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STUDY OF IONOSPHERIC IRREGULARITIES DURING INTENSE MAGNETIC STORMS

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ABSTRACT. The effects of two intense magnetic storms over ionospheric irregularities were analyzed using GPS signal scintillation data from the stations of São Luís (2.57°S, 44.21°W, dip latitude 1.73°S) in the equatorial region, São José dos Campos (23.07°S, 45.86°W, dip latitude 18.01°S) and Cachoeira Paulista (22.57°S, 45.07°W, dip latitude 18.12°S) both under the Equatorial Ionization Anomaly (EIA), and São Martinho da Serra (29.28°S, 53.82°W, dip latitude 18.57°S), located in the South of Brazil. Total Electron Content (TEC) data for São Luís and São José dos Campos, were also analyzed. The analyzed storms occurred on October 28-31, 2003 and on November 7-11, 2004. Both storm periods presented two main phases. In the nights of 29/30 and 30/31 of October, during the two storm main phase, it was observed that TEC over São José dos Campos reached higher values than the TEC for the magnetically quiet day of October 10, due to the effect of eastward electric field prompt penetration to magnetic equator that intensified the EIA. Compared to a quiet day (Oct 10), scintillation in the GPS signal amplitude due to ionospheric irregularity, quantified by the scintillation index S4, was stronger for Cachoeira Paulista (under EIA) during the night of 30/31but not for the night of 29/30 and for São Martinho da Serra was stronger during the nights of 29/30 and 30/31. Scintillation for the nights of 29/30 and 30/31 at these two stations lasted longer than on October 10, reaching the post midnight time sector. During the November 7-11 storm, TEC kept the behavior of a quiet day except during days 10 and 11 (up to 9 UT), when a large TEC decrease was observed. The GPS scintillation, compared to the quiet day November 19, was larger at the equatorial station of São Luís during the nights of 7/8 and 8/9 and it was completely inhibited for the São Luís and São José dos Campos stations during the nights of 9/10 and 10/11, probably due to action of westward disturbance dynamo electric field penetration to equator.

Keywords: GPS, ionospheric scintillation, magnetic storm, TEC (Total Electron Content).

RESUMO. Os efeitos de duas tempestades magnéticas intensas sobre irregularidades ionosféricas foram analisados usando dados de cintilação do sinal de GPS das estações São Luís (2,57°S, 44,21°W, inclinação magnética 1,73°S) na região equatorial, São José dos Campos (23,07°S, 45,86°W, inclinação magnética 18,01°S) e Cachoeira Paulista (22,57°S, 45,07°W, inclinação magnética 18,12°S) ambas sob a Anomalia da Ionização Equatorial (AIE) e São Martinho da Serra (29,28°S, 53,82°W, inclinação magnética 18,57°S), localizada no sul do Brasil. Dados de CET (Conteúdo Eletrônico Total) também foram analisados. As tempestades analisadas ocorreram em 28-31 de outubro de 2003 e em 7-11 de novembro de 2004. Ambos períodos de tempestades apresentaram duas fases principais. Nas noites de 29/30 e 30/31 de outubro, durante as duas fases principais da tempestade, foi observado que o CET em São José dos Campos alcançou valores mais altos que do dia 10 de outubro que foi magneticamente calmo, devido ao efeito de penetração instantânea ao equador magnético de campo elétrico dirigido para leste e intensificando a AIE. Comparada a um dia calmo (10 de outubro), a cintilação na amplitude do sinal de GPS devido à irregularidade ionosférica, representada pelo índice de cintilação S4, foi mais forte em Cachoeira Paulista (sob a AIE) durante a noite de 30/31 mas não para a noite 29/30 e em São Martinho da Serra, durante as noites 29/30 e 30/31. A cintilação para as noites 29/30 e 30/31 nestas duas estações tiveram maior duração do que para a noite de 10 de outubro, alcançando o setor das horas após meia noite. Durante a tempestade de 7-11 de novembro, o CET teve o comportamento de um dia calmo, exceto durante os dias 10 e 11 (até 09 UT), quando uma diminuição significativa de CET foi observada. A cintilação, comparada ao dia 19 de novembro que foi calmo, foi maior na estação equatorial de São Luís durante as noites de 7/8 e 8/9 e foi completamente inibida para as estações de São Luís e São José dos Campos durante as noites 9/10 e 10/11, provavelmente devido à ação da penetração ao equador de campo elétrico do dínamo perturbado dirigido para oeste.

Palavras-chave: GPS, cintilação ionosférica, tempestade magnética, CET (Conteúdo Eletrônico Total).

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INTRODUCTION

The ionospheric irregularities are generated after sunset over the magnetic equator due to plasma instabilities and the most important parameter for their development is the equatorial evening vertical plasma drift $(\mathbf{E} \times \mathbf{B}/B^2)$ (Fejer et al., 1999) known as prereversal enhancement in vertical drift, when the eastward electric field is intensified due to the action of the F-region dynamo. During magnetic storms strong eastward (westward) electric field from the magnetosphere (disturbance dynamo) can penetrate to equatorial region intensifying (weakening) the upward plasma drift and consequently triggering (inhibiting) the ionospheric irregularities. This subject has been studied by many authors (Basu et al., 2001a, b; de Paula et al., 2004) since ionospheric irregularities cause scintillation in the GPS signal amplitude and phase and can affect telecommunication systems, and magnetically quiet time scintillation pattern can be modified during storms. The storms also can affect drastically the CET (Lin et al., 2005). As there is a strong interplay between the magnetospheric, ionospheric and atmospheric processes, which are substantially modified during magnetic storms (Abdu, 1997; Abdu et al., 1991, 2003; Batista et al., 1991, 2006; Tsurutani et al., 2004) we present in the next sections a short description of their quiet and disturbed behavior.

During magnetic storms supersonic solar plasma emissions distort the magnetosphere (see Fig. 1), that is a cavity formed by the interaction of the solar wind with the Earth's magnetic field. The magnetosphere has a long tail, that extends in the opposite direction to the Sun (Davies, 1990). According to Gonzalez et al. (1994), a magnetic storm occurs when a long-lasting interplanetary convection electric field leads, through a substantial energization in the magnetosphere-ionosphere system, to an intensified ring current sufficiently strong to exceed some key threshold of the quantifying storm time Dst index. Energy from the solar wind is transferred to the ionosphere-thermosphere-magnetosphere system, intensifying convection electric fields in the magnetosphere and producing an enhancement of particles precipitation, and currents in the high latitude ionosphere. During magnetically disturbed periods the magnetospheric shielding layer is not effective to shield magnetospheric electric fields which therefore penetrate directly to low latitudes The structure and dynamics of the thermosphere and ionosphere is globally affected due to the increase of ionospheric conductivity, the Joule heating and the ion drag in the upper atmosphere of high latitudes and the disturbance dynamo gives origin to westward electric field that penetrates to equatorial region that could last up to 30 hours after the end of the storm main phase. The disturbed thermospheric circulation changes and the thermospheric meridional wind moves the plasma along magnetic field lines modifying the the neutral composition distribution and consequently the recombination rates of ionized species (Fedrizzi, 2003; Fuller-Rowell et al., 2002).

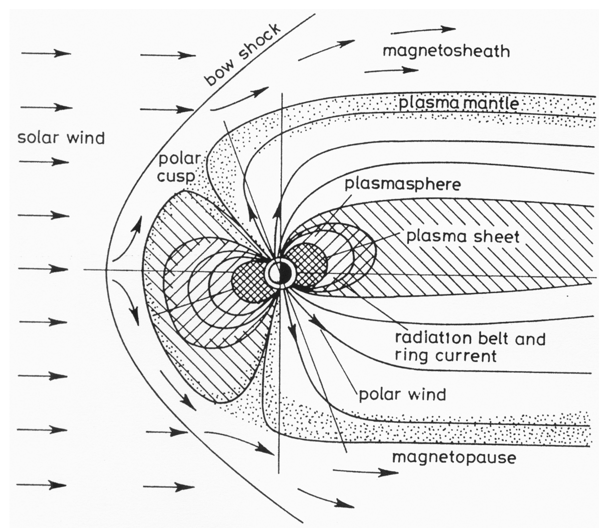

Figure 1 – Earth magnetic field. Source: Davies (1990).

The disturbed magnetospheric electric fields that penetrate to equatorial ionospheric region affect drastically the prereversal peak that is an intensification of the vertical plasma drift around 18-21 LT (21 LT corresponds to 24 UT for the Brazilian region under investigation in this work). The prereversal peak is explained through the action of uniform neutral wind in the F region (see Fig. 2). According to Farley et al. (1986) the electric field E_z generated by the F region dynamo $(-\mathbf{U} \times \mathbf{B})$ is mapped to the conjugated E-region along magnetic field lines as an electric field E_θ directed to the equator. This electric field generates a low latitude Hall current, $J_{\theta\phi}$, directed to west. A peculiar situation occurs at regions close to the day-night terminator. Due to the much larger dayside conductivity (as compared to the nightside), no current flows in the nocturnal E-region and consequently negative charge accumulates in the terminator and gives origin to an E_ϕ field and to a current $J_{\phi\phi}$ that tries to cancel $J_{\theta\phi}$ (shown in Fig. 2). E_ϕ is then mapped back to the F region and it causes, firstly, an upward $\mathbf{E} \times \mathbf{B}$ drift of the plasma to higher altitudes and soon after, a downward drift around 21 LT.

At low latitudes the ionosphere presents the Equatorial Ionization Anomaly (EIA) or Appleton Anomaly, that consists of an ionospheric region with high electronic density peaks, observed around 15 degrees north and south of the magnetic equator. This electronic density increase in low latitudes has its origin in

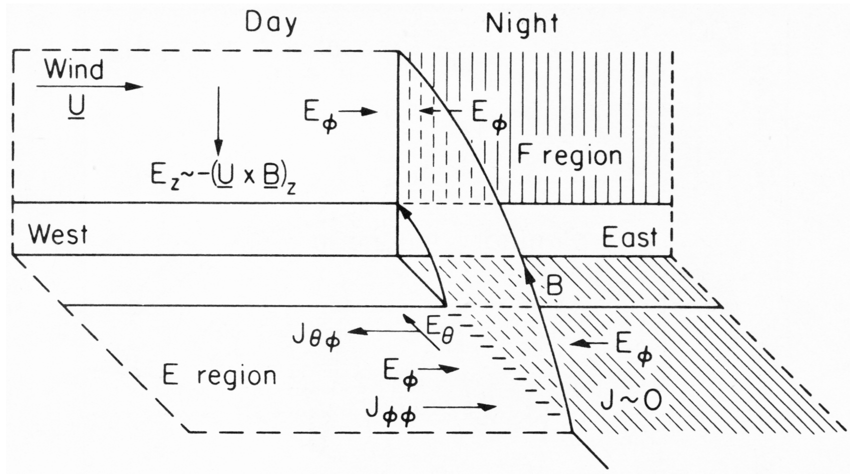

Figure 2 – Simple model to explain the prereversal peak caused by a uniform wind U. Source: Kelley (1989).

the upward vertical $\mathbf{E} \times \mathbf{B}$ plasma drift of the equatorial F layer. As previously shown, the zonal electric field that exists in the equatorial ionosphere is directed to the east during day, creating an upward $\mathbf{E} \times \mathbf{B}/B^2$ vertical drift velocity. Soon after the sunset, this eastward electric field is intensified (prereversal peak) by the F region dynamo and the plasma from F region is uplifted to high altitudes. Meanwhile, the plasma from low altitudes quickly decline due decreasing of the intensity of incident solar radiation (Kelley, 1989). After lifting to high altitudes in the equatorial region, the plasma starts a descent movement along magnetic field lines. This movement happens due to the action of gravity $(\mathbf{g})$ and pressure gradient (∇p) forces. This phenomenon (the plasma elevation and the subsequent descent along magnetic field lines to low latitudes) is known as the fountain effect (see the scheme in Fig. 3), giving origin to the Equatorial Ionization Anomaly.

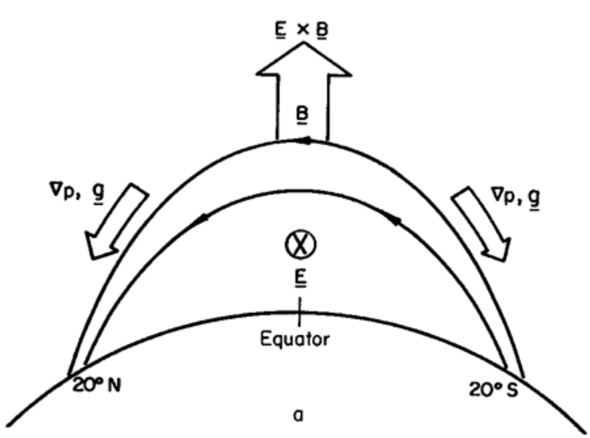

Figure 3 – Appleton Anomaly scheme.

The upward vertical plasma drift in the equator after sunset that gives origin to the prereversal peak, is the main factor responsible for the plasma irregularity generation (Fejer et al., 1999). The irregularities in the electronic density causes a GPS signal to scintillate and the corresponding amplitude pattern which is elongated in the north-south direction on the grounds drift from west to east during magnetically quiet period (Kintner et al., 2001). The ionospheric scintillation can be defined as fluctuations in the amplitude or phase of a radio wave. As the ionospheric scintillations are highly dependent of the upward vertical plasma drift in the equator driven by east-west electric fields, the penetration to equator of eastward (westward) electric field from magnetospheric (disturbance dynamo) origin during storms can trigger (inhibit) them. The scintillation amplitude is dependent also from the background ionization (TEC).

METHODOLOGY

In this work the magnetic indices Dst (Disturbance Storm Time), Kp (planetarische Kennziffer) and AE (Auroral Electrojet) were used to analyze the intensity of the storms. Other parameters like TEC and S_4 scintillation index were used to study the magnetically disturbed behavior of the plasma and of the ionospheric irregularities, respectively. TEC corresponds to the number of electrons contained in the column of unitary base that extends from Earth surface to a determined height in the atmosphere. This parameter is measured in TEC units (1 TECU = 1 $\times$ 10^{16} electrons/m^2). The S_4 index is the normalized standard deviation of the GPS signal intensity which is measured at one-minute resolution. We used the double frequency Turbo Rogue ICS-4000Z, Allen-Osborne Associates receivers to measure TEC and SCINTMON

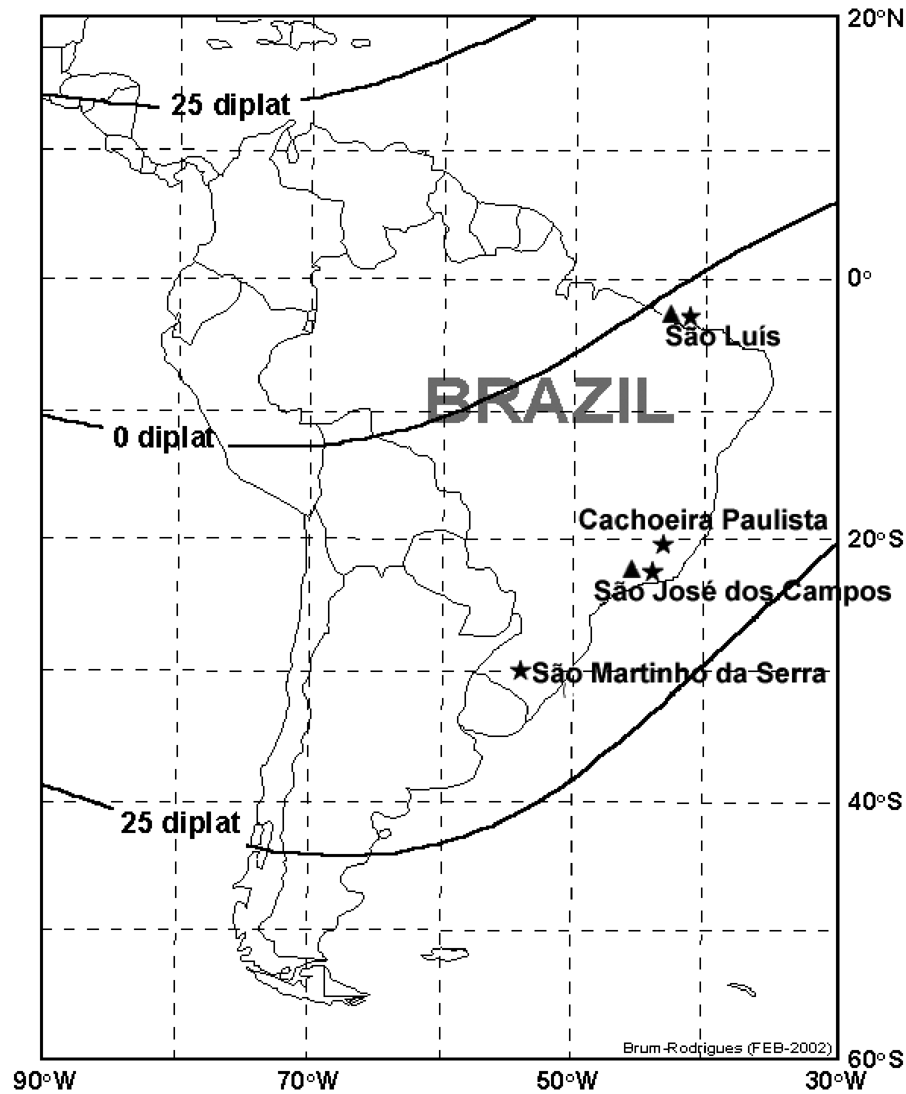

Figure 4 – Location of the GPS receivers: SCINTMON (★) and Allen-Osborne (▲).

receivers for scintillation monitoring. Turbo Rogue is an optimized receiver for ionospheric TEC measurements that is able to track up to 8 satellites simultaneously. The SCINTMON receiver was implemented through an ISA GPS Card (GEC Plessey GPS Builder-2^{TM}). It is able to sample simultaneously signals from up to 11 satellites. The data are only collected from satellites with elevation angle higher than 10 degrees. GPS Wide Band Power (WBP) of L1 (1.57542 GHz) that is transmitted by GPS satellites is sampled at 50 Hz rate. The SCINTMON receivers data analyzed were for São Luís, São José dos Campos, Cachoeira Paulista and São Martinho da Serra stations and TEC data (from Allen-Osborne receivers) were analyzed for the São Luís and São José dos Campos stations (see Fig. 4). The disturbed days parameters were compared to those for quiet days. Prior and post-storm periods were analyzed.

RESULTS AND DISCUSSIONS

The scintillation period in the Brazilian territory occurs in the months from September to March, from 21 to 03 UT (18 to 24 LT) and the scintillation amplitude and frequency of occurrence increases with the solar flux increase. Scintillation also presents a dependence with the season and with the latitude. Previous works (de Paula et al., 2003; Kintner et al., 2007) showed that the GPS scintillation amplitude is larger under regions with larger TEC, like under the EIA. There is also a complex dependence of the ionospheric irregularities with the magnetic activity, what is the main topic of this paper. Magnetic storms can inhibit the irregularities during their period of occurrence or can trigger irregularities at any month of the year, even during a period when irregularities are not expected (de Paula et al., 2004). This behavior during storm is very complex because it depends of the hour of the storm commencement, of the season, and if the storm occurred in the recovery phase of another storm. During a magnetic storm an eastward (westward) electric field of magnetospheric origin can penetrate to equator through direct penetration (disturbance dynamo) reinforcing (weakening) the normal eastward E layer during day and F2 layer from18-21 LT electric fields, triggering (inhibiting) irregularities. Eastward electric field penetration during magnetic storms also can trigger irregularities during the midnight-sunrise time sector.

For the October 28-31, 2003 storm, the first main phase occurred around 0100 UT on 30 of October when Dst reached –345 nT, the second one (strongest) occurred around 2300 UT on the same day and reached –401 nT (see Dst index in Fig. 5). The November 7-11, 2004 strong magnetic storm also presented two storm main phases. The first one reached –373 nT at 07 UT on the day 8 and the other –295 nT around 10 UT on day 10.

In Figure 5 are plotted the magnetic indices AE, Kp, and Dst and the S4 indices for the stations of São Martinho da Serra, Cachoeira Paulista (close to São José dos Campos) and São Luís and TEC for São Luís and São José dos Campos, during the storm period of October 28-31, 2003. The S4 indices represent the larger values between all available GPS satellites with elevation angles larger than 40°, for each one minute.

We observed in Figure 5 that TEC had different behavior compared to the reference quiet day of October 10, 2003. Over São José dos Campos, under the EIA, during the nights of October 29/30 and 30/31, TEC reached higher values than during the day of October 10, simultaneously with a TEC decrease at equatorial station of São Luís (see Fig. 5). This is an evidence of magnetospheric eastward electric field prompt penetration to low latitudes during this storm, intensifying the EIA, and moving plasma from equator to low latitudes.

During this storm and considering that only S4 larger than 0.2 represents GPS scintillation, it was observed (see Fig. 5) larger (except for Cachoeira Paulista in the 29/30 night before 02 UT) and longer lasting scintillations at Cachoeira Paulista and São Martinho da Serra on the nights 29/30 and 30/31 compared to the quiet night (Oct. 10/11). At São Luís, the equatorial station, the scintillation amplitude was smaller during the nights of 29/30 and 30/31. Normally at the Brazilian sector there is no scintillation after midnight. Magnetic storms can trigger post midnight scintillations.

The same magnetic and ionospheric parameters of Figure 5 were plotted in the Figure 6 for the November 7-11, 2004 storm. For this storm the main phase maximum (Dst reached –373 nT) of the first storm occurred around 07 UT in November 8, when the ionospheric ionization was still low, and TEC had a quiet day behavior for both stations and presented a substantial decrease for days 10 (all day) and 11 up to 09 UT. Compared to the quiet day November 19, the scintillation increased for the night 7/8 (S4 = 0.4) and less significantly for the next night 8/9 (S4 = 0.2) at São Luís, but it was completely inhibited for São Luís and São José dos Campos stations in the following two nights 9/10 and 10/11 (see Fig. 6) when TEC values were extremely low, even though these nights were under the second main phase effects.

CONCLUSIONS

The effects of two intense magnetic storms (October 2003 and November 2004) on TEC and ionospheric scintillations measured from GPS receivers over equatorial and low latitude stations, relative to quiet time days, were analyzed. It is shown that large variation of these two parameters were observed during the occurrence of such storms, what is following presented.

During the October 2003 disturbed period, the storm induced eastward magnetospheric electric field that penetrated to the magnetic equator on the 29/30 and 30/31 nights and intensified the vertical plasma drift, increasing TEC values over the low latitude station of São José dos Campos and decreasing over the equatorial station of São Luís, and creating favorable conditions for the irregularities to grow at the stations of Cachoeira Paulista (however no scintillation increase was observed for this station on the 29/30 night) and São Martinho da Serra that are located under the south EIA crest. On this storm, the scintillation occurred even after 03 UT for those 2 stations and at our longitude sector this behavior is observed only during storm time.

In the November period, the storm first main phase occurred from about 21 UT (day 7) to 6 UT (day 8), moderate scintillation (S4 = 0.40) was observed in the 7/8 night and weak scintillation (S4 = 0.20) in the 8/9 night, at São Luís and São José dos Campos. These scintillations were larger for São Luís and smaller for São José dos Campos than the quiet time day (Nov. 19) during the 7/8 and 8/9 nights. No scintillation was observed in the subsequent nights 9/10 and 10/11 under the effect of the second main phase for these 2 stations. This scintillation inhibition in the nights 9/10 and 10/11 was probably due to the

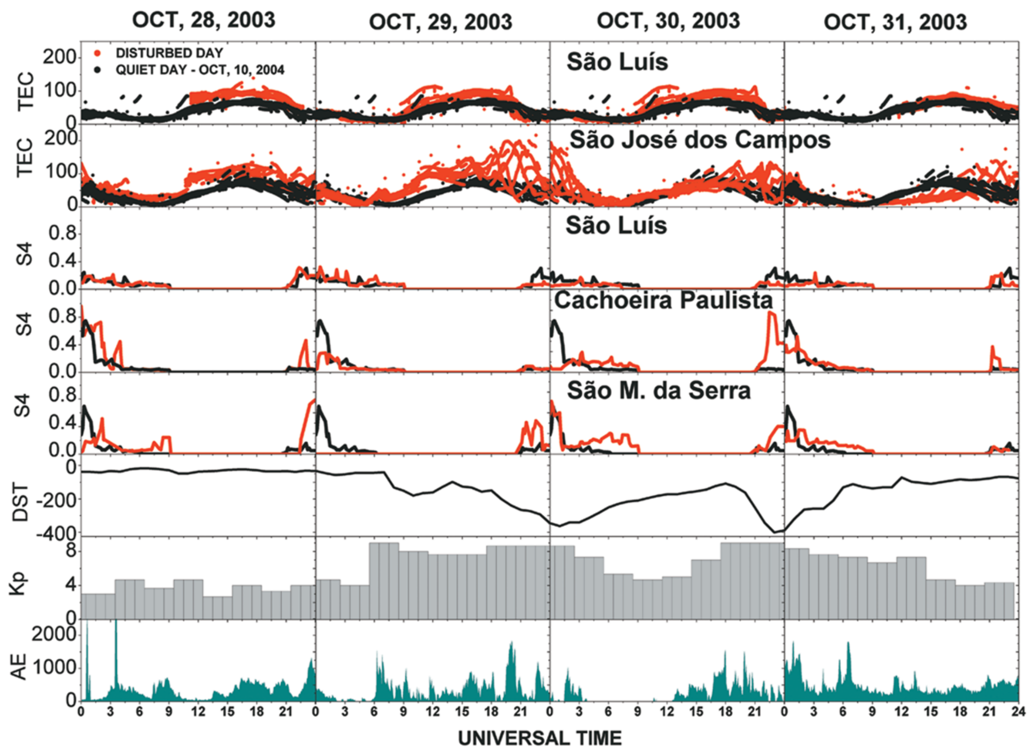

Figure 5 – Total Electron Content (TEC), scintillation index (S_4) and the magnetic indices Dst, Kp, and AE for the period of October 28-31, 2003.

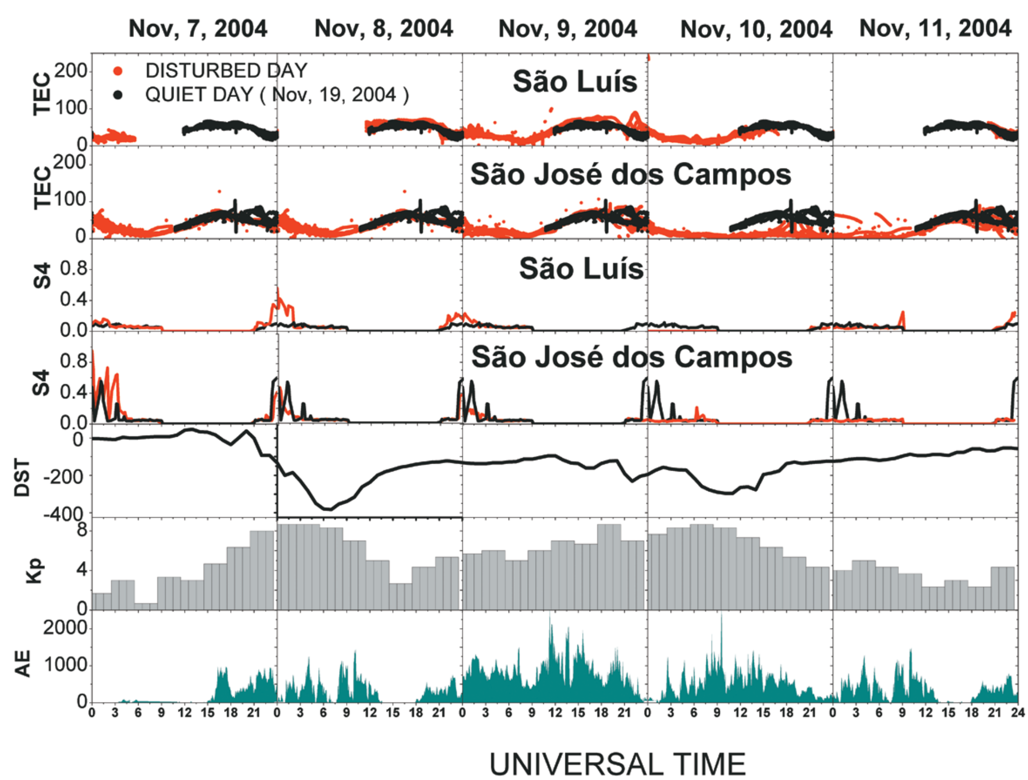

Figure 6 – Total Electron Content (TEC), scintillation index (S_4) and the magnetic indices Dst, Kp, and AE for the period November 7-11, 2004.

action of the westward magnetospheric electric field generated by the disturbance dynamo (Fejer & Scherliess, 1995; Scherliess & Fejer, 1997) that penetrated to the magnetic equator and inhibited the prereversal plasma drift after sunset. The TEC was completely washed out at São José dos Campos, during November 10 and 11 up to 9 UT what contributed substantially for the scintillation inhibition.

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