# Computational Fluctuation Analysis of ionosphere plasma irregularities

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## Abstract

In this work, in-situ E-F valley region irregularities are studied using Detrended Fluctuation Analysis (DFA). Our analysis show that the valley region's electron density fluctuations exhibit long-range correlation with crossovers that is intrinsic to the data. The range of scaling exponents acquired from DFA technique is compared with former equivalent results obtained from PSD method. This comparison show a wide range of spectral index variation with standard deviation ($\sigma_m \gg 50\%$). This variation confirms the lack of universality class and supports the non-homogeneous energy cascade in the equatorial ionospheric irregularities.

**Keywords**: Detrendeding Fluctuation Analysis; Equatorial ionospheric plasma irregularities; E-F valley region irregularities.

## 1. Introduction

The E-F valley region is still a less explored area of research compared to F-layer given to the technical limitations in observing it; and is possible using powerful incoherent scatter Radar and in-situ experiments. Various studies are reported on the study of E-F valley region and also on correlation of the valley-region irregularities with equatorial plasma instabilities in the F-layer. (Vickrey et al., 1982,1984,Prakash 1999, Sinha et al.,1999, Patra et al., 2002; Muralikrishna et al.,2003, Yokoyama et al., 2005; Li et al., 2011, Kherani et al., 2012, Odriozola et al.,2017). Power Spectral Density (PSD) has been a conventional method to study in-situ data. In this work, DFA technique is applied to the E-F valley region electron density fluctuation data. The paper is organized as follows: section 2 describes the in-situ data along with the vertical electron density profile; DFA method and analysis is presented in section 3 followed by the concluding remarks in section 4.

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## 2. Data

A two-stage VS-30 Orion sounding rocket experiment launched from an equatorial rocket launching station, Alcântara (2.24°S, 44.4°W, dip latitude 5.5°S), on December 8, 2012 at 19:00 LT, under quite geomagnetic conditions. At the time of launch, ground based equipment detected conditions favorable for the generation of plasma bubbles in F-region. During the ~11 min flight, the vertical profile of electron densities are obtained from onboard Conical Langmuir Probe (CLP). Odriozola et al. [1] reported presence of several small and medium-scale plasma irregularities in the valley region (100 − 300 km) during both the ascent and descent, and were preeminent during the descent of the rocket. Figure 1 shows variations in the vertically distributed electron densities in the downleg (descent of the rocket) trajectory of the flight. The inset in Figure 1 shows the time series for the mean height of 143 km that is analyzed in the current work.

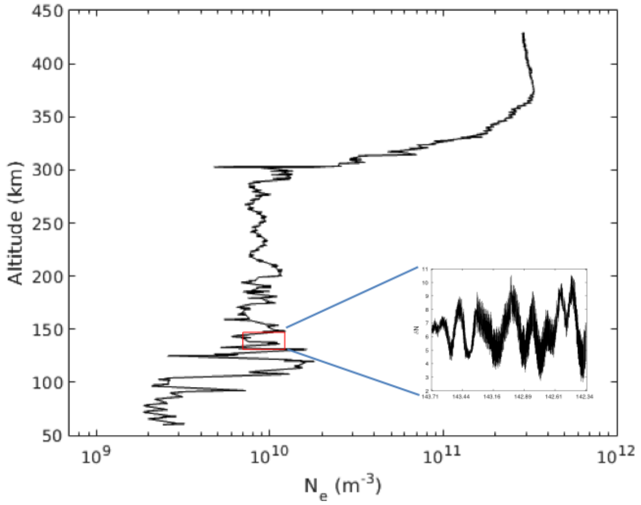

**Figure 1** - Downleg profile of the electron density fluctuations. The inset show the time series for the mean height of 143 km.

## 3. Methodology

Detrended Fluctuation Analysis (DFA) proposed by Peng et al. [2] is a potential method that could render insights into the statistical properties of the turbulence phenomena. Originally proposed to detect long-range correlations in DNA sequences and in data influenced by trends, DFA is widely used in many branches of sciences like medicine, physics, finance and social sciences to understand complexity of the systems through its scaling exponent that characterizes fractal dynamics of the system [3].

The robustness of DFA can be owed to some of its interesting features for instance, (1) Coronado & Carpena [4] investigated the influence of the length of a time series in quantifying the correlation behavior. The comparison study revealed that DFA is practically unaffected by the length of the time series contrary to that observed from the results of Hurst analysis or autocorrelation analysis. (2) another interesting feature is reported by Chen et al. [5] who alter the time series by excluding parts of it, stitching the rest and subjecting it to the DFA. The study revealed that even with the removal of 50% of the time series, the scaling behavior of positively correlated signals is unaltered implying that the time series need not be continuous. (3) Kiyono [6] showed that equivalence relation between the PSD exponent, $\beta$ and the DFA exponent, $\alpha$ given by $\beta \equiv 2\alpha - 1$ is valid for higher order DFA analysis subjected to the constraint $0 < \alpha < m + 1$ where $m$ is order of detrending polynomial in DFA method.

Detrended Fluctuation Analysis technique applied to a time series, $y$, of length $N$ consists of :

- obtain cumulative sum of the mean subtracted time series followed by dividing it into non-overlapping segments, $S$, referred to as scales.
- Detrend these segments using linear least squares or higher order ($m$) and calculate the variance. Depending on the detrending order, $m$, of the polynomial used, the analyses are referred to as DFA$m$.
- Average the RMS over the segments to get the fluctuation function, $F(S)$.

$$F(S) = \sqrt{\frac{1}{N}\sum_{k=1}^{N}[y(k) - y_s(k)]^2} \tag{1}$$

- Linear fit to the fluctuation function profile yields the scaling exponent ($\alpha$).

The time series corresponding to the mean height of 143 km is subjected to DFA analysis. Scales are varied from 4 to $N/4$ with a factor of $2^{\frac{1}{8}}$, where $N$ is the length of time series [7]. The fluctuation function computed from DFA is plotted as a function of scales on a log-log scale. The fluctuation function exhibits long-range correlation with a crossover. Crossover refers to a change in the scaling exponent for different scale ranges and it usually arises due to change in the correlation properties over different spatial or temporal scales, or from trends in the data. The exponents, $\alpha 1$ & $\alpha 2$, are obtained from the linear fit to the $F(S)$, where $\alpha 1$ refers to smaller scales while $\alpha 2$ refers to the larger scales. In our analysis we found $\alpha 1$ =0.39 and $\alpha 2$=1.5.

In order to be sure that the obtained crossover is intrinsic to the data and not an artifact, we investigated the time series with higher order DFAs, i.e. of the order $1-5$. For this investigation, we have used the methodology prescribed by Kantelhardt et al. [8] to identify false crossovers. Artificial crossover exhibits similar characteristic length with identical scaling. Figure 2 presents analysis for downleg time series corresponding to the mean height of 143 km with DFA $1^{st}$ order to $5^{th}$ order. It can be observed that as the order of detrending increases, crossover point moves towards the larger scales and have different scaling exponents. In addition, the exponents are not increasing with the increasing order of DFA. This investigation confirms that obtained crossover is an intrinsic property of the electron density data in the E-F valley region.

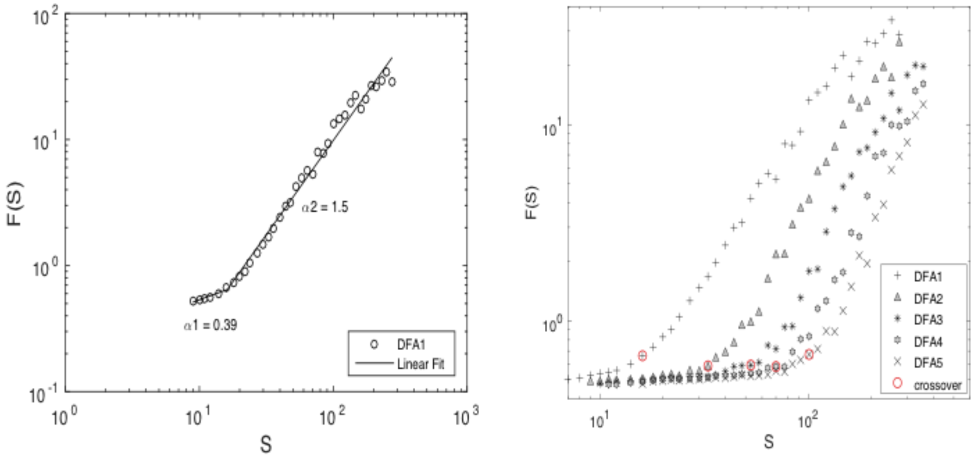

**Figure 2** - DFA analysis: left panel show the fluctuation function as a function of scales for the chosen time series with linear fit and the right

panel show the similar profile for different orders $[DFA1, DFA2, ..., DFA5]$ with crossovers indicated by red open circles.

Using computed DFA exponent in our analysis, PSD exponent, $\beta$, is calculated using the equivalence relationship and then variation around its mean is determined by calculating standard deviation $\sigma_m\%$ which affirms that underlying mechanism for instabilities differ from K41 homogeneous turbulence as accepted deviation is $\sigma_m \leq 2\%$ [9]. Table 1 summarizes the variations in the $\beta$ exponent obtained from previous equivalent studies and compares with the present work. All studies reported in Table 1 are based on electron density data obtained through rocket experiment. Wide variations of the scaling exponent from the K41 theory are observed implying that the ionospheric plasma instabilities are non-homogeneous.

Table 1: Comparison among PSD spectral indices ($\beta$) found in previous equivalent studies and for $\beta$ obtained here from DFA technique. All results measured using rockets are related to electronic density measurements during the experiment.

| Date and Time | Spacecraft | Altitude (km) | $\beta$-range | $\langle\beta\rangle$ | $\sigma_m$ | References |
|---|---|---|---|---|---|---|
| 31/10/1986, 03:00 UT | Rocket | 100 to 220 | -1.54 to -3.30 | -2.42 | 88% | [10] |
| 15/01/2007, 16:43 UT | Rocket | - to 127 | -1.60 to -2.70 | -2.15 | 55% | [11] |
| 29/01/2008, 15:49 UT | Rocket | - to 117 | -2.00 to -3.50 | -2.75 | 75% | [12] |
| 08/12/2012, 22:00 UT | Rocket | 70 to 317 | -0.98 to -2.14 | -1.56 | 58% | This paper |

## 4. Concluding Remark

In this work, in-situ E-F valley region irregularities are studied using DFA technique for the mean height of 143 km. Our analysis show that the valley region electron density fluctuations exhibit long-range correlation with crossovers that is intrinsic to the data. Crossover reveals the different fractal scaling exponent. This may implies that two different mechanism are responsible for the irregularities in this ionospheric region yielding different scaling exponents. Existence of crossover may support the finding of two or three different slopes obtained with the Power Spectral Density (PSD) method. PSD exponent $\beta$ is computed using equivalence relation from DFA exponent $\alpha$ for the current data and compared with earlier similar experiments. We found deviations in $\beta$, $\sigma_m \gg 50\%$. Above finding implies that the ionospheric plasma instabilities are non-homogeneous and our result confirms the result of previous finding of Fornari et al. [13] that these findings are not due to biased in any analytical method.

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