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Multifractal behaviour of the ionospheric scintillation index time series over an Indian low latitude station Surat

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ABSTRACT

The amplitude scintillation information recorded by the GSV4004B GISTM (Global Ionospheric Scintillation TEC Monitor) GPS receiver at an Indian low latitude station Surat (21.16°N, 72.78°E) for 48 months during the years 2009, 2010, 2011 and 2012 are utilized in the present work. Multifractal detrended fluctuation analysis (MF-DFA) have been carried out along with computation of q-order fluctuation function, q-order Hurst exponent, q-order mass exponent and multifractal spectrums for each monthly post-sunset S_4 index time series. The non-linear dependence of mass exponent and dependence of q-order Hurst exponent on q-values reflect the existence of nonlinear interaction between different scales and multifractal structure in the system, respectively. The comparison of broadness and shape of spectra with the occurrence of scintillation activities registered in the same period reveal the existence of multifractality/complexity in the turbulent ionosphere, which is influenced by the small-scale intermittency and solar flux indices. The truncation of the spectrum is the evidence of manifestation of small-scale intermittency of the turbulent ionosphere. The higher values of the Hölder exponent α_0, calculated from the spectrum, imply the irregular nature of the underlying process. The present study suggests that, MF-DFA may act as an important non-linear technique for identifying the effect of large and small-scale fluctuations in complex and turbulent ionosphere.

1. Introduction

In any real world system, the energy dissipation cannot be neglected, when one tries to obtain a realistic picture of their evolution, since all natural processes somehow interacts with their surroundings. Such process should be treated in the general framework involving fluctuations in the environment and the system itself. There is a possibility for a presence of weak coupling between the degrees of freedom in a process, which act in a coherent way exhibiting nonlinear properties (Unnikrishnan, 2010; Unnikrishnan and Ravindran, 2010). The ionosphere is a reservoir of energy and neutral atoms/molecules for ionization process and is well recognized as a complex non-linear system. The momentum equation, energy and mass balance for the matter and its chemistry, plus Maxwell equations for the electromagnetic field govern the ionospheric physics. Even if, being governed by classical equations, this is a dynamical system of non-linearly coupled fields, with apparently random terms. Indeed, the space and time variability of the real ionosphere shows chaos, pattern formation, random behavior and self-organization (Materassi et al., 2003). Ionosphere therefore behaves as a large system showing strong variability in its concentration fluctuations over a different time scales. One of the most dramatic manifestations of the "irregularity" of the ionosphere is the fluctuation of radio signals crossing it. The rapid fluctuation of amplitude and phase of the radio signal passing through the ionospheric region, embedded with plasma density irregularities refers to as the ionospheric scintillation. The existence of ionospheric scintillation degrades the performance of satellite based communication system, resulting in signal fading below the fad margin of the receiver, and leading to the signal loss and cycle slips (Singh et al., 2006; Seo et al., 2011). This renders a study of ionospheric scintillation very interesting and challenging for both space scientists and radio communication systems engineers.

Many researchers have explained the complex interaction between electric field, neutral winds and earth's magnetic field leading to the formation and evolution of ionospheric turbulence. In the presence of enhanced eastward electric fields and meridional neutral winds during some evening periods, the ionosphere becomes destabilized and causes the formation of plasma bubbles that penetrate into the topside ionosphere (McClure et al., 1977; Basu et al., 1999). These plasma bubbles hold various scales-size irregularities from a few centimetres to hundreds of kilometres, which cause scintillations at least up to 7 GHz (Zou, 2011). For the development of robust specification and forecasting model,

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an extensive knowledge of the non-linearity in the ionospheric irregularities is necessary besides the classical morphological statistical and spectral studies. The morphological studies of ionospheric scintillation have found that scintillation activity varies with solar activity, 11-year solar cycle, geographic location, local time and seasons (Paula et al., 2003; Gwal et al., 2006; Muella et al., 2008; Shang et al., 2008; Li et al., 2008). It is well documented in literature that, scintillation theory relates the observed signal statistics to the statistics of ionospheric electron density irregularities. Many studies of the inhomogeneous structure of the ionospheric region were performed by standard methods of spectral analysis of fluctuating signals, which can be used for statistical processing of quasistationary random processes. This has been found for instance, that phase and amplitude spectra can be used to deduce the scintillation spectrum of electron density fluctuations (Yeh and Liu, 1982). However, Costa and Kelley (1978) and Bhattacharya (1990) have reported that power spectrum dose not describe unambiguously the turbulent nature of the ionosphere. For the characterization of ionospheric turbulence, some alternative nonlinear analysis methods have been suggested by Wernik et al. (2003) which are wavelet transform, higher order moments, fractal and multifractal analysis, etc. An attempt to obtain statistical features of ionospheric irregularities and its generation mechanism at low latitude station Varanasi (25.3°N, 83°E), the spectral analysis of VHF scintillation has been made by Singh et al. (2006) who have also reported that for studying the observation of turbulent nature of the ionosphere, an accurate nonlinear theory must be developed. While the studies of atmospheric turbulence expressed by radio waves, the studies of turbulent ionosphere did not even employ the method of the second-order function (Alimov et al., 2008d). Moreover, Alimov et al. (2008a–d) have made extensive studies on turbulent ionosphere and electron density in homogeneities in the mid-latitude ionosphere and noted the efficiency of fractals and similar non-linear methods over the conventional spectral analysis of radio scintillations.

To this end it is noted that, to characterize the turbulent ionosphere, especially from behavioral standpoints, proper understanding of the non-linear properties of trans-ionospheric satellite signal on different time scales is necessary. Hence, the present paper deals with fractal properties of amplitude scintillation S_4 index time series, recorded by the GSV4004B GPS receiver at Suart.

Mathematically fractal geometry characterizes the systems that are irregular at all scales. In the real world system, a specific state between determinacy and chaos is, in turn characterized by existence of self-invariance, when parts of an object somehow resemble the whole. To put it in a more rigorous way, a self-similar, scale-irreverent structure without any characteristic scale appears as a fractal (Mandelbrot, 1982; Feder, 1988; Takayasu, 1989; Schroeder, 1991). Fractals can be classified into two categories: monofractals and multifractals. Monofractals are those, whose scaling properties are the same in different regions of the system meaning that, one single scaling exponent is sufficient to describe its scaling properties. However, in natural fractals, the self-similarity does not hold in a single scaling exponent but it holds statistically over a finite range of scales i.e. multifractal (Hu et al., 2001; Chen et al., 2002; Kantelhardt et al., 2002). Thus, a fundamental characteristic of multifractal structure is that the scaling properties may be different in different segments of the system requiring more than one scaling exponent to be completely described.

The simplest type of multifractal analysis is based upon the standard partition function multifractal formalism, which has been developed for the multifractal characterization of normalized, stationary measurements (Feder, 1988; Barabasi and Vicsek, 1991; Peitgen et al., 1992; Bacry et al., 2001). However, this standard formalism does not give correct results for non-stationary time series that are affected by trends or that cannot be normalized. Therefore, an improved multifractal formalism was developed known as the wavelet transform modulus maxima (WTMM) method (Muzy et al., 1991), which is based on the wavelet analysis and involves tracing the maxima lines in the continuous wavelet transform over all scales. In order to get the multifractal spectra of TEC time series recorded from the Brazilian sector, Bolzan et al. (2009, 2013) have used this WTMM method. Peng et al. (1995) have introduced the detrended fluctuation analysis (DFA) Method, to study the properties of DNA sequences. Since its introduction, this method has been widely used in diverse fields of solar activities to the earth science (e.g. Geology, DNA sequences, neuron spiking, heart rate dynamics, economic time series and also weather related and earthquake signals) (Arneodo et al., 1995; Molchanov and Hayakawa, 1995; Hayakawa et al., 1999; Kantelhardt et al., 2001; Telesca et al., 2001; Varotsos et al., 2002, 2003; Vyushin et al., 2004). By generalizing this standard DFA method, Kantelhardt et al. (2002) have conceived the multifractal detrended fluctuation analysis (MFDFA), which allows the global detection of multifractal behavior. By applying this MF-DFA method to the sunspot number time series, Movahed et al. (2006) and Hu et al. (2009) have found that the presence of multifractality in the sunspot number fluctuations. Yu et al. (2009) have performed the multifractal analysis through the same MF-DFA method to the D_{st}, a_p and solar X-ray brightness indices and during the active period, they obtained the significant relationship between these three indices.

The remainder of the paper is organized as follows. In the following section, we briefly describe the data and methodology. The required steps for producing MF-DFA method are detailed in Section 3. Our results are presented and discussed in Section 4 and, finally, the concluding remarks of this work are summarized in Section 5.

2. Data and methodology

The GSV4004B receiver is capable of tracking up to 11 GPS satellites at the L1 and L2 frequencies simultaneously. It measures amplitude and phase at a 50-Hz rate for each satellite tracked on L1 and calculates amplitude and phase scintillation parameters in real time. The amplitude scintillation index S_4 is the standard deviation of the received signal intensity (SI) divided by its mean value which, is calculated every 60 s using 3000 points of detrended signal intensity measurements. This produces the total S_4 (S_{4T}) which includes the effects of ambient noise. The signal intensity is actually received signal power. Detrended signal intensity is obtained by filtering the intensity measurements in a low-pass filter. The total S_4 (S_{4T}) stored in the GSV4004B receiver's data log is defined as follows (Van Dierendonck et al., 1993):

$$S_{4T} = \sqrt{\frac{\langle I^2 \rangle - \langle I \rangle^2}{\langle I \rangle^2}}$$

here I is the detrended signal intensity, and the brackets indicate average value over the 60-s interval. In order to remove the effects of ambient noise to the total $S_{4,}$ the GSV4004B receiver also calculates a corrections i.e. $S_{4N0.}$ This is achieved by estimating the average of the signal-to-noise density, S/N_0, over the same 60-s interval. Thus the corrected S_4 with the effects of ambient noise removed can be computed as follows (Zou and Wang, 2009)

$$s_4 = \sqrt{s_{4T}^2 - s_{4N_0}^2}$$

To confirm consistent statistics, following three criteria have been used in the present analysis:

(1) Data for only equatorial/low latitude scintillation-post-sunset hours (18:30 LT-06:30 LT) were used (Aarons, 1982;