p relation. In addition, a correct separation between 'quiet' and 'storm' conditions depends also on the quality of approximation. On the other hand, the approximation function should not be very complex as it will make the above-mentioned linearisation difficult. If possible, the approximation should be of the same type for both TEC and f_oF2.

By assuming that the geomagnetic activity is the sole cause of the TEC perturbations (respectively, the TEC relative deviations from the monthly medians), the average behaviour of the above perturbations can be presented as a function of the planetary geomagnetic index K_p (alternatively, the A_p index). Proposed is a polynomial approximation of this dependence to be used as an index. Considering the analysis in the previous part and the TEC-based calculations, it follows that a second-degree polynomial is not good enough to describe the complex TEC response. Therefore, the following third-degree polynomial (Θ), depending on month of year (μ), geomagnetic latitude (φ) and longitude (λ), is hereby proposed :

$$\Theta(\varphi, \lambda, \mu) = \sum_{i=0}^{3} c_i(\varphi, \lambda, \mu) \cdot K_p^i . \tag{2}$$

The analysis shows that the TEC perturbations induced by the geomagnetic activity demonstrate strong spatial and temporal (seasonal, local-time) variability. The polynomial coefficients for the sites of the European ionosonde stations have already been obtained. For example, presented here are the coefficients calculated for the three stations that were used in the analysis (Table I). In view of further developments in the global storms modelling and short-term forecasting, this synthetic index should be deduced on a global scale. TEC relative deviations are expected to depend also on the local time as it was proven for the f_oF2 relative deviations at middle latitudes (Kutiev and Muhtarov 2001). However, it should be mentioned that the limited database does not yet allow us to perform a full range statistical analysis of the same type as for f_oF2. GPS TEC data series for an entire solar cycle is a pre-requisite as the TEC dependence on solar activity is also quite strong (Stankov et al. 2001, Stankov 2002). On top of that, the observed differences between f_oF2 and TEC storm behaviour make the task even more difficult since the experience based on f_oF2 is not directly applicable.

5. Applications

Several applications of the described experience have been made, for example, in the operational reconstruction of the electron density and in the nowcast/forecast of space weather conditions for use in improving positioning services based on Global Navigation Satellite Systems (GNSS).

5.1 Operational reconstruction of the vertical ionisation

Developed was an operational model for real-time reconstruction of the vertical electron density distribution from concurrent GPS-based total electron content and ionosonde measurements. Originally, the model was based on the novel approach (Stankov and Muhtarov 2001, Stankov et al. 2002) for deducing the topside ion scale heights assuming Epstein-type of vertical distribution. The required input data were submitted on-line to an operational centre (Dourbes) where processing was carried out immediately and the electron density profile derived with a latency of only 1–2 minutes. First tests have been already performed (Stankov 2002) and acknowledged at an IAG (International Association of Geodesy) EUREF (the IAG Reference Frame Sub-Commission for Europe) symposium (Bruyninx et al. 2002). The long-term goal of this experiment is to forecast the ionospheric conditions for real-time GNSS applications. The model has been upgraded with options for other ionospheric profilers to be used and also, pointed out the need of geomagnetic

Table I. Coefficients for the 3rd degree polynomial approximation for use in the development of a TEC-based synthetic index of local response to geomagnetic activity. Results based on measurements from the period 1995–2001 for the sites of ionosonde stations Lerwick (358.8°E, 60.1°N), Slough (359.4°E, 51.5°N), and Ebre (0.49°E, 40.8°N)

Degree	0	1	2	3
LERWICK				
JAN	-3.15004×10^{-3}	$+5.08573\times10^{-2}$	-3.39416×10^{-2}	$+6.65073\times10^{-3}$
FEB	$+3.92457\times10^{-2}$	-9.25860×10^{-2}	$+3.85024\times10^{-2}$	-2.82362×10^{-3}
MAR	$+9.53839\times10^{-2}$	-1.29344×10^{-1}	$+4.67148\times10^{-2}$	-4.41373×10^{-3}
APR	$+7.60262\times10^{-2}$	-2.91054×10^{-2}	-3.42287×10^{-3}	$+5.30661\times10^{-4}$
MAY	$+4.92617\times10^{-2}$	-2.19606×10^{-2}	-4.60323×10^{-3}	$+6.44569\times10^{-4}$
JUN	-7.89404×10^{-3}	$+8.40049\times10^{-2}$	-4.39476×10^{-2}	$+4.66968\times10^{-3}$
JUL	$+1.07895\times10^{-1}$	-9.87833×10^{-2}	$+2.49447\times10^{-2}$	-1.83409×10^{-3}
AUG	$+1.61411\times10^{-2}$	$+2.88412\times10^{-2}$	-1.30401×10^{-2}	$+3.08943\times10^{-4}$
SEP	$+6.46467\times10^{-2}$	-3.52940×10^{-2}	$+5.19716\times10^{-3}$	-2.54330×10^{-4}
OCT	$+1.07113\times10^{-1}$	-1.75858×10^{-1}	$+6.40719\times10^{-2}$	-5.90020×10^{-3}
NOV	-5.22770×10^{-2}	$+1.89916\times10^{-3}$	$+1.54437\times10^{-2}$	-1.35671×10^{-3}
DEC	-4.27628×10^{-2}	$+6.04943\times10^{-2}$	-1.64924×10^{-2}	$+3.46755\times10^{-3}$
SLOUGH				
JAN	$+4.81981\times10^{-2}$	-2.28353×10^{-2}	-3.20366×10^{-3}	$+1.97123\times10^{-3}$
FEB	-1.97672×10^{-2}	$+4.09025\times10^{-2}$	-1.41465×10^{-2}	$+1.82806\times10^{-3}$
MAR	$+6.51627\times10^{-2}$	-7.42769×10^{-2}	$+2.54639\times10^{-2}$	-2.29862×10^{-3}
APR	$+3.81891\times10^{-2}$	$+9.66277\times10^{-3}$	-1.40484×10^{-2}	$+1.39891\times10^{-3}$
MAY	$+1.78878\times10^{-2}$	-1.00038×10^{-2}	-3.15998×10^{-3}	$+6.02891\times10^{-4}$
JUN	-3.40790×10^{-2}	$+8.89468\times10^{-2}$	-3.73211×10^{-2}	$+3.78615\times10^{-3}$
JUL	$+7.16682\times10^{-2}$	-7.16401×10^{-2}	$+2.69126\times10^{-2}$	-2.53663×10^{-3}
AUG	$+1.31134\times10^{-2}$	-1.96442×10^{-2}	$+1.17969\times10^{-2}$	-2.03752×10^{-3}
SEP	$+4.85791\times10^{-2}$	-4.09538×10^{-2}	$+1.36448\times10^{-2}$	-1.54202×10^{-3}
OCT	$+7.65764\times10^{-2}$	-1.52300×10^{-1}	$+6.02785\times10^{-2}$	-5.74559×10^{-3}
NOV	-4.01791×10^{-2}	-1.49795×10^{-2}	$+2.10279\times10^{-2}$	-1.99790×10^{-3}
DEC	-8.14568×10^{-3}	$+2.17547\times10^{-2}$	-2.22273×10^{-3}	$+5.00161\times10^{-4}$
EBRE				
JAN	$+1.75217\times10^{-2}$	-2.85582×10^{-2}	$+1.46209\times10^{-2}$	-1.19256×10^{-3}
FEB	-1.89927×10^{-2}	$+9.41147\times10^{-4}$	$+8.25970\times10^{-3}$	-7.05562×10^{-4}
MAR	$+3.55263\times10^{-2}$	-5.67516×10^{-2}	$+2.16366\times10^{-2}$	-1.62993×10^{-3}
APR	$+1.12222\times10^{-2}$	$+2.24124\times10^{-2}$	-1.29707×10^{-2}	$+1.49852\times10^{-3}$
MAY	$+4.78803\times10^{-2}$	-8.33133×10^{-2}	$+2.71683\times10^{-2}$	-2.06908×10^{-3}
JUN	-3.78911×10^{-2}	$+5.13936\times10^{-2}$	-1.51496×10^{-2}	$+1.28453\times10^{-3}$
JUL	$+5.24720\times10^{-2}$	-7.66677×10^{-2}	$+3.30861\times10^{-2}$	-3.24792×10^{-3}
AUG	$+1.25327\times10^{-3}$	-3.74665×10^{-2}	$+2.26224\times10^{-2}$	-2.88688×10^{-3}
SEP	$+9.02681\times10^{-3}$	-2.96481×10^{-2}	$+1.51745\times10^{-2}$	-1.60990×10^{-3}
OCT	$+3.14029\times10^{-2}$	-1.21016×10^{-1}	$+5.72140\times10^{-2}$	-5.48030×10^{-3}
NOV	-4.21225×10^{-2}	-3.12555×10^{-2}	$+3.08677\times10^{-2}$	-2.63514×10^{-3}
DEC	-2.90052×10^{-3}	-1.01570×10^{-3}	$+1.13335\times10^{-2}$	-1.57484×10^{-3}

activity and TEC value forecasts for improving such types of services (Stankov et al. 2003).

5.2 Space weather conditions forecast for use in GNSS-based positioning services

It is now well recognised that space-weather-induced effects, such as the ionosphere-plasmasphere disturbances, can cause various technological problems. Such problems include: range errors, rapid phase and amplitude fluctuations (radio scintillations) of satellite signals, etc., all leading to pronounced signal degradation, degradation in the system performance, its accuracy and reliability. SWIPPA (Space Weather Impact on Precise Positioning Applications of GNSS) is a project, initiated by DLR, aiming at establishing a specific space weather service to help GNSS users mitigating (some of) the above-mentioned problems. This activity is considered a substantial part of the preparations for the future European Space Weather Programme. Several products/services are offered to designated users, research institutions, and general public. GNSS users can benefit from warnings, nowcasts and forecast of the ionosphere state provide better positioning services and eventually reduce operation and/or production costs (Jakowski et al. 2002). One of the products is the TEC forecast based on the here presented results.

6. Summary and conclusion

A new procedure is being developed for TEC — based forecasting (Stankov et al. 2004), which relates the forecasted TEC behaviour much closer to the past, current and predicted space-weather conditions. The procedure requires the development of a new synthetic index of local ionospheric response to geomagnetic activity based on TEC observations. For the purpose, the ionospheric GPS TEC relative deviations from the corresponding monthly medians were investigated and compared with f_oF2 deviations. Preliminary estimates of the index coefficient were obtained and presented. The main conclusions can be summarized as follows:

- Strong temporal and spatial variability observed in the TEC response to increased geomagnetic activity.
- The strength of both, the positive and negative responses of TEC, is increasing in poleward direction.
- TEC relative deviations may be negative for some months around equinoxes but there are signs of sustained positive response in the remaining months, most noticeably during winter.
- Significant differences are observed between the responses of TEC and f_oF2 values to increased geomagnetic activity; in general, the TEC response is stronger and more complex than the f_oF2 response.
- Indications appear of day-time and night-time differences in the strength and sign of the TEC relative deviations but more data required for definite conclusions.

— A second-degree polynomial approximation might be sufficiently good to represent the mean f_oF2 relative deviations but higher-degree polynomials are necessary for adequately describing the TEC mean relative deviations.

It is a well known fact that the ionospheric response to geomagnetic forcing comes with a delay (Proelss 1995, Foerster and Jakowski 2000, Kutiev and Muhtarov 2001, Stankov 2002). Although a significant progress has already been achieved, further analysis of this time delay is needed and the abundant TEC measurements can be of significant help. Finally, in regard to the TEC relative deviations, it appears that these deviations are strongly influenced by the storm time elapsed (i.e. the time elapsed from the storm onset) and the latter may have even stronger influence than the local time and season; the issue is currently being investigated and will be presented in a follow-on publication.

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