

F-Region electron density irregularities during the development of equatorial plasma bubbles

P. Muralikrishna

Instituto Nacional de Pesquisas Espaciais, São José dos Campos-SP, Brasil.

Received: November 6, 1998; accepted: March 15, 1999.

RESUMEN

Algunos resultados nuevos que se obtuvieron de mediciones *in situ* de la variación de la densidad electrónica hechas con sondas instaladas en cohetes para medir la densidad electrónica durante dos campañas que se llevaron a cabo en Alcántara (2.31° Sur 32.5° Oeste) se presentan aquí. Durante la primera campaña que se llevó a cabo en colaboración con la NASA (campaña de Iguará donde se lanzó el cohete Black Brant X el 14 de octubre de 1994) para investigar el fenómeno de los eventos de dispersión F que ocurren en altas altitudes en zonas ecuatoriales. Adicionalmente a algunos instrumentos de diagnóstico de plasma que fueron provistos por otros institutos participantes, la División de Aeronomía del Instituto de Pesquisas Espaciais en Brasil, proporcionó una sonda de capacitancia de alta frecuencia que midió el perfil de alturas de la densidad electrónica. Durante la segunda campaña el cohete sonda 3 hecho en Brasil fue lanzado el 18 de diciembre de 1995. El cohete llevaba instrumentos para medir la densidad electrónica que determinaron el perfil de densidades electrónicas en la ionosfera. Algunos equipos fueron operados desde tierra para asegurarnos que los cohetes fueran lanzados en condiciones favorables para la generación de burbujas de plasma en la región F; los cohetes en ambas ocasiones atravesaron algunas burbujas de plasma en desarrollo. El espectro K de las irregularidades de plasma se obtuvo por análisis espectral de las fluctuaciones de la densidad electrónica. Las irregularidades en la densidad electrónica asociadas con las burbujas de plasma tienen líneas muy agudas en sus espectros K; estas líneas se extienden sobre un amplio rango de alturas. Lo que podría esperarse de las teorías existentes en la generación de irregularidades de pequeña escala por el proceso de cascada es un espectro K plano. Los resultados actuales podrían indicarnos la presencia de modos de onda preferidos en burbujas de plasma en desarrollo.

PALABRAS CLAVE: Ionosfera, densidad electrónica, burbujas de plasma.

ABSTRACT

The height variation of the ionospheric electron density was measured with rocket-borne electron density probes in two campaigns conducted from Alcantara (2.31°S; 35.2°W), Brazil. A Black Brant X sounding rocket was launched on 14 October 1994 at 1955hrs (LT) to investigate the phenomenon of high-altitude equatorial spread-F events. A Brazilian-made SONDA III rocket was launched on 18 December, 1995 at 2117 hrs (LT). Ground equipment was operated during these campaigns to ensure that the rockets were launched under conditions favourable for the generation of plasma bubbles in the F-region. The rockets, in both occasions, passed through several developing plasma bubbles. The k-spectra of plasma irregularities were obtained by spectral analysis of the electron density fluctuation data. The electron density irregularities associated with plasma bubbles had sharp lines in their k-spectra, extending over a wide range of altitudes. Existing theories on the generation of small scale irregularities by cascading predict a flat k-spectrum. Present results may be indicative of the presence of preferred wave modes in developing plasma bubbles.

KEY WORDS: Ionosphere, electron density, plasma bubbles.

INTRODUCTION

Electron density irregularities in the ionosphere adopt different forms at different heights and times, including sporadic-E, spread-F, radio star scintillations and VHF radar echoes. Basic knowledge of plasma irregularities responsible for these phenomena, has progressed considerably since the discovery of strong VHF radar echoes from the equatorial ionosphere (Bowles *et al.*, 1960, 1963). Balsley (1969) classified plasma irregularities into two groups, namely Type I and Type II. Type I irregularities are now identified to be

consistent with the two-stream instability mechanism (Farley, 1963; Sato, 1972). Type II irregularities are known to be produced by the nonlinear cross-field instability mechanism (Rogister and d'Angelo, 1970, 1972; Balsley and Farley, 1973).

Direct observations by Prakash *et al.*, (1970, 1971a,b) using rocket-borne Langmuir probes flown from India, confirm the existence of Type II irregularities in the equatorial E-region. Type II irregularities are characterized by scale sizes from a few meters up to tens of kilometers. The short

wavelength irregularities seem to be generated from larger scale nonlinear coupling or cascading (Rogister, 1972; Rogister and d'Angelo, 1970, 1972; Sato 1971, 1973; Sudan *et al.*, 1973). Neutral turbulence may be another probable mechanism responsible for the generation of plasma irregularities (Prakash *et al.*, 1970). The spectral characteristics of the different types of irregularities have been studied in detail (Prakash *et al.*, 1970; Ott and Farley, 1974).

Plasma bubbles are flux tubes of depleted plasma density observed frequently in the equatorial nighttime ionosphere (see Abdu *et al.*, 1991 and references therein). These bubbles are characterised by scale lengths of thousands of kilometers along the geomagnetic field lines and tens to hundreds of kilometers perpendicular to the field lines. Their generation by Rayleigh-Taylor (R-T) gravitational instability and subsequent cascading, by secondary processes, into a hierarchy of irregularities, was suggested by Haerendal (1974).

Some new results of *in situ* measurements of height variation of the ionospheric electron density from rocket-borne electron density probes during two campaigns conducted from Alcantara (2.31°S; 35.2°W) in Brazil are presented here.

EXPERIMENT AND FLIGHT DETAILS

Guará Campaign

During the Guará campaign a Black Brant X rocket was launched on 14 October, 1994 at 1955hrs (LT) to observe the equatorial ionosphere during the presence of high-altitude plasma bubbles. The electron density profile and the electron density fluctuations were measured simultaneously by a High Frequency Capacitance (HFC) probe, a conventional Langmuir Probe (LP), and a Plasma Frequency Probe (PFP).

The HFC Probe used a spherical sensor of 52mm diameter mounted on a short boom deployed 108s after the launch of the rocket. To cover the large dynamic range of electron density and to study the behaviour of the ion sheath, the HFC experiment operated in two alternating modes with frequencies of about 5MHz and 10MHz. The duration of operation in each mode was about 60ms, thus providing a data point in each mode every 120ms. A swept frequency type Plasma Frequency Probe (PFP) and a conventional Langmuir Probe were also launched along with the HFC probe to measure plasma density. For the PFP, a signal with swept frequency is transmitted using a short antenna on board the rocket. The signal modified by the plasma is received on another short antenna on board. When the signal frequency is equal to the plasma frequency the signal amplitude falls drastically due to resonant absorption by the ambient plasma.

We monitor the height variation in plasma frequency as produced by the local plasma density. In the conventional Langmuir probe, the electron or ion current collected by a metallic sensor is measured as a function of the potential applied to the sensor. When the sensor operates in the saturation mode the current collected is directly proportional to the local electron density. The High Frequency Capacitance probe was designed and developed at the Aeronomy Division of the Instituto Nacional de Pesquisas Espaciais-INPE/MCT, while scientists from the Department of Physics and Astronomy, Dartmouth College, were responsible for the PFP and LP experiments.

IONEX-II Campaign

The IONEX-II campaign had the principal objective of measuring the electric field, the electron density, the electron kinetic temperature and the spectral distribution of plasma irregularities associated with ionospheric plasma bubbles. A Brazilian made SONDA III rocket was launched on 18 December, 1995 at 2117 hrs (LT) from the equatorial rocket launching station Alcantara. The rocket reached an apogee altitude of 557km and covered a horizontal range of 589km. The payload consisted of an Electric Field Double Probe (EFP), a Langmuir Probe (LP), and a High Frequency Capacitance probe (HFC).

In situ measurements of the height variation of the ionospheric electron density variations were made with two different rocket-borne electron density probes. Ground equipment was operated during the launch to monitor ionospheric conditions in order to launch the rocket into an F-region containing large plasma bubbles. The rocket passed through several medium-size plasma bubbles and the electron-density probes detected a wide spectrum of electron density irregularities.

The main objective of the EFP was to measure fluctuations of the dc electric field associated with ionospheric plasma irregularities. Two spherical electric field sensors were mounted at the extremities of two booms deployed after the rocket nose cone was ejected at an altitude of about 65km. In the fully deployed state, the separation between the sensors should have been more than 3m but the booms did not open fully due to an unexpectedly low spin rate of the rocket. Thus the separation between sensors was only about 1.3m. This made observing the dc component of the electric field much more difficult. Dc and ac components of the horizontal electric field were obtained in the altitude range of about 95 to 557km and are being analysed.

Details of the electronics of the LP and HFC experiments are given in Muralikrishna and Abdu (1991). The Langmuir Probe was used to measure the electron density and the electron kinetic temperature. A spherical LP sensor

of diameter about 60mm was mounted at the extremity of a boom of about 50cm in length that remained inside the rocket nose cone. This boom was deployed along with the EFP booms soon after the ejection of the rocket nose cone. A swept voltage varying from -1V to +2.5V in about 2.5sec was applied to the LP sensor.

The main objective of the HFC probe was to measure the electron density profile. The HFC sensor was identical to the LP sensor and was mounted at the tip of a 50cm boom kept folded inside the rocket nose cone till ejection. The sensor was a part of the tank circuit of an electronic oscillator, and changes in the sensor capacitance caused by fluctuations in electron density were measured by a counting circuit and telemetered to the ground.

RESULTS AND DISCUSSION

Electron density profiles obtained during the Guará campaign are shown in Figures 1 and 2. The plasma density profiles estimated from the three experiments agree well with each other. The LP and PFP experiments have sufficient height resolution to study amplitude fluctuations in small

scale plasma irregularities. Note the wide spectrum of scale sizes in the plasma irregularities. The upleg height profiles show the presence of irregularities associated with high-altitude Spread-F. The presence of medium size plasma bubbles in the high altitude region can be seen in the HFC upleg profile. The other two profiles from the LP and PFP experiments give an idea of the distribution of small-scale irregularities in this height region. The rocket downleg profiles in Figure 2 do not show the presence of a wide spectrum of irregularities in the high-altitude region. This may be due to the limited horizontal extent of the high-altitude Spread-F event responsible for the generation of plasma irregularities. The horizontal separation of the upleg and downleg paths of the rocket in this height region can vary from a few tens to about 200km, roughly representing the east-west horizontal extension of the high altitude plasma bubbles or the high-altitude Spread-F associated with these bubbles. Spectral analysis of the density data at different height region yields the spectral distribution of plasma irregularities in order to investigate the plasma instability mechanisms responsible for their generation.

Typical k-spectra obtained from the spectral analysis

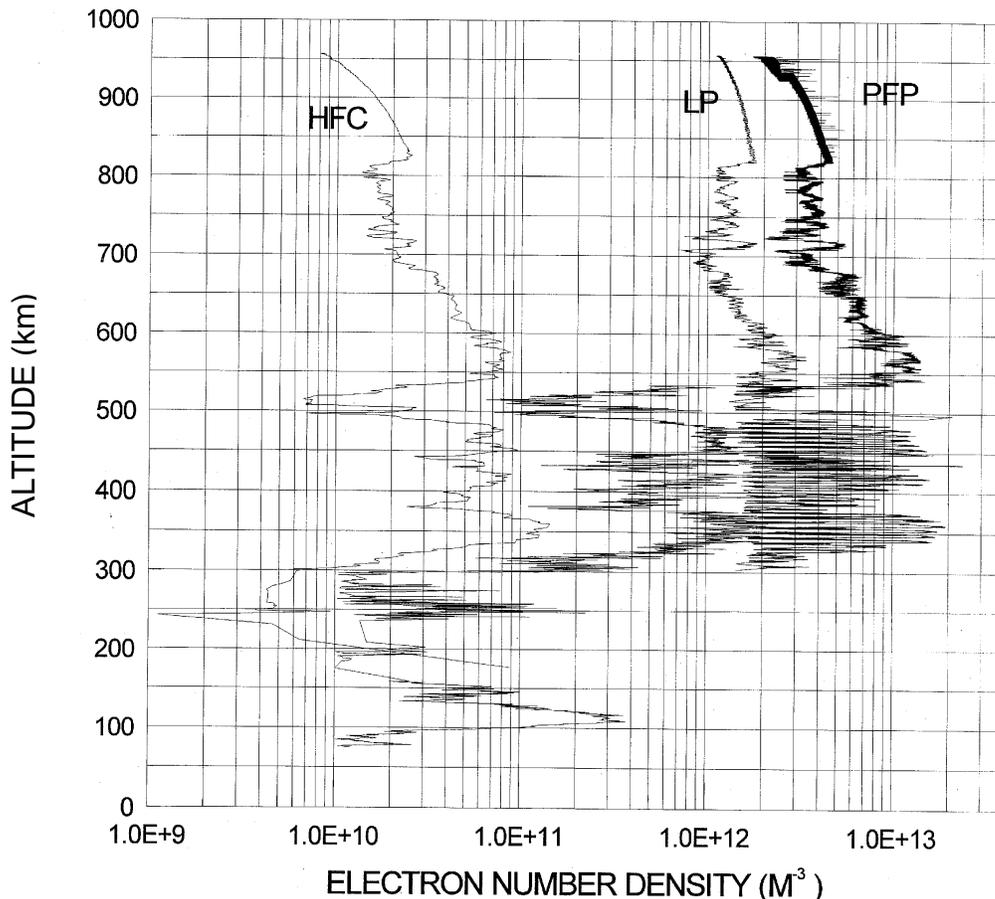


Fig. 1. Upleg electron density profiles obtained from three different plasma density probes during the Guará campaign.

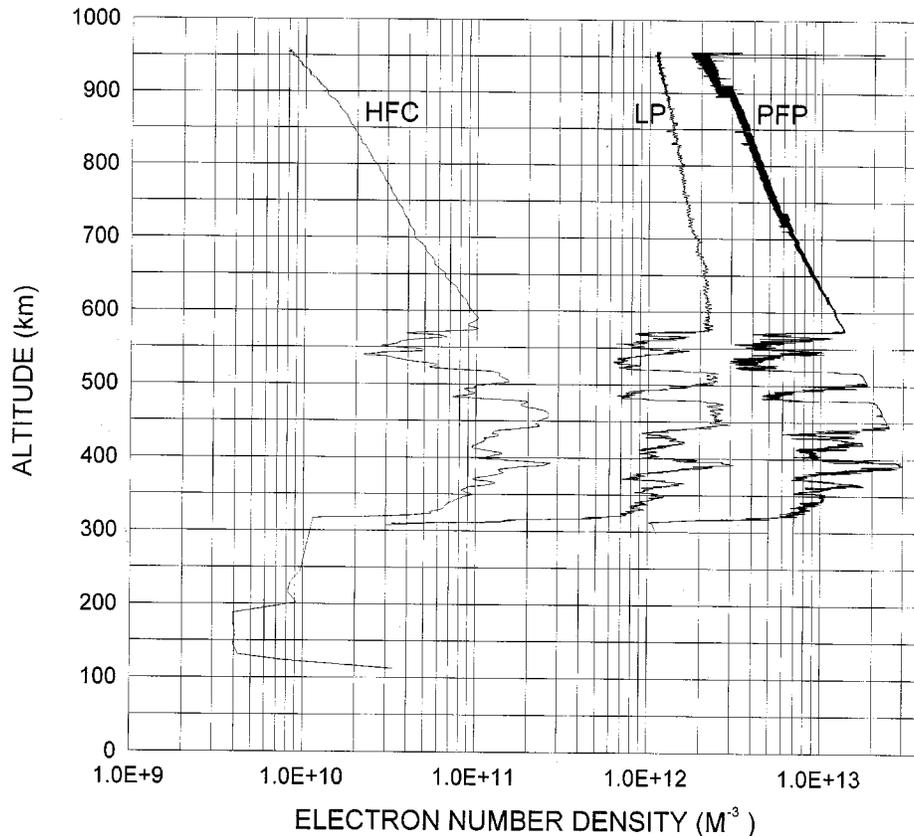


Fig. 2. Downleg electron density profiles obtained from three plasma density probes during the Guar campaign.

of the electron density fluctuation data of the HFC, LP and PFP experiments are shown in Figures 3, 4 and 5. Striking spectral peaks of large amplitudes are found in practically all the k-spectra.

During the IONEX-II campaign the rocket was launched at a time when the network of ground experiments indicated a possible development of plasma bubble events. The preliminary profiles of electron density are shown in Figure 6. The rocket did pass through a series of plasma bubbles of varying amplitudes during the ascent and descent of the rocket. The bubble structures in the upleg profile (Figure 6) are rather weak and confined mainly to the bottom F-layer, while those in the downleg profile are larger and are found both on the bottom side and the topside of the F-layer. The electron density profiles obtained with the LP experiment were similar to the HFC profiles. The LP experiment measured ac fluctuations in electron density up to a frequency of about 625Hz equivalent to a wavelength of about 3,2m in a height region where the rocket velocity is about 2km/s. Thus near the apogee, where the vertical component of the rocket velocity is small, the lowest irregularity size that can be measured goes down to practically zero. The HFC data does not permit the measurement of rapid fluctuations in

electron density. Since the time duration needed to obtain one measurement with the HFC experiment is about 120ms, the distance between data points in a height region where the rocket velocity is about 2km/sec is roughly 240m. Thus the minimum size of irregularities that can be measured with the HFC in this region is about 480m. Other differences in the data provided by the LP and HFC experiments may be found in Muralikrishna and Abdu (1991).

A typical sequence of k-spectra estimated from the LP current variations is shown in Figure 7. Note the large spectral peaks in the k-spectra of the plasma irregularities.

Bubble structures in the nighttime ionosphere are familiar. The generation of large scale plasma irregularities by cross-field instability is now reasonably well understood (Reid, 1968; Tsuda *et al.*, 1969). A necessary condition is an electron density gradient in the direction of the ambient electric field. In the nighttime ionosphere the Hall polarisation field is generally downwards and so the height regions favorable for the C-F instability mechanism are those where the electron density gradients are downwards. Large bubble structures in the bottom side F-region where the E-field is supposed to be downwards and the electron density gradient

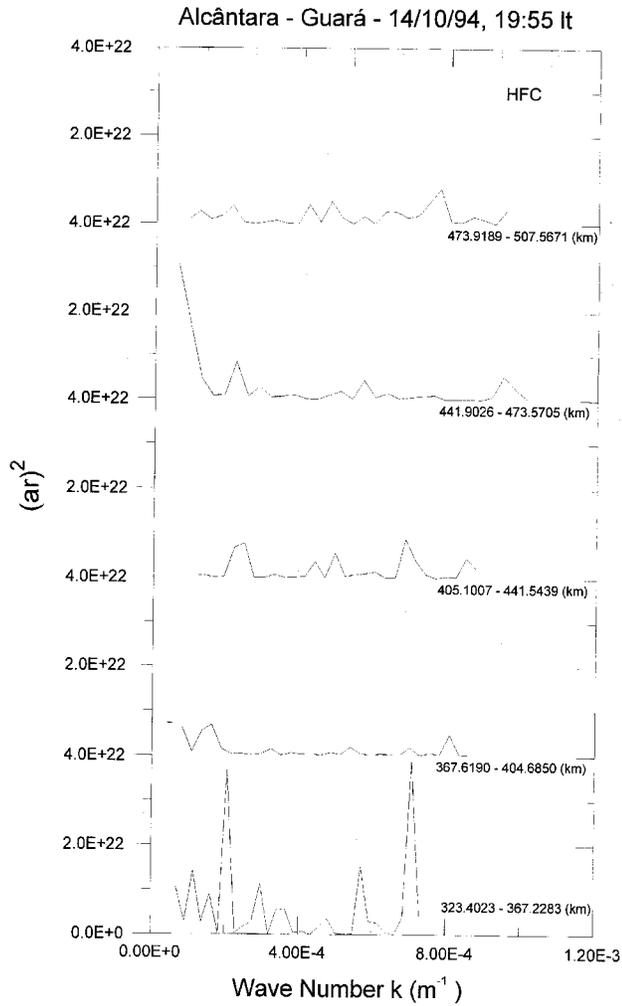


Fig. 3. Typical nature of the k-spectra of plasma irregularities, obtained from the HFC probe measurements showing the presence of sharp peaks (Guará Campaign).

is upwards cannot be attributed to the cross-field instability mechanism. However, small scale plasma irregularities can be generated in a region of downward electron density gradients associated with large scale bubbles.

Plasma bubbles are characterised by scale lengths of thousands of kilometers along the geomagnetic field lines and tens to hundreds of kilometers perpendicular to the field lines. Their generation by a Rayleigh-Taylor (R-T) gravitational instability process and subsequent cascading by secondary processes into a hierarchy of irregularities was suggested by Haerendal (1974). The spectral characteristics of the different types of irregularities associated with the phenomenon of spread-F have been studied in detail (Prakash *et al.*, 1970; Ott and Farley, 1974). These small scale irregularities are expected to have a rather flat k-spectrum as the earlier observations showed and as predicted by the existing theories on the generation of plasma irregularities.

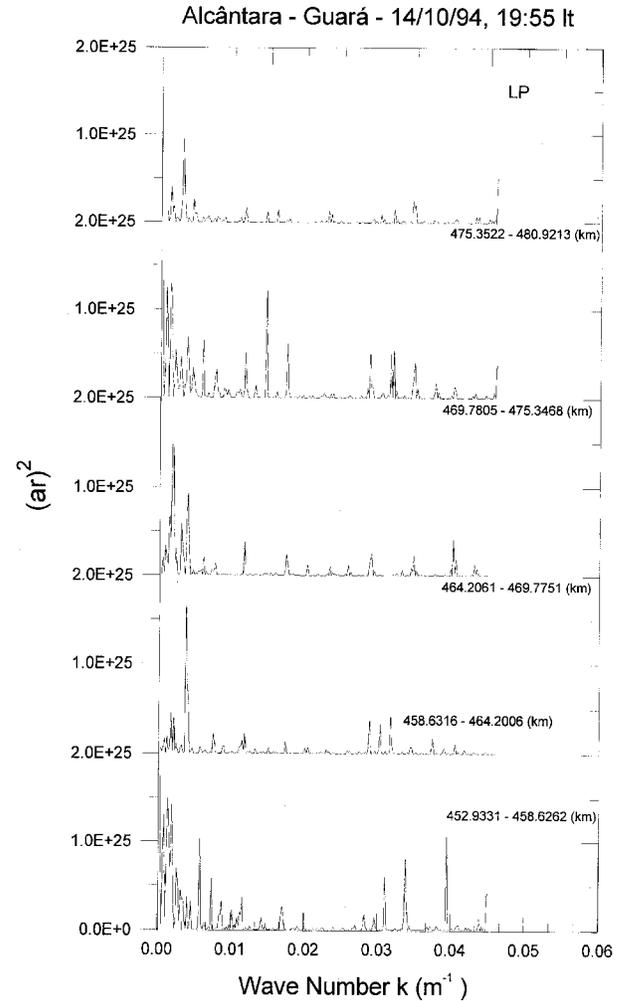


Fig. 4. Typical nature of the k-spectra of plasma irregularities, obtained from the Langmuir probe (LP) measurements showing the presence of sharp peaks (Guará Campaign).

A striking new feature observed during our experiments is the presence of large spectral peaks in the k-spectra of the plasma irregularities. Both rocket flights were conducted during the onset of the ionospheric plasma bubbles and may represent characteristic features of plasma irregularities associated with new or developing plasma bubbles. At later times the plasma irregularities responsible for these spectral peaks may transfer their energy to smaller irregularities, thus eventually leading to a flat k-spectrum when the process attains a stable state. A theory that can explain these spectral peaks during the development phase of plasma bubbles is not available.

CONCLUSIONS

1. Electron Density profiles estimated from different types of experiments during the occurrence of High Altitude Spread-F agree well with each other.

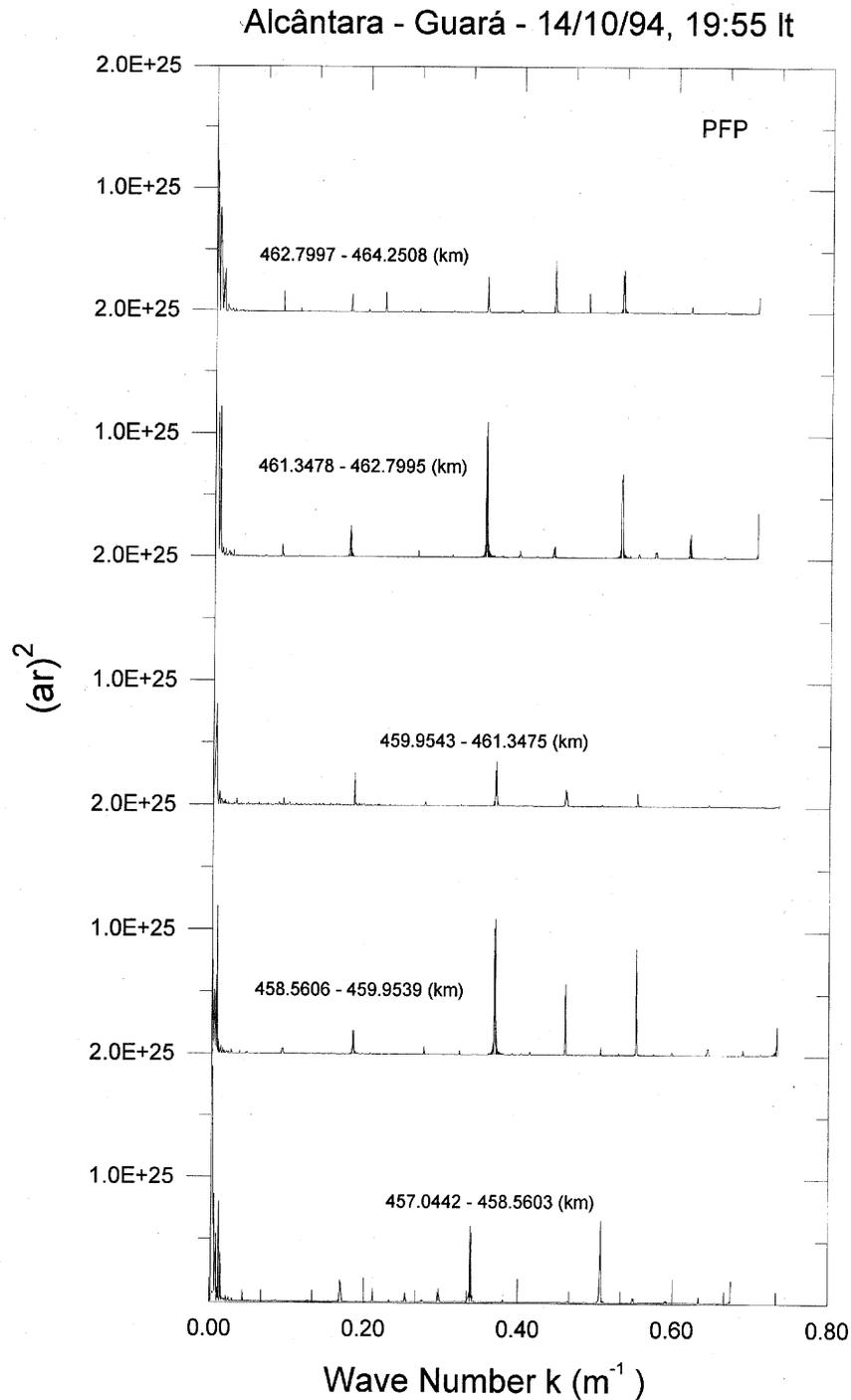


Fig. 5. Typical nature of the k -spectra of plasma irregularities, obtained from the Plasma Frequency Probe (PFP) probe measurements showing the presence of sharp peaks (Guar Campaign).

2. Plasma irregularities in a wide range of sizes are dominantly seen in the height regions of downward electron density gradients, in agreement with an association with a cross-field instability mechanism for the generation of plasma irregularities.
3. The generation of large scale plasma structures in the bottom side of the F-region cannot be explained by cross-field instability as the vertical electric field and the electron density gradient must be in the same direction.

Fig. 6. Upleg and downleg electron density profiles obtained from the Langmuir probe (LP) during the campaign IONEX-II.

4. Bubble regions are associated with a wide spectrum of plasma irregularities or electron density fluctuations. Spectral analysis of the ac data shows large peaks in the k-spectra of the plasma irregularities.
5. The existing theories for the generation of plasma irregularities cannot explain the sharp spectral peaks observed in the k-spectra.
6. One possible explanation is that large peaks in the k-spectrum of irregularities may be associated only with developing plasma bubbles and may dissipate their energy with time, thus leading to a flat k-spectrum as the steady state is reached.

ACKNOWLEDGEMENTS

The authors are grateful to the Directors of IAE/CTA and CLA, Alcantara for providing the rockets and the launch facilities respectively, and to the staff of IAE and CLA for their help during the pre-launch tests of the experiments and during the launching of the rockets. Sincere thanks to Sinval Domingos, Agnaldo Eras and Narli Baesso Lisboa for their technical help in the development testing and integration of the experiments. This work was partially supported by FINEP under contract FINEP-537/CT, and by CNPq under process 300253/89-3/GM/FV.

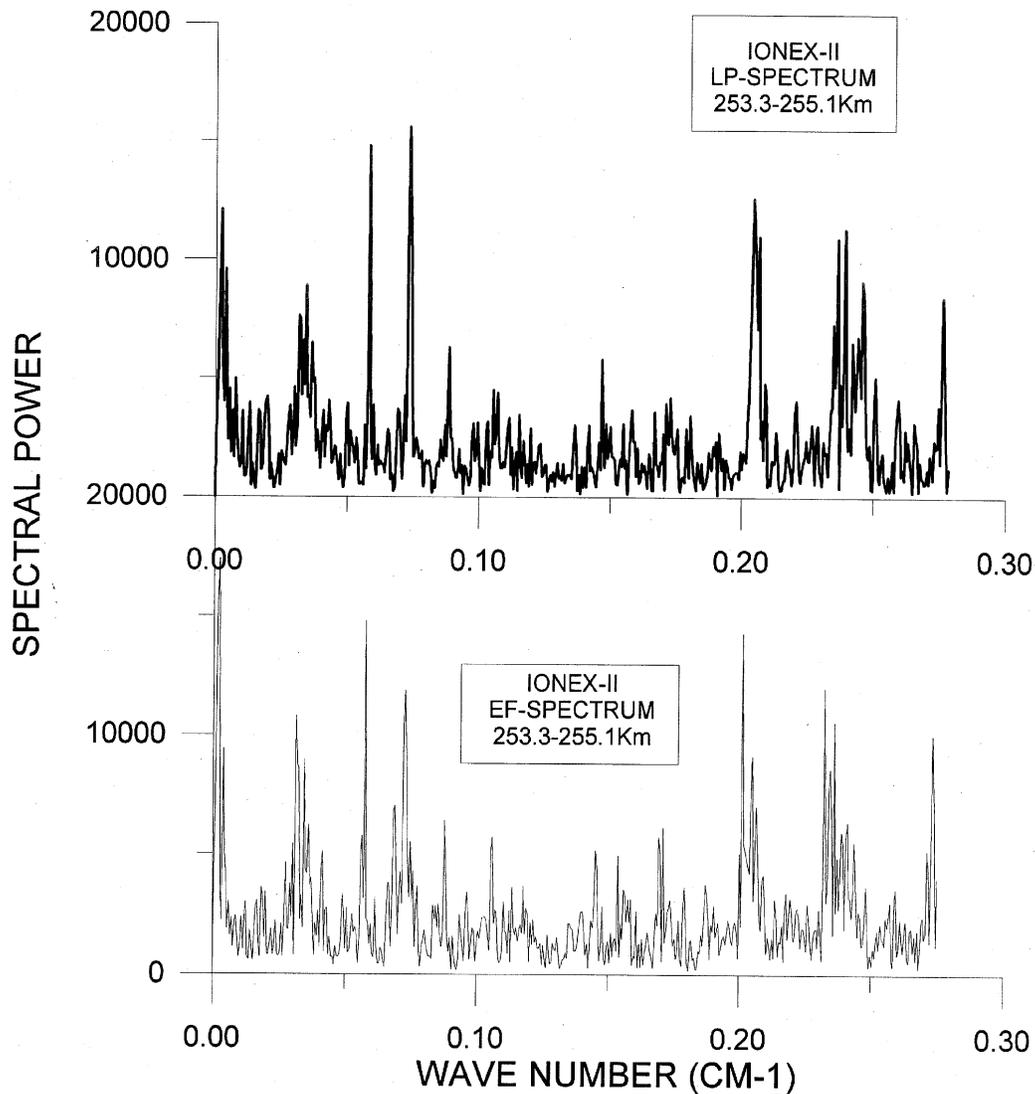


Fig. 7. Typical nature of the k-spectra of plasma irregularities, obtained from the Langmuir probe and Electric Field Double Probe measurements showing the presence of similar sharp peaks.

BIBLIOGRAPHY

ABDU, M. A., P. MURALIKRISHNA, I. S. BATISTA and J.H.A. SOBRAL, 1991. Rocket observation of equatorial plasma bubbles over Natal, Brazil using a High Frequency Capacitance probe. *J. Geophys. Res.*, 96, 7689-7695.

BALSLEY, B. B., 1969. Some characteristics of non-two-stream irregularities in the equatorial electrojet. *J. Geophys. Res.*, 74, 2333-2347.

BALSLEY, B.B. and D.T. FARLEY, 1973. Radar observation of two dimensional turbulence in the equatorial electrojet. *J. Geophys. Res.*, 78, 7471-7479.

BOWLES, K.L., R. COHEN, A.R. OCHS and B.B. BALSLEY, 1960. Radar echoes from field aligned ionization above the magnetic equator and their resemblance to auroral echoes. *J. Geophys. Res.*, 65, 1853-1855.

BOWLES, K. L., B. B. BALSLEY and R. COHEN, 1963. Field aligned E-region irregularities identified with acoustic plasma waves. *J. Geophys. Res.*, 68, 2485-2501.

FARLEY, D. T., 1963. Two stream instability as a source of irregularities in the ionospheres. *Phys. Rev. Lett.*, 10, 279-282.

HAERENDAL, G., 1974. Theory of equatorial spread-F, Max

- Planck Institut fur Physik und Astrophysik, Garching, Germany.
- MURALIKRISHNA, P. and M.A. ABDU, 1991. In-situ measurement of ionospheric electron density by two different techniques - a comparison. *J. Atmos. Terr. Phys.*, 53, 787-793.
- OTT, E. and D. T. FARLEY, 1974. The k spectrum of ionospheric irregularities. *J. Geophys. Res.*, 79, 2469-2472.
- PRAKASH, S., S. P. GUPTA and B. H. SUBBARAYA, 1970. A study of irregularities in the nighttime equatorial E-region using a Langmuir probe and a plasma noise probe. *Planet. Space Sci.*, 18, 1307-1318.
- PRAKASH, S., S.P. GUPTA and B.H. SUBBARAYA, 1971a. Cross-field instability and ionization irregularities in equatorial E-region. *Nature Phys. Sci.*, 230, 170.
- PRAKASH, S.; S. P. GUPTA; B. H. SUBBARAYA and C. L. JAIN, 1971b. Electrostatic plasma instabilities in the equatorial electrojet. *Nature Phys. Sci.*, 233, 56.
- REID, G. C., 1968. Small scale irregularities in the ionosphere. *J. Geophys. Res.*, 73, 1627-1640.
- ROGISTER, A. and N. D'ANGELO, 1970. Type II irregularities in the equatorial electrojet. *J. Geophys. Res.*, 75, 3879-3887.
- ROGISTER, A., 1972. Nonlinear theory of cross-field instability with application to the equatorial electrojet. *J. Geophys. Res.*, 77, 2975-2981.
- ROGISTER, A. and N. D'ANGELO, 1972. On the origin of small scale Type II irregularities in the equatorial electrojet. *J. Geophys. Res.*, 77, 6298-6299.
- SATO, T., 1971. Nonlinear theory of the cross-field instability-explosive mode coupling, *Phys. Fluids*, 14, 2426-2435.
- SATO, T., 1972. Stabilization of the two stream instability in the equatorial electrojet. *Phys. Rev. Lett.*, 28, 732-734.
- SATO, T., 1973. A unified theory of Type I and II irregularities in the equatorial electrojet. *J. Geophys. Res.*, 78, 2232-2243.
- SUDAN, R. N., J. AKINRIMISI and D. T. FARLEY, 1973. Generation of small scale irregularities in the equatorial electrojet. *J. Geophys. Res.*, 78, 240-248.
- TSUDA, T., T. SATO and S. MATSUSHITA, 1969. Ionospheric irregularities and cross-field plasma instability. *J. Geophys. Res.*, 74, 2923-2932.
-
- P. Muralikrishna**
Instituto Nacional de Pesquisas Espaciais,
C.P.515, 12227-010, São José dos Campos-SP, Brasil.