The Low-latitude Ionosphere: Monitoring its Behaviour with GPS

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BIOGRAPHY

Mariangel Fedrizzi is a Ph.D. student at the Instituto Nacional de Pesquisas Espaciais (INPE), Brazil, where she got her Master's degree in Space Geophysics in 1999. Currently, she is a visiting graduate student at University of New Brunswick, Canada, under the supervision of Dr. Richard Langley. She has worked on ionospheric studies using GPS data since 1997.

Richard Langley is a professor in the Department of Geodesy and Geomatics Engineering at the University of New Brunswick, where he has been teaching since 1981. He has a B.Sc. in applied physics from the University of Waterloo and a Ph.D. in experimental space science from York University, Toronto. After obtaining his Ph.D., Prof. Langley spent two years with the Department of Earth and Planetary Sciences of the Massachusetts Institute of Technology where he carried out research in lunar laser ranging and very long baseline interferometry. Prof. Langley has worked extensively with GPS, specializing in atmospheric propagation delay modeling.

Attila Komjathy is currently a technical staff member at the NASA Jet Propulsion Laboratory specializing in atmospheric and ionospheric remote sensing techniques using the Global Positioning System. Prior to his joining JPL in July 2001, Dr. Komjathy worked on the utilization of GPS reflected signals as a research associate at the University of Colorado's Center for Astrodynamics Research for four years. He received his Ph.D. from the Department of Geodesy and Geomatics Engineering of the University of New Brunswick, Canada in 1997. His dissertation on ionospheric total electron content mapping using GPS won the 1998 Canadian Governor General's Gold Medal.

Marcelo Santos is an associate professor at the Department of Geodesy and Geomatics Engineering, University of New Brunswick, Canada. He holds an M. Sc. E. Degree in Geophysics from the National Observatory in Rio de Janeiro, and a Ph.D. Degree in Geodesy from the University of New Brunswick. He has been involved in research in the fields of geodesy and navigation.

Eurico R. de Paula received his Ph.D. degree at INPE in 1986. After that date he worked 4.5 years at Utah State University on Jicamarca drifts. He has been collaborating with Cornell University on GPS amplitude scintillations and with Clemson University with VHF coherent radar to study ionospheric irregularities. With INPE's group he is studying TEC behaviour during geomagnetic storms over South America.

Ivan Jelinek Kantor received his Ph.D. degree at Rice University in 1972 and participated in a postdoctoral program at the Max Planck Institut fuer Aeronomie in 1991. He worked on ionospheric heating experiments in Arecibo, Puerto Rico. At INPE, he worked with Faraday total electron content, measurements of electron temperature using Langmuir probes in rockets and total electron content and scintillation using GPS data. With INPE's group he is currently studying TEC during storms over South America. He also teaches graduate and postgraduate courses.

ABSTRACT

Since the late 1980's various research groups have been investigating the behaviour of the ionosphere using Global Positioning System (GPS) data. These investigations are based on the total electron content (TEC) measurements derived from dual-frequency GPS observations taking advantage of the dispersive nature of the ionospheric medium.

Currently, there is a large number of GPS receivers in continuous operation worldwide. Even though large in number, these stations are unevenly distributed, being situated mostly in the northern hemisphere region. The relatively smaller number of GPS receivers in the southern hemisphere, and consequently the reduced number of available TEC measurements, causes ionospheric modelling to be less accurate for this region.

GPS data from the Brazilian Network for Continuous Monitoring by GPS (RBMC) have been used for the first time to obtain TEC values in order to monitor the

ionospheric behaviour in the South American region. For this task, we are using the University of New Brunswick (UNB) Ionospheric Modelling Technique which uses a spatial linear approximation of the vertical TEC above each station using stochastic parameters in a Kalman filter estimation to describe the local time and geomagnetic latitude dependence of the TEC. The utilisation of the RBMC GPS data to monitor the ionosphere over South America can help us to obtain a better understanding of many important low latitude ionospheric phenomena, such as the Appleton Equatorial Anomaly and the South Atlantic Anomaly as well as more accurate and representative regional and global ionospheric models. Furthermore, the effect of geomagnetic storms on the equatorial and low-latitude ionosphere is discussed, as well as the integrity of GPS data obtained in equatorial and low-latitude regions.

INTRODUCTION

Despite the significant recent progress in studies of the behaviour of the ionosphere, there are still many questions to be investigated in order to get a better understanding of the energy coupling processes between the Sun and the Earth (e.g., Prölss, 1995; Prölss, 1997; Fuller-Rowell, 1997; Buonsanto, 1999). Various observing techniques, such as transionospheric radio signals, ionosonde measurements and incoherent scattering radars, have been used to study the ionospheric behaviour during both magnetically quiet and disturbed periods. However, previous ionospheric studies were based mainly on measurements obtained either from a single station or a local network of instruments. On a global scale, isolated orbiting satellites carrying ionospheric sensors also were not able to monitor ionospheric behaviour due to the lack of instantaneous worldwide coverage.

The understanding of the coupling processes between the magnetosphere and the ionosphere-thermosphere require a global monitoring system in continuous operation. The utilization of simultaneous global observations to monitor the ionosphere, such as the observations carried out with the extensive network of GPS receivers, is making possible the assessment of variations in ionospheric total electron content during quiet and disturbed periods, on both global and regional scales. These observations are also assisting researchers in the investigation of the energy flux dissipation and transport processes which occur in the ionosphere.

Computing the TEC from GPS data is feasible due to the dispersive nature of the ionosphere, which affects the speed of propagation of the electromagnetic waves transmitted by the GPS satellites on two L-band frequencies (L1=1575.42 MHz and L2=1227.60 MHz) as they travel through that region of the atmosphere. The (biased) signal propagation time between the satellite and the receiver is directly proportional to the number of free electrons in the ionosphere which, multiplied by the vacuum speed of light, results in the pseudorange and carrier phase GPS observables. After forming the linear combination of these measurements on the L1 and L2 frequencies, the carrier phase and the pseudorange TEC are obtained.

For the work described in this paper, data from more than 30 GPS stations located in the South American sector, including stations from the Brazilian Network for Continuous Monitoring by GPS (RBMC), which is maintained and operated by the Brazilian Institute of Geography and Statistics (IBGE), and the International GPS Service (IGS), were used to investigate the TEC variations during the July 15, 2000 (St. Swithin's Day) geomagnetic storm. Digisonde data from Cachoeira Paulista (geomagnetic latitude: 17.6°S), as well as interplanetary magnetic field (IMF) data, were additionally used to explain the observed TEC variations which occurred during the geomagnetic storm. To investigate the ionospheric behaviour in the South American region we are using the Ionospheric Modelling Technique developed at the University of New Brunswick, which uses a spatial linear approximation of the vertical TEC above each station using stochastic parameters in a Kalman filter estimation to describe the local time and geomagnetic latitude dependence of the TEC.

UNB IONOSPHERIC MODELLING TECHNIQUE

The UNB ionospheric modelling technique (Komjathy and Langley, 1996; Komjathy, 1997) uses the single-layer ionospheric model to obtain the TEC from a GPS receiver, according to the following observation equation:

$$I_r^s(t_k) = M(e_r^s)\,\left[a_{0,r}(t_k) + a_{1,r}(t_k)\ d\lambda_r^s + a_{2,r}(t_k)\ d\varphi_r^s\right] + b_r + b^s \qquad (1)$$

where

$I_r^s(t_k)$ is the line-of-sight L1-L2 phase-levelled measurement (in TEC units) obtained by the receiver r observing satellite s at epoch t_k,

$M(t_k)$ is the thin shell elevation-angle mapping function,

$a_{0,r}, a_{1,r}, a_{2,r}$ are the stochastic parameters for spatial linear approximation of TEC to be estimated per station assuming a first-order Gauss-Markov stochastic process,

$d\lambda_r^s = \lambda_r^s - \lambda_0$ is the difference between the longitude of the subionospheric point and the mean longitude of the sun,

$d\varphi_r^s = \varphi_r^s - \varphi_r$ is the difference between the geomagnetic latitude of the subionospheric point and the geomagnetic latitude of the station and,

b_r, b^s are the receiver and the satellite instrumental differential delay biases, respectively.

The PhasEdit version 2.2 automatic data editing program (Freymueller, 2001) was used to detect bad points and cycle slips, as well as repair the cycle slips and adjust phase ambiguities using the undifferenced GPS data. The program takes advantage of the high precision dual-frequency pseudorange measurements to adjust L1 and L2 phases by an integer number of cycles to agree with the pseudorange measurements. The combined satellite-receiver differential delays for a reference station are estimated using the Kalman filter algorithm and, in a network solution, additional biases for the other stations are estimated based on the fact that the other receivers have different instrumental delays. Therefore, for each station other than the reference station, an additional differential delay parameter is estimated, which is the difference between the receiver differential delay of a station in the network and the reference station. This technique is described by Sardon et al. (1994).

The mapping function we used for our work is the standard geometric mapping function, which computes the secant of the zenith angle of the signal geometric ray path at the ionospheric pierce point at a shell height of 400 km. The standard geometric mapping function is given by (Komjathy, 1997):

$$M(e) = \left[1 - r_E^2 \cos^2 e / (r_E + h)^2\right]^{-1/2} \quad (2)$$

where

e is the satellite elevation angle,

r_E is the mean radius of the earth and,

h is the mean value for the height of the ionosphere (assumed shell height).

Because of the dependence of the ionosphere on the solar radiation and the geomagnetic field, a solar-geomagnetic reference frame is used to compute the TEC at each station. The ionospheric model was evaluated for the four closest stations to a grid node at which a TEC value is computed. Subsequently, the inverse distance squared weighted average of the individual TEC data values for the four GPS stations was computed. The closer a particular grid node is to a GPS station, the more weight was put on the TEC values computed by evaluating the ionospheric model describing the temporal and spatial variation of the ionosphere above the particular station. The ionospheric maps were produced using a 5-degree grid spacing. Each hourly map contains the observations obtained from 30 minutes before to 30 minutes after the respective hour.

OBSERVATIONS AND RESULTS

Despite the fact that there is a large number of GPS receivers in continuous operation around the world, these stations are unevenly distributed, being situated mostly in the northern hemisphere region. The relatively smaller number of GPS receivers in the southern hemisphere, and consequently the reduced number of available TEC measurements, causes ionospheric modelling to be less accurate for this region (Ho et al., 1997; Mannucci et al., 1998; Iijima et al., 1999).

In our work, we have used GPS data from the RBMC and the IGS networks to investigate the ionospheric response over the South American region to a very intense geomagnetic storm which occurred on July 15, 2000. Figure 1 shows the observed values for the Disturbance Storm-Time (DST) geomagnetic index during the period from July 7 to 21, 2000 when a significant decrease occurred in the DST value at about 20-21 UT on July 15. Its value reached –300 nT, which according to Gonzales at al. (1994), is classified as a very intense geomagnetic storm.

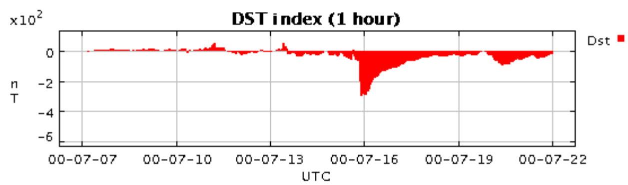

Figure 1. DST index during the period 7-21 July 2000 (SPIDR, 2001).

The region covered by the TEC maps in our study is shown in Figure 2. We used data from 33 to 37 stations (depending on the day) located between 70°S and 30°N geographic latitude and 150°W and 40°E geographic longitude for data processing, in order to obtain reliable values for the TEC over the oceanic area bordering South America (23 of the stations are shown in Figure 2; the other stations lie outside the map boundaries), where there are very few GPS stations. The quality of the GPS data was checked for all stations using the Translate/Edit/Quality Check (TEQC) software (UNAVCO, 2001). Based on the QC results, we have chosen Rio Grande (designated in Figure 1 as riog; geomagnetic latitude: 30.5°S) as the reference station since, amongst the stations located in a geomagnetic mid-latitude region where the ionosphere is fairly well behaved, it had the best results in terms of data quality during the period analysed (July 13-18, 2000).

The TEC maps, generated using the Generic Mapping Tools (Wessel and Smith, 1998), for the storm period (19-22 UT of July 15) are shown in Figure 3a. For comparison purposes, the TEC maps for the day prior to the storm are shown in Figure 3b. Some TEC enhancements were observed at both 19 UT and 20 UT on July 15 over the geographic latitudes of 25°S and 10°N and the longitude sector of approximately 300°. Such increasing TEC became very clear in the succeeding hours (21-22 UT), when such conditions were observed at both sides of the geomagnetic equator (which runs approximately across

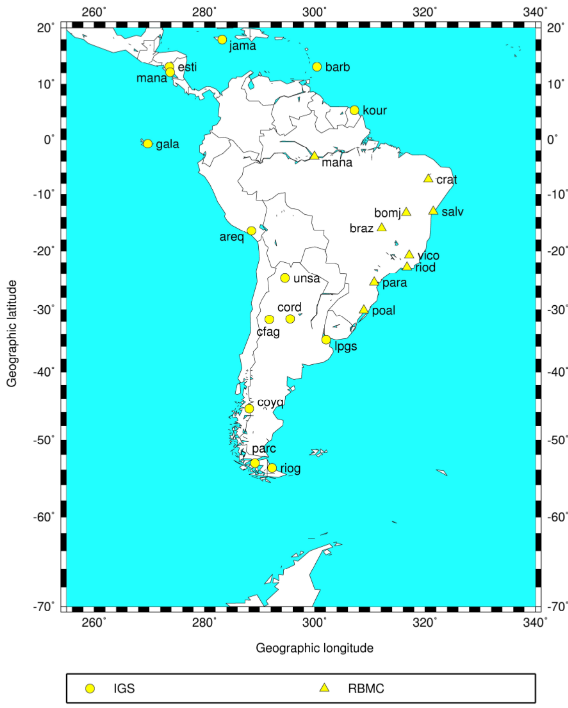

Figure 2. RBMC and IGS stations in the South American region.

Crato (crat) and Arequipa (areq) stations). This TEC enhancement reached a maximum value of about 210 TECU at 22 UT, when an unusually poleward expansion of the equatorial anomaly crests was observed. Due to the fact that data from O'Higgins station (Antarctic Peninsula) were not available for that period, the TEC values ranging between 60°S and 70°S are not very reliable.

The high TEC values observed on July 15 at 22 UT, as well as the expansion of the equatorial anomaly zone towards to the higher latitudes, seems to be associated with a plasma uplift due to the penetration of an eastward electric field to the low-latitude ionosphere. Measurements of the direction and intensity of the interplanetary magnetic field (IMF) presented in Figure 4 show that Bz turned to the south at about 19 UT (15 LT in the South American sector) and had its absolute value significantly increased. In this case, the magnetospheric convection is increased and the associated dawn-dusk electric fields can penetrate to the low latitude ionosphere before they are opposed by effects of shielding in the inner magnetosphere (Fejer, 1997; Buonsanto, 1999). The eastward electric fields on the dayside ionosphere cause vertical plasma drifts at the equatorial and low latitudes (also known as the fountain effect) that dominate the electron density structure of the entire low-latitude ionosphere. A plasma uplift in the low latitude ionosphere was observed by digisonde measurements at Cachoeira Paulista (geomagnetic latitude: 17.6°S), where the F2 layer peak height (hmF2) increased from 400 to 600 km at about 20 UT (17 LT) on July 15, as shown in Figure 5.

Another feature observed during this storm was the decrease in the ionization density, which characterises the negative phase of the ionospheric storms. TEC decreases larger than 100% relative to magnetically quiet values were observed in the equatorial and low latitude ionosphere from about 9 UT on July 16 to 11 UT on July 17, which seems to be associated with the interactions between seasonal and storm-induced thermospheric winds. In summer, both types of winds are in phase and the composition disturbance zone is transported much further equatorwards, producing negative phases of an ionospheric storm (Prölss, 1995; Fuller-Rowell, 1997; Buonsanto, 1999). Figure 6 ilustrates such TEC decreases observed in the equatorial and low latitude ionosphere. For comparison purposes, the TEC map for the day prior to the storm is also shown.

CONCLUSIONS AND FUTURE RESEARCH

Despite the significant progress in understanding the behaviour of the ionosphere, there are still many outstanding questions to be answered in order to get a better understanding of the energy coupling processes between the Sun and the Earth. The results presented here are preliminary and represent the first stage of a series of studies of the physics and dynamics of the ionosphere during both quiet and disturbed periods. Nevertheless, from these early results it was possible to identify some of the ionospheric responses to geomagnetic storms, such as prompt electric field penetration to low latitudes, intensification of the fountain effect and TEC decreasing in the low latitude ionosphere due to the interactions between seasonal and storm-induced thermospheric winds. The methodology to compute TEC from GPS data is being improved, and the continuously increasing number of worldwide permanent GPS stations will make possible a more detailed monitoring of the energy flux dissipation and transport processes of the ionosphere.

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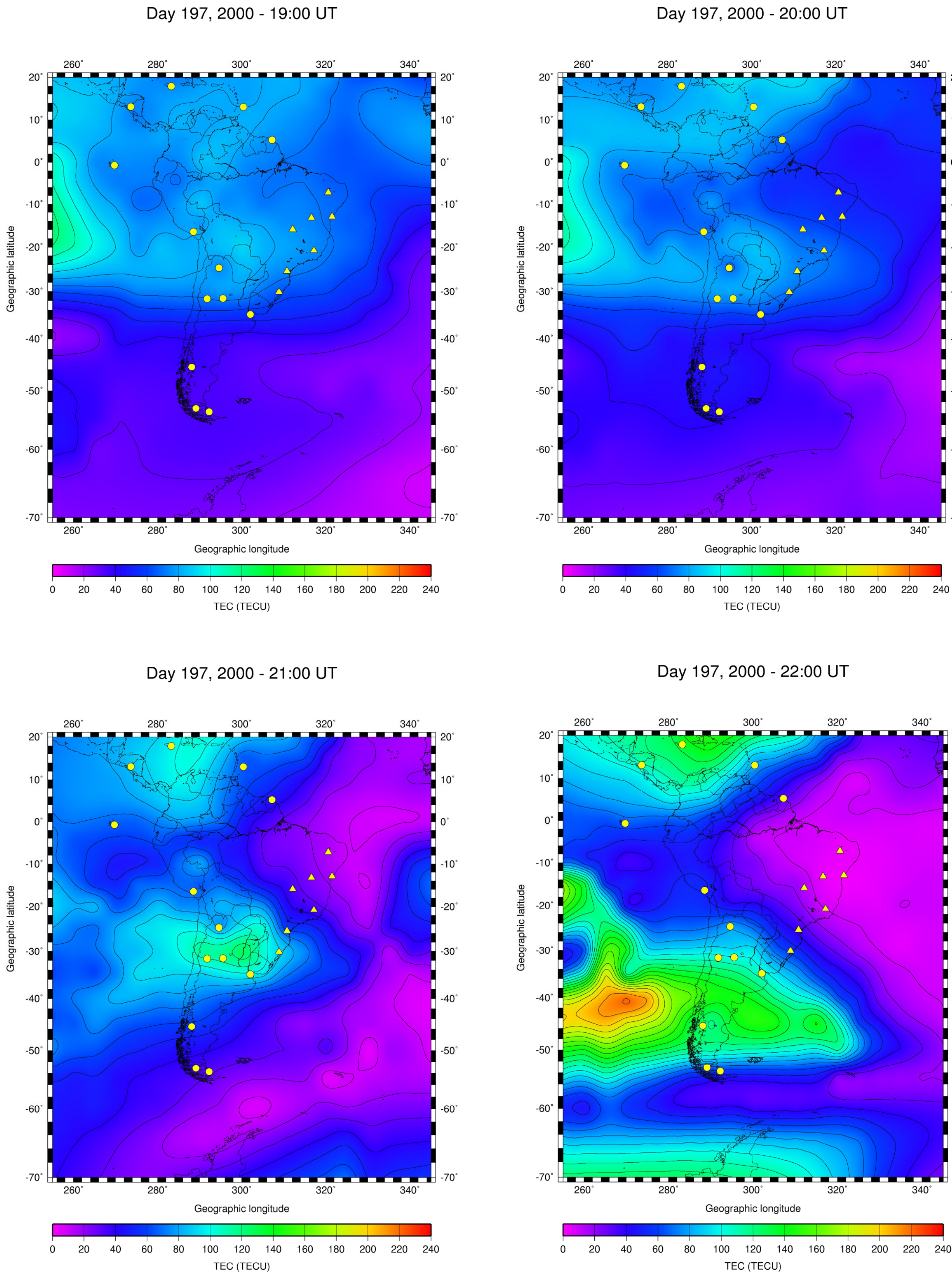

Figure 3a. Ionospheric TEC maps for the storm time on July 15, 2000. TEC enhancements were observed from 19-22 UT on July 15, 2000 for the dayside ionosphere over the South American sector.

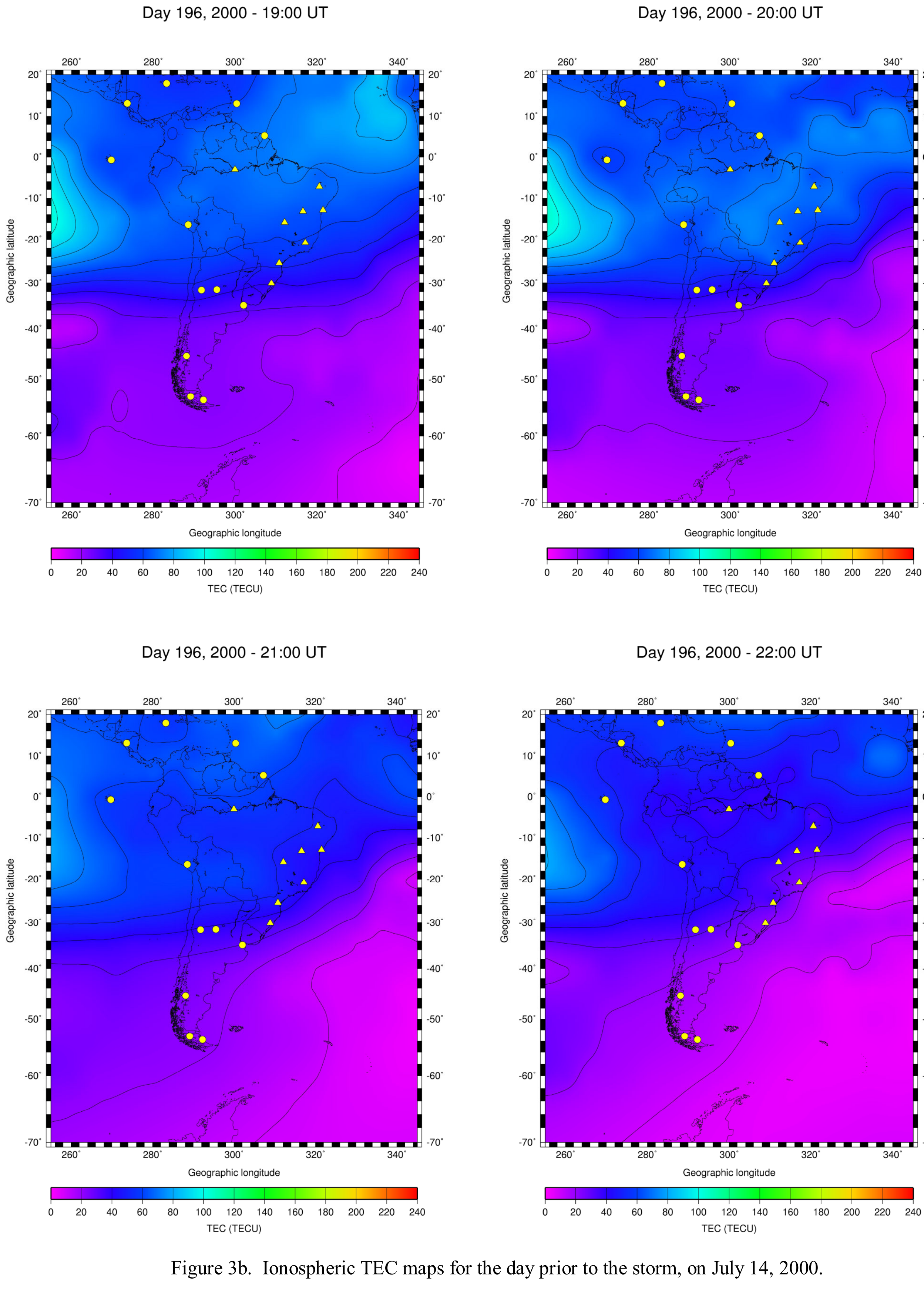

Figure 3b. Ionospheric TEC maps for the day prior to the storm, on July 14, 2000.

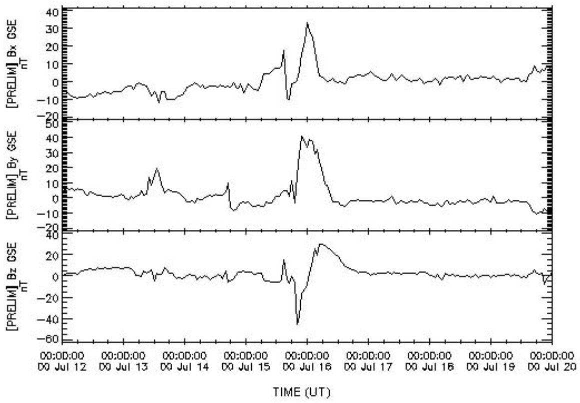

Figure 4. Preliminary values of the interplanetary magnetic field vector in geocentric-solar-ecliptic (GSE) Cartesian coordinates provided by the ACE spacecraft, for the period 12-19 July, 2000.

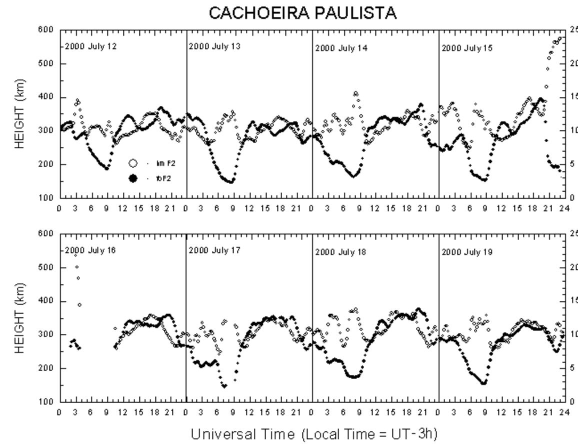

Figure 5. F2 layer peak height (hmF2) and F2 layer critical frequency (foF2) obtained from digisonde measurements at Cachoeira Paulista for the period 12-19 July, 2000.

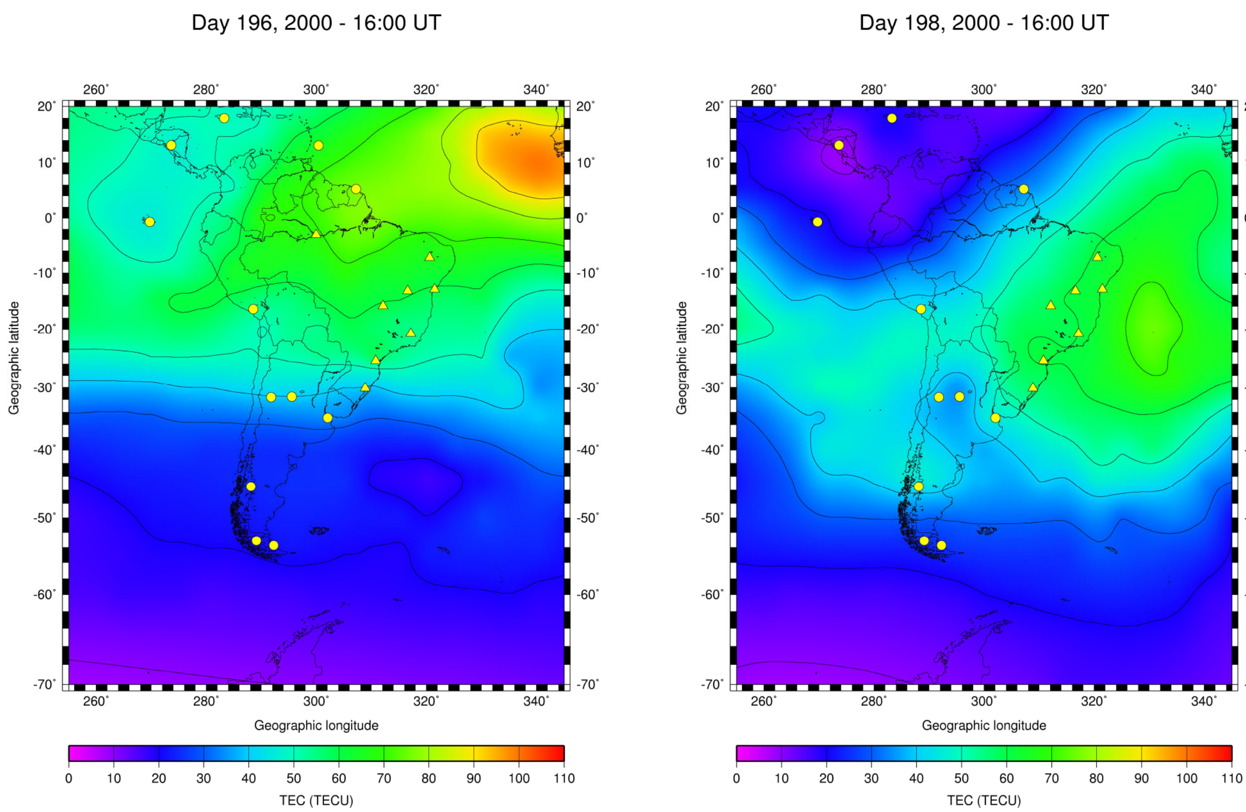

Figure 6. Ionospheric TEC maps showing the decrease in the ionization density at the equatorial and low latitude ionosphere on July 16 (right), relative to the same time in the day prior to the storm (left).

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