Equatorial ionosphere bottom-type spread F observed by OI 630.0 nm airglow imaging

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[1] Bottom-type spread F events were observed in the south American equatorial region by a VHF coherent radar and an ionosonde at São Luís (2.5°S, 44.3°W), an ionosonde at Fortaleza (3.9°S, 38.4° W) and an airglow OI 630.0 nm imager at Cariri (7.4°S, 36.5°W) and Brasilia (14.8°S, 47.6°W). In the evening of September 30, 2005, a long duration (~70 minutes) bottom side scattering layer, confined in a narrow height region, was observed. At the same time all-sky imager observed sinusoidal intensity depletions in the zonal plane extending more than 1500 km and elongated along the magnetic meridian. No strong spread F structures developed during the period. Subsequently well developed plasma bubbles were observed. This suggests that the observed bottom-type spread F is an initial phase of the plasma bubbles. We report, for the first time, longitudinal and latitudinal extension of the bottom-type spread F as diagnosed by optical imagers.
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1. Introduction

[2] In the equatorial ionosphere evening condition, there frequently appears a thin layer of VHF radar backscattering in the bottom side of the F-layer, around 250 – 300 km of altitude. The radar echoes are diffused but confined to a narrow range of altitude and lasts for a few tens of minutes to ~ hours. It is known as bottom-type spread F, first observed by *Woodman and La Hoz* [1976]. From Jicamarca JULIA radar, *Hysell and Burcham* [1998] reported that the bottom-type spread F mainly occurs during the equinox season in the solar minimum period, and it frequently occurs as a precursor to the large scale top side irregularities (plumes). *Hysell et al.* [2004] observed horizontal and vertical structure of the bottom-type scattering layer using multiple baseline interferometry method (aperture synthesis imaging technique) at Jicamarca. They analyzed two cases of the bottom-type spread F. One case was monotonous bottom side scattering without developing spread F. In the second case they observed horizontal patchy structures in the bottom side scattering with the horizontal distance of ~30 km that was followed by irregularity development at higher altitudes. They concluded that the periodic patchy structure of the bottom-type spread F could be precursor of large scale Rayleigh-Taylor instabilities.

[3] All of the previous works have been carried out from Jicamarca radar observatory. From Kwajalein islands (Central Pacific) *Hysell et al.* [2005, 2006] observed a bottom-type scattering layer at 200–250 km altitude with patchy forms separated by about 150–200 km. They used a radar which was a combination of coherent and incoherent scattering modes. The former detected plasma irregularities and the latter measured plasma density which made it possible to get a vertical profile of the F-layer electron density. During the patchy structure event in the bottom-type scattering, similar periodic wave forms in the F-layer bottom side densities were also seen. Later, the bottom-type layers developed upwards generating large scale irregularities. Thus it seems that when the bottom-type spread F is observed, there is a large scale periodic wave form in the bottom side F layer.

[4] The radar backscatter observations of the F-layer made it possible to investigate vertical and zonal structure of the bottom-type scattering layers. However, the diagnostics of the irregularities was limited by the field of view, temporal and spatial resolution of the radar in use. A two dimensional horizontal view of the scattering layer can be achieved if the airglow OI 630.0 nm emission layer could be monitored by an all-sky imager. The emission layer is normally located below the F-layer peak height, around 240–260 km of altitude. The field of view of the imager covers more than 1500 km of horizontal extension at an emission altitude of 250 km. Therefore simultaneous monitoring of the bottom-type scattering layer by coherent radar and airglow imager can permit us to observe vertical and horizontal structures of the bottom-type spread F. The purpose of the present work is, therefore, to investigate the bottom-type spread F in terms of its vertical and horizontal structures and their time evolution using three different observational techniques, a VHF coherent radar, two ionosondes and two OI 630.0 nm all sky imagers.

2. Observation

[5] The First SpreadFEx campaign was carried out from September 20 to November 05, 2005, as a part of the NASA Living with a Star Program. The main purpose of the cam-

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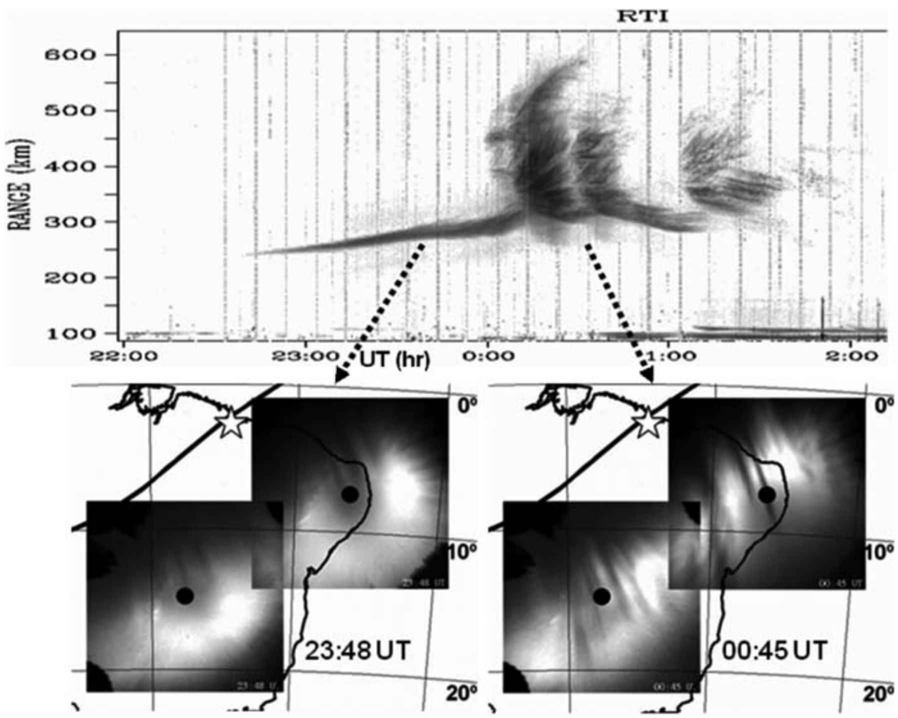

Figure 1. VHF radar Range-Time-Intensity (RTI) at (top) São Luís and airglow OI 630.0 nm image maps at (bottom) Cariri and Brasilia at (left) 23:48 UT and (right) 00:45 UT on the night of September 30, 2005. The star mark is São Luís radar site.

paign was to investigate possible effects of gravity waves on the seeding of ionospheric bubbles in the equatorial region. Some preliminary results have been presented by *Fritts et al.* [2008]. In the present work two 630.0 nm airglow all-sky imagers, located near Brasilia (14.8°S, 47.6°W, geomag. 11°S) and at Cariri (7.4°S, 36.5°W, geomag. 11°S) were operated simultaneously observing the equatorial ionospheric bubble structures and their time evolution. The near Brasilia site is located southwest of Cariri with a distance of ~1400 km. The optical imaging observation started soon after (~30 min.) the local sunset and used a time integration of 90 seconds. The characteristics of the all-sky imagers have been presented elsewhere [*Takahashi et al.,* 2009]. The 630.0 nm image deploys the spatial irregularities of the emission layer in a two dimensional form, with a horizontal extension of ~2000 km (at the zenith angle of 80°), permitting to monitor bottom side F-layer plasma irregularities at an altitude of 250 km. The observed images (spherical axis) were transformed into the flat field geographical coordinates. The plasma bubble zonal structures (bubble separation distance) were, then, calculated.

[6] The 30 MHz coherent radar at São Luís (2.5°S, 44.3°W) provides backscatter echoes as a function of height and time (RTI map). Characteristics of the radar have been presented by *de Paula and Hysell* [2004]. Plasma irregularities with scale size of 5 meters can be detected. The radar echo images can show how it comes from a localized structure with a field of view of 16 degrees, corresponding to ~76 km horizontal extension at 270 km of altitude. The ionograms observed at Fortaleza (3.9°S, 38.4° W) and São Luís by Digital ionosondes (DSP-4) are also used in order to determine the spread F condition and the vertical drift of the F layer bottom height. Ionograms were taken with a 10-minute interval.

3. Results

[7] In the evening of September 30, 2005, the coherent radar at São Luís registered a short range (20–30 km of thickness) bottom-type back scattering layer between 22:40 and 00:00 UT as can be noted in the Range Time Intensity (RTI) map shown in Figure 1. During the period the scattering layer moved upward from around 240 km to 290–300 km. However, the spread F did not develop vertically, and the scattering layer thickness remaining by about 30 km, until around 00:00UT. Just after 00:00 UT the spread F quickly developed, its vertical extension reaching above 550 km of altitude.

[8] On the other hand the OI 630.0 nm all sky imagers at Cariri and Brasilia observed airglow depletions with periodic (rather sinusoidal) zonal structure during the bottom-type spread F occurrence from 23:00 to 00:00 UT as shown in an example at 23:48 UT in Figure 1 (bottom, left-hand side). The observed images are projected on geographical coordinates and assuming that the OI 630.0 nm emission layer is located at around 250 km of altitude. The images are presented in a square area that has a horizontal extension of 1500 km. It can be noted that the depletions are aligned in the magnetic meridian (the declination at Cariri: −22°) and they are separated approximately equidistant from one another. From the time sequence of the images it appears that the depletions drifted eastward with a velocity of approximately 170 m/sec. The distance between the depletions was around 120 km [*Takahashi et al.,* 2009]. The sim-

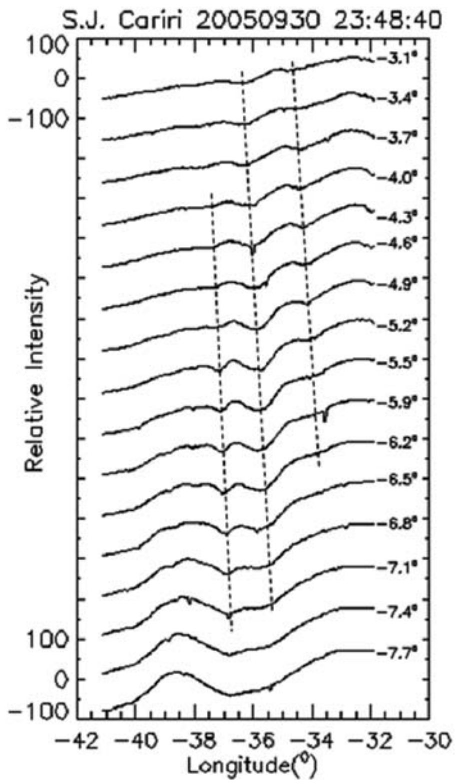

Figure 2. Longitudinal OI 630.0 nm intensity variations over the fixed latitudes from 4.5° S to 7.7° S, observed by the all-sky imager at Cariri.

ilar sinusoidal depletion structures at Brasilia and Cariri would indicate that these depletions are distributed in a longitudinal region that extend by more than 1500 km.

[9] From the image at 23:48 UT, one can notice that the depletions extend from the northern horizon to the zenith of the observation site. In order to see their latitudinal extension, longitudinal cuts of the OI 630.0 nm intensity variations at successive latitudes are plotted in Figure 2. Two intensity depletions can be seen up to 7.0° S, which indicates that they extend to 600–700 km of distance away from the magnetic equator. It should be pointed out that these depletions are similar to the well known signatures of plasma bubbles. From the present results, however, it was not possible to determine if the depletions extended beyond the magnetic equator up to the northern conjugate point.

[10] The OI 630.0 nm image map at 00:45 UT is shown in Figure 1 (bottom, right-hand side). The depletions now extend further southward of the zenith both at Cariri and Brasilia. The horizontal (zonal) distances between the depletions are similar to those of the depletions in the 23:48 UT image, but in some cases they are longer, one case showing a distance of ~200 km. The coherent radar also showed well developed plumes after 00:00 UT, thereby indicating that these depletions are typical signatures of the plasma bubble.

[11] The ionogram true heights at some selected plasma frequencies over Fortaleza observed on this night are shown in Figure 3. The fixed frequencies at Fortaleza (Figure 3, top) present sinusoidal oscillation of height with the amplitude of ~30 km and a period of around 60 minutes during the 22:30 to 24:00 UT time interval. Also shown are ionograms at 23:40 UT observed both at Fortaleza and São Luís. The ionogram at Fortaleza registered satellite traces (double/multiple F layer trace structure), but not at São Luís. The traces have a range separation of about 50 km. These facts indicate that the F layer bottom side over Fortaleza had large scale horizontal gradients (layer tilt).

[12] The presence of such wave structures have been shown to constitute a precursor condition for an ensuing spread F development [see, e.g., *Abdu et al.,* 2009a]. The horizontal scale length is about 170 km at an altitude of 270 km corresponding to the observed range difference of almost 50 km. This must be related to the wavelike oscillation seen in Figure 3 (top). It is interesting to note that the ionogram also displays somewhat limited spread F condition in a range of 2.0–3.5 MHz, indicating that the F-layer bottom height is partially perturbed. A similar partial spread F condition can be seen in the ionogram at São Luís (Figure 3, bottom), but no horizontal gradient similar to that observed at Fortaleza was seen. It displays just a bottom layer spread F in a range of 2 to 4 MHz (between 270 and 300 km). This corresponds to what we observed in the radar RTI image. No clear irregularity can be seen above 4.5 MHz (above 350 km). The ionogram at 00:40 UT (not shown here), on the other hand, presents typical range type spread F, in much

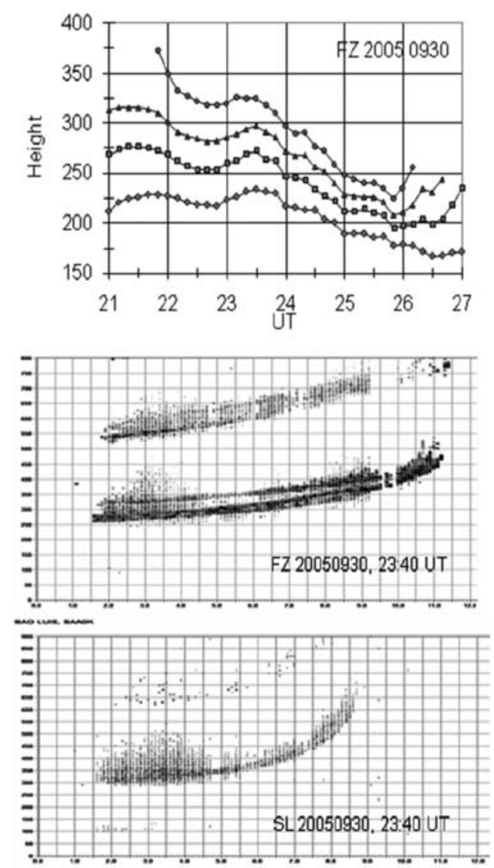

Figure 3. (top) Temporal variations of the true heights at the plasma frequencies, 10, 8, 5 and 1 MHz (from top to down), (middle) ionogram trace at 23:40 UT observed at Fortaleza, and (bottom) ionogram at São Luís at 23:40 UT on the night of September 30, 2005.

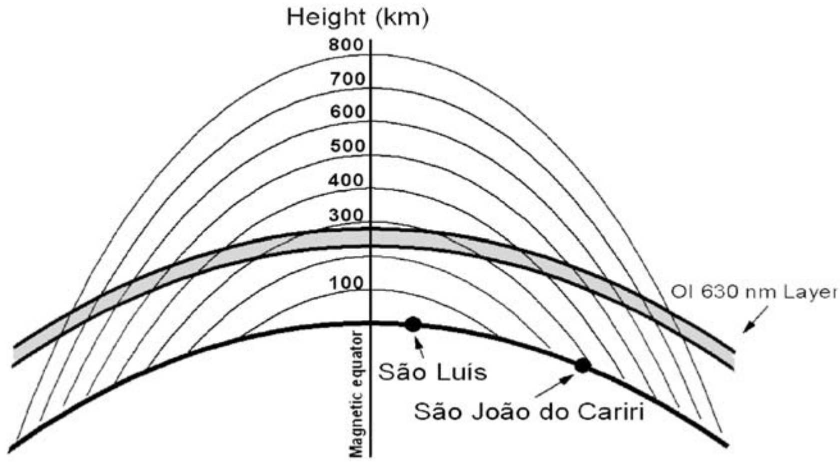

Figure 4. Geomagnetic field lines and Apex height over the geomagnetic equator. The shaded area indicates the OI 630.0 nm emission layer. Geomagnetic latitude of Cariri is around −11°S.

of the frequency and height ranges, indicating presence of plasma bubble over São Luís.

4. Discussion

[13] On September 30, 2005, São Luís coherent radar registered a bottom-type spread F, a thin scattering layer situated near 250–300 km of altitude with a thickness of 20–50 km and lasting for more than one hour. The layer resembles what have been observed earlier from Jicamarca and Kwajalein [*Hysell et al.,* 2004, 2006]. The São Luís ionosonde revealed echo-spread in the lower frequency range. The Fortaleza ionosonde presented horizontal gradient of the F-layer at the time of the bottom-type spread F. Simultaneously, the OI 630.0 nm all-sky imager at Cariri observed sinusoidal structures in the airglow intensity in a form of undulation in the zonal plane. The airglow depletions that were aligned in the magnetic meridian were present in an extended longitude range of more than 1500 km. Such a long extended undulation structure of the OI 630.0 nm emission has not been reported before, and should be worthwhile to investigate further.

[14] The dissociative recombination process, $O_2^+ + e \rightarrow O(^1D) + O^*$, where * indicates an excited state, is responsible for the ionospheric OI 630.0 nm emission. The emission rate is therefore dependent on the atmospheric density (O_2) and the electron density. It means that if the F layer bottom height oscillates, the corresponding up and down motion will produce a decrease and an increase, respectively, of the OI 630.0 nm emission rate. Thus, the observed OI 630.0 nm sinusoidal structure might be caused by such vertical oscillation of the F layer. The horizontal gradient in the F layer bottom height observed at Fortaleza supports the present hypothesis. It should be noted that Fortaleza and Cariri are located in the same magnetic meridian.

[15] In order to understand what mechanism was responsible for generation of such oscillations (or wave structure) in the F layer bottom height, several processes could be taken into account. F region dynamo electric field generated by the lower thermosphere neutral wind oscillation could be one of the possible mechanisms. A direct effect of plasma density perturbation cannot also be ruled out. In Figure 4 the OI 630.0 nm emission layer and the geomagnetic field lines in the magnetic N-S plane are visualized in a simple form. The apex height of the magnetic field line crossing the OI 630.0 nm emission layer over Cariri is about 500 – 600 km in the magnetic equatorial plane. No clear spread F condition was observed in this height region over São Luís at 23:40 UT as seen in Figure 3. Therefore it is difficult to assume that the undulation structure observed at Cariri (off-magnetic equator) was originated from the magnetic equatorial region through the flux tube mapping. The airglow undulation observed at Cariri might be generated in the F-layer bottom height. The vertical perturbation of the bottom height was, however, not sufficient to develop plume-like plasma depletions detectable by the coherent radar at São Luís in the evening of September 30, 2005, as shown in Figure 1.

[16] Simultaneous presence of wave structures in bottom-type spread F as diagnosed by the coherent radar at São Luís and the digisonde at Fortaleza on the night of October 5, 2005, was reported by *Abdu et al.* [2009b] as it representing the precursor conditions for subsequent spread F vertical development. Our present case is similar to them and further reveals that the bottom-type spread F and the associated wave structure have in some cases a large longitudinal extension by more than 1500 km. We may point out that this is the first case that a bottom-type spread F was observed simultaneously by three different instruments, ionosonde, coherent radar and all sky imager in a three dimensional form. Simultaneous appearance of the OI 6300 depletion and bottom type spread F has also been observed in the other nights during the SpreadFEx campaign. It seems that the phenomenon is not uncommon in this region at least during the equinox season as *Hysell and Burcham* [1998] reported. It would be worthwhile to further investigate the relation of the bottom-type spread F and development of plasma bubbles.

5. Conclusion

[17] We observed a bottom-type spread F by a coherent radar, ionosonde and airglow OI 630.0 nm all-sky imager from three different observation sites near the magnetic equatorial regions in the evening of September 30, 2005. The bottom-type spread F was confined in a narrow height

region (~20–50 km) and lasted more than one hour then developing into vertically well extended plasma bubbles. During the bottom-type spread F occurrence, the OI 630.0 nm imager at Cariri observed sinusoidal depletions similar to the plasma bubbles but without meridional (and vertical) development and they were distributed in longitudinal plane extending by more than 1500 km. The ionosonde at Fortaleza observed horizontal gradient of the F layer bottom height. These observational evidences suggest that there were vertical oscillations in the F-layer bottom height in this evening which generate plasma instability, and then resulting vertical growth of plasma bubbles. It might indicate that the observed bottom-type spread F with associated wave structures represents an initial phase of the equatorial plasma bubbles.

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