Geofísica Internacional
ISSN: 0016-7169
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Universidad Nacional Autónoma de México
México

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Geofísica Internacional, vol. 43, núm. 2, april-june, 2004, pp. 165-172
Universidad Nacional Autónoma de México
Distrito Federal, México

Geofísica Internacional (2004), Vol. 43, Num. 2, pp. 165-172

Deviations from model predictions in measured electron density profiles for low latitudes: A critique

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Received: March 31, 2002; accepted: June 14, 2002

RESUMEN

Se comparan los perfiles obtenidos *in situ* de las estaciones ecuatoriales de Brasil, usando pruebas de Langmuir y de Frecuencia de Alta Capacitancia, con las predicciones del modelo IRI, en el contexto de las distribuciones espectrales de las irregularidades observadas en la densidad del plasma. Se asume que las inestabilidades de Rayleigh-Taylor y la de Campo Cruzado, son las responsables de la generación de las irregularidades observadas en el plasma, y con ellas se estima el tiempo de crecimiento y el tamaño mínimo de las irregularidades que se observan en diferentes alturas para el perfil de densidad electrónica. Para ello se usan aproximaciones polinomiales simples para representar el perfil observado. La comparación entre las características de las irregularidades observadas del plasma con las esperadas a partir de la teoría nos puede dar información sobre la confiabilidad del perfil observado. La confiabilidad se vuelve particularmente importante de estimar debido a que las técnicas de medición de densidad electrónica se asocian a algunos problemas. Entonces se puede ver que si las desviaciones observadas del perfil comparadas con el modelo IRI son reales o no. De este estudio comparativo uno puede saber cuales son los parámetros físicos responsables por las desviaciones observadas y sugerir mejoras en los métodos usados en las predicciones de IRI a bajas latitudes.

PALABRAS CLAVE: Región F, ionosfera, densidad electrónica, modelo IRI, burbujas de plasma, prueba de Langmuir.

ABSTRACT

In situ electron density profiles obtained from equatorial stations in Brazil using conventional Langmuir probes and High Frequency Capacitance probes are compared with IRI predictions in the light of the spectral distribution of the plasma density irregularities observed. Plasma instability mechanisms, especially Rayleigh-Taylor and Cross-Field instability mechanisms responsible for the generation of observed plasma irregularities, are used to estimate the growth time and the minimum scale size of irregularities at different height regions along the electron density profile. Simple polynomial approximations are used to represent the observed electron density profiles. A comparative study of the observed plasma irregularities with those expected from theory can give information on the reliability of the observed profiles. This reliability estimate is important because the techniques used for the measurement of electron density are known to be associated with some problems. Thus one can see whether the deviations of the observed electron density profiles from IRI predictions are genuine, and what are the physical parameters responsible for the observed deviations in the profiles. Some improvements in the methods used for IRI predictions in low latitudes are suggested.

KEY WORDS: F-region, ionosphere, electron density, IRI model, plasma bubble, Langmuir probe.

INTRODUCTION

The International Reference Ionosphere (IRI), first publication in 1978 by Rawer *et al*. (1978), has undergone periodic modifications in attempts to improve its accuracy for representing the quiet-time ionospheric parameters as functions of height, geographic location, local time and sunspot number. *In situ* measurements of electron density and electron temperature, undertaken from the equatorial region in Brazil, were to provide a larger data base for these modifications. In the equatorial and low latitude regions in the Americas, the ionospheric models proposed so far seem to be less accurate, probably due to electrodynamic and dynamic processes produced by the large magnetic declination angle in this region (Abdu *et al*., 1981). Abdu *et al*. (1990) reported *in situ* measurements of electron density and compared them with IRI predictions. They found reasonable agreement between the IRI predictions and rocket measurements, especially during the daytime. However, the electron temperature estimates from Langmuir Probe measurements reported by Kantor *et al*. (1990) deviated considerably from IRI predictions for this region.

Several rockets carrying plasma diagnostic experiments were launched from 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 (n_e) and electron temperature (T_e) and High Frequency Capacitance (HFC) probes were used to measure n_e. The main objectives of the studies reported here are the following.

• To compare the observed n_e profiles with the IRI Model predictions.
• To study the spectral characteristics of the plasma irregularities observed at different height regions in the light of their generation mechanisms.

• To have a critical view on the reliability of the observed n_e profiles by comparing the expected and observed characteristics of the plasma irregularities.
• To look into the possible reasons for the deviations of the observed n_e profiles from the IRI predictions.

RESULTS AND DISCUSSION

Table 1 is a summary of the selected rocket flights discussed here. These five flights were chosen since one was launched during daytime, three during post sunset hours under conditions favourable for the presence of plasma bubbles and one under conditions of no spread-F in the ionogram traces. The Table provides date and time of launch, location, experiments flown on board and the apogee height reached by the rocket.

Table 1

Date	Time	Location	Experiments	Apogee
26-07-84	15:05	Natal	HFC	565km
11-12-85	21:30	Natal	HFC, LP	516km
31-10-86	23:59	Natal	HFC, LP	444km
14-10-94	19:15	Alcantara	HFC, LP	957km
18-12-95	21:17	Alcantara	EF, HFC, LP	564km

Launch of 26 July 1984

The first *in situ* measurements of electron density from the equatorial region in Brazil were made on 26 July, 1984 using a High Frequency Capacitance Probe on board a Brazilian SONDA III rocket. The rocket was launched from Natal, Brazil at 15:05 hrs local time and reached an apogee altitude of 565 km. The results from this day time launch are discussed in detail in Abdu *et al*. (1988). The upleg and downleg electron density profiles obtained from this launch (shown in Figure 1) were compared with the IRI-10 and SLIM model profiles by Abdu *et al*. (1990). The experimental and model profiles were agreeing with each other reasonably well. Figue 1 shows the comparison of the HFC profiles with the IRI 95 model profile. The agreement between the measured and model profiles, in this case is very good. This being a daytime launch (15:05hrs. LT), one is tempted to believe that the IRI-95 model represents well the daytime equatorial E- and F-region electron density profiles.

Launch of 11 December 1985

A Brazilian SONDA III rocket carrying LP and HFC experiments in addition to other airglow experiments was launched into the post sunset ionosphere from Natal under ionospheric conditions favorable for the development of plasma bubbles (Abdu *et al*., 1991). The ground ionograms showed the presence of intense spread-F activity. The upleg and downleg electron density profiles estimated from the HFC experiments are shown in Figure 2. Also shown in the figure is the electron density profile calculated from the IRI-95 model appropriate for the location, local time and the solar activity index.

As can be seen from Figure 2 the electron density profiles estimated from the HFC measurements, though show an overall agreement with the IRI-95 prediction, the measured profiles deviate considerably from the model profile in the height region below the F-region base as also at heights above 400 km. The most striking difference in the profiles is that the observed F-region base is 60 –70 km above that predicted by the model. The most probable reason for this is the post sunset uplift of the F-region due to the action of electrodynamic forces. It should be noted here that the HFC experiment has a measurement accuracy of about 17 Hz in the frequency of an oscillator of mean frequency of oscillation of about 8 MHz that corresponds to an estimated accuracy of about 100 electrons/cm^3 in the electron number density. The accuracy of measurement of the LP experiment varies almost logarithmically in the measurement range. At low electron densities the accuracy of measurement is about 10% (corresponding to about 100 electrons/cm^3) while at higher electron densities one can obtain an accuracy of about 2% comparing the dc measurements with the corresponding ac measurements.

A sample of the irregularity power spectra, known commonly as k-spectra, where k is the wave number of the plasma irregularity, at five selected height regions is shown in Figure 3. These are estimated form the LP data. As can be seen at 100 km and 200 km height regions, the spectral power is

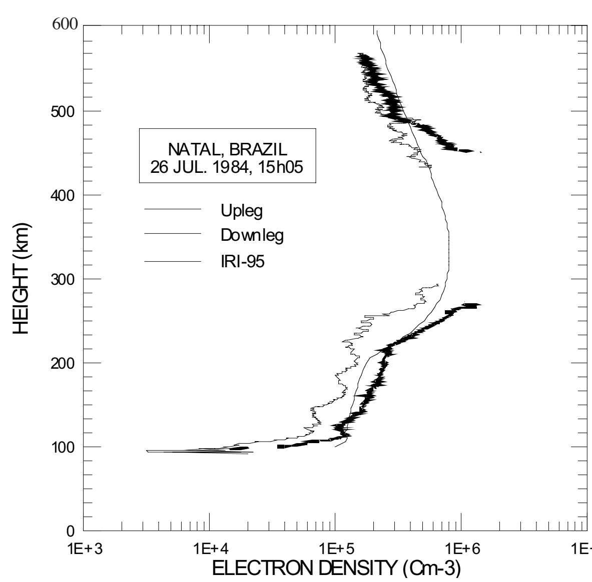

Fig. 1. Upleg and downleg n_e profiles from HFC measurements made on 26-th July, 1984 compared with the IRI-95 profile.

very low compared to that at higher heights. At the other height regions, namely 250 km, 275 km and 300 km, that correspond to the F-region base, the spectral features and the spectral index correspond to plasma irregularities, most probably produced by a cascade process involving the Rayleigh-Taylor and the cross-field instability mechanisms. The collisional Rayleigh-Taylor (R-T) instability mechanism (Haerendal, 1974) 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. Under conditions, favourable for the generation of plasma bubbles the bottom side of the F-layer becomes unstable for the Rayleigh-Taylor instability mechanism, thus producing the observed plasma irregularities. The observed spectral characteristics thus confirm that the observation of a higher F-region base than that given by the IRI model, is genuine and is an effect of the uplifting of the F layer.

Launch of 31 October 1986

On 31 October 1986, a Brazilian SONDA III rocket was launched during the post sunset hours, carrying LP and

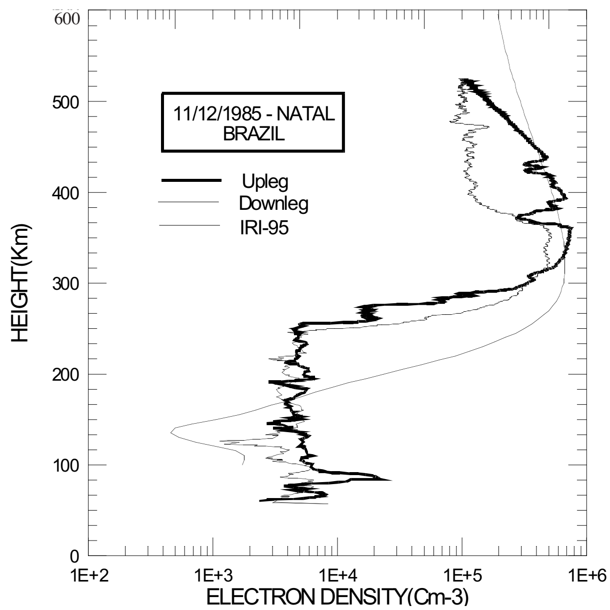

Fig. 2. Upleg n_e profiles from the LP and HFC measurements made on 11-th December, 1985 compared with the IRI-95 profile.

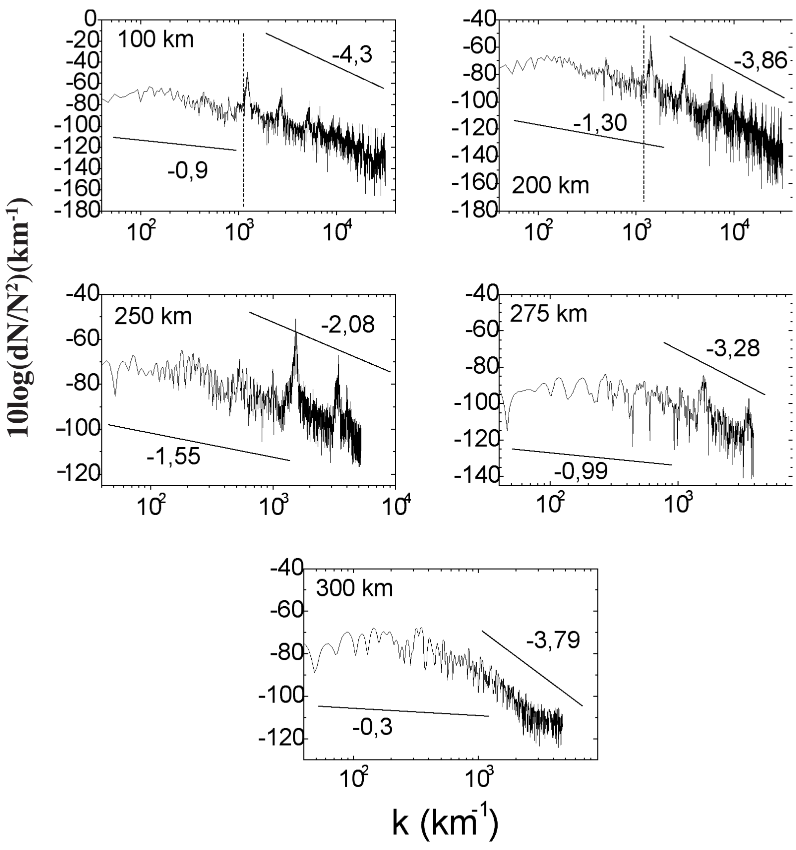

Fig. 3. Upleg plasma irregularity spectra observed by the Langmuir probe on 11-th December, 1985 corresponding to selected height regions.

HFC experiments in addition to a set of air glow photometers. The main objective of the launch was to study the post sunset F-region under conditions of no spread-F. The upleg and downleg electron density height profiles obtained from the HFC data, during this launch are shown in Figure 4. Also given in the figure is the IRI-95 model electron density profile for the purpose of comparison. As can be seen from Figure 4, at the time of launch the F-region base was at a low height, typical feature on days of no spread-F activities. The F region base heights given by the IRI-95 model and that observed during both upleg and downleg of the rocket are practically the same.

Sample k-spectra of irregularities observed at the F-region base is shown in Figure 5. The spectra observed at 100 km and 180 km have rather very low power. The spectral indices of higher than –4.3 observed in the spectra at 200 km and 220 km, that correspond to the base of the F-region are not representatives of neither the Rayleigh-Taylor instability mechanism nor the cross-field instability mechanism. Also, for the operation of the cross-field instability mechanism, one of the important conditions to be satisfied is that the ambient polarisation electric field should be in the same direction as the ambient electron density gradient. In

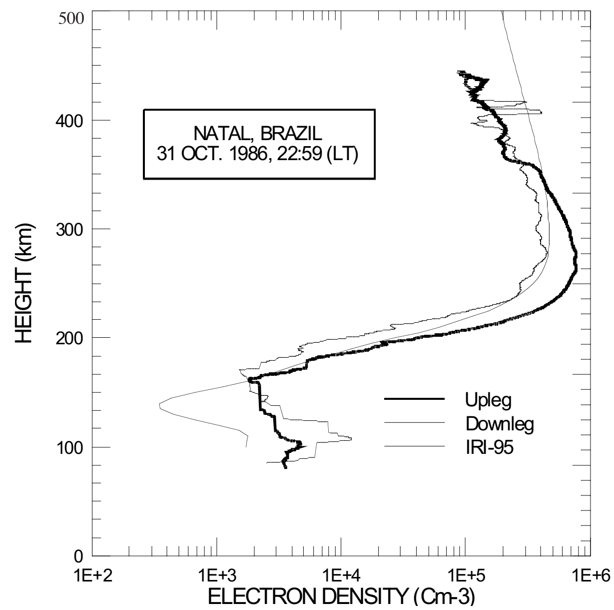

Fig. 4. Upleg and downleg n_e profiles estimated from HFC measurements on 31 October, 1986 compared with the IRI-95 profile.

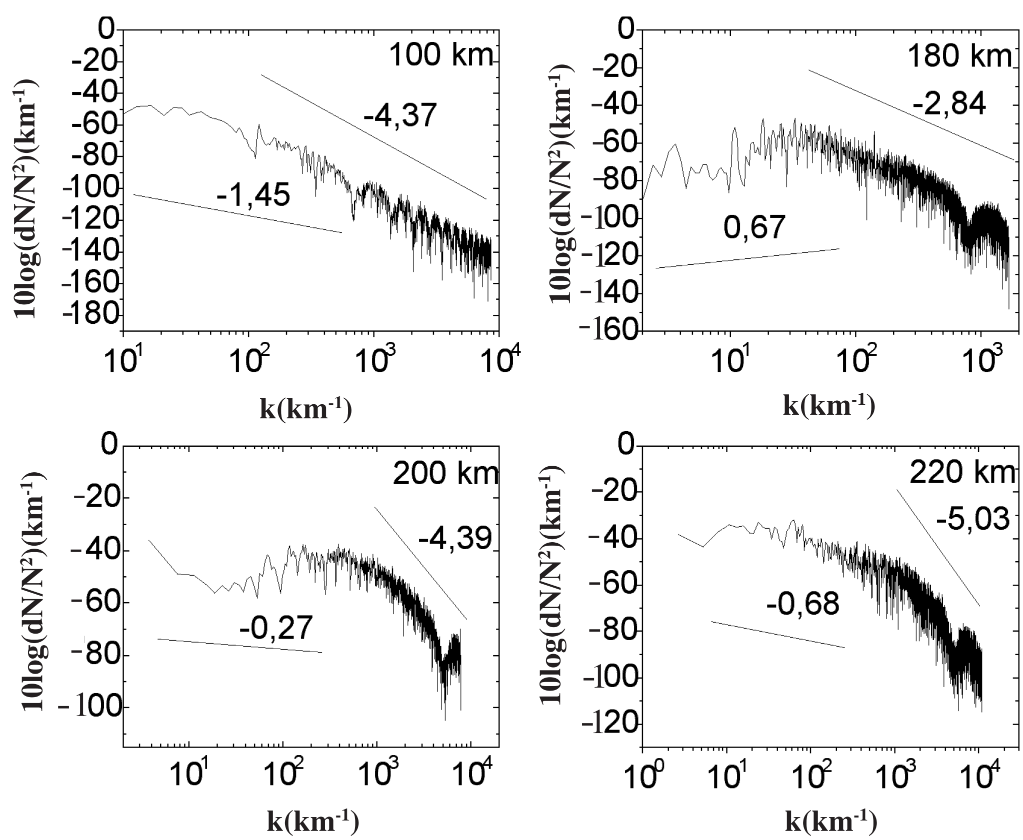

Fig. 5. Upleg plasma irregularity spectra observed by the Langmuir probe on 31 October, 1986 corresponding to selected height regions.

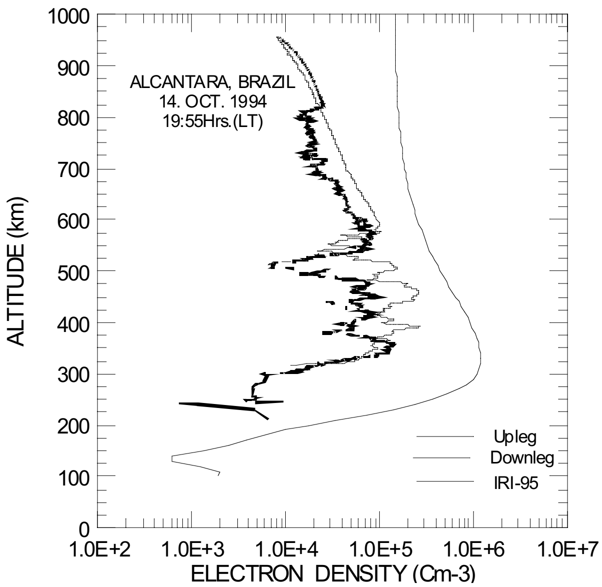

Fig. 6. Upleg and downleg n_e profiles estimated from HFC probe measurements on 14-th October, 1994 compared with the IRI-95 profile.

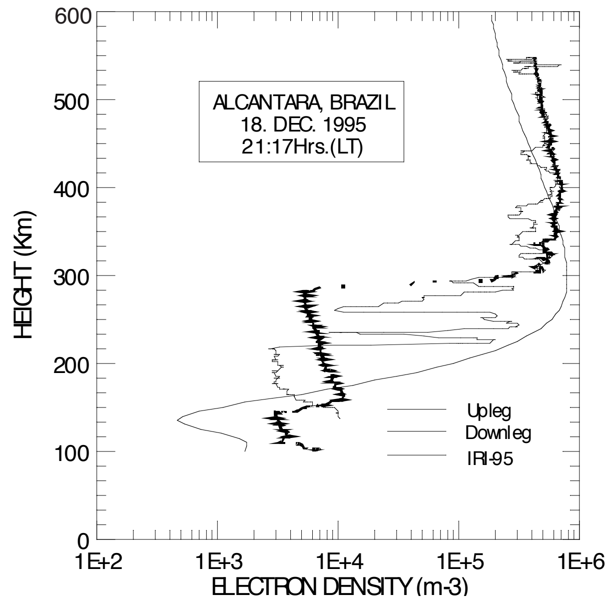

Fig. 7. Upleg plasma irregularity spectra observed by the Langmuir probe on 14-th October, 1994 corresponding to selected height regions.

the nighttime ionosphere, the polarisation electric field normally being downwards this condition is not satisfied in the base of the F-region where the electron density gradient is upwards. Thus the spectral observations are consistent with the measured electron density profiles.

Launch of 14 October 1994

On 14, Oct. 1994, a Black Brant X rocket carrying several plasma diagnostic experiments were launched to study the equatorial ionosphere under ionospheric conditions favorable for the generation of high altitude spread-F. The rocket was launched when the network of ground experiments which included a coherent VHF radar, indicated the spread-F activities at altitudes of 700-800 km. The upleg and downleg electron density profiles obtained by a HFC probe are shown in Figure 6. The IRI-95 model electron density profile estimated is also shown in the figure.

It can be clearly seen from Figure 6 that the rocket passed through a large number medium and large scale plasma bubbles during both upleg and downleg. The figure also shows that there is almost an order of magnitude difference between the observed and the model electron density profiles. Such a large difference in the absolute values of the electron density probably is partly due to a possible error in the normalizing factor used in converting the LP current into electron density values as also due to the effect of an inadequately chosen plasma sheath factor used in the conversion of the HFC measurements into electron density. The IRI-model also seems to be partly unrealistic in representing the F-region under conditions favorable for the generation plasma bubbles. This inadequacy of the model can also be seen from the fact that the height corresponding to the F-region base is more than 100 km above that predicted by the IRI model. However the spectral features of the plasma irregularities shown in Figure 7 indicate the existence of plasma irregularities generated by the cascading process that involves the operation of the cross-field instability mechanism, preceded by the Rayleigh-Taylor instability mechanism.

Launch of 18 December 1995

In situ measurements of the height variation of the ionospheric electron density were made on 18 December, 1995 at 2117 hrs (LT) from Alcantara with two different types of electron density probes. The main objective of the experiment was to study the characteristic features of the electron density fluctuations associated with plasma bubbles. Several ground equipments were operated during the launch campaign with the specific objective of knowing the ionospheric conditions at the time of launch and thereby to launch the rocket into an F-region prone to the presence of plasma bubbles. The rocket reached an apogee altitude of 557 km covering a horizontal range of 589 km, and in fact passed through several medium scale plasma bubbles mainly during the downleg, as can be seen from Figure 8. The upleg electron density profile showed the presence of a very clearly defined base for the F-region around 300 km, while the downleg profile showed the presence of a wide spectrum of electric field and electron density irregularities in this height region as well as in the upper F-region. Also shown in Figure 8 is the IRI-95 model profile. Except in the height region below the F-region base the model and observed profiles are in good agreement. As in the other cases presented earlier the height of the F-region base as given by the model is 70 to 80 km below that observed by the experiment. In this case also the electrodynamic uplifting of the F-region seems to be responsible for the large height difference.

A sample of the irregularity power spectra at selected height regions is shown in Figure 9. These are estimated from the LP data. As can be seen from this figure the spectral power estimated is rather low at all the height regions during the upleg of the rocket. It should be noted here that the upleg profile does not show the presence of large plasma bubbles, thereby indicating that the low power of the plasma irregularities is actually what is expected. The observed spectral characteristics thus confirm that the observation of a higher F-region base than that given by the IRI model, is genuine and is an effect of the uplifting of the F-layer.

Several linear and non-linear theories have been invoked to explain the wide spectrum of electron density irregularities observed in the night-time ionosphere (Reid, 1968, Hudson *et al*., 1973, Sudan *et al.,* 1973). Haerendal (1974) suggested a multi-step process to explain the large

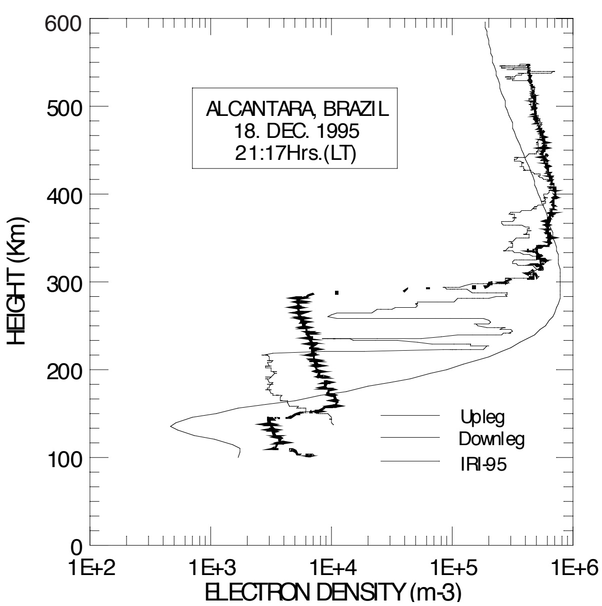

Fig. 8. Upleg and downleg n_e profiles estimated from Langmuir probe measurements on 18 Dec. 1995 compared with the IRI-95 profile

range of wavelengths observed, from several kilometres down to few centimetres. 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. Hysell *et al*. (1994) showed that irregularities in the scalesize 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.

Thus, while the spectral observations of the irregularities under different ionospheric conditions can be explained on the basis of the observed electron density profiles, what seems to be rather difficult to explain is the deviation of the observed electron density profiles from the IRI model predictions. The main cause of this deviation seems to be the inadequacy of the model to incorporate into it the large day to day variability of the electron density distribution in the equatorial ionosphere over the American sector. However, errors in the LP estimates of the electron density, introduced through the use of relations based on unrealistic approximations also seem to be partly responsible for the large deviation of the model from the observations. For example, one can easily see that the saturation electron current is not strictly proportional to the electron number density, but depends also on the mean thermal velocity of electrons and thereby also on the electron temperature and the so called "constant" of proportionality increases with increasing T_e. At lower altitudes, where T_e is lower, the constant of proportionality is also lower when compared with its value at higher altitudes where T_e is higher and consequently the constant of proportionality is also higher. In other words the use of an altitude independent constant of proportionality overestimates the electron density values at lower altitudes where T_e is lower. This seems to be one of the reasons why the electron density values estimated from the LP measurements are higher than the model predictions at lower altitudes. Muralikrishna and Abdu (1991) report that the formation of plasma sheath surrounding the LP sensor can increase the effective surface area of the sensor and thereby result in an overestimation of the electron density as originally suggested by Baker *et al.* (1985). They also report on the possible effect of the changing floating potential of the rocket on the LP electron density values especially at higher altitudes resulting in an underestimation of the electron density in this height region. Of course, this is a very simplified and qualitative picture of what really occurs; a detailed analysis will be much more complicated and is beyond the scope of this paper.

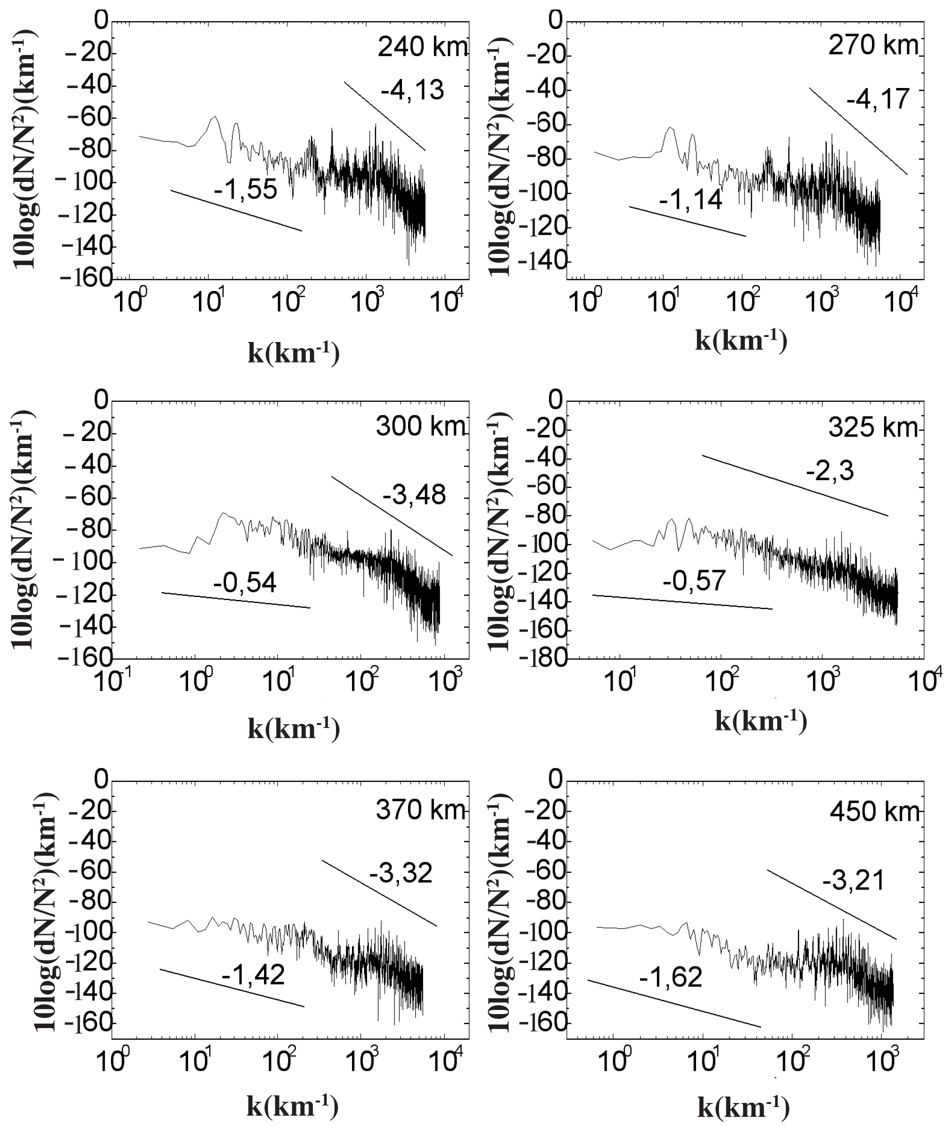

Fig. 9. Upleg plasma irregularity spectra observed by the Langmuir probe on 18-th Dec. 1995 corresponding to selected height regions.

CONCLUSIONS

The electron density profiles estimated from the Langmuir and the HFC probe measurements, qualitatively, match with the IRI-95 model profiles computed for the equatorial E- and F- region over Natal and Alcantara, Brazil, especially during day time or during night time when the F-region base is rather at a low level. However, quantitatively, the model profiles deviate considerably from the observations. These deviations can be attributed to one or more of the following (a) Inadequacy of the IRI-95 model to represent the equatorial ionosphere over Brazilian region which is not adequately represented in the data base used in the IRI model formulation; (b) The non-inclusion of the effects of electrodynamic forces in the IRI model. These processes are extremely important in the low latitude ionosphere. (c) Non inclusion of the effect of electron temperature variation on the saturation electron current and thereby on the proportionality constant that relates the sensor current collected with the electron number density. This can result in an overestimation of the electron density in regions of lower electron temperature; (d) Non inclusion of the negative plasma sheath effect in the sensor current electron density relationship.

Thus, day to day variations in the electrodynamic processes and meridional winds (by vertically drifting the ionospheric layers) are responsible for the large deviations of the observed electron density profiles from the IRI predictions. The IRI-95 model seems to be inadequate to explain also the observed electron temperature variations in the ionosphere over the American sector (Kantor *et al*., 1990). IRI model has to be improved considerably to represent the equatorial ionosphere, especially during the post sunset period when the electrodynamic processes seem to dominate in the equatorial F-region.

ACKNOWLEDGEMENTS

The rocket experiments reported here were undertaken in collaboration with the Instituto de Aeronautica e Espaço IAE/CTA and NASA. The authors are thankful to the director of INPE, Eng Marcio Nogueira Barbosa for his encouragement. Dedicated efforts of the Engineers Sinval Domingos, Agnaldo Eras, Narli Baesso and Humberto Freire Barreiros and other technical staff of the electronic laboratories and the mechanical workshop in the construction and testing of the rocket payloads are gratefully acknowledged. The IRI-95 models used here were provided by NASA through their online internet service. The work reported here was partially supported by the FNDCT under contract FINEP 537/CT and by the Conselho Nacional de Desenvolvimento Científico e Tecnológico - CNPq under processes 300253/89-3(RN) and 300509/89-8(RN).

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