Measurement of electron density and electron temperature in the equatorial ionosphere over brazil in the last two decades

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Abstract

A series of in situ measurements of electron density and electron temperature, in addition to other plasma parameters was undertaken from the equatorial region in Brazil, with the main objectives of studying the electrodynamics of plasma in the equatorial ionosphere and providing a larger data base needed for modeling purposes. In the equatorial and low latitude regions in the American sector, the ionospheric models proposed so far seem to be less accurate, probably due to the diverse electrodynamic and dynamic processes, produced by the large magnetic declination angle characteristic of this region. Since the first launch in 1984 of a Brazilian SONDA III rocket carrying an electron density probe, several rockets carrying plasma diagnostic experiments were launched in the last two decades 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 (n_e) and electron temperature (T_e) and High Frequency Capacitance (HFC) probes were used to measure n_e. The main objectives of these measurements were: (1) to compare the observed n_e and T_e profiles with the Model predictions, (2) to study the spectral characteristics of the plasma irregularities observed at different height regions in the light of their generation mechanisms, and (3) to look into the possible reasons for the deviations of the observed n_e profiles from the model predictions. Depending on the specific objectives of each campaign, the rockets were launched during daytime, nighttime or evening twilight hours. This provided a large data base to study the variability in the electron density and electron temperature profiles in the equatorial ionospheric regions over Brazil. The first results of this study are presented and discussed here.

Introduction

A series of in situ measurements of electron density and electron temperature, undertaken from the equatorial region in Brazil in the last two decades had the main objectives of studying the electrodynamics of plasma in the equatorial ionosphere and of providing a larger database needed for modeling purposes The International Reference Ionosphere (IRI), since its first publication in 1978 by Rawer et al. (1978) has undergone periodic modifications in attempts to improve its accuracy in representing the quiet time ionospheric parameters as functions of height, geographic location, local time and sunspot number. In the equatorial and low latitude regions in the American sector, the ionospheric models proposed so far seem to be less accurate, probably due to the diverse electrodynamic and dynamic processes, produced by the large magnetic declination angle characteristic of this region (Abdu et al., 1981). Abdu et al. (1990) reported in situ measurements of electron density from this region, and for the first time compared them with the IRI predictions. They found reasonable agreement between the IRI predictions and the rocket measurements, especially during daytime. However the electron temperature estimates made form Langmuir Probe measurements, for the same region, reported by Kantor et al. (1990) deviated considerably from the IRI predictions.

Several rockets carrying plasma diagnostic experiments were launched from the Brazilian rocket launching stations in Natal (5.9°S, 35.2°W geographic coordinates) and Alcantara (2.31°S, 44.4°W geographic coordinates). 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 ranges 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 electron density (n_e) profiles from the IRI predictions.

Results and discussion

Given in Table 1 is a summary of the five selected rocket flights discussed here. These five flights are chosen since three of them were launched during the post sunset hours in the presence of spread-F traces in the ionograms and the ionospheric conditions, at the time of launch, as monitored by a net work of ground stations showed the presence of plasma bubbles. The other two launches were under conditions of no spread-F in the ionogram traces. Also given in the Table are the date and time of launch, the location, the experiments flown on board and the apogee height reached by the rocket.

Table 1

Date	*Time*	*Location*	*Experiments*	*Apogee*
26-07-84	1505	Natal	HFC	565km
11-12-85	2130	Natal	HFC, LP	516km
31-10-86	2359	Natal	HFC, LP	444km
31-05-92	2351	Alcantara	LP, ETP	282km
14-10-94	1915	Alcantara	HFC, LP	957km

Brazilian SONDA III rockets and a Black Brant X rocket carrying plasma and optical 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 the electron density and electron temperature and High Frequency Capacitance probes (HFC) were used to measure the electron density. The height profiles of electron density and electron temperature obtained on various occasions are compared with the IRI predictions appropriate for the location and time and an attempt is made to understand the differences between them.

Electron Density Profiles

The electron density profiles and the spectral features of the plasma irregularities observed in selected height ranges, estimated from the LP and/or HFC experiment data obtained during the five rocket flights summarized in Table 1 are shown in Figures 1 to 6. Also shown in the figures are the electron density profiles calculated from the IRI95 model appropriate for the location, local time and the solar activity index. As can be seen from Figures 1 to 6 the electron density profiles estimated deviate considerably from the IRI95 model profiles. 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 Te. At lower altitudes, where Te is lower, the constant of proportionality is also lower when compared with its value at higher altitudes where Te 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 Te 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.

It should be noted here that the HFC experiment has a measurement accuracy of about 17hz in the frequency of an oscillator of mean frequency of oscillation of about 8MHz. 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. Some additional observations on the characteristic features of the plasma irregularities are summarized below.

Launch on 11, Dec. 1985

The 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. Electron density profiles and the power spectra of plasma irregularities at selected height regions, estimated from LP and HFC experiments are shown in Figures 1 and 2. Also shown in the figures are the electron density profiles calculated from the IRI 95 model appropriate for the location, local time and the solar activity index. The IRI 95 model profiles presented here were obtained by running the model program available through the appropriate web site of NSSDC/NASA. These profiles are presented without making any adjustment in the peak density or peak altitude. The peak densities observed by the LP and HFC experiments were adjusted to match the peak densities estimated from the ionograms obtained at the time of launch.

As can be seen from Figure 1 the electron density profiles estimated from the LP and HFC measurements, though show good agreement with the IRI prediction at and above the F-peak, the height of the F-layer base observed is more than 50 km above that given by the IRI 95 model. The probable reasons for this will be discussed later. 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 8MHz, 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.

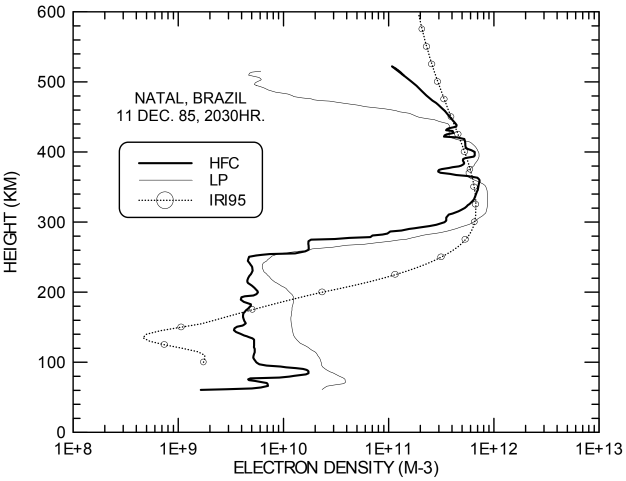

Figure 1 - n_e profiles from the LP and HFC measurements made on 11-th December 1985 compared with the IRI 95 profile

A sample of the k-spectra of the plasma irregularities, where k is the wave number, at three selected height regions is shown in Figure 2. At 250 km height that corresponds to the top of 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 confirm this.

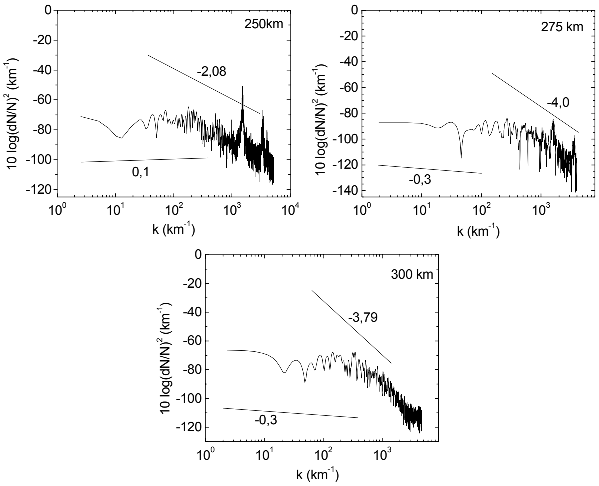

Figure. 2 - Plasma irregularity spectra corresponding to selected height regions observed during upleg

Several linear and non-linear theories have been invoked to explain the wide spectrum of electron density irregularities observed in the nighttime ionosphere (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. 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 scale size range of 100 m- 2 km display a power law behaviour with spectral index $n \approx -2$ that increased to –4.5 for wavelength around 100 m and below when F-layer is high.

Launch on 31, Oct. 1986

On 31, Oct. 1986, a Brazilian SONDA III rocket was launched during the post sunset hours, carrying LP and HFC experiments in addition to a set of airglow photometers. The main objective of the launch was to study the post sunset F-region under conditions of no spread-F. The electron density height profiles obtained from the LP and HFC data, during this launch are shown in Figure 3. Also given in the figure is the IRI 95 model electron density profile for the purpose of comparison. As can be seen from Figure 3, at the time of launch the F-region base was at a low height, typical feature on days of no spread-F activities. Also, the observed and model profiles are in excellent agreement with each other.

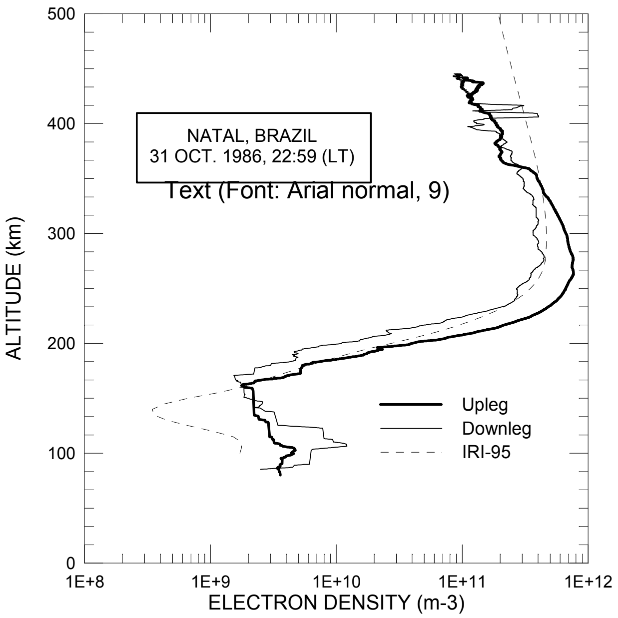

Fig. 3. n_e measurements made with HFC and Langmuir Probes on 31-st October, 1986 compared with the IRI 95 profile

Sample k-spectra of irregularities observed at the F-region base is shown in Figure 4. The spectral indices of smaller than –5 observed in both the spectra, as mentioned earlier, do not represent neither the Rayleigh-Taylor instability mechanism nor the cross-field instability mechanism. The plasma irregularities observed in this case are probably produced by some other plasma instability mechanism

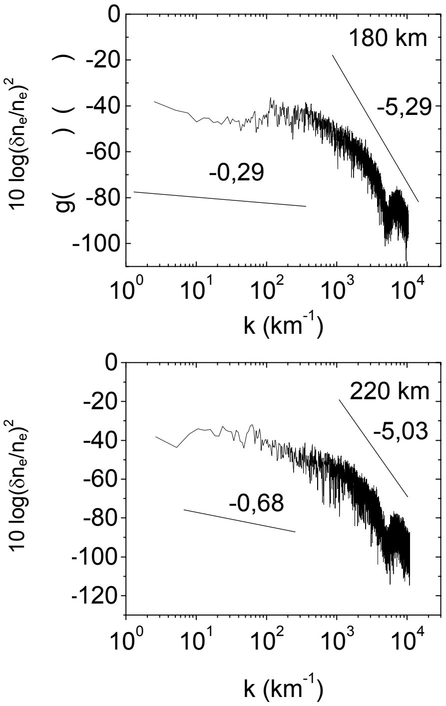

Figure 4 - Irregularity spectra corresponding to selected height regions observed during upleg

Launch on 14, Oct. 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 700-800km. The upleg and downleg electron density profiles obtained by a HFC probe are shown in Figure 5. The IRI 95 model electron density profile estimated is also shown in the figure. It can be clearly seen from Figure 5 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. The height corresponding to the F-region base is more than 100km above that predicted by the IRI model. However the spectral features of the plasma irregularities shown in Figure 6 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.

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.

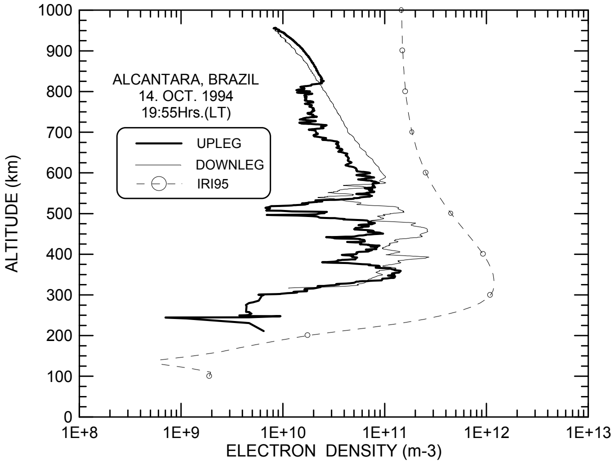

Figure 5 - Upleg and downleg n_e measurements made with an HFC Probe on 14-th October, 1994 compared with the IRI 95 profile

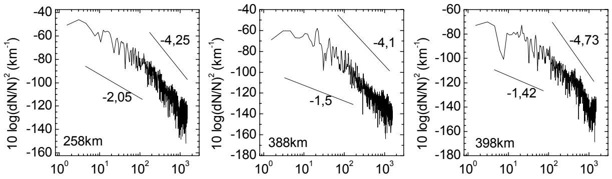

Figure 6 - Plasma irregularity spectra corresponding toselected height regions observed during upleg

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.

Electron Temperature Profiles

Electron temperature was estimated from the slope of the current voltage characteristics of the Langmuir Probe. In estimating Te from the slope of the I-V characteristic curve one generally assumes that the positive ion current is much less than the electron current (consequences of such an assumption will be discussed later).

T_e values thus obtained are shown in Figures 7 to 9 for two rocket flights. In one of these flights the LP operated alternately in continuous and pulsed sweep modes and useful data for estimating T_e were obtained during both the operation modes. T_e values estimated for both the modes of operation are presented in Figures 8 and 9. Also given in figures 7 to 9 are the IRI model temperature profiles for the purpose of comparison with the observed profiles. As in the case of electron density profile, one can see from Figures 7 to 9 that the model predictions deviate considerably from the observations. An important point to be noted here is that the electron temperatures obtained in the continuous and pulsed sweep modes are practically same at all altitudes.

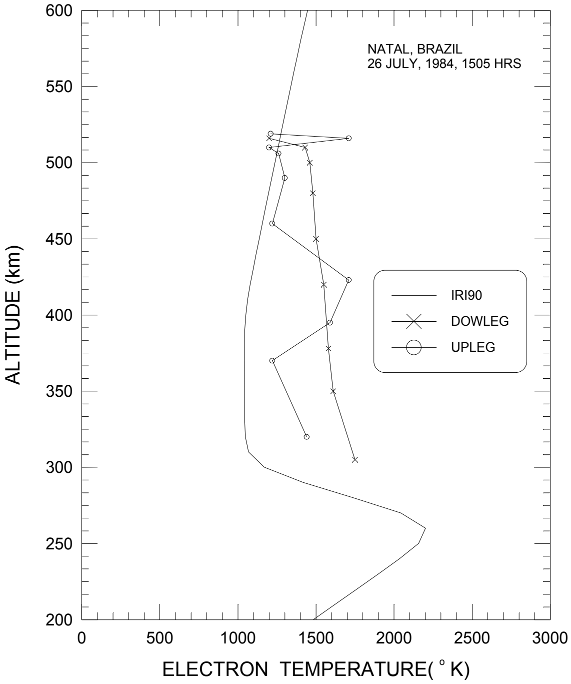

Figure 7 - Daytime electron temperature height variation observed on 26-th July, 1984 compared with IRI90 profile.

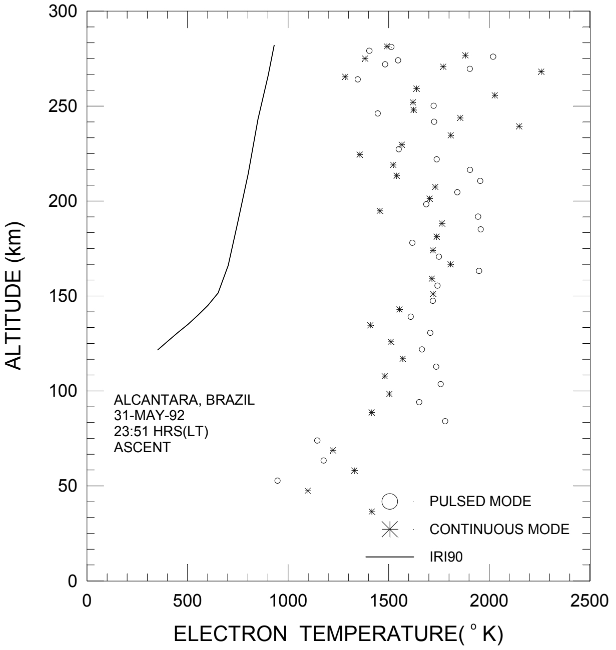

Figure 8 - Nighttime electron temperature height variation observed on 31-st May, 1992 during the rocket upleg compared with IRI90 profile.

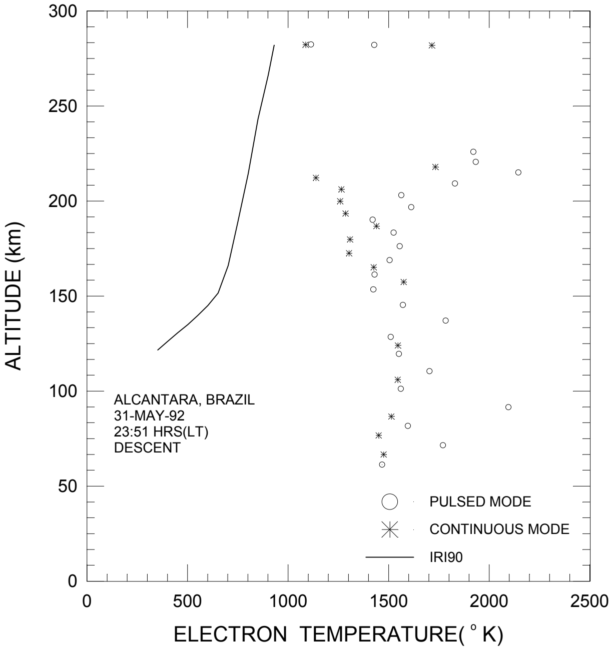

Figure 9 - Nighttime electron temperature height variation observed on 31-st May, 1992 during the rocket downleg compared with IRI90 profile.

As in the case of electron density the main cause of this seems to be the inadequacy of the model to represent accurately the day to day variability of the electron temperature. Other major candidates responsible for introducing errors in electron temperature estimations are the following.

(a) Effect of the positive ion current collected by the sensor
(b) Surface contamination of the LP sensor
(c) Effect of plasma sheath surrounding the LP sensor

Conclusions

The electron density and temperature 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. 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) 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; (c) Non inclusion of the negative plasma sheath effect in the sensor current electron density relationship.

Day to day variations in the electrodynamic processes and meridional winds (by vertically drifting the ionospheric layers) also 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.

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