Equatorial F-region irregularities generated by the Rayleigh-Taylor instability mechanism – rocket observations from Brazil

P. Muralikrishna and L.P. Vieira, Instituto Nacional de Pesquisas Espaciais – INPE, C.P. 515, 12201-970, São José dos Campos-SP, Brazil

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Abstract

Several sounding rockets carrying plasma diagnostic experiments were launched from the Brazilian rocket launching stations in Natal (5.9°S, 35.2°W Geog. Lat.) and Alcantara (2.31°S, 44.4°W Geog. Lat.). Langmuir Probes (LP) were used to measure the height profiles of electron density and electron temperature and High Frequency Capacitance (HFC) probes were used to measure electron density. The LP's were also used to measure the amplitude of electron density fluctuations ranging in scale size from a few meters to several kilometers. A detailed study of the characteristic features of large scale electron density irregularities observed by rocket-borne electron density probes under different ionospheric conditions is presented here. The main objective of these studies is the identification of these irregularities from the point of view of the dynamic and eletrodynamic processes responsible for their generation. The existing theories of the Rayleigh Taylor Instability mechanism are adapted for conditions of the geomagnetic equatorial ionosphere over Brazil. Appropriately modified equations are used to estimate the minimum expected wavelength of the irregularities, the minimum growth time of irregularities, and the wavelength of irregularities corresponding to the minimum growth time. Through these parameters it is possible to discuss about the importance of the RTI mechanism for the ionosphere. The observed characteristics of the irregularities during four rocket launches are compared with the theoretically expected characteristics. These results confirm the operation of a cascade process that is responsible for the generation of a wide spectrum of irregularities. The cascade process is initiated by conditions favourable for the operation of Gradient Drift Instability (GDI) mechanism, though the growth times expected from theories do not always match with the observations. The large scale irregularities are first generated probably by the RTI mechanism that creates conditions favourable for the operation of the GDI mechanism. From the k-spectra of irregularities it is possible to obtain the spectral index *n* corresponding to the height chosen. In most of the cases the estimated spectral indices agree well with those published in the literature for the cases of irregularities generated by the GDI mechanism.

Introduction

Several linear and non-linear theories have been invoked to explain the wide spectrum of electron density irregularities observed in the nighttime F-region (Reid, 1968, Hudson et al, 1973, Sudan et al 1973). Haerendal (1974) suggested a multi-step process to explain the large range of wavelengths observed, from several kilometres down to few centimetres. The collisional Rayleigh-Taylor (R-T) instability mechanism driven by gravity in the bottom side of the F-region gives rise to large plasma depletions or plasma bubbles. The large density gradients associated with these rising bubbles are favourable for the operation of the gradient drift instability mechanism. Collisionless R-T instability mechanism is then invoked and kinetic drift waves grow upon these irregularities after they reach large amplitude. Chaturvedi and Kaw (1976) put forward a two-step theory of longer wavelength R-T modes directly coupling with kinetic collisional drift waves to explain the measured k^{-2} spectra of the electron density irregularities. Scannapieco and Ossakow (1976) from numerical simulation showed that the collisional R-T instability generated irregularities and bubbles on the bottom side of the F-region, which rose beyond the F-peak by Hall drift. These bubble phenomena were later confirmed by experimental observations of plasma density depletions (Kelly et al, 1976; McClure et al, 1977, Woodman and La Hoz, 1976). Analytical models for the rise of collisional and collisionless R-T bubbles were presented by Ott (1978). It is now known that bubbles are mostly aligned with the geomagnetic field with plasma density decreases of up to 3 orders of magnitude. These depletions are generally produced over geomagnetic equator and they connect upwards through the F-layer peak to the topside ionosphere, reaching altitudes as high as 1200 km or more (Woodman and La Hoz, 1976). The post-sunset equatorial F-layer can become unstable under the influence of any disturbance produced by gravity waves, neutral winds or electric field fields, and can generate plasma irregularities through the R-T instability mechanism (Hysell et al, 1990, Singh et al, 1997). Steep plasma density gradients associated with the long wavelength R-T mode, create a condition which leads to the hierarchy of plasma instabilities giving rise to a wide spectrum of irregularities.

Five major rocket campaigns have been reported for studying the phenomenon of spread-F in the American region (Kelly et al, 1976, Morse et al, 1977, Rino et al, 1981; Szuszczewicz et al, 1981, Kelley et al, 1982; Hysell et al, 1994) and a few campaigns in the Indian zone (Raghavarao et al, 1987; Prakash et al, 1991, Sinha et al, 1999, Raizada and Sinha, 2000, Sinha and Raizada, 2000). From simultaneous in situ measurements of electron density and electric field fluctuations Hysell et al (1994) showed that irregularities in the scale size range of 100 m- 2 km display a power law behaviour with spectral index n ≈ -2 that increased to –4.5 for wavelength around 100 m and below when F-layer is high. The spectral indices as well as the exact relationship between the electron density and electric field fluctuations depend on the type and the scale size of irregularities. Measurement of these parameters, thereby, can give us valuable information on the plasma instability mechanism responsible for the generation of these irregularities.

As mentioned earlier the following are the well-known plasma instability mechanisms that are known to be responsible for the generation of plasma irregularities in the nighttime F-region:

- Rayleigh-Taylor Instability (collisional or non-collisional)
- Gradient Drift or Cross-field Instability

The effective linear growth rate for the irregularities generated through the Generalised Rayleigh-Taylor (GRT) instability mechanism including the effect of vertical winds can be written as:

$$\gamma_g = \frac{g}{\nu_{in} L} - \frac{E}{BL} - \frac{U}{L} - \frac{W}{L} - \eta_R$$

where, g is the acceleration due to gravity, U and W respectively are the horizontal and vertical components of the neutral wind (taken positive upward and eastward), ν_{in} is the ion-neutral collision frequency, L is the gradient scale length (taken positive upward), E is the horizontal electric field (taken positive eastward) and η_R is the recombination coefficient. As can be seen from this relation, when L is positive (base of the F-region for example), westward electric field and a neutral wind with downward and westward components will increase the growth rate of the R-T irregularities.

The gradient-drift or cross-field instability mechanism occurs in regions where E is parallel to the electron density gradient (Reid, 1968; Tsuda et al., 1969). In other words height regions where E and L have the same sign are favourable for the generation of irregularities by this mechanism. As mentioned earlier the steep electron density gradients associated with the plasma bubbles produced by the collisional or noncollisional R-T instability create conditions favourable for the generation of smaller scale size irregularities by the gradient-drift and other instability mechanisms.

Results and Discussion

Rocket Flight on 11-th December 1985

A Brazilian Sonda III rocket, carrying a Langmuir probe (LP) and a High Frequency Capacitance (HFC) probe in addition to other airglow photometers, were launched at 2130 (LT) on 11-th December, 1985, from the equatorial rocket launching station in Natal-RN, Brazil. The rocket reached an apogee altitude of 516 km and a horizontal range of 484 km. The LP used could measure electron density irregularities in a wide range of scale sizes from several meters to several tens of kilometres. The data sample rate used was more than 1600samples per second.

Figure 1 shows the altitude profiles of the electron density estimated for the rocket upleg and downleg.

Electron density structures

The upleg electron density profile shows continuous structures of small-scale electron density irregularities, some of them being rather steep. Two distinct regions of irregularities were observed during the rocket upleg, one of them in the height region close to 270 km and the other close to 280 km. In the first region the vertical extension of the irregularities is in the range of 1 to 5 km in which the electron density varied by a factor of 1.4 within a vertical extent of 2 km. In the second height region electron density irregularities were observed in a vertical extension of about 3 km, and the density varied by a factor of about 1.4, as in the first height region. During the rocket downleg electron density irregularities were practically absent in these height regions.

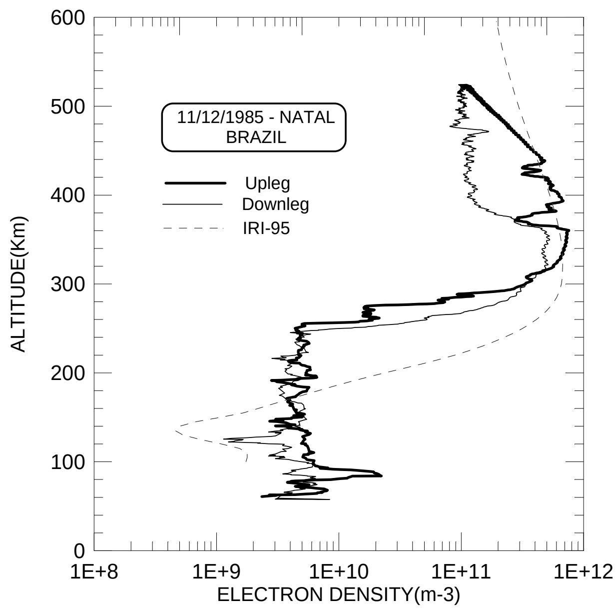

Figure 1: Altitude profiles of the electron density estimated for the rocket upleg and downleg on 11-th December, 1985.

In the height region above 350 km, electron density depletions were observed in the height regions of 360,4 to 393 km and 419 to 438,7 km. In the first height region the density depletion was by a factor of about 2.7 in a height extent of 11.4 km, that recovered by a factor of 2.2 in a height extent of 10 km. In the second height region the density depletion was by a factor of 1,5 within 4.4 km and the recovery was by a factor of 1.4 within a vertical extension of 4.2 km. During the rocket downleg electron density depletions were observed starting at about 359 km in which a large number of small-scale irregularities were observed with depletion factor as high as 4.3 within a vertical extension of 38.8 km.

The large positive electron density gradient observed in the base of the F-region extending from about 260 km to about 305 km seems to be responsible for the generation of the electron density structures in this height region through the Rayleigh-Taylor Instability mechanism. Other regions of large electron density gradients observed at height regions of 353 km, 380 km, 436 km and 478 km are associated with negative electron density gradients and thereby are favourable for the generation of plasma irregularities by the Cross-field instability mechanism During the rocket downleg electron density gradients are observed at 288 km and 374 km, the first one being positive and the second one negative.

The k-spectra of the electron density irregularities were estimated by conventional spectral analysis of the electron density fluctuation data. The existing theories on the generation of plasma irregularities are unable to explain all the spectral features observed. However, for irregularity wave numbers in the range of 0,3 $km^{-1} < k <$ 63 km^{-1}, it is known that the main generation mechanism responsible is the Generalized Rayleigh Taylor Instability and for irregularity wave numbers in the range of 63 $km^{-1} < k <$ 6283 km^{-1} the generation mechanism is the gradient drift or two-stream instability mechanism (see Kelley, 1989).

Rocket Flight on 31-st October 1986

On 31-st October, 1986 a Brazilian Sonda III rocket, carrying a Langmuir probe (LP) and a High Frequency Capacitance (HFC) probe in addition to other airglow photometers, were launched at 2400hrs (LT) from the equatorial rocket launching station in Natal-RN, Brazil. The rocket reached an apogee altitude of 444 km and a horizontal range of 656 km. The LP used could measure electron density irregularities in a wide range of scale sizes from several meters to several tens of kilometers. The data sample rate used was more than 1600samples per second. The main objective of the launch was to study the equatorial ionosphere under conditions unfavourable for the generation of bubbles and thereby for the non-operation of the Rayleigh-Taylor instability mechanism.

The electron density profiles obtained for the rocket upleg and downleg are shown in figure 2.

One of the major aspects of the electron density profiles observed is the presence of the F-region base at a relatively low altitude, close to 200 km during both upleg and downleg of the rocket. In this height region the recombination coefficient for the electron density is rather height and it can be shown that this condition is not favourable for the operation of the Rayleigh-Taylor Instability mechanism. Predominantly negative gradients are observed in the height regions close to 322 km, 360 km, and 407 km during the rocket upleg. Such gradients favour the generation of smaller scale plasma irregularities through the cross-field instability mechanism. During downleg, in addition to the positive electron density gradient observed at the F-region base, the only height region where negative gradients are observed is close to 361 km.

Rocket Flight on 14-th October 1994

During this launch, a *Black Brant X* rocket carried on board several plasma density probes and an electric field double probe. The rocket was launched from the Brazilian equatorial launch station in Alacantara-MA at 1955hrs (LT) on 14-th October, 1994 and reached an apogee altitude of 957 km and a horizontal range of 532 km (LaBelle, 1997). The plasma probes included a conventional Langmuir probe (LP), a High Frequency Capacitance (HFC) probe and a Plasma Frequency probe (PFP). The LP had a sampling rate of 500 per second, the PFP a sampling rate of about 8000 samples per second and the HFC a low sampling rate.

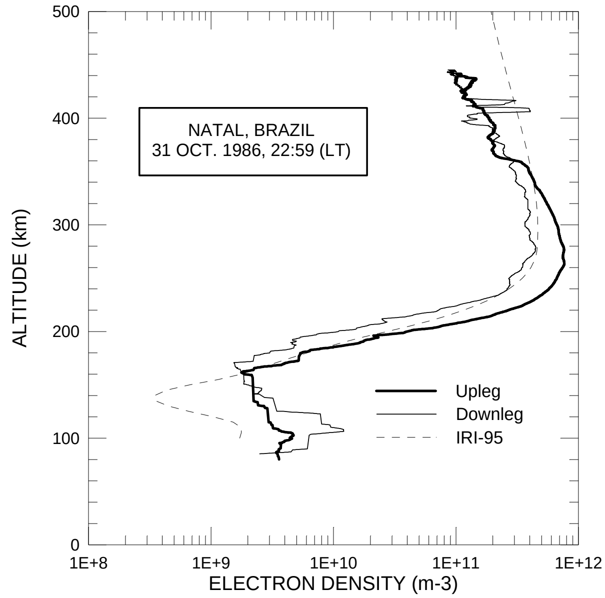

Figure 2: Altitude profiles of the electron density estimated for the rocket upleg and downleg on 31-st October, 1986

The figure 3 shows the electron density profiles for the rocket upleg and downleg estimated from the HFC probe data.

Electron density structures

Electron density irregularities of a wide range of scale sizes were observed during this flight in the height region of 340 km to 817 km during rocket upleg and height region of 600km to 310 km during the rocket downleg. The F-region base was seen well above 300 km that is considered to be favourable for the operation of the Rayleigh-Taylor Instability mechanism. Large-scale electron density structures are produced by the RTI mechanism, the scale sizes ranging from several kilometres to several tens of kilometres. Electron density depletions where the density reduced by a factor of 2.6 in a vertical extension of about 1 km is seen in the height region of about 497 km. In the height region close to 535 km the density increased again by a factor of 1.8 within a vertical height range of 2.7 km. Electron density structures of scale sizes of hundreds of metres were also seen superposed on the large scale structures. It is now rather well established that these smaller scale structures are generated by the cross-field instability mechanism.

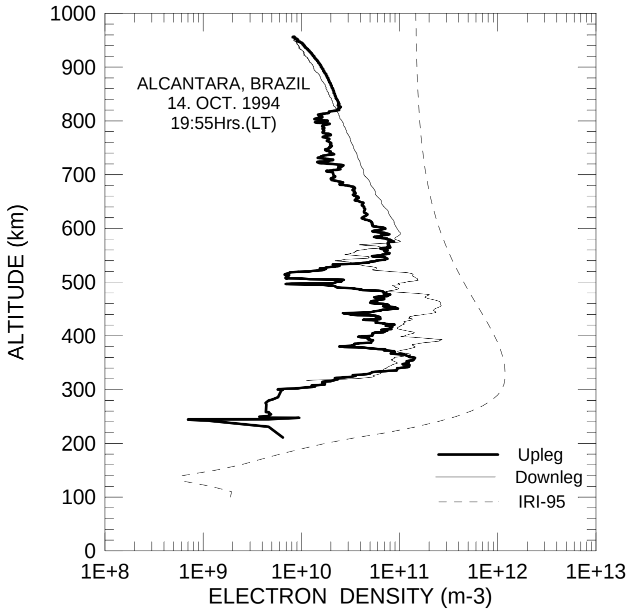

Figure 3: Altitude profiles of the electron density estimated for the rocket upleg and downleg on 14-th October, 1994

Dominant positive electron density gradients were observed during the rocket upleg in two height regions, one close to 313 km, and the other close to 547 km. Dominant negative electron density gradients were observed during the rocket upleg close to 396 km, 475 km, and 627 km. The downleg profile shows less number of regions of electron density gradients, dominant positive gradients being observed close to 373 km and 505,5 km. A comparison of the amplitudes of electron density fluctuations with the height regions of large density gradients clearly shows that the fluctuation amplitudes are higher where the electron density gradients are also higher, especially the positive electron density gradients that are responsible for the operation of the RTI mechanism.

Rocket Flight on 18-th December 1995

A Brazilian Sonda III rocket, carrying a Langmuir probe (LP), a High Frequency Capacitance (HFC) probe and an Electric Field double probe (EFP) was launched at 2117 hrs (LT) on the 18-th December, 1995 from the Brazilian equatorial launching station Alcantara-MA. The rocket reached an apogee altitude of 557 km and a horizontal range of 589 km. The ac data from the LP and EFP experiments were sampled at 1250 samples per second, that enabled the study of small scale electron density electric field fluctuations of scale sizes less than 3 meters.

The figure 4 shows the variation of electron density with altitude estimated from the LP data for both the upleg and downleg of therocket.

Electron density structures

As can be seen from Figure 4 the upleg profile shows the presence of a rather steep F-region base close to 300 km, free of any large scale electron density depletions or bubbles, while the downleg profile shows the presence of a large number of plasma bubbles The downleg profile does not show a sharp F-region base. The positive electron density gradient at the base of the F-region extends from about 280 km to above 300 km, the electron

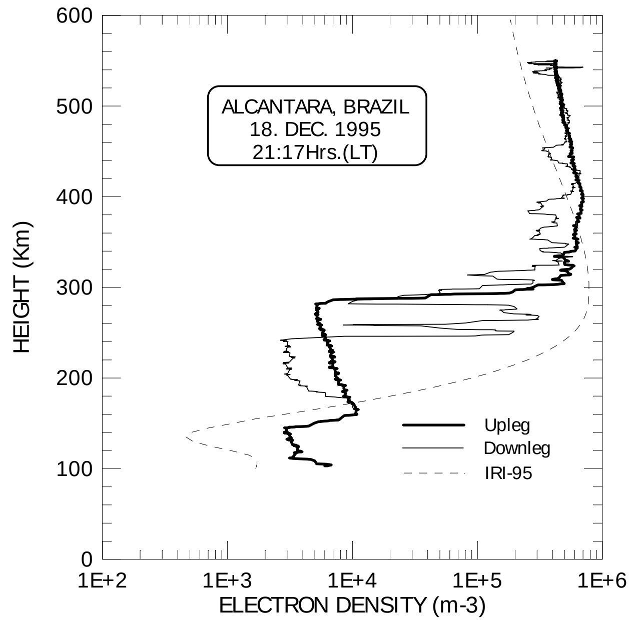

Figure 4: Altitude profiles of the electron density estimated for the rocket upleg and downleg on 18-th December, 1995

density in this region increasing by a factor of 7 over a vertical extension of about 7 km. This condition is favourable for the operation of RTI mechanism. At the same time one should remember that large scale irregularities known to be produced by the RTI mechanism are not observed in the upleg profile. This probably is due to the fact that the RTI mechanism had just started operating and the large scale irregularities produced could only be seen in the rocket downleg profile. Enhanced electron densities were seen in the downleg profile close to the height regions of 253 km, 269 km and 276 km, and depleted regions close to 259 km and 282 km.

Analysis of the k-spectra of irregularities estimated shows larger spectral indices at height regions of 240 km and 270 km during upleg and at 270 km during rocket downleg. These height regions correspond to the base of the F-region where the internal gravity wave generated winds are known to be strong (Raizada, 2000). But, analysing the height regions close to 300 km, 325 km and 370 km, which are just above the base of the F-region, one can see that these are the regions where the plasma bubbles start developing as seen in the upleg profile, and where large-scale bubbles are well developed as seen in the downleg profile. The presence of smaller scale irregularities in these height regions indicate the operation of cross-field instability also, thus confirming the hypothesis that the Rayleigh-Taylor and Cross-field instability mechanisms operate in a sequential manner, the larger scale sizes being generated first by the RTI mechanism and then the smaller scale sizes being generated at regions of favourable electron density gradients by the CFI mechanism.

Conclusions

- Under favourable conditions ionospheric plasma at the base of the F-region can become unstable for perturbations and large-scale plasma irregularities maybe produced by the Rayleigh-Taylor instability mechanism.
- Present observations indicate that F-region base at a higher altitude is more favoured for the operation of RTI mechanism than at lower altitude.
- A cascade process seems to be initiated by first by the operation of RTI mechanism resulting in the development of plasma bubbles or large-scale irregularities. In the height regions of large electron density gradients inside these bubbles the plasma may become unstable for the CFI mechanism, causing the generation of smaller scale irregularities.

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