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Latitudinal variations of scintillation activity and zonal plasma drifts in South America

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[1] Latitudinal variations of scintillation activity and zonal plasma drifts were investigated simultaneously at three locations in Brazil during 23 November to 26 December 1999 using Global Positioning System measurements. The scintillation morphology at 1.575 GHz showed large latitudinal differences in scintillation activity. At the magnetic equator the occurrence probability was very low without showing strong scintillation ($S_4 > 0.5$) during the solar maximum period, whereas strong scintillation was observed during most of the days at the equatorial ionization anomaly (EIA). The scintillation activity was mostly limited to 1900–2400 LT at the magnetic equator and to 2000–0200 LT at the EIA. The scintillation onset time delay of about an hour at the EIA compared to that at the magnetic equator illustrates the development of ionospheric irregularities at the magnetic equator and then their expansion to higher latitude by drifting upward. The zonal velocities of the ionospheric irregularities were inferred using the cross-correlation technique, and the eastward velocity of all observations decreased with local time. However, the zonal velocity magnitude also decreased in proceeding from the magnetic equator to the EIA, which indicates negative vertical shear of the eastward plasma drift velocity at nighttime in the equatorial ionosphere. *INDEX TERMS:* 2415 Ionosphere: Equatorial ionosphere; 2437 Ionosphere: Ionospheric dynamics; 2439 Ionosphere: Ionospheric irregularities; *KEYWORDS:* equatorial spread F, scintillation, zonal velocity, vertical shear

1. Introduction

[2] While radio scintillations are problematic in radio communications, they have been exploited as a tool to study ionospheric conditions. Season-longitudinal morphology of the equatorial spread *F* phenomenon was identified from the long-term observations of scintillation activity at numerous radio stations in the low-latitude region [*Tsunoda*, 1985; *Aarons*, 1993]. The ionospheric zonal velocity can be estimated from the time delay of scintillation patterns in the presence of electron density irregularities [*Basu et al.*, 1991, 1996; *Valladares et al.*, 1996; *Kil et al.*, 2000]. The measured zonal velocities varied with magnetic latitudes [*Abdu et al.*, 1985; *Aggson et al.*, 1987; *Coley and Heelis*, 1989; *Basu et al.*, 1996], and the latitudinal difference of them was understood as an indication of vertical shear of the bulk zonal plasma flow because of the extended nature of the ionospheric irregularities along the magnetic field. However, the latitudinal gradient of the zonal velocities was different from measurement to measurement. Since the zonal velocity is variable with ionospheric conditions, seasons, locations, and measurement techniques, measuring the zonal velocities simultaneously using the same technique is required to understand the variability.

[3] The establishment of Global Positioning System (GPS) enables measurement of the zonal velocity simultaneously at worldwide locations. Cornell GPS receivers were developed to log the signal amplitude of GPS L1 frequency (1.5 GHz) at 50 samples/s rate [*Beach*, 1998] and distributed at several places in South America. In cooperation with Instituto Nacional Pesquisas Espaciais (INPE) in Brazil the Cornell space physics group conducted a GPS campaign for a month in

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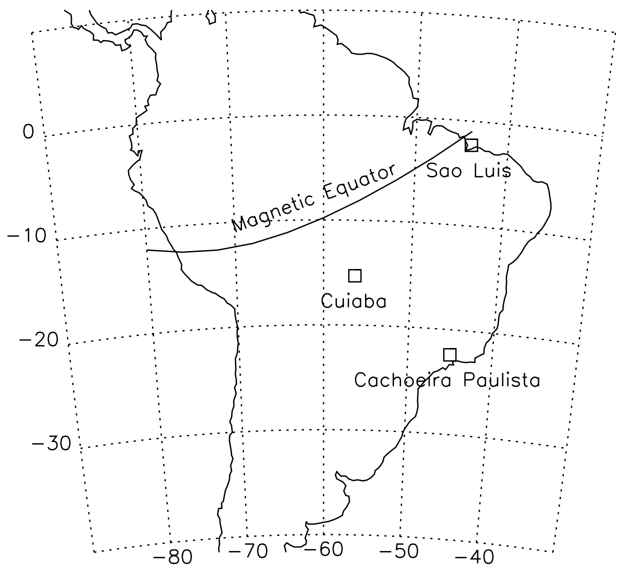

Figure 1. Locations of Cornell GPS stations in Brazil.

November–December 1999 at three stations, São Luís (SL) (2.3°S, 44.0°W, dip latitude 1.3°S), Cuiabã (15.3°S, 56.4°W, dip latitude 6.1°S), and Cachoeira Paulista (CP) (22.4°S, 45.0°W, dip latitude 17.8°S). At each station, receivers were spaced east west magnetically 70 m at SL, 37 m at Cuiabá, and 55 m at CP. Figure 1 shows the locations of GPS stations. Each station is separated about 8° in magnetic longitude, but all stations have large westward magnetic declinations (SL, 20.7°W; CP, 20.4°W; Cuiabá, 14.4°W). In this paper we investigated the scintillation activity at the three latitude regions and the latitudinal variations of zonal plasma drift velocity.

2. Results and Discussion

[4] The GPS campaign was conducted during the most pronounced spread *F* season (23 November to 26 December 1999) in the Brazilian sector during a solar maximum period. As an indicator of scintillation strength, we calculated S_4 index, defined as the ratio of the standard deviation of signal intensities to their average, every 1 min. The scintillation level is determined by the irregularity amplitude and the background plasma density integrated over the thickness of the irregularity layer. Because of the movements of GPS satellites the path length that the radio wave passes through varies with satellite elevations, which significantly affects the calculated S_4 index. To minimize the contribution of geometric factor to the S_4 index, we only included observations made above 40° elevations. The daily variations of scintillation occurrence probability at the three stations are presented in Figure 2. Here the occurrence probability is defined as the percentage of events (S_4 > 0.1 or S_4 > 0.5) over all the observed data points during the time interval (between 2100 and 2300 LT) from all satellites above 40° elevations (normally three or four satellites). The scintillation strength and occurrence probability become larger in proceeding from the magnetic equator (SL) to the equatorial ionization anomaly (EIA) at CP where the maximum plasma density is formed. Comparison with the previous GPS observations at CP (they are not presented here) showed a notable enhancement of scintillation activity at the EIA with an increase of sunspot number.

[5] Since we started data collection during this campaign at SL, we cannot confirm how much the scintillation activity was enhanced at the magnetic equator with an increase of solar activity. However, considering the low occurrence probability and absence of strong scintillations at SL, it is expected that the scintillation activity at 1.6 GHz is more influenced by the solar activity at the EIA than that at the magnetic equator. That is, the enhancement of the background ionization density is much more pronounced at the EIA than at the magnetic equator because of stronger plasma transport from the equator to the EIA during the solar maximum [*Anderson*, 1973]. It should be noted that the scintillation strength increases with a decrease of the transmitted radio frequency. *Basu et al.* [1996] observed strong 250 MHz scintillations at Ancon (magnetic latitude (MLAT) 1.46°N) in Peru even during the solar minimum period. The scintillation level was comparable to that at Agua Verde in Chile (MLAT 11.3°S) during the same period. The scintillation strength at gigahertz frequencies responded more sensitively to the change of the background electron density induced by the change of solar activity, although over all, scintillation strength at 1.6 GHz is much lower than that at 250 MHz. The daily variations of scintillation activity did not show good correlations at the three stations. As an example, the occurrence probabilities at SL were very low on days 351–355 compared to those at Cuiabá and CP. During those days, K_p index was below 3°, and therefore it may not be attributed to the magnetic disturbance effect. Since the stations are separated by long distances, the day-to-day spread *F* occurrence may be controlled by the local ionospheric conditions rather than by the transport of the irregularities from the west.

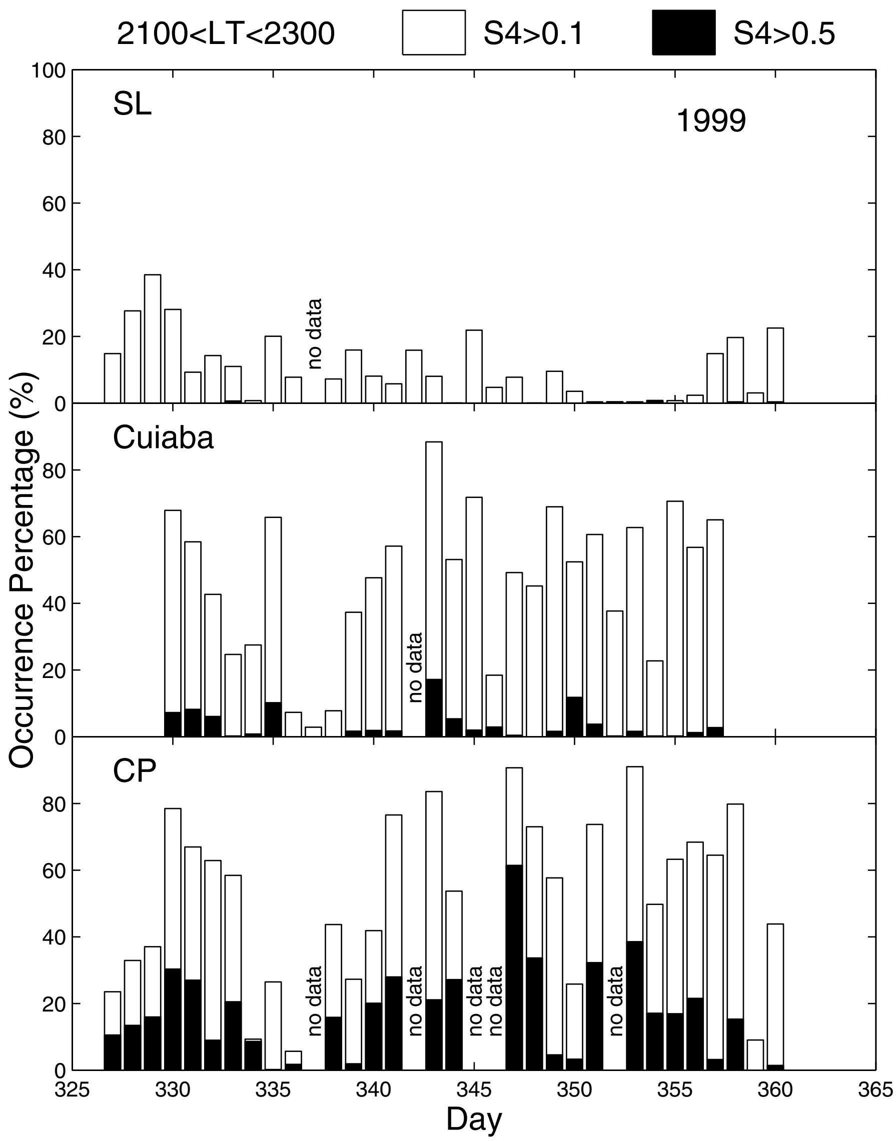

Figure 2. Daily variations of scintillation activity during the campaign period.

[6] Figure 3 shows the local time distributions of scintillation activity. The scintillation activity at gigahertz frequencies is mostly concentrated during premidnight hours. The radio scintillation at 1.6 GHz is predominantly produced by the electron density irregularities of 400 m horizontal scale. Since the small-scale irregularities decay faster than the large-scale irregularities [*Basu et al.*, 1978; *Kil and Heelis*, 1998] by cross-field diffusion the scintillation activity at 1.6 GHz is much reduced after midnight compared to 250 MHz. As was shown in Figure 2, the strong scintillation activity (S_4 > 0.5) is negligible at the magnetic equator. The scintillation onset time at SL and Cuiabá occurred at 1850–1910 LT, while that at CP occurred at 1950–2000 LT. There is an onset time delay of about an hour at the EIA. The ionospheric irregularities develop on the bottomside *F* region at the magnetic equator, and then they can appear at a higher-latitude region as the low-density plasma drifts upward. Irregularities can be observed at 17° magnetic latitude when the plasma bubbles have achieved an apex height of about 1000 km. The time that the irregularities drifted from the bottomside *F* region to 1000 km appeared as an onset time delay between the magnetic equator and the EIA.

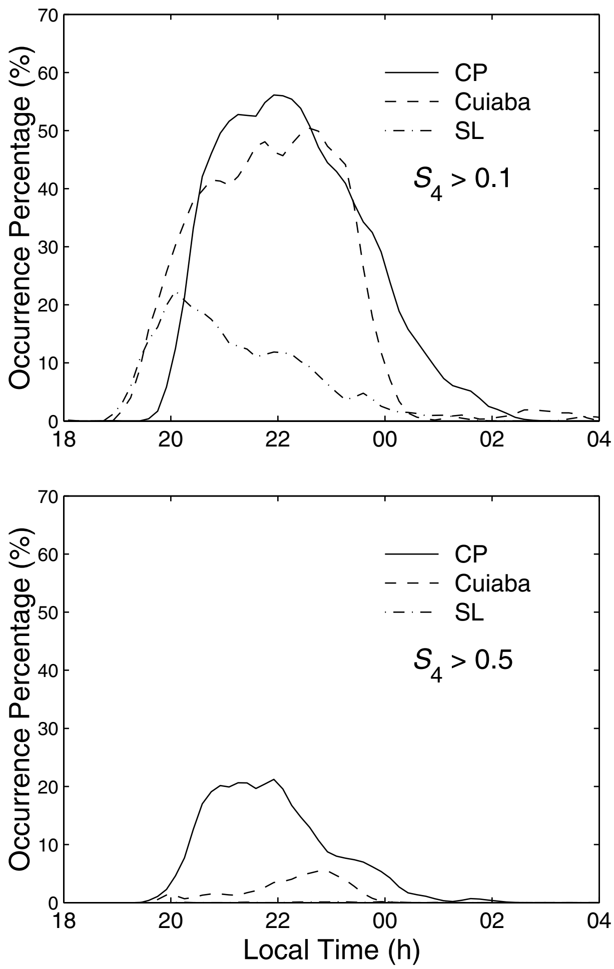

Figure 3. Local time distributions of scintillation activity.

Considering the eastward drift of the ionosphere during nighttime, there is a possibility that the irregularities that passed over CP and SL originated from Cuiabá. In that case, we have to take into account the zonal drift as well as upward drift in the time delay. However, it takes more than 80 min for the irregularities to drift from Cuiabá to CP assuming 1000 km distance with 200 m/s eastward velocity. Then the zonal drift time becomes longer than the onset time delay between the two places, which implies that there were already locally generated irregularities before the irregularities originated at Cuiabá arrived at CP. Irregularities can be generated at any longitude region, and therefore the onset time delay purely reflects the time of vertical drifts on average. The onset time delay between SL and Cuiabá is just a few minutes. The relatively short time delay is because of the small difference of the apex heights between the two places and may be also because of the large vertical drift velocity of plasma bubbles near the *F* peak. As the bubbles drift upward, the density gradient between the bubble and the background decreases owing to the decrease of background plasma density. Then the polarization electric field produced by the gravitational Rayleigh-Taylor instability decreases with altitude, which reduces the $\mathbf{E} \times \mathbf{B}$ vertical drift velocity at higher altitude.

[7] Using spaced receivers, we inferred the zonal velocities of the ionospheric irregularities. For a rigorous calculation of the true zonal velocity we have to take into account the random motions of the irregularities. However, the characteristic random velocity is normally less than 10 m/s and rapidly decreases as the night progresses [*Spatz et al.*, 1988]. So the apparent zonal velocity inferred under the assumption of frozen-in irregularities during a few seconds may be well approximated to the true zonal velocity. Practically, for our observations, the decorrelation between scintillation patterns was dominated by the noise rather than by the random motion of irregularities. The zonal velocities described below imply the apparent zonal velocity without using the term "apparent." Figure 4 shows the average velocities within hourly bins during the campaign period. In this analysis, we included data of cross-correlation index greater than 0.7. The standard deviations of the velocity at CP are also presented as error bars. All observations show that the velocity decreases with local time, which agrees with previous observations at Jicamarca [*Fejer et al.*, 1991]. At the magnetic equator the zonal velocity was 190 m/s at 2000 LT and 150 m/s at 2400 LT. At the EIA it was 165 m/s at 2000 LT and 120 m/s at 2400 LT. On average, the zonal velocity at the EIA is smaller by about 30 m/s than that at the magnetic equator. The differences were mostly within the error bars, but the daily and monthly average velocities showed a consistently negative latitudinal gradient of the zonal velocity. The velocities at different latitudes can be projected at different heights on the equatorial plane. If the longitudinal variations of the zonal velocities are negligible in the regions of the same magnetic declination, then the latitudinal variations of the zonal velocities indicate a vertical shear of the zonal plasma flow. Since the irregularities drift zonally often with comparable velocity to the ambient plasma, they can be used as tracers of the background ionosphere. Our observations show negative latitudinal gradient of the zonal velocity and

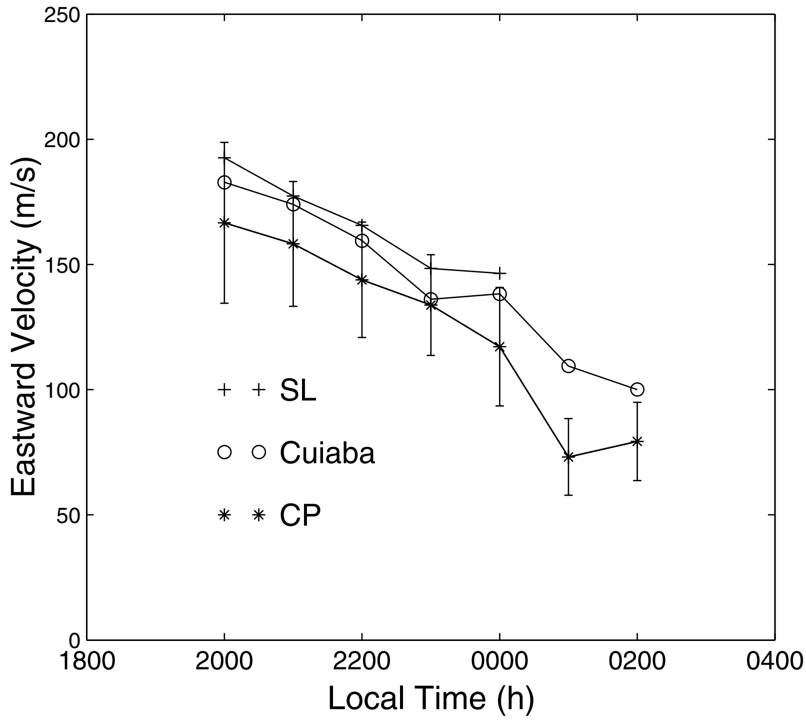

Figure 4. Average zonal velocities of a month at the three stations.

therefore negative vertical gradient of the zonal plasma flow on the topside of the *F* region.

[8] The nighttime ionospheric zonal drift in the equatorial region is mainly controlled by the *F* region dynamo electric field induced by the zonal neutral wind. Eastward neutral wind at nighttime generates a vertically downward polarization electric field and causes the plasma to drift eastward in the **E** × **B** [*Kelley*, 1989] direction. Owing to the high conductivity along a magnetic field line the plasma drift is governed by the electric field generated by the flux tube integrated currents. *Anderson and Mendillo* [1983] showed that the zonal velocity of the flux tube is expressed as a product of the zonal neutral wind velocity and the Pedersen conductivity integrated along the field line. Their model showed an opposite altitudinal profile of the zonal plasma drift in the topside *F* region depending on the assumed neutral wind velocity. That is, the eastward plasma drift velocity increased with increasing altitude when they assumed latitudinally constant eastward neutral wind velocity, whereas it decreased with increasing altitude when they input decreasing wind velocity with increasing latitude. The model calculation implies that the latitudinal profile of the eastward neutral velocity plays a crucial role to the observed vertical shear or latitudinal gradient of the zonal plasma flow. The DE 2 satellite measurements clearly showed an anticorrelation of the electron density and the eastward wind velocity in the equatorial region [*Raghavarao et al.*, 1991]. That is, the eastward wind velocity was maximum at the magnetic equator and was minimum at the EIA. This latitudinal variation of the zonal wind velocity is associated with the latitudinal variations of the ion drag force due to the development of peak plasma density at the EIA. Since the development of EIA is closely related to the solar activity, the latitudinal variations of the wind velocity and, consequently, the zonal plasma drift velocity are considered to be dependent on solar cycle.

[9] More evidence of the negative vertical shear of the zonal plasma drifts can be found from the westward tilt of the plumes often observed over Jicamarca [*Woodman and La Hoz*, 1976]. Since the eastward velocity of the irregularities, which are assumed to drift with comparable velocity to the ambient plasma, decreases with an increase of altitude, the westward tilt will increase with increasing time. Alternatively, the westward tilt of the plume can be explained by assuming a reduced polarization electric field inside the plume owing to the reduced plasma density. Then, the **E** × **B** eastward drift velocity inside the depleted region becomes smaller than

that in the ambient background plasma, which causes westward tilt of the depletions as they rise [*Woodman and La Hoz*, 1976]. This mechanism does not require latitudinal gradient of the zonal neutral wind velocity but implies differential zonal velocities between the irregularities and ambient plasma. Effectiveness of either mechanism on the westward tilt may depend on the development of the EIA, which causes large latitudinal gradient of the zonal wind velocity, and the density depletion level of the plasma bubbles, which reduces the electric field inside the bubble.

3. Summary

[10] We investigated latitudinal differences of scintillation activity and zonal plasma drift velocity using 1.575 GHz amplitude scintillation measurements at three GPS stations in Brazil. The scintillation occurrence probability was very low, and strong scintillation activity ($S_4 > 0.5$) was totally absent at the magnetic equator, although the campaign was conducted during the spread *F* season in the Brazilian sector during the solar maximum period. This contrasted with the strong scintillation activity at the EIA during most of the days. Compared to previous observations between the solar minimum and solar maximum periods, the enhancement of scintillation activity at the EIA was pronounced with increasing solar activity. Different scintillation occurrence patterns at the three stations imply that the irregularities observed at each station are primarily produced locally rather than transported from the west. Therefore the scintillation onset time delay at the EIA indicates the time required so that the irregularities generated at the magnetic equator can reach a higher apex height and appear at the EIA.

[11] Simultaneous measurements of the zonal plasma drift velocities using the same technique during the same period minimized the possible errors caused by ionospheric conditions and by measurement technique. Our observations consistently showed maximum eastward irregularity drift velocity at the magnetic equator and its minimum at the EIA during 2000–0200 LT. The negative latitudinal gradient implies decreasing eastward velocity with increasing altitude when it is projected in the equatorial plane. This observation agrees with the westward tilt of the plasma bubbles often observed over Jicamarca.

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