F region electric field effects on the intermediate layer dynamics during the evening prereversal enhancement at the equatorial region over Brazil

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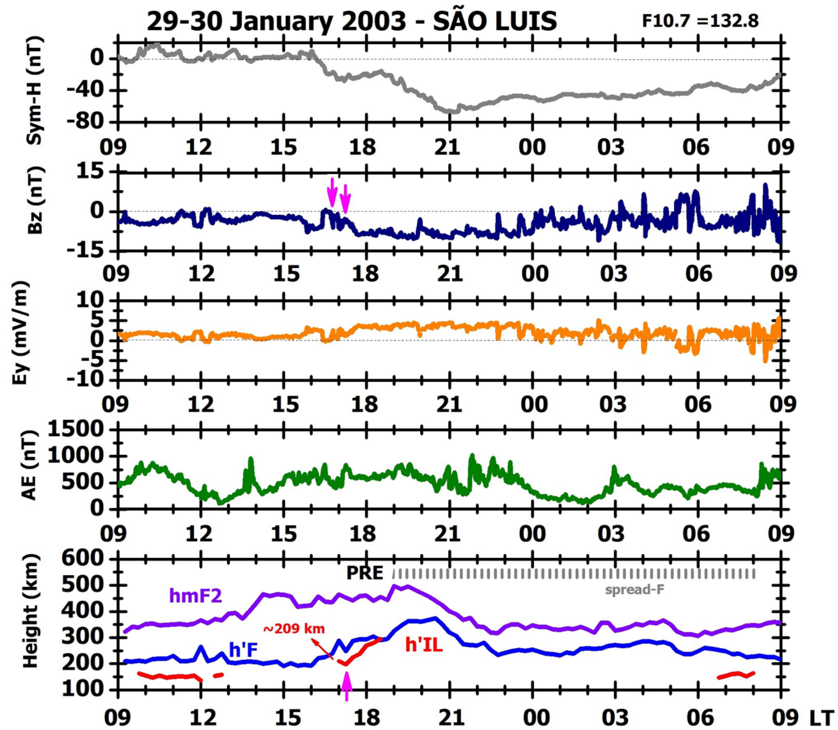
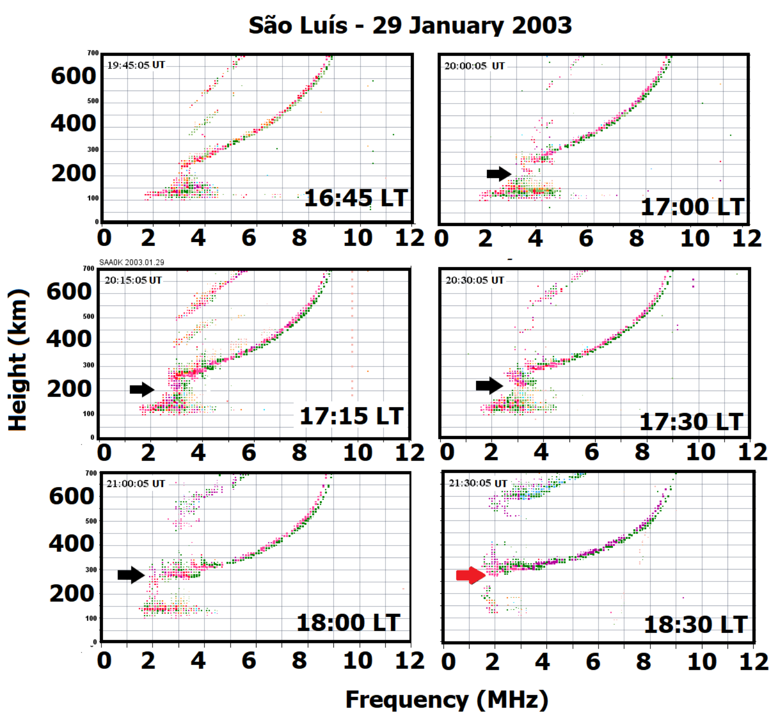
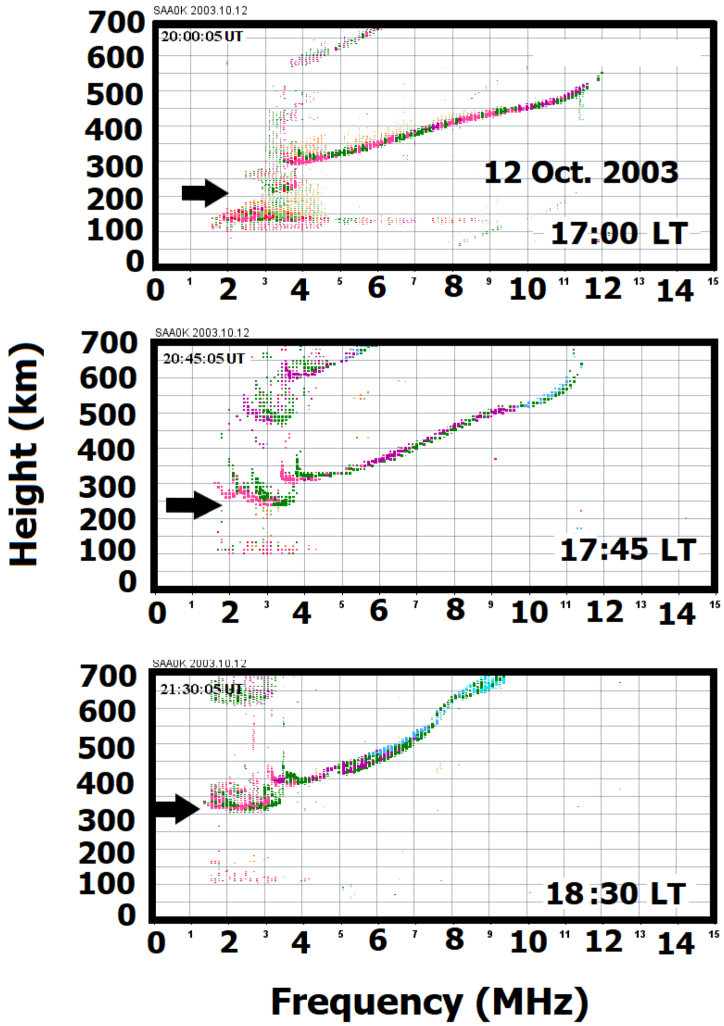
Abstract

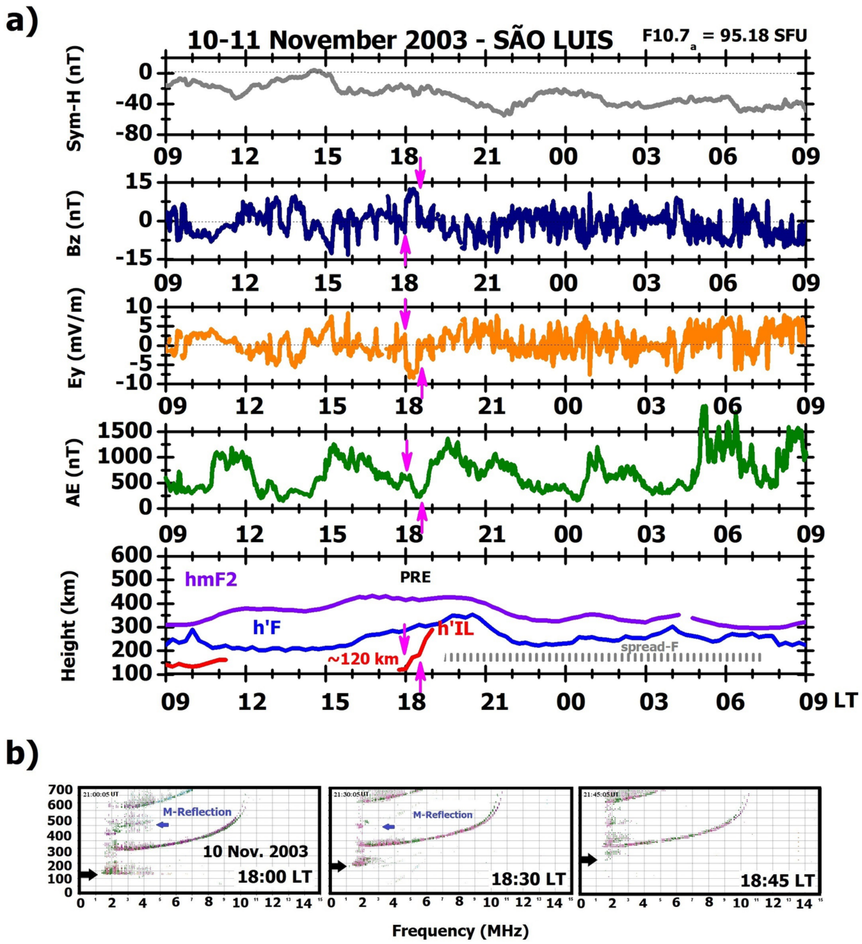
Using ionograms from the Brazilian equatorial region of São Luís (SL, 2° S; 44° W, I =-3.8°), the relation between the uplift of the intermediated layers (ILs) at sunset and the prereversal enhancement of the zonal electric field (PRE) is investigated. The ILs were studied during periods of maximum (2003) and minimum solar activity (2009). The presence of the ILs during the PRE occurrence time was very low for both years. In 2003, six ILs' events were observed, being four of them in the summer solstice and one in the March equinox. In 2009, only a single event was registered and occurred during the December month. The results show that depending on the height at which the ILs are located, their upward movement at sunset can be in some way related to the normal F layer rise at sunset due to the PRE. Additionally, the eastward prompt penetration electric fields (PPEF) during weak magnetic storms can also contribute to the IL's rise. An interesting case of uplift of a sporadic-E layer from ˜120 to 290 km of altitude probably due to the PPEF is investigated. The absence of answers of the F layer to the same disturbed electric field reveals the complex nature of the layers located in the ionosphere valley region.

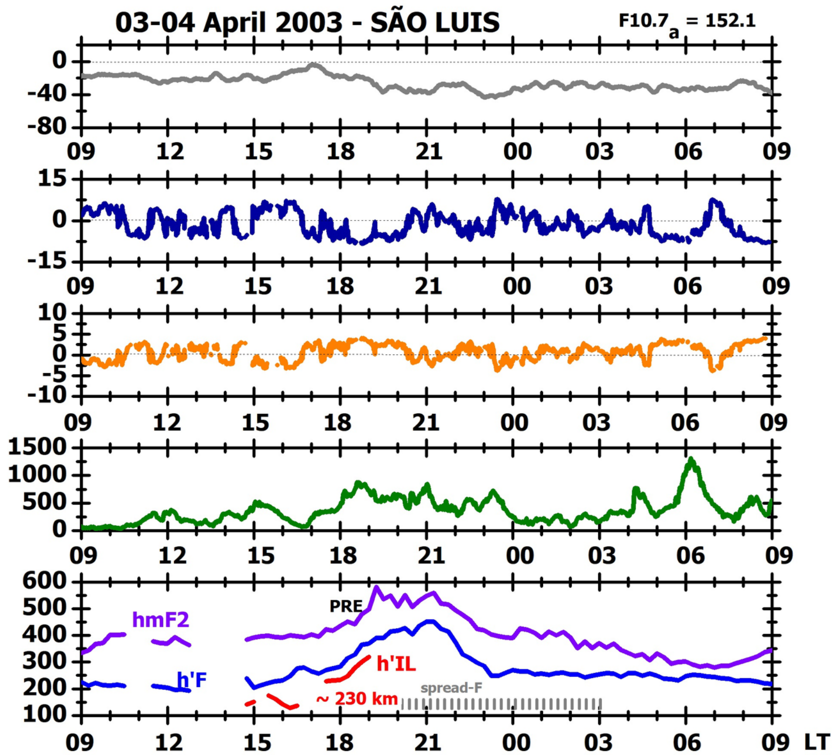

29-30 January 2003 - SÃO LUIS
F10.7 =132.8
Sym-H (nT)
Bz (nT)
Ey (mV/m)
AE (nT)
Height (km)
PRE
spread-F
hmF2
h'F
~209 km
h'IL
09 12 15 18 21 00 03 06 09 LT


São Luís - 29 January 2003
16:45 LT
17:00 LT
17:15 LT
17:30 LT
18:00 LT
18:30 LT
Height (km)
Frequency (MHz)



SAA0K 2003.10.12
20:00:05 UT
12 Oct. 2003
17:00 LT
SAA0K 2003.10.12
20:45:05 UT
17:45 LT
SAA0K 2003.10.12
21:30:05 UT
18:30 LT
Height (km)
Frequency (MHz)


a)
10-11 November 2003 - SÃO LUIS
F10.7a = 95.18 SFU
Sym-H (nT)
Bz (nT)
Ey (mV/m)
AE (nT)
Height (km)
hmF2
PRE
h'F
h'IL
~120 km
spread-F
LT
b)
M-Reflection
10 Nov. 2003
18:00 LT
18:30 LT
18:45 LT
Frequency (MHz)



03-04 April 2003 - SÃO LUIS
F10.7a = 152.1
hmF2
h'F
h'IL
PRE
~ 230 km
spread-F
LT

F region electric field effects on the intermediate layer dynamics during the evening prereversal enhancement at the equatorial region over Brazil

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Key Points:

- The PRE can cause an upward movement of the intermediate layers (ILs) located in altitudes higher than ~170 km.
- The prompt penetration electric field also can contribute to the uplift of the ILs and Es layers.
- The uplift of the ILs at sunset seems to be more common over the equatorial sector during maximum solar activity.

Abstract

Using ionograms from the Brazilian equatorial region of São Luís (SL, 2° S; 44° W, I =-3.8°), the relation between the uplift of the intermediated layers (ILs) at sunset and the prereversal enhancement of the zonal electric field (PRE) is investigated. The ILs were studied during periods of maximum (2003) and minimum solar activity (2009). The presence of the ILs during the PRE occurrence time was very low for both years. In 2003, six ILs' events were observed, being four of them in the summer solstice and one in the March equinox. In 2009, only a single event was registered and occurred during the December month. The results show that depending on the height at which the ILs are located, their upward movement at sunset can be in some way related to the normal F layer rise at sunset due to the PRE. Additionally, the eastward prompt penetration electric fields (PPEF) during weak magnetic storms can also contribute to the IL's rise. An interesting case of uplift of a sporadic-E layer from ~120 to 290 km of altitude probably due to the PPEF is investigated. The absence of answers of the F layer to the same disturbed electric field reveals the complex nature of the layers located in the ionosphere valley region.

1. Introduction

It is well known that the electric field that controls the ionospheric plasma drifts is generated by the dynamo process that occurs in the E and F regions. During the day, the zonal electric field is directed to east and produces the upward vertical drift, however, before its reversal to west in the evening, a significant and fairly sharp increase in the eastward electric field is observed. This intensification in the vertical drift that is known as prereversal enhancement of the zonal electric field (PRE) is caused by the F region dynamo driven by the thermospheric zonal wind in the presence of a rapid decrease in the E layer conductivity across the terminator (Heelis et al., 1974; Farley et al., 1986; Rishbeth, 1971; Batista et al., 1986). The magnitude of the PRE depends upon various factors, such as the upward propagating planetary waves (Abdu et al., 2006), the disturbed electric fields (Sastri et al.,1997; Abdu, 1997; Fejer and Scherliess, 1997; Richmond et al., 2003; Abdu et al., 2009; Santos et al. 2016), the disturbance winds during magnetic storms (Abdu et al., 1995) and the variability in the solar flux (Fejer et al., 1979, 1991; Batista et al., 1996; Abdu et al., 2010; Santos et al., 2013).

The PRE controls the major phenomena of the equatorial ionosphere, such as the post-sunset resurgence of the equatorial ionization anomaly and the plasma instability processes responsible for the development of the plasma bubble irregularities/spread F that have been extensively discussed in the literature (see for example Huang, 2018; Balan et al. 2018). However, the direct or indirect effect of the PRE on the layers located in the upper and lower E region hasn’t received much attention. Using observational data over Fortaleza, Abdu et al. (1996) showed, for the first time, that the disappearance of the sporadic-E (Es) layers could be related to the evening F layer vertical uplift. Additional analysis over this same sector was made later on by Abdu et al. (2003) which confirmed the earlier results presented by Abdu et al. (1996). They mentioned that in this case, the influence of the PRE in the Es layer development could operate in an indirect way through the Hall conduction upward electric field induced by the zonal eastward electric field associated with the PRE. Such an upward electric field can cause the partial or complete disruption of an ongoing Es layer. Abdu et al. (2003) showed that in general, a higher value of the PRE could disrupt the Es layers whereas for smaller PRE amplitudes such disruption may not occur. They further showed that the Es layer disruption might not occur when the PRE amplitude decreased or became inhibited during a magnetic storm. Using numerical simulation, Carrasco et al. (2007) also reported that depending on the direction of the vertical electric field associated with the PRE, the Es layer over Fortaleza and São Luis can be disrupted or enhanced. Abdu et al. (2013) mentioned that during magnetic storms, the formation and disruption of the Es layers over the low-latitude sector can be strongly controlled also by the magnetospheric electric fields that penetrate to the equatorial ionosphere. In agreement with the above cited works, it is evident that the control of the formation and disruption of the Es layers at sunset appears to be a complex process and includes the mapping of the equatorial vertical electric field to the low latitude E region.

Differently from the Es layers formed through the wind shear, there are also those layers that are formed in the upper E region or in the ionospheric valley region. As will be shown in the present work, these layers, which are known as “intermediate layers (ILs)”, can be also influenced by the evening enhancement of the zonal electric field. Dos Santos et al. (2019) and Santos et al. (2020) studied the behavior of the ILs over the Brazilian equatorial and low latitude sites of São Luís (SL) and Cachoeira Paulista (CP), respectively, during periods of maximum and minimum solar activity. It was found that: (1) the IL’s occurrence over both regions is high; however, it seems to be dependent of the magnetic inclination angle; (2) the ILs’ occurrence rate appears to be independent (or weakly dependent) on the solar activity; (3) the dynamic of the ILs can be influenced by atmospheric tides, gravity waves and electric fields; (4) the ILs are predominantly diurnal and present a well-defined downward movement; however nocturnal and ascending ILs also can be observed over the Brazilian region; (5) depending on the height at which the ILs are formed, they can descend and merge with the normal sporadic E layers; (6) the IL's lifetime is higher in solar minimum period (both over SL and CP) and lower over the equator independently of the solar activity, and; (7) the descending rate of the ILs over SL and CP seems to be compatible with the semidiurnal and quarter-diurnal tides. However, larger descending rate over SL in some cases (> 10 km/h) may reveal the additional influence of the gravity waves in the IL's dynamics.

In this paper, we will address for the first time the impacts of the PRE in the ascending movement of the ILs located, in most of the cases, at altitudes higher than 170 km, during both quiet and disturbed periods. Besides that, we will discuss an interesting case of a normal Es layer that presented a strong uplift near the PRE time, displacing from ~ 120 km to 290 km of height in approximately one hour, possibly due to the effect of a prompt penetration electric field.

2. Observational data

To investigate the connection between the PRE and the uplift of the intermediate layers, we examined the data from digisonde operating over the equatorial region of São Luis (SL, 2° S; 44° W; dip angle in 2003: -3.8°). The presence of ascending ILs over the equator at sunset times can be considered abnormal since in a total 357 days analyzed in 2003 and 293 days in 2009, only 7 cases of ascending ILs at sunset times were detected, being 6 of them during high solar activity and 1 during low solar activity. Over the low latitude sector of Cachoeira Paulista, no event was observed during the same periods (341 days in 2003 and 361 days in 2009). As mentioned previously, the occurrence of the ILs is very frequent over the Brazilian sector. The ILs are predominantly diurnal and present a well-defined downward movement. ***Figure 1*** shows an example of IL over SL on 27 March 2009. It is possible to observe that near to the PRE occurrence time (~ 18:20 LT, indicated by the dashed blue line), the IL that was in progress at a height of ~150 km (see blue arrow) was interrupted. The IL in this case was formed initially at 15:50 LT at ~ 194 km from a detachment of the F1 layer (not shown here). On the other hand, the Es layer that was in progress (see red arrow) presented moments of weakening and intensification during the same interval being interrupted only at 19:20 LT (not shown here).

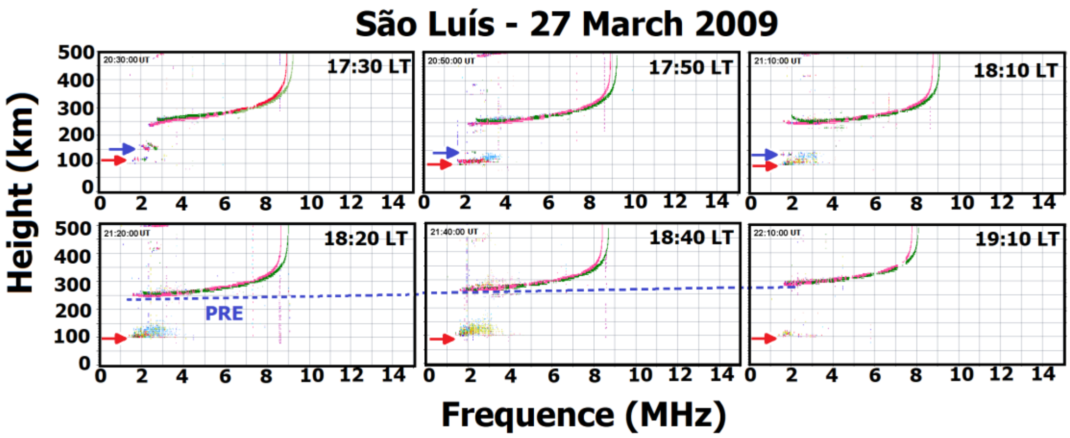

Figure 1: Ionograms over SL on March 27, 2009 showing an example of interruption of IL at the PRE occurrence time.

Santos et al. (2020) reported that the probability of an intermediate layer to occur near or after ~18:00 LT is quite small. As can be seen in Figures 4a and 4b from Dos Santos et al. (2019), at ~ 18:00 LT (21:00 UT) the ILs are either interrupted or continue their downward movement (to altitudes lower than 130 km). Differently from the example of Figure 1, over the equatorial site Sao Luis, some cases were observed in which the ILs raised up simultaneously with the F layer elevation due to the enhancement of the zonal electric field instead of being interrupted or continuing their downward movement. In 2003, this feature was observed in January (1 day), April (2 days), October (1 day), and November (2 days). In 2009, only in December the same characteristic was detected. Each one of these events will be detailed in the present study.

Event 1: January 29, 2003

From top to bottom, ***Figure 2*** shows the one-minute resolution magnetic index Sym-H, the interplanetary magnetic field Bz, the zonal interplanetary electric field Ey and the auroral electrojet activity index AE from 09:00 LT on January 29 to 09:00 LT on January 30, 2003. The virtual heights of the F layer (h'F, blue line), of the F2 layer peak (hmF2, purple line), and of the intermediate layer (h'IL, red line) are presented in the last panel. The spread-F occurrence is also indicated by the horizontal gray bar in the same panel. A weak magnetic storm started at 16:00 LT as can be seen by the decrease in the Sym-H index (first panel). At ~ 16:35 LT, the Bz turned to southward (as indicated by the pink arrow) and remained in this direction (with some fluctuations) for several hours. The interplanetary electric field Ey remained directed to the east (with small variation) during the main phase and during a part of the recovery phase of the storm. During the period covered in ***Figure 2***, it is possible to observe the presence of descending and ascending intermediate layers (last panel, red curves). The first layer was observed on January 29 at ~ 09:45 LT at about 162 km of altitude and remained nearly at the same height till 12:00 LT. A second layer appeared at ~153 km for a brief period starting at ~12:30 LT.

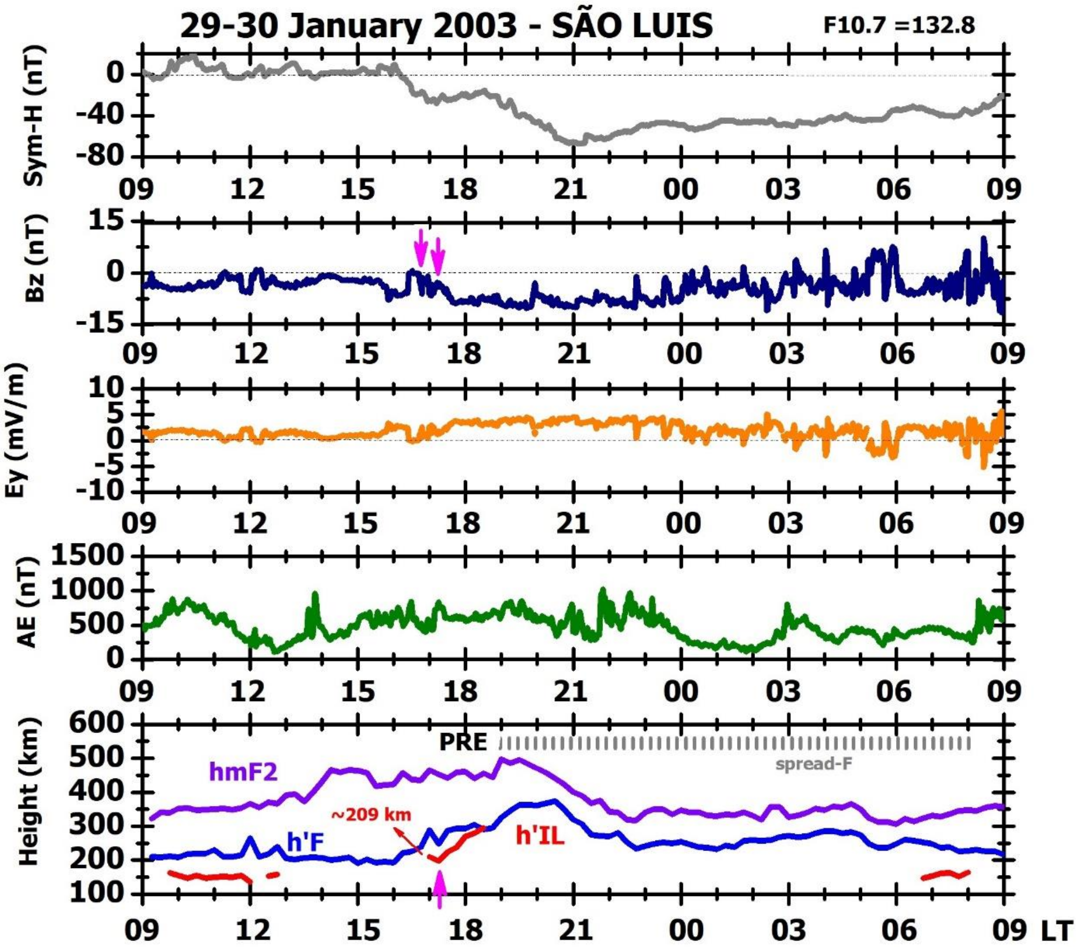

Figure 2 – Ascending intermediate layer over São Luis on January 29, 2003 and the geophysical conditions for the period. From the top to the bottom panels: 1 min. values of the Sym-H index (first panel), the interplanetary magnetic field Bz (second panel), the interplanetary zonal electric field Ey (third panel), and the auroral index (fourth panel). The virtual heights of the F layer (h'F, blue line), of the F2 layer peak (hmF2, purple line), of the intermediate layer (h'IL, red line), and the spread-F occurrence (horizontal gray bar) are shown in the last panel. The heights of the ILs are also indicated in the last panel.

The most complex event was the formation of the third IL at about 17:00 LT at a height of ~ 209 km (see the last panel of Figure 2). Shortly after its formation, the IL presented a rise almost simultaneously with the rise of the F layer due to the pre-reversal enhancement of the zonal electric field (PRE). As can be seen in the ionograms of ***Figure 3***, before starting its rise, the IL became intensified at 17:30 LT and possibly blocked the low density part of the F layer similar to the blanketing caused by the sporadic E layer in the 17:00 LT ionogram. It is possible to observe that the minimum frequency of the F layer presented a slight increase of ~ 0.4 MHz between 17:15 LT and 17:30 LT. At 18:30 LT, as indicated by the red arrow in the last ionogram of ***Figure 3***, the IL merged with the F layer. Two characteristics are very relevant in this analysis. The first one refers to the exact moment at which the IL is formed. As indicated by the pink arrow in Figure 2, the IMF Bz suffered a quick intensification to south starting at about 17:15 LT that could indicate the possible influence of a prompt penetration electric field (PEEF) of eastward polarity in the dynamics of the IL. The second point is related to the fact that the IL underwent an upward movement of the IL during the PRE occurrence time. It was verified that the peak of the average vertical drift velocity (V_{zp}), calculated from the F layer true height (*hF*) variations at 5 and 6 MHz plasma frequencies as *dhF/dt*, occurred at 18:30 LT and attained a value of ~ 40 m/s, that corresponds to a zonal electric field of ~ 1 mV/m. So, in this context, it is possible that both the PRE and the PPEF could have contributed to the formation and dynamics of the IL during this evening and its subsequent junction with the F layer later on. A careful analysis of the January 29, 2003 ionograms raised a hypothesis that the IL on this day became intensified at 17:30 LT due to the detachment of the F layer base (dos Santos et al. 2019), that in this case presented an increase in the minimum frequency of ~ 0.4 MHz. However, the lack of information between 17:30 LT and 17:45 LT made difficult the interpretation of this possible detachment.

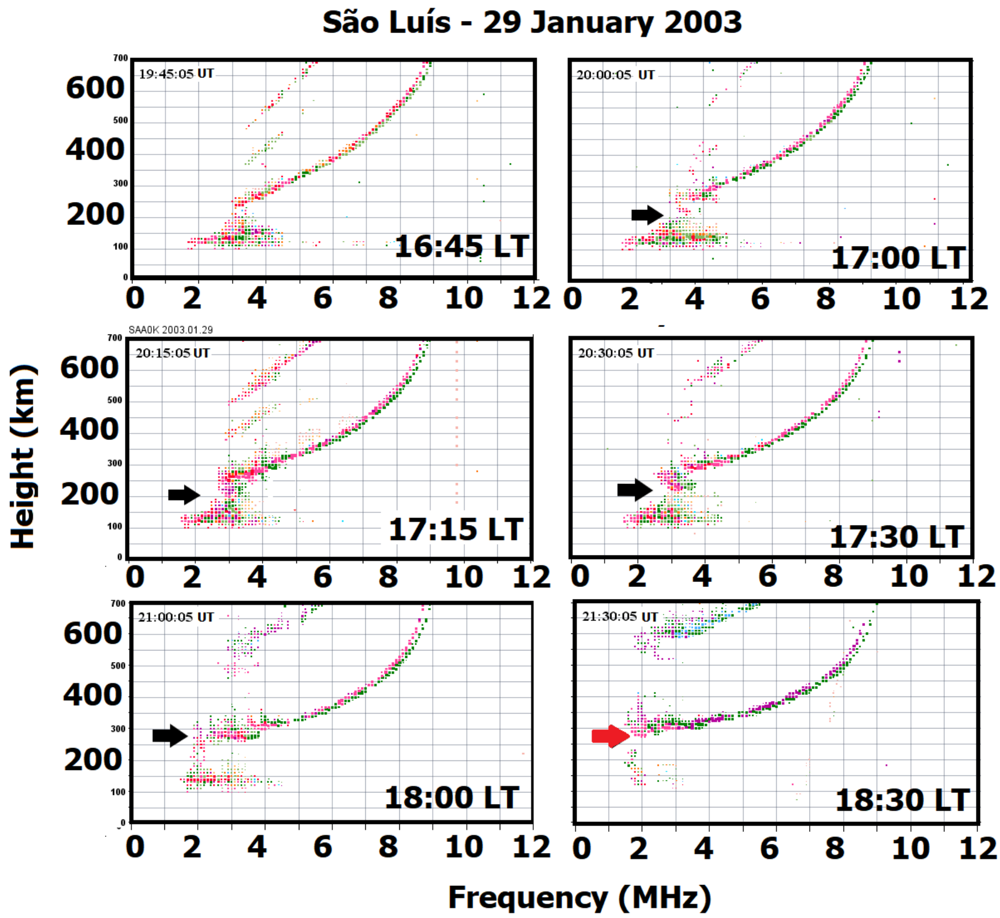

Figure 3 - Ionograms over SL showing the uplift of the intermediate layer and their subsequent junction with the F layer on January 29, 2003.

Event 2: April 03, 2003

Figure 4 shows the same parameters described in ***Figure 2*** but for April 03, 2003. Similar to event 1, the Sym-H index indicates that the ascent of the IL occurred during the main phase of a weak magnetic storm. In this case, the Sym-H attained a minimum value of ~-40 nT at 23:00 LT. We can observe through the red curve in the last panel that during this day, the IL occurred in three different time intervals, being the last one close to sunset time. When this third event was detected, at 17:30 LT, the IL was very close to the F layer base (~230 km) and a simultaneous ascent of the height parameters hmF2, h'F and h'IL can be clearly identified. In this event, there is no evidence that the uplift of the IL has been caused by a disturbance electric field since no abrupt change was observed in the F layer as well as in the intermediate layer height. It is probable that the uplift of the IL, in this case, has been caused by the prereversal enhancement of the zonal electric field, that in terms of V_{zp} attained a peak of 47 m/s (~1.17 mV/m) at 18:45 LT. During its ascent, the IL' top frequency (ftIL) reduced from 3.1 to 2.1 MHz.

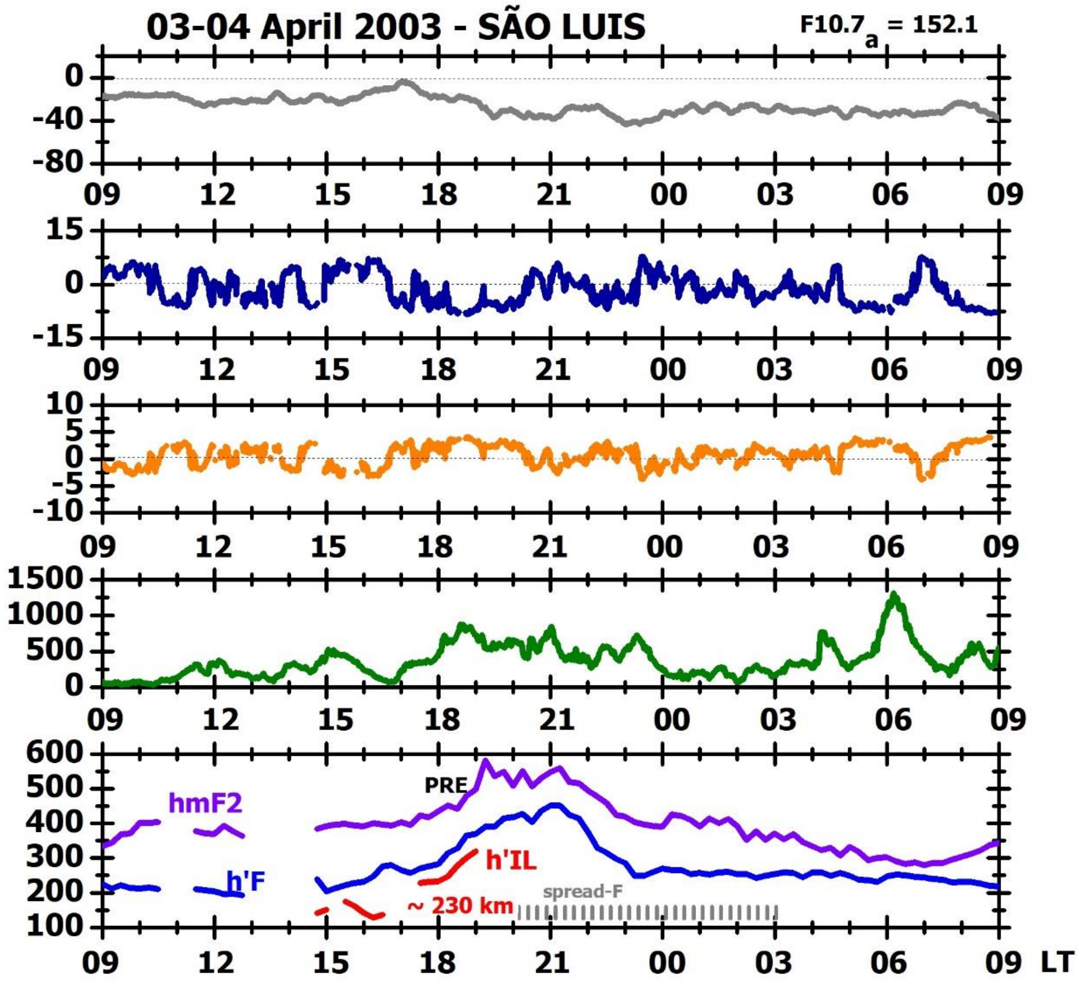

Figure 4 – Similar to Figure 2, but for April 03, 2003.

Events 3a and 3b: April 08, 2003.

Figure 5 shows the behavior of the ILs on April 08, 2003 during the recovery phase of a weak magnetic storm. It is interesting to observe the presence of two simultaneous ILs occurring around the PRE, that reached the maximum value of ~16 m/s (~ 0.4 mV/m) at 18:30 LT. During the interval in which the ILs were observed, the Bz was directed to the north with small fluctuations and the auroral activity remained around zero. It can be observed that only the IL located in ~ 200 km of height (event 3a) seemed to respond to the PRE. Its lifetime was short and it was difficult to distinguish if this IL was interrupted at 18:45 LT or merged with the upper IL. Regarding the layer located at ~253 km at 18:30 LT (event 3b), we can observe that the IL presented a weak downward movement, not being sensitive to the PRE as the IL located in ~200 km. The upper IL presented some level of spread after 19:00 LT. This can have prejudiced the interpretation of the data. It is possible to note that the interruption of the upper IL was coincident with the beginning of the spread-F at about 19:30 LT.

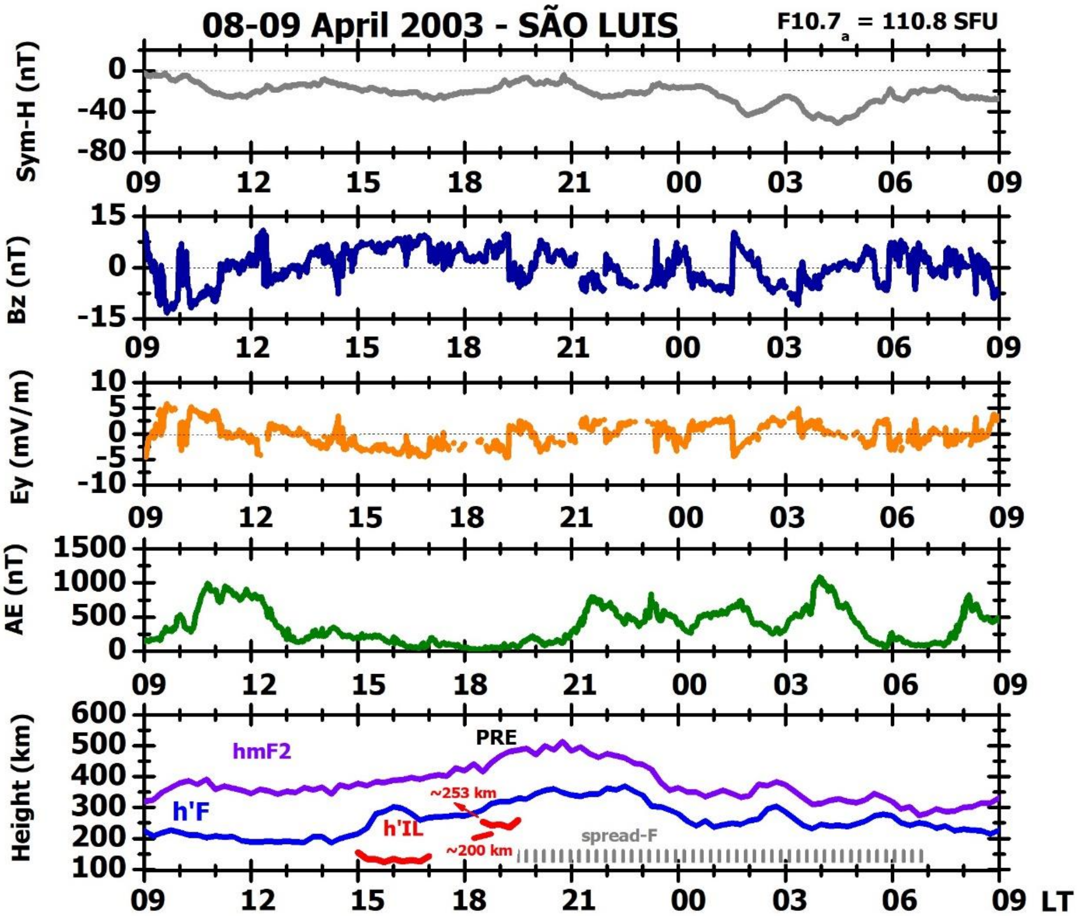

Figure 5 – Similar to Figure 2, but for April 08, 2003. In this case, two simultaneous layers were observed after to 18:30 LT.

Event 4: October 12, 2003.

The single event of ascending IL observed on October 12, 2003 was detected at 16:45 LT at ~ 188 km (***Figure 6***). In this case, the IL's rise occurred in the absence of any magnetic storm. Although the Bz was weakly to the south, the behavior of Sym-H and AE indices, and the magnetosphere electric field Ey exclude any possibility of interference of disturbed electric fields during the interval in which the IL was observed. In this context, it is possible that the uplift of IL had been caused by the quiet-time electric field from the F region dynamo. The spread-F occurrence started immediately after the interruption of the IL at ~18:30 LT. In the time interval between 16:45 and 18:30 LT, the ftIL decreased by ~ 0.6 MHz. The V_{zp} rechead ~40m/s which corresponds to an electric field of 1 mV/m at 18:30 LT.

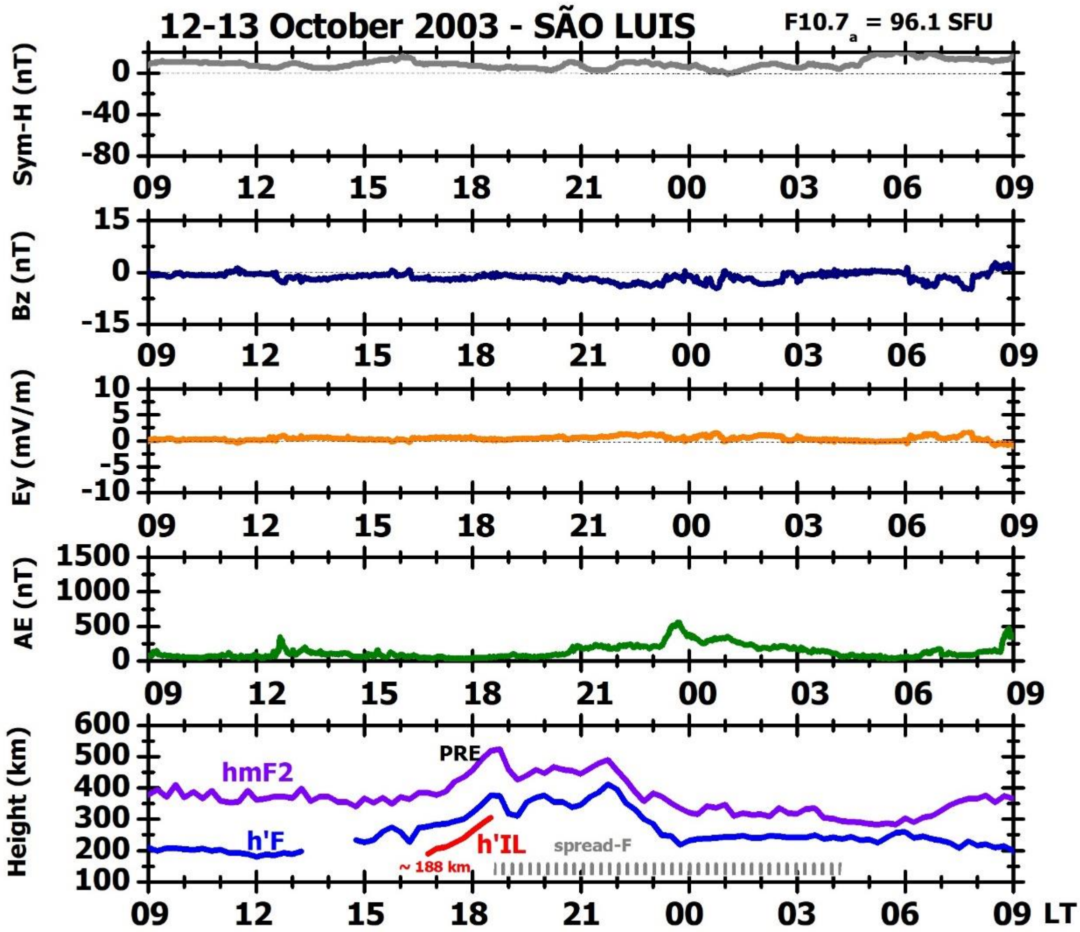

Figure 6 – Similar to Figure 2, but for October 12, 2003.

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The ionograms from Figure 7 show how the digisonde registered the IL and the F layer during some specific times on October 12. It is interesting to note that the formation of the IL (~ 17:00 LT) do not appear to be connected with the F layer. However, during its development (see the ionogram at 17:45 LT), the IL became intensified and with strong tendency to merge with the F layer base. The format in which the IL appeared on this day was very peculiar. Generally, the ILs presented a flat format or at most showed a retardation at the lower frequency end, very similar to the ionogram at 17:30 LT in Figure 3. On the October 12, specifically, the retardation was observed in the IL high frequency end, very similar to the F1 layer trace. However, the ionogram at 17:00 LT (and at other times not show here) allows us to exclude the possibility of this trace to refer to the F1 layer.

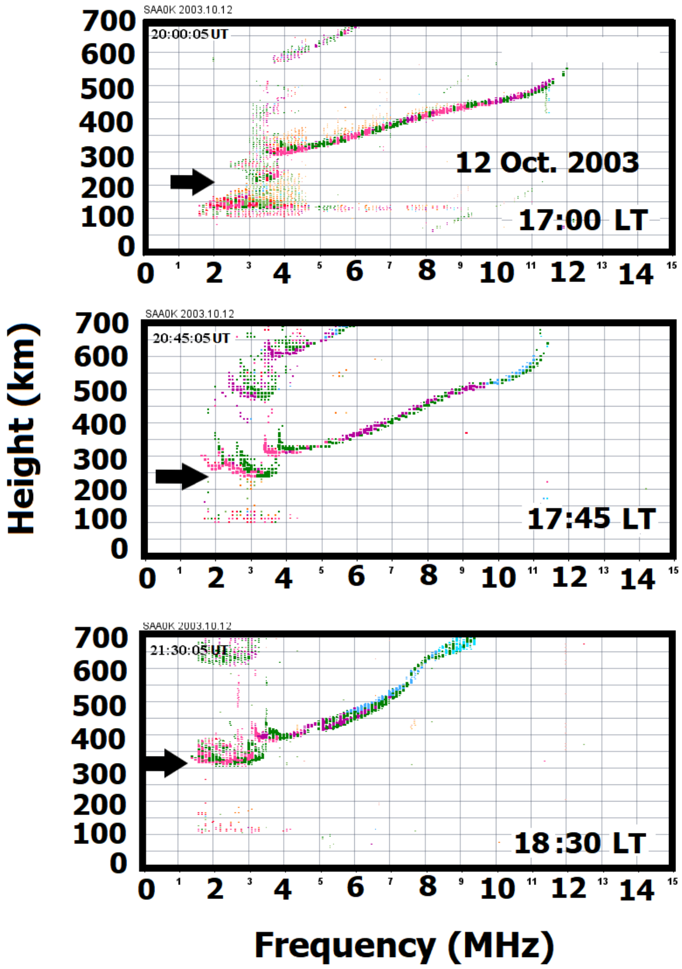

Figure 7 – Ionograms for October 12, 2003. The black arrows indicated the ascending intermediate layer.

Event 5: November 08, 2003.

Similar to the event 4, the IL on November 08, 2003 was formed at altitudes lower than 200 km at 18:00 LT as can be seen in ***Figure 8***. Although the Sym-H and AE indices do not indicate occurrence of magnetic storm on this day, the formation of the IL appeared to be coincident with a weak southward inversion of Bz, while their interruption coincides with the inversion of Bz to north, a process that could generate a disturbed eastward and westward electric field, respectively. The interval between the end of the IL (18:30 LT) and the beginning of the spread-F (19:30 LT) was approximately one hour. Compared with the previous events, the distance between the F layer and the IL was higher (~ 90 km) in the present case. The ftIL in this event decreased from 2.5 to 1.8 MHz before the IL became interrupted at 18:30 LT. The V_{zp} occurred at 18:30 LT and reached ~ 36 m/s (0.9 mV/m).

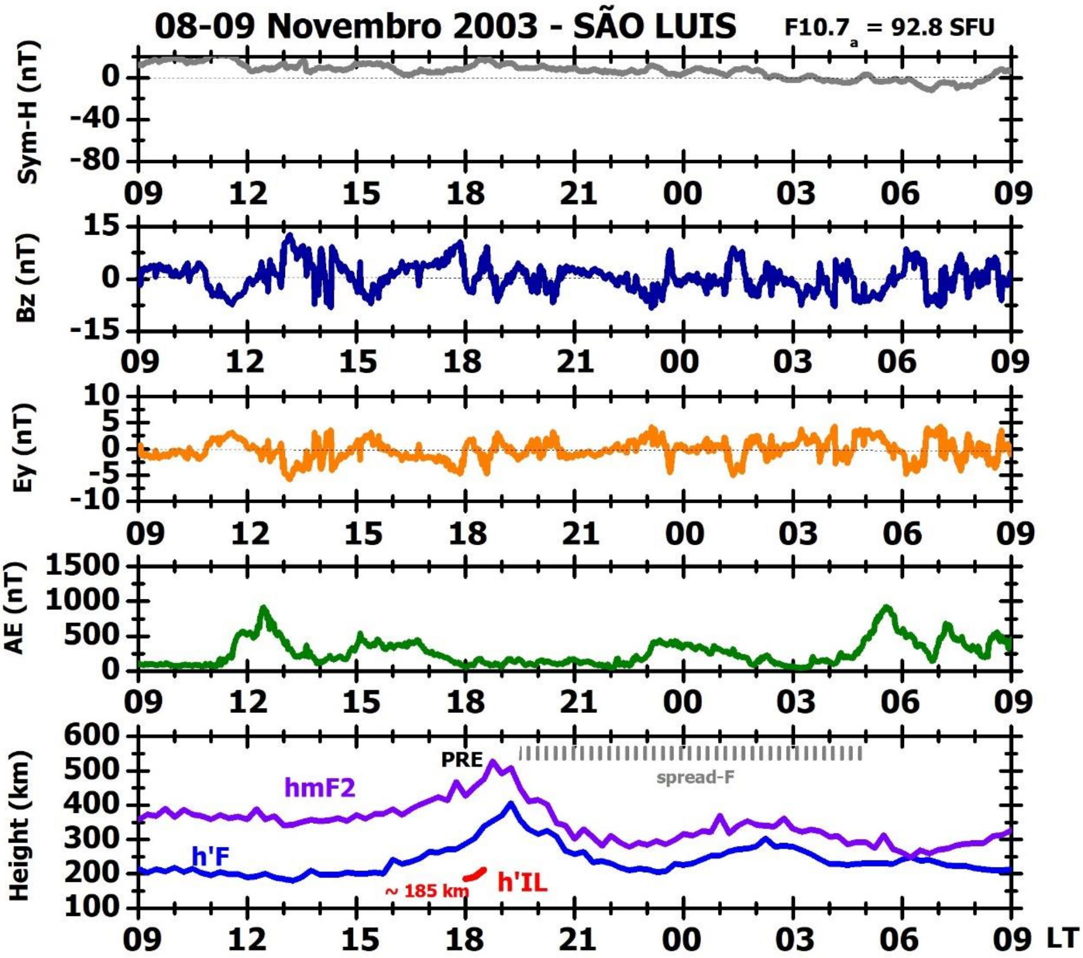

Figure 8 – Similar to Figure 2, but for November 08, 2003.

Event 6: November 10, 2003.

This event was very interesting in that it showed the uplift of a dense sporadic layer (Es) first detected at ~ 120 km on November 10 during a weak magnetic storm (Sym-H_{min} = -60 T at ~ 21:50 LT). This day was particularly active in terms of sporadic-E occurrence. It stated with c-type Es layers, which persisted until 11:15 LT sometime becoming strong enough to partially block the F-layer reflection. From 09:15 LT onwards q-type Es (Es_q) was observed simultaneously with the c-type. The Es_q persisted until 16:15 LT with a few interruptions. Starting at 14:00 LT there is a clear indication in the ionograms that a dense Es layer occurs simultaneously with the Es_q. ***Figure 9a*** shows that at 18:00 LT, Bz turned northward (reaching ~ 10 nT), the AE index showed a recovery and the Ey presented a variation of ~ 10 mV/m westward. Being under the day-to-night transition period the polarity of the associate electric field can be either eastward or westward. In the present case the polarity was initially westward, and soon (within ~25 minutes) turned eastward (as can be noted in upward arrow marked in the figure) which seems to have produced a PPEF to eastward that was responsible for the first abrupt increase of the Es height from 120 km to 180 km as can be seen in the 18:00 LT and 18:30 LT ionograms in Figure 9b. In these ionograms, it is possible to observe the presence of the mixed Es and F multiple reflection known as M-reflection (as identified by the blue arrows in ***Figure 9a***) evidencing that a zonal electric field can also be responsible for the vertical displacement of the sporadic layers believed to be formed by the wind shear mechanism. Note that at 18:30 LT the Es was already located in the ionospheric valley region; so from now on, this layer will be classified as an IL. At around 18:30 LT, the Bz turned to the south, and a second abrupt increase in the IL, probably due to a PPEF to eastward, again was noted. In this case, the IL moved from ~180 km to 290 km in ~ 30 minutes. This second IL rise was coincident with an intensification in the auroral index from ~250 nT to 650 nT, and its interruption at 19:00 LT, coincident with a reversion of the Bz to northward, should have produced a disturbed electric field with westward polarity. This westward electric field probably contributed to the weakening and subsequent disruption of the IL at 19:00 LT. During this event, the V_{zp} reached ~ 25 m/s at 18:00 LT, which corresponds to a zonal electric field of 0.6 mV/m. It appears that only the Es (and later on the IL) was responsive to the disturbance electric fields during all the intervals discussed. As can be noted, the parameters h'F and hmF2 (blue and purple curves, respectively) in ***Figure 9*** did not show any abrupt change compatible with the variation in the Es/IL that could be associated with the PPEF. Some oscillations can be seen in hmF2 around the time of the PRE, but in this case, they were probably associated to the 15 min. sounding cadence used to probe the ionosphere. This was the last case in which ascending ILs were observed close to the sunset over São Luis during the year 2003.

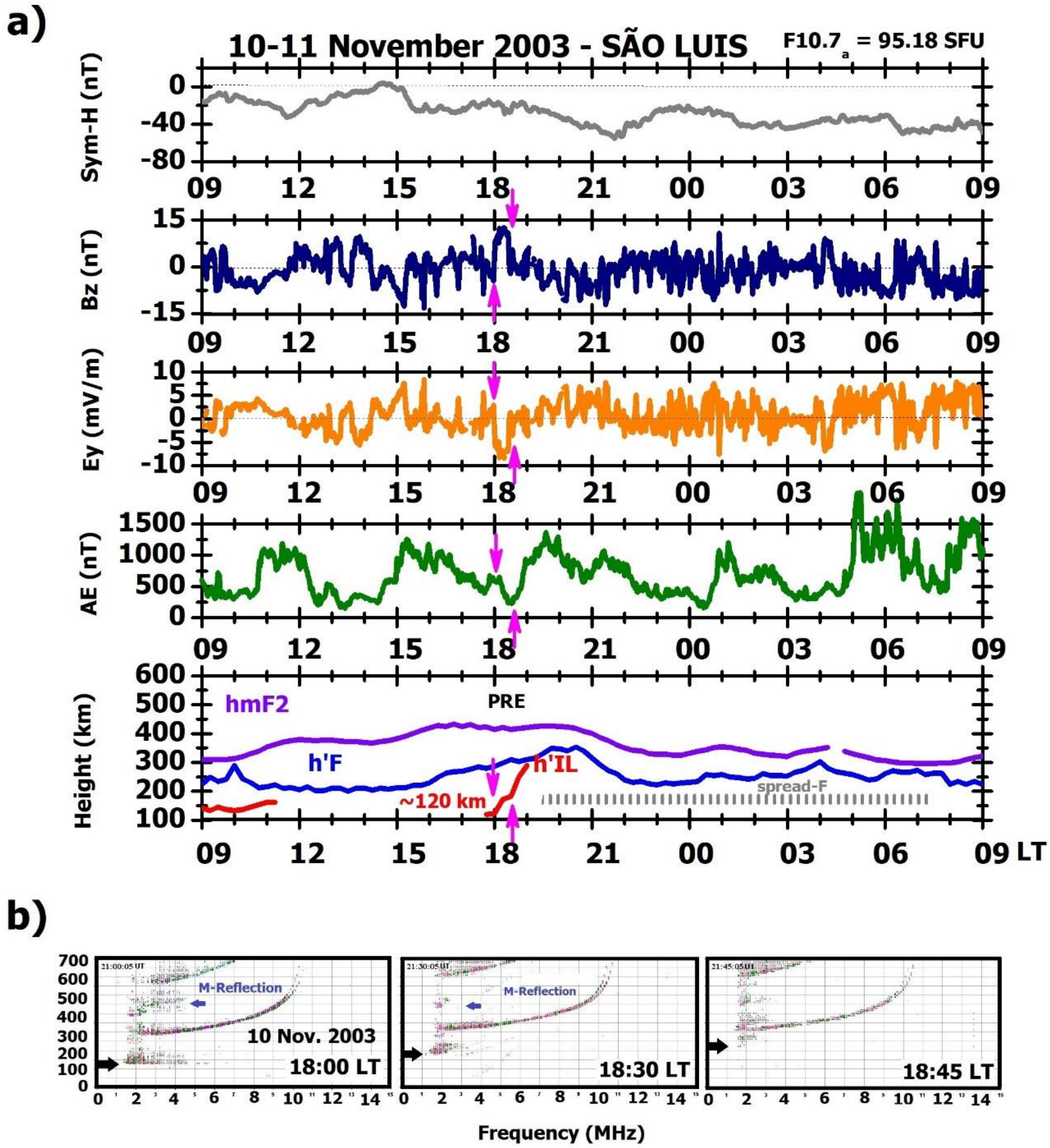

Figure 9 – a) Ascending sporadic -E layer and IL on November 10, 2003. From top to bottom are shown: 1 min. values of the Sym-H index (upper panel), the interplanetary magnetic field Bz (second panel), the interplanetary zonal electric field Ey (third panel), and the auroral index (fourth panel). The virtual heights of the F layer (h’F, blue line), of the F2 layer peak (hmF2, purple line), of the intermediate layer (h’IL, red line), and the spread-F occurrence (horizontal gray bar) are shown in the last panel. b) Ionograms from São Luis during some intervals that are discussed in the text.

Event 7: December 14, 2009.

The single case in which the upward movement of the IL was observed around the sunset in the solar minimum period occurred on December 14, 2009. The average F10.7cm solar flux for this period was ~ 80 SFU. As can be seen in ***Figure 10***, the interplanetary magnetic field Bz, the Sym-H, and the AE reveal the absence of any magnetic storm during this day. The first IL measurement was registered at a height of ~ 175 km at 18:30 LT. As the layer rose slowly in response to the PRE, its intensity was decreasing until becoming interrupted at ~19:20 LT. It is interesting to observe that this was the only event in which the IL continued being registered during the occurrence of spread-F. In the other cases discussed previously, the development of the spread-F occurred immediately after the interruption of the IL or some minutes later. It was verified in the ionograms of this day (not shown here) that as the spread-F increased, the intensity of the IL decreased until it became interrupted at 19:20 LT. The V_{zp} on December 14 reached ~ 21 m/s (0.5 mV/m) at ~18:10 LT. This was the only case in which the F layer height for the fixed frequencies of 5 and 6 MHz was below 300 km. In this case, the methodology we have used previously to derive the vertical drift does not represent the true velocity of the F layer and corrections are needed. The correction was done using the same methodology explained in Nogueira et al. (2011) (see also Subbarao and Krishnamurthy, 1983; Somayajulu et al., 1991).

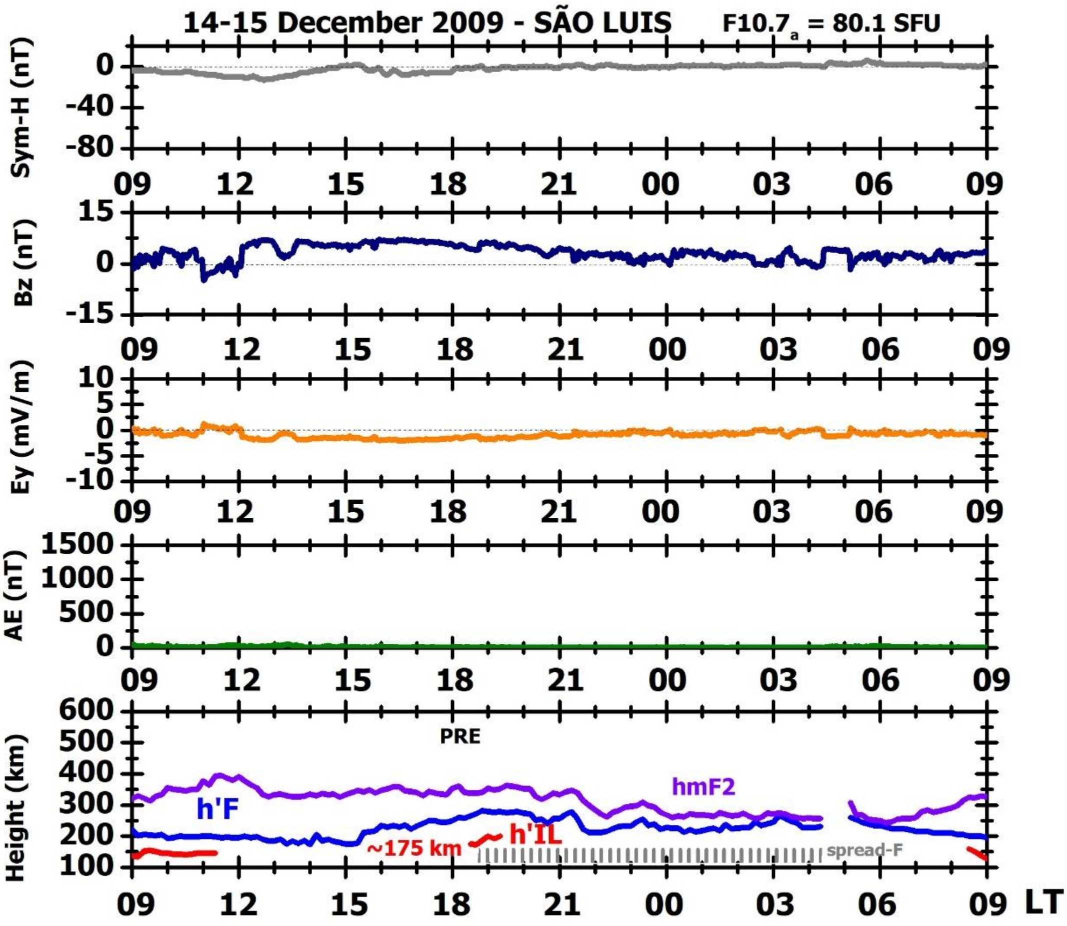

Figure 10 – Similar to Figure 4, but for 14 December 2009.

The parameters discussed in the events above are summarized in **Table 1**. The letters ***t_o (t_f), h_o (h_f), f_o (f_f)*** are used to describe the time occurrence (in local time), height (km), and top frequency (MHz) in which the ILs was formed (interrupted). The vertical drift peak (V_{zp}, m/s), the time of occurrence of V_{zp} (LT), and the IL's duration (hours) are also shown in this Table.

Table 1: Ionospheric parameters of the ILs and Vzp information

Event number	***Day***	***t_o (LT)***	***t_f (LT)***	***Duration (hour)***	***h_o (km)***	***h_f (km)***	***f_o (MHz)***	***f_f (MHz)***	***Vzp (m/s)***	***Time of Vzp (LT)***
1	***Jan. 29, 2003***	17:00	18:30	1.5	209	295	3.9	3.7	40	18:30
2	***Apr. 03, 2003***	17:30	19:00	1.5	230	320	3.1	2.1	47	18:45
3a	***08 Apr 2003***	18:15	18:45	0.5	200	214	2.2	1.7	16	18:30
3b	***Apr. 08, 2003***	18:30	19:30	1	253	259	2.5	3.8	16	18:30
4	***Oct. 12, 2003***	16:45	18:30	1.75	188	306	3.8	3.2	40	18:30
5	***Nov. 08, 2003***	18:00	18:30	0.5	185	211	2.5	1.8	36	18:30
6	***Nov. 10, 2003***	17:45	19:00	1.25	120	289	7.1	2.0	25	18:00
7	***Dec. 14, 2009***	18:30	19:20	0.8	175	201	2.0	1.9	21	18:10

Table 1 shows that, in most of the cases, the ILs were formed before the vertical drift attained its maximum value. The formation of one of the ILs on April 08, 2003 (event 3b,) occurred at the same time that the peak in the vertical drift was observed. Only in event 7 the ILs rise presented a delay with relation to V_{zp} of ~ 20 min. In general, the ILs duration varied from 0.5 to 1.75 hours.

3. Discussion and Conclusions

A detailed study about the intermediate layers over the equatorial and low latitudes regions of Brazil was made by dos Santos et al. (2019) and Santos et al. (2020). The latter investigated the behavior of the IL over São Luis (equatorial) and Cachoeira Paulista (low latitude site) locations, during the same years in which the ILs were studied in the present paper, that is, 2003 and 2009. Interesting results were found over the equator, such as the higher IL's occurrence rate in 2009 compared to that of 2003. The difference observed between these two periods was attributed to the displacement of the magnetic equator away from São Luis, thereby providing evidence on the role of the wind shear in the ILs formation over regions outside of the magnetic equator. Besides this, the authors found that the average values of the IL's height (h'IL) over SL mainly after noon local time (see Figure 4 of Santos et al. 2020) was greater in 2003 (being h'IL > 150 km) during the equinox and summer solstice. On the other hand, the IL's lifetime was lower when compared to the lifetime in 2009. Additionally, the month to month analysis of the average h'IL values proved to be more variable in 2003 when compared to 2009. These results, and others that can be found in dos Santos et al. (2019) and Santos et al. (2020), gives us some support to understand why the majority of the uplifts of the ILs at sunset were observed in 2003.

Figure 1 showed a common situation in which the IL is interrupted as the sunset approached. In that example, the intermediate layer was located at about 150 km of height. In the events studied here, the ILs were observed at altitudes close to 180 km, and in most of the cases they presented a weakening in the top frequency as they rose. Based on the results presented here and on the results presented by Santos et al. (2020), we believe that there must be a height limit between the E and F regions from which the intermediate layer can respond to the electric fields of the F region, more specifically to the PRE, and that this limit should vary between ~ 160 and 170 km of altitude. Furthermore, the higher occurrence of the ascending ILs at sunset in 2003 probably is related to the more intense electric fields that were observed during this epoch. Abdu et al. (2010) showed that the higher is the solar flux, higher will be the vertical drift peak/PRE (see also Fejer et al., 1979, 1991; Batista et al., 1996, Santos et al., 2013). During periods of high solar activity, the thermospheric eastward wind and the degree of the conductivity local time/longitude gradient in the evening, responsible for the intensity of the PRE, are strongly affected by the solar activity condition. Based on model calculations, Goel et al. (1990) showed that the E region conductivity gradient in the postsunset period is higher by a factor of 2 from high to low solar activity. This same factor was found for the thermospheric winds over Arequipa, Peru (16.5^{o}S, 71.4^{o}W), where the zonal wind presented an increase of 100 m/s eastward between 21 LT and 23 LT, for a variation of 100 units of solar flux. Besides that, it is interesting to observe that the rise of the ILs occurred between the months of October and April; none of the events occurred during the winter period in the southern hemisphere. Therefore, the more intense thermospheric winds generated during this period (that are very important for the development of the PRE) can be one of the factors responsible for the uplift of the ILs over São Luis. We observe that in most of the events (for example, events 1, 2, 3, 5 and 7), the rise of the ILs appears to have been caused by the normal enhancement of the zonal electric field at sunset. However, it is interesting to observe that only in event 7 (the only one during solar minimum) the IL was observed during the development phase of the spread-F and not before it as in other cases. This indicates that the rise of the ILs occurred during the reversal phase of the PRE when the intensity of the eastward zonal electric field is decreasing. Additionally, event 7 was the only case in which the IL got intensified (in terms of top frequency – ftIL) during its development, although, minutes later, the ftIL had been drastically reduced. It is interesting to observe that in almost all the cases, the rise of the ILs occurred during a period in which the PRE is more pronounced over the Brazilian sector in agreement with Abdu et al. (2010). In all the cases, the ILs' lifetime was shorter, lasting no more than 1h45min. This lower ILs' duration may have been caused due the ILs being located in a region where the layering process operates less efficiently than in a background of relatively smaller electron density (Santos et al. 2020).

As mentioned previously, the impacts of the evening zonal electric filed enhancement in the sporadic layers located away of the magnetic equator have been discussed in the literature (see for example Abdu et al., 2003; Carrasco et al., 2007; Rastogi et al., 2012). It was observed that the Es layer formation during the post-sunset hours can be disrupted or enhanced depending upon the vertical structure of the electric field arising from sunset electrodynamic process. Whilst an upward vertical electric field of Hall conduction induced by an eastward electric field is capable of disrupting an ongoing sporadic layer, the downward electric field induced by a westward electric field can favor its formation or even intensification. Abdu et al. (2003) showed that the interruption of the Es is dependent on the intensity of the PRE. Making a parallel with the intermediate layers studied over Brazil, we can say that near sunset (see Figure 4a from dos Santos et al., 2019), the ILs may present a weakening (and in some cases be interrupted) similar to what is observed in the Es layers. However, differently from the Es, the ILs can suffer a rise together with the F layer, and the dependence on the PRE intensity in these cases were not very clear in our analysis, since in some events the uplift of the F layer was very smooth (see for example event 7), indicating a lower value of the PRE, compared to other events, wherein the F layer rise was more intense (see for example event 2). Abdu et al. (2003) showed some cases in which a peak in vertical plasma drift (V_{zp}) of ~25 m/s was not enough to interrupt an ongoing Es layer over Fortaleza. In the present study, the IL was interrupted in all the cases, independently of the magnitude of the PRE, and did not reappear at later time as generally is observed for the Es layer. As shown in Table 1, V_{zp} varied from ~ 21 m/s to 47 m/s, which corresponds to zonal electric field variation from ~ 0.5 to 1.1 mV; however, the IL's uplift and the subsequent disruption was observed in all the cases. Another interesting characteristic is related to the IL's lifetime. Differently from the sporadic layers, the ILs were located at altitudes higher than 170 km and as mentioned previously, the lower lifetime observed in all the cases can be related to the chemical processes that lead to loss of ionization of these layers in this range of altitude.

The influence of the PPEF appeared to be more effective in the IL on November 10, 2003 (event 6). This event was very interesting because differently from the other cases, it refers to the uplift of a dense sporadic layer probably formed by the wind shear mechanism, as evidenced by the multiple reflection in some ionograms. The classification of the Es type in this case was difficult since in some ionograms preceding the rise, the Es layer apparently occurred together with the q-type Es layer (Es_q). This event showed an abnormal development of the Es that presented a rise and an interruption probably due to the prompt penetration electric fields. The Es displaced from ~120 km to 290 km in ~ 1h15min time interval. As indicated in the ionograms of ***Figure 9b***, as the layer rose, its top frequency decreased and attained a value of ~ 2 MHz before being disrupted. This abrupt change in the Es-IL height was probably caused by the PPEF, however, it is interesting to observe that this disturbance electric field affected more effectively the Es-IL layer than the F region. It was observed that the F layer also rose, but with slower velocity than that of the IL. This could occur due to the lower conductivity at the intermediate heights between the E and F regions. In this range of altitude, the geomagnetic field lines tend to be fully immersed at night earlier than at higher heights, therefore in a region of less conductivity. This could have contributed to a strong and faster Es/IL rise. Dos Santos et al. (2019) showed also a case in which the uplift of the IL probably was caused by PPEF and gravity waves, but differently from the present case, the rise was observed during the daytime. This was the only case in which the uplift of the Es/IL and F layers did not follow similar patterns. It is important to emphasize the unprecedented result reported here both for the ILs as well as for the normal Es layer: at the same time the PRE modifies the intensity of these layers, it can also move them up.

In summary, the effects of the F region electric field on the vertical movement of the intermediate layer during the evening prereversal enhancement were presented and discussed in this work. The outstanding results of this study may be summarized as follows:

1) The uplift of the ILs located at altitudes higher than 170 km can be caused by the prereversal electric field PRE and in some cases by an additional contribution from the PPEF;

2) The rise of the IL can occur during the main and recovery phase of a weak magnetic storm or in the absence of any interplanetary disturbance;

3) Most of the cases of IL's rise near to the PRE occurrence time were observed in 2003, a period in which the geophysical condition was different from that of 2009. The more intense winds during the periods in which the ILs' rise was observed (October to April) can be one of the factors responsible for the elevation of the ILs at sunset.

4) The uplift of the ILs was observed only in the equatorial region during the years of 2003 and 2009, and;

5) Eastward prompt penetration electric fields can cause ascending movement of the sporadic/intermediate layers.

Additional studies involving the observational data and numerical simulation are needed for a better understanding of the PRE effects in the ascending movement of the ILs.

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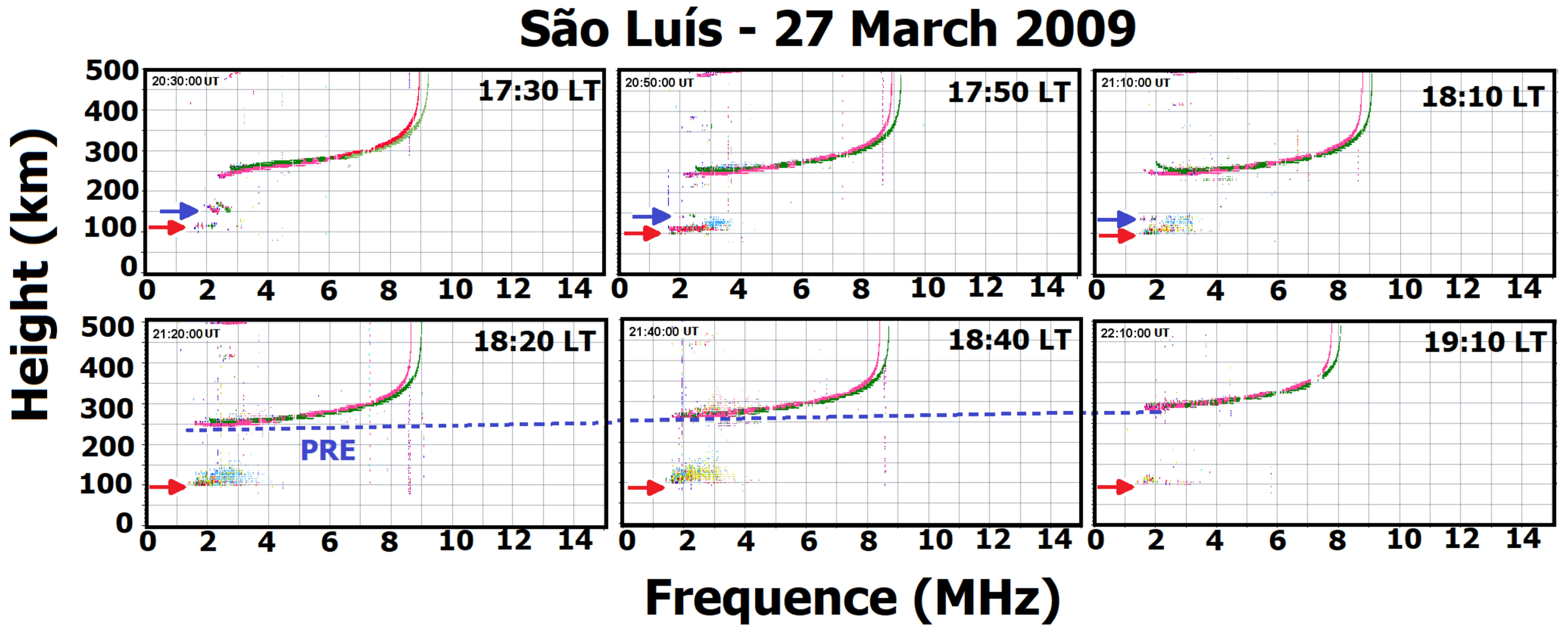
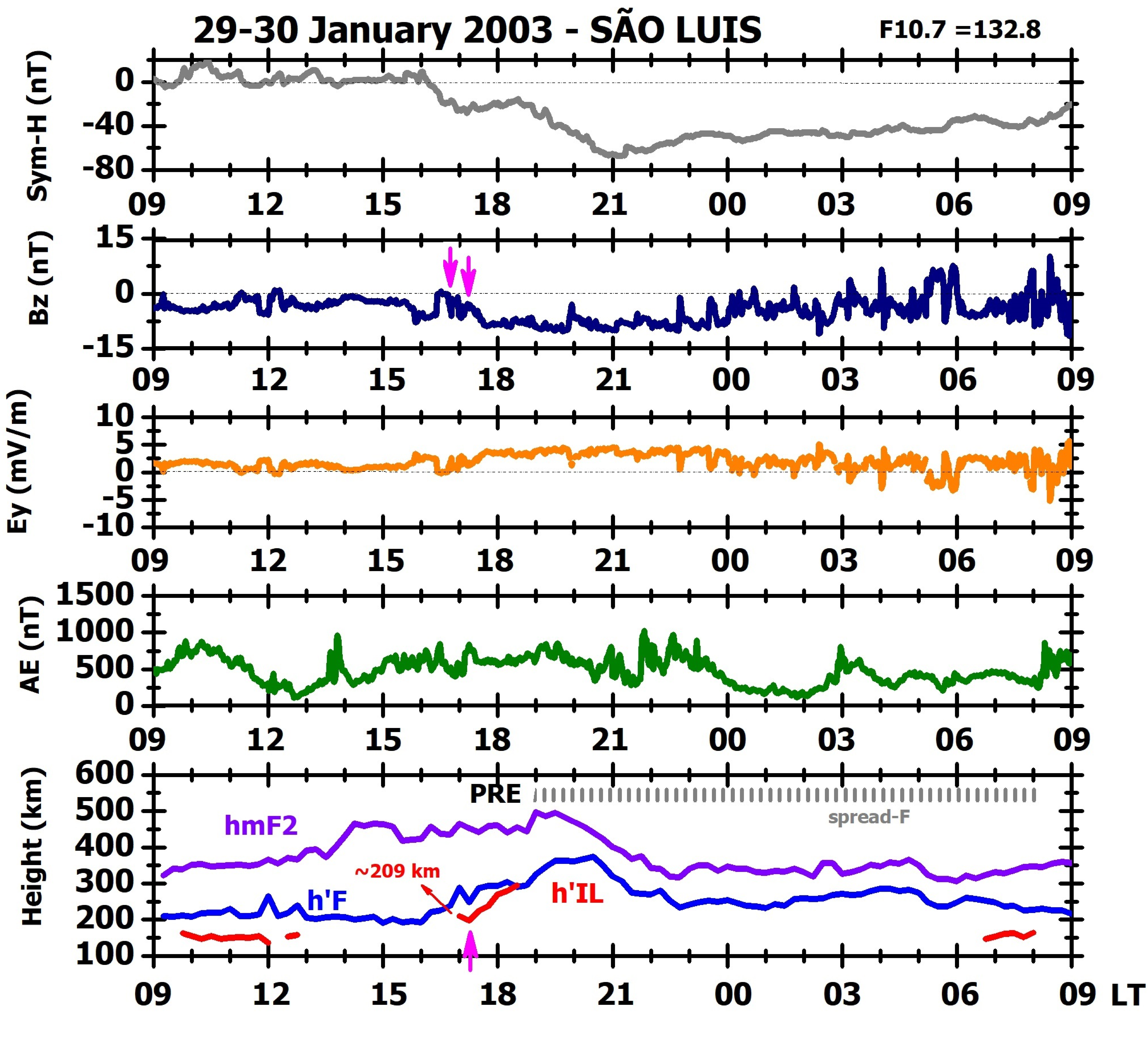
Figure 1.



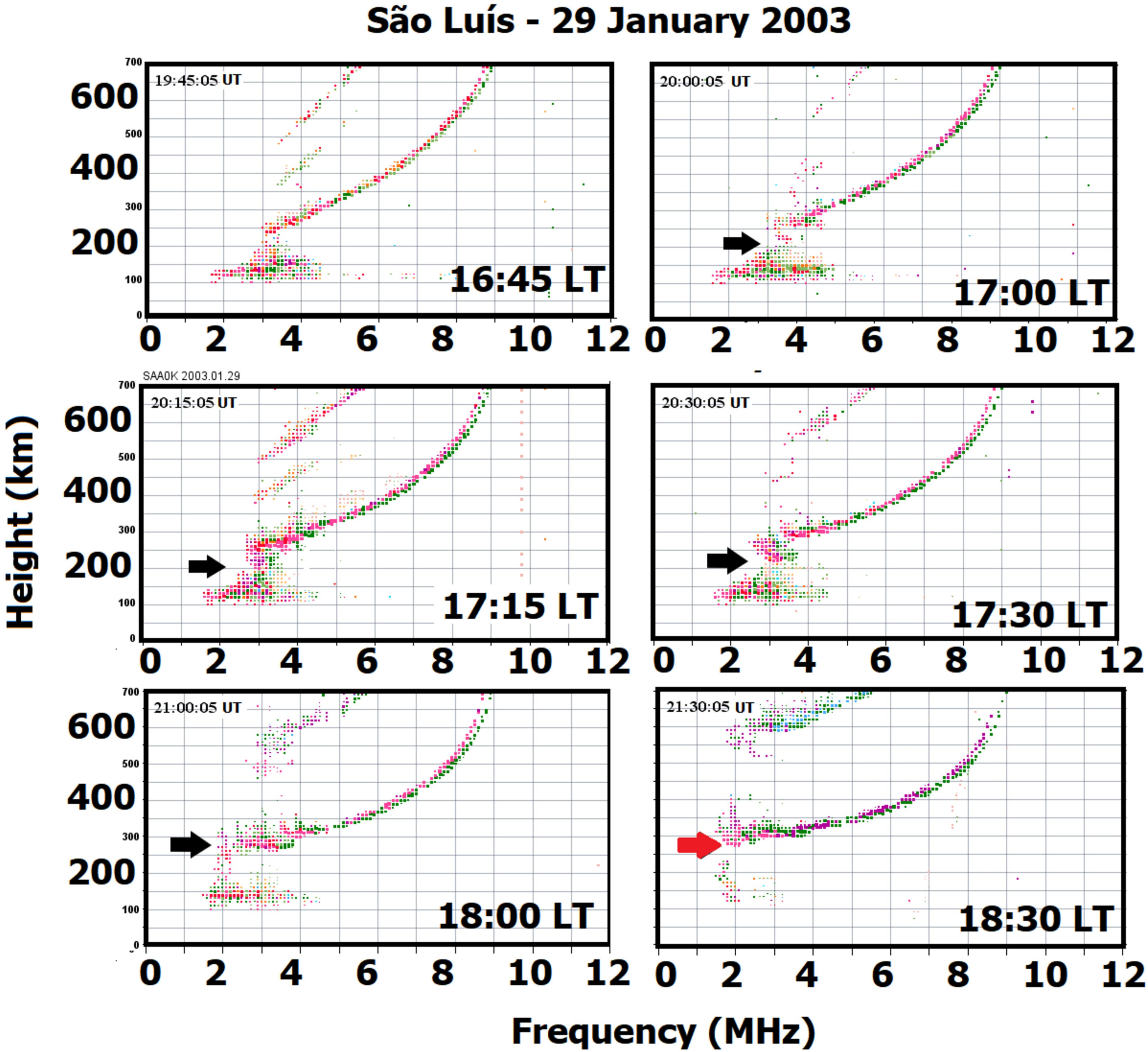
São Luís - 27 March 2009
Height (km)
Frequence (MHz)
20:30:00 UT
17:30 LT
20:50:00 UT
17:50 LT
21:10:00 UT
18:10 LT
21:20:00 UT
18:20 LT
21:40:00 UT
18:40 LT
22:10:00 UT
19:10 LT
PRE
0
100
200
300
400
500
0
2
4
6
8
10
12
14

Figure 2.



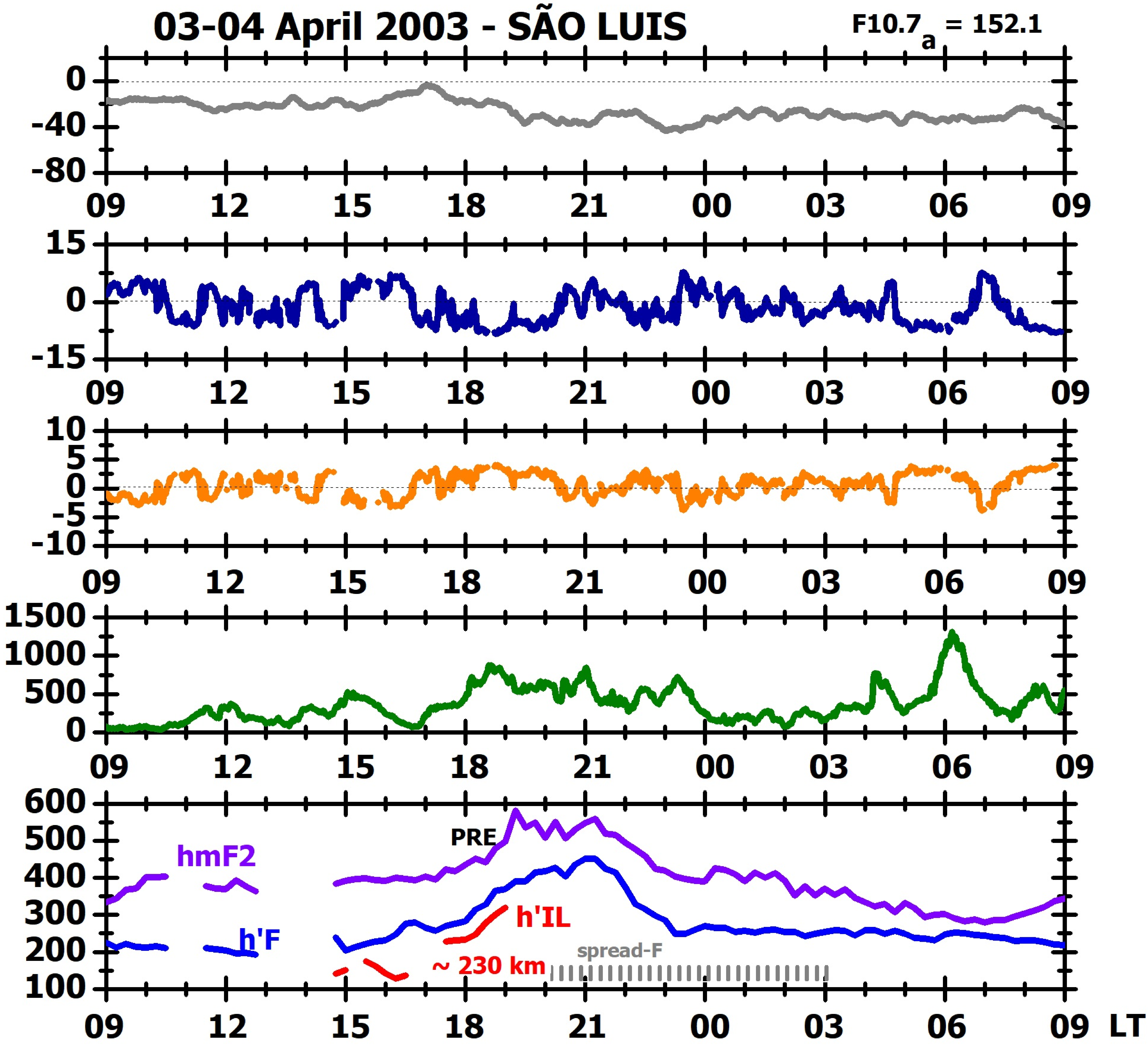
29-30 January 2003 - SÃO LUIS
F10.7 =132.8
Sym-H (nT)
Bz (nT)
Ey (mV/m)
AE (nT)
Height (km)
hmF2
h'F
h'IL
~209 km
PRE
spread-F
LT

Figure 3.



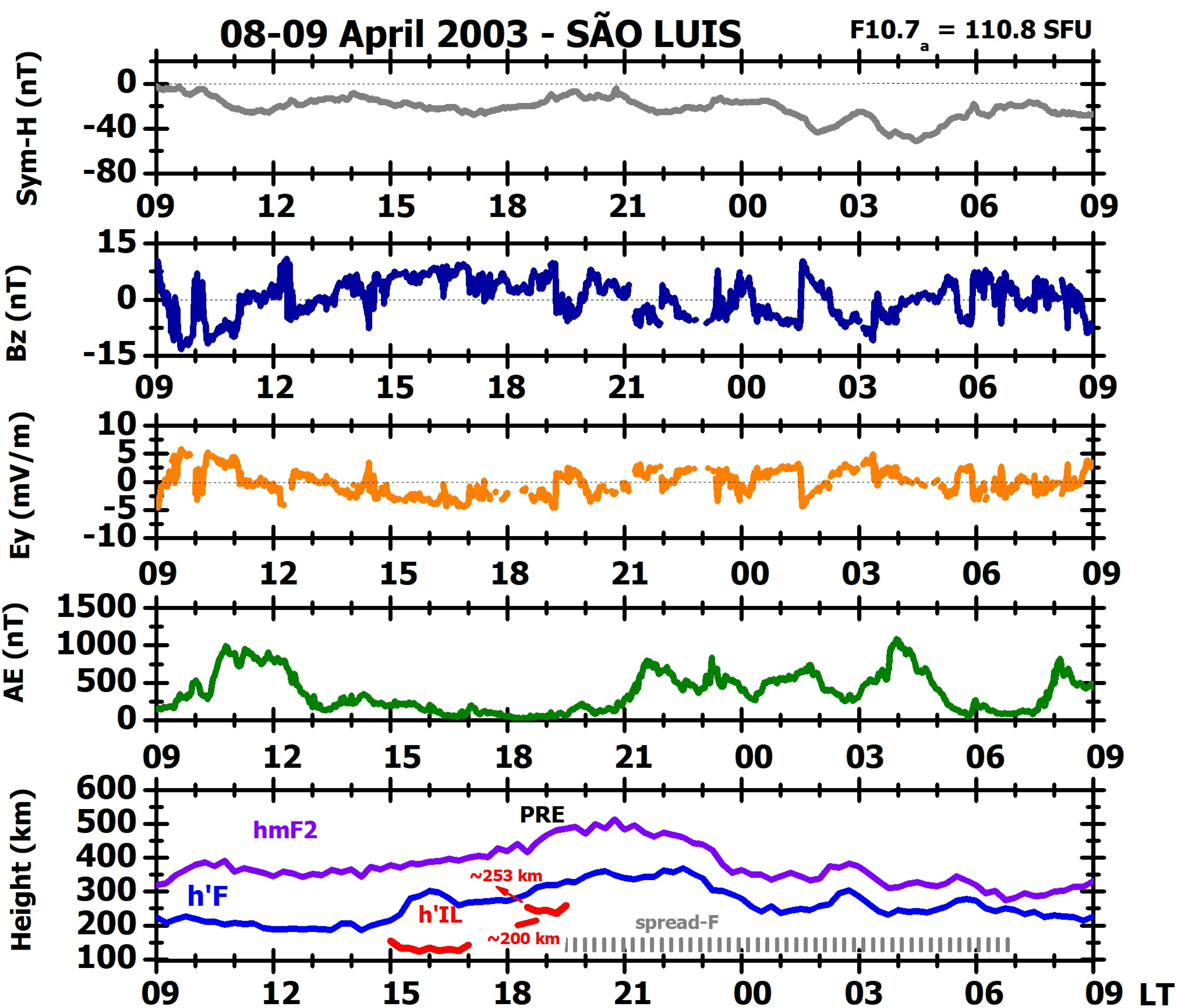
São Luís - 29 January 2003
19:45:05 UT
16:45 LT
20:00:05 UT
17:00 LT
SAA0K 2003.01.29
20:15:05 UT
17:15 LT
20:30:05 UT
17:30 LT
21:00:05 UT
18:00 LT
21:30:05 UT
18:30 LT
Height (km)
Frequency (MHz)

Figure 4.



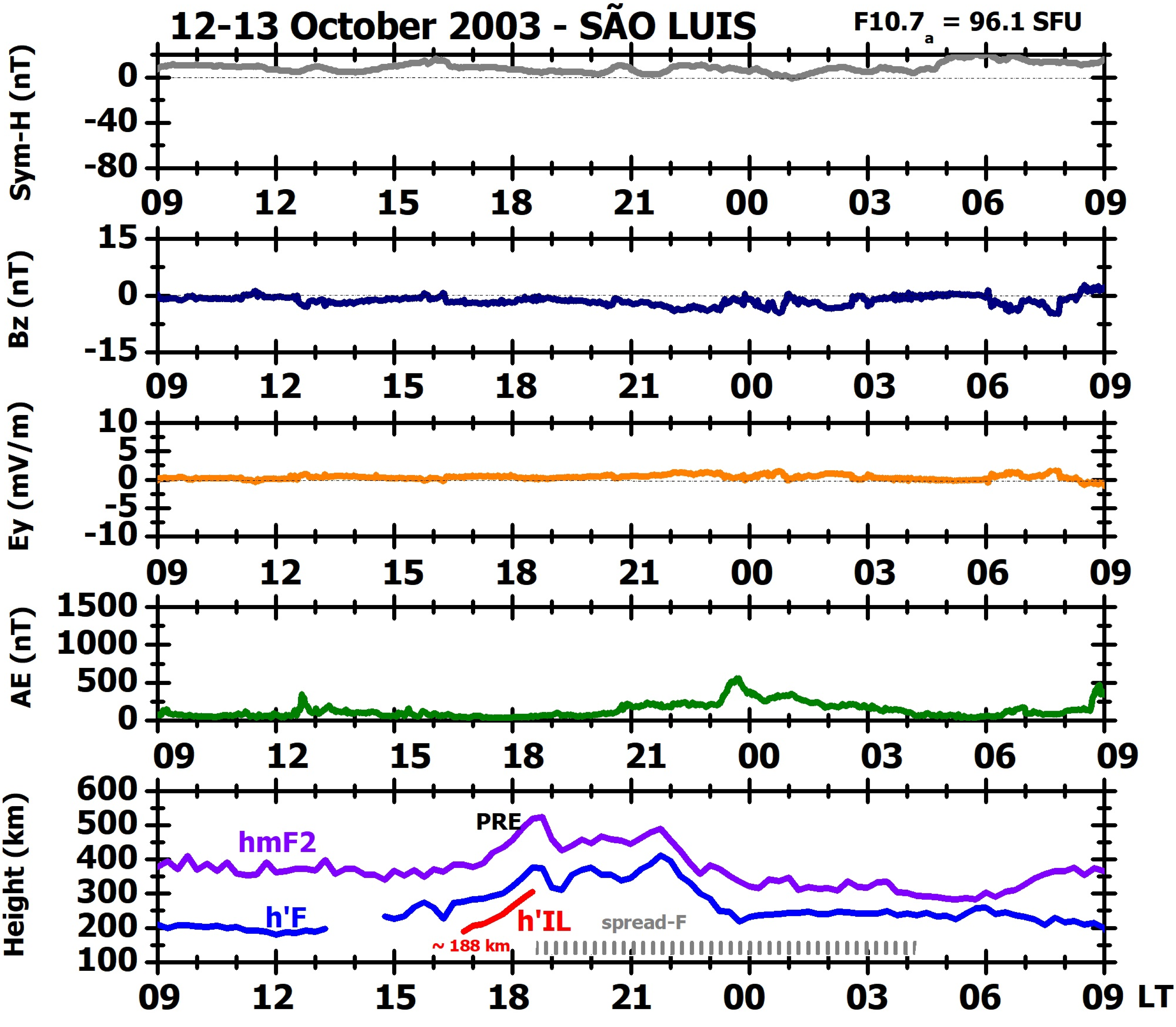
03-04 April 2003 - SÃO LUIS
F10.7a = 152.1
0
-40
-80
09
12
15
18
21
00
03
06
09
15
0
-15
10
5
0
-5
-10
1500
1000
500
0
600
500
400
300
200
100
hmF2
PRE
h'IL
h'F
spread-F
~ 230 km
LT

Figure 5.



08-09 April 2003 - SÃO LUIS
F10.7a = 110.8 SFU
Sym-H (nT)
0
-40
-80
09
12
15
18
21
00
03
06
09
Bz (nT)
15
0
-15
Ey (mV/m)
10
5
0
-5
-10
AE (nT)
1500
1000
500
0
Height (km)
600
500
400
300
200
100
hmF2
PRE
h'F
h'IL
~253 km
~200 km
spread-F
LT

Figure 6.



12-13 October 2003 - SÃO LUIS
F10.7a = 96.1 SFU
Sym-H (nT)
0
-40
-80
09 12 15 18 21 00 03 06 09
Bz (nT)
15
0
-15
09 12 15 18 21 00 03 06 09
Ey (mV/m)
10
5
0
-5
-10
09 12 15 18 21 00 03 06 09
AE (nT)
1500
1000
500
0
09 12 15 18 21 00 03 06 09
Height (km)
600
500
400
300
200
100
PRE
hmF2
h'F
h'IL
~ 188 km
spread-F
09 12 15 18 21 00 03 06 09 LT

Figure 7.

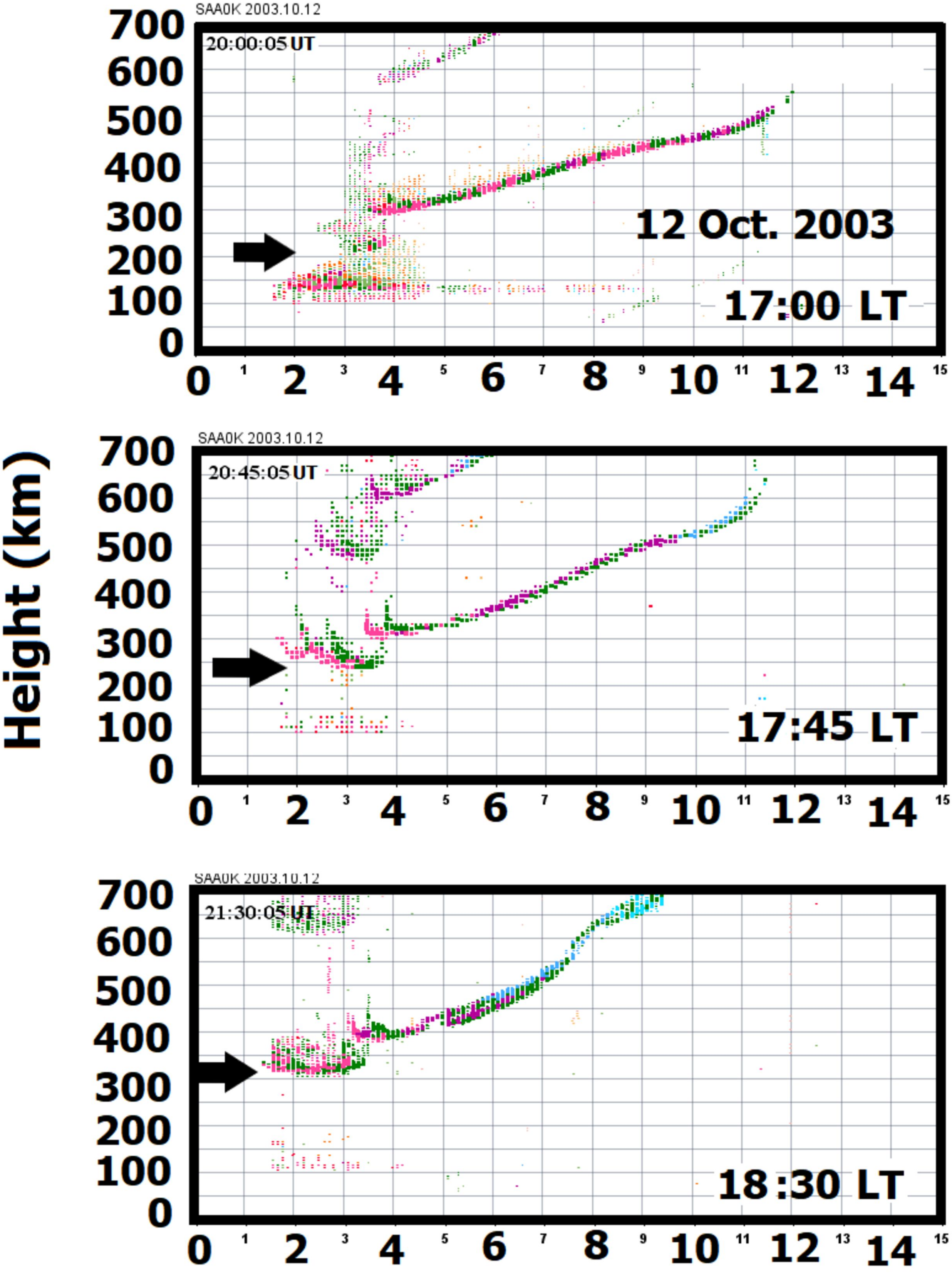
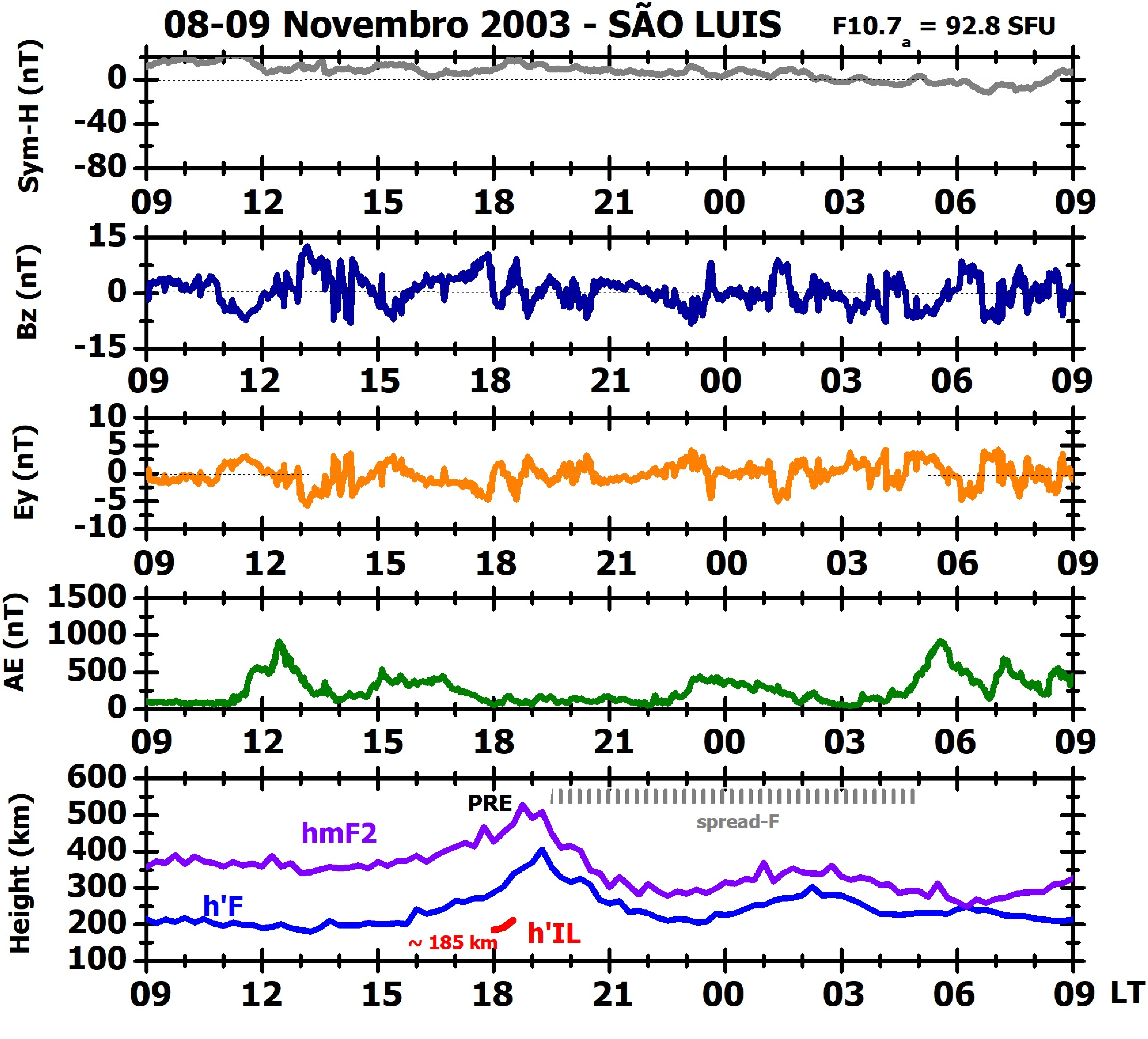
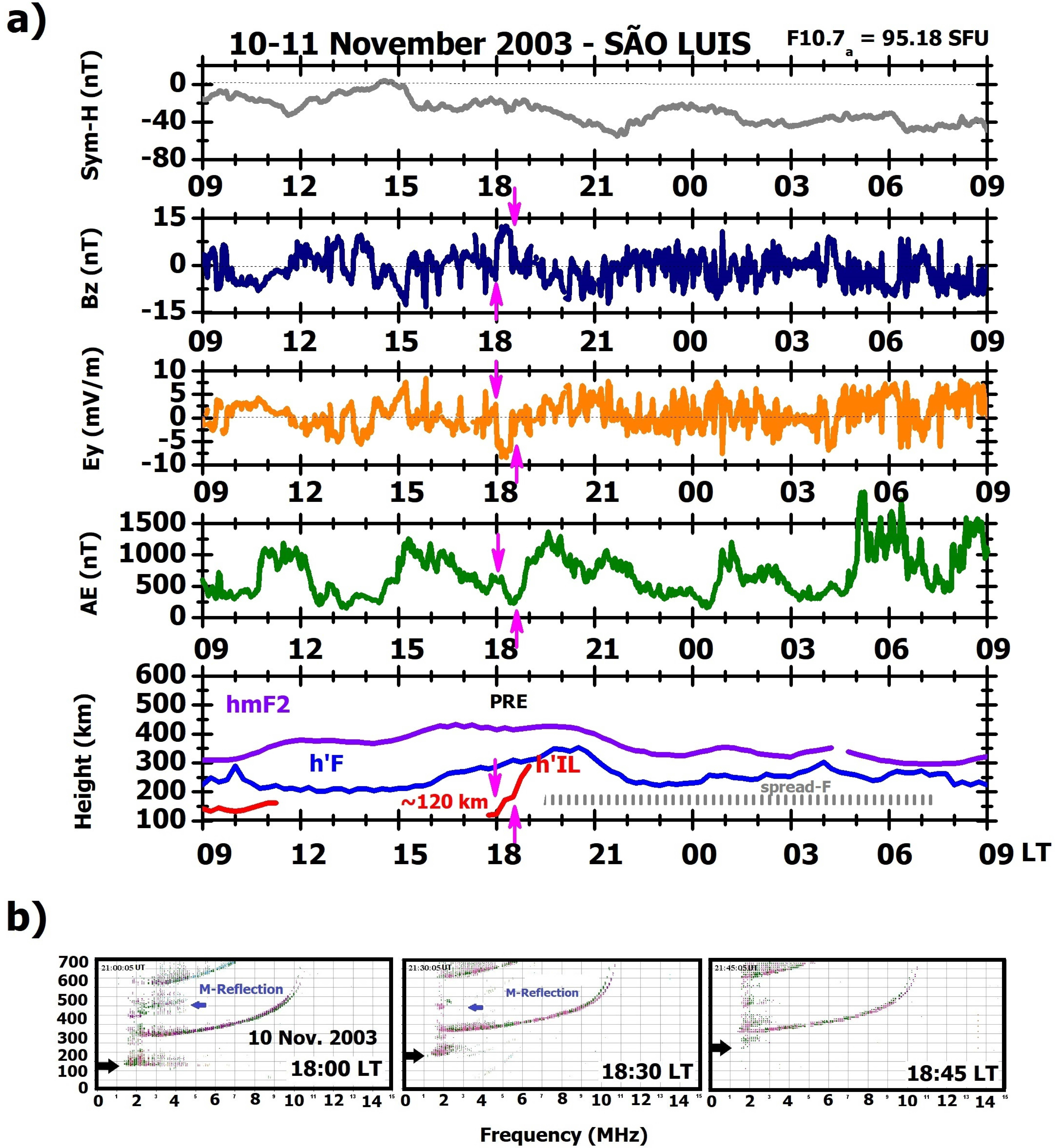

SAA0K 2003.10.12
20:00:05 UT
12 Oct. 2003
17:00 LT
SAA0K 2003.10.12
20:45:05 UT
17:45 LT
SAA0K 2003.10.12
21:30:05 UT
18:30 LT
Height (km)
Frequency (MHz)
0
100
200
300
400
500
600
700
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15

Figure 8.



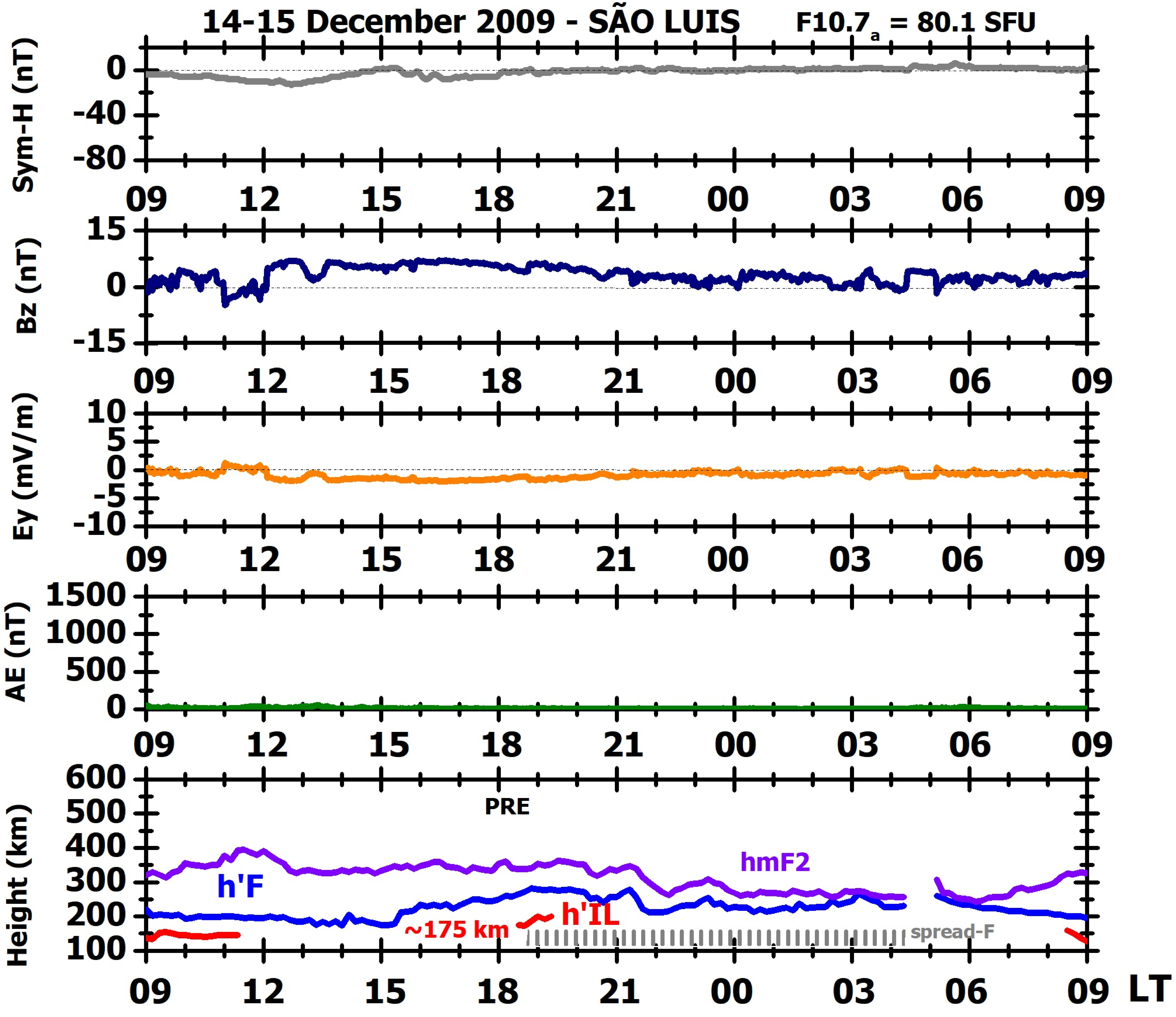
08-09 Novembro 2003 - SÃO LUIS
F10.7a = 92.8 SFU
Sym-H (nT)
0
-40
-80
09
12
15
18
21
00
03
06
09
Bz (nT)
15
0
-15
Ey (nT)
10
5
0
-5
-10
AE (nT)
1500
1000
500
0
Height (km)
600
500
400
300
200
100
PRE
spread-F
hmF2
h'F
~ 185 km
h'IL
LT

Figure 9.



a)
10-11 November 2003 - SÃO LUIS
F10.7a = 95.18 SFU
Sym-H (nT)
Bz (nT)
Ey (mV/m)
AE (nT)
Height (km)
hmF2
PRE
h'F
h'IL
~120 km
spread-F
LT
b)
M-Reflection
10 Nov. 2003
18:00 LT
18:30 LT
18:45 LT
Frequency (MHz)

Figure 10.


14-15 December 2009 - SÃO LUIS
F10.7a = 80.1 SFU
Sym-H (nT)
0
-40
-80
09 12 15 18 21 00 03 06 09
Bz (nT)
15
0
-15
Ey (mV/m)
10
5
0
-5
-10
AE (nT)
1500
1000
500
0
Height (km)
600
500
400
300
200
100
PRE
hmF2
h'F
h'IL
~175 km
spread-F
LT