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Characteristics of the ionospheric F-region plasma irregularities over Brazilian longitudinal sector

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Based on the data obtained from a network of GPS L1 band receivers deployed in Brazil, are presented here the characteristics of the 400 m ionospheric irregularities during magnetically quiet and disturbed conditions. The network is composed of 12 GPS scintillation monitors and covers the latitudinal region from the magnetic equator up to the southern crest of the Equatorial Ionization Anomaly (EIA), which is characterized by large horizontal gradients in the electron density distribution. Some results on equatorial spread-F statistics obtained from digisonde data over Cachoeira Paulista (22.41° S, 45° W, dip latitude 14.89° S) and from ionosonde data over Tucumán (64.5° W, 27° S, dip latitude 13.71° S) are also used in this work to complement the results from GPS network. The effects of local time, season, latitude, longitude, background ionization, solar cycle and magnetic activity on the ionospheric irregularities are presented. The ionospheric irregularity zonal velocities determined by magnetically east-west spaced GPS receivers are also presented. The influence of the ionospheric irregularities on GPS based navigational systems is discussed. These observations, complemented by computational simulations, may improve our understanding of the factors responsible for the generation, growth and dynamics of the equatorial F-region plasma irregularities.

Keywords: Ionospheric plasma irregularities, GPS scintillation monitor, Space based augmentation system (SBAS)

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1 Introduction

In the post-sunset equatorial ionosphere, plasma depleted regions/bubbles with associated irregularity structures of scale sizes varying from centimeters to kilometers are generated due to plasma instability processes[1-5]. The phase and amplitude of a radio signal passing through these irregularities undergo significant fluctuations, and such fluctuations can cause degradation in the GPS navigational accuracy and limitations in the GPS system tracking performance[6-8].

The ionospheric irregularities present a large dependence on the solar flux, the local time, the season, the latitude and longitude and the magnetic disturbances. In this paper an analysis of the distribution of the GPS L-band scintillations according to these different parameters will be presented. In the Brazilian longitudinal sector the ionospheric F-region irregularities present pecularities due to several local physical conditions such as the high magnetic declination angle that characterize this region[9-10]. The separation between the magnetic and the geographic equators and the presence of the EIA associated with large background electron densities and the large electron density horizontal gradients due to the anomaly crests also produce important pecularities in the irregularity distributions.

The potential effects on GPS performance and communications systems caused by the ionospheric scintillations include the loss of lock, increased dilution of precision (degradation of accuracy), and decrease in the number of available GPS satellites, affecting substantially the SBAS (Space Based Augmentation System).

2 Instrumentation and methodology

To analyze the behaviour of the ionospheric irregularities based on scintillation data, an array of 12 GPS scintilation monitors (SCINTMON) has been in operation over Brazilian territory. The SCINTMON receivers were developed at Cornell University using a GEC-Plessey GPS Builder-2 card[11]. Each of these receivers can sample the L1 band signal from 11 satellites at a rate of 50 Hz (50 samples/s) with an elevation mask of 10°. The GPS L1 signals are sensitive to irregularities of about 400 m scale sizes. To quantify the scintillation intensity amplitude the S4 index was used. This index represents the ratio of the standard deviation to the average signal amplitude calculated at each minute. Figure 1 shows the GPS receiver network. At the sites of São Martinho da Serra, Cachoeira Paulista, Cuiabá and São Luís two GPS receivers were used in spaced geometry in the magnetic east-west direction for irregularity zonal drift determination using the cross-correlation method[12]. This network has been upgraded with the installation of more receivers to improve scintillation coverage over the Brazilian territory. The spread-F occurrence distributions at different longitudinal sectors in South America as obtained by Abdu *et al.*[13] based on digisonde data from Cachoeira Paulista and ionosonde data from Tucumán are also presented here for complementing the study.

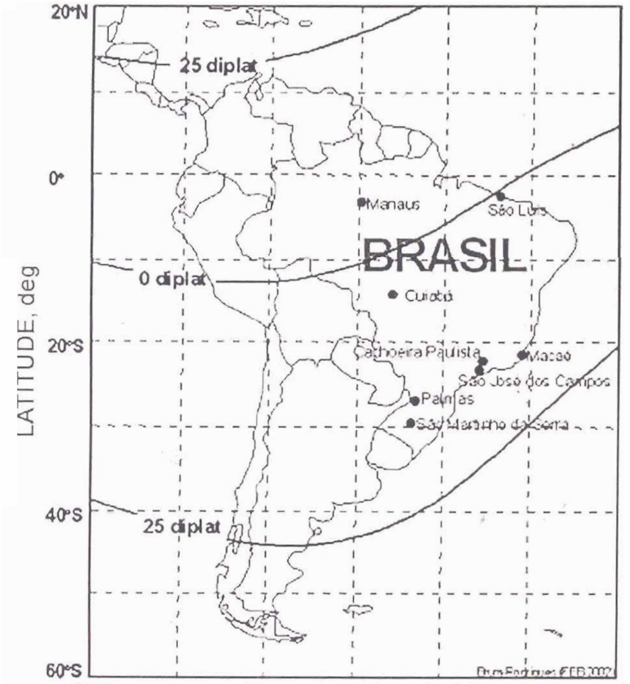

Fig. 1 — GPS scintillation monitors network in the Brazilian territory

3 Local time, seasonal, and solar flux effects

Figure 2 shows the monthly percentage of occurrence of the GPS scintillation over São José dos Campos (23.21° S, 45.86° W, dip latitude 17.8° S), for the period extending from September 1997 (low solar flux) to June 2002 (high solar flux), as a function of

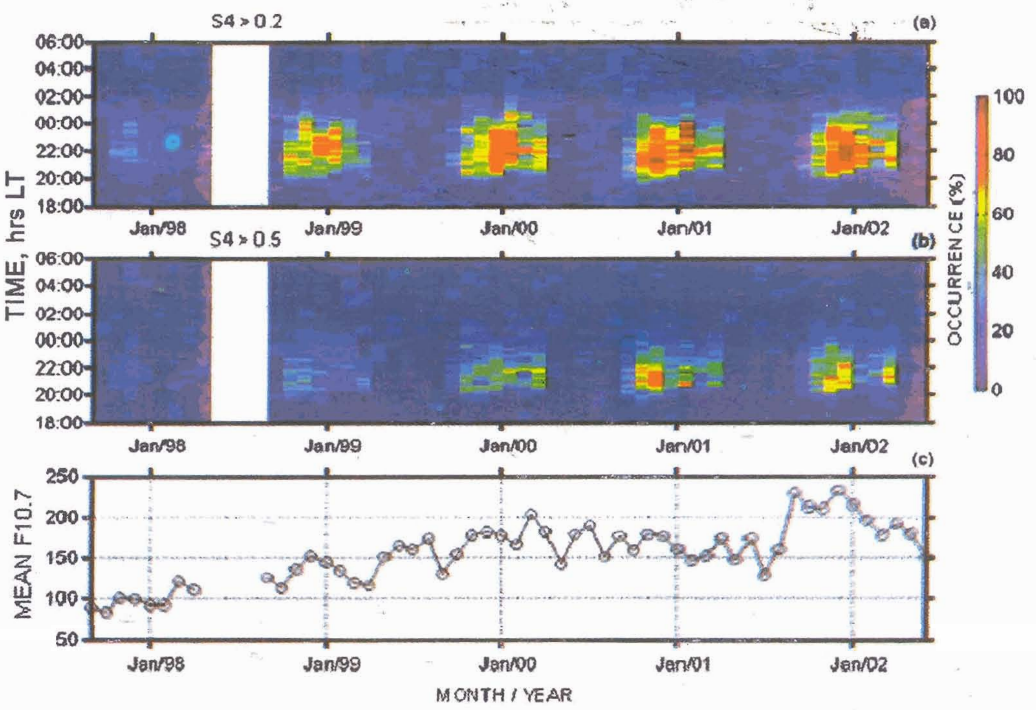

Fig. 2 — Scintillation percentage of occurrence from September 1997 to June 2002, at São José dos Campos, for two levels of scintillation indices as a function of LT and mean F10.7 cm solar flux index[16]

local time from 1800 hrs LT to 0600 hrs LT the next day at one-minute resolution. The upper panel shows the distribution of scintillation for S4 > 0.2 and the middle panel for S4 > 0.5 (strong scintillations). Data from GPS satellites with elevation larger than 45° were included in the analysis and the percentage of occurrence was calculated as the ratio of the minutes with scintillations to the total minutes of observation. Only data for magnetically quiet days (K_p <4 for each of the eight daily values) were used in the analysis.The monthly mean F10.7 cm solar flux is presented in the lower panel. Scintillations occur predominantly from September to March and from 2000 hrs LT till midnight. It can be observed in the upper panel that the percentage of scintillation occurrence generally increases with the increase in solar flux. Comparison between the upper and the middle panels shows that scintillation occurrence is smaller for stronger scintillations (S4 > 0.5). São José dos Campos is located at low latitudes so it takes about one-and-a-half hours for the bubble that is generated at the magnetic equator, to develop to topside and map along magnetic field lines to this site[14]. The large magnetic declination over Brazilian longitudes is responsible for the seasonal maximum in the scintillation to occur during the summer (December) solstice[9] as observed in Fig. 2. As São José dos Campos is located under the EIA southern crest, where the background ionization is large, the S4 amplitude is larger than at equatorial stations[15].

4 Latitudinal effect

Figure 3 presents spatial distribution along the satellite tracks (GPS signal ionospheric pierce points projections) of the S4 values over the Brazilian territory for 17 Mar. 2002 during the local time interval from 1800 hrs LT to local midnight. The circle diameters are proportional to the scintillation intensity and the colour code on the right represents the S4 values. It is clear from this figure that the scintillation intensity is larger under the southern EIA crest (that was located around –17° of dip latitude for this period) than in the equatorial region. There is not enough scintillation data coverage of the northern crest.

5 Longitudinal effect

To analyse the longitudinal effect on the ionospheric irregularities in the South American sector, the monthly percentage of ESF (range spread-F) occurrence as

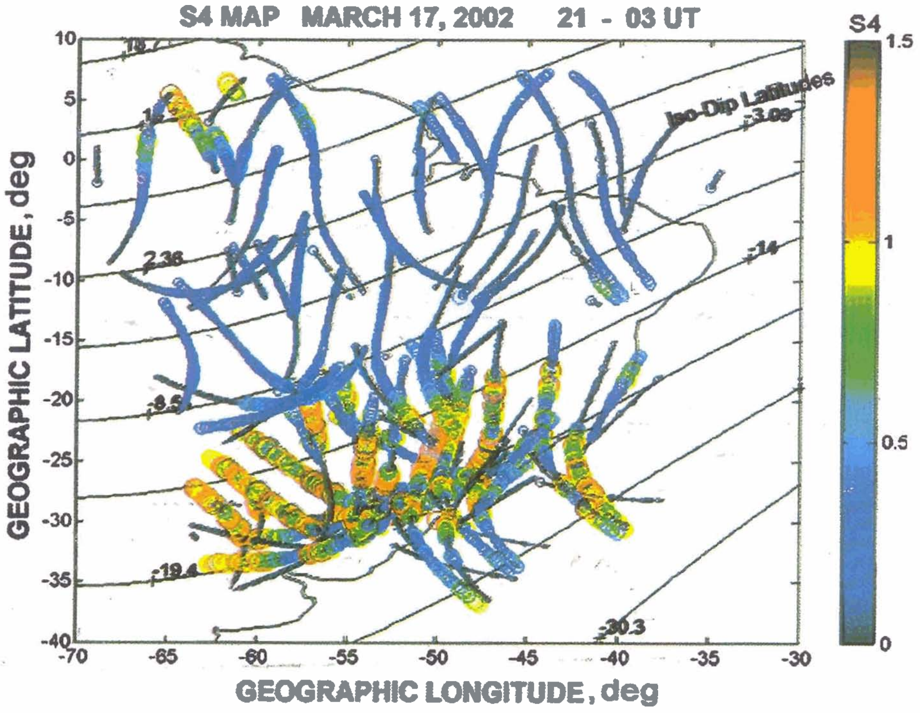

Fig 3 — Spatial scintillation (S4 index) distribution over Brazilian territory[16] for 17 Mar. 2002 for the time interval from 1800 to 2400 hrs LT obtained from digisonde data over Cachoeira Paulista (22.41° S, 45° W, dip latitude14.89° S) and from ionosonde data over Tucumán (27° S, 64.5° W, dip latitude 13.71° S) are presented as iso-lines of occurrence rates in month versus local time format[13] in Fig. 4. In this figure the ESF data are presented for four intervals: 1980-81 (average F10.7: 161.5) and 1988-89 (average F10.7: 173.8) representing solar maximum conditions, and 1984-85/1986-87 (average F10.7: 83.7/73.6) representing solar minimum conditions. Even though Cachoeira Paulista and Tucumán dip latitudes are almost the same there is a drastic longitudinal variation in the ESF/plasma bubble occurrence rate between these two sites, with much lower ESF occurrence at Tucumán. The magnetic declination at Cachoeira Paulista is about 21° W and Tucumán declination is about 0°. Evidences of the magnetic declination control of the seasonal ESF occurrences were presented by Abdu *et al.*[9,13], Batista *et al.*[10], Maruyama[17] and other authors.

In this paper the study of the longitudinal effects over the scintillation activity was restricted to the Brazilian/Argentinian sector. Tsunoda[18] developed a detailed study of the seasonal and latitudinal occurrence of equatorial scintillations for all longitude sectors. He showed that magnetic declination and the geographic latitude of the dip equator, which have large variation with the longitude sector, control the seasonal dependence of equatorial scintillation activity. According to Tsunoda[18] the occurrence of scintillation was found to maximize during times of the year when sunset at the conjugate points is most nearly simultaneous, and when complete E-region darkness occurred earliest in LT. He further showed that scintillation activity is associated with the gradient rather than with the value of the integrated E-region conductivity.

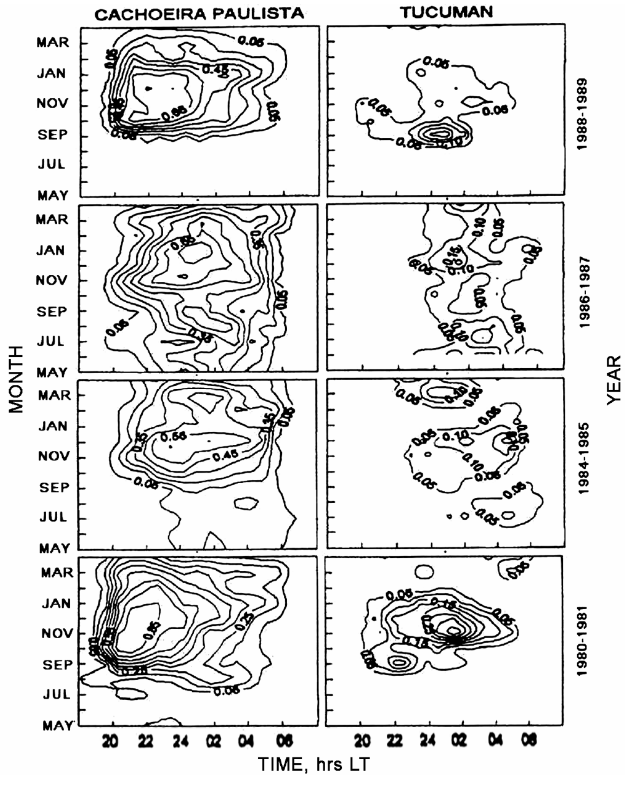

Fig. 4 — ESF at two longitudinal sectors in South America for solar minimum and maximum conditions[13]

6 Magnetic activity

The study of the characteristics of irregularities during magnetic storm gives insight into the role of electric fields of magnetospheric origin[19] in the irregularity process and is of interest in the impact on global VHF/UHF communication systems[20]. One important parameter responsible for the growth of ionospheric plasma instabilities after sunset is the equatorial upward vertical plasma drift[21], which is driven by the F-layer dynamo zonal (eastward) electric field, known as the pre-reversal electric field.

This paper shows two case studies of the local time influence of the zonal magnetospheric electric field penetration to equatorial latitude in the generation/inhibition of scintillation, during magnetic storms. A statistical study on this subject is underway.

During magnetic storms direct penetration of eastward magnetospheric electric fields, occurring during the post sunset hours can intensify the pre-reversal electric field thereby enhancing the irregularity process, or triggering irregularities, even during epochs outside of the irregularity season in Brazil (see for example, Abdu *et al.*[23]). One example of storm triggered irregularities that caused strong GPS scintillation outside of the irregularities season in Brazilian sector (September to March) is presented in Fig. 5. This figure shows, for 10-14 Apr. 2001, the D_{st} magnetic index in the top panel and the scintillation indices S4 for 6 different satellites and at the equatorial station of São Luís (2.33° S, 44° W, dip latitude 1.3° S). The SSC occurred at 13:43 UT on April 11, 2001 and the D_{st} reached its largest negative incursion at about 2400 hrs UT (2100 hrs LT) in the night of 11/12, when eastward magnetospheric electric field penetrated to magnetic equator. Large scintillations observed at GPS amplitude signals were

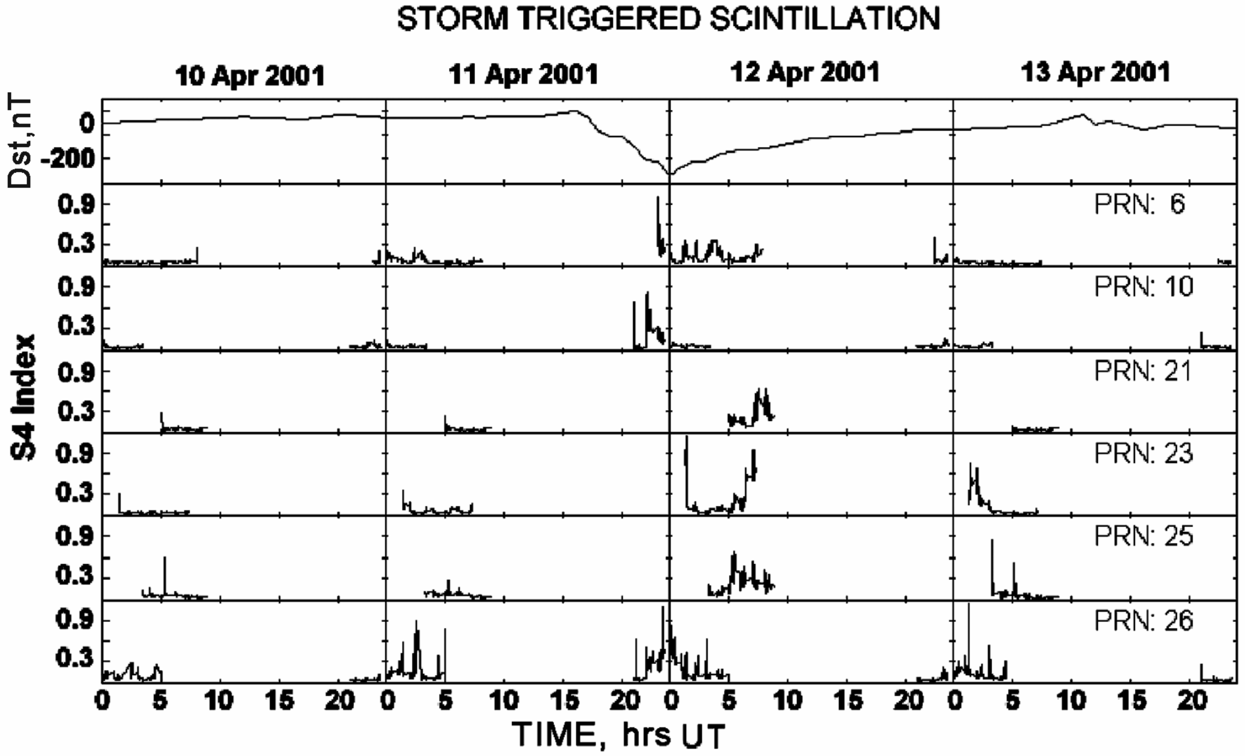

Fig. 5 — Storm triggered GPS scintillations for the 11 Apr. 2001 magnetic storm at the São Luís equatorial station

triggered in the night of 11/12 for the satellites 6, 10, 21, 23 and 25 and were intensified for the satellite 26. Multi-technique investigations of the ionospheric irregularities for this magnetic storm were presented by de Paula *et al.*[19].

Disturbance dynamo westward zonal electric fields during some magnetic storms[23,24] can reach low latitudes with a delay of 9-30 h after the storm onset and reduce the plasma upward drift during day and downward drift during night. In this way the pre-reversal vertical drift peak is inhibited/reduced in amplitude and, as a result, the ionospheric irregularity generation is weakened or inhibited. One example of such inhibition of irregularity generation is shown in Fig. 6 during the magnetic storm of 20-22 Nov. 2003. This figure presents the D_{st} variation in the upper panel and the S4 scintillation index over São José dos Campos (23.21° S, 45° W, dip latitude 17.8° S) for eight GPS satellites during the days 19-22 Nov. 2003 in the lower panel. Strong GPS scintillations were observed in the nights of 18/19 and 19/20 Nov. 2003 previous to the SSC and in the night of 21/22 during the storm recovery phase. In this example the storm energy deposition occurred during daytime hours and the westward disturbance dynamo electric field was present at low latitudes during the post-sunset hours inhibiting the pre-reversal electric field enhancement and hence the irregularity development.

7 Small scale ionospheric irregularity zonal velocity

Using a system of two GPS receivers spaced by 55 m in the magnetic east-west direction, the zonal drift velocities of the small scale (~400 m) ionospheric irregularity were calculated for Cachoeira Paulista (under the EIA crest) during December 1998, January and February 1999. A cross-correlation method was used to determine the offsets between the amplitude patterns of the signal intensities from the two spaced receivers for maximum correlation. The calculation of the zonal drift velocity from the offset values assumed a subionospheric point (ionospheric pierce point) at 350 km in all calculations[12, 25]. Figure 7 shows the average zonal irregularity velocity and their standard deviation. Only data from satellites with elevation angles larger than 40° and with maximum values of cross-correlation functions larger than 0.9 were used in the calculations.The irregularity velocities were eastward with amplitudes of about 150 m/s around 2000 hrs LT, 130 m/s at midnight, and decrease after midnight. The zonal drift velocities presented a large scatter. This scatter is due to the

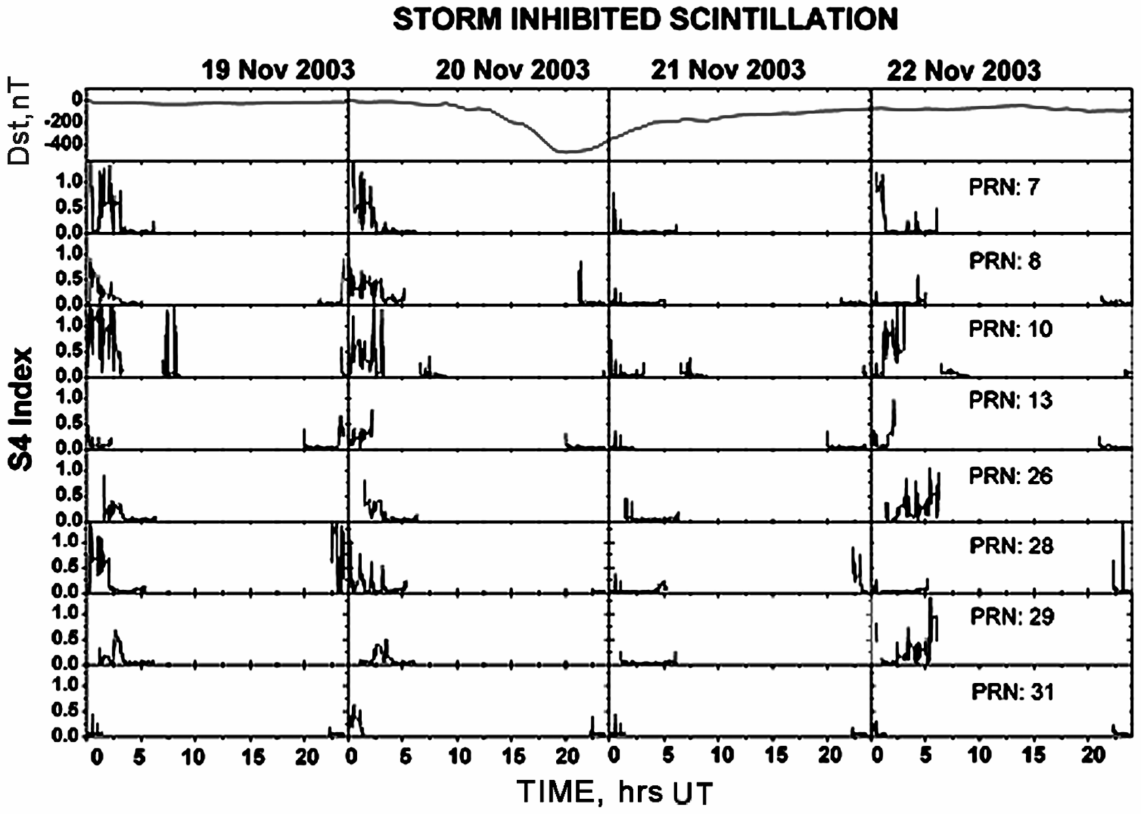

Fig. 6 — Disturbance dynamo westward electric field GPS scintillation inhibition for the 20-22 Nov. 2003 magnetic storm at São José dos Campos

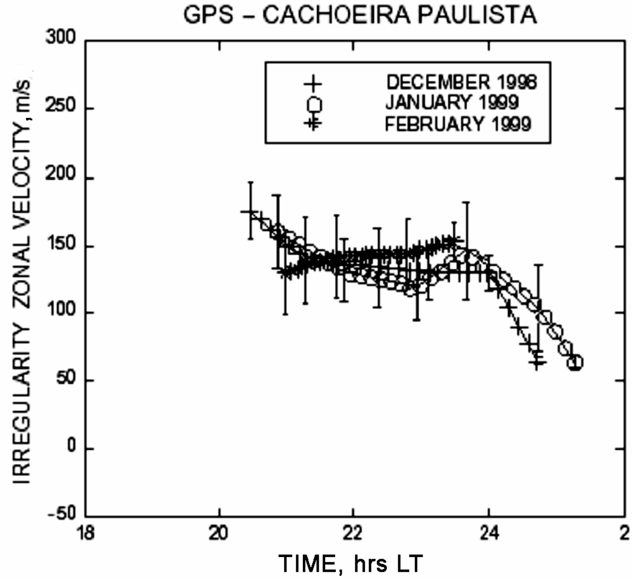

Fig. 7 — Small scale average zonal velocities and their standard deviations for December 1998, January and February 1999 at Cachoeira Paulista, inferred from spaced GPS receivers[12]

vertical movement of the irregularities during their growth phase and other factors discussed by de Paula *et al.*[12]

The irregularity zonal velocities normally have eastward movement relative to the ground and during some magnetic storms this movement changes to west[22]. However some rare cases of bubbles moving to west during magnetically quiet nights have also been reported by Sobral *et al.*[26].

8 Effects of ionospheric irregularities over positioning and navigation

Ionospheric irregularities can cause a significant impact on precise positioning applications[7, 27] and can affect drastically the GPS performance causing losses of lock in the GPS signal, increasing in the GDOP (Geometric Dilution of Precision) and decreasing the number of available GPS satellites. In sections 8.1 and 8.2 these potential effects will be presented and discussed.

8.1 Loss of lock

During the occurrence of strong irregularities there are large phase and amplitude scintillations (called fades) in the GPS signal and when the fades are deep enough and long enough there are possibilities of occurrence of loss of lock or lengthening of acquisition times[28]. The necessary receiver amplitude level for the receiver[28] to maintain lock is 26-27 dB. Figure 8 shows two examples of short duration (around 2126 hrs LT) losses of lock and one long duration (64 s) loss of lock that occurred on 6 Dec. 2001 at São José dos Campos.

8.2 GDOP and decrease of available satellite number

Figure 9 shows the S4 scintillation indices (the thin continuous line in the upper panel is the largest S4 for that time period), the number of losses of lock, the number of available GPS satellites and the GDOP for the night of 4/5 Oct. 1998 at São José dos Campos. S4 values larger than 1.41 are errors generated during the data processing. The GDOP is a scalar factor based on the satellite geometry that maps the individual satellite ranging error to the error in the receiver position. Smaller values of GDOP yield more accurate receiver positions. To obtain the best navigation solution, it is desirable to obtain a set of six or more satellites available. The author here consider $\text{GDOP} \leq 4$ as optimum geometry, $\text{GDOP} \geq 5$ and $\text{GDOP} \leq 8$, acceptable, and $\text{GDOP} \geq 9$, representing a poor geometry. From about 2320 and 2420 hrs LT the number of available satellites decreased to 4 many times, which is considered a very critical situation for a reliable GPS performance. Also during this time interval GDOP reached very high values ($\text{GDOP}>9$) meaning poor GPS satellite geometry for an accurate navigation solution.

9 Map of S4 over Brazil

To follow the bubble time evolution over the Brazilian territory during the night of 17/18 Mar. 2002, S4 maps were generated for each 10 min using data from the SCINTMON network (Fig. 1). The S4 index was interpolated using deterministic models. The S4 mapping methods are described in more details in the paper of de Rezende[30]. Fig. 10 presents the bubbles evolutions, represented by the S4 index, for some selected local times (at the 45° W longitude) and dots are the ionospheric pierce points projections whose S4 values were used in the interpolation. The sites of São Luís (magnetic equator) and São José dos Campos (crest of EIA) are marked as red stars.The S4 begins to increase close to the magnetic equator after sunset with an apparent westward movement due to the terminator passing. At 2100 hrs LT one bubble signature (dark yellow) tilted along the magnetic field line (due to the large declination at this region) is covering the Brazilian territory. At 2110 hrs LT this structure has moved to east relative to the ground. After this time the intensities of the irregularities represented by S4 begin to decline.

10 Suggestions to mitigate scintillations effects over SBAS

To mitigate ionospheric scintillation effects over the SBAS (Space Based Augmentation System) it is necessary to increase the number of available satellites (Galileo for instance). This is necessary to build more robust GPS receivers decreasing the bandwidth of receivers and to implement real time scintillation detectors to flag areas where large error in the GPS system could occur. Also a carefully selection of the geostationary SBAS satellite locations[31] with adequate longitudinal separation could mitigate effects of the ionospheric scintillations on the GPS performance, increasing its continuity and service availability.

11 Conclusions

In this paper the most important characteristics of the small scale (~ 400 m) ionospheric irregularities over the Brazilian territory are presented based on GPS L1 band signal intensities, which present strong scintillations during such irregularities. Also the potential effects of such irregularities over the GPS system performance are presented.

The small scale irregularity characteristics over the Brazilian region are as follows:

(i) They occur predominantly from September to March and can occur at any epoch of the year during magnetic storms
(ii) Their occurrence and intensities increase with the increase in solar flux values
(iii) Their intensities measured by the S4 scintillation index increase with the ionospheric background ionization and consequently present the largest intensities under the southern EIA crest
(iv) They occur in the sunset–midnight local time sector during magnetically quiet period and extend to the midnight-sunrise sector during some magnetic storms
(v) They present a large longitudinal variation in the South American sector with higher occurrence of irregularities in the Brazilian sector compared to the Argentinian sector due to the large magnetic declination variation that characterizes this region

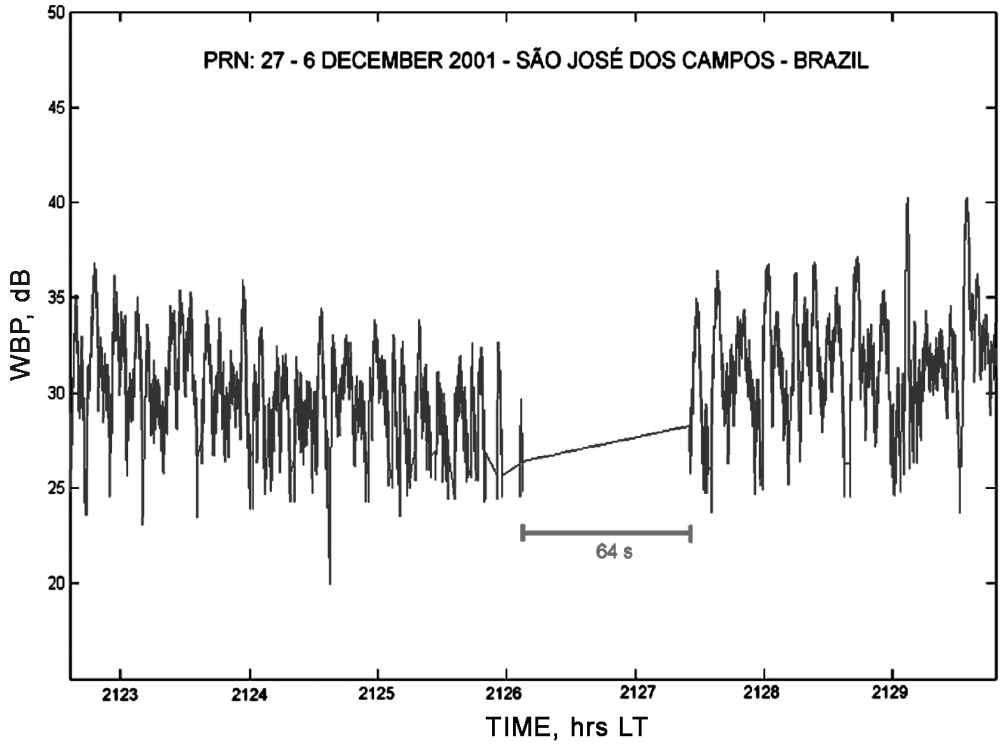

Fig. 8 — Examples of loss of lock during ionospheric scintillations[29]

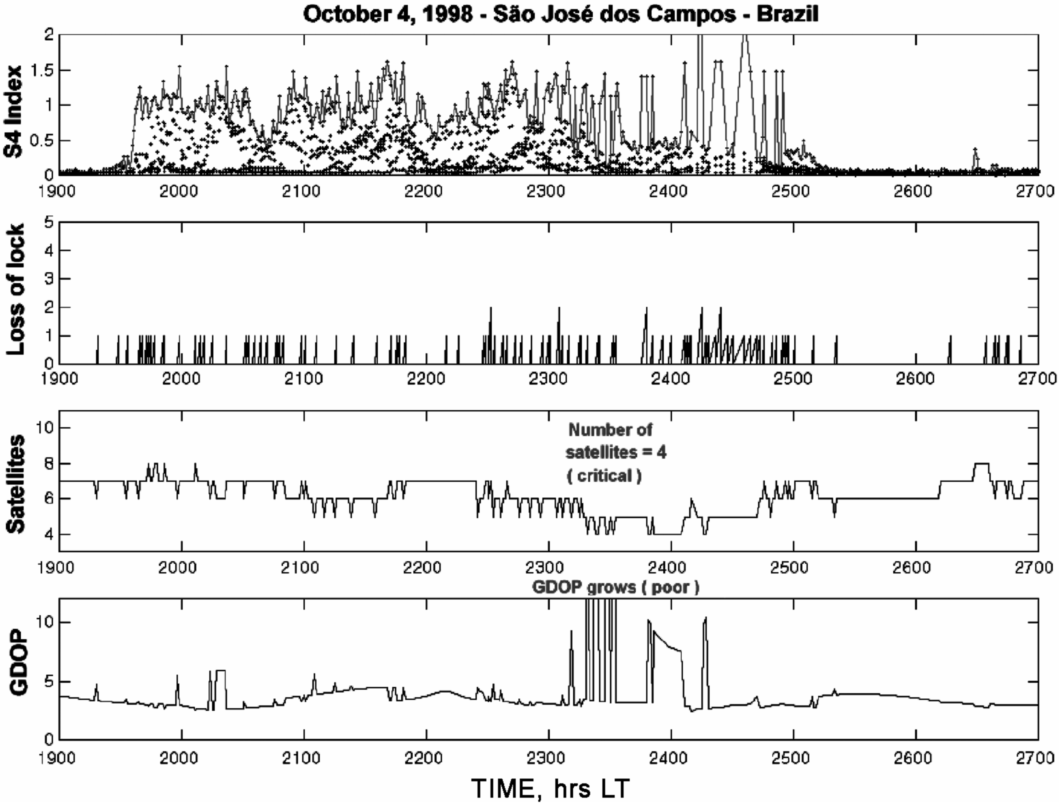

Fig. 9 — S4 scintillation indices (thin continuous line in the upper panel is the larger S4 for that time), the number of losses of lock, the number of available GPS satellites and the Geometric Dilution of Precision (GDOP) for the night of 4/5 Oct. 1998 at São José dos Campos

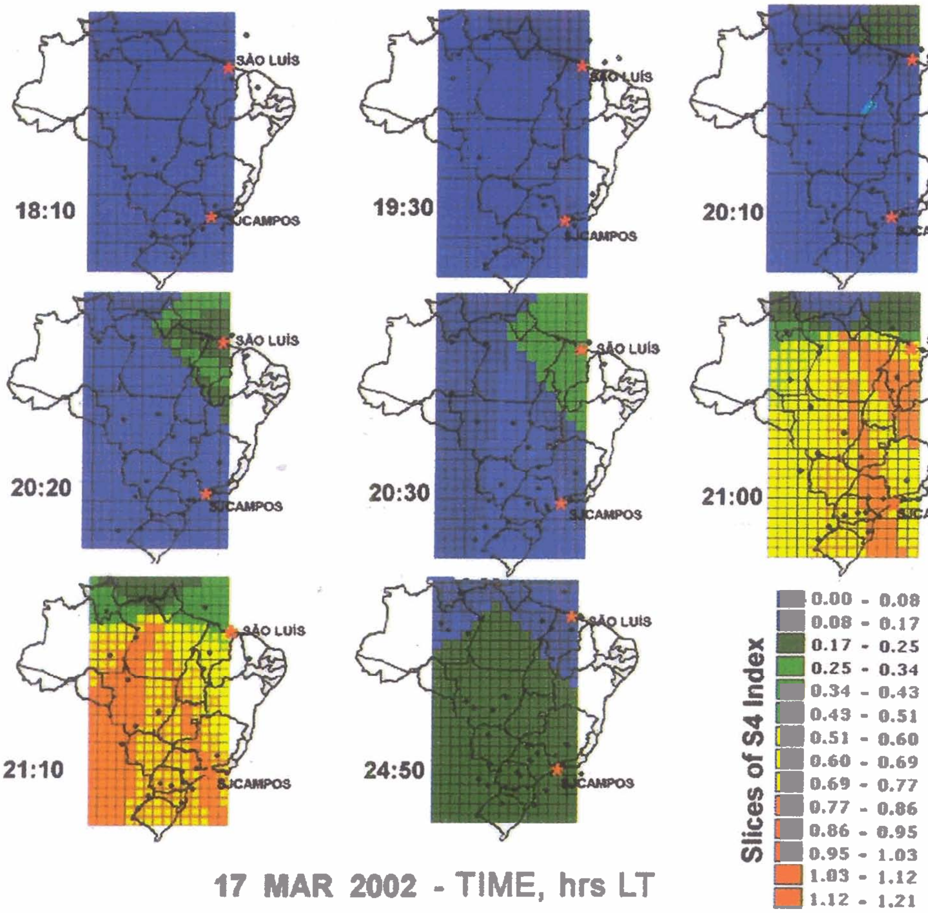

Fig. 10—S4 scintillation indices time and spatial evolution over Brazil for the night of 17/18 Mar. 2002

(vi) They are suppressed during magnetic storms with main phase occurring during daylight, and several hours prior to sunset, causing the disturbance dynamo electric fields to reach the equatorial latitudes and leading to the inhibition of the pre-reversal electric field.

(vii) They can also be triggered or intensified during any season when magnetic storm main phase, and therefore eastward electric field penetration to equatorial latitudes coincides with the pre-reversal electric field enhancement peak hours.

(viii) Their zonal velocities under the EIA crest for the December 1998 to February 1999 period were eastward with values of about 150 m/s around 2000 hrs LT, 130 m/s around midnight, and decrease after midnight. During some magnetic storms westward drifts are also observed in the post-midnight sector.

Ionospheric irregularities can affect the GPS positioning and navigation due to losses of lock during strong scintillations, what increase the GDOP and decrease the number of available GPS satellites. To mitigate these effects it is suggested to increase the number of available satellites (Galileo), to decrease the bandwidth of the GPS receivers, to implement real time scintillation detectors as a warning system and to select carefully the positioning of the geostationary SBAS satellites.

Ionospheric irregularities present large day-to-day variabilities and they depend on local time, season, solar cycle activity and magnetic activity, so many aspects of their generation and evolution still remain to be clarified and more in-situ and remote measurements need to be performed.

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