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Ionospheric Total Electron Content and Critical Frequencies over Europe at Solar Minimum

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Abstract

The paper presents results obtained by analyzing high-resolution ionospheric vertical total electron content (*vTEC*) data set evaluated from a chain of European ground-based Global Positioning System (GPS) stations and its equivalent slab thickness, as well as the F2-layer critical frequency *fo*F2 and propagation factor *M*(3000)F2 from nearby ionosonde stations over the period 2006-2007. The study covers data within an area between 36°N and 68°N geographic latitude, and 7°W and 21°E geographic longitude during these last two years of minimum solar activity in the 23rd solar cycle. It reveals 15 extraordinary events, all of which exhibited some form of large short-lived *vTEC* and *fo*F2 enhancements of the duration of small-magnitude solar-terrestrial events. The results clearly show a well-defined *vTEC* and *fo*F2 storm-like disturbance patterns developed under these conditions. They prove that there are still some open questions related to the large electron density variations during weak disturbances that require additional study for both their relevance to different Global Navigation Satellite Systems (GNSS) applications and their role in the formation and evolution of the daytime ionosphere at middle latitudes.

Key words: ionosphere, GNSS, geomagnetic storms.

1. INTRODUCTION

Continuous observations of ionospheric variability are necessary for monitoring and forecasting space weather conditions. Although the worst-case ionosphere disturbances impose a serious concern, it is feasible to mitigate the threat on radio communication and navigation systems to certain extend by various monitoring and modelling methods (Zolesi and Cander 2004, Bourdillon *et al*. 2009). With the worldwide use of global navigation satellite systems, like the Global Positioning System (GPS), it has been possible to continuously monitor the total electron content (TEC) of the ionosphere and plasmasphere up to a height of about 20,000 km. One of the features that has frequently been observed during severe space weather events at middle latitudes is an enhancement of the dayside ionospheric *TEC* (Foster and Rideout 2005). This *TEC* increase can be as large as a factor of two or more. The largest *TEC* increases are usually seen across the afternoon sector from noon to dusk over European and American sectors during geomagnetic storms. According to Heelis *et al.* (2009), the physical mechanisms responsible for these *TEC* enhancements are still unclear.

Many related studies have been done under geomagnetic disturbed conditions during solar maximum. However, since the ionospheric behaviours could be different between solar maximum and minimum, it is necessary to study the characteristics of the ionospheric parameters during solar minimum. Here we present some results from two years study (2006-2007) of vertical *TEC* and its equivalent slab thickness from a chain of European ground-based GPS stations, and of critical frequency *fo*F2 and propagation factor *M*(3000)F2 from nearby ionosonde stations. We used data from a few stations located between 36°N and 68°N geographic latitude and 7°W and 21°E geographic longitude. This study is provoked by examination of all available 15-minute resolution *vTEC* values at these stations from January 2006 to December 2007. They clearly shows 15 events (8 in 2006 and 7 in 2007), exhibiting some form of large *vTEC* enhancement focused exclusively on small-magnitude solar-terrestrial events in 23rd solar cycle, if any of the kind at all. These events are listed as follows: 16-18 April 2007, 27-29 April 2007, 06-08 May 2007, 21-23 May 2007, 13-15 July 2007, 19-21 July 2007, 19-21 November 2007, 22-24 January 2006, 17-19 March 2006, 03-05 May 2006, 05-07 June 2006, 18-20 August 2006, 26-28 August 2006, 29 September - 01 October 2006, and 12-14 October 2006.

In this paper, we will focus on the results for the following best examples: 19-21 November 2007, 16-18 April 2007, 12-14 October 2006, and 26-28 August 2006, paying particular consideration on the repeatable features of the event that are less likely to be captured into an empirical ionospheric model (Cander 2008). They are also related to the seasonal variation in *TEC*, which maximizes during the equinox months followed by winter and minimizes during the summer months. It is important to note that similar increase is simultaneously seen in *fo*F2. The observations of ionospheric storm-like effects in ionospheric vertical *TEC* and *fo*F2, which could be of serious concern in radio propagation forecasting as well as in navigation, are described in Section 2. The analysis of the processes causing these effects is presented in Section 3. We conclude in Section 4 with a summary of the new features, discussing their consequences on ionospheric monitoring and modelling.

2. DATA AND RESULTS

A general discussion on the method of GPS signal evaluation and the detailed descriptions of the technique of processing GPS data are given by Ciraolo (1993). It can be summarized as follows. The data are extracted from the RINEX files for stations in Table 1, available at several global and regional centers of the International GNSS Service (IGS, http://igscb.jpl.nasa.gov/). Each RINEX file contains phase and group propagation delays at two frequencies, observed by one individual station during an UTC day. Upon correctly differencing these delays, respectively on phase and group, two quantities proportional to slant *TEC* are obtained, commonly known as "phase" and "group" (or "code") slants. Slants are affected by hardware biases (group) and offsets (phase) that are both unknowns. The first step before using them for ionospheric investigation is evaluating biases and offsets, which is the process of "calibration" or "de-biasing". Both phase and code slants can be used for this step, but generally a combination of them is used, the "levelled" slants, in order to obtain quantities free from ambiguities inherent to phase observations and free, to some extent, of multi-path, strongly affecting code slants. Denoting by Ω the phase offset, β and γ the satellite and station hardware biases, m the multi-path, and < > a weighted average operator, the three quantities so far obtained can be written as

phase slants: $S_\Phi = TEC + \Omega$,

code slants: $S_G = TEC + \beta + m$,

levelled slants: $S = S_\Phi - \langle S_\Phi - S_G \rangle = TEC + \beta + \gamma + \langle m \rangle$.

Table 1

IGS stations in this study

id	City	Location	Longitude E	Latitude N
EBRE	Roquetes	Spain	0.4924	40.8209
HERS	Hailsham	England	0.3362	50.8673
KIRU	Kiruna	Sweden	20.9684	67.8573
MATE	Matera	Italy	16.7045	40.6491
POTS	Potsdam	Germany	13.0700	52.3800
SFER	San Fernando	Spain	353.7944	36.4640

The observables used for the calibration in the present work are always the levelled slants. As the single station calibration is performed, β and γ cannot be separated, and β will generally indicate their sum. Still, the <*m*> contribution is neglected.

Under these assumptions, from one station, we gain the set of slants to each satellite *i* at time *t*

$$S_{it} = TEC_{it} + \beta_i \ .$$

According to the thin shell approach, the slant is written as

$$TEC = VEC \sec\chi \ .$$

Here *VEC* is assumed to be the vertical *TEC*, a function of the (horizontal) position of the ionospheric (or pierce) point P identified by the intersection of the thin shell with the ray, χ being the angle between the ray itself and the vertical in P. Afterwards, *VEC* is expressed as a proper expansion of horizontal coordinates (l, f) with one set of coefficients at each time

$$VEC_{Eq}(l, f) = \sum_n c_n p_n(l, f) \, .$$

The equations of observation will therefore be written as

$$S_{it} = \sum_n c_{tn} p_n(l_{it}, f_{it}) \sec\chi_{it} + \beta_i \, .$$

The equations for the above set of slants are written for every UTC day for every station. The reference height for the computation of χ_{REF} has been taken at 400 km. The horizontal coordinates are local time and Rawer modified dip latitude (modip). The set of equations is linear in the unknown coefficients c_{tn} and biases β_i. Its solution provides the actual *TEC*'s (or calibrated slants) as $TEC_{it} = S_{it} - \beta_i$, and the vertical *TEC* over the station from the expansion $V_{Eq}(l, f) = \sum_n c_n p_n(l, f)$, using for (l,f) the coordinates of the station itself.

First, we concentrate on the observations in the winter month in Figs. 1a-e. The vertical *TEC* values at ground GPS middle latitude stations HERS and MATE for 19, 20, and 21 November 2007 are displayed in Figs. 1a and b, respectively. It is most interesting to note that there are very small differences between the *vTEC* values observed on 19 and 21 November. However, a stronger positive storm-like effect can be seen in the data at both HERS and MATE on 20 November from 10:00 to 16:00 UT. The *vTEC* is increased from 10 to 19 TECU (a total electron content unit is 10^{16} electron/m^2 column density) during the 4-h period at HERS and *vTEC* is increased from 10 to 17 TECU during the 6-h period at MATE. The *vTEC* values increase on 20 November by about 12 TECU at its peak in HERS and about 7 TECU at

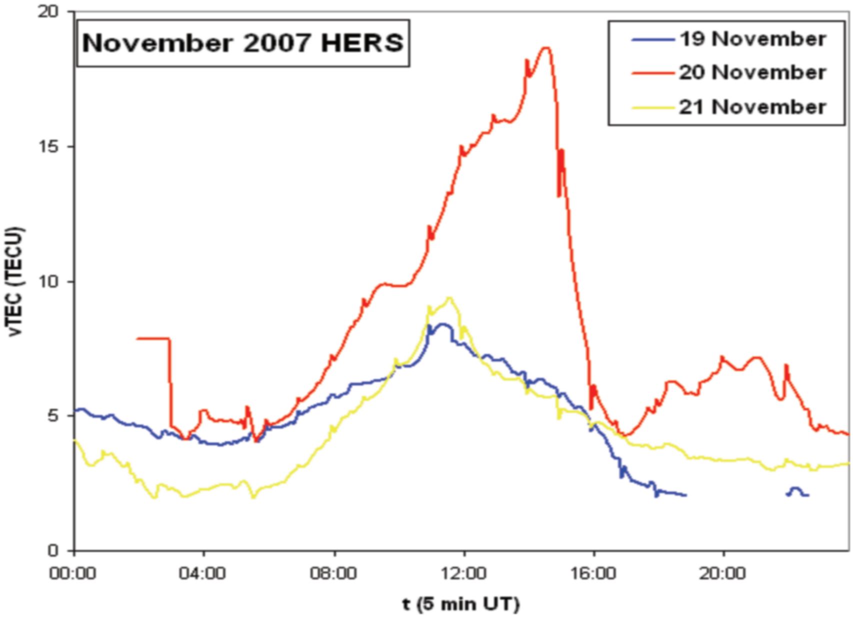

Fig. 1a. Daily values of *vTEC* with 5-min resolution over HERS during 19-21 November 2007. Colour version of this figure is available in electronic edition only.

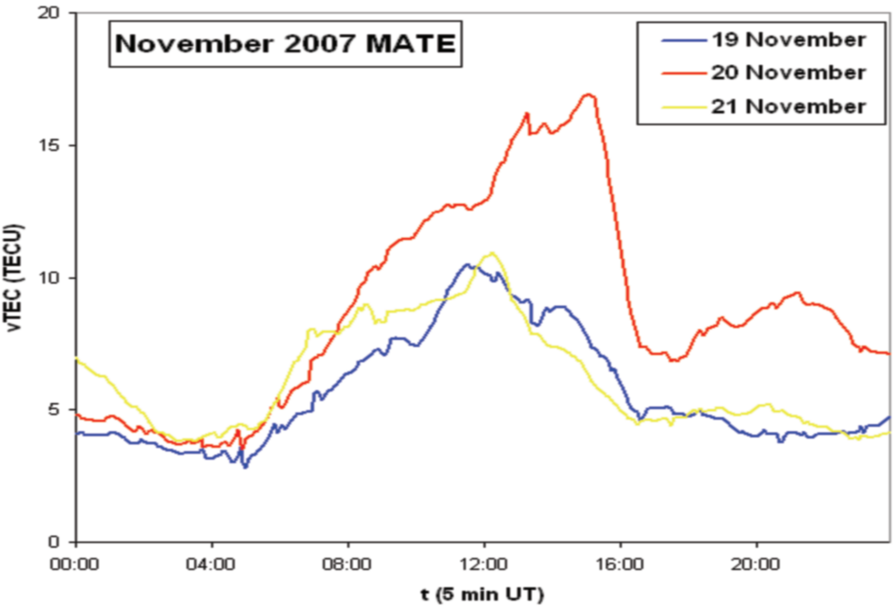

Fig. 1b. Daily values of *vTEC* with 5-min resolution over MATE during 19-21 November 2007. Colour version of this figure is available in electronic edition only.

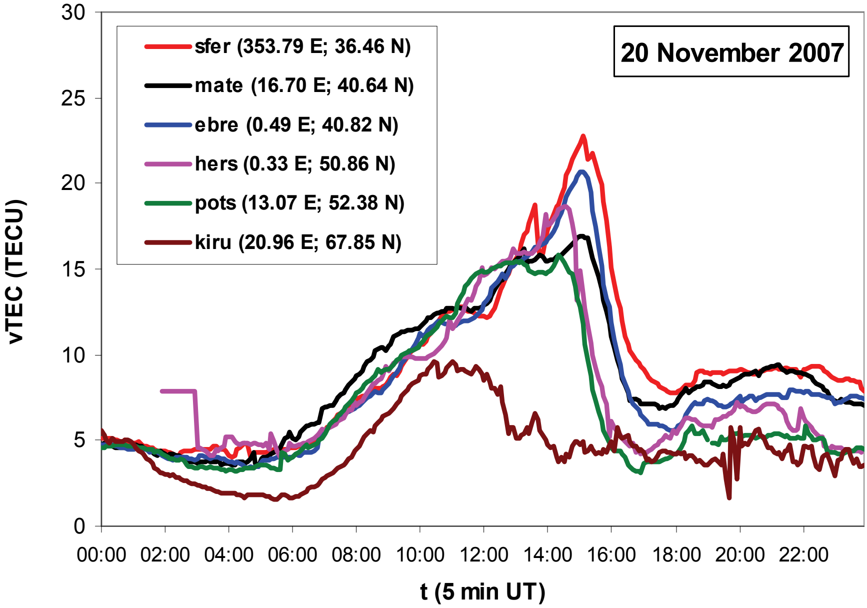

Fig. 1c. Daily values of *vTEC* with 5-min resolution over SFER, MATE, EBRE, HERS, POTS and KIRU on 20 November 2007. Colour version of this figure is available in electronic edition only.

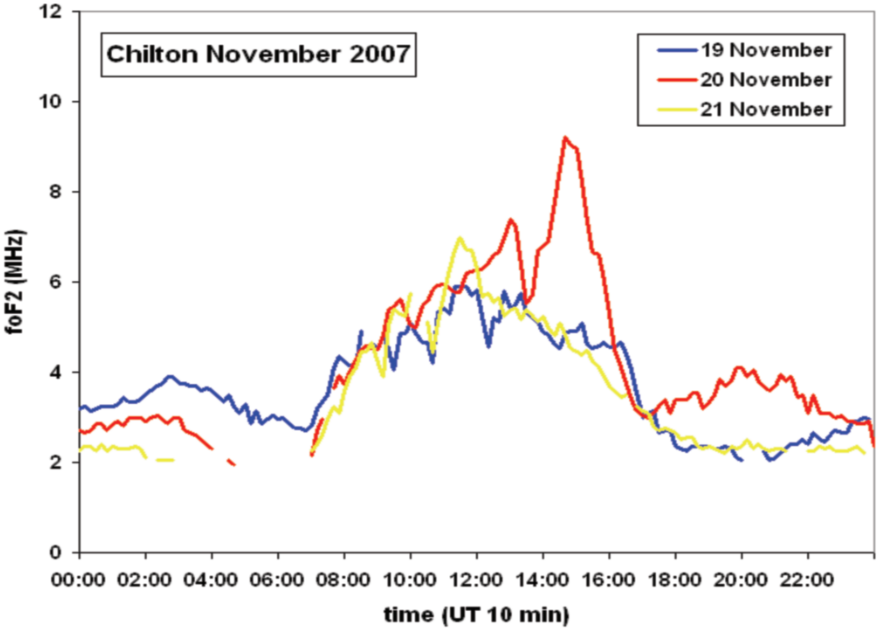

Fig. 1d. Daily values of *fo*F2 with 10-min resolution over Chilton during 19-21 November 2007. Colour version of this figure is available in electronic edition only.

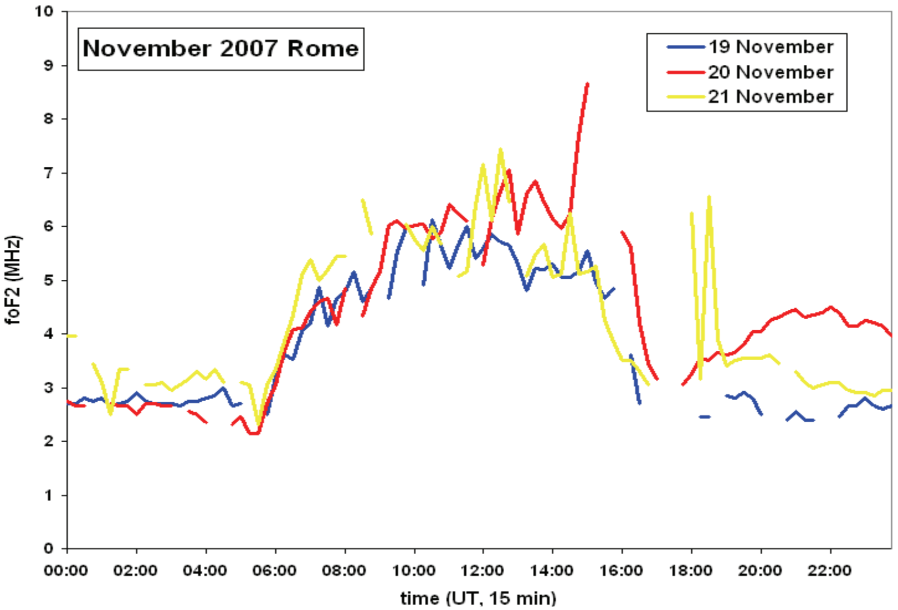

Fig. 1e. Daily values of *fo*F2 with 15-min resolution over Rome during 19-21 November 2007. Colour version of this figure is available in electronic edition only.

MATE, compared with the previous and subsequent days of 19 and 21 November conditions. It is worth noting that the nighttime *vTEC* values show obvious increases from 17:00 to 00:00 UT as well. Finally, Fig. 1c captured the temporal and spatial variations of the ionospheric storm-like effects seen in the GPS *vTEC* observations at all stations including SFER, EBRE, POTS and KIRU on 20 November 2007. These enhancements become less pronounced in Figs. 1d and e, but still could be clearly observed in the *fo*F2 variations over collocated ionosonde stations Chilton (358.70 E, 51.60 N) and Rome (12.52 E, 41.90 N), respectively. The *fo*F2 is increased from 5 to 9 MHz during the 2-h period at Chilton and *fo*F2 is increased from 6 to >8 MHz during the 2-h period at Rome.

Figures 2a-e have the same format as Figs. 1a-e and show the equinoctial month of April 2007. Again, there are no large changes in *vTEC* values at all stations on 16 and 18 April, indicating the geomagnetically quiet conditions. In addition, there are no large changes in *vTEC* values in the nighttime sector, even though *vTEC* increases significantly during a few daytime hours on 17 April at both HERS and MATE, as shown clearly in Figs. 2a and 2b, respectively. The *vTEC* is increased from 10 to 17 TECU during the 4-h period at HERS and *vTEC* is increased from 11 to 19 TECU during the 4-h period at MATE. The *vTEC* values increase on 17 April by about 8 TECU at its peak in HERS and about 9 TECU at MATE, compared with the previous and

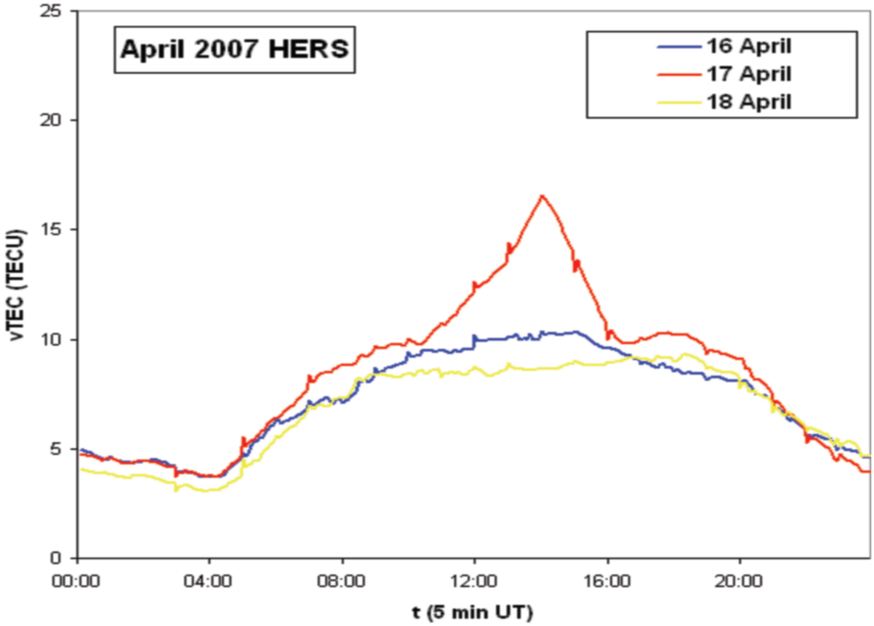

Fig. 2a. Daily values of *vTEC* with 5-min resolution over HERS during 16-18 April 2007. Colour version of this figure is available in electronic edition only.

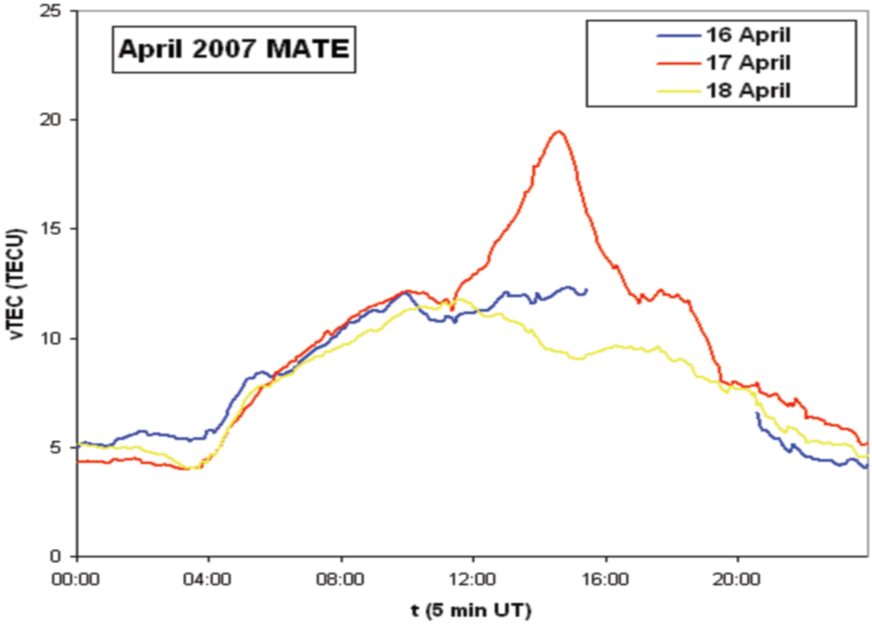

Fig. 2b. Daily values of *vTEC* with 5-min resolution over MATE during 16-18 April 2007. Colour version of this figure is available in electronic edition only.

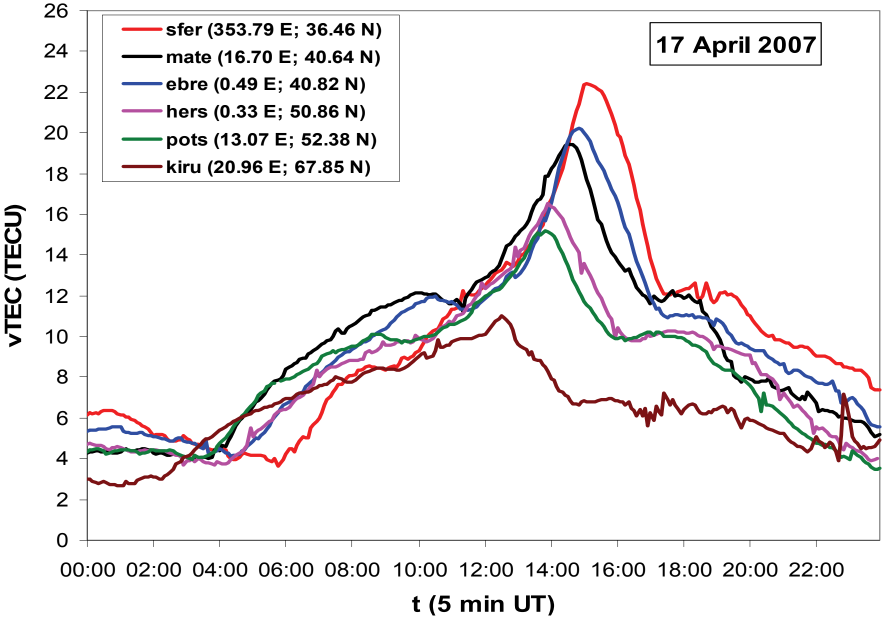

Fig. 2c. Daily values of *vTEC* with 5-min resolution over SFER, MATE, EBRE, HERS, POTS and KIRU on 17 April 2007. Colour version of this figure is available in electronic edition only.

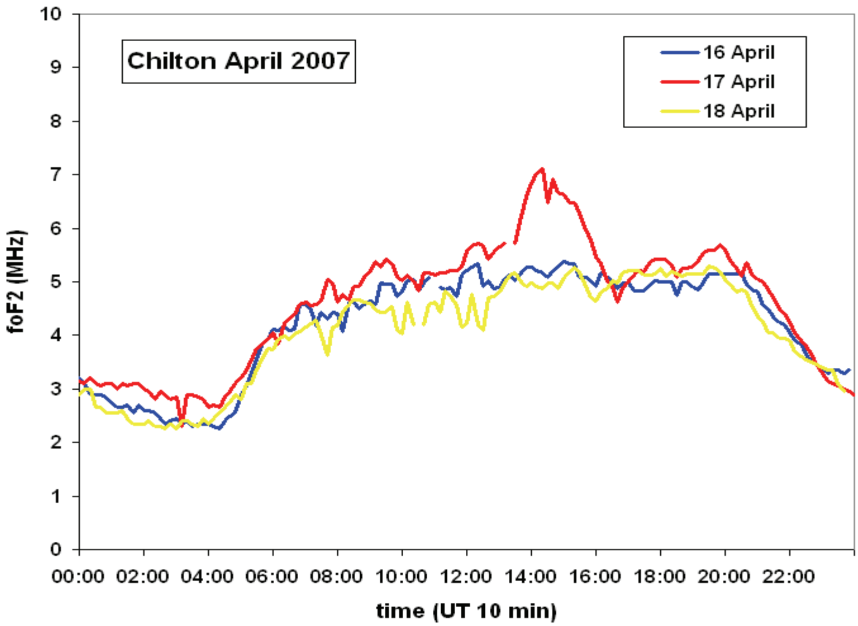

Fig. 2d. Daily values of *fo*F2 with 10-min resolution over Chilton during 16-18 April 2007. Colour version of this figure is available in electronic edition only.

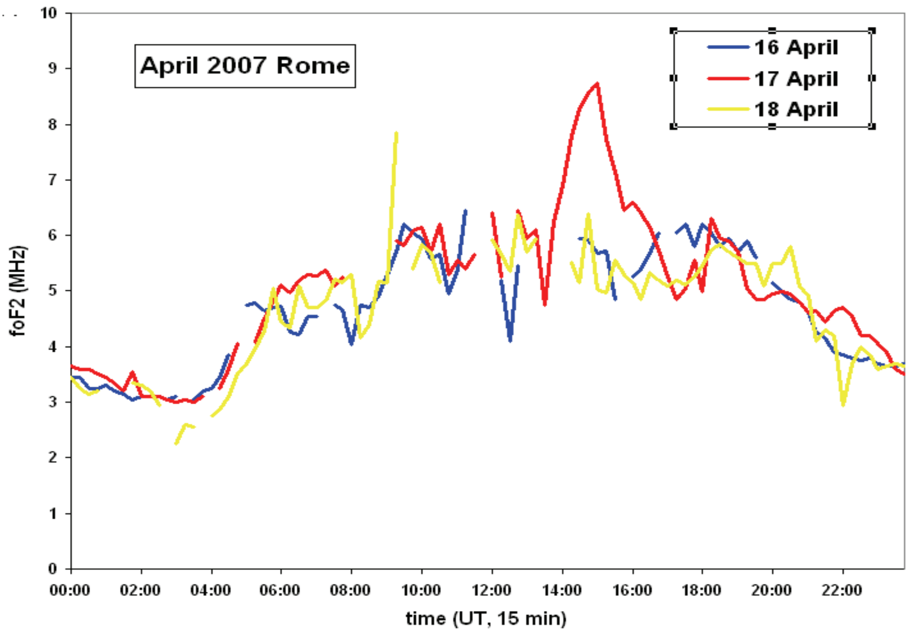

Fig. 2e. Daily values of *fo*F2 with 15-min resolution over Rome during 16-18 April 2007. Colour version of this figure is available in electronic edition only.

subsequent days of 16 and 18 April conditions. Figure 1c shows that enhancements in ionospheric vertical total electron content were of ~80% (SFER) and ~30% (KIRU) nominal values for the 17 April 2007 event. The difference of *vTEC* values at the low mid-latitude station SFER and at the high mid-latitude station KIRU at midday is of ~250%. These enhancements could be clearly observed in the *fo*F2 variations over collocated ionosonde stations Chilton and Rome, respectively. On 17 April 2007, *fo*F2 is increased from 5 to 7 MHz during the 2-h period at Chilton and *fo*F2 is increased from 5 to 9 MHz during the 2-h period at Rome.

Equinoctial month of October 2006 shows an excellent example of the effects considered at GPS ground-based stations HERS and MATE (Figs. 3a-b). The *vTEC* is increased from 9 to 22 TECU during the 4-h period at HERS and there is *vTEC* increase from 11 to 27 TECU during the same time period at MATE. Figure 3c includes the *vTEC* observations from all six stations. At these stations, the increase in *vTEC* from nominal values to peak occurs within ~2 hours on 13 October and has a magnitude of ~18 TECU, that is, more than 100%, being even higher at the lower latitude station SFER. The positive phase can also be seen in the data at SFER from 19:00 to 22:00 UT. It is evident that as time advances, the *vTEC* increases during daytime are displaced toward lower latitudes. At the same day,

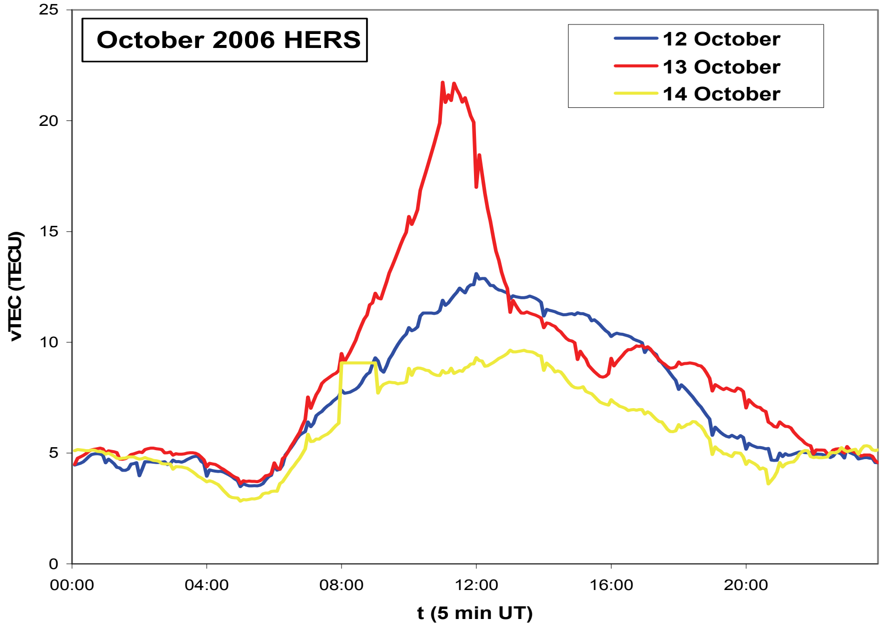

Fig. 3a. Daily values of *vTEC* with 5-min resolution over HERS during 12-14 October 2006. Colour version of this figure is available in electronic edition only.

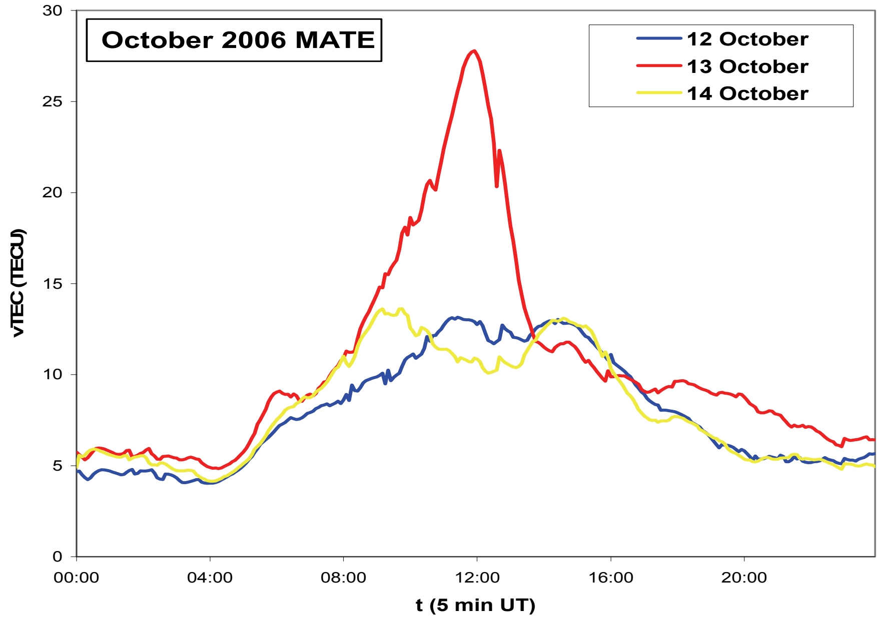

Fig. 3b. Daily values of *vTEC* with 5-min resolution over MATE during 12-14 October 2006. Colour version of this figure is available in electronic edition only.

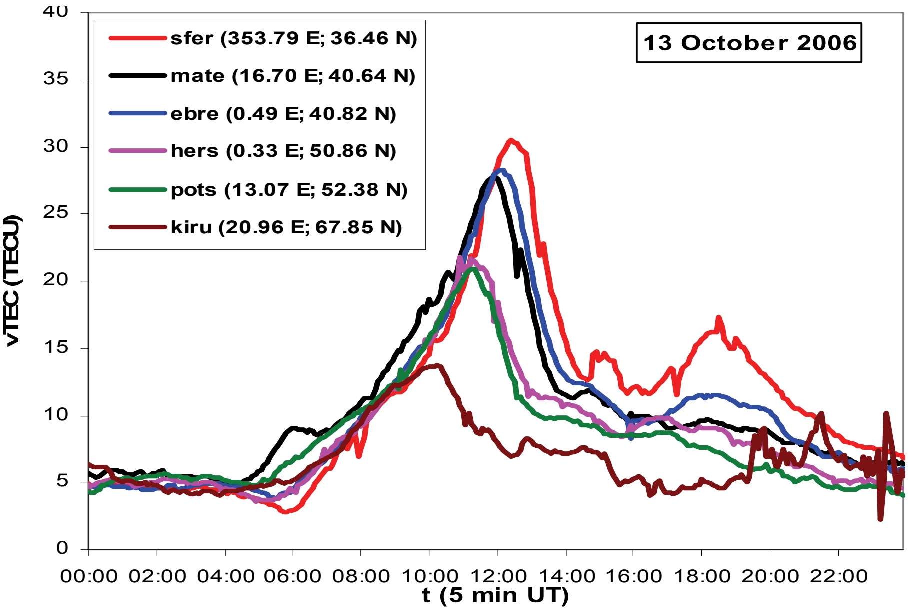

Fig. 3c. Daily values of *vTEC* with 5-min resolution over SFER, MATE, EBRE, HERS, POTS and KIRU on 13 October 2006. Colour version of this figure is available in electronic edition only.

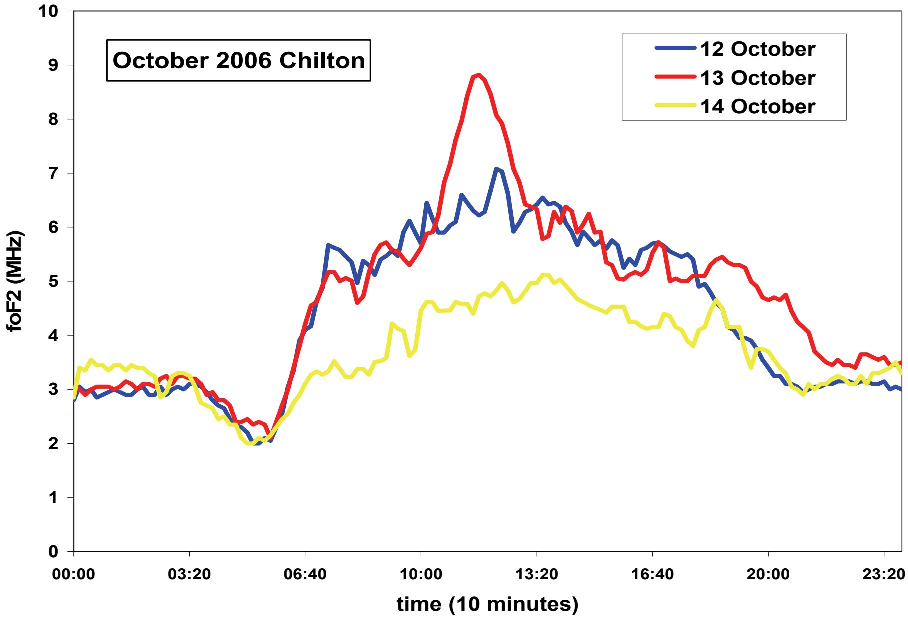

Fig. 3d. Daily values of *fo*F2 with 10-min resolution over Chilton during 12-14 October 2006. Colour version of this figure is available in electronic edition only.

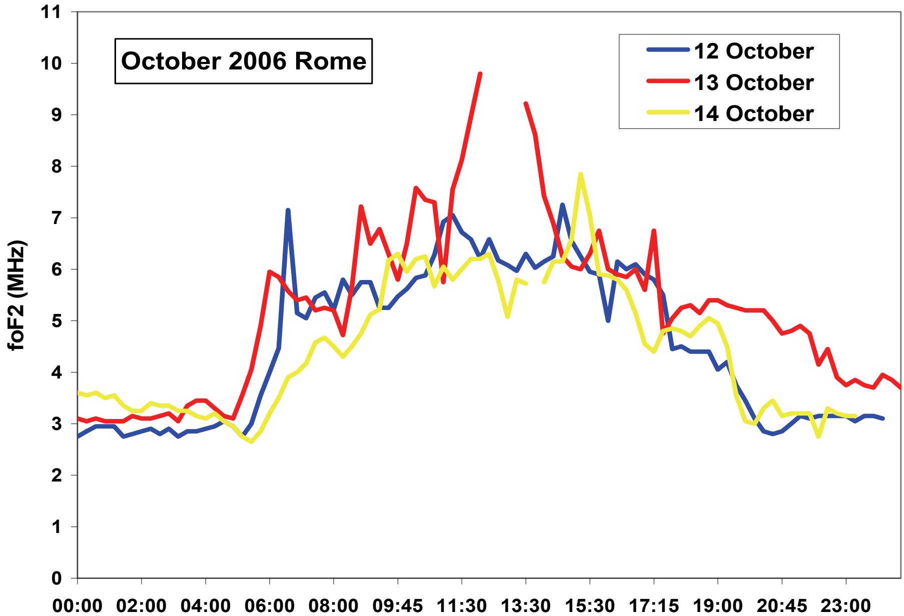

Fig. 3e. Daily values of *fo*F2 with 15-min resolution over Rome during 12-14 October 2006. Colour version of this figure is available in electronic edition only.

Figs. 3d and 3e show that *fo*F2 is increased from 6 to 9 MHz during the 2-h period at Chilton and *fo*F2 is increased from 6 to >10 MHz during the 2-h period at Rome ionosonde stations.

For the summer month, the vertical *TEC* values for 26-28 August 2006 are displayed in Figs. 4a-c. The variations in *vTEC* are mostly similar to that in the equinoctial months, except during the nighttime. It is shown in Figs. 4a and 4b that the *vTEC* is increased from 10 to 18 TECU during the 6-h period at HERS and *vTEC* is increased from 11 to 20 TECU during the 4-h period at MATE. Figure 5c gives the difference of *vTEC* values at the low mid-latitude station SFER and at the high mid-latitude station KIRU at midday of ~125%. Figures 4d and 4e indicate that *fo*F2 is increased from 5 to 7 MHz during the 4-h period at Chilton while *fo*F2 is increased from 6 to 8 MHz during the 2-h period at Rome, respectively.

3. DISCUSSION

Data and results in the previous section show that in the reported days during two years (2006 and 2007) of low solar activity, the *vTEC* and *fo*F2 values were dramatically increased. According to the literature, such an increase in *vTEC* and *fo*F2 is usually observed during the initial phase of a large geomagnetic storm and/or solar flare (Foster and Rideout 2005). We have used

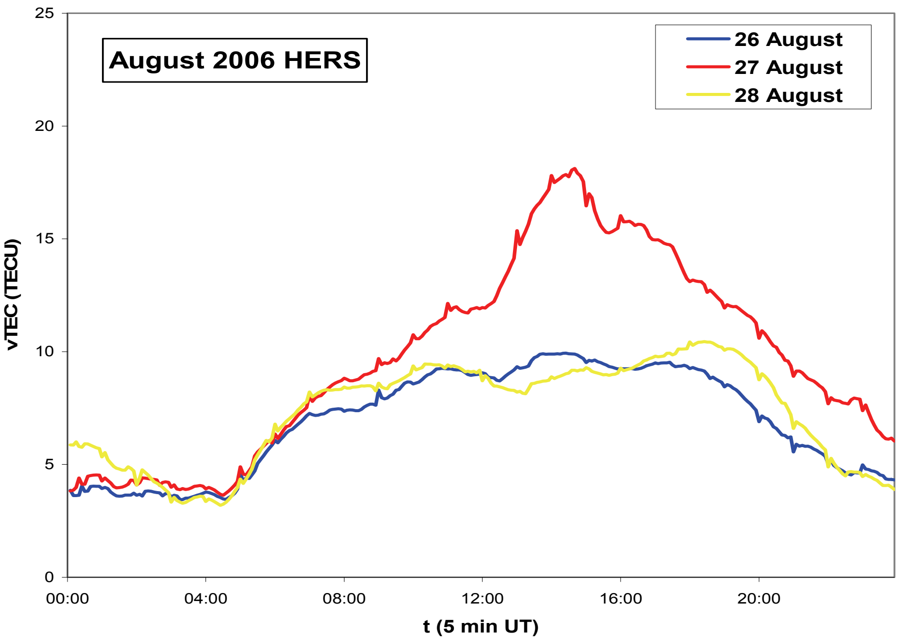

Fig. 4a. Daily values of *vTEC* with 5-min resolution over HERS during 26-28 August 2006. Colour version of this figure is available in electronic edition only.

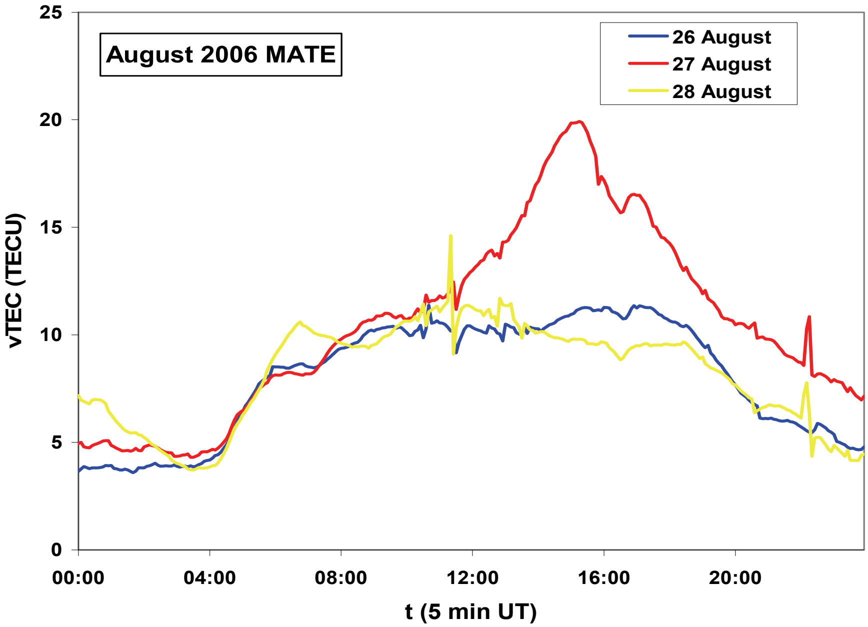

Fig. 4b. Daily values of *vTEC* with 5-min resolution over MATE during 26-28 August 2006. Colour version of this figure is available in electronic edition only.

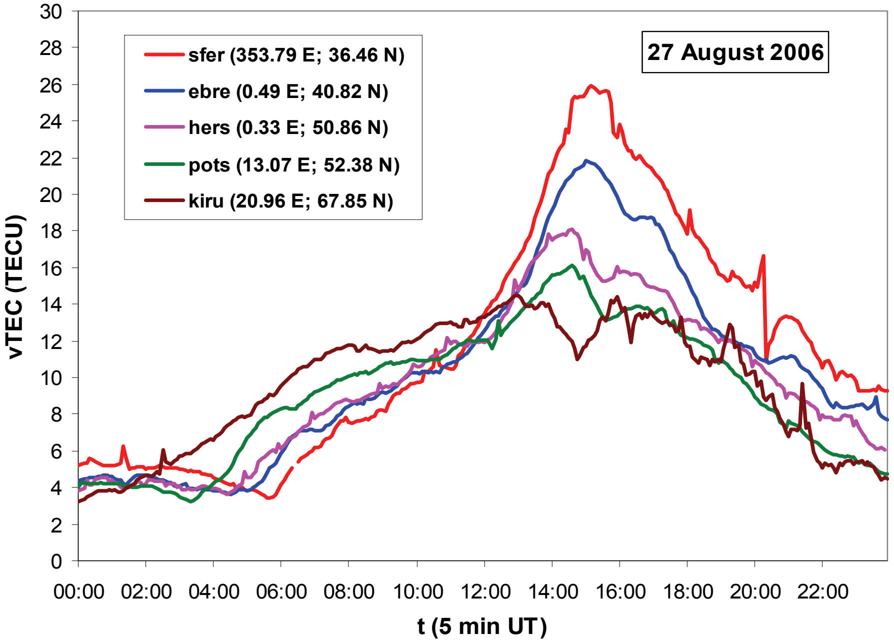

Fig. 4c. Daily values of *vTEC* with 5-min resolution over SFER, MATE, EBRE, HERS, POTS and KIRU on 27 August 2006. Colour version of this figure is available in electronic edition only.

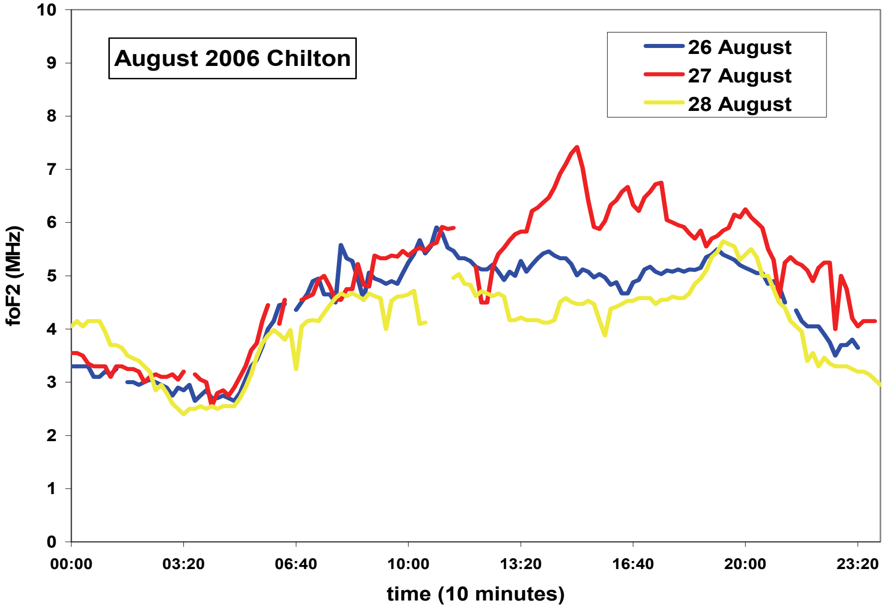

Fig. 4d. Daily values of *fo*F2 with 10-min resolution over Chilton during 26-28 August 2006. Colour version of this figure is available in electronic edition only.

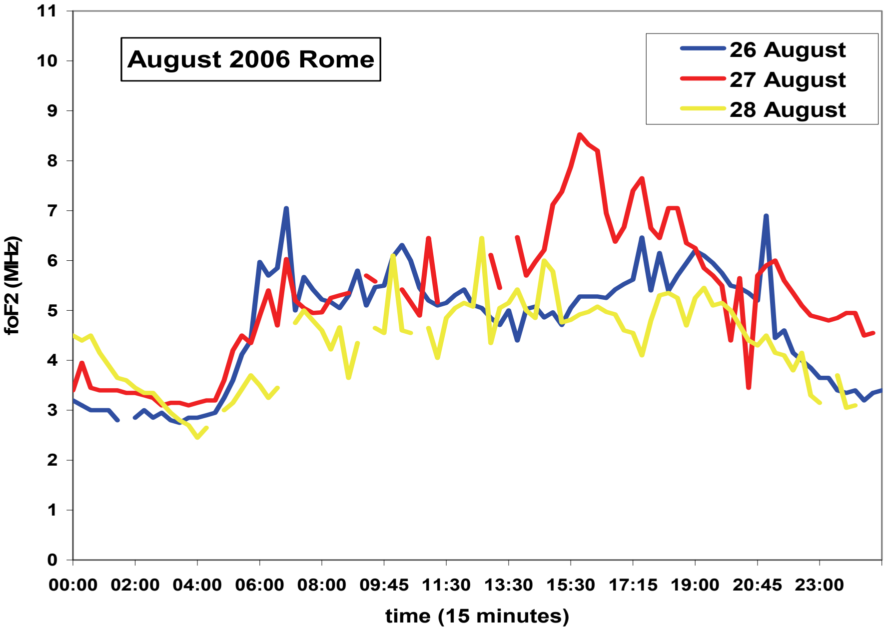

Fig. 4e. Daily values of *fo*F2 with 15-min resolution over Rome during 26-28 August 2006. Colour version of this figure is available in electronic edition only.

in our investigation the *Ap* index as a measure of the general level of geomagnetic activity over the globe for a given (UT) day. It is derived from measurements made at a number of stations worldwide of the variation of the geomagnetic field due to currents flowing in the Earth's ionosphere and, to a lesser extent, in the Earth's magnetosphere. The daily *Ap* index ranges from 0 (very quiet) to 400 (extremely disturbed). An *Ap* index of 30 or greater indicates local geomagnetic storm conditions (http://www.nws.noaa.gov/). On the other hand, it should be noted that the geomagnetic quiet condition is defined as $\Sigma Kp < 24$, where ΣKp is the sum of the eight 3-h *Kp* indices for the day. *Kp* indices were originally defined to measure effects of solar particles on the geomagnetic field (Lee 2008).

As the interplanetary magnetic field measured by the ACE spacecraft showed strong excursions on 19 November 2007 and the sudden storm commencement (SSC) occurred at 08:11 UT on 19 November 2007, *Ap* index reached 24 while $\Sigma Kp = 28$ on 20 November and recovered to $Ap = 16$ and $\Sigma Kp = 23$ on the following day (http://www.nws.noaa.gov). According to the previous definitions, this storm was exceptionally weak but encompassed the day of significant modification of the ionosphere as seen in Figs. 1a-e. It is extremely important to emphasize that during the period in question, 19-21

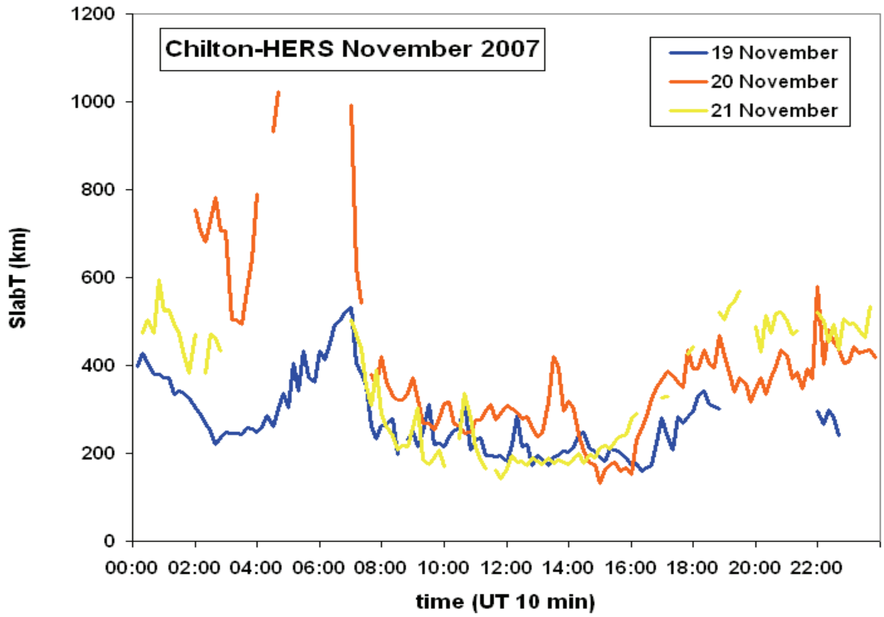

Fig. 5a. Daily values of the equivalent slab thickness with 10-min resolution for November 2007 case at Chilton-HERS location. Colour version of this figure is available in electronic edition only.

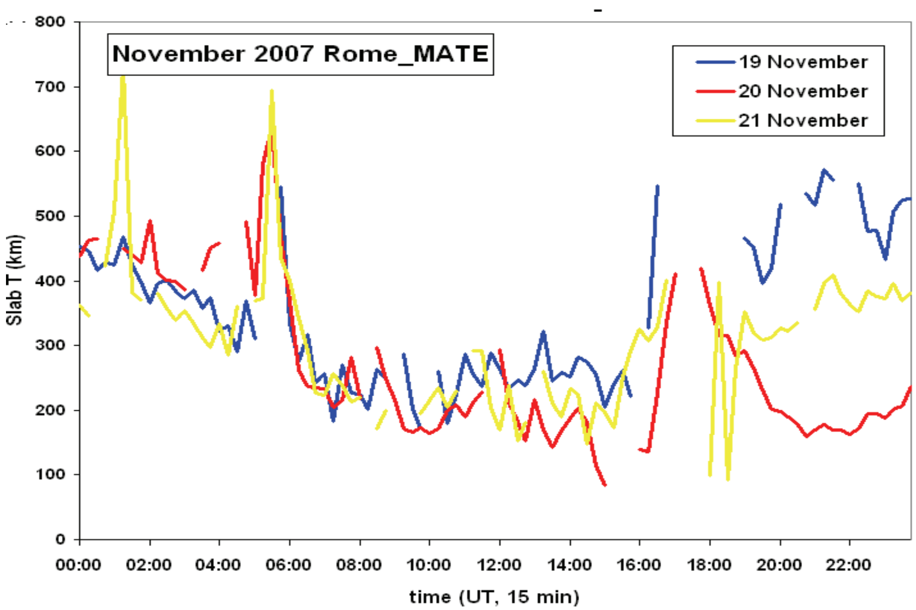

Fig. 5b. Daily values of the equivalent slab thickness with 15-min resolution for November 2007 case at Rome-MATE location. Colour version of this figure is available in electronic edition only.

November 2007, the solar activity was very low (F10.7 = 70) and there were no X-ray flares in M and X classes (http://www.sidc.be/products/bul).

The case of April 2007 eliminates the effects of geomagnetic disturbances all along, because $\Sigma Kp = 0$, 16 and 16 and $Ap = 0, 9, 9$ for 16, 17 and 18 April, respectively (http://www.nws.noaa.gov) showing that the geomagnetic field remained quiet. According to http://www.sidc.be/products/bul the solar activity was extremely low (F10.7 = 69) and there were no X-ray flares in M and X classes. However, the solar wind picked up speed late on 16 and 17 April, reaching a moderate 400 km/s. This came together with –10 nT excursions of the *Bz* component of the IMF. The magnetosphere responded with unsettled to active conditions on 17 and early 18 April. By 19 April, the wind speed started to decline continuously until 21 April. The ionospheric effects can be seen in Figs. 2a-2e.

Although on 12-14 October 2006 there is no sudden storm commencement (SSC), *Ap* index reached 29, while $\Sigma Kp = 31$ on 13 October and slowly recovered to $Ap = 23$ / $\Sigma Kp = 29$ on the following day (http://www.nws.noaa.gov). One event caused geomagnetic active to minor storm conditions on 13 October. This was caused by the passage of the high speed wind stream from the small equatorial coronal hole. The high stream arrived at L1 late on 12 October. The solar wind speed was pushed up to 550 km/s and the *Bz* went negative to –10 nT causing mostly active conditions with minor storm intervals http://www.sidc.be/products/bul. The solar activity was very quiet (F10.7 = 73) and there were no X-ray flares in M and X classes. Again, it is important to note that such a very weak geomagnetic storm period encompasses a day of significant modification of the ionosphere, as shown in Figs. 3a-e.

The case of August 2006 eliminates the effects of geomagnetic disturbances as well, because $\Sigma Kp = 5$, 23 and 20 and $Ap = 3, 16, 12$ for 26, 27 and 28 August, respectively (http://www.nws.noaa.gov) show geomagnetic quiet conditions. However, in the interplanetary medium the solar wind speed rose steeply to 650 km/s in the second half of 27 August, marking the arrival of a recurrent fast stream. During a few hours, the interplanetary magnetic field became highly turbulent with negative *Bz* fluctuations down to –15 nT http://www.sidc.be/products/bul. At the same time, the solar activity was very low (F10.7 = 79) and there were no X-ray flares in M and X classes. Still the *vTEC* variations at SFER, HERS and KIRU on 27 August were quite different from the *vTEC* variations on the previous and subsequent quiet days (Fig. 4c). Soon after sunrise, the *vTEC* values started to increase, and the enhancement reinforced it at least few times until midnight.

It is well known that severe space weather events can cause extreme ionospheric effects (Tsurutani *et al.* 2005, Cander and Mihajlovic 2005, Mendillo 2006, Mendillo and Klobuchar 2006). Ionospheric storm effects at middle latitude may display short lived but very long lasting strong enhancements in electron density (positive phase) or multiple periods of depletion (negative phase). Depending on the local time, positive and/or negative effects may constitute the ionospheric storm development. A balance between several processes controls the response of the mid-latitude ionosphere to these events. Firstly, the transport of neutral composition changes to mid-latitudes from their source at high latitude, by storm-time winds and the background seasonal circulation, drives a predominantly negative phase. Secondly, transport of plasma upward along the inclined magnetic field by increased meridional wind surges and thermal expansion drives a predominantly positive phase. Thirdly, the electrodynamic changes from both prompt penetration and disturbance dynamo electric fields can dramatically redistribute existing plasma (see, Prolss 1995 and references therein). The negative phase has long been attributed to thermospheric expansion and composition changes initiated by heating in the auroral zones. At the same time, the positive phase still under active investigation involves mechanisms of electrodynamics and neutral wind perturbations. For example, if the increases in the electron density last for about 6 hours or more, they can be termed a long duration positive phase. During this period, meridional winds (positive northward) become more poleward at high latitudes and less poleward at low-middle latitudes. Consequently, these weaker poleward winds or stronger upward ion drifts during storm time than those during quiet time can result in increases of daytime electron densities at low and mid-latitudes.

However, these severe *TEC* decreases and increases were different in many aspects from the *vTEC* and *fo*F2 enhancements in daytime mid-latitude ionosphere over European area seen in Figs. 1-4. Results of our analysis have clearly shown that in the reported days during two years (2006 and 2007) of low solar activity, some anomalous increase of *vTEC* and *fo*F2 is observed, which is not likely to be associated to the NOAA (http://www.nws.noaa.gov/) and SIDC RWC-Belgium (http://www.sidc.be/products/bul) reports on solar activity and/or geomagnetic indices. According to the literature, an increase in *vTEC* is usually observed during the initial phase of the strong geomagnetic storm or solar flare. Several mechanisms may enhance the ionospheric *TEC*. Among them, ionospheric disturbances owing to disturbed electric fields are significant, such as prompt penetrating (PP) and disturbance dynamo (DD) electric fields, both of which occur during periods of geomagnetic disturbance. Furthermore, *TEC* increases simultaneously in a wide latitude range when a PP electric field directs eastward in sunlit hours. Other examples of *TEC* disturbance are the so-called storm enhanced density (SED), which also occurs associated with geomagnetic disturbances (Scone *et al.* 2004).

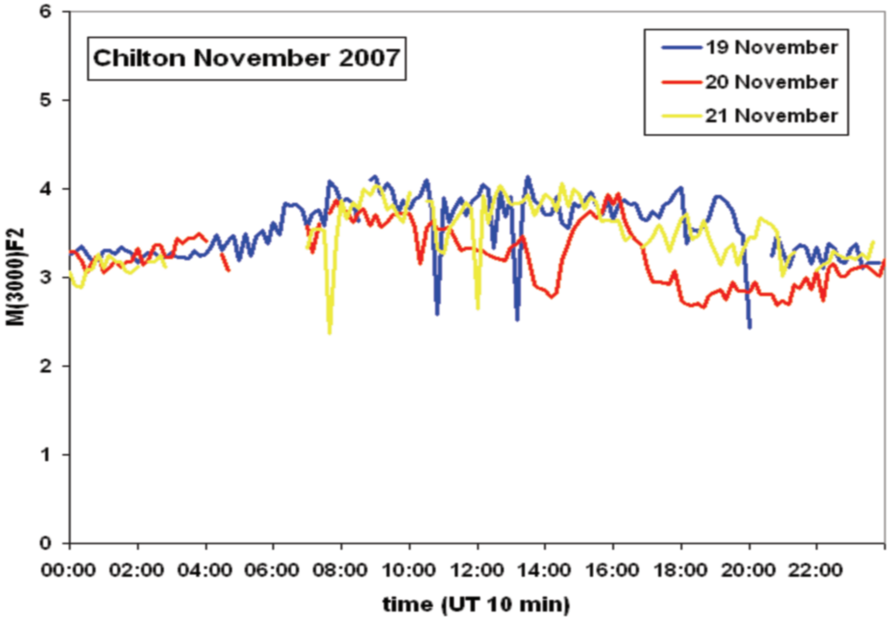

Fig. 6a. Daily values of *M*(3000)F2 with 10-min resolution over Chilton during 19-21 November 2007. Colour version of this figure is available in electronic edition only.

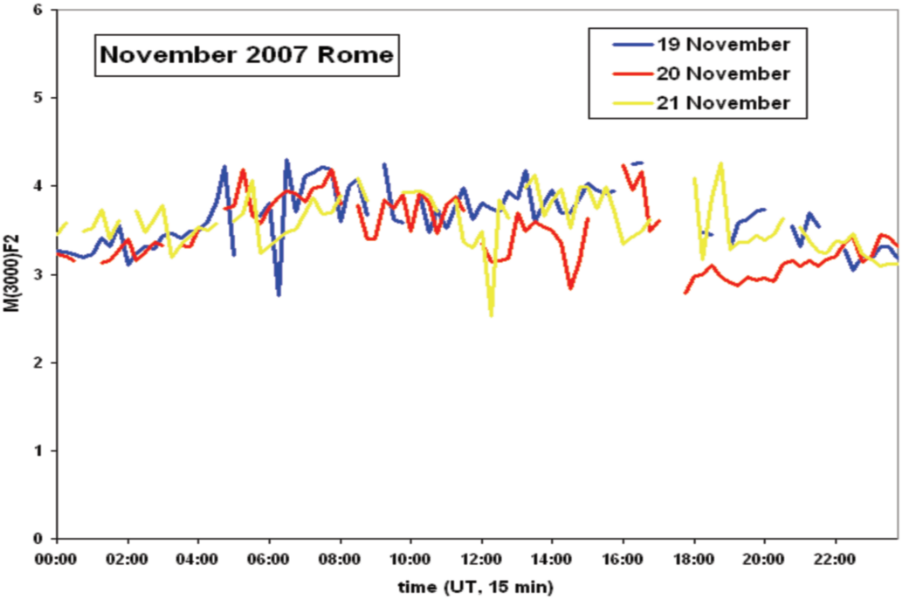

Fig. 6b. Daily values of *M*(3000)F2 with 15-min resolution over Rome during 19-21 November 2007. Colour version of this figure is available in electronic edition only.

In our cases, as Figs. 1-4 illustrate, while large short-lived *vTEC* and *fo*F2 enhancements developed on 20 November 2007, 17 April 2007, 13 October 2006, and 27 August 2006, the geomagnetic disturbances were not in progress. It is very well known that the behaviour of *vTEC* is similar to that of *fo*F2 but is not necessarily the same, especially during geomagnetic disturbances. It means that if *TEC* was significantly increased but *fo*F2 was not, it gives abnormally large equivalent slab thickness, indicating that the diffusive equilibrium was not established under the highly dynamic conditions. Plots of the equivalent slab thickness for November 2007 case at Chilton-HERS and Rome-MATE locations are presented in Figs. 5a and 5b, respectively. It may be seen from these figures that the diurnal variations of equivalent slab thickness for each of these two locations do not fluctuate significantly during the daytime hours (08:00-16:00). Some seemingly interesting features in the nighttime equivalent slab thickness variations come from the missing data at the particular times. The ionosonde data for the propagation factor *M*(3000)F2 during the same period at Chilton and Rome ionosonde stations shown in Figs. 6a and 6b respectively, suggest more or less the same midday variability behaviour.

4. CONCLUSIONS

This study has used the network of ground-based GPS measurements of *TEC* and ionosonde network measurements of *fo*F2 and *M*(3000)F2 over Europe when the solar activity was very low, and the geomagnetic activity was not very significant. We have also evaluated quantitatively from these measurements the equivalent slab thickness. A sample of 4 events among 15 identified has been processed and the results analyzed. Our main results can be summarized as follows:

- ❑ Observations indicate the increases in *vTEC* and *fo*F2 that are of short durations but significant in the sunlit local time region between noon and dusk;
- ❑ These increases occur with no seasonal dependence;
- ❑ Daytime *vTEC*, *fo*F2 and their perturbations were larger at lower latitudes; and
- ❑ There is no sufficient evidence to support a physical explanation used for positive ionospheric storms.

These conclusions are relevant for developing accurate and reliable satellite-based augmentation systems (SBAS) where ionosphere models can suffer degraded performance due to large spatial gradients in total electron content at mid-latitudes. As one of the greatest challenges in developing such augmentation systems is modelling of ionospheric effects, presented observations of a severe positive ionospheric storm pattern may be a significant source of error in the SBAS correction models. Future work will be focused on open question related to these large *TEC* and *fo*F2 variations during weak disturbances which requires additional study for their relevance to different GNSS applications. Our study leads to two findings that require further study: comparison of *vTEC* at solar minimum over Europe with *vTEC* at solar minimum over American sector in order to understand the response and the relative roles in restructuring the ionosphere of the range of physical processes operating at mid-latitude ionosphere.

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