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GPS L-band scintillations and ionospheric irregularity zonal drifts inferred at equatorial and low-latitude regions

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A B S T R A C T

The main scientific objective of this research is to study the spatial variability and dynamics of the F-region irregularities. To achieve this, amplitude scintillations at the L-band, total electron content (TEC) and irregularity drifts were measured, as part of the Conjugate Point Equatorial Experiment (COPEX) campaign, by a network of ground-based global positioning system (GPS) receivers. The observations reveal a strong variability in the evolution of the irregularities from the equator to low-latitudes, and their zonal velocities at conjugate sites present a decrease with local time, and also with latitude. Moreover, the scintillations appear to be correlated with strong TEC gradients in the equatorward edge of the enhanced equatorial anomaly peaks. Other relevant aspects of the observations are highlighted and discussed.

1. Introduction

The effects of ionosphere on the satellite signals used for transionospheric telecommunications and navigation have been extensively investigated in the last decade. The ionosphere is known to be the principal source of receiver failure and degradation for the global positioning system (GPS), and is a concern for life critical navigation, such as civilian air travel, in equatorial and low-latitude regions. The primary effect of the ionosphere on transionospheric propagation occurs even during periods of undisturbed electron density, causing the radio signal's group velocity to decrease and the wave phase to advance. These effects on the signals transmitted from GPS satellites allow the determination of the total electron content (TEC) in the signal path from the satellite and the ground receiver. The TEC can be determined by comparing the signals received from the two GPS dual frequency transmissions on L1 (1.575 GHz) and L2 (1.227 GHz). One method utilizes the differential carrier-phase measurements, and the other one uses range calculations from group delay measurements to determine the TEC. The former provides the relative TEC and the latter yields an absolute measure of the TEC along the signal path, but both methods may be combined to derive a more accurate TEC estimation (Bhattacharyya et al., 2000).

In the last decade, ground-based GPS measurements have also been used very effectively for studies of equatorial ionospheric irregularities by measuring the scintillations in amplitude and phase of the radio wave signals caused by the irregularities (see for example, Aarons et al., 1997; Basu et al., 1999; Beach and Kintner, 1999; de Paula et al., 2003, and many others). The change of the radio wave phase imposed by the irregularities results in the amplitude and phase scintillation of the GPS signals at the receiver sites. The *F*-layer irregularities, known to be the main causes of GPS amplitude scintillations, can cause significant reduction in the GPS signal

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amplitude level, leading to loss of the receiver lock and degradation in the performance and the navigation accuracy. For the GPS L1 frequency (1.575 GHz) and 350 km altitude irregularities, the scale sizes of the plasma structures probed are of the order of ~370 m, which corresponds to the first Fresnel zone (Yeh and Liu, 1982).

The GPS receivers can also be used to investigate dynamic features of the equatorial irregularities. Kil et al. (2000) and de Paula et al. (2002) have estimated the ionospheric irregularity zonal velocities using a technique employing two-spaced ground-based GPS receivers. Kintner et al. (2004) used the same technique to estimate the north–south and east–west lengths of scintillation patterns and the characteristic velocities of the irregularities. Thus the GPS technology has been demonstrated throughout the last decade to be a potential tool for ionospheric research, providing relevant information of the dynamical and climatologic aspects of the ionosphere at equatorial and low latitudes.

In this paper, we present results of simultaneous GPS measurements carried out in the Brazilian longitudinal sector from October 1 to November 30, 2002, during the Conjugate Point Equatorial Experiment (COPEX) campaign. For the scientific objectives and related information on the COPEX campaign, see Abdu et al. (2008). For the purpose of ionospheric irregularities studies, GPS L1 amplitude scintillations data were collected simultaneously at seven sites distributed latitudinally from the central to the eastern sides of the Brazilian territory. Ionospheric irregularity zonal drift velocities and vertical TEC (VTEC) were measured simultaneously at the three stations of the COPEX geometry (Boa Vista, Cachimbo and Campo Grande) located along a same magnetic field with a 350 km apex over the equator (Muella et al., 2007). It is the first time that measurements from the GPS network presented in this work provide a picture of the latitudinal extension of L-band amplitude scintillation in the central-eastern South America. The configuration of the COPEX sites also provides a unique opportunity to study conjugate nature of small-scale irregularities and their zonal drift velocity. In this study the data were collected during months of high scintillation activity, which are associated with periods of high occurrence of ionospheric plasma bubbles. The average decimetric solar radio flux in 10.7 cm ($F_{10.7}$) for this period of increased solar activity was about 156.

Section 2 describes the experiment and presents the methodology used in the different observations. The results of the investigations from simultaneous measurements of the three important geophysical quantities (scintillation, TEC and zonal velocities) monitored by ground-based GPS receivers are discussed in Section 3. Finally in Section 4 we present a summary of the main results.

2. Experiment description

The GPS receivers operated at each site included a scintillation monitor, named SCINTMON, developed by the space plasma physics group from Cornell University and designed to monitor the amplitude scintillations at the L1 frequency (1.575 MHz). The SCINTMON is capable of logging the signal intensity at 50 samples per second for up to 11 visible satellites simultaneously, then the data collected are post-processed via software, and for each 60 s interval of data (3000 data points) the S_4 scintillation index is computed for all satellites tracked during the observation nights (1800–0600 LT). The S_4 index is the most used parameter to measure ionospheric amplitude scintillation and is defined as the normalized standard deviation of the received signal power intensity expressed as (Yeh and Liu, 1982)

$$S_4^2 = \frac{\langle I^2\rangle - \langle I\rangle^2}{\langle I\rangle^2} \tag{1}$$

where I is the signal power.

In order to infer the ionospheric irregularity zonal drift velocities, the spaced GPS scintillation monitors configuration is adopted in our observations. This technique allows the determination of an apparent velocity V_a of the irregularities from the time lag of the maximum cross-correlation of the scintillation patterns between two-spaced receivers. Since the GPS satellites are not stationary, the apparent drift velocity V_r of the irregularities includes the motion of the GPS signal ionospheric pierce point (IPP) velocity, and the apparent velocity can be calculated from the following relation (Kil et al., 2000; Otsuha et al., 2006):

$$V_r = \frac{d}{(n_{off}/f_S)} \tag{2}$$

where d is the sub-ionospheric distance at 350 km, n_{off} is an offset number determined by the cross-correlation method and f_s is the sampling rate (50 samples/s). Then, assuming that the scintillation pattern velocity is constant during the time lag, the satellite east–west movement V_{sat} gives the same effect as the irregularity structures moving in the opposite direction of the satellite. Therefore, with respect to the ground, the apparent irregularity zonal drift velocity V_a can be determined by the relation $V_a = V_r + V_{sat}$. For the same reasons described by Kil et al. (2002), the apparent irregularity zonal velocity calculated in this paper may be approximated to the true zonal velocity. Only the satellites with elevation angle higher than 40° were used to infer the zonal drift velocities, which reduces the effects due to the variations of the sub-ionospheric distances at 350 km (Kil et al., 2000; de Paula et al., 2002).

In order to obtain TEC measurements, Ashtech GPS receivers from the American Air Force Research Laboratory were used in the observations. The Ashtech is considered to be a robust dual-frequency receiver because of its capability to provide amplitude scintillation monitoring for both GPS L1 (1.575 MHz) and L2 (1.227 MHz) frequencies, as well as TEC informations (Groves et al., 2000). By processing the Ashtech data from both L1 and L2 frequencies it was possible to estimate the TEC, which can be defined as the number of electrons found in a column with one square meter centered on the signal path, being proportional to the ionospheric delay between the GPS L1 and L2 frequencies. For convenience this is presented in TEC units (TECU), which corresponds to 10^{16}

electrons per square meter. It has been reported from previous studies that ionospheric irregularities and bubbles cause large reductions of TEC values (Pi et al., 1997; Beach and Kintner, 1999; Basu et al., 1999), and their signatures can clearly be noted in the TEC plots.

3. Results and discussions

3.1. GPS scintillation activity

Table 1 lists the geographic and geomagnetic coordinates of the seven sites located in the Brazilian territory used in this experiment. Fig. 1 shows a map of South America where the GPS network is in operation. The panels in Fig. 2 show the scintillations measured by the GPS receivers at all stations (as listed in Table 1) during the months of October and November 2002. The panels are organized according to the latitude of the stations, the northern most station being indicated by the letter (a) and the southern most station being indicated by the letter (g). The contour plots in the panels present the maximum scintillation index (S_4) derived at each station throughout the nights when the data were collected.

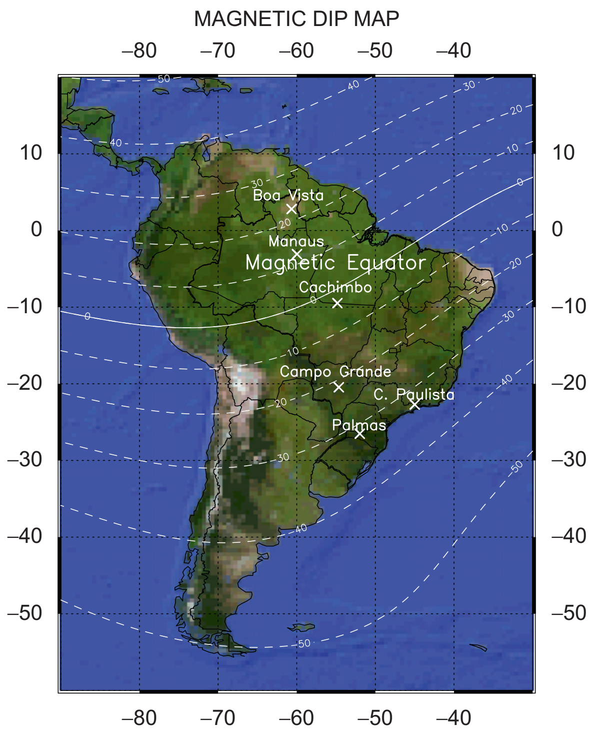

Fig. 1. GPS scintillation monitors network in the Brazilian territory.

Table 1
Geographic coordinates of the ground-based stations and their overhead geomagnetic coordinates for an ionospheric pierce point (IPP) at 350 km height

Station	Geographic		Geomagnetic		
	Lat.	Long.	MLat.	Inclination	Declination
Boa Vista	2.8°N	60.7°W	11.45°N	22.05°	−13.0°
Manaus	3.1°S	59.9°W	6.1°N	12.0°	−12.9°
Cachimbo	9.5°S	54.8°W	1.88°S	−3.75°	−15.3°
C. Grande	20.5°S	54.7°W	11.38°S	−21.92°	−13.7°
C. Paulista	22.4°S	45.0°W	16.8°S	−31.9°	−18.7°
S. J. Campos	23.1°S	45.8°W	17.1°S	−32.0°	−18.2°
Palmas	26.4°S	51.9°W	17.7°S	−31.5°	−13.9°

The panels in Fig. 2 reveal that at all stations the scintillation activity is higher in November than in October. From the contour plots it is also possible to notice that the occurrence of scintillation is lower at the equator and tends to increase towards low latitudes near the crests of the equatorial ionization anomaly (EIA). For instance, Fig. 2 shows that the scintillation activity and scintillation intensity appear to be higher at the low-latitude stations of Campo Grande (d), Cachoeira Paulista (e), São José dos Campos (f) and Palmas (g) than over Cachimbo (c) and Manaus (b), which are closer to the dip equator. On the other hand, the contour plots also reveal that, on a given night, the S_4 level may be lower or higher in one of the low-latitude stations in comparison to another, thus illustrating that, in addition to the normal day-to-day variability of the irregularities, there exists an extreme spatial variability in their evolution. Recently, Valladares et al. (2004) have shown from observations of a network of GPS receivers installed in the west coast of South America, the existence of a very close relationship between the location of the scintillations and the latitudinal extension of the EIA. They reported that the occurrence of scintillations was mostly confined within the boundaries of the anomaly, and the scintillations tended to be limited within the region where the anomaly was fully developed. Since the anomaly presents its day-to-day variability, one may expect that the scintillation activity may present its own variability. Unfortunately, we cannot demonstrate statistically in this work any relationship of the scintillation levels and activity with the amplitude and width of the EIA crests. However, in two recent presentations, one at the *Conferencia Latino Americana de Geofisica Espacial* (VII COLAGE), held in the year 2004, and the other one in the 2005 *URSI General Assembly*, Groves et al. (2004, 2005) reported from observations at the conjugate stations of Boa Vista and Campo Grande that the scintillation activity was relatively independent of background TEC variations near the crests of the EIA. They presented that at the conjugate stations of Boa Vista and Campo Grande the overall peak electron density decreased by ~20% from October to November, whereas the scintillation activity and intensity continuously increased during the same period at both stations, which may indicate the control by other factors also on the S_4 scintillation intensity. The contour plots for the conjugate stations of Boa Vista and Campo Grande in Figs. 2a and d show that the scintillation activity at Campo Grande is somewhat more intense than over Boa Vista in both months. The small arrows in Figs. 2a and d at days 4, 8 and 14–16 November 2002 are used to emphasize examples of nearly symmetrical features in the latitudinal extension of the scintillations at the conjugate stations. We may observe that this symmetry is apparent during onset time of the scintillations but after the first hour, the scintillation pattern begins to change between the stations, which illustrate the existence of spatial variability in the evolution of the irregularities.

From the overall behavior of the scintillations it is also noticed that their onset may occur on average at least 30 min earlier in November than in October at all stations. At Boa Vista, Manaus, Cachimbo and Campo Grande the onset of the scintillation appears to occur around 30–45 min earlier than at Cachoeira Paulista and São José dos Campos, and at least 60 min earlier than in Palmas. The onset time delay of the scintillation for the stations off the equator may be explained in terms of the time required for irregularities, generated at the magnetic equator, to reach the apex height which maps along the magnetic flux tubes to *F*-region heights over off-equatorial latitudes (for example, Abdu et al., 1983).

The contour plots in Fig. 2 show that the highest levels of scintillation observed at all stations are mostly concentrated in the pre-midnight hours. At Cachimbo and Manaus the occurrence of scintillation was mainly in the pre-midnight hours and rarely occurred after 0000 LT. On the other hand, at the low-latitude stations some structures causing scintillations in the GPS signals can be observed until 0300 h. Since the ionospheric plasma bubbles are field aligned structures which tend to drift eastward, some structures detected in the post-midnight hours at stations such as Cachoeira Paulista, São José dos Campos and Palmas were probably generated in the equator further to the west of these stations.

3.2. Occurrence of scintillation by sectors of the sky

Fig. 3 depicts the percentage of occurrence of scintillations for the sub-ionospheric points at different sectors of the sky at the seven Brazilian stations. This kind of observation has not been exploited in most investigations to study in more detail north–south/east–west asymmetries in scintillation from different sites. The occurrence of scintillations was calculated for the IPPs from all GPS satellites with elevation angle higher than 40° tracked

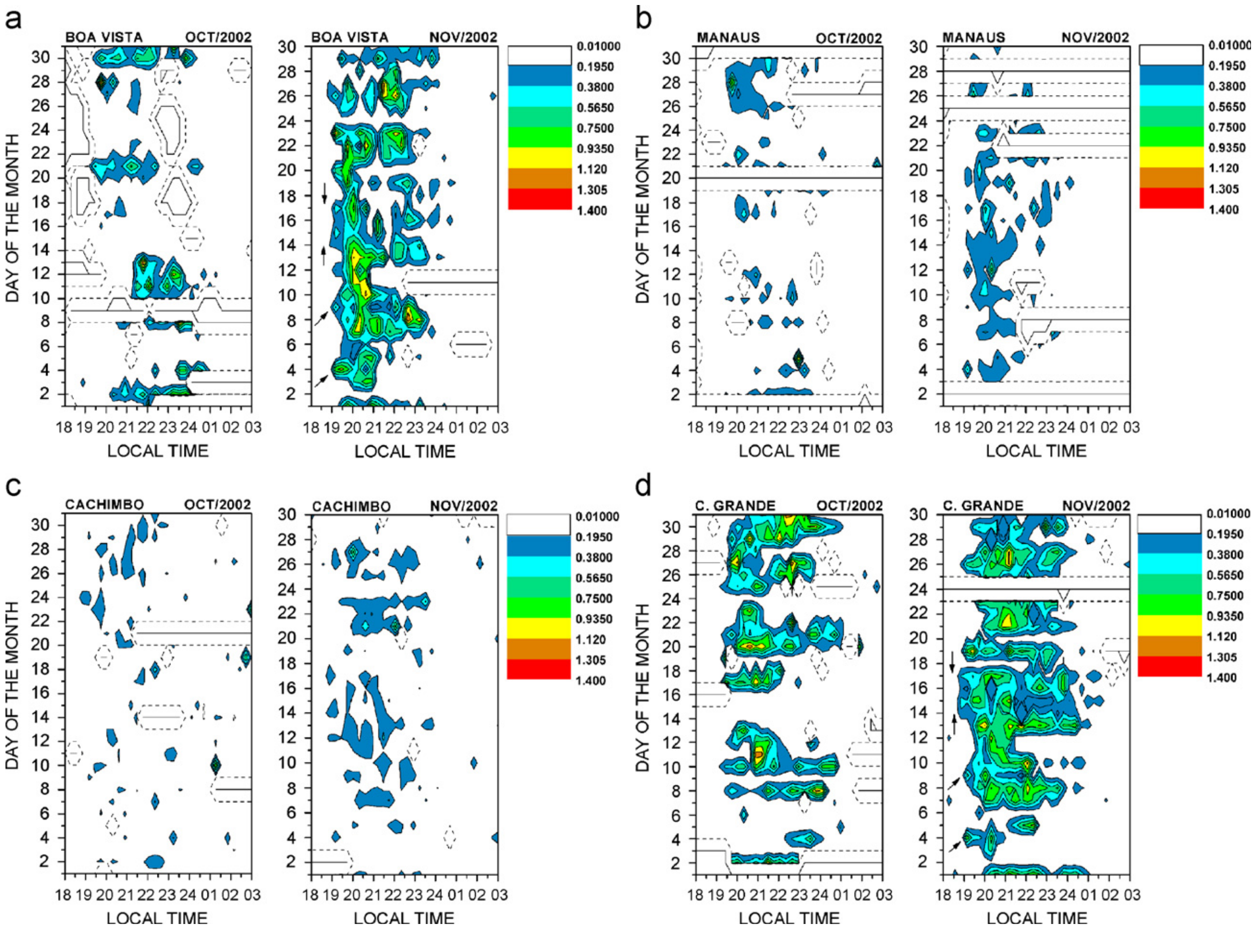

Fig. 2. The contour plots above represent the scintillation activity (in S_4 index) during the months of October (left columns) and November (right columns), 2002, at seven sites located in the Brazilian territory. In order to reduce space spreading of the scintillation data only satellites with elevation angles higher than 40° were used in the analysis. The color scale bars indicate the S_4 index levels used in the contour plots. The contours with dotted lines indicate inexistence of data. The white parts in the contour plots are valid for the time with lack of data or when the scintillation index S_4 did not exceed 0.195 (within the multipath and noise effect levels). The arrows in the panels of Boa Vista and Campo Grande during the month of November depict the days when nearly symmetric scintillations were observed in the conjugate stations.

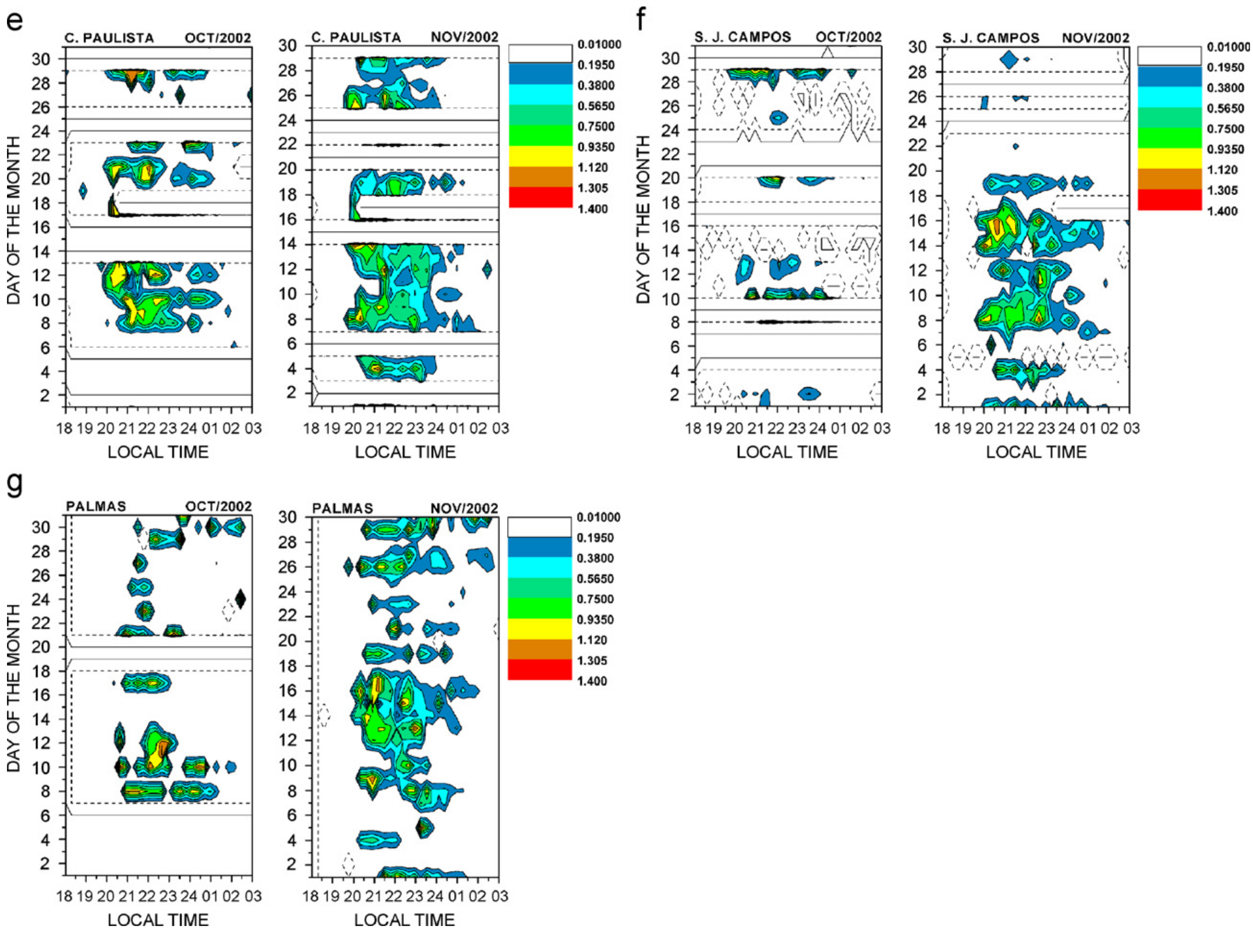

Fig. 2. (*Continued*)

during the entire nights of October and November 2002. Here the occurrence probability is defined as the percentage of events at each sector of the sky where $S_4 \geqslant 0.2$. It can be seen that for the northern magnetic stations of Boa Vista and Manaus in both months scintillations mostly occurred in the north sector of the sky. At Boa Vista during October the occurrence of the scintillation is 31.66% between the north and east sectors, whereas 28.87% was sampled between the south and west sectors. In the same month, but at the station of Manaus, the scintillations were greater between the north and west sectors of the sky with about 35% of occurrence. The coincidence between the two stations during the month of October is that the occurrence is lower between the southeast and south sectors. However, the most marked difference occurred in Manaus between the west and northwest sectors, where the percentage of occurrence was higher (20.96%) in October, but in November reduced significantly to about 6%. The decrease in the percentage of occurrence at this sector of the sky during November is also noticeable at the station of Boa Vista. During November the occurrence of scintillations was mostly sampled between the northwest and the north sectors, and between the northeast and east sectors of the sky above Boa Vista (38.89%) and Manaus (44.27%). Otherwise, at the equatorial station of Cachimbo in both months the scintillations were greater between the south and southwest sectors of the sky, with 25.08% of occurrence in October and 30.89% of occurrence in November. At Cachimbo the occurrence of scintillation was lesser between the north and northeast sectors, which are also the sectors sampled at Campo Grande with less percentage of occurrence of scintillations.

The overall agreement between all the southern stations in the 2 months analyzed in this study is that the occurrence of scintillations to the south is greater than to the north. It can be seen that the occurrence of scintillation appears to be greater between the southeast and southwest (SE–SW) sectors of the sky at all stations. At Campo Grande about 43% of the occurrence was sampled in both months between SE–SW sectors, whereas at Cachoeira Paulista, São José dos Campos and Palmas the occurrence at these sectors was between about 37% and 39%. Our results for the southern stations are in fair agreement with the observations of Ezquer et al. (2003) which reported for Tucuman (26.9°S; 65.4°W; dip latitude: −15.5°), Argentina, that the scintillation occurrence increases when the satellites are south of this station and at higher elevation angles. It may also be observed from our results that the differences in the occurrence of

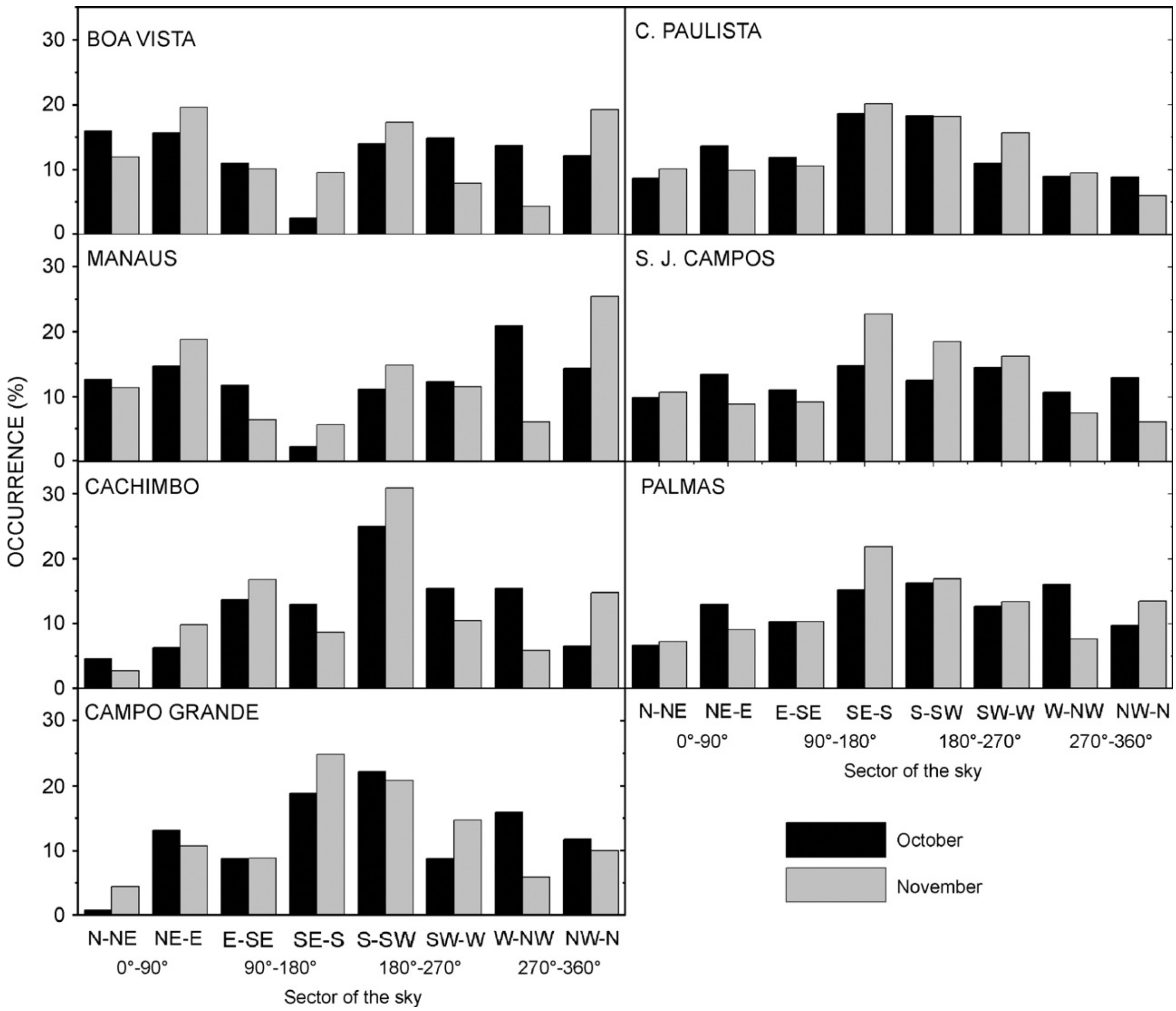

Fig. 3. Percentage of occurrence of scintillation at different sectors of the sky over the seven Brazilian sites. It is valid for all satellites tracked during the months of October and November 2002 with elevation angle higher than 40°. N, S, E and W indicate, respectively, north, south, east and west.

scintillations between the south and the north sectors are less for the northern stations and also tend to reduce as the latitude of the stations increases. For instance, at Cachimbo and Campo Grande most of the occurrence of scintillation are observed when the satellites are in the south, whereas at Cachoeira, São José dos Campos and Palmas the occurrence of scintillation increases at the north and decreases in the south, but continues higher at the south sector.

3.3. Scintillation and TEC observations

Figs. 4 and 5 present two cases of ionospheric irregularities signatures observed on GPS signals at the three COPEX stations. Our intention in this work is not to combine statistics of GPS scintillations occurrences, TEC depletions and TEC symmetries/asymmetries, but to point out some features of the irregularities signatures on the GPS signals and also to present some relevant aspects of the ionospheric quantities measured by the GPS receivers during the occurrence of the *F*-region irregularities. It is important to mention that we are dealing with case studies, and some features discussed below might not represent a general feature.

Fig. 4a shows an example of the measurements of signal power, the associated scintillation index and the verticalized TEC from the GPS receivers operated at the three COPEX sites (Cachimbo is equatorial, and Boa Vista and Campo Grande are magnetic conjugate stations). Fig. 4b depicts the sky maps with azimuth-elevation coordinates for the satellite path at 350 km as detected by the receivers installed at each observatory. The widths of the paths are proportional to the magnitude of the S_4 index. The data were collected during the overpass of the GPS satellite 20 (PRN 20) on the night of October 13–14, 2002. Notice that for Cachimbo and Campo Grande LT = UT−3.6 h, and for Boa Vista LT = UT−4 h.

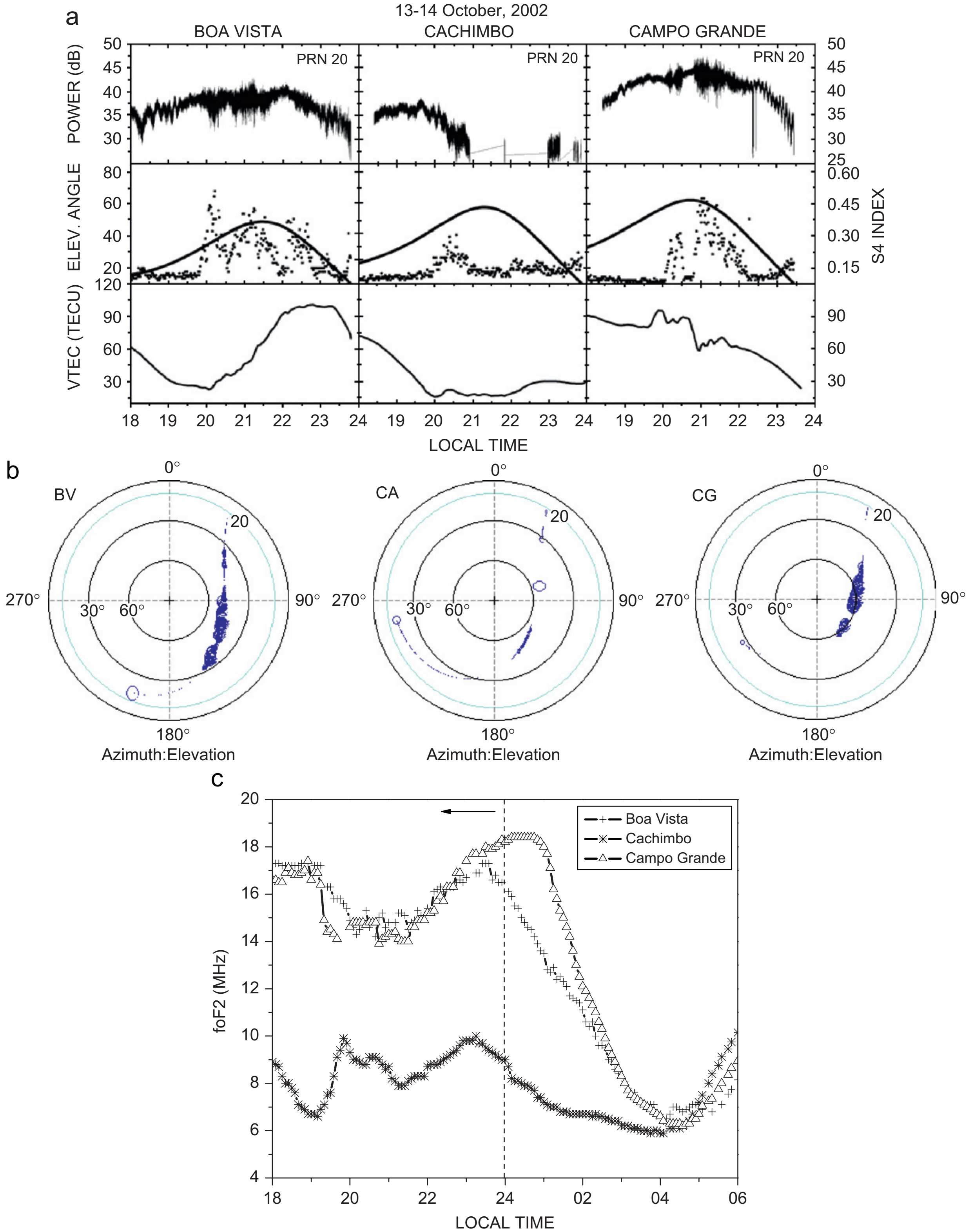

Fig. 4. (a) Data collected for the conjugate stations of Boa Vista (BV) (left column) and Campo Grande (CG) (right column), and the equatorial station of Cachimbo (CA) (middle column) during the night of October 13–14, 2002. Top panels: high-resolution signal amplitude data (50 samples/s) from satellite 20 (PRN 20). Middle panels: S_4 index measured over 60 s intervals and the satellite (PRN 20) elevation angle. Bottom panels: equivalent vertical TEC given in TECU ($10^{16}/m^2$). (b) Azimuth-elevation diagrams showing the satellite paths as detected at each station (BV, CA and CG). The path width is made proportional to the magnitude of the S_4 index. (c) The critical frequency *foF2* measured from the digital ionosondes operated at the field-aligned stations.

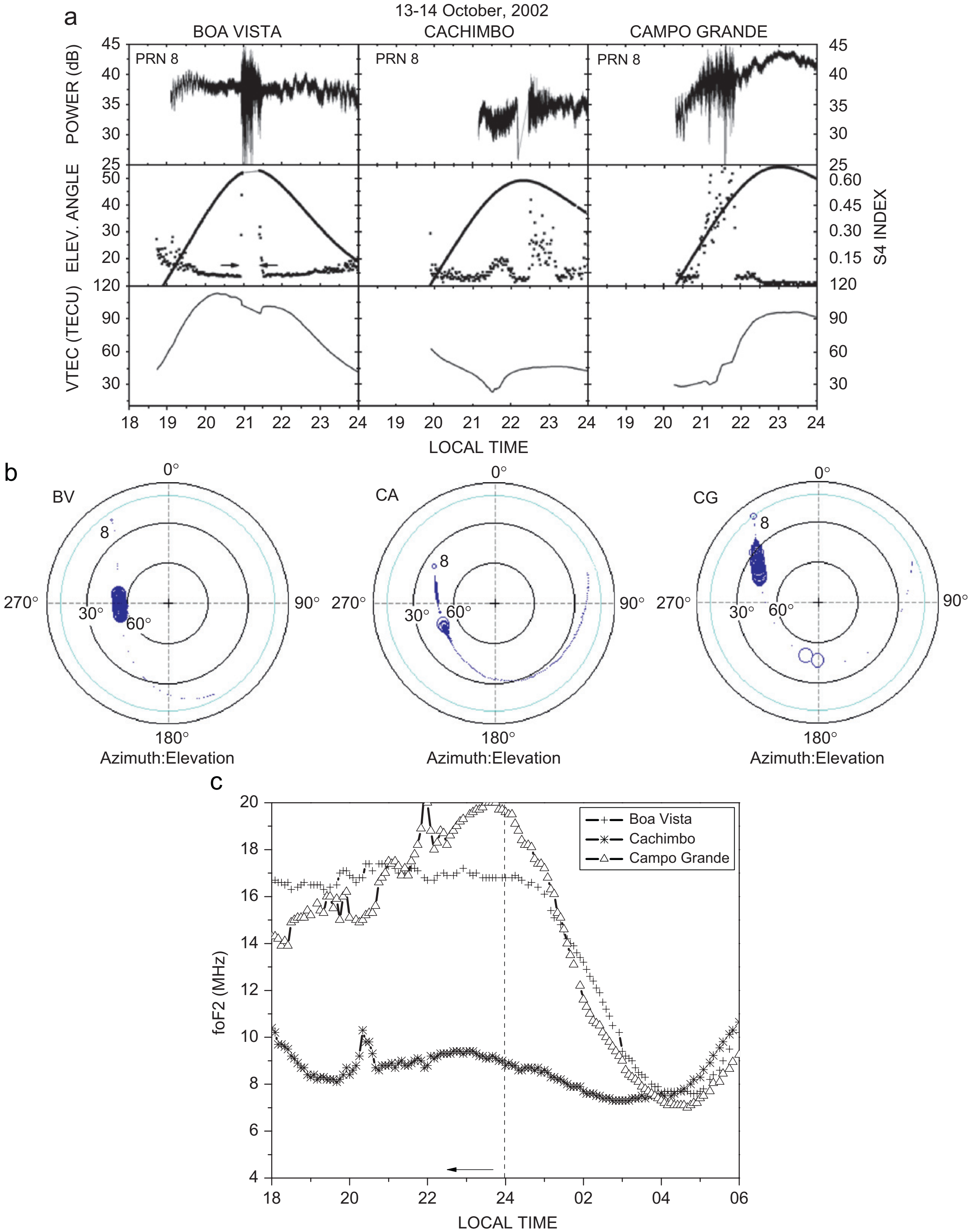

Fig. 5. The panels and the diagrams are the same as in Fig. 4 but for the signals recorded from the satellite PRN 8 and during the night of October 18–19, 2002. The arrows in the middle panel (S_4 index and elevation angle plots) for Boa Vista (left column) indicate the occurrence of loss of lock in one of the receivers installed at this station.

In the top row of panels in Fig. 4a an example of field aligned structures, indicated by the amplitude scintillation of the GPS signals, is observed over the conjugate stations of Boa Vista and Campo Grande around 1945–2000 LT. The amplitude fluctuations are observed around 1945 LT over Boa Vista and Cachimbo and around 2000 LT over Campo Grande. Such a difference in the onset time of the scintillations might be attributed to the difference in longitude (6°) between the conjugate stations. The lack of data in Cachimbo between 2100 and 2300 LT was due to a problem in reading the raw data.

In the middle row of panels in Fig. 4a is shown that the satellite (PRN 20) as seen from Boa Vista reaches $\sim 30^{\circ}$ of elevation angle around 1945 LT, whereas over Campo Grande the elevation angle of the satellite at this time approaches 55°. For comparison, the maximum power of the signal at Campo Grande is $\sim$43 dB around 1945 LT, whereas at Boa Vista it is measured at $\sim$40 dB. In this case the signal power amplitude measured at Campo Grande is higher than in Boa Vista because the satellite elevation angle is higher where the antenna gain is also larger. For Boa Vista, after $\sim$2130 LT the TEC increased as the satellite elevation angle decreased. Part of the increase in the TEC can be explained by an increase in the length of the signal path through the *F*-region. However, strong depletions were not associated with the increase in the TEC and the occurrence of scintillations. At Campo Grande, despite of the similar decrease in the satellite elevation angle after $\sim$21 LT, the TEC values decreased throughout the night. The maximum values of TEC at Boa Vista occurred between around 2245 and 2315 when it begins to decrease, which agrees with the *foF2* measurements conducted at this station. At the equatorial station (Cachimbo) from 1800 to 2000 LT, mainly due to the action of the fountain effect and additionally due to the increase of the satellite elevation angle, the TEC decreased from $\sim$75 to 15 TECU. During 2000–2200 LT when the fountain effect is becoming fully developed, the electron density assumes low values at the equator as observed from the TEC measurements. This is approximately the time period when the scintillations were observed simultaneously over the three stations. The scintillation levels are lesser at Cachimbo between 2000 and 2200 LT due to the smaller electron density at the equator, whereas at the conjugate stations that are near the peak of the anomaly the observations show that the scintillations levels are comparatively greater. Around 2200 LT the slow increase in the TEC values at the equator might indicate that the vertical drift of the equatorial ionosphere reversed downward. A few minutes after 2200 LT it is possible to observe that, associated with the reversion in the vertical drift, there is a slight increase in the scintillation levels over Cachimbo, whereas the scintillation intensity begins to cease at Campo Grande. In the same instant, at Boa Vista, since the electron density is increasing in its overhead ionosphere the scintillations appear to be observed until 2300 LT, when the satellite attains low elevation angles. The observation of asymmetries in the scintillation pattern and in the TEC depletions between the two conjugate stations might also be associated with differences in the elevation angle of the satellite as seen from each station, and due to differences in the sector of the sky where the IPPs were sampled from the satellite signal. The sky maps in Fig. 4b show that the IPPs for the satellite PRN 20 during the occurrence of scintillations moved slowly from west to east and passed from south-east (SE) to north-east (NE) sectors of the sky over Boa Vista (BV) and Campo Grande (CG), whereas over Cachimbo (CA) the scintillations were sampled when the satellite was in the south–east sector of the sky.

In the bottom panels of Fig. 4a two different highlights may be considered. Firstly, at Campo Grande, simultaneously with the occurrence of moderate scintillations (maximum S_4 of 0.5 is present in the middle panel), the measured vertical TEC presented signatures of depletions passing through short maxima and minima. These signatures in the TEC plots indicate that the overhead ionosphere is disturbed by ionospheric plasma bubbles (Kil et al., 2000). A maximum TEC depletion of $\sim$30 TECU was observed at Campo Grande around 2100 LT. Secondly, over Boa Vista such depletion in the TEC plots was not well noticed simultaneously with the onset of the scintillations, probably because the measured TEC was comparatively lower in Boa Vista at this time. Over symmetric conditions, the conjugate stations of Boa Vista and Campo Grande during the periods analyzed in this study are not expected to be located exactly under the crest of the EIA, but under the equatorward edge of the enhanced anomaly peaks. However, during the night, depicted in Fig. 4a, the TEC values measured over Campo Grande from satellite PRN 20 is $\sim$65 TECU higher than over Boa Vista around 2000 LT. It would suggest a strong asymmetry in the movements of the anomaly peaks off-equator during the present night, but simultaneous measurements of F2-layer critical frequency (foF2) by ionosondes do not suggest the existence of this asymmetry.

Fig. 4c depicts the values of *foF2* measured at Boa Vista (line with crosses), Cachimbo (line with asterisks) and Campo Grande (line with triangles) for the night of October 13–14, 2002. It shows that from 2000 to until around 2330 LT the values of critical frequency as measured over the conjugate stations do not differ significantly, which indicate that there is no prominent asymmetry in the maximum electron density over these stations. Hence, the observations suggest that the low values of TEC as measured over Boa Vista around 2000–2100 LT might be caused by the natural redistribution of the electron density in the ionosphere caused by the plasma fountain effect, which led to a masking of the TEC depletions caused by the irregularities. A similar feature has been reported by Valladares et al. (2004). In addition, we may consider the effects due to the differences in the elevation angle of the satellite as detected at each conjugate site.

Fig. 5a shows another example of the effects of ionospheric irregularities on GPS signals as measured by the GPS receivers located at the same stations presented in Fig. 4. The data were collected during the overpass of the satellite PRN 8 on the night of October 18–19, 2002. For Boa Vista where two spaced receivers were installed, one receiver was able to measure the power signal fluctuations, as shown in the top row of panels. On the other hand, in the other receiver, located 100 m away, a loss of signal lock around 2100 LT was observed which caused a lack of data during approximately 30 min, and the scintillation index could not be calculated throughout the elapsed time. Nearly simultaneous intense signal fluctuations were detected in the conjugate station of Campo Grande.

From the middle and bottom panels of Fig. 5a weak depletions in the TEC plots that occurred simultaneously with the scintillations are observed for the conjugate stations. The TEC measurements from satellite PRN 8 suggest asymmetric latitudinal distribution of the peaks of the anomaly. Similar to the observation over Boa Vista on the night presented in Fig. 4a, the scintillations over Campo Grande in Fig. 5a occurred during periods of declined values of TEC (~30 TECU). While the northern crest of the anomaly appears to be overhead Boa Vista around 2100 LT (~105 TECU), over Campo Grande the scintillation events might be correlated with strong TEC gradients on the equatorward edge of the enhanced southern anomaly peak. Fig. 5c shows an asymmetry in the values of foF2 between Boa Vista and Campo Grande before and after 2100 LT, which agrees well with the observations of TEC. Before 2100 LT the elevation angle of the satellite PRN 8, over Campo Grande, was below 30° which makes an interpretation difficult, but after 2100 LT the increase in the TEC values at Campo Grande agrees with the increase in the values of foF2, as recorded by the ionosonde. At the conjugate stations, the TEC depletions (~10 TECU for Boa Vista and ~3 TECU for Campo Grande) were smaller than in the night presented in Fig. 4; on the other hand, the scintillations levels were comparatively higher ($S_4 = 0.75$ in Campo Grande). Over Cachimbo two maximums in the scintillations levels were observed, the first one with low levels ($S_4 = 0.2$) occurred between 2100 and 2200 LT, and nearly simultaneous with those observed at Boa Vista and Campo Grande. At this time a TEC depletion of ~6.5 TECU was observed. The second one with moderate levels ($S_4 = 0.43$) was observed between 2230 and 2330 LT, and simultaneously depletions in the TEC plots were not observed. However, the TEC presented a different trend after depletion, and an increase in its value at Cachimbo after 2145 LT, before the occurrence of the second maximum, may indicate a reverse in the plasma fountain, and the no observation of scintillations at the same time over the conjugate stations might be considered due to the fact that the irregularities did not reach the field line apex over equator that maps to the *F*-region at the latitudes of Boa Vista and Campo Grande. As pointed out by many authors (Zalesak et al., 1982; Sultan, 1996; Abdu, 2001) the bubbles are flux tube-aligned structures which extend vertically over equator, their growth/vertical development depending on field line-integrated quantities. The vertical growth causes the bubbles to extend latitudinally away from the equator, and to be observed in the *F*-region over an off-equatorial station.

The sky maps in Fig. 5b depict the azimuth and elevation diagrams for the satellite PRN 8 as detected from the signals measured by the receivers installed at each observatory. They show that the IPPs for the satellite PRN 8 during the occurrence of scintillations passed from the north-–west (NW) to the south-west (SW) sectors of the sky over Boa Vista (BV) and Cachimbo (CA), whereas over Campo Grande (CG) the scintillations were sampled only in the NW sector of the sky.

3.4. Irregularity zonal drift velocity

Fig. 6 shows the average and the standard deviations (σ) of the zonal drift velocities of the ionospheric irregularities calculated from the GPS spaced receiver data. The average zonal drift velocities were calculated for 15 nights during October (2 nights) and November (13 nights) 2002, with simultaneous occurrence of scintillation over Boa Vista, Cachimbo and Campo Grande. In this calculation, we included data of elevation angle higher than 40°, S_4 index$\geqslant$0.2 and cross-correlation index (c_i)$\geqslant$0.9. The standard deviations of the velocities for each observation site are presented as error bars. The general view of the zonal drift velocities present some common features at all the three stations: (a) a first maximum in the zonal drift occurs between around 2000 and 2030 LT; (b) after the first maximum the magnitude of the zonal velocities tend to decrease throughout the night, but it is not always monotonic and present secondary peaks; (c) the last maximum in the magnitude of the zonal velocities occurs around 2330–2400 LT and after that the rate of decay of the velocities becomes faster.

At Cachimbo the zonal velocities are ~220 ms^{-1} around 2030 LT, ~150 ms^{-1} around 2300 LT, and show an increase to about 160 ms^{-1} just after midnight. At the northern conjugate station (Boa Vista), the zonal velocity is about 190 ms^{-1} at 2030 LT, 130 ms^{-1} near 2300 LT, and shows a slight increase to about 145 ms^{-1} around 2330 LT. At the southern conjugate station of Campo Grande the velocity was ~175 ms^{-1} around 2045 LT and ~150 ms^{-1} at 2300 LT. The zonal drift magnitudes tend to decrease with

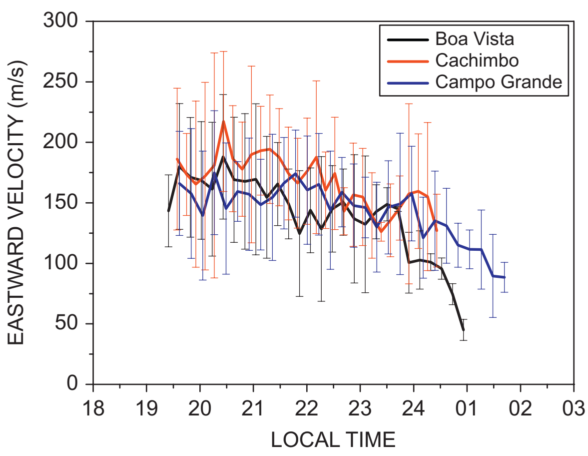

Fig. 6. Average zonal velocities of the irregularities and the standard deviations inferred at the field-aligned stations of Boa Vista, Cachimbo and Campo Grande during 15 nights in October–November 2002.

local time, but at different decrease rates at each station. At the station of Boa Vista the mean rate is approximately $-36.2\,\mathrm{ms}^{-1}$/h between 2030 and 2130 LT, $-10\,\mathrm{ms}^{-1}$/h between 2130 and 2230 and $-50\,\mathrm{ms}^{-1}$/h after 2330 LT, whereas at the conjugate station of Campo Grande the rate is approximately $-24.6\,\mathrm{ms}^{-1}$/h between 2115 and 2215 LT and attains $-42.8\,\mathrm{ms}^{-1}$/h after midnight. At Cachimbo the mean rates between 2030–2130 and 2130–2230 are, respectively, ~ -27 and $-10.7\,\mathrm{ms}^{-1}$/h.

In a first approximation, the average zonal drift velocities calculated at the two conjugate stations should be the same (see also, Sobral et al., 2008). However, in the technique to derive the zonal drift velocities from spaced GPS receivers data, we compute the mean zonal velocities obtained from all satellites within two criteria: (1) elevation mask ($>40^\circ$), and (2) 90% of correlation. Thus we include in the calculations the satellites signals sampling different sectors (IPPs) of the sky, or different irregularities structures over the stations. Consequently, it probably introduces bias in the calculations of the irregularity zonal drift velocities, thus contributing for their discrepancies in magnitude. Otherwise, the differences in the zonal velocities between the conjugate stations were mostly within the σ bars. Fig. 6 also suggests the presence of a negative latitudinal gradient in the inferred zonal drift velocities. The magnitude of the zonal drift velocities at both conjugate stations is subtly smaller than that at the magnetic equator mainly before 2230 LT. These observations are consistent with previous studies from Sobral and Abdu (1991) and Kil et al. (2002), in which the latitudinal variations of the zonal velocities for regions where the magnetic declination angle does not vary significantly indicate the presence of a vertical shear of the eastward plasma flow. The eastward plasma flows during nighttime are mainly controlled by the presence of polarization electric fields, which tend to decrease with increasing altitude. Considering the nature elongation of the irregularities along the magnetic field lines, and the field line mapping of the large-scale electric fields driving the ambient plasma, the height where the irregularities were sampled over Boa Vista and Campo Grande correspond to a mean apex height which is higher than that of the irregularities sampled over Cachimbo. Thus, the lower zonal drift velocities over Boa Vista and Campo Grande might suggest the presence of a comparatively small height gradient in the zonal plasma flows. Such difference in the magnitude of the irregularity drifts is absent between about 2230 and 2345 LT at the three stations.

4. Summary

This study comprises three topics related to the understanding of the ionospheric irregularity phenomenon at equatorial and low-latitude regions which have drawn attention and motivated concerted efforts from the community: conjugacy, variability and latitudinal/temporal dependence.

The main results of the present investigation are summarized as follows:

(a) The scintillation activity, during the 2 months analyzed in this study, showed to be weaker at equatorial latitudes, but significantly higher intensities at stations located nearer to the crests of the equatorial anomaly. Over Boa Vista and Campo Grande examples of nearly symmetric features in the latitudinal extension of the scintillations were seen. However, the overall behavior of the scintillations reveals that in addition to the significant day-to-day variability there is evidence of a strong spatial variability in the generation and evolution of the ionospheric plasma bubble irregularities.

(b) The results show that the occurrence of scintillations at the northern magnetic stations of Boa Vista and Manaus are more frequent when the satellites are between the north and east sectors, and between the north and west sectors of the sky. On the other hand, at the southern conjugate stations the occurrence of scintillations is more frequent between the southeast and southwest (SE–SW) sectors of the sky. However, the difference in the occurrence of scintillations between the south and the north sectors appears to reduce as the latitude increases.

(c) We have noted that relationship between the width of the TEC depletion and the intensity of the scintillation (S_4 index) as obtained from the same GPS satellite track is not straightforward. In two cases we have shown that smaller or no TEC depletion may occur concurrently with moderate–strong scintillation. Asymmetries in the scintillation intensity and in the width of the TEC depletions between two conjugate stations may also be caused by differences in the elevation angle and in the sector of the sky where the ionospheric pierce points (IPPs) were sampled from the satellite.

(d) In the two case-study events presented in Figs. 4 and 5 the observations suggest that scintillations at low latitudes may occur during both symmetric and asymmetric developments of the EIA crest. This is in accord with observations by Groves et al. (2005) and Valladares et al. (2004) who reported that the scintillation activity may occur independently of background TEC variations near the crests of the EIA.

(e) Our observations also reveal that scintillation enhancement may occur over equator during periods of reversal of the equatorial fountain, but several competing process may be acting at the same time to inhibit the vertical growth of the irregularities and their consequent extent to off-equatorial latitudes.

(f) The observations revealed, from the analysis of the case studies, that small-scale irregularities causing GPS scintillations may be correlated with strong TEC gradients in the edges of the enhanced anomaly peak.

(g) Latitudinal differences of the simultaneous measurements of the irregularity zonal drift velocities inferred using the spaced receiver technique, and the cross-correlation method, indicate the effects of the vertical shear of the plasma flow, once that velocities at different latitudes are projected to different heights in the equatorial plane (Sobral and Abdu, 1991; Kil et al., 2002).

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