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ORIGINAL ARTICLE

Monitoring storm-enhanced density using IGS reference station data

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Abstract Storm-enhanced density (SED) is a geomagnetic storm phenomenon, characterized by a plume of enhanced total electron content (TEC) that initially moves poleward and sunward extending out from a larger region of enhanced TEC in the mid-latitudes. SED is associated with extreme mid-latitude space weather effects. Sharp gradients in the TEC are found along the borders of SED plumes and at the boundaries of the larger TEC region (the base of the plume). These large TEC gradients can cause significant errors in DGPS and WADGPS positioning and can result in serious consequences for applications such as railway control, highway traffic management, emergency response, commercial aviation and marine navigation, all of which require high precision, real-time positioning. Data from the global IGS network of GPS receivers have enabled the spatial and temporal visualization of these SED plumes, allowing ionospheric researchers to study this phenomenon and investigate the potential for developing prediction techniques and real-time warning systems. GPS TEC maps provided by analysis of the data from the IGS network have now been widely disseminated throughout the atmospheric research community and have become one of the standard means of studying the effects of geomagnetic storms on the ionosphere. These maps have enabled researchers to identify that the SED phenomenon occurs globally, is associated with large TEC gradients (at times greater than 100 TEC units per degree latitude), and is a magnetically conjugate phenomenon. This paper reports on the recent advances in our understanding of the SED phenomenon enabled by GPS observations.

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1 Introduction

Storm-enhanced density (SED) is a geomagnetic storm phenomenon, characterized by a plume of enhanced total electron content (TEC). The SED phenomenon is of interest to the geodetic community because it associated with some of the most severe space weather effects observed in the mid-latitudes. Sharp gradients in the TEC are found along the borders of SED plumes and at the boundaries of the larger TEC region (the base of the plume). At times, TEC gradients have been observed to exceed 100 TECU/degree. These large gradients can lead to increases in DGPS and WADGPS positioning errors by factors of 10–30 (Skone et al. 2005; Skone and Coster 2007a) and can impose serious consequences on applications such as railway control, highway traffic management, emergency response, commercial aviation and marine navigation, all of which require high precision, real-time positioning. These gradients also complicate the analysis of GPS occultation data. During the 29–30 October 2003 geomagnetic storms, the system used by the U.S. Federal Aviation Administration to augment GPS navigation, the Wide Area Augmentation Service (WAAS), had no vertical navigation service over its entire service area for 26.3 h during this 2-day period (Doherty et al. 2004). In previous studies of SED events in the North American sector, marine DGPS positioning errors of 20 m or more have persisted for hours and gradients of up to 50 ppm have been observed

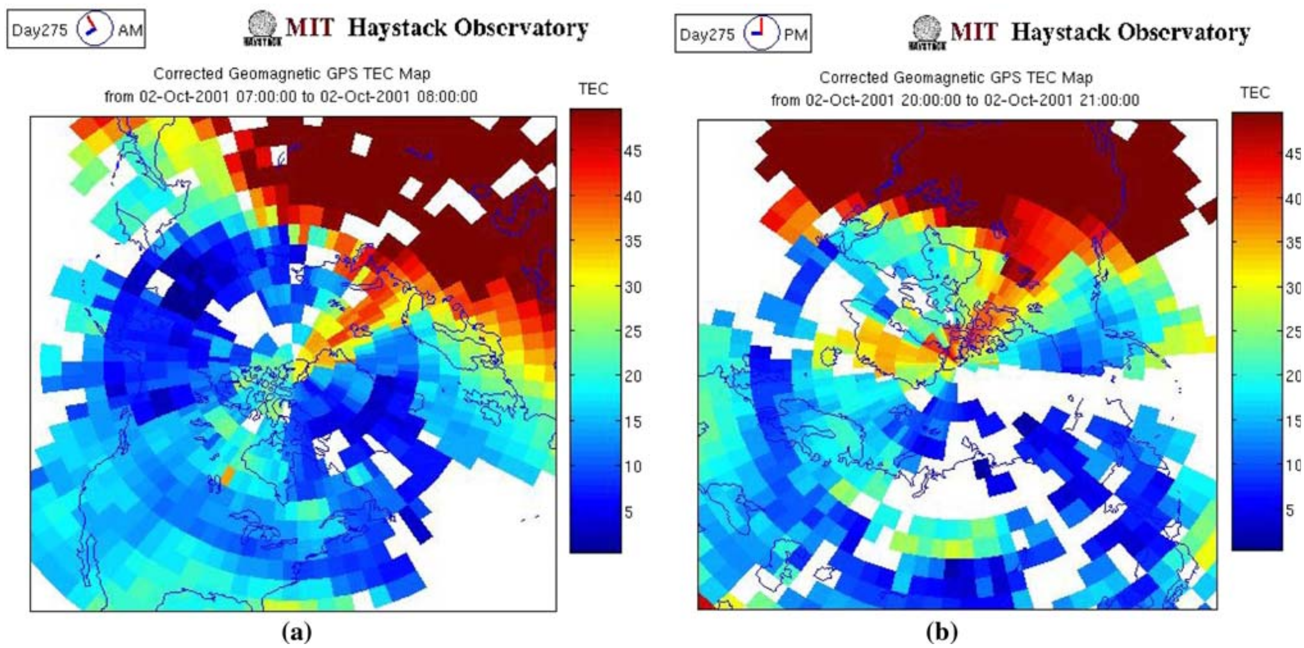


Fig. 1 Polar views of SED. **a** An SED forming over Europe between 07:00 and 08:00 UT on 2 October 2001, and **b** the same feature over North America between 20:00 and 21:00 UT

(Skone et al. 2005). Some of the geodetic implications of SED are described in the companion paper, "Studies of storm enhanced density impact on DGPS using IGS reference station data," by Skone and Coster, published in this issue.

During geomagnetic storms, the SED plume of ionization forms in the noon to dusk sector and initially moves poleward and sunward extending up from a large region of enhanced TEC in the mid-latitudes. SED plumes of ionization are believed to be produced by the dynamic interaction of ionospheric plasma with storm–time electric fields imposed on the ionosphere from the magnetosphere. The sub-auroral polarization stream (SAPS) (Foster and Burke 2002; Foster and Vo 2002) is believed to be responsible for driving the plasma within the SED in a northward and westward direction. The enhanced mid-latitude TEC at the base of the plume is likely related to storm–time penetration electric fields. These penetration electric fields are responsible for the uplift of mid- and low-latitude plasma and the redistribution of this plasma to the mid- and high-latitude ionosphere (Yin et al. 2004; Kelley et al. 2004). Additional forces such as neutral winds and internally generated electric fields (those produced within the ionosphere) also contribute to the SED formation. The exact role of each of these forces and their dynamic interaction in the formation of the SED plume is still an area of extensive investigation. The TEC in the SED plume is associated with velocities of $800\,\mathrm{m\,s^{-1}}$, giving plasma a $\sim 2\,\mathrm{h}$ transit time from its source at low latitudes to the polar cap at noon. Foster et al. (2004) estimated a plasma flux to the dayside cusp ionosphere of $10^{14}\,\mathrm{m^{-2}s^{-1}}$. The SED feature has been observed in North and South America (Foster 1993; Coster et al. 2003), Europe (Yizengaw et al. 2006), Japan (Maruyama 2006), and Australia (Skone and Coster 2007b). Figure 1a, b shows SEDs forming over Europe and North America on 2 October 2001.

2 Use of IGS network to monitor SED

The feature of SED was first described by Foster (1993) using the large data base of incoherent scatter radar (ISR) measurements from the Millstone Hill ISR radar. ISR measurements can provide detailed information as a function of altitude about the electron density and ion and electron temperatures as a function of altitude. ISR data can also be used to infer electric fields and winds. The ISR data however are spatially limited to observing structure only within the field of view of the radar, and the ISR processing requires relatively long integration times to obtain statistically significant signal-to-noise ratios (SNR). The network of GPS receivers in the IGS network offered a new way to view the changes in the ionosphere, especially those due to magnetic storms. Unlike the ISR measurements, ground-based GPS systems only measure the line of sight total electron density (TEC), and thus do not provide background information about the ion and electron profiles. However, by combining TEC information from a network of GPS receivers, global maps of the TEC could be made providing both temporal and spatial information of the changes in TEC during geomagnetic events at an unprecedented level of detail.

The importance of the IGS service in developing the use of GPS for ionospheric monitoring purposes and for studying the structure of world-wide space weather events cannot be understated. The IGS service provides high-quality data in a standard format that is freely available and easily accessible through the World-Wide Web to all scientists. With the establishment of the IGS network, ionospheric scientists began investigating the use of producing maps of vertical TEC by combining data from the global network of receivers. In the early 1990s, these TEC maps were sub-daily and covered only the northern hemisphere (Wilson et al. 1992, 1995; Mannucci et al. 1993). By the end of the 1990s, the first global TEC maps were produced (Komjathy and Langley 1996; Komjathy 1997; Mannucci et al. 1998). In the early part of this decade (century), the initial real-time (or near real-time) TEC maps over the northern hemisphere were produced (Fuller-Rowell 2005). It is anticipated that in the future, global real-time TEC maps will become a routine product.

Data from about 1,000 GPS receivers are currently available on a daily basis to monitor the temporal and spatial variabilities of the global ionosphere. In addition to the IGS network of receivers, this number includes receivers in additional networks, such as the continuously operating reference stations (CORS). Algorithms have been developed to process all of these data sets in a time-efficient manner, enabling daily monitoring of the quiet and storm-time ionosphere that affects satellite-based radio navigation systems, such as GPS, GLONASS, and the future Galileo (Feltens and Schaer 1998; Komjathy et al. 2005; Rideout and Coster 2006).

Prior to 2000, the density of GPS receivers in the IGS network was fairly sparse and the GPS TEC data were integrated into ionospheric models to produce continuous maps of vertical TEC. MIT Haystack was the first group to make use of all available GPS data to produce strictly data-driven plots of the TEC using no underlying models to smooth out gradients (Coster et al. 2003; Rideout and Coster 2006). Because of this lack of smoothing, the narrow plumes of SED that form over the US during geomagnetic storms could be observed in the TEC maps (Coster et al. 2001). In a ground-breaking paper, Foster et al. (2002) were able to link the GPS TEC observations as measured from the ground with the plasmaspheric plumes as seen from NASA's IMAGE satellite in space at 8 Earth radii. Figure 2a shows the plasmaspheric plume as observed by the EUV imager on the IMAGE satellite. Figure 2b shows the ionospheric SED feature, which is outlined in red. In Foster et al. (2002), it was shown that there is a one-to-one correspondence between the two features. This observation clearly demonstrated that a dense network of ground-based receivers can play a significant role in the monitoring the coupling between the ionosphere and magnetosphere during geomagnetic storm events. In recent years,

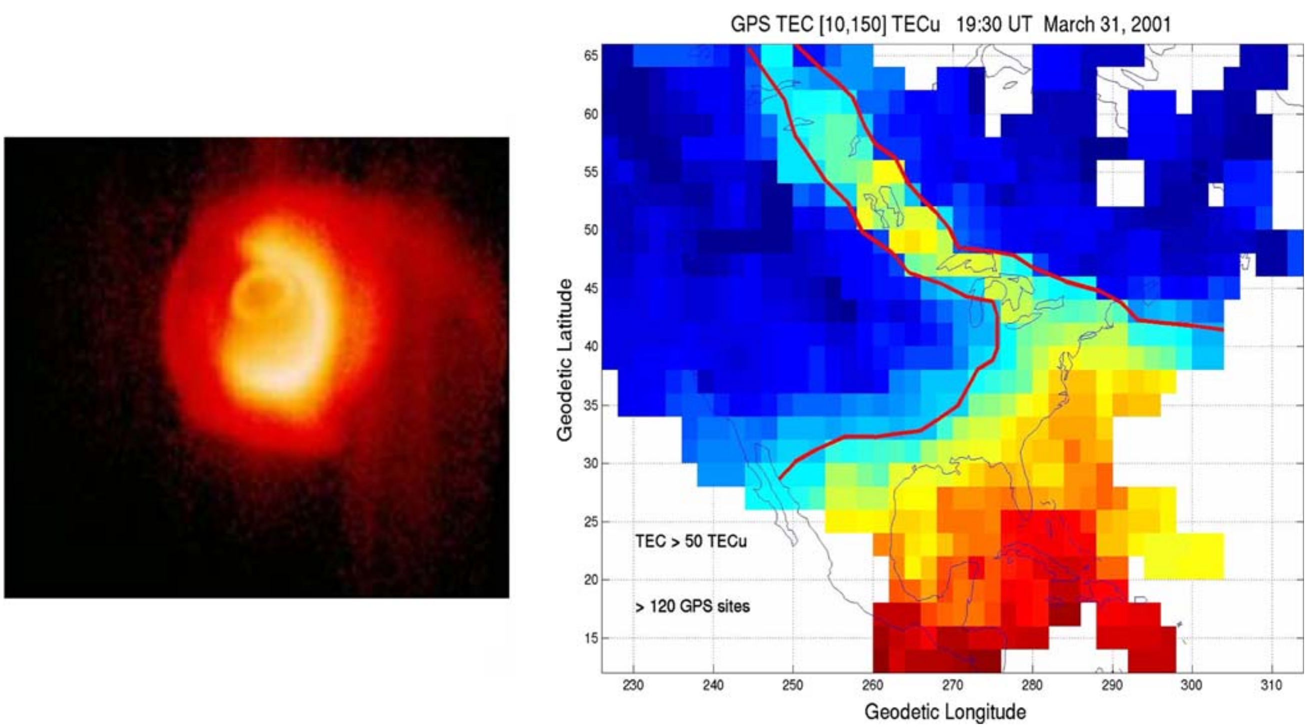


Fig. 2 The 31 March 2001 data showing **a** the plasmaspheric plume detected by the IMAGE satellite and **b** the SED plume observed by the network of GPS receivers over the US

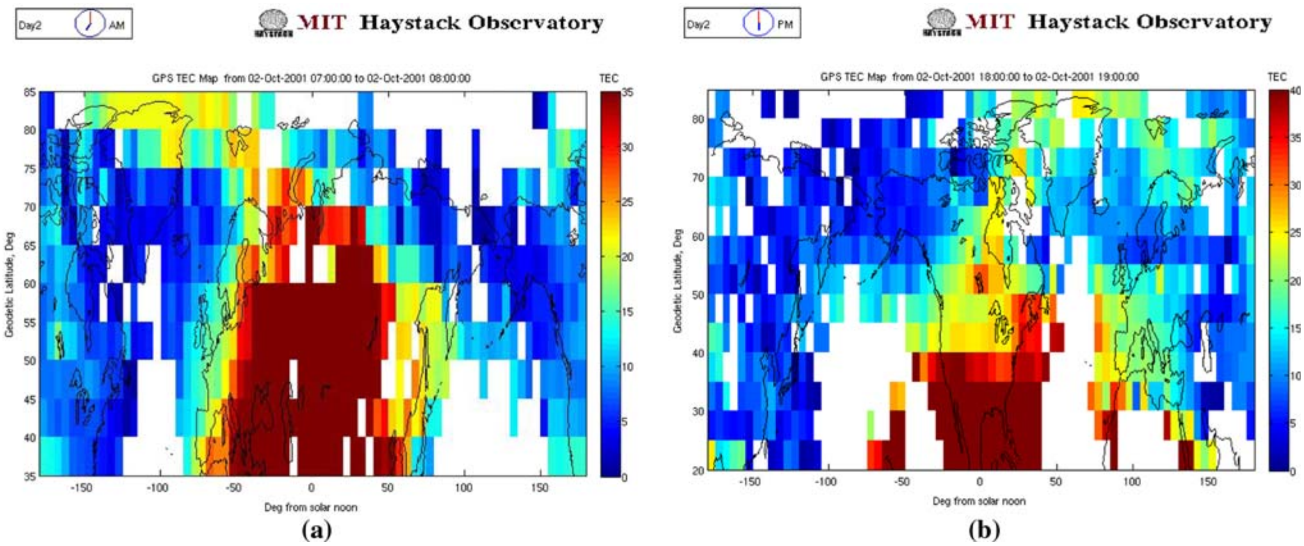


Fig. 3 The SED feature over Europe and N. America as a function of latitude and local solar time. **a** An SED forming over Europe between 07:00 and 08:00 UT on 2 October 2001, and **b** the same feature over North America between 18:00 and 19:00 UT

GPS TEC maps have been widely disseminated throughout the atmospheric research community and have become one of the standard means to study the effects of geomagnetic storms on the ionosphere.

The GPS studies have provided scientists the following information on SED characteristics : (1) SED is a global phenomenon that is observed near local noon, although along the East Coast of the US, SED formation continues until dusk; (2) SED appears to exhibit conjugacy, appearing in both hemispheres at the same time, although not necessarily with the same magnitude in TEC; and (3) the magnitude and gradients of the SED effects appear to be larger in the American longitude sector than other sectors.

2.1 Time dependence of SED

With the exception of the North American sector, SED appears to develop near local noon. Coster et al. (2007) reported on the development of SED events in Russia and Europe on 1–3 October 2001 and on 18 April 2002 between 4 and 7 UT. These SED events remained fixed near local noon as the Earth rotates underneath. Three of these four SED events were later observed over the American sector between 17 and 23 UT. The SED events in Europe appear to exhibit westward motion at approximately the corotation speed of the Earth. Over North America, however, the SED events appear to slow down over the east coast of the US perhaps due to the dip in the magnetic field in this longitude sector. This time dependence can be observed in Fig. 3a, b where the 2 October 2001 data for both Europe (Fig. 3a) and North America (Fig. 3b) are plotted as a function of degrees from local solar noon. The center point represents local noon.

2.2 Conjugacy of SED

Figure 4 illustrates the magnetic conjugacy of the SED phenomenon observed in the 2 October 2001 storm. Figure 4 shows the global TEC data between 20:30 and 21:00 UT in North and South America. In this figure, the magnetic conjugate points are denoted by white and magenta circles. Two locations are defined to be geomagnetically conjugate if they have the same geomagnetic latitude, but have geomagnetic longitudes of opposite sign. Geomagnetically conjugate points are important because electric fields map along magnetic field lines between the two hemispheres. Events that exhibit aspects of magnetic conjugacy are of general interest because of the implications concerning the processes that electrically couple the magnetosphere and ionosphere.

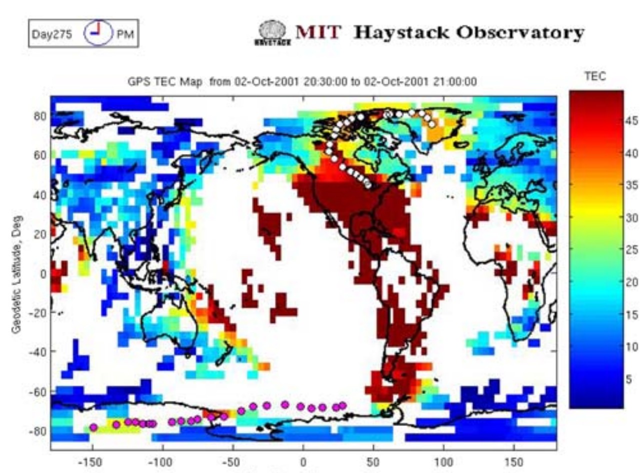


Fig. 4 Illustration of the magnetic conjugacy of the SED phenomenon

Foster and Rideout (2007) intercompared simultaneous observations of ground-based TEC measurements with Jason and TOPEX satellite TEC measurements to investigate the magnetic conjugacy characteristics of the SED plumes and other storm time density and TEC enhancements. They found that the TEC enhancements at the base of the SED plumes exhibit localized and longitude-dependent features which are not strictly magnetically conjugate, whereas the SED plumes streaming away from these source regions closely follow magnetic conjugate paths, confirming that SED is a convection electric field dominated effect.

The primary conclusions of the Foster and Rideout (2007) study include:

(1) The SED plume occurs in magnetically conjugate regions in both hemispheres.
(2) The position of the sharp poleward edge of the SED plume is closely conjugate.
(3) The SED plume enters into the polar cap near noon, forming the polar tongue of ionization (TOI) and is seen in both hemispheres in magnetically conjugate regions.

2.3 SED TEC gradients

The TEC gradients associated with SED have been extensively studied in the North America sector. To date, the largest TEC gradients have been observed in North America during major magnetic storms ($K_p = 9$ events) and during the peak of the last solar cycle (30–31 October 2003 and 20 November 2003). The fact that the largest TEC gradients are observed in North America may be the result of the dip in the geomagnetic field in the North American longitude sector. Foster and Rideout (2007) reported that the strong TEC enhancement at the base of the SED plume in the North American sector is more extensive than in its magnetic conjugate region.

Figure 5 shows a single satellite pass through an SED plume on 20 November 2003. The top plot gives an indication of where the satellite pass is with respect to the TEC plume, and is shown here for context only. The time period of the

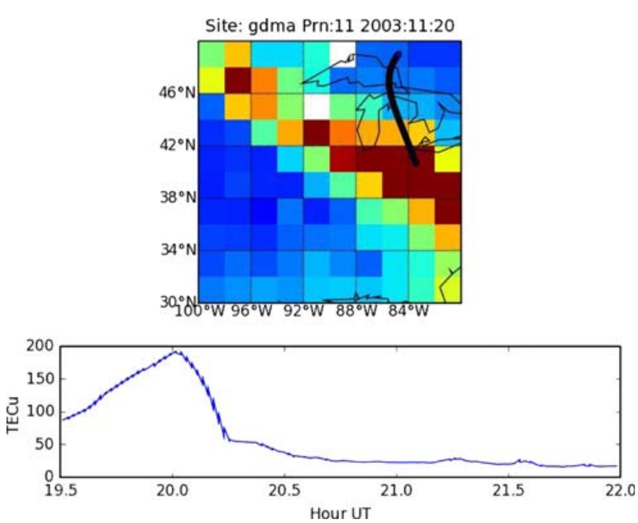
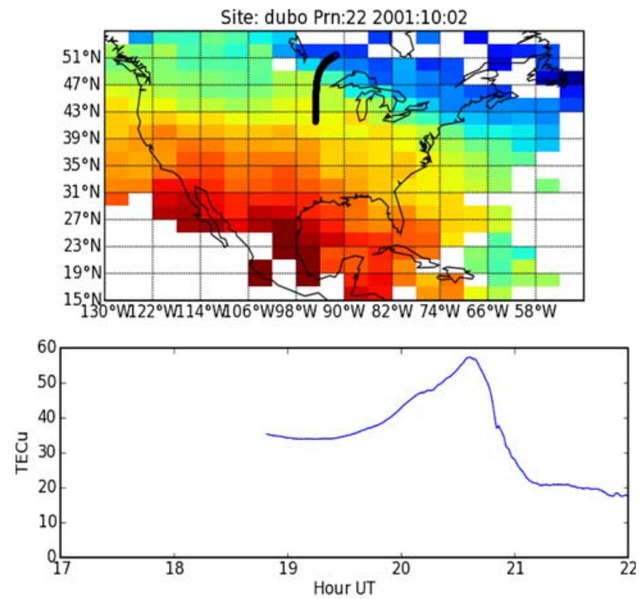
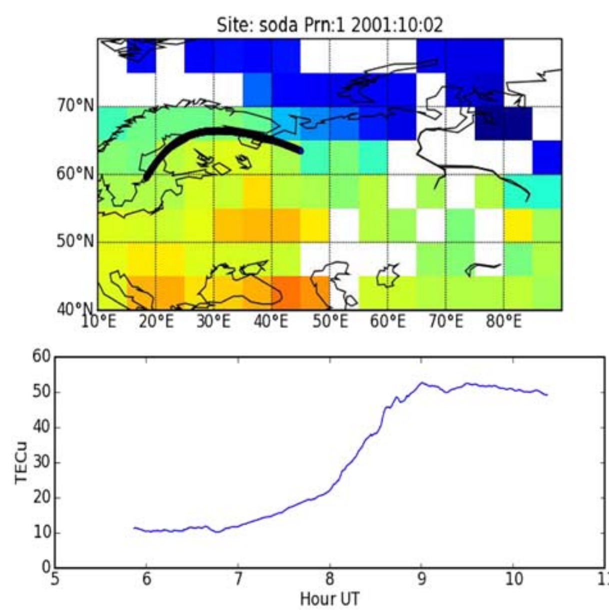


Fig. 5 Data from 20 November 2003. *Top plot* indicates the pass of a GPS satellite through a TEC plume. The *bottom plot* shows the measured TEC along the path



(a) TEC Gradient observed in North America



(b) TEC Gradient Observed in Europe

Fig. 6 Data from 2 October 2001. **a**, **b** The *top plot* shows the satellite path overlaid on the TEC map that represents the time period from the middle of the pass. The *bottom plot* shows the line of sight TEC measured over the pass

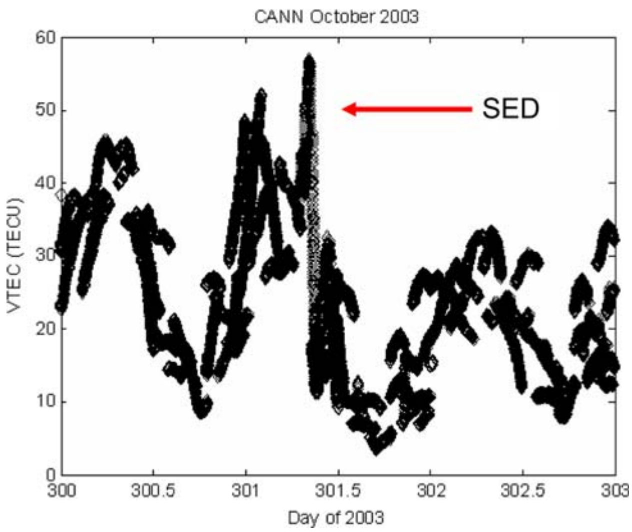


Fig. 7 Absolute vertical TEC values for reference station CANN 28 October (day 300) to 30 October (day 302) 2003. (Skone and Coster 2007b)

plume shown represents an average of 20 min in the middle of the pass. The bottom plot shows the line of sight TEC to this GPS satellite. The peak TEC observed was 200 TEC units, and 10 min later the TEC along the satellite path had dropped to 50 TEC units, or a 150 TEC unit differential between the two satellite paths.

A similar study was undertaken for the moderate geomagnetic storm that occurred on 2 October 2001 (data from this geomagnetic storm were shown in Figs. 1 and 3). On this day, the K_p (geomagnetic index) remained at the moderate level of 6. During this time period, the GPS TEC gradients observed in Europe and the US are remarkably similar. Figure 6a shows a single satellite pass in North America where the peak line of sight TEC value is about 60 TEC units, and this value drops to approximately 15 TEC units within 10–15 min. Compare this to the data shown in Fig. 6b showing a single satellite pass in Europe. Here, the initial value of the line of sight TEC is 20 TEC units and it increases to 55 TEC units within a time period of approximately an hour.

Finally, Fig. 7 shows a large TEC gradient observed in the southeast region of Australia associated with an SED on 29 October 2003. At this time, there appeared to be a conjugate SED event observed over Europe and Asia (not shown). The SED feature and associated TEC gradients persisted for more than 60 min in the region near Melbourne. Figure 7 shows an estimate of the vertical TEC observed along the line of sight to all of the GPS satellites that could be viewed above 50° elevation at the Cann River GPSnet site (CANN) located to the southeast of Melbourne. The signature of SED can be clearly observed in the sharp drop in the TEC.

Considerable work remains to characterize the TEC gradients associated with SED events in Europe, North and South America, and Australia. However, evidence exists that this feature can be observed globally (Yizengaw et al. 2006; Maruyama 2006; Coster et al. 2007; Skone and Coster 2007b) and can introduce TEC gradients that can significantly degrade precise positioning capabilities.

3 Summary

The SED has been shown to be a significant space weather feature of the mid-latitudes. The presence of SED and its associated TEC gradients can lead to large errors in DGPS and WADGPS positioning accuracies. This, in turn, can have significant effects on users who depend on highly accurate real-time positioning for uses in marine navigation, highway traffic management, emergency response, and aviation. Studying and observing the SED phenomenon with the GPS mapping techniques have been of immeasurable value to the ionospheric community. As our understanding of the physics involved in the formation of this feature increases, so perhaps will our ability to predict it.

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