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A statistical analysis of electric self-potential time series associated to two 1993 earthquakes in Mexico

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Abstract. Recent studies related with earthquake prediction involve statistical studies of the ground electric self-potential behavior. Published results about the complexity of this kind of processes encourage us to study the statistical behavior of the ground electric self-potential recorded in Guerrero state, Mexico. This region is characterized by high seismicity. The electric self-potential variations were recorded in the Acapulco station directly from the ground. The sampling period was four seconds and the data were stored from March to December of 1993. Two significant earthquakes (EQs) occurred near this station, 15 May and 24 October whose magnitudes were Mw=6.0 and Mw=6.6 respectively. A preliminary processing was carried out consisting of a moving average of the original time series in order to filter the very high frequencies and to complete short lacks of data and outliers. Then, a visual inspection of the complete filtered signal was performed to search some seismic electric signals (SES), which were ambiguously depicted. Subsequently, a detrending of $\mu=0$ was applied with the windows of 3.3, 6.6 and 10 h. Later, the analysis of the spectral exponent β was made, showing changes during the total period examined, and the most evident changes occurred during the preparation mechanism of the Mw=6.6 EQ. Fifteen days before the 24 October EQ, a Brownian-noise like behavior was displayed ($\beta\approx2$), having a duration of about two days. In addition a Higuchi fractal method and wavelet analysis were made confirming the presence of the β-anomaly.

1 Introduction

Observations of changes in the electromagnetic field before earthquake (EQ) occurrences have been proposed as one of the possible methods in earthquake prediction (e.g. Honkura, et al., 1981, 2002; Varotsos and Alexopolous, 1984a, b; Varotsos and Sarlis, 2002, and references therein). However, observational evidence with a clear physical mechanism has not been defined, although some possible mechanisms have been proposed to account for ambiguous observational results (Honkura et al., 2002). The electrokinetic effect (Mizutani et al., 1976; Ishido and Mizutani, 1981; Gershenzon et al., 1993; Haartsen and Pride, 1997), the piezoelectric effect (Gershenzon et al., 1993), the piezomagnetic effect (Stacey and Johnston, 1972; Sasai, 1980), and the electromagnetic induction effect (Gershenzon et al., 1993; Iyemori et al., 1996; Honkura et al., 2000; Matsushima et al., 2002), have been considered as possible processes to explain those observations.

Recent examples of clear electric field changes indicate that the arrival of electric signals to registering stations are sometimes synchronized with the arrival of seismic waves (Yamada and Murakami, 1982; Mogi et al., 2000; Nagao et al., 2000); others arrived before the EQ events (Varotsos and Alexopolous, 1984a, b; Varotsos et al., 1988, Ramirez-Rojas et al., 2004a, b), but a possibility also exists that the magnetic field shows changes and, moreover, it started before the arrival of seismic waves (Iyemori et al., 1996; Nikolopoulos et al., 2004). Then, the study of electromagnetic field changes is extremely valuable in searching for precursor signs associated with EQs. The seismic electric signals (SES) were introduced by Varotsos and Alexopoulos (1984a, b). The named

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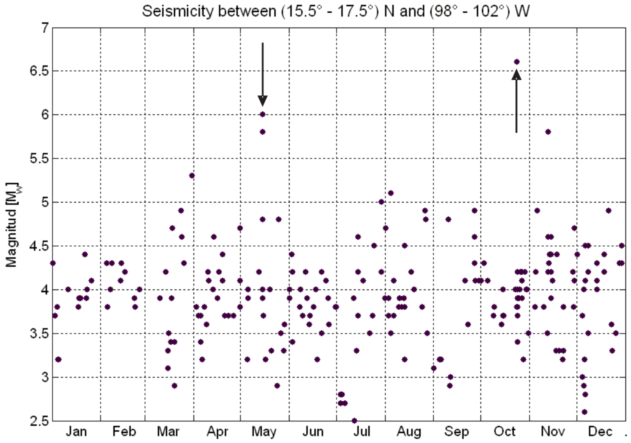

Fig. 1. Plot of EQs occurred in the studied region, whose distance between epicenter and the monitoring station (ACA) is between 100 and 200 km and their magnitude Mw>2.5. The two studied EQs were marked with arrows.

VAN group (acronym of Varotsos, Alexopoulos and Nomicos) proposed the methodology to register the SES, and suggested it as a method for searching for seismic precursors. In 2002, Varotsos and Sarlis published a review of the efforts on understanding the SES generation, their properties and how to interpret them. The VAN group proposed that the natural electric self-potential (NESP) must be normalized by the distance between electrodes.

Some overall characteristics of electric and magnetic field changes were already shown (Honkura et al., 2000; Matsushima et al., 2002), and the attention has been focused on statistical processes of these changes to look for new findings.

Novel papers involving fractal methods have been applied to electromagnetic field changes in order to provide some possible EQ precursory signature from scaling properties. Some reports including the magnetic field data, are Hayakawa et al. (1999, 2000); Smirnova et al. (2001); Telesca et al. (2001); Gotoh et al. (2003), Ida et al. (2005); Ida and Hayakawa (2006) and for the electric signals, Ramirez-Rojas et al. (2004a, b); Varotsos et al. (2002, 2003a); Kapiris et al. (2003, 2004).

It has been found that the power spectrum of electric Ultra Low Frequencies (ULF) emissions, on average, exhibits a power-law behavior of the type $S(f)\alpha f^{-\beta}$, which is a fingerprint of typical fractal (self-affine) time series. In most of the cases, the spectral exponent β displays a tendency to decrease gradually when approaching the EQ date (Ramirez-Rojas et al., 2004b). Such a tendency shows a gradual evolution of the structure of the ULF noise towards a typical flicker noise structure ($1/f$ noise-like) in the proximity of a large EQ. This behavior has been suggested as an EQ precursor signature (Hayakawa et al., 1999; Smirnova et al., 2001; Ramirez-Rojas et al., 2004a, b).

Ramirez-Rojas et al. (2004) made a spectral and multifractal analysis of NESP registered at the Acapulco station associated to the Mw=6.6 EQ, on 24 October 1993. They reported that the spectral and multifractal studies were made over the original NESP, just on the N-S time series, without any preliminary processing. However, they found an anticorrelation between the spectral exponent β and the multifractal spectrum width. They also reported studies made by means of detrended fluctuation analysis (DFA) and multifractal analysis, obtaining some additional properties of the NESP.

In this work we present a statistical study of self-potential electric time series monitored in 1993 at the Acapulco station (16.54° N, 98.98° W), introducing now a pre-processing of the data. Firstly, the higher frequencies were removed from the original time series by a moving average algorithm, and then a detrending procedure was applied. We show that the time series display a trend of SES probably associated to an EQ. Also, by using the spectral method, we carried out a statistical study of the spectral exponent β, from the preprocessed series, probably associated to the mechanism of EQ preparation. Finally, the statistical study of the NESP was complemented by means of a fractal analysis (Higuchi's method) applied to the original preprocessed data and to the series transformed by means of wavelets.

2 Seismological and NESP data

Particularly, the western and southwestern coast of Mexico has had an important number of EQs per year due to the tectonic processes associated to the tectonic plates confluence; the subduction zone along the Southwest coast and the Middle American Trench are the main triggerers of these EQs. The National Seismological Service (SSN, Servicio Sismológico Nacional dependent of the National Autonomous University of Mexico, UNAM), is in charge of monitoring the seismic and volcanic risk, and of producing the records of these events and also the reports of the specific parameters (magnitude, epicenter and depth). According to the SSN 1993 seismic catalogues, there were registered 238 events with Mw>2, within the Guerrero coast, between 15.5° and 17.5° latitude N and between 98° and 102° longitude W.

A selection of EQ events was done taken into account their magnitudes and the distance between the epicenter and the monitoring station (see Table1). Particularly, we are interested in the events occurred on 15 May and 24 October because the distance between the epicenter and the monitoring station is around 100 km and their magnitude Mw>5.5 (Fig. 1).

Electric self-potential data consist of the observation of the electric potential differences, ΔV, between two electrodes buried 2 m of deep into the ground and separated by 50 m in distance. A couple of electrodes was oriented in the North-South direction (NS series) and other couple in the East-

Table 1. Guerrero coast EQs whose distance to the monitoring station is around 100 km and Mw>5.

day	month	year	h	min	s	Latitude N	Longitude W	Magnitude	Distance to the epicenter (km)
31	March	1993	10	18	15.5	17.18	101.02	5.3	137.78
15	May	1993	3	9	39.4	16.43	98.74	5.8	120.24
15	May	1993	3	11	56	16.47	98.72	6	120.68
24	Oct	1993	7	52	18.2	16.54	98.98	6.6	091.89
13	Nov	1993	0	16	44.5	15.63	99.02	5.8	156.34

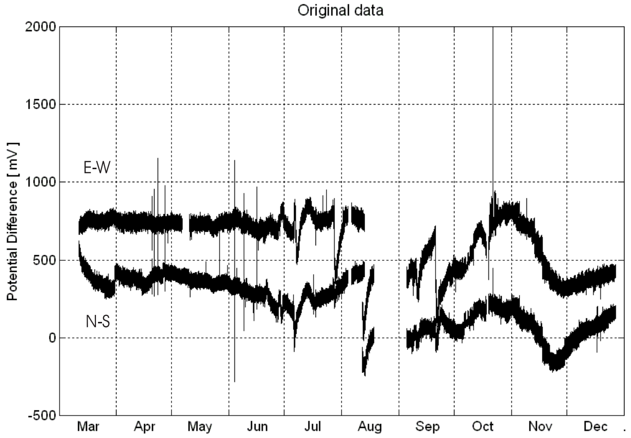

Fig. 2. The total data recorded in 1993, some lacks of data and outliers can be observed.

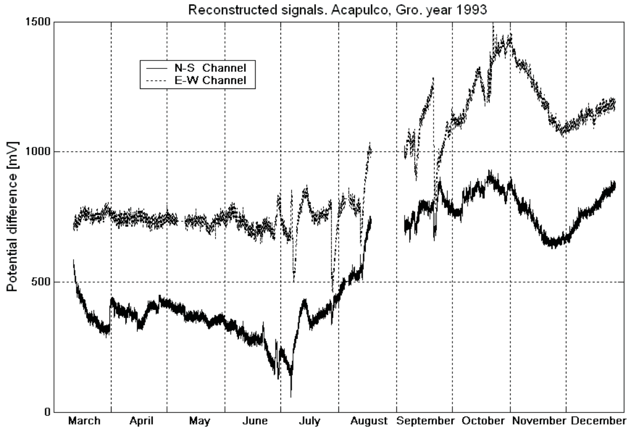

Fig. 3. Pre-processed NS and EW series; filtered data by using moving average each two minutes are showed; the outliers were also removed.

West direction (EW series), following the VAN methodology (Varotsos and Alexopodus, 1984a, b; Varotsos et al., 1988). The survey project consisted of six monitoring stations in charge of the Instituto Politecnico Nacional (IPN), from 1992 to 1996 (for details, see Yepez et al., 1995).

3 Data processing

The data considered in this study were obtained at the Acapulco station during the year 1993. The time series were recorded in both directions, with two different sampling rates, Δt=4 s and Δt=2 s, in different time intervals. The total data recorded along the year are depicted in Fig. 2. Some problems in collecting the data inherent to the storage process can be observed, as some lacks of data and outliers, among others. The data were filtered by using a moving average each two minutes, so that more homogeneous data were obtained to minimize these problems (see Fig. 3). The higher frequencies were removed and small lacks were filled. Also, the elimination of outliers was done to have the same reference level.

An attempt was done to search SES, by a simple visual inspection of Fig. 3, following the method proposed by VAN group. Varotsos and Lazaridou (1991) defined SES as a fluctuation of the NESP in the ground having the following properties: 1) Duration between 1/2 min and several hours; 2) the time lag for isolated events lies between 7 h and 11 days, and no longer than 22 days from the EQ date; 3) it may have a gradual and abrupt onset and/or cessation and 4) Large and small-scale properties of the earth's crust play an important role in SES. Finally, the relation between SES amplitude ($\Delta V/L$) and the EQ magnitude could be solely obtained in cases with several monitoring stations within 100 km of distance of the EQ epicenter (Varotsos and Alexopoulos, 2006).

The visual inspection of Fig. 3 shows some fluctuations of the electric self-potential along the year as well as some differences in these fluctuations that could be associated to EQ occurrences. Nevertheless the well-defined properties of SES, their detection depends of visual inspection, this is not adequate to decide which fluctuation really corresponds to a SES related to a future EQ, except perhaps for the biggest ones. Depending on the criterion adopted to select the SES, we can find a significant number of SES or none. Figure 4 shows a two days segment of the self-potential signal, that shows some fluctuations that could be identified as a SES, but we can not identify which of them are related with an EQ. Then we search for a systematic statistical alternative to characterize the electric self-potential signal.

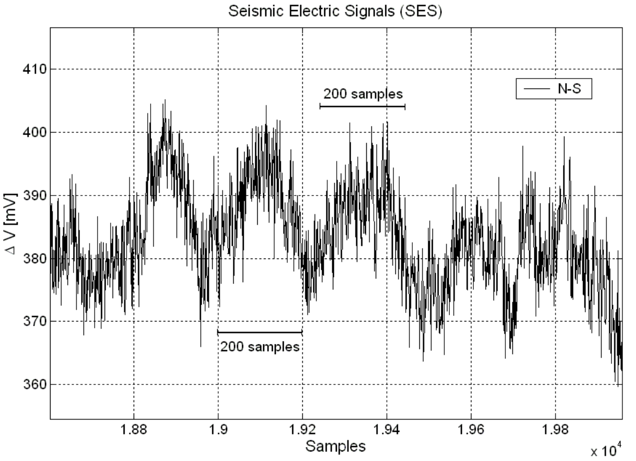

Fig. 4. An example of a trend of possible SES is depicted in a window of six hours.

The standard spectral analysis has been applied for a statistical study of signals to characterize them in the ULF range. This considers that the power spectrum behaves as a power law: $S(f) \propto \frac{1}{f^{\beta}}$. The spectral exponent β is estimated by the slope of the best-fit straight line to $\ln S(f)$ vs. $\ln(f)$ and, according to Malamud and Turcotte (2001), β characterizes the temporal fluctuations of the time series. For example, a white noise-type has $\beta=0$, for a flicker noise or $\frac{1}{f}$ noise, $\beta=1$, and for a Brownian motion $\beta=2$. Some applications of this methodology have been previously used in time series analysis with encouraging results (Ramirez-Rojas et al., 2004a, b; Telesca et al., 2001).

Two approaches were followed to estimate the spectral exponent β of our time series. Because of the size of the probable SES (Fig. 4) in the electric self-potential, three different windows were selected, corresponding to 3.3, 6.6 and 10 h, respectively. As a first approach, the β exponent was estimated from a simple plot of $\ln(S)$ vs. $\ln(f)$ of ΔV-time series. In a second approach, the NESP has been normalized by the distance between electrodes obtaining $(\Delta V/L)$, following the normalization proposed by VAN group. Then, a detrending of $\mu=0$ was applied in the selected windows. Finally, the spectral exponent β was computed over the detrended signal. In the search of more consistent methodologies for the analysis of possible SES, we also employed the calculation of the so called Higuchi's fractal dimension (Higuchi, 1988, 1990) of the NESP-time series an their wavelet transforms (Goswani and Chan, 1999; Resnikoff and Wells, 1998).

4 Results and discussion

The power spectrum $S(f)$ was calculated for the selected windows, and then the corresponding β exponent was estimated. We found that $S(f)$ shows two patterns, one corresponding to low frequencies ($0.0001<f<0.004$ Hz), and other for high frequencies $f>0.004$ Hz). Generally, very high frequencies are related to white noise behavior and $\beta\approx0$ for frequencies higher than 0.004 Hz.

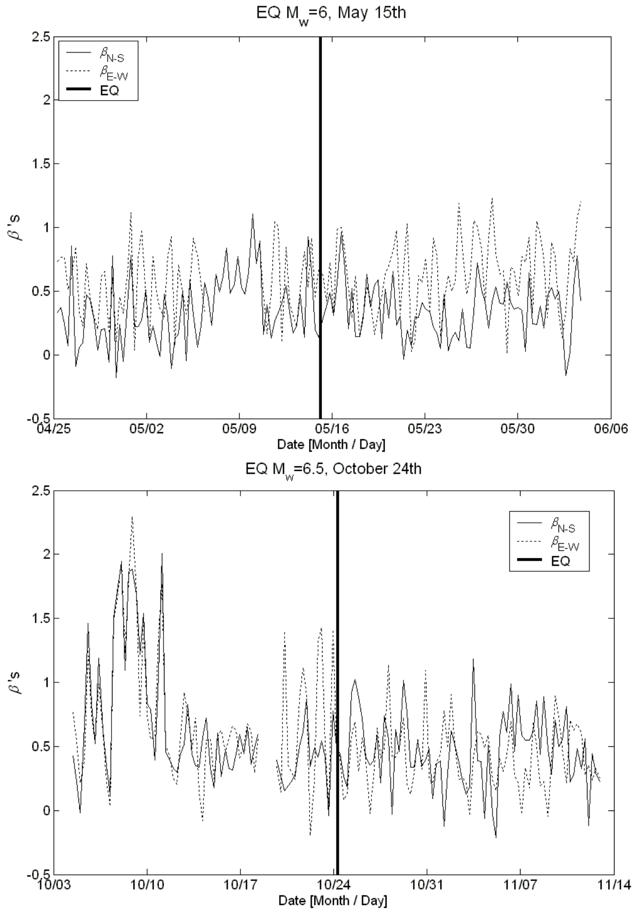

Fig. 5. β exponent evolution computed from 20 days before until 20 days after of EQs occurred: **(a)** 15 May and **(b)** 24 October EQ. The EQs are marked with vertical lines.

We can observe an evolution along the year in the value of the β exponent ($0.5\leq\beta\leq1$) that indicates a change in the behavior of the system showing correlations.

Now, we focused our attention on the periods before and after the occurrence of the selected EQs. Figure 5a shows the evolution of the β exponent 20 days after and 20 days before the EQ occurred on 15 May. Figure 5b depicts the evolution of the β exponent for the same interval for the 24 October EQ. We can observe the values of the β exponent between 0 and 1 in most of the cases, however fifteen days before the 24 October EQ we clearly observe an increase in the β exponent value, that rise up to β=2, this means a β exponent usually identified with a Brownian motion. Thus, the system has changed its behavior and has a different kind of organization.

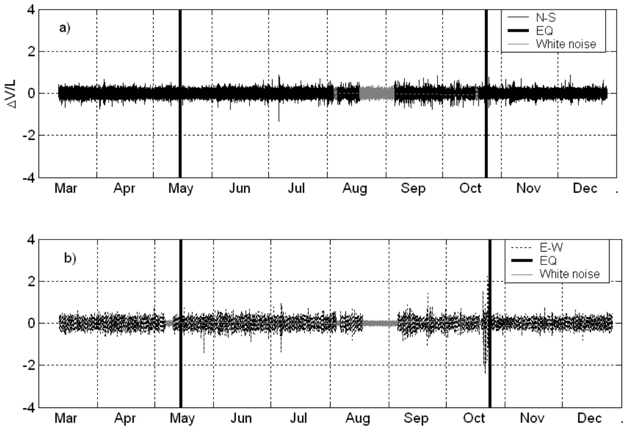

Fig. 6. The electric field ($\Delta V/L$) vs. time. Detrended signal with six hours windows with μ=0; no remarkable features are evident. Vertical lines mark the dates of the two EQs. The lack of data in the series were filled by means of white noise (gray line).

Figure 6 shows the results of the second approach to process the NESP signals after being normalized ($\Delta V/L$), and detrended (μ=0). The lacks of data were filled with white noise. It is possible to observe that no characteristic features are evident. However, it is possible to observe the variation of the computed β values along the year 1993 from March to December as depicted in Fig. 7a (for a 3.3 h window), especially for the 24 October EQ, that rise up to 2, just fifteen days before the EQ occurrence. This event could mean an organization of the system prior to the EQ or during the EQ preparation, coincident with the trend of SES depicted in Fig. 4.

We performed the same process for windows of 6.6 and 10 h, in order to determine if the size of the window influences the computed values of β. The results are shown in Figs. 7b and c, where we see that the increase up to β=2 is also present fifteen days before the EQ occurrence for the two cases.

However, a complementary analysis is necessary to confirm the possible presence of the SES anomaly observed in the β exponent behavior. We also calculated the fractal dimension of the pre-processed NESP-time series by means of the Higuchi's algorithm (1988, 1990). This method consisted in the calculation of the fractal dimension of the time series. This is done in terms of the straight-line slope that fits the length of the curve and the time interval (the k lag) in a double log plot. The length of the curve is calculated for several k time lags. If the average length $<L(k)>$ depends on k as a power law, $<L(k)>\propto k^{-D}$, then D is its fractal dimension. Figures 8a (NS series) and 8b (EW series) depict the time evolution of D for the time series displayed in Fig. 6. At a first glance, there is not an evident SES where the β anomaly is located. However, if we calculate the cross-correlation between both series, we find that all the D-points are weakly

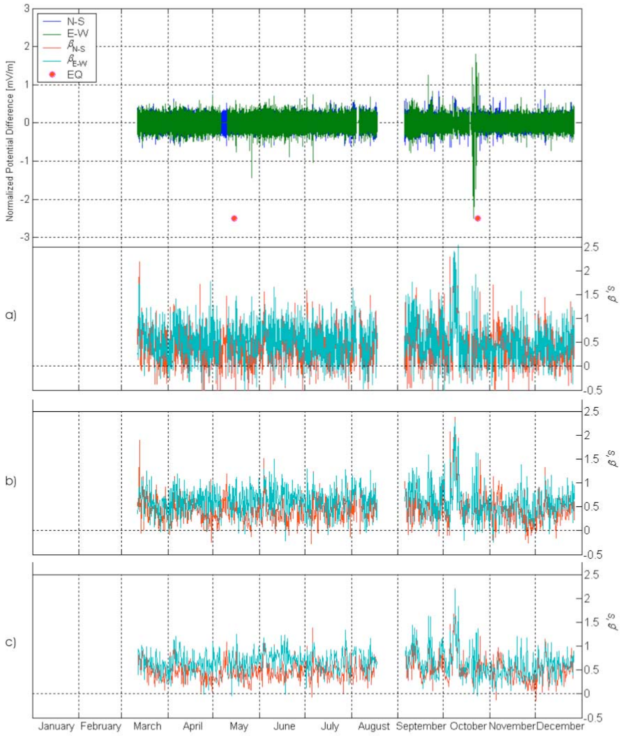

Fig. 7. β exponent computed from March to December of 1993, after the treatment of the second approach. **(a)** window of 3.3 h, **(b)** window of 6.6 h and **(c)** window of 10 h. β values rise up to 2, fifteen days before the occurrence of the 24 October EQ in all cases.

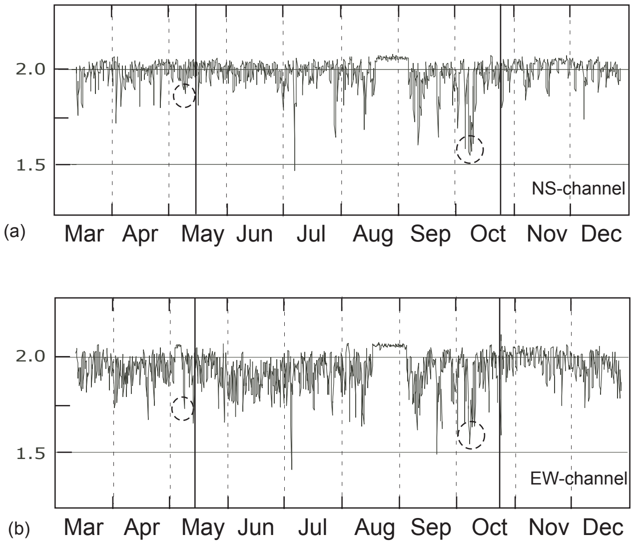

Fig. 8. Computation of fractal dimension by Higuchi's method. Evolution of D exponent computed from March to December of 1993, after the second approach of series (data lacks filled by white noise, Fig. 6). **(a)** Higuchi exponent D for the NS series, **(b)** Higuchi exponent D for the EW series. The occurrences of 15 May and 24 October EQs are also showed (vertical lines).

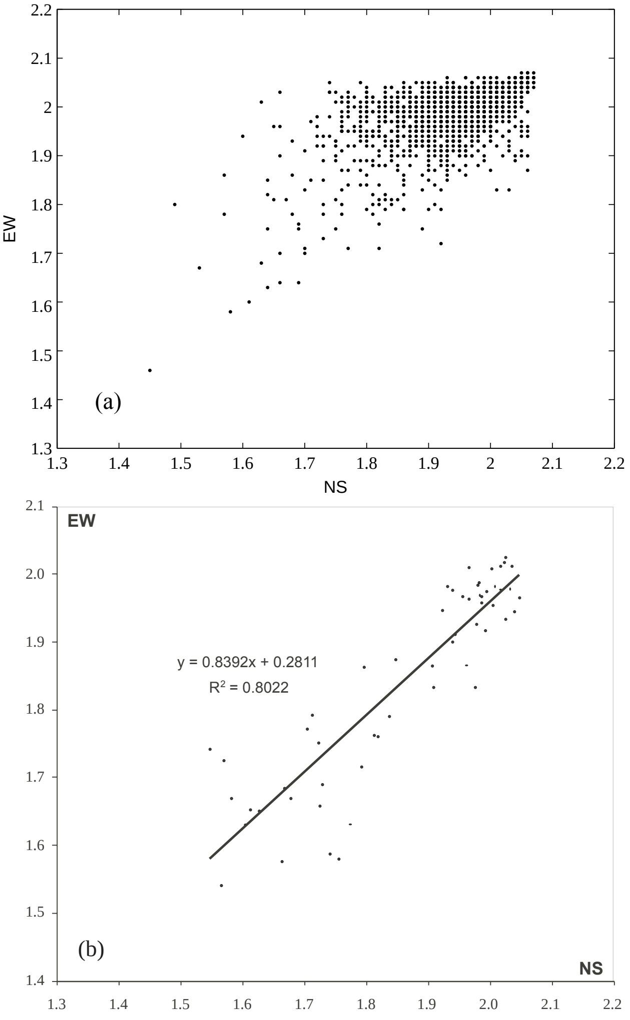

Fig. 9. (a) The scatter plot between NS vs. EW Higuchi exponent along the year. **(b)** The scatter plot between the same signals but just for data corresponding to the β anomaly.

correlated (see Fig. 9a). Nevertheless, if we calculate the cross-correlation only for the points pertaining to the subset of the β anomaly, we find a cross-correlation with R^2=0.80 (see Fig. 9b), which is, a reasonable high correlation between both signals. This suggests that during the SES time interval, an electromagnetic perturbation coming from a far source simultaneously affects both signals. We have employed an additional approach for the SES analysis as follows: first, we obtain the wavelet transform of the pre-processed NESP-time series by using a Haar window at second level (Goswani and Chan, 1999; Resnikoff and Wells, 1998). Second, we applied again the Higuchi's algorithm over the wavelet transformed series to calculate the fractal dimension D. The result of this procedure was completely similar to the previous one. It means that only the points corresponding to the SES have a significant cross-correlation for both NS and EW signals (see Fig. 9). When we applied Higuchi's method and wavelets transform over the surrogated NESP-data, we only find uncorrelated data.

5 Concluding remarks

In general geophysical phenomena are very complex, especially those underlying EQs. During the last years, the analysis of geophysical time series has been made mainly by methods involving statistical physics and non-linear dynamics. Pre-processing techniques are convenient when the time series are very noisy with many undesirable influences present. In the present investigation we reported some statistical studies of self-potential time series possibly associated to EQ's in the south-western Mexican coast (Yepez et al., 1995, Ramirez-Rojas et al., 2004a, b) with preliminary data processing. We have analyzed some electric time series previously cleaned by means of a moving average algorithm and a detrending procedure, and no unambiguously SES signals were observed. However, the analysis of the spectral exponent β shows changes along the total period examined, and the most evident occurred during the preparation mechanism some days before of the occurrence of the 24 October EQ.

For the studied EQs during the year 1993 the results can be summarized as follows: It was not possible to distinguish a clear change in the behavior of the β exponent for the EQs corresponding to magnitudes Mw<6 (see Table 1) and epicenters situated more than 100 km away from the monitoring station. In Fig. 7 some peaks with $\beta \geq 1$ are depicted that could be associated with EQs with magnitudes between 4.5 and 5.5. The 24 October EQ had a magnitude of Mw=6.6 and its epicenter was located 92 km away from the monitoring station. Before this EQ, we observed a trend of possible SES (Fig. 4), as well as an organization of the self-potential electric field, showing a correlation. The β exponent is on average 0.5, which is correlated with stationary data with weak persistence during the total monitoring time (Malamud and Turcotte, 2001). Fifteen days before the EQ, a behavior like a Brownian motion is displayed ($\beta \approx 2$), having a duration around two days. In search of a more complete study of the possible β-anomaly fifteen days before the Mw=6.6 EQ, we also analyzed the whole 1993 data by means of both the Higuchi's fractal dimension and the wavelet transform. In both cases we found that for the points corresponding to the possible β-anomaly in both series the cross-correlation (Koening, 1991) reached significant values ($R^2 \approx 0.8$), while for the rest of the time series the data remained weakly correlated. This can suggest that during the SES time interval a distant electromagnetic perturbation arrived to both NS and EW lines. In summary, the present work shows some time series features possibly linked to EQ preparation processes, but with not enough clearness to assure that these features are seismic precursors.

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