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# Fractal and wavelet analysis evaluation of the mid latitude ionospheric disturbances associated with major geomagnetic storms

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## Abstract

Variations of the total electron content (TEC) of the ionosphere are mainly associated with major geomagnetic storms occurring with the arrival of coronal mass ejections (CMEs) to the Earth environment. The purpose of this paper is to show results of the analysis we made of the impact of all major geomagnetic storms ($\mathrm{Dst} < -200\,\mathrm{nT}$) on the ionosphere at mid latitudes, which have occurred since 2000. The analysis consists in the calculation of TEC of the ionosphere using data from several Mexican GPS stations, with the purpose of quantifying the impact into the ionosphere to these latitudes, through the variations in amplitude, Hurst index, that is roughness, and wavelet transform of the time series of TEC. Indeed, during the geomagnetic storms of April 7, 2000, July 16, 2000, October 30, 2003, November 20, 2003 and November 8, 2004, major ionospheric disturbances at mid latitudes took place with changes in amplitude of TEC going from 3.29 to 8.82 sigmas. These ionospheric disturbances were probably associated with prompt penetration electric fields (PPEFs) and equatorward neutral winds. On the other hand, during four geomagnetic storms (August 12, 2000, March 31, 2001, April 11, 2001 and May 15, 2005), there were negative ionospheric storms that pushed the TEC to significantly lower values. This has been interpreted as the presence of regions in which the neutral composition is changed. Also, in some cases during the disturbed days, the Hurst values were smaller than during the undisturbed days, i.e. during these geomagnetic storms, the roughness of the time series of TEC increased. The wavelet analysis showed a strong influence of the diurnal variation on TEC values (periodicities of 12 h), and periodicities characteristics of ionospheric disturbances of 1–8 h. It is found that large geomagnetic storms produce significant ionospheric disturbances at mid latitudes, as shown by the wavelet analysis and, in some cases, changes in the roughness of the time series of TEC as shown by the Hurst exponent.

*Keywords:* Total electron content; Geomagnetic storms; Ionospheric disturbances; Fractal analysis; Wavelet analysis

## 1. Introduction

The Earth's ionosphere is generated by the ionization produced by the solar ultraviolet radiation upon arriving to the top of the atmosphere (Appleton and Barnett, 1925; Ratcliffe and Ashworth, 1972). However, the variations of the total electron content (TEC) of the ionosphere are mainly associated with geomagnetic storms occurring with the arrival of coronal mass ejections (CMEs) to the Earth environment (see Mendillo (1973) and Fuller-Rowell et al. (1994)). Furthermore, during geomagnetic storms, magnetospheric electric fields penetrate into the ionospheric causing ionospheric variations. In fact, during major geomagnetic storms, associated with southward

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interplanetary magnetic field (IMF), dayside positive ionospheric storms are caused by eastward prompt penetration electric fields (PPEFs) and equatorward neutral wind (Lin et al., 2005; Lu et al., 2008; Tsurutani et al., 2008; Balan et al., 2010) and the negative ionospheric storms are caused by the composition change effect of equatorward neutral winds (Prölss, 1991; Prölss, 1993; Fuller-Rowell et al., 1994). Other important mechanisms in the formation of the ionospheric disturbances during a geomagnetic storm, are the heat energy obtained from joule heating and the impact of auroral particles. These polar disturbances are modified in density, height and latitude by local atmospheric conditions, thermospheric winds, local time, among others, and they are transported at high speeds toward mid latitudes (Prölss, 1991, 1993; Millward et al., 1993; Fuller-Rowell et al., 1994). In spite of the fact that the high energy electromagnetic radiation like ultraviolet and X-rays intensifies during large solar flares, their impact on the diurnal variation of TEC is usually of little importance.

Currently, one of the most frequently used techniques to explore the ionospheric behavior changes due to the influence of space weather, is the calculation of TEC from Global Positioning System (GPS) data (Sardón et al., 1994; Eftaxiadis et al., 1999; Arikan et al., 2003; Stankov et al., 2003; Blagoveshchensky et al., 2005; Afraimovich et al., 2008; Rothkaehl et al., 2008; Bishop et al., 2009). This is a relatively low-cost system consisting of a large global network of GPS devices, with a good spatial distribution and with a virtually free access to the data.

In fact, in López-Montes et al. (2012), when large X-ray class flares were analyzed using TEC, a clear relationship of ionospheric disturbances associated with PPEFs and equatorward neutral winds during geomagnetic storms was found. Examples of this were the storms of July 2000, April 2001, Halloween 2003, January 2005 and December 2006.

The purpose of this paper is to show results of the analysis we made of the impact of all major geomagnetic storms (Dst $< -200$ nT) on the ionosphere at mid latitudes, which have occurred since 2000 (taken from World Data Center for Geomagnetism, Kyoto[1]), regardless of whether there is any previous geomagnetic activity. Such analysis consists on studying variations of the amplitude, Hurst index, and the wavelet transform of the time series of TEC using data from several GPS Mexican stations, during these periods.

In the next section we show the storms chosen for the analysis, and the GPS stations used for calculating the TEC (in units of $10^{16}$ electrons m$^{-2}$) for each storm. We also describe the fractal method used to measure changes in the roughness and the wavelet analysis preformed on the TEC series. In Section 3 we show the results of the analysis storm by storm. Finally, in Section 4 we discuss the results obtained and give a possible explanation of them in the contest of the present literature.

## 2. Data analysis

For this analysis, a total of 11 geomagnetic storms were analyzed (see Table 1) where the $\mathrm{Dst}_{Min}$ and ap index maximum values are given, together with the time and speed of the first associated CME (The CME catalog used is generated and maintained at the CDAW Data Center by NASA and The Catholic University of America in cooperation with the Naval Research Laboratory. SOHO is a project of international cooperation between ESA and NASA) and, when it was the case, the flare intensity that could be associated. TEC was calculated (see Erickson et al. (2001) and Araujo-Pradere (2005)) for eight days around the event, and we use one of the 6 GPS Mexican stations in Table 2 for which we could find data for the events considered. For each storm we took for the analysis the one with more data.

In Table 3, the maximum Dst fall, the maximum, mean and variation of TEC with respect to the mean in standard deviations as given by the formula $Var = \frac{(TEC)max-(TEC)mean}{std(TEC)}$, as well as the maximum and minimum values of Hurst index for each storm are shown. To calculate the Hurst index, we used the Benoit 1.3 program (TruSoft Intern, 1999). This we did for 256 points in the series so that a total of 12 values are given for every event.

We also calculated the wavelet transform of the detrended TEC time series for the same periods to eliminate the diurnal variations. The calculation of the wavelet is important because it provides information about the frequencies at which variations occur, as well as the times where they occur.

### 2.1. Hurst exponent

The Hurst exponent was proposed by the hydrologist Harold Edwin Hurst in 1951 with the technique of Rescaled range analysis (R/S) (Hurst, 1951). The Hurst exponent measures the growth of the standardized range of the partial sum of deviations of a data set from its mean (Ellis, 2007) for the time series. If we have a function $h(x)$, of one variable, i.e., fractional Brownian motion (Falconer, 1990), where $x$ is the horizontal variable and $h$, the vertical, the self-affinity is defined by (Simonsen et al., 1998)

$$x \to \lambda x, \tag{1}$$

$$h \to \lambda^{H} h, \tag{2}$$

where $H$ is the Hurst exponent, and if both are combined, can create the affine group. In fact, Therefore, the self-affine surfaces are invariant under the affine group. This invariance can be expressed by

$$h(x) \simeq \lambda^{-H} h(\lambda x), \tag{3}$$

where $\simeq$ represents the statistical equality. The Hurst exponent, is limited to the range $0 \leqslant H \leqslant 1$ and is associated with the fractal dimension with a simple expression:

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[1] WDC for Geomagnetism, Kyoto:<http://wdc.kugi.kyoto-u.ac.jp/dst-dir/>.