Day-to-day variability in the development of plasma bubbles associated with geomagnetic disturbances

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[1] The development of equatorial ionospheric irregularities into large-scale ionospheric plasma bubbles continues to be an active area for scientific investigations. In this paper, we present simultaneous OI 630.0-nm emission all-sky imaging observations carried out at the Astrophysics National Laboratory (LNA), Brazopolis (22.5°S, 45.6°W, altitude 1860 m) and ionospheric sounding observations carried out at Palmas (10.2°S, 48.2°W; located close to the magnetic equator) and Sao Jose dos Campos (23.2°S, 45.9°W; located under the southern crest of equatorial ionospheric anomaly, close to Brazopolis), Brazil, to study the day-to-day variability in the development of ionospheric plasma bubbles during both geomagnetically disturbed and quiet periods in September–October 2002. Also, we present simultaneous complementary phase fluctuation (ROT) data obtained from the global position system (GPS) meridional chain operated by the Brazilian Institute of Geography and Statistic (IBGE). On the three nights studied in the present investigation (one geomagnetically quiet and two geomagnetically disturbed), it has been observed that the geomagnetic disturbances, during this spring equinox period, have a strong effect on the generation and development of ionospheric plasma bubbles.

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1. Introduction

[2] The nighttime phenomenon of plasma irregularities in the equatorial F region ionosphere caused by the plasma instabilities are called equatorial spread F (ESF). ESF takes its name from the range or frequency spread in ionograms and usually occurs just after local sunset with the scale sizes of the irregularities ranging from centimeters to hundreds of kilometers.

[3] The general morphological features, such as the variability of ESF with local time, season, geographical location, solar activity and geomagnetic activity conditions, have been extensively reported by several researchers [e.g., *Chandra and Rastogi*, 1972; *Woodman and LaHoz*, 1976; *Sastri et al.*, 1979; *Fejer and Kelley*, 1980; *Abdu et al.*, 1981; *Aarons*, 1993; *Fagundes et al.*, 1999; *Fejer et al.*, 1999; *Sahai et al.*, 2000, 2004a, 2004b, 2007; *Hysell and Burcham*, 2002; *Pimenta et al.*, 2003]. However, the accurate forecasting of ESF on a day-to-day basis, which is an essential requirement for satellite-based communication and navigational systems, is still far from reality, owing to the enigmatic day-to-day randomness in their occurrence.

[4] Many researchers [e.g., *Tsunoda et al.*, 1982; *Zalesack et al.*, 1982; *Kelley*, 1989; *Sultan*, 1996], based on the previous investigations, have proposed that the basic mechanism of both ESF and development of plasma bubbles is the gravitational Rayleigh-Taylor (GRT) instability and the E X B instability [*Kelley*, 1989; *Abdu*, 2001].

[5] However, it is known that there are some conditions that contribute to the generation and development of ESF irregularities. These are the prereversal enhancement in upward E X B drift and associated uplifting of the F layer around sunset time [*Rishbeth et al.*, 1978; *Fejer et al.*, 1999; *Whalen*, 2002]; the transequatorial component of the thermospheric winds [*Maruyama and Matuura*, 1984; *Muruyama*, 1988; *Mendillo et al.*, 1992, 2001]; a sharp gradient at the bottom side of the F layer [*Kelley*, 1989]; and a simultaneous decay of the E region conductivity at both ends of the magnetic field line [*Tsunoda*, 1985; *Stephen et al.*, 2002].

[6] In this paper we consider a relevant role played by geomagnetic disturbances on the day-to-day variability in the generation and development of plasma bubbles during spring equinox period of relatively high solar activity, as observed by the OI 630 nm all-sky imaging system, digital ionosondes, and GPS equipment over equatorial and low

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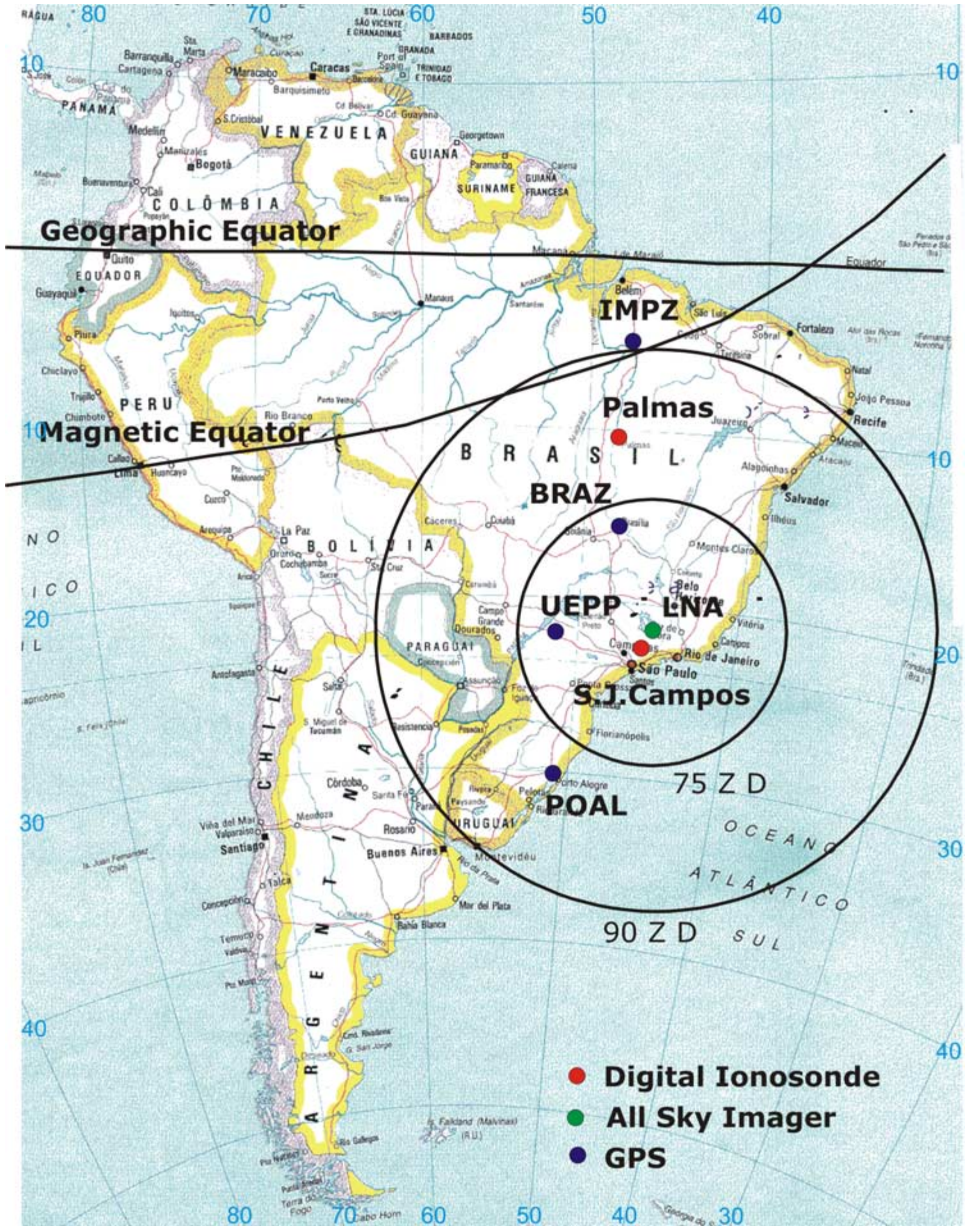

Figure 1. Locations of observatories used to study equatorial plasma depletions. The red points show the two digital ionosonde stations: Palmas (10.2°S, 48.2°) and Sao Jose dos Campos (23.2°S, 45.9°W); the blue points show the four observatories of the Brazilian Network for Continuous Monitoring (''RBMC''): Imperatriz (IMPZ; 05.29°S, 47.29°W), Brasilia (BRAZ; 15,56°S, 47.52°W), Presidente Prudente (UEPP; 22.07°S, 51.24°W), and Porto Alegre (POAL; 30.04°S, 51.07°W); and the green point shows the all-sky imaging system located at Brazopolis (''LNA''; 22.5°S, 45.6°W). The circles indicate the fields of view at a zenith angle of 75° and 90° projected at a 280-km altitude. Also, the geographic and magnetic equators are shown.

latitude sites in Brazil. On the four nights studied the all-sky imaging system observations show strong effect on the generation of equatorial ionospheric irregularities and development of ionospheric plasma bubbles.

2. Instrumentation and Observations

[7] We present observations from an all-sky (180° field of view) multispectral imaging system belonging to ''Universidade do Vale do Paraiba'' (UNIVAP) and installed for routine operation since September 2002 at the Astrophysics National Laboratory (''LNA'') in Brazopolis (22.5°S, 45.6°W; dip latitude 17.5°S; altitude 1860 m; hereafter referred as LNA), Brazil, for the OI 630.0-nm emission on three nights of 2002 (28–29 September and 2–3 and 3–4 October). The ionospheric sounding observations of the F region minimum virtual height (h'F) and F region critical frequency (foF2) at the two digital ionosonde stations

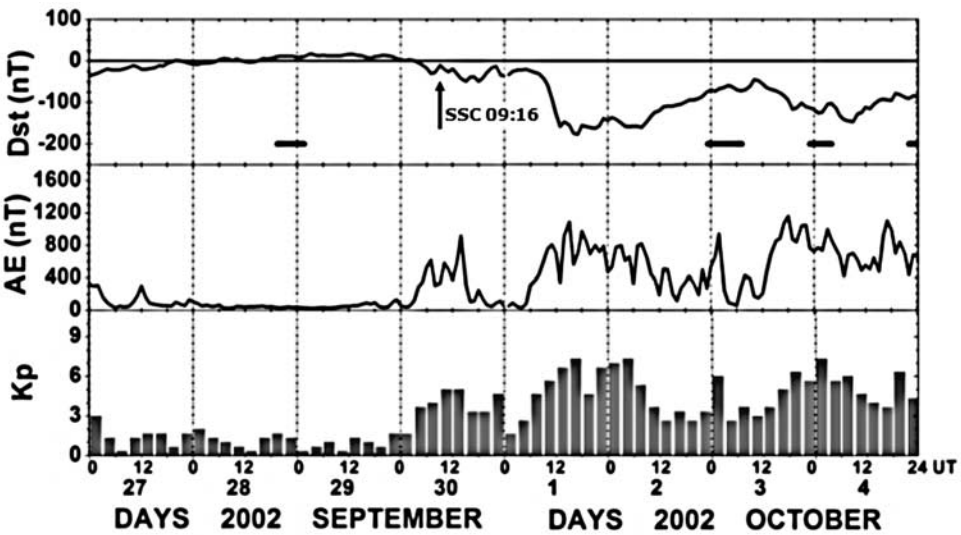

Figure 2. Variations of the Dst, AE, and Kp geomagnetic indices for the period 27 September to 5 October 2002 (UT days). Note that the three nights with imaging observations are 28–29 September (geomagnetically quiet) and 2–3 and 2–3 October (geomagnetically disturbed). Only the nights of 28–29 September and 2–3 October show the presence of ionospheric plasma bubbles. The horizontal bars in the Dst plot panel indicate the time periods of the OI 630.0-nm emission imaging observations on 28–29 September (22:20–03:15), 2–3 (23:20–07:30) and 3–4 (23:10–07:15) October. The vertical arrow indicates the SSC on 30 September at 09:16 UT.

of the UNIVAP network, namely: Palmas (10.2°S, 48.2°W: dip latitude 5.7°S; hereafter referred as PAL) and Sao Jose dos Campos (23.2°S, 45.9°W; dip latitude 17.6°S; hereafter referred as SJC), Brazil, for 6 days of spring equinox period of 2002 (27–29 September and 1–3 October); and phase fluctuations of the vertical total electron content observations obtained from four GPS (Global Positioning System) operated by the Brazilian Institute of Geography and Statistic ("IBGE"; Brazilian Network for Continuous Monitoring ("RBMC") project): Imperatriz (05.29°S, 47.29°W; hereafter referred as IMPZ), Brasilia (15,56°S, 47.52°W; hereafter referred as BRAZ), Presidente Prudente (22.07°S, 51.24°W; hereafter referred as UEPP) and Porto Alegre (30.04°S, 51.07°W; hereafter referred as POAL), during the period of 27 September to 4 October 2002, are also presented. Figure 1 shows the locations of the different observational locations used in the present study.

[8] The all-sky imaging system at LNA is one of the three equipment of the UNIVAP network of all-sky imaging systems and ionosondes. The imaging system has an eight position filter wheel and uses seven 3-inch diameter interference filters (two filters of 1.5 nm bandwidth for OI 777.4 nm, N_2^+ 427.8 nm emissions; two filters of 2.0 nm bandwidth for OI 630.0 nm, OI 557.5 nm emissions; one filter of 2.5 nm bandwidth for NaD 589.3 nm emission; one filter of 12 nm bandwidth for O2 (0, 1 band at 864.5 nm) emission; and a wide-band filter (190 nm) for several OH bands). One position is without a filter to measure the dark current [*Abalde et al.*, 2001, 2004; *Sahai et al.*, 2006]. The two digital ionosonde stations are equipped with the Canadian Advanced Digital Ionosonde (CADI [*Grant et al.*, 1995; *Abalde et al.*, 2001, 2004; *Sahai et al.*, 2004b]) and the ground-based global positioning system (GPS) data were obtained by IBGE-RBMC stations with TRIMBLE 4000SSI receivers.

3. Data Analysis and Discussion

[9] Figure 2 presents the universal time variations of the Dst (hourly values), AE and Kp (3 hourly values) geomagnetic indices for the period 27 September to 5 October, 2002 obtained from the Website http://swdcwww.kugi.kyoto-u.ac.jp/wdc/Sec3.html. Figure 2 also shows the start of the geomagnetic disturbance on 30 September (SSC at 09:16 UT) and the Dst index reached minimum value of −162 nT at 21:00 UT on 1 October and −160 nT at 08:00 UT on 2 October. Also, it is observed from Figure 2 that the earlier days of 28, 29 and 30 (only early part) September were geomagnetically quiet.

[10] Figures 3 and 4 show sequences of the OI 630.0-nm emission all-sky images observed at LNA with the spatial temporal evolution of the equatorial ionospheric plasma bubbles, seen as large-scale quasi north-south magnetic field–aligned dark band structures. Figure 3 presents a sequence of the OI 630.0-nm emission all-sky images with ionospheric plasma bubbles on the quiet night on 28–29 September 2002 and Figure 4 on the disturbed night on 2–3 October 2002. In spite of the fact that the two nights had different geomagnetic indices (28–29 September was a quiet night whereas 2–3 October was a disturbed night), the two image sequences look fairly similar. However, it is noted that some of the ionospheric plasma bubbles on the night of 2–3 October present unusually stronger depletions (e.g., the images between 20:31:49 and 21:00:24 in Figure 4).

[11] The all-sky image observations at LNA on the nights of 3–4 October 2002 show only small ionospheric

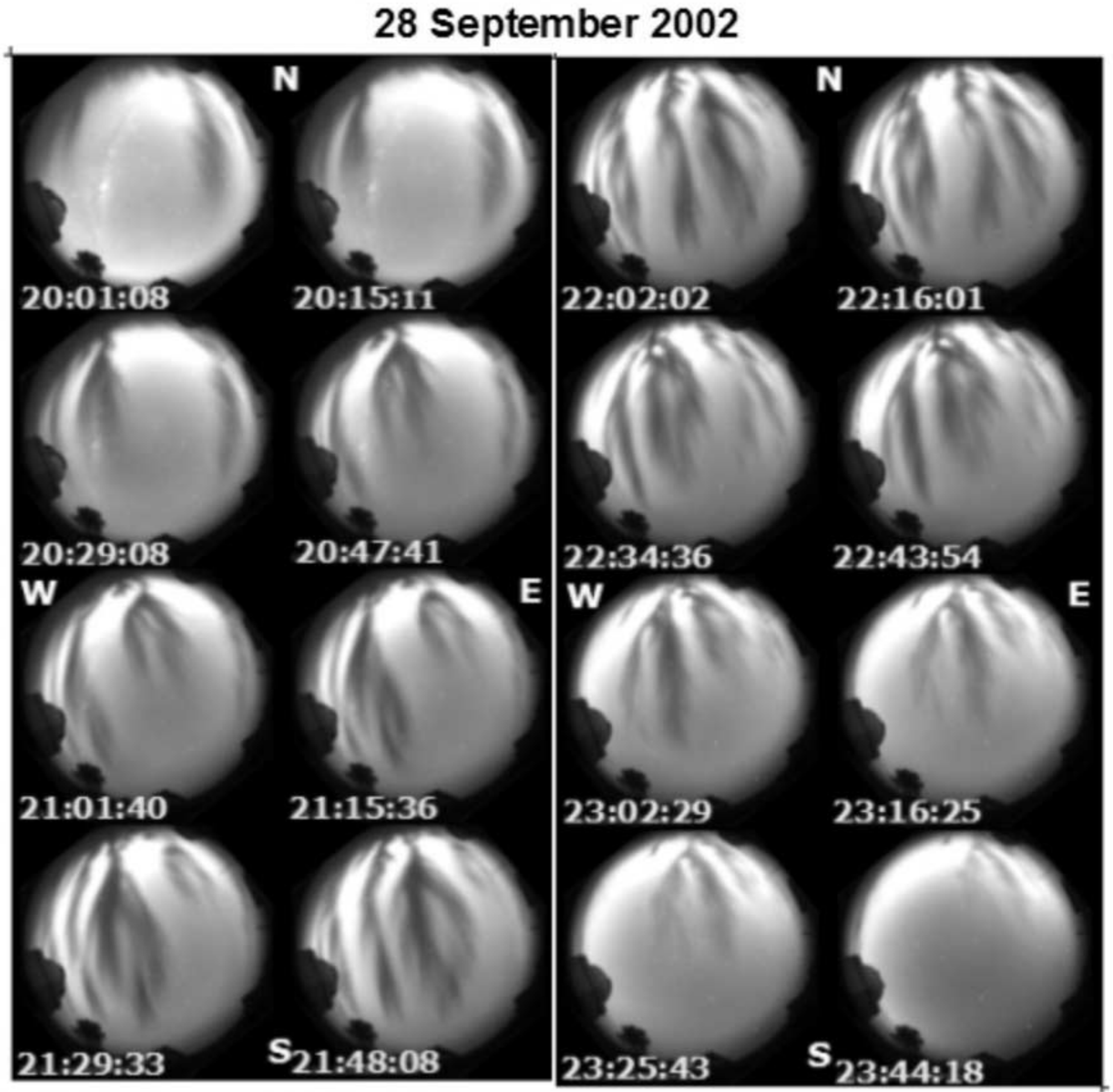

Figure 3. Sequence of the OI 630.0-nm emission all-sky images observed at Astrophysics National Laboratory ("LNA") at Brazopolis (22.5°S, 45.6°W), showing the time evolution (between 20:00 and 23:45 LT, approximately every 15 minutes) and spatial characteristics of ionospheric plasma bubble events on the night of 28–29 September 2002.

plasma depletions (dark structures) restricted to the extreme northern part of the sky (close to the magnetic equatorial region), although these nights had geomagnetic perturbations (Figure 2). This indicates that the equatorial ionospheric irregularities on these nights were limited only to the region close to the magnetic equator and macroscopic plasma bubbles did not develop [*Whalen*, 2002]. Figure 5 shows a sequence of the OI 630 nm emission images observed on the night of 3–4 October (geomagnetically disturbed). On this night only short dark bands in the northern side are seen in the first two images.

[12] Figures 6 and 7 show the time variations of the ionospheric parameters h'F and foF2 observed at PAL and SJC, for the periods of 3 days 27–29 September and 1–3 October 2002, respectively. Figure 2 indicates that the first period was geomagnetically quiet and the second period was geomagnetically disturbed. The day-to-day variability observed in ESF and plasma bubbles in Figure 6 (quiet period) was possibly associated with several factors discussed by *Tsunoda* [2005, 2006]. However, the day-to-day variability observed during geomagnetically disturbed period (Figure 7) warrants a more detailed study. On the night of 1–2 October during the prereversal enhancement (PRE) time there was simultaneous unusual uplifting of the F layer both at PAL and SJC indicating prompt penetration of electric field of magnetospheric origin (Figure 7). However, on this night only ESF was observed at PAL, near the equatorial region and the ESF does not develop in large-scale plasma bubbles (no ESF was observed at SJC). This prompt penetration of electric field occurs at a time when Dst was at its more or less minimum value for an extended period of about 22 hours. Therefore the unusual uplifting of the F layer during this nearly constant large Dst values did not result in plasma bubble generation. On the other hand,

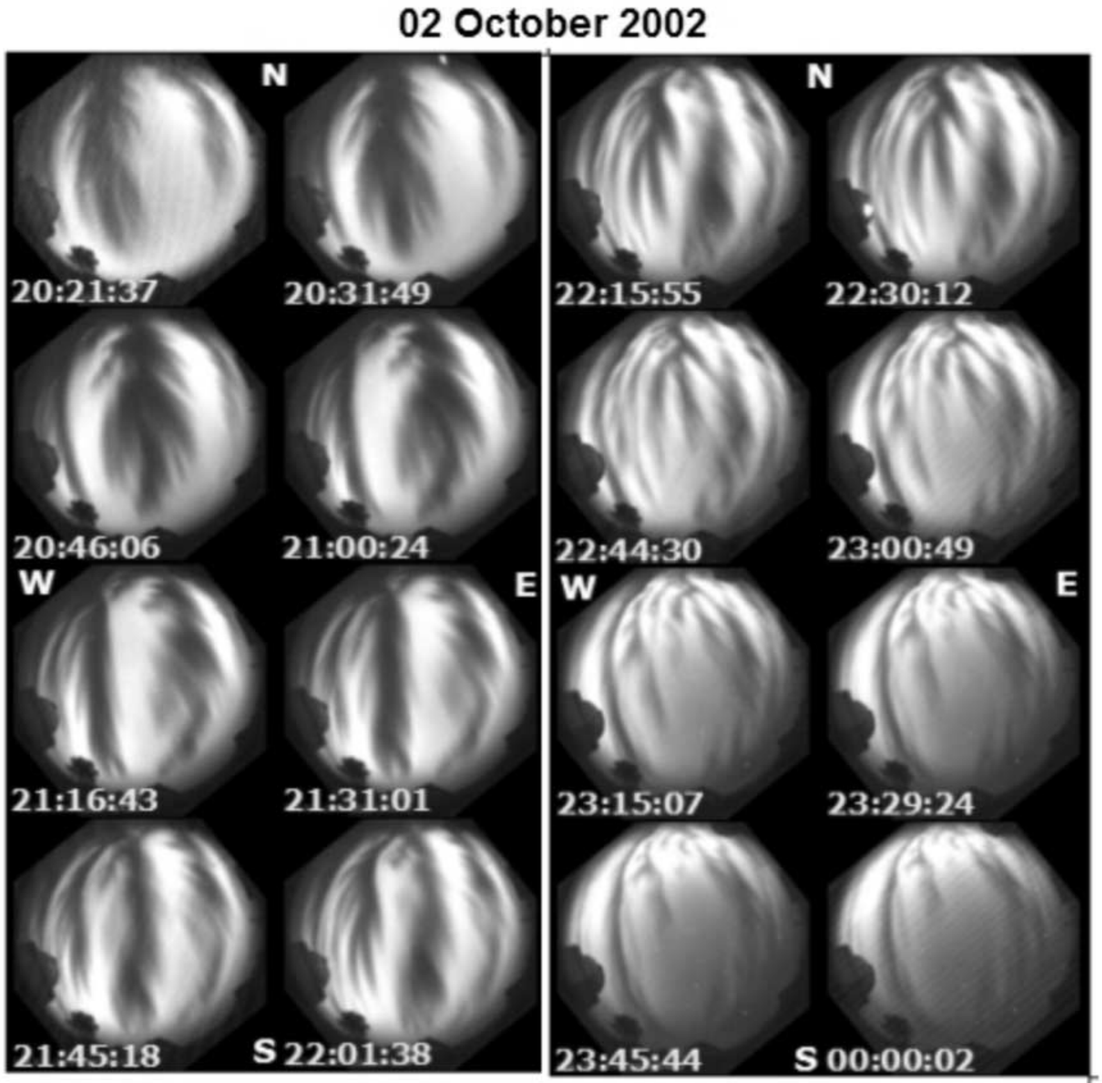

Figure 4. Sequence of the OI 630.0-nm emission all-sky images observed at Astrophysics National Laboratory ("LNA") at Brazopolis (22.5°S, 45.6°W), showing the time evolution (between about 20:00 and 24:00 LT, approximately every 15 minutes) and spatial characteristics of ionospheric plasma bubble events on the night of 2–3 October 2002.

on the night of 2–3 October, during the recovery phase of the geomagnetic storm, again we observe unusual uplifting of the F layer [*Keskinen et al.*, 2006] at PAL and SJC during the PRE period. During the PRE period on 2–3 October, the uplifting of the F layer at PAL indicates double peak large enhancement in foF2 was observed at SJC. The unusual enhancement in electron density at SJC indicates diffusion of ionospheric plasma along the field lines to low latitudes when the F layer is uplifted at the magnetic equator. On this night, we have the unusual development of large-scale plasma bubbles (all-sky imaging shows fairly broad plasma bubbles during 20:31:49 and 21:00:24 LT) and are similar to those observed by *Sahai et al.* [2004a] on the night 26–27 August 1998. On the night of 3–4 October during the PRE period with no indication of prompt penetration of electric field, the ESF and small plasma bubbles (Figure 5) were limited to PAL. Therefore the ionospheric sounding observations presented for the three nights show considerable day-to-day variability during the geomagnetically disturbed period. It has been observed that the prompt penetration of electric field during PRE at the time of large Dst gradient (2–3 October, recovery phase) resulted in an unusual generation of plasma bubbles.

[13] Figure 8 shows complementary ionospheric observations (time rate change of TEC, ROT (TECU/min)), a measure of large phase fluctuations (irregularities of scale size greater than kilometer [*Aarons et al.*, 1997] from the four GPS stations (see Figure 1): Imperatriz (IMPZ; 5.5 S, 47.5 W; dip latitude 2.9 S), Brasilia (BRAZ; 15.9 S,47.5 W; dip latitude 11.7 S), Presidente Prudente (UEPP; 22.3 S, 51.4 W; dip latitude 14.9 S) and Porto Alegre (POAL; 30.1 S,51.1 W; dip latitude 20.7 S), Brazil, on UT days 27 September to 4 October 2002. The observations presented are when the satellite elevation was greater than 30°. Unfortunately, Imperatriz GPS station in the Brazilian equatorial sector was not operational on the day 1 October

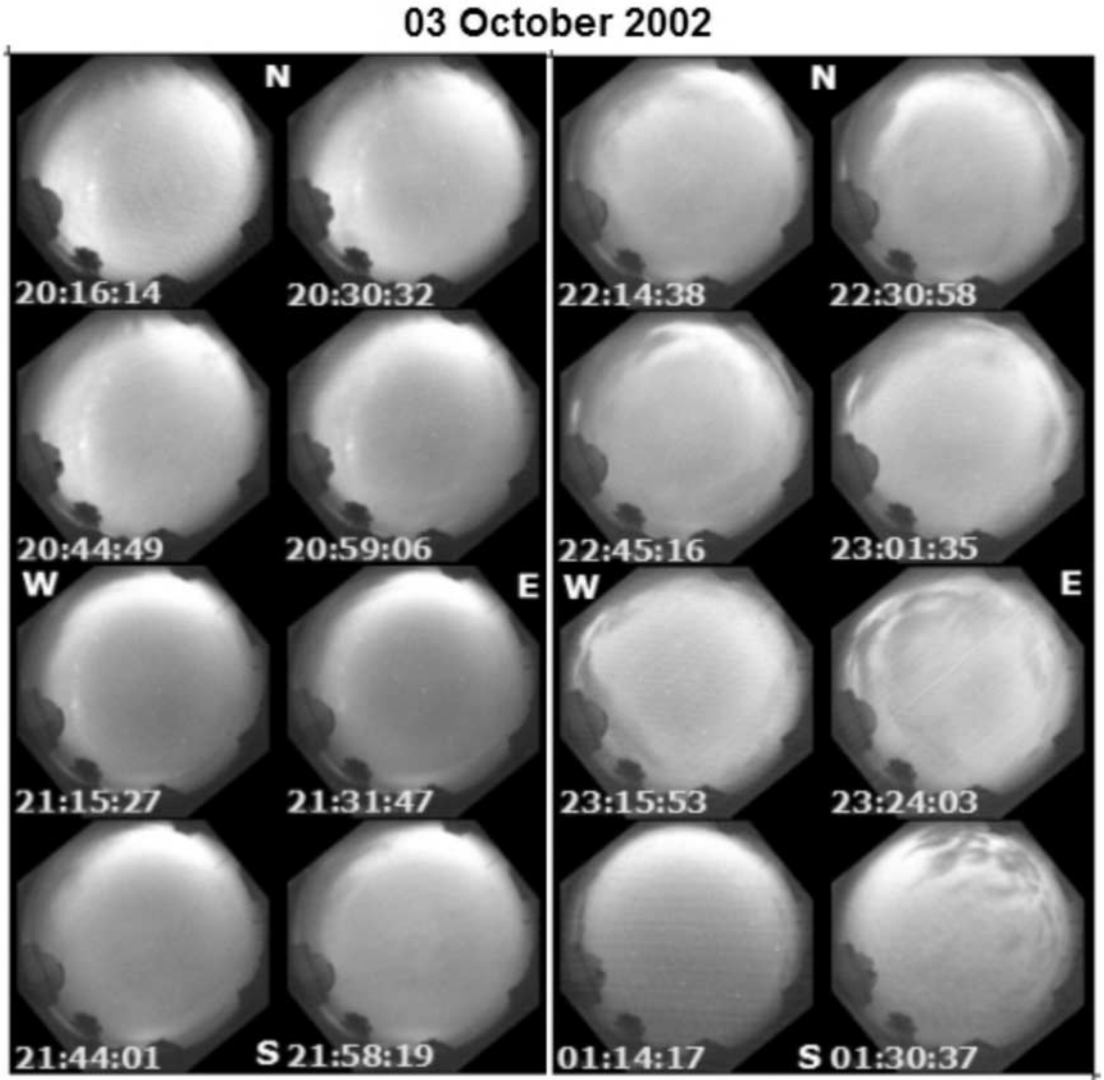

Figure 5. Sequence of the OI 630.0-nm emission all-sky images observed at Astrophysics National Laboratory (“LNA”) at Brazopolis (22.5°S, 45.6°W), showing the time evolution (between about 20:00 and 01:30 LT, approximately every 15 minutes) and spatial characteristics of ionospheric plasma bubble events on the night of 3–4 October 2002. Only small ionospheric plasma bubbles (confined to the magnetic equator region) are observed during the early period (the first two images at 20:30:32 and 20:44:49 LT).

during the SSC disturbed period (see Dst index at Figure 2, top). Figure 8 shows phase fluctuations at IMPZ, BRAZ and UEPP, on the nights of 26–27 and 27–28 September, indicating that the equatorial plasma bubbles reach only up to UEPP. The night of 30 September–1 October presents no phase fluctuations. On the night of 3–4 October possibly phase fluctuations are limited to only at IMPZ (see small OI 630 nm emission plasma bubbles in the northern part in Figure 5). On the night of 29–30 September phase fluctuations extend only up to BRAZ. However, on the nights of 28–29 September and 2–3 October, when we have simultaneous optical observations, phase fluctuations are seen from IMPZ to POAL, indicating evolution of plasma bubbles extending to the southern most part of Brazil (Figures 3 and 4). Also, Figure 8 indicates much stronger phase fluctuations at all the four stations on the night of 2–3 October (geomagnetically disturbed) compared to the night of 28–29 September (geomagnetically quiet). This seems to indicate the influence of geomagnetic activity on the development of plasma bubbles. In addition, Figure 8 clearly indicates day-to-day variability in the development of plasma bubbles and the influence of geomagnetic activity on the development of plasma bubbles.

4. Conclusions

[14] We studied in this investigation the day-to-day variability in the development of ionospheric plasma bubbles during geomagnetically quiet and disturbed periods in September–October 2002 (a period of spring (southern hemisphere) during high solar activity). We have analyzed simultaneous ionospheric sounding, OI 630.0-nm emission all-sky imaging, and

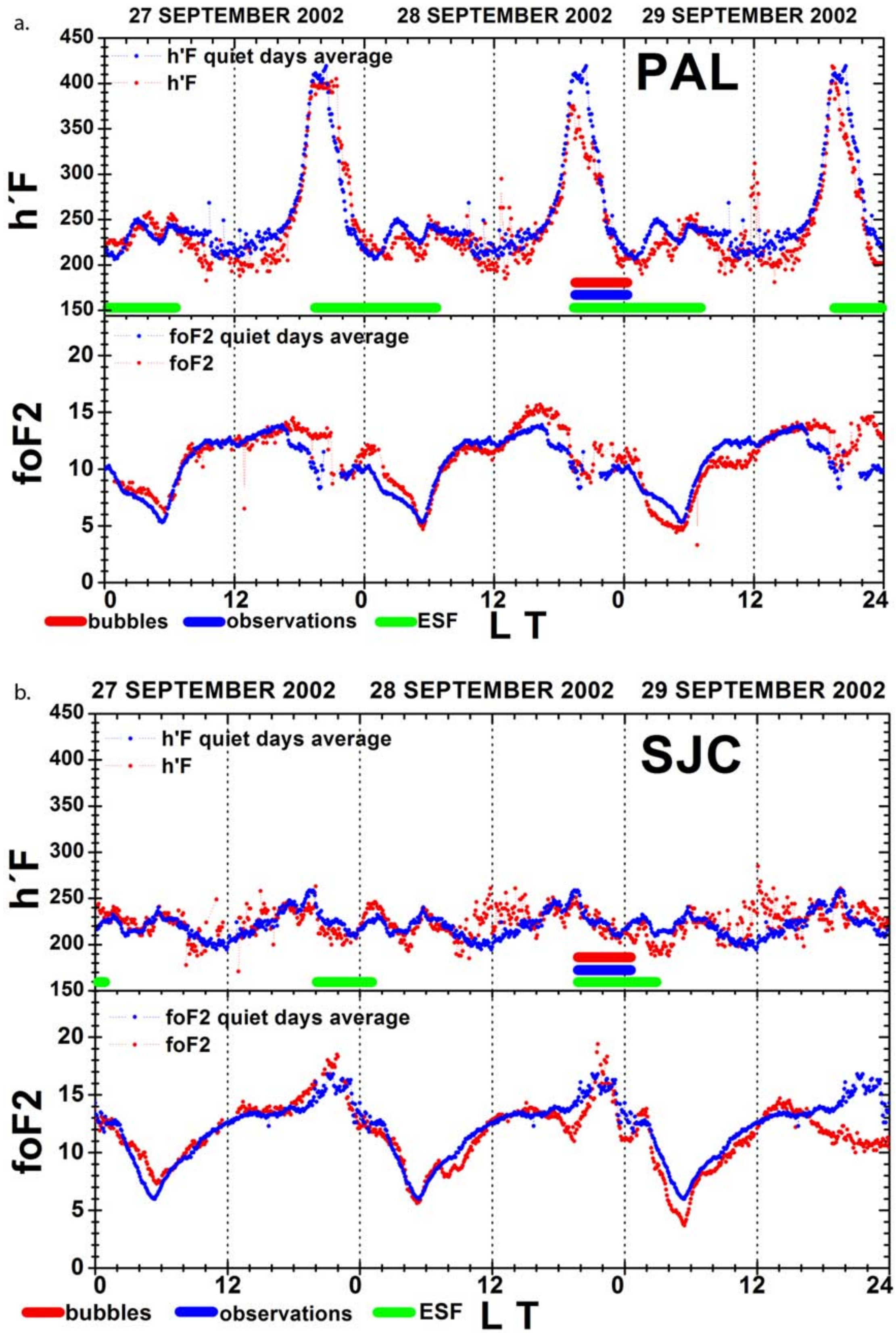

Figure 6. Variations of the ionospheric parameters h'F and foF2 (red dots) observed at Palmas (PAL) and Sao Jose dos Campos (SJC) during the period 27–29 September 2002. The blue dots are the quiet days' (3 days in September and 3 days in October) average values. The horizontal bars indicate the presence of spread F (green) detected in ionospheric sounding plots (ionograms) and plasma bubbles (red, detected by the OI 630-nm emission all-sky images) and all-sky imaging system observation period (blue).

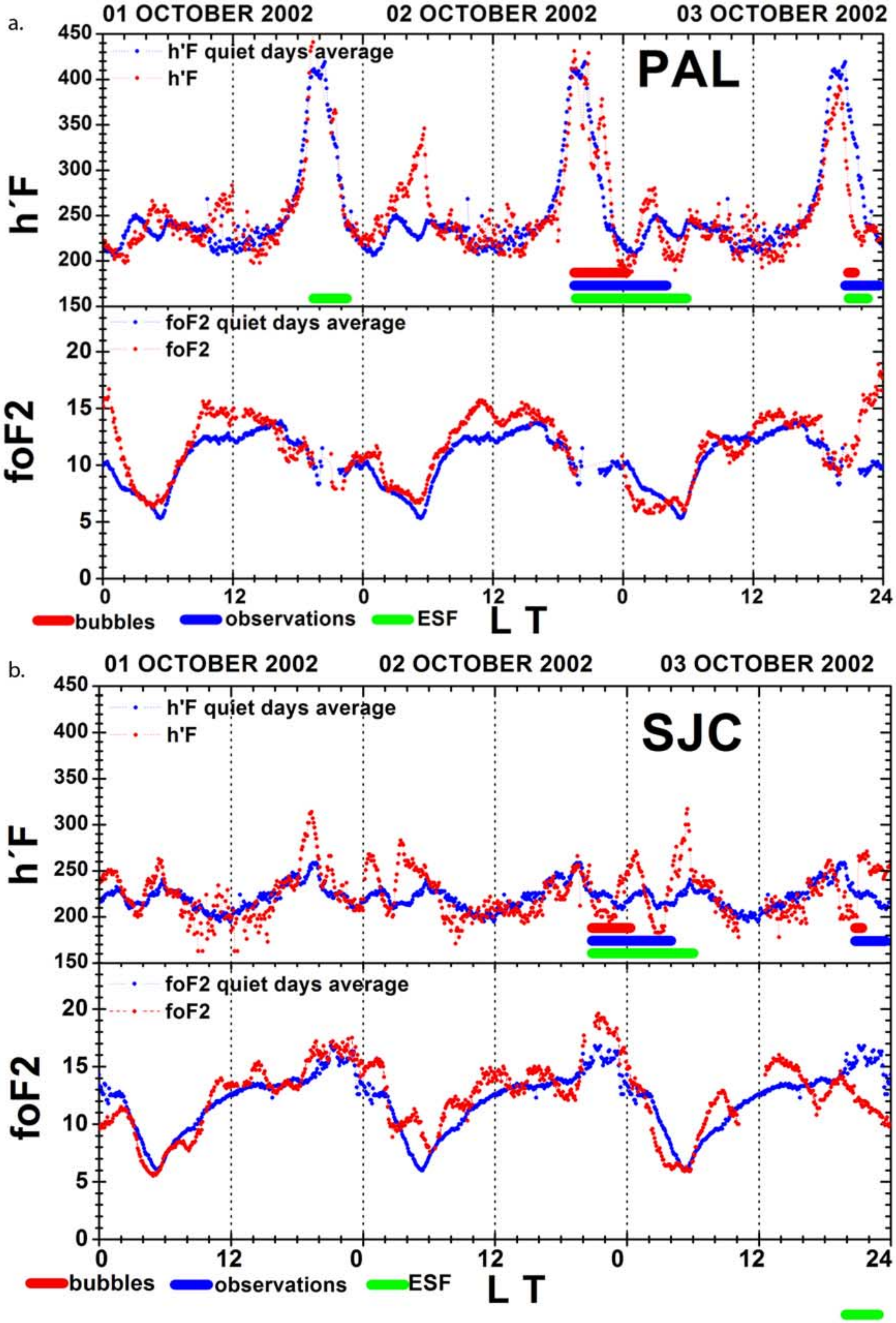

Figure 7. Variations of the ionospheric parameters h'F and foF2 (red dots) observed at Palmas (PAL) and Sao Jose dos Campos (SJC) during the period 1–3 October 2002. The blue dots are the quiet days' (3 days in September and 3 days in October) average values. The horizontal bars indicate the presence of spread F (green) detected in ionospheric sounding plots (ionograms) and plasma bubbles (red, detected by the OI 630-nm emission all-sky images) and all-sky imaging system observation period (blue).

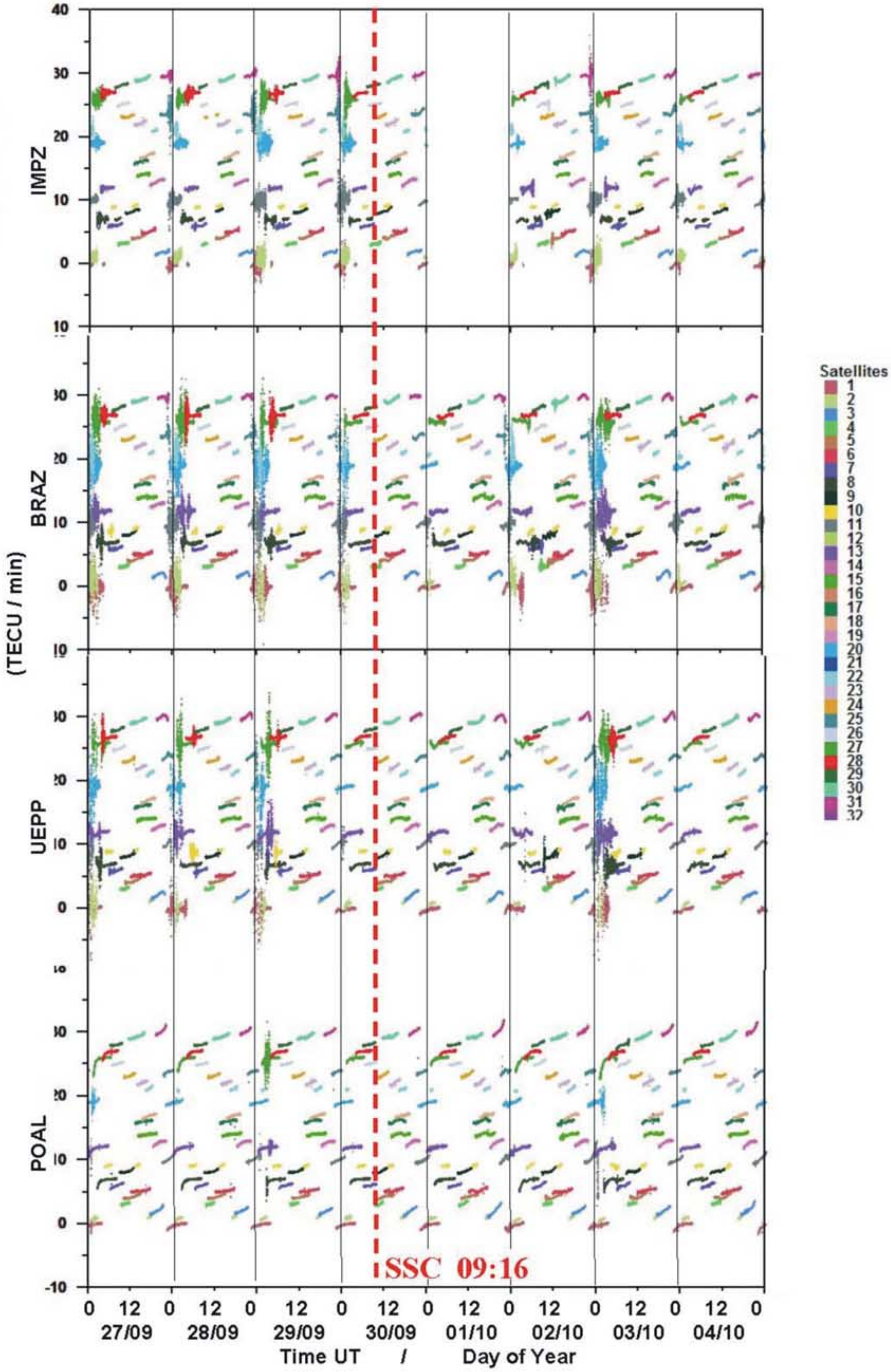

Figure 8. The time rate change of TEC, ROT (TECU/min) measured using the data of different satellites present in the GPS station Imperatriz (IMPZ), Brasilia (BRAZ), Presidente Prudente (UEPP), and Porto Alegre (POAL), Brazil, on UT days 27 September–4 October 2002.

GPS observations during the period 27 September to 3 October 2002. The main results are as follows:

[15] (1) On geomagnetically quiet nights ionospheric plasma bubbles were observed on the nights of 27–28 and 28–29 September 2002. Figure 3 shows the OI 630.0-nm emission images with ionospheric plasma bubbles on the night of 28–29 September. No ionospheric plasma bubbles were observed on the night of 29–30 September 2002. These results are in agreement with the phase fluctuations obtained from the GPS observations.

[16] (2) After the SSC on the 30 September, no phase fluctuations, even close to the magnetic equator, were observed on the night of 30 September–1 October. Unfortunately, no ionospheric sounding data were obtained on this night at PAL and SJC.

[17] (3) On the geomagnetically disturbed night of 1–2 October, only ESF was observed at PAL (ionospheric sounding), and IMPZ and BRAZ (phase fluctuations).

[18] (4) On the geomagnetically disturbed night of 2–3 October, strong ionospheric plasma bubbles (ionospheric sounding, OI 630.0 nm images and phase fluctuations) were observed. On this night PRE (prereversed enhancement) shows a secondary peak possibly associated with prompt penetration of electric field of magnetospheric origin. Also, the foF2 variations at SJC show enhancements at this time.

[19] (5) On the night of 3–4 October the equatorial ionospheric irregularities are limited to close to the magnetic equator (ionospheric sounding, OI 630.0 nm images and phase fluctuations).

[20] (6) The present investigation clearly indicates the day-to-day variability in the generation of ionospheric plasma bubbles during both geomagnetically disturbed and quiet periods.

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