Geofísica Internacional
ISSN: 0016-7169
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México

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Geofísica Internacional, vol. 44, núm. 2, april-june, 2005, pp. 211-218
Universidad Nacional Autónoma de México
Distrito Federal, México

Geofísica Internacional (2005), Vol. 44, Num. 2, pp. 211-218

GPS-derived total electron content response for the Bastille Day magnetic storm of 2000 at a low mid-latitude station

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Received: July 22, 2003; accepted: August 13, 2004

RESUMEN

El desarrollo de un modelo empírico para la corrección de la predicción por modelos climatológicos del Contenido Total Electrónico vertical (VTEC), equivalente al modelo STORM para el pico de concentración de la capa F2 (Araujo-Pradere y Fuller-Rowell, 2002, Araujo-Pradere *et al*., 2002), se encuentra ahora en su etapa inicial en el Space Environment Center (SEC) de NOAA. El programa para la obtención del TEC, el proyecto Win Tec (Anghel y Codrescu, 2002), utiliza los archivos de formato de intercambio independiente del receptor (RINEX) para derivar el TEC vertical a partir del retraso de las señales del Sistema de Posicionamiento Global (GPS).

Con un valor máximo del Dst de –287.6 (máximo a_p = 400), la tormenta de julio 2000, conocida como la tormenta del Día de la Bastille, ha sido una de las más intensas perturbaciones en el ciclo solar actual. En este trabajo se analiza la respuesta del TEC, obtenido del retardo que sufren el código y la fase de la señal de GPS a su paso por la ionosfera, para la tormenta de julio 2000. Los valores de TEC vertical en la estación receptora **ccv3** (Cabo Cañaveral, Florida, latitud 28.46 N, longitud 279.45 E) sufrieron un súbito incremento, más del 250% con respecto a los días tranquilos previos, seguido por un fuerte gradiente negativo, y una lenta recuperación. El cuadro es aun más complejo por la presencia de estos gradientes, responsables por la degradación de la calidad del posicionamiento obtenido por GPS.

PALABRAS CLAVES: Ionosfera, tormentas magnéticas, TEC, GPS.

ABSTRACT

First steps toward the development of a vertical Total Electron Content (VTEC) storm-time correction empirical ionospheric model, equivalent to the STORM model for the peak concentration of the F2 region (Araujo-Pradere and Fuller-Rowell, 2002, Araujo-Pradere *et al*., 2002), are currently in progress in the NOAA's Space Environment Center (SEC). The program to obtain VTEC, the SEC's Win TEC Project (Anghel and Codrescu, 2002), use the RINEX (Receiver Independent Exchange format) files to derive the vertical TEC from the delay of the Global Position System (GPS) signals.

With a maximum Dst of –287.6 (maximum a_p = 400), the storm of July 2000, known as the Bastille Day storm, has been one of the most intense perturbations in the present solar cycle. The response of the TEC at a low mid-latitude station, as obtained from the delay in code and phase of the GPS signals, is analyzed for this storm. The vertical TEC at **ccv3** (Cape Canaveral, Florida, latitude 28.46 N, longitude 279.45 E) suffered a sudden increase, over 250% with respect to quiet conditions, for the first day of the storm, followed by a sharp negative gradient, and a slow recovery. The picture is further complicated by the presence of very steep gradients, responsible for the degradation of the GPS positioning accuracy.

KEYWORDS: Ionosphere, magnetic storms, TEC, GPS.

INTRODUCTION

The ionospheric total electron content TEC is a well-suited parameter for the study of ionospheric perturbed conditions and is particularly important for the correction of positioning information for single-frequency GPS user. Ionospheric TEC at a given station can change by tens or even hundreds of TEC units, introducing tens of meters error in position. Several papers (*e.g*. Mendillo, 1971; Mendillo *et al*., 1972; Mendillo and Klobuchar, 1974) have examined the average TEC patterns of storm-time disturbances as measured by the departure from the average behavior. These studies laid the foundation for much of the work that has followed in the last 25 years. For the mid-latitude station considered they demonstrated a clearly defined positive phase early in the storm periods followed by a long lived negative phase. They concluded that the negative phase of the ionospheric storm probably results from heating effects of the neutral atmosphere, which in turn upset the normal ionospheric production-loss processes, while the mechanism behind the positive phase was more difficult to assign. Surprisingly, they did not find a strong seasonal dependence as has been shown in the more recent NmF2 results (Wrenn *et al*., 1987; Araujo Pradere *et al*., 2000), which may be due to the station latitude. The long recovery in the TEC response, more than 5 days, most likely reflects the time to refill the plasmasphere at this latitude after the expansion of the magnetospheric convection has stripped away the plasma.

The work of Mendillo *et al*. (1972) used Faraday rotation measurements of TEC. Codrescu *et al*. (2001) used TOPEX/POSEIDON measurements to derive the TEC climatology (up to 2000 km) as a function of geomagnetic activity. They found that midlatitude TEC values increased from low to medium activity, and subsequently decreases for the high activity conditions. The explanation suggested that for stronger storms, the region of upwelling and enhanced molecular nitrogen, is able to penetrate further equatorward.

The increase in availability of TEC data over the last ten years has largely come from a rapid increase in the number of Global Position System (GPS) TEC data over land. This has been augmented by the TOPEX TEC data coverage over the oceans and the demonstration of the potential for space based GPS occultation from the GPS-MET satellite. Compared with the long record, almost fifty years, of ionospheric F-region observations from ground-based measurements, the TEC record from GPS and TOPEX is relatively short. The exponential increase in the number of GPS sites, however, now provides at least as much data, as is available for the F-region ionosonde studies. By performing a similar analysis with the GPS data it will be possible to determine the TEC storm time response, and compare and contrast it with the equivalent response of the ionospheric F-region to find and study consistent statistical features in both sets of data under geomagnetic perturbed conditions. Identification of the observed TEC storm-time response can also be used to compare with physical model predictions to identify limitations in current understanding.

TEC DERIVATION FROM GPS MEASUREMENTS

GPS observables, and the navigation message and additional information, are stored in a binary (receiver dependent) format that can be converted into computer independent ASCII format during data downloading (Hofman-Wellenhof *et al*., 1997). To promote data exchange, a receiver independent format of GPS data has been designed. The SEC's Win TEC Project use as the input the RINEX (Receiver Independent Exchange format) files, first defined by Gurtner *et al*. (1989), and later published in a second version by Gurtner and Mader (1990). This format consists of four different types of ASCII files: the observation data file, the meteorological data file, and the GLONASS navigation message file.

GPS observables are pseudoranges derived from code or carrier phase measurements. The measured raw phase can be modeled by $\Phi=(\rho/\lambda)+f)$ $(\Delta\rho+N-(\Delta^{\text{iono}}/\lambda)$, where ρ is the geometric range between satellite and receiver, f the frequency, λ the wavelength, N the integer ambiguity, and Δ^{iono} the ionospheric delay. The equivalent model for the code is $R = \rho + c.\ \Delta\rho + \Delta^{\text{iono}} + \Delta^{\text{trop}}$, c being the vacuum speed of light, and Δ^{trop} the tropospheric delay. The initial integer number N of cycles between the satellite and the receiver is unknown, and this phase ambiguity N remains constant as long as no loss of the signal lock occurs.

The group and phase refractive indices for a single electromagnetic wave propagation in space with frequency f, and a group of waves with slightly different frequencies, can be approximated by $n_{gr} = 1 - (c\ ^2/f^2)$, and $n_{ph} = 1 + (c\ _2/f^2)$, plus high order terms, where $c_2 = -40.3\ N_e$, $TEC = \int N_e\ .\ ds_o$, Ne is the electron density and TEC represents the total electron content.

The dispersion, or time delay between signals at two frequencies, provides a measure of integral TEC along the entire propagation path. Measured range and geometric range are defined by $s=\int n\ .\ ds$ and $s_o=\int ds_o$, and the difference between them represents the ionospheric refraction $\Delta^{\text{iono}}=s-s_o$. From the previous formulas it is possible to obtain both delays: $\Delta_{gr}^{iono}=(40.3/f^2).\ TEC$, $\Delta_{ph}^{iono}=(40.3/f^2).\ TEC$ (in meters).

The GPS observations equations for the code pseudorange are:

$$R_1 = \rho + c.\Delta\rho + \Delta_{f_1}^{iono} + \Delta^{trop} + b_{f_1}^{S} + b_{f_1}^{R} + m_{R_1} + \varepsilon_{R_1}$$

$$R_1 = \rho + c.\Delta\rho + \aleph.\Delta_{f_1}^{iono} + \Delta^{trop} + b_{f_2}^{S} + b_{f_2}^{R} + m_{R_2} + \varepsilon_{R_2};$$

$$\aleph = \left(f_1/f_2\right)^2,$$

where $b_{f_1}^{s}, b_{f_2}^{s}$ are the satellite delays, $b_{f_1}^{R}, b_{f_2}^{R}$ the receiver delays, m_{R_1}, m_{R_2} the multipath effects, and $\varepsilon_{R_1}, \varepsilon_{R_2}$ the receiver noises, all of them for the code pseudorange observations.

From the combination of the previous equations, the expression for the total electron content using pseudorange observations is

$$TEC_R = 9.52\ (R_2 - R_1) \qquad (1)$$

which is unambiguous but noisy.

The GPS observation equations for the carrier phase measurements are:

$$\lambda_1.\Phi_1 = \rho + c.\Delta\rho + \lambda_1.N_1 - \Delta_{f_1}^{iono} + \Delta^{trop} + b_{f_1}^{S,\Phi} + b_{f_1}^{R,\Phi} + m_{\Phi_1} + \varepsilon_{\Phi_1}$$

$$\lambda_2, \Phi_2 = \rho + c.\Delta\rho + \lambda_2.N_2 - \aleph.\Delta_{f_1}^{iono} + \Delta^{trop} + b_{f_2}^{S,\Phi} + b_{f_2}^{R,\Phi} + m_{\Phi_2} + \varepsilon_{\Phi_2}$$

$$\aleph = \left(f_1/f_2\right)^2,$$

where N_1 and N_2 are the unknown carrier phase ambiguities, $b_{f_1}^{S,\Phi}, b_{f_2}^{S,\Phi}$ the satellite delays, $b_{f_1}^{R,\Phi}, b_{f_2}^{R,\Phi}$ the receiver delays,

m_{Φ_1}, m_{Φ_2} the multipath effects, and $\varepsilon_{\Phi_1}, \varepsilon_{\Phi_2}$ the receiver noises, all of them for the carrier phase observations. $b^S = b^{S,\Phi}_{f_1} - b^{S,\Phi}_{f_2}$ is the satellite differential delay, $b^R = b^{R,\Phi}_{f_1} - b^{R,\Phi}_{f_2}$ is the receiver differential delay, and $b^R + b^S$ is the total (satellite-receiver) delay.

Combining the previous equations, the expression for the total electron content using carrier phase observations is

$$TEC_\Phi = 9.52.(\lambda_1.\Phi_1 - \lambda_2.\Phi_2) \qquad (2)$$

which is precise but ambiguous.

Incorporating both, the very precise but ambiguous carrier phase observations (equation 2), and the unambiguous but less precise code pseudorange observations (equation 1), a new ionospheric observation, the combined TEC (TEC_{comb}, it is called *combined* due to the fact that both, pseudorange and phase, are used in its derivation), can be obtained:

$$TEC_{comb_i} = TEC_{\Phi_i} - \left(\frac{\sum_{j=i-n(j\neq 1)}^{i+n} p_j.\left(TEC_{\Phi_j} - TEC_{R_j}\right)}{\sum_{j=i-n(j\neq 1)}^{i+n} p_j} \right) \qquad (3)$$

DATA SOURCES

With a maximum Dst of -301.0 (with a strong dDst/dt of approximately of 130 nT/hour), and a maximum ap = 400, the storm of July 2000, Bastille Day storm, has been one of the most intense perturbations in the present solar cycle. Figure 1 shows the a_p (gray bars) and Dst (white bars) geomagnetic activity indices for this storm period.

This period has been extensively studied. For a good collection of papers related to the Bastille Day storm, see *Solar Physics*, volume 204, a Topical Issue on the 2000 Bastille Day Flare Event.

The National Geodetic Survey (NGS), an office of NOAA's National Ocean Service, coordinates a network of continuously operating reference stations (CORS) that provide Global Positioning System (GPS) carrier phase and code range measurements in support of 3 dimensional positioning activities throughout the United States and its territories. The CORS ftp site (ftp://ftp.ngs.noaa.gov/cors/rinex/) enables the transfer of the RINEX files used as the input for the Win TEC project.

Cape Canaveral 3 station (latitude 28.46 N, longitude 279.45 E) has a receiver type Ashtech Z-XII3, with an antenna type ASH700829.3. Due to its particular position, near the Caribbean peak, the data from the receiver at **ccv3**, with a steady record of data covering from early 1994 to today, have been used by several researchers to analize the the TEC

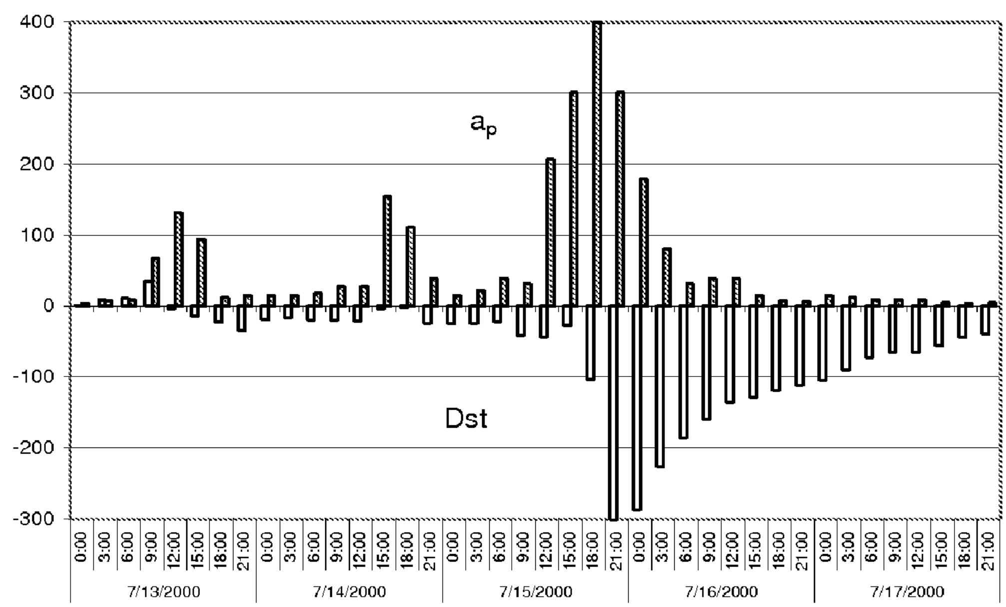

Fig. 1. Geomagnetic activity for the period of interest (from Araujo-Pradere and Fuller Rowell, 2001).

variations (*e.g.,* Skone *et al*., 2002, Coster *et al*., 2001) for quiet and perturbed conditions.

RESULTS

The final product from the Win TEC Project, for the particular storm and station of this study, is shown in Figure 2. The data is plotted in the same interval of acquisition (every 15 seconds), and the panels are organized following the steps of the process (they will be revised next). The period represented goes from July 12 (day of the year, doy = 194) to July 19 (doy = 201), 2000.

The top panel corresponds to the values extracted from the RINEX files, the combined TEC. To level the phase to the pseudorange, the program use a 40 minutes running win-

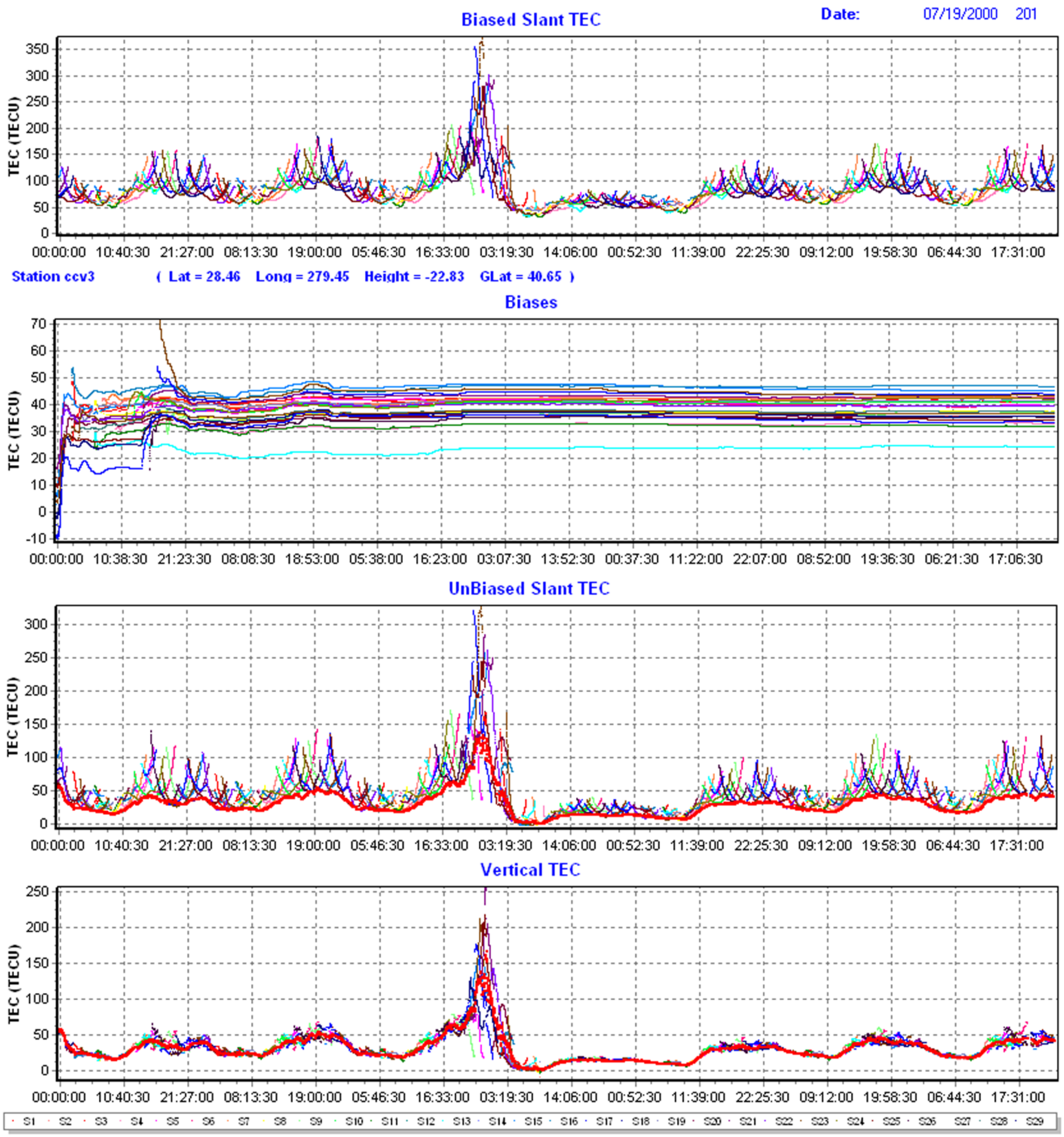

Fig. 2. Output of the Win TEC project for the Bastille Day storm: biased Slant TEC, satellite-receiver biases, unbiased slant TEC, and Vertical TEC for a seven-day period.

dow to obtain the average difference, for each satellite, between the TEC from the phase and the TEC from the pseudorange, and this value is subtracted from the TEC derived from the phase (equation 3).

Applying Kalman filter method (Kalman, 1960, Kalman and Bucy, 1961) to this result, the biases for each satellite, the unbiased slant TEC, and the vertical TEC are obtained.

The second panel from the top contains the total bias for each satellite-receiver pair, and the third panel is the difference between the two previous, *i.e.* the unbiased slant TEC. The bottom panel is the derived Vertical TEC (VTEC), the final output of the program.

For all panels the vertical axes are in TEC units (TECU), and the horizontal axes correspond to the universal time (UT). The color coding identifies the track for each satellite. In the third and fourth panels a heavy red line, representing the mean value for each time, was added. The mean value of the vertical TEC will be used as the final VTEC in this work.

In order to avoid unreal negative values of the VTEC, that frequently appear with previous versions of Win TEC Project, further constraints were imposed to the biases for each satellite-receiver pair, the second panel from the top in Figure 2. Namely, sudden jumps were prohibited, limiting the gradients between close points to certain values, depending of the level of geomagnetic activity. With this adjust, we don't have now abrupt changes of the biases during the main phase of the storm, where before there was an increase of up to 10 TEC units, that appear while the Kalman filter was reaching its steady state.

A general feature of the bottom panel of Figure 2 is the diurnal variation, with a minimum before sunrise, an abrupt increase toward a peak in the afternoon, and a slow decay through the night. The maximum value for each cycle is a function of the geomagnetic activity, decreasing (increasing) with decreased (increased) activity level. Compared with higher latitudes, the morning peak occurs earlier, which is consistent with the fountain effect as plasma in the fountain is first seen at the equator, before it diffuses down to form the crests (Codrescu *et al.*, 2001).

To put in perspective the behavior of the ionospheric total electron content for this storm interval, Figure 3 shows the ratio of the vertical TEC, obtained from the expression $VTEC_{ratio}=(VTEC_{quietmean}/VTEC_{observation})$, where $VTEC_{quietmean}$ is the average, for each observation time, over the first two days (doy = 194 and 195, 2002) of the interval. From this definition, VTECratio = 1 represents the less perturbed conditions. The top panel is the $VTEC_{ratio}$ vs. time (day of the year), with the maximum and minimum values displayed. The bottom panel is the daily distribution of the $VTEC_{ratio}$ (all values in the day interval are vertically aligned for that day). For both panels the y-axis is the $VTEC_{ratio}$ and the x-axis is the day of the year 2000.

The first two days are our quiet reference days (less affected by the storm), while the third day shows an increasing of the VTEC value, followed by a sudden decrease. This feature can be related to the first small peak in geomagnetic activity for this period, visible in the a_p index, in Figure 1, for July 14 (doy = 196).

The same picture, but several times amplified, can be seen in the fourth day of the period, when there is a increase of more than 250% over quiet conditions, followed by a very sharp, negative gradient, that shows final values close to zero (*i.e.,* plasma-empty flux tubes over this location), trailed by a 3-day period of a slow recovering, lastly reaching quiet conditions values for the last two days of the period (doy = 200 and 201).

The complex behavior of the equatorial F region for perturbed conditions, as compared to quiet condition, is due to the dynamic coupling between high and low latitudes (Basu *et al.*, 2001), mainly explained by two basics mechanisms: solar wind magnetospheric dynamo (Spiro *et al.*, 1988), and ionospheric disturbance dynamo (Blanc and Richmond, 1980). The first mechanism is responsible for the changes in the solar cap potential, which causes prompt penetration of electric field to low latitudes. The second mechanism is caused by changes in the global circulation induced by Joule heating at auroral latitudes during magnetic storms (Scherliess and Fejer, 1997)

While the profiles of the two peaks in Figure 3 are similar, the physical interpretations are different. In general, due to the downwelling of air parcels rich in atomic oxygen, a positive phase (TEC increasing) is expected at mid-latitudes for the initial part of the storm, and for small storms. For high activity conditions, the statistical analysis shows that the downwelling zone moves equatorward, and the arrival of the neutral density bulge (Fuller-Rowell *et al.*, 1994, 1996) produces a decrease in TEC values (negative phase) below quiet-time levels (Codrescu *et al.*, 2001).

Figure 4 shows the more likely reason for the sharp decrease, to almost zero, of the VTEC values. Plots represent ion density variation (cm^{-3}) as a function of geomagnetic latitude, for July 15 and 16, 2000 (doy = 197, and 198), as obtained from the DMSP satellites, near Fortaleza, Brazil.

Both days show a critical thinning of the ion density (to less than 10^3 cm^{-3}), for an extended amplitude interval of approximately 30°, which support the idea that, in this sector during the post-sunset period, a strong eastward electric

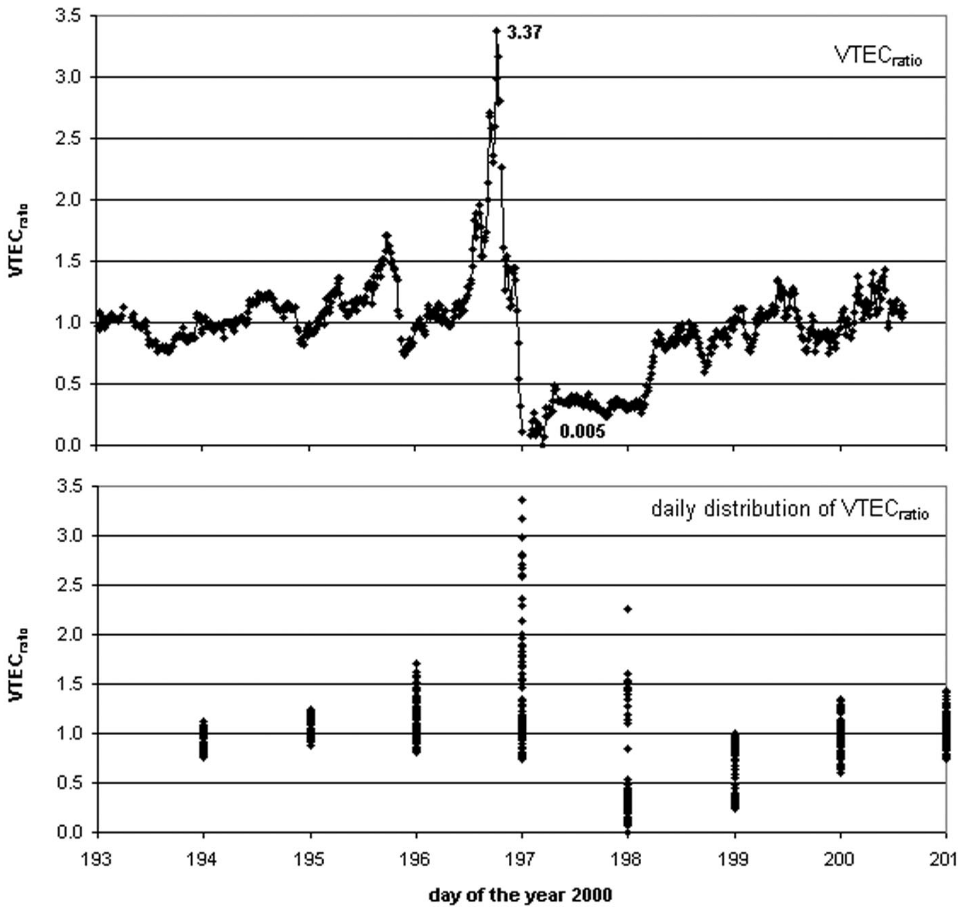

Fig. 3. Ratio of the Vertical TEC as function of time (top panel), and the corresponding daily distributions of VTEC values (bottom panel).

field may have lifted the bottomside F region to altitudes over 840 km, altitude of the DMSP satellites (Basu *et al.*, 2001).

A similar phenomenon is related to the negative phase at **ccv3**. The peak densities of the crests are lifted to high altitudes by the strong eastward electric field, while the crests are moving farther away from the equator. At some point, this particular site, **ccv3**, will have the maximum of the northern crest overhead, originating the sharp positive phase, just to be immediately followed by the valley of the Appleton anomaly, deeply diminished by the fountain effect (the diffusing down of the plasma that generates the crests), which corresponds to the deep negative phase observed in Figure 2.

Finally, the slow recovery is based in the normal production process that now has to replenish the empty flux tubes. This process, for the particular case of this storm and this site, takes about three days to boost the average value of VTEC to a similar pre-storm level, as it is possible to see in

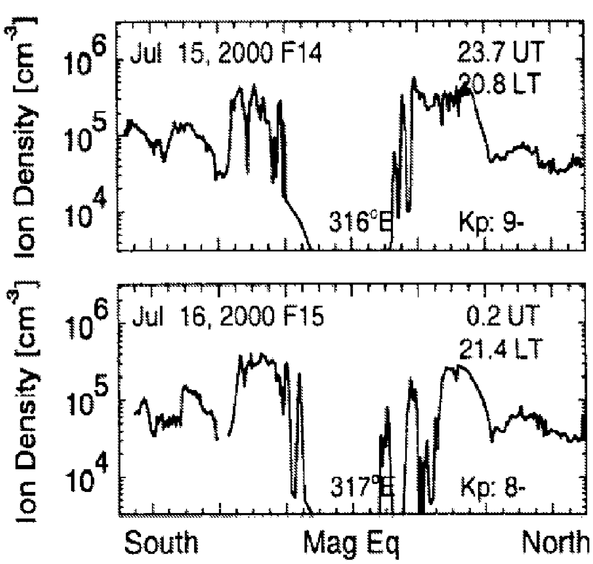

Fig. 4. Ion-density variation as a function of geomagnetic latitude, recorded by DMSP F14 and F15 satellites near Fortaleza, Brazil (from Basu *et al.*, 2001).

the bottom panel of Figure 3 for the last two days of the period analyzed (doy = 200 and 201).

CONCLUSIONS

The response of the TEC at a low mid-latitude station, as obtained from the delay in code and phase of the GPS signals, is analyzed for the Bastille Day storm (July 2000). The vertical TEC at **ccv3** (Cape Canaveral, Florida, latitude 28.46 N, longitude 279.45 E) suffered a sudden increase, over 250% with respect to quiet conditions, for the first day of the storm, followed by a sharp negative gradient, and a slow recovery. The positive phase appears when the peak densities of the crests are lifted to high altitudes by the strong eastward electric field, while the negative phase corresponds to the widening of the Appleton anomaly, the diffusing down of the plasma that generates the crests.

ACKNOWLEDGMENTS

The author thanks A. Anghel and M.V. Codrescu for their useful comments and the access to the Win TEC Project software. NSF Grant ATM-0208069 supported this work.

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