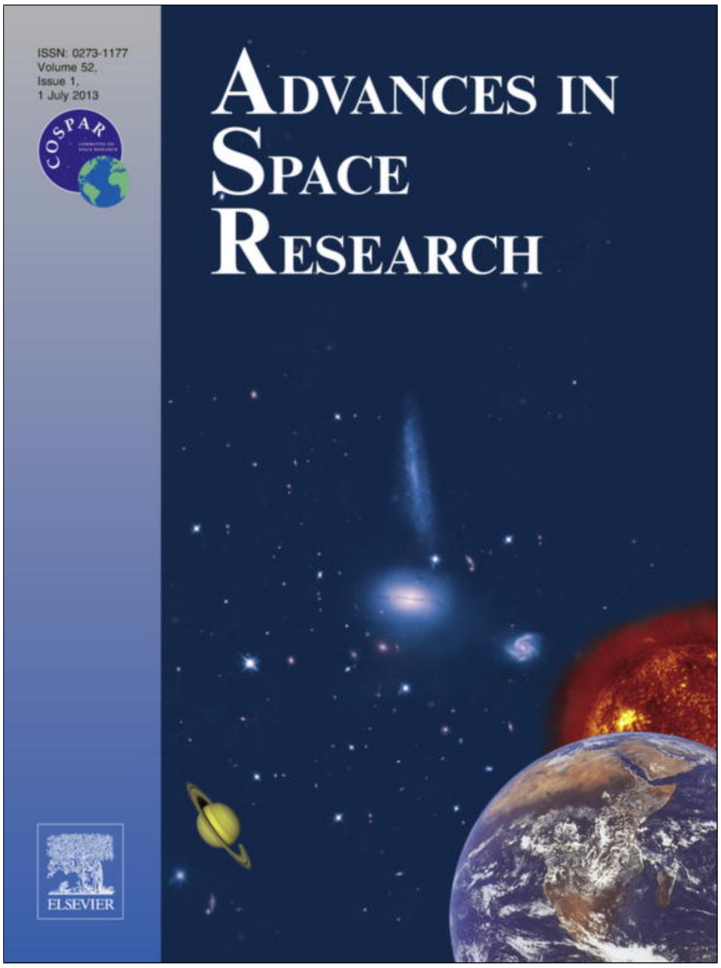
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Response of equatorial, low- and mid-latitude F-region in the American sector during the intense geomagnetic storm on 24–25 October 2011

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Abstract

In this paper, we present and discuss the response of the ionospheric F-region in the American sector during the intense geomagnetic storm which occurred on 24–25 October 2011. In this investigation ionospheric sounding data obtained of 23, 24, 25, and 26 October 2011 at Puerto Rico (United States), Jicamarca (Peru), Palmas, São José dos Campos (Brazil), and Port Stanley, are presented. Also, the GPS observations obtained at 12 stations in the equatorial, low-, mid- and high-mid-latitude regions in the American sector are presented. During the fast decrease of Dst (about ∼54 nT/h between 23:00 and 01:00 UT) on the night of 24–25 October (main phase), there is a prompt penetration of electric field of magnetospheric origin resulting an unusual uplifting of the F region at equatorial stations. On the night of 24–25 October 2011 (recovery phase) equatorial, low- and mid-latitude stations show h′F variations much larger than the average variations possibly associated with traveling ionospheric disturbances (TIDs) caused by Joule heating at high latitudes. The foF2 variations at mid-latitude stations and the GPS-VTEC observations at mid- and low-latitude stations show a positive ionospheric storm on the night of 24–25 October, possibly due to changes in the large-scale wind circulation. The foF2 observations at mid-latitude station and the GPS-VTEC observations at mid- and high-mid-latitude stations show a negative ionospheric storm on the night of 24–25 October, probably associated with an increase in the density of molecular nitrogen. During the daytime on 25 October, the variations in foF2 at mid-latitude stations show large negative ionospheric storm, possibly due to changes in the O/N2 ratio. On the night of 24–25, ionospheric plasma bubbles (equatorial irregularities that extended to the low- and mid-latitude regions) are observed at equatorial, low- and mid-latitude stations. Also, on the night of 25–26, ionospheric plasma bubbles are observed at equatorial and low-latitude regions.

Keywords: Space weather; Geomagnetic storm; Ionosphere; Ionospheric irregularities

1. Introduction

During geomagnetic storms the upper atmosphere can be drastically changed due to the imposition of adverse space weather conditions (Buonsanto, 1999). As described by Dungey (1961), geomagnetic storms are related to the penetration of solar wind energy in the Earth's magnetosphere by reconnection process. The reconnection process occurs when there is an interconnection between the lines of the interplanetary magnetic field (southward) and the geomagnetic field lines (northward) on the day side, carrying the energy of the solar wind on the polar cap toward the tail of the magnetosphere where a new reconnection occurs, and solar wind energy is injected into the magnetosphere (Dungey, 1961; Tsurutani et al., 1997).

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A large amount of energy is dissipated at high latitudes during the geomagnetic storms, and can generate traveling atmospheric disturbances (TADs) that produce ionospheric disturbances (Lee et al., 2002, 2004; Sahai et al., 2009a; de Jesus et al., 2012). The TADs can propagate to regions of mid- and low-latitudes. It should be mentioned that when the TADs propagate through the ionosphere are called traveling ionospheric disturbances (TIDs). As discussed by Abdu (1997), major changes in the equatorial ionosphere–thermosphere system during magnetospheric disturbances are produced due to: (1) prompt equatorward penetration of the magnetospheric electric fields, (2) disturbance dynamo driven by enhanced global thermospheric circulation (resulting from energy injected at high latitudes), and (3) disturbance winds (meridional and zonal) modifying the equatorial thermospheric dynamics. When the electron density in the F region shows an increase during geomagnetic storm relative to geomagnetically quiet period, results in ionospheric disturbances called positive ionospheric storm or positive phase of ionospheric storm (Sahai et al., 2007a; de Jesus et al., 2010; de Abreu et al., 2010a). As described by Ngwira et al. (2012), a long-duration positive ionospheric storm (over 6 h of enhancement) is often associated the equatorward neutral wind of large-scale thermospheric circulation. Also, during geomagnetic storms can occur decrease of the ionospheric electron density as compared with quiet periods, which results in ionospheric disturbances called negative ionospheric storm or negative phase of ionospheric storm (Sahai et al., 2005, 2009c; de Abreu et al., 2011). According to Prolss, (1980), negative ionospheric storms are related to the change in composition of the neutral gas which increases the ratio of N_2/O at high- and mid-latitude during geomagnetic storms.

During the past several excellent reviews on ionospheric storms covering low-, mid- and high-latitude regions have been provided by Schunk and Sojka (1996), Abdu (1997) and Buonosanto (1999). However, individual studies of magnetosphere–ionosphere interactions at equatorial, low-, mid-, and high-latitude regions during geomagnetic storms use both observational (Pirog et al., 2007; Sahai et al., 2009b; de Jesus et al., 2010; Balan et al., 2010) and modeling (Balan et al., 2009; Balan et al., 2010; Lu et al., 2008; Lin et al., 2009a; Lin et al., 2009b; Klimenko et al., 2011a,b; Klimenko and Klimenko, 2012) results continue to be published. Klimenko and Klimenko (2012) have reported that, the prompt penetration electric field occurs in the early stages of geomagnetic storm with an increase of geomagnetic activity and results in equatorial ionization anomaly intensification. Balan et al. (2009), Balan et al. (2010) and Klimenko et al. (2011a,b) have shown that the additional eastward electric field (during geomagnetic storms) such as prompt penetration electric field on its own is unlikely to cause positive ionospheric storms. According to Balan et al. (2009), Balan et al. (2010) an equatorward neutral wind is necessary to produce positive ionospheric storms. As mentioned by Lu et al. (2008) and Klimenko et al. (2011a,b), positive ionospheric storms are caused by the meridional component of thermosphere wind velocity. As discussed by Lin et al. (2009b), the storm time meridional neutral wind is important to produce an additional ionospheric layer underneath the equatorial ionization anomaly crest during an intense geomagnetic storm. As described by Lin et al. (2009a), theoretical model simulations for an intense geomagnetic storm have shown the generation of a low-latitude electron density arch aligned along the geomagnetic field generated by an unusual uplifting of the F_2-region that is driven by the penetration electric field.

Effects observed in the ionospheric F-region during intense geomagnetic storms remain an important issue related to space weather studies. In this investigation, we present and discuss the response of the ionospheric F-region in the equatorial, low-, mid- and high-mid-latitude regions in the American sector during the intense geomagnetic storm which occurred on 24–25 October 2011, using ionospheric sounding data (5 ionosonde stations) and Global Positioning System (GPS) (12 GPS stations) observations. The principal objectives of this paper have been to study the generation or inhibition of equatorial ionospheric irregularities (ESF) (Martinis et al., 2005), and ionospheric dynamics in the American sector during the geomagnetic storm on 24–25 October 2011.

2. Observations

In this investigation we present ionospheric sounding data F-region critical frequency (foF2) and minimum F-region virtual height (h′F) obtained at the five stations located in the American sector, Puerto Rico (hereafter referred as PTR; 18.5°N, 67.2°W, dip latitude 26.5°N; every 30 min), United States; Jicamarca (hereafter referred as JIC; 12.0°S, 76.8°W, dip latitude 0.13°S; every 30 min), Peru; Palmas (hereafter referred as PAL; 10.2°S, 48.2°W; dip latitude 7.2°S; every 15 min), São José dos Campos (hereafter referred as SJC; 23.2°S, 45.9°W; dip latitude 19.1°S; every 15 min), Brazil; and Port Stanley (hereafter referred as PST; 51.6°S, 57.9°W, dip latitude 31.5°S; every 30 min), on 23, 24, 25 and 26 October 2011. The ionospheric parameters (h′F and foF2) at PAL (a near equatorial station) and SJC (low-latitude station located under the southern crest of equatorial ionization anomaly) were obtained from the ionograms (manually scaled data), using the software UDIDA (UNIVAP Digital Ionosonde Data Analysis) (Sahai et al., 2007b; de Abreu et al., 2010b; de Jesus et al., 2011). The PTR (mid-latitude station) ionospheric parameters (auto-scaled data) were obtained from the Space Physics Interactive Data Resource (SPIDR Home) by the site http://spidr.ngdc.noaa.gov/spidr/. The JIC (equatorial station) and PST (mid-latitude station) ionospheric parameters (manually scaled data) were obtained from the Digital Ionogram DataBase (DIDBase) by the site http://ulcar.uml.edu/DIDBase/.

The complementary Global Positioning System (GPS) observations from 12 receiving stations in American (see

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Table 1
Details of the Global Positioning System and digital ionosonde sites used in the present investigation. *GPS, global positioning system; DI, digital ionosonde.

Location	Symbol used (Network)	Observations*	Geog. lat	Geog. long.	Dip. lat.	Local time (LT)
Puerto Rico, United States	PTR	DI	18.5°N	67.2°W	26.5°N	LT = UT − 4 h
Virgin Islands, United States	CRO1 (IGS)	GPS	17.6°N	64.6°W	24.9°N	LT = UT − 4 h
Caraca, Venezuela	CRCS (SIRGAS)	GPS	10.5°N	66.9°W	19.3°N	LT = UT − 4 h
Iquitos, Peru	IQUI (SIRGAS)	GPS	03.8°S	73.3°W	07.6°S	LT = UT − 5 h
Belém, Brazil	BELE (RBMC)	GPS	01.4°S	48.4°W	0.73°S	LT = UT − 3 h
Jicamarca, Peru	JIC	DI	12.0°S	76.8°W	0.13°S	LT = UT − 5 h
Palmas, Brazil	PAL (RBMC)	GPS/DI	10.2°S	48.2°W	07.2°S	LT = UT − 3 h
São José dos Campos, Brazil	SJC (UNIVAP)	GPS/DI	23.2°S	45.9°W	19.1°S	LT = UT − 3 h
Porto Alegre, Brazil	POAL (RBMC)	GPS	30.1°S	51.1°W	21.4°S	LT = UT − 3 h
Uruguay	UYRO (SIRGAS)	GPS	34.0°S	53.5°W	23.0°S	LT = UT − 4 h
Bahia Blanca, Argentina	VBCA (SIRGAS)	GPS	38.7°S	62.3°W	23.5°S	LT = UT − 4 h
Port Stanley	PST	DI	51.6°S	57.9°W	31.5°S	LT = UT − 4 h
Ushuaia, Argentina	AUTF (SIRGAS)	GPS	54.8°S	68.3°W	32.8°S	LT = UT − 5 h
Antartic	PALM (IGS)	GPS	64.8°S	64.1°W	39.4°S	LT = UT − 4 h
Antartic	VESL (IGS)	GPS	71.7°S	02.8°W	44.5°S	LT = UT − 0 h

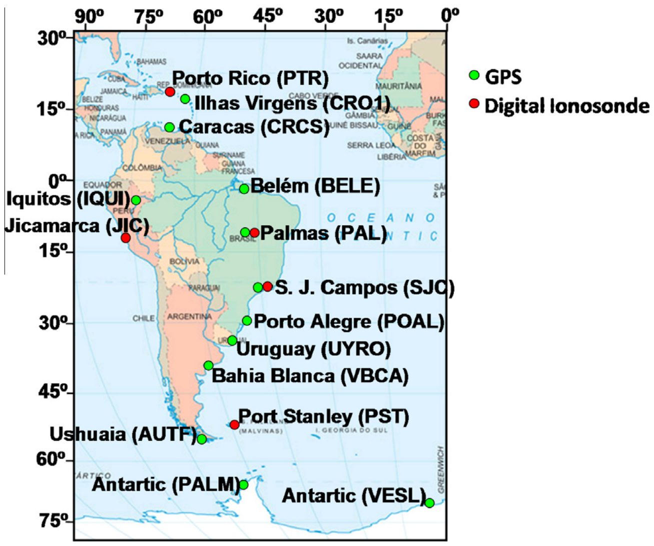

Fig. 1. A map of America showing the locations of the digital ionosonde and GPS stations, used in the present investigations.

Table 1 and Fig. 1), have been used to calculate the vertical total electron content (VTEC) and phase fluctuation (rate of change of TEC; TEC/min) (Aarons et al., 1996, 1997) for the period 23–26 October 2011. The VTEC is calculated in units of TEC (1 TECU = 10^{16} electrons/m^2) (Wanninger & July, 1993; Yizengaw et al., 2009; Sahai et al., 2011). Fig. 1 and Table 1 show details of the ionospheric sounding and GPS stations used in the present investigation. The dip latitudes presented for the ionosonde and GPS stations were calculated for the year 2011 using International Geomagnetic Reference Field-11 (IGRF-11) (Finlay et al., 2010) at an altitude of 300 km. The Belém (BELE), Palmas (PAL), and Porto Alegre (POAL) stations belong to the "Rede Brasileira de Monitoramento Continuo" (RBMC), operated by the "Instituto Brasileiro de Geografia e Estatística" (IBGE). The São José dos Campos (SJC) station belongs to the UNIVAP network. The Caracas (CRCS), Iquitos (IQUI), Uruguay (UYRO), Bahia Blanca (VBCA), and Ushuaia (AUTF) stations belong to the "Sistema de Referência Geocêntrico para as Américas" (SIRGAS). The Virgin Islands (CRO1), Antartic (PALM and VESL) stations belong to the International GNSS Service (IGS) for Geodynamics.

In order to calculate the median values of the ionospheric parameters (h′F, and foF2) and VTEC we have used measurements obtained on quiet days 22, 23, 28 and 29 October 2011 (with geomagnetic index Kp < 3).

Fig. 2 shows the solar wind speed (Vp), IMF (total magnetic field B and IMF component Bz) and variations of the geomagnetic indeces Dst, Kp, AE during the period 23–26 October 2011. Vertical dashed line indicates sudden storm commencement (SSC) at 18:31 UT on 24 October 2011. The horizontal orange bars indicate no data. It should be mentioned that (for the solar wind ion density) we do not have data (from the ACE satellite) available during the period 23–26 October 2011. The solar wind speed (Vp) and IMF (B and Bz component) are shifted in time with respect to ground-based parameters (Dst, Kp and AE). Also, it shall be mentioned that there is a delay of about 40 min between solar wind impacting the Earth's magnetosphere and effects observed in the geomagnetic indices. A sudden increase in solar wind speed and IMF total field occurred at 18:07 UT on 24 October 2011. The solar wind speed jumps from ∼494 km/s to ∼523 km/s. The total magnetic field magnitude shows an abrupt increase from ∼15 nT to ∼19 nT. The IMF Bz turned southward at 20:40 UT on 24 October 2011. The minimum value of Bz = ∼20 nT was reached at 00:03 UT on 25 October 2011. The SSC started at 18:31 UT on 24 October 2011. The Dst index sharply came down from 22:00 UT (30 nT) (on 24 October) to a minimum value of −135 nT, which was reached by 02:00 UT (on 25 October). After the SSC, the Kp index reached 7+ on the early morning of 25 October. Nearly at the time of the SSC, AE index shows an abrupt increase to about 1200 nT and reaches a maximum value of about

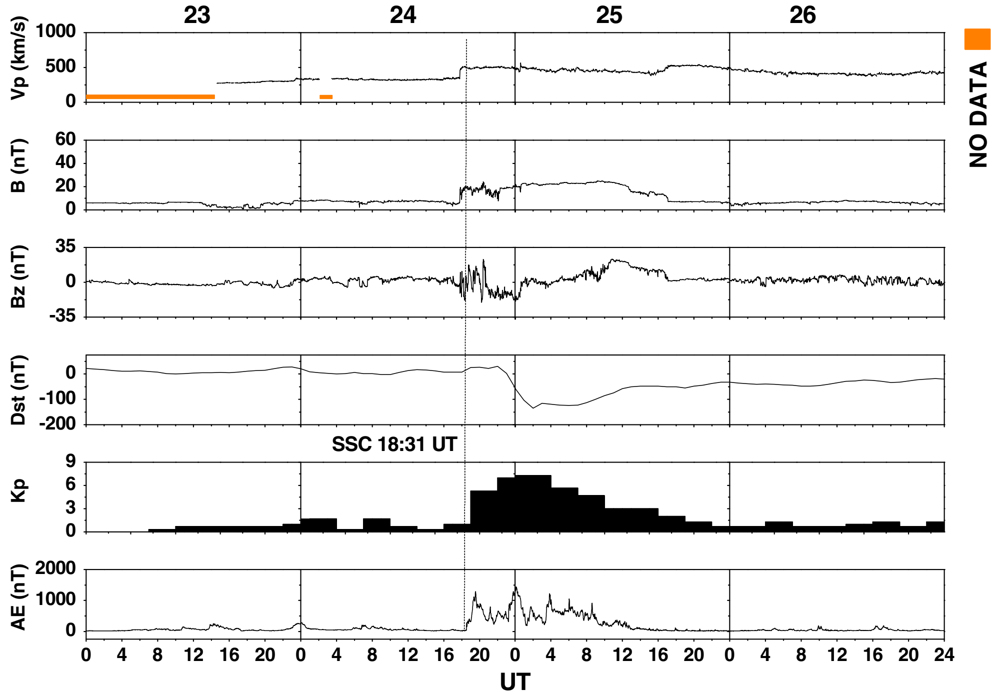

Fig. 2. UT variations of the solar wind proton bulk velocity Vp, total interplanetary magnetic field (IMF) *B*, and *z* component of IMF Bz in GSM coordinates, obtained from the ACE satellite during the period 23–26 October 2011. Also, the Dst, Kp and AE geomagnetic indices during the period 23–26 October 2011 are presented. The black vertical dashed line indicates the time of SSC.

1500 nT at 00:00 UT on 25 October 2011. The increased AE activity lasts until at about 14:00 UT of October 25.

3. Results and discussion

Fig. 3 shows the variations of the ionospheric parameter, h′F (red lines), observed at PTR, JIC, PAL, SJC and PST, covering the days on 23, 24, 25 and 26 October 2011. Also, Fig. 3 shows the times when the presence of sporadic-E (the horizontal blue bars), and spread-F (the horizontal black bars) was observed from the respective ionograms. The horizontal orange bars indicate no data. It also shows the average of the observations on quiet days 22, 23, 28 and 29 October 2011 as green bands with ± 1 standard deviation. The hatched portions indicate local nighttime periods (18:00–06:00 LT). The black vertical dashed line indicates the time of SSC. At the top of Fig. 3 is shown the Dst index variations during days 23–26 October 2011. The enhancements in h′F (and the occurrence of spread-F) (Fig. 3) observed on 23–26 October 2011 are discussed later with phase fluctuations (Fig. 4) observations.

Fig. 3 shows strong standard deviations in h′F in quiet conditions, especially in the SJC, probably associated with the presence of strong spread-F that can cause changes in h′F. Also, Fig. 3 shows that, in general, on 23 and 24 October 2011 (geomagnetically quiet) (before SSC), the red lines follow the average patterns at all the five stations (PTR, JIC, PAL, SJC and PST). It should be mentioned that, the differences between h′F (see Fig. 3) on the night of 22–23/10/2011 and median values with standard deviations at PAL and SJC stations are probably related with the day-to-day variability.

Fig. 4 shows the phase fluctuations (rate of change of TEC, TECU/min) of GPS signals from 23 to 26 October 2011 at CRO1, CRCS, IQUI, BELE, PAL, SJC, POAL, UYRO, VBCA, AUTF, PALM and VESL.

Figs. 3 and 4 indicate that on the night of 22–23 and 23–24 October 2011 (before SSC) during the pre-reversal period resulted in the generation of equatorial ionospheric irregularities and plasma bubbles (CRCS, IQUI, JIC, BELE, PAL, SJC and POAL on the night of 22–23), and on the night of 23–24 at BELE, PAL, SJC and POAL, in the American sector. It is observed that no spread-F or plasma bubbles are generated in the western part of American sector on the night of 23–24, possibly associated with the day-to-day variability. It is normally accepted that a rapid upward drift of the ionospheric F region (in the postsunset period), under the action of the pre-reversal enhancement in zonal electric field, is the single most important condition for plasma bubbles (equatorial ionospheric irregularities) to occur (Martinis et al., 2005; Abdu, 2012). The rapid upward motion of the ionospheric F layer creates favorable conditions for generation of equatorial ionospheric irregularities, via gravitationally driven Rayleigh–Taylor instability mechanism (Martinis et al., 2005).

After the SSC (during the storm main phase) there is an unusual uplifting of the F region at JIC (equatorial station) and PAL (a near equatorial station) (Fig. 3), possibly due to prompt penetration of the magnetospheric electric field

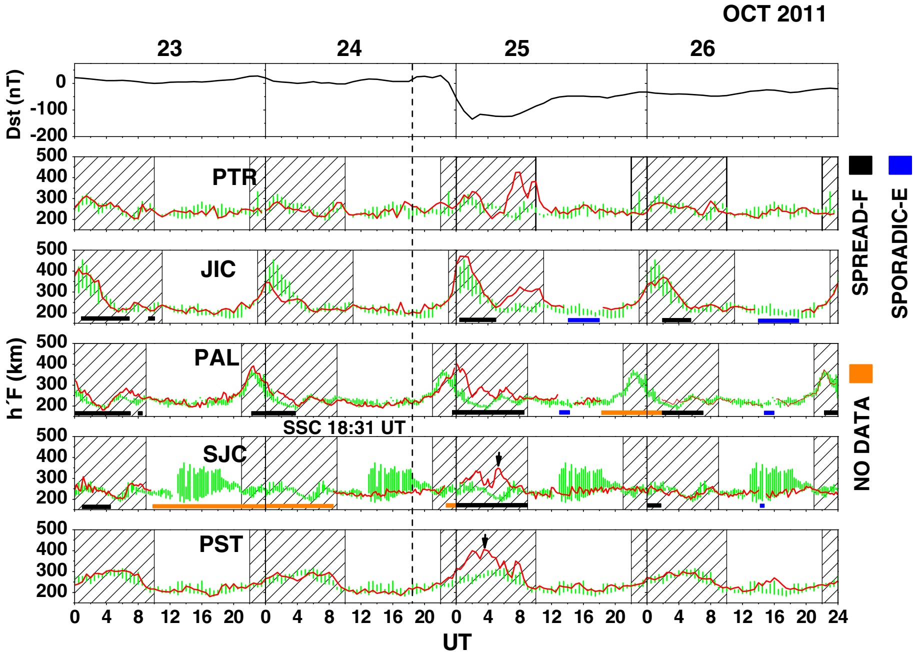

Fig. 3. UT variations of the ionospheric parameter h′F (red lines) observed at PTR, JIC, PAL, SJC and PST during the period 23–26 October 2011. It also shows the average of the observations on quiet days 22, 23, 28 and 29 October 2011 as green bands with ±1 standard deviation. The horizontal black bars indicate periods when spread-F occurred. The horizontal orange bars indicate no data. Also, the horizontal blue bars indicate sporadic-E. The black vertical dashed line indicates the time of SSC. The hatched portions indicate local nighttime periods (18:00–06:00 LT). Also, the Dst index during the period 23–26 October 2011 are presented. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

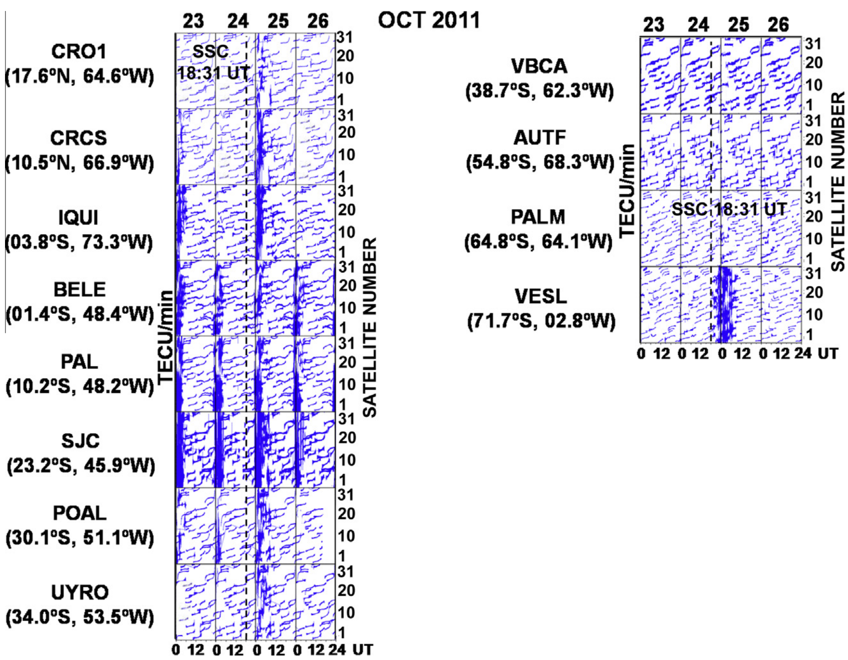

Fig. 4. TEC fluctuations (phase) from GPS signals obtained from different satellites at 12 receiving stations (CRO1, CRCS, IQUI, BELE, PAL, SJC, POAL, UYRO, VBCA, AUTF, PALM and VESL) during the period 23–26 October 2011.

during the fast decrease (about ~54 nT/h between 23:00 and 01:00 UT, on the night of 24–25) of the Dst index (Fig. 2).

On the night of 24–25 October 2011 (Fig. 3), PTR (mid-latitude station) (between ~07:00 and 12:00 UT), JIC (equatorial station) (between ~06:00 and 12:00 UT), PAL (a near equatorial station) (between ~01:00 and 07:30 UT), SJC (low-latitude station) (between ~00:00 and 07:00 UT) and PST (mid-latitude station) (between ~00:00 and 08:30 UT) show h′F variations much larger than the average variations (related to traveling ionospheric disturbances (TIDs)). Joule heating at high latitudes (as evidenced by the large enhancements in the auroral electrojet (AE) index starting at about 19:00 UT on 24 October and continuing for several hours (Fig. 2)) can produce TIDs. Becker-Guedes et al. (2004) have reported (on the night of 17–18 September 2000, during the intense geomagnetic storm that occurred on 17–18 September 2000) strong oscillations of the F-region base height at SJC (low-latitude station) related with traveling atmospheric disturbances (TADs) generated by Joule heating at high-latitude. It should be mentioned that TADs manifest themselves in the ionosphere as TIDs. In the present investigations, Fig. 3 also shows that on the night of 24–25 October 2011, PST (mid-latitude station), SJC (low-latitude station) and PAL (a near equatorial station) have oscillations in h′F propagating from PST (mid-latitude station) to PAL (a near equatorial station), possibly associated with TIDs caused by Joule heating at high latitudes. The vertical arrows in Fig. 3 on the night of 24–25 October indicate the possible passage of TID from PST (mid-latitude station) (at ∼03:30 UT) to SJC (low-latitude station) (at ∼05:30 UT) in about 2 h. Considering that the distance between PST and SJC is about 3888 km, this gives a velocity of propagation of about 540 m/s (1944 km/h) for the TID. The present results on the night of 24–25 October 2011 (see Fig. 3) confirm the observations during another intense geomagnetic storm studied by Becker-Guedes et al. (2004).

Several investigators (e.g., Martinis et al., 2005; Sahai et al., 2005; de Jesus et al., 2010; de Abreu et al., 2010a) have reported that, geomagnetic storms may cause or inhibit the formation of equatorial ionospheric irregularities. de Jesus et al. (2010) have reported an extensive latitudinal coverage of equatorial ionospheric irregularities (in the South American Sector) during an intense geomagnetic storm that occurred on 14 December 2006. In the present investigations, on the night of 24–25 October (geomagnetically disturbed), Fig. 3 shows equatorial spread-F at JIC (equatorial station) (between ∼00:30 and 05:00 UT), PAL (a near equatorial station) (between ∼23:00 and 08:30 UT) and SJC (low-latitude station) (between ∼00:00 and 09:00 UT). In addition, Fig. 3 shows that on the night of 24–25 October 2011, equatorial spread-F is observed first at PAL (a near equatorial station) and then at SJC (low-latitude station). The spread-F observed at JIC, PAL and SJC, on the night of 24–25 October 2011, are probably associated with uplift of the F-region due to prompt penetration of the magnetospheric electric field and TIDs (mentioned earlier), and creating favorable condition for spread-F generation at low-latitude and equatorial region. Fig. 4 shows that phase fluctuations were observed close to UT midnights on 24–25 October at equatorial (IQUI and BELE), near equatorial (PAL), low- (CRCS, SJC and POAL) and mid- (CRO1 and UYRO) latitude regions over the American sector in both Northern and Southern American Hemispheres, indicating that plasma bubbles extended to the low- and mid-latitude regions. In the present investigations, our results confirm the observations during another intense geomagnetic storm researched by de Jesus et al. (2010).

Also (on the night of 24–25 October 2011), see phase fluctuations at VESL (high-mid-latitude station) (Fig. 4). It should be mentioned that VESL (71.1°S, 02.8°W; high-mid-latitude station) is located further east than the other stations (CRO1, CRCS, IQUI, BELE, PAL, SJC, POAL, UYRO, VBCA, AUTF and PALM). Aarons and Lin (1999) have investigated the development of high-latitude phase fluctuations during the geomagnetic storms of 10 January, 10–11 April, and 15 May, 1997. Aarons and Lin (1999) have reported that the development of irregularities (phase fluctuations observed at high-latitude stations) is controlled by either magnetic local time or universal time.

Fig. 3 shows presence of sporadic-E at JIC (between ∼14:00 and 18:00 UT) and PAL (between ∼13:00 and 14:00 UT) on October 25, 2011 (daytime). It should be mentioned that the ionospheric sounding observations from JIC (between ∼14:00 and 19:00 UT), PAL (between ∼14:30 and 16:00 UT) and SJC (between ∼14:00 and 15:00 UT) on 26 October (Fig. 3), also show the presence of sporadic-E on this day.

Another importance feature (Fig. 3) is the presence of spread-F on the night of 25–26 October (post-midnight) (during the recovery phase) at JIC (equatorial station) (between ∼02:00 and 05:30 UT), PAL (a near equatorial station) (between ∼02:00 and 07:00 UT) and SJC (low-latitude station) (between ∼00:00 and 02:00 UT). It should be mentioned that at PAL (a near equatorial station) we do not have data between ∼21:00 and 02:00 UT on the night of 25–26 October 2011. Fig. 4 shows that phase fluctuations (rate of change of TEC) were observed close to UT midnights on 25–26 October 2011 (recovery phase) at BELE (equatorial station), PAL (a near equatorial station) and SJC (low-latitude station), indicating that plasma bubbles extended to the low-latitude region (in the Southern American Hemisphere). The GPS data (phase fluctuation) presented here corroborate the ionospheric sounding observations (on the night of 25–26 October 2011) presented in Fig. 3. As mentioned by Sahai et al. (2005), the onset of the equatorial ionospheric irregularities is generally related with the rapid upward motion of the ionospheric F region that normally occurs after sunset, near the magnetic equator.

On the night of 26–27 October (geomagnetically quiet; after geomagnetic storm), the present spread-F observations at PAL (a near equatorial station) (between ∼22:00 and 24:00 UT) (Fig. 3), and phase fluctuations (Fig. 4) at BELE (equatorial station) and PAL (a near equatorial station) (close to UT midnight) is probably related with bottom side spread-F (Whalen, 2002). According to Whalen (2002), bottomside spread-F is an event that occurs frequently in regions near the magnetic equator and rarely extends to low-latitudes. It should be mentioned that BELE and PAL are stations located in the Brazilian sector.

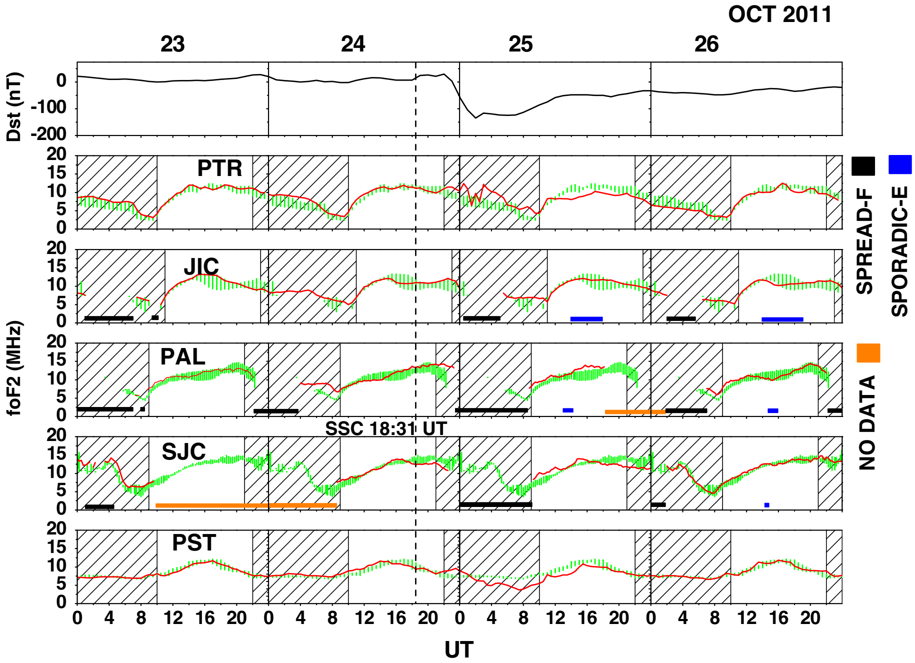

Fig. 5. UT variations of the ionospheric parameter foF2 (red lines) observed at PTR, JIC, PAL, SJC and PST during the period 23–26 October 2011. It also shows the average of the observations on quiet days 22, 23, 28 and 29 October 2011 as green bands with ±1 standard deviation. The black vertical dashed line indicates the time of SSC. The horizontal orange bars indicate no data. The horizontal black bars indicate periods when spread-F occurred. Also, the horizontal blue bars indicate sporadic-E. The hatched portions indicate local nighttime periods (18:00–06:00 LT). Also, the Dst index during the period 23–26 October 2011 are presented. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Sahai, Fagundes, and Bittencourt (2000) have reported that the seasonal occurrence of the equatorial ionospheric irregularities (in the Brazilian sector) is maximum between October and March.

Fig. 5 shows the universal time variations of the ionospheric parameter, F-region critical frequency (foF2, red lines), observed at PTR, JIC, PAL, SJC and PST, for the period studied (23–26 October 2011). The average daily variations (obtained from observations on quiet days 22, 23, 28 and 29 October 2011) of foF2 are shown in Fig. 5, as green bands and its width corresponding to ±1 standard deviation. Also, Fig. 5 shows the time variations of the Dst index for the period studied (23–26 October 2011). The hatched portions indicate local nighttime periods. The horizontal blue bars indicate the periods when sporadic-E occurred. The black vertical dashed line on 24 October 2011 (at 18:31 UT) indicates the time of the SSC. The horizontal orange bars indicate no data. The horizontal black bars indicate periods when spread-F occurred. The enhancements in foF2 (Fig. 5) observed on 23, 24, 25 and 26 October 2011 are discussed later with VTEC (Fig. 6) observations.

Fig. 6 presents the average VTEC variations from GPS observations in UT at 12 receiving stations (see Fig. 1) during the period from 23 to 26 October 2011 (red lines). It also shows the average of the observations on quiet days 22, 23, 28 and 29 October 2011 as green bands with ±1 standard deviation. The hatched portions indicate local nighttime periods (18:00–06:00 LT). On October 24, 2011, the black vertical dashed line indicates the time of the SSC.

In Fig. 5 the foF2 variations at PTR (mid-latitude station located in the Northern Hemisphere) and PST (mid-latitude station located in the Southern Hemisphere) show a positive ionospheric storm between ~22:00 and 01:00 UT (on the night of 24–25 October) (during the storm main phase). A perusal of VTEC data obtained at different stations in Fig. 6 (during the storm main phase) indicates that positive ionospheric storm is observed during the daytime (more specifically at the end of the daytime) on 24 October 2011 and on the night of 24–25 October at AUTF (mid-latitude station) (between ~21:00 and 01:45 UT) and PALM (high-mid-latitude station) (between ~21:00 and 23:00 UT). In addition, on the night of 24–25 October (during the end of main phase and first day of the recovery phase) positive ionospheric storm is observed (Fig. 6) at POAL (low-latitude station) (between ~00:00 and 05:00 UT), UYRO (mid-latitude station) (between ~00:00 and 05:00 UT) and VBCA (mid-latitude station) (between ~00:00 and 06:00 UT). These positive ionospheric storms observed at POAL, UYRO, VBCA, PTR, PST, AUTF and PALM (mentioned earlier) are possibly associated with an equatorward neutral wind (Balan et al., 2009; Balan et al., 2010).

Fig. 5 shows that PTR (mid-latitude station located in the Northern Hemisphere) has pronounced electron density enhancements (positive ionospheric storm) on the night of 24–25 October 2011 (during nearly 03:00–06:00 UT and 08:00–10:00 UT) (recovery phase). On the night of 24–25 October (between ~01:00 and 10:00 UT),

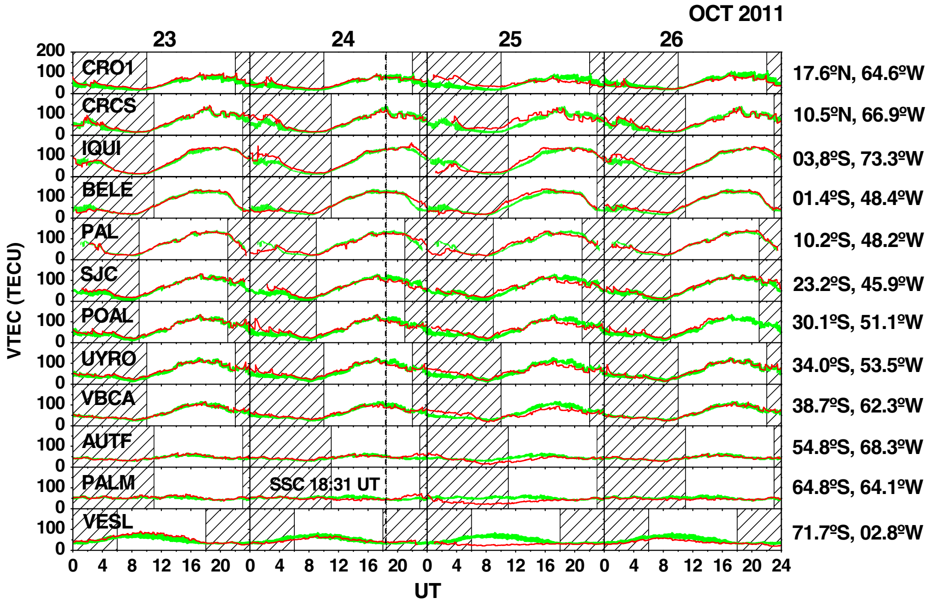

Fig. 6. The vertical total electron content (VTEC) measured using different satellites at America (12 receiving stations) during the period 23–26 October 2011. The red lines are observations on the respective day. The green bands are ±1 standard deviation of the average quiet day (22, 23, 28 and 29 October 2011) values. The black vertical dashed line indicates the time of SSC. The hatched portions indicate local nighttime periods (18:00–06:00 LT). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

during the end of main phase and first day of the recovery phase, the VTEC observations (Fig. 6), particularly at CRO1 (mid-latitude station located in the Northern Hemisphere) (between ~01:00 and 10:00 UT), show positive ionospheric storm. The positive ionospheric storm (mentioned earlier), at PTR (during nearly 03:00–06:00 UT and 08:00–10:00 UT) and CRO1 (between ~01:00 and 10:00 UT) (mid-latitude stations located in the Northern Hemisphere) on the night of 24–25 October 2011, are probably related with an equatorward neutral wind (Balan et al., 2009).

It should be mentioned that to explain the occurrence of positive ionospheric storms several mechanisms are proposed (e. g., Rishbeth, Fuller-Rowell, & Rees, 1987; Ngwira et al., 2012). Ngwira et al. (2012) have investigated ionospheric response during the geomagnetic storm events on 24–27 July 2004 in the South Africa region in mid-latitudes using ionospheric sounding data and GPS observations. Ngwira et al. (2012) observed (on 25 and 27 July 2004) at mid-latitudes in the South Africa sector a long-duration positive ionospheric storm (over 6 h of enhancement). In the present investigations (Fig. 6), positive ionospheric storm observed at CRO1 (mid-latitude station) (between ~01:00 and 10:00 UT) on the night of 24–25 October lasted over 8 h, and can be classified as long-duration positive ionospheric storm effects. According to Ngwira et al. (2012), the long-duration positive ionospheric storm observed at mid-latitudes in the South Africa sector have been caused by the equatorward neutral wind of large-scale thermospheric circulation.

The foF2 variations (see Fig. 5) at PST (mid-latitude station located in the Southern Hemisphere) show a negative ionospheric storm phase on the night of 24–25 October (between ~02:00 and 10:00 UT) (recovery phase). Fig. 6 presents the VTEC observations (in the recovery phase), on the night of 24–25 October and during the daytime on 25 October 2011, showing negative ionospheric storm at AUTF (mid-latitude station) (between ~07:30 and 16:00 UT), PALM and VESL (high-mid-latitude stations) (between ~02:00 and 16:00 UT), and the effect increasing from AUTF (mid-latitude station) to VESL (high-mid-latitude station). It should be mentioned that AUTF, PALM and VESL are stations located in the Southern Hemisphere. In addition, during the daytime on 25 October 2011 (recovery phase) (Fig. 6), a slight negative ionospheric storm is observed at VBCA (between ~13:00 and 20:00 UT), UYRO (between ~16:00 and 20:30 UT) (mid-latitude stations), POAL, SJC (low-latitude stations) (between ~17:30 and 21:00 UT) and PAL (a near equatorial station) (between ~18:00 and 21:00 UT) (Southern Hemisphere). These negative ionospheric storms (mentioned earlier) observed at PST (on the night of 24–25 October), AUTF, PALM and VESL (on the night of 24–25 October and during the daytime on 25 October 2011), VBCA, UYRO, POAL, SJC, and PAL (during the daytime on 25 October 2011), are associated with an increase in the density of molecular nitrogen.

During the daytime on 25 October (recovery phase) (Fig. 5), the foF2 variations show a negative ionospheric storm at PTR (between ~12:00 and 20:00 UT) and PST (between ~11:00 and 18:00 UT) (mid-latitude stations). It should be mentioned that PTR is a mid-latitude station located in the Northern Hemisphere and PST is a mid-latitude station located in the Southern Hemisphere. As discussed by Prolss (1980), the negative ionospheric storms are related with the neutral gas composition changes that decrease the O/N_2 ratio at mid- and high-latitudes during a geomagnetic storm.

At PAL (a near equatorial station) (during nearly 09:00–12:00 UT and 14:30–18:00 UT) and SJC (low-latitude station) (during nearly 09:00–12:00 UT and 14:30–16:00 UT) (see Fig. 5) we observed a slight positive storm phase (in foF2) during the daytime on 25 October (recovery phase). According to Balan et al. (2009), Balan et al. (2010), positive ionospheric storm is related with an equatorward neutral wind.

In Fig. 5, on October 25, the foF2 variations only at SJC (low-latitude station) show a negative ionospheric storm (with maximum negative amplitude around −3 MHz only) between ~20:00 and 22:00 UT (daytime and nighttime) (recovery phase). It should be mentioned that at PAL (a near equatorial station) we do not have data on October 25, 2011 (between ~18:30 and 24:00 UT). As described by Sobral et al. (2001), a negative ionospheric storm at low-latitude (with maximum negative amplitude around −3 MHz only) is possibly associated with the local chemical composition changes.

4. Conclusions

In this investigation, we present the analysis of the response of the ionospheric F-region in the American sector during the intense geomagnetic storm on 24–25 October 2011, using GPS observation from 12 receiving stations covering the equatorial to high-mid-latitude regions. We also present ionospheric sounding observations from 5 stations locations: PTR (mid-latitude station located in the Northern Hemisphere), JIC (equatorial station), PAL (a near equatorial station), SJC (low-latitude station) and PST (mid-latitude station) (Southern Hemisphere) in the American sector. Some of the salient features observed during this investigation are summarized below:

1. An unusual uplifting of the F-region was observed at equatorial stations (JIC and PAL) (between 23:00 and 01:00 UT) on the night of 24–25 October, possibly due to the prompt penetration of magnetospheric electric field generated during the main phase of the geomagnetic storm.
2. A near equatorial (PAL), low- (SJC) and mid- (PST) latitude stations located in the Southern Hemisphere showed strong oscillations of the F-region (h′F) on the night of 24–25 October due to the propagation of traveling ionospheric disturbances (TIDs) by Joule heating in the auroral regions. Also, a mid-latitude station located in the Northern Hemisphere (PTR) and an equatorial station located in the Sourthern Hemisphere (JIC) (on the night of 24–25 October 2011) showed h′F variations much larger than the average variations probably related with TIDs caused by Joule heating at high latitudes.
3. Plasma bubbles (equatorial ionospheric irregularities) were observed on the geomagnetically disturbed night of 24–25 October up to CRO1, United States (a mid-latitude station located in the Northern Hemisphere), and up to UYRO (a mid-latitude station located in the Southern Hemisphere), after the rapid uplifting of the F-layer in the equatorial stations (JIC and PAL; Fig. 3). Also, phase fluctuations (irregularities) were observed at VESL (high-mid-latitude station) on the night of 24–25 October 2011.
4. The foF2 variations at PTR and PST (mid-latitude stations) and the GPS-VTEC observations at CRO1, UYRO, VBCA, AUTF (mid-latitude stations) and POAL (low-latitude station) showed a positive ionospheric storm on the night of 24–25 October, associated with changes in the large-scale wind circulation in the Southern and Northern Hemispheres.
5. The variations in foF2 at PST (mid-latitude station) and the GPS-VTEC observations at AUTF (mid-latitude station), PALM and VESL (high-mid-latitude stations) in the Southern American sector showed a negative ionospheric storm on the night of 24–25 October associated with an increase in the density of molecular nitrogen.
6. During the daytime on 25 October, in the recovery phase, the foF2 observations showed large negative ionospheric storm at mid-latitude stations located in the Northern (PTR) and Southern (PST) Hemisphere, presumably due to changes in the O/N_2 ratio in the Northern and Southern hemisphere.

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