EXPERIMENTAL CHANGES OF THE HURST EXPONENT BEHAVIOR OF THE GEOELECTRICAL POTENTIAL AND ITS POSSIBLE RELATION TO THE CHANGES OF SPECTRAL POWER-LAW EXPONENT OF THE SEISMIC ACTIVITY IN WESTERN GREECE

Apostolos Ifantis[a,b,], Christos Theoharatos[a,c], Vassilis Tsagaris[a,c] and Gerasimos-Akis Tselentis[b]*

[a]Department of Electrical Engineering, Control System and Signal Laboratory, Technological Institute of Patras, Patras, Greece
[b]Department of Geology, Seismological Laboratory, University of Patras, Patras 26500, Greece.
[c]Department of Physics, Electronics Laboratory, University of Patras, Patras 26500, Greece.
[*] Corresponding author. E-mail addresses: ifantisa@teipat.gr, ifantis@geology.upatras.gr (A. Ifantis).

ABSTRACT

This paper presents observations of the long-term Geoelectric Potential Difference. The data have been collected during a five-year (1993-1997) experimental investigation. For data acquisition an automatic system for collection, transfer and processing of Geoelectric measurements operates at the Earthquake prediction section of the University of Patras Seismological Laboratory (UPSL). The emphasis in this work is given towards investigation of experimental changes of the Hurst exponent behavior of the geoelectrical potential difference and its possible relation with the changes of the spectral power-law exponent of the seismic activity in Western Greece. The comparison of both parameters leads to a possible correlation between geoelectrical time fluctuations and earthquakes in the seismic area. A theoretical explanation of the above results is also given.

1. INTRODUCTION

Investigations of the changes of geoelectriomagnetics signals for the purpose of earthquake prediction are carried out in United States, Russia, Japan, China, Italian, Bulgaria, and other countries. Among the different presented methods, the study of anomalies in the behavior of the geoelectromagnetic field has attracted most of the attention and over the last two decades geoelectrical measurements over a broad frequency range have been carried out. Detected signals vary in duration pattern, having specific features and spectral characteristics. There is strong evidence that anomalous changes of the geoelectromagnetic field take place prior to strong earthquakes and great effort has been made to correlate this activity with the impending earthquakes. Geoelectromagnetic precursors to earthquakes have been reported by a number of researchers, raising hopes that prediction of damaging earthquakes might be possible [1-7].

Among the most extensive and promising reports of precursor electromagnetic signals are the observations of the Long-Term Geoelectric Potential (LTGP). An earthquake is not an instantaneous phenomenon; it is accompanied with pre-seismic geotectonic variations, therefore a possible correlation of the behavior of the LTGP and an oncoming earthquake is of great importance. Recently, Hayakawa [8], Uyeda [9] and Telesca [10,11] proposed a fractal analysis of Ultra Low Frequency geoelectric data showing that strong earthquakes were preceded by a decrease of the spectral power-law exponent approaching unity.

The data presented in this paper have been collected during a five-year (1993-1997) independent experimental investigation at the Earthquake Prediction Section of the University of Patras Seismological Laboratory (UPSL). During the period 1993-1997 several destructive earthquakes occurred in Western Greece, a territory with the highest seismic activity in Europe. In this work, correlation between Hurst coefficient strongly connected with the geoelectrical time series and the power-law spectral exponent of the inter event seismic intervals is presented.

The remainder of this paper is organized as follows. In Section 2 the acquisition system along with the data are described. Section 3 provides the necessary theoretical background for data analysis. Results including a short discussion are presented in Section 4. Finally, conclusions are drawn.

2. LTGP ACQUISITION SYSTEM

In this system the monitoring of the geoelectric potential difference is achieved by one set of dipoles arranged in short as well as long distances. This dipole makes use of Pb-$PbCl_2$ electrodes. The set has an electrode separation of 100m and direction E-W and will be referred to as Channel 1. The dipole is located at the outskirts of the University of Patras, in Rio, in a rather quiet countryside and is based in Pleistocene compact conglomerates. The exact geographical position of the station can be found in fig. 1. The signal produced by this dipole is initially directed to an electronic VAN device. Afterwards, it is directed to an A/D converter, which is set to digitize at a rate of 3 samples/min. The converter is connected to an ordinary PC where monitoring and processing of the signals is taking place. This channel is also connected to a pen-recorder and a graph paper illustrates continuously the changes in the area. The obtained electro-telluric signal is transmitted via a dedicated line to the control room. The channel signal is therefore anti-alias filtered with a 30Hz Butterworth low-pass filter sampled at 100Hz and converted to digital form with a 32-bit resolution.

2.1 Observed Signals

Reported electromagnetic precursor signals appear to have a wide range of time duration, amplitude level and spectral characteristics. The parameters, which are measured continuously with the above data acquisition system, are the long time variations of the geoelectric potential. The digitization rate for observing long time variations in our station is set at 1sample/hr. That is, approximately 43600 data (points) have been obtained during the period 1993-1997.

The geoelectric potential difference that has been monitored during the five-year investigation (1993-1997) is presented in fig. 2 (Channel No 1). The major earthquakes (>4.8M_S) which occurred during this period are shown at the top of each figure. Table 1 provides additional details about these.

Table 1: Major earthquakes occurred in Western Greece during the period 1993-1997.

No	Point	Magnitude	Distance (km)	Date	Depth (km)
1	1543	5.3	176	05/03/93	6.4
2	1863	4.9	44	18/03/93	1.5
3	2055	5.0	100	26/03/93	18.3
4	3960	5.4	192	13/06/93	40.0
5	4700	5.1	15	14/07/93	50.2
6	10082	5.3	147	25/02/94	49.7
7	11304	5.3	182	16/04/94	36.4
8	16744	4.9	159	29/11/94	28.2
9	16783	4.8	148	01/12/94	35.8
10	21505	5.6	42	15/06/95	50.9
11	21506	5.1	43	15/06/95	3.7
12	24030	4.8	29	28/09/95	30.4
13	30064	4.9	130	06/06/96	35.8
14	42453	4.9	55	05/11/97	28.3
15	42616	4.8	200	12/11/97	56.6
16	42757	6.1	206	18/11/97	36.9
17	42758	5.6	183	18/11/97	48.3
18	42759	5.0	209	18/11/97	32.4

3. BACKGROUND

The temporal fluctuation of a time series can be studied by means of power spectral density. In this work the spectral analysis of geoelectrical signals, using the well-known Periodogram method, is employed. Let us denote by x_n the geoelectrical signal measured at time t_n and by $\bar{x}$ its mean value. The periodogram of this signal is defined as:

$$P(\omega)=\frac{1}{2\sigma^2}\left\{\frac{\left[\sum_n (x_n-\bar{x})\sin\omega(t_n-\tau)\right]^2}{\sum_n \sin^2\omega(t_n-\tau)^2}+\frac{\left[\sum_n (x_n-\bar{x})\cos\omega(t_n-\tau)\right]^2}{\sum_n \cos^2\omega(t_n-\tau)^2}\right\}$$

where τ is given by

$$\tan(2\omega\tau)=\frac{\sum_n \sin 2\omega t_n}{\sum_n \cos 2\omega t_n}$$

and $\omega=2\pi f$ with f the frequency. For a time series with scaling behavior the power spectrum behaves as a power-law function of the frequency f, $P(f)\propto 1/f^a$, where a characterizes the temporal fluctuations of the time series (for white noise time series, $a=0$). In this work the temporal fluctuations of the earthquakes, occurred in the area of Western Greece from 1993 to 1997, are studied analyzing the sequence of the inter-event intervals using the Spectral Power Law exponent.

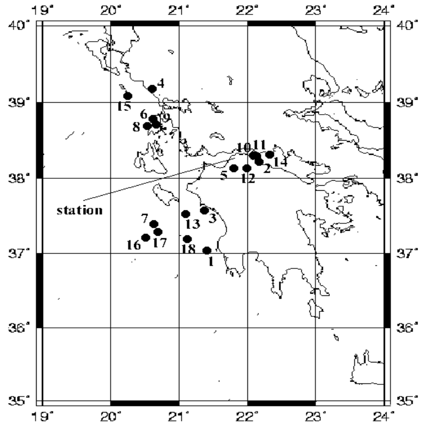

Figure 1: Epicenters of the major earthquakes in Western Greece during the period 1993-1997.

On the other hand, the geoelectrical potential is studied by means of the Hurst exponent, H [12,13]. The basic idea in order to estimate H from the recorded data consisting of $SP(t_i)$ values sampled at uniform intervals of Δt, is to determine how the range of the cumulative fluctuations depends on the length of the subset of the data analyzed.

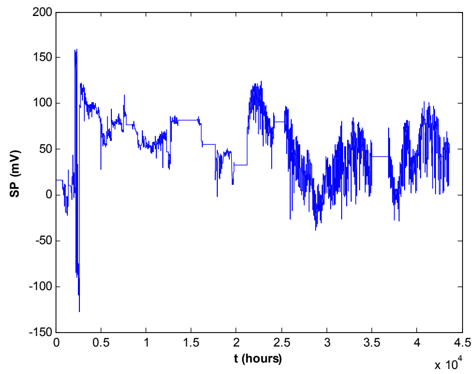

Figure 2: Geoelectric signal of Channel 1.

Consider the whole data set covering a total duration $\tau_{\max}=N_{\max}\Delta t$. Its mean value over the whole data, $\bar{SP}(\tau_{\max})$, for $\tau=\tau_{\max}$ and $N=N_{\max}$ is given by:

$$\bar{SP}(\tau_{max}) = \frac{1}{N}\sum_{i=1}^{N} SP(t_i) \quad (1)$$

The accumulated departure at each time point $D(N,k)$ from the beginning of the period up to any time $k\Delta t$, is calculated by summing the differences in (1) from the mean:

$$D(N,k) = \sum_{i=1}^{k}\left(SP(t_i) - \bar{SP}(\tau_{max})\right) \text{ for } 1 \le k \le N, \quad (2)$$

where $D(N,k)$ is equated to $D(\tau,u)$, and $u = k\Delta t$, and $\tau = N\Delta t$.

The range $R(\tau)$ is estimated as the difference between the maximum D_{max} and the minimum D_{min} accumulated departure in (2), for $1 \le k \le N$:

$$R(\tau) = D_{max} - D_{min} \quad (3)$$

The standard deviation $S(\tau)$ of the samples $SP(t_i)$ over the period τ during which the local mean is $SP(\tau)$ is given by:

$$S(\tau) = \sqrt{\frac{\sum_{i=1}^{N}\left(SP(t_i) - \bar{SP}(\tau_{max})\right)}{N}}, \quad (4)$$

and the "rescaled range" is the range of the deviations calculated in (3), rescaled or renormalized by the standard deviation in (4):

$$R/S = R(\tau)/S(\tau) \quad (5)$$

At this first stage, N equals the total number of all the values in the time series and provides a point at τ_{max}. For the next stage, N will cover a fraction of the entire data sample set. The procedure described above will be repeatedly continued and R/S will be calculated for each segment of the data set. The processing will continue using successively shorter τ's at each stage, dividing the data set into overlapping segments and finding the average value R/S at each segment. The functional relationship over intervals of lengths τ compared to a reference length τ_0 is:

$$R(\tau)/S(\tau) = R(\tau_0)/S(\tau_0)\cdot(\tau/\tau_0)^H, \quad (6)$$

with H the Hurst coefficient. The equation for the best fitting straight line is determined by using the linear Y on X regression with $Y = \log(R/S)$ and $X = \log(\tau/\tau_0)$, where the exponent H is the slope of the regression line. For a purely random sequence with no correlations among intervals, $H = 0.5$. A value of $H \ne 0.5$ indicates autocorrelation in the signal, $H > 0.5$ means positive correlation, while $H < 0.5$ means negative correlation or anti-persistence [14]. For $H > 0.5$ the data sequence is characterized by persistence [10] because increases are more likely to be followed by increases at all distances and vice versa for $H < 0.5$.

4. RESULTS AND DISCUSSION

During the recording period (January 1993 to December 1997), 3032 earthquakes with magnitude Ms ≥ 3.0R were recorded among which 18 where significant seismic events with magnitude Ms ≥ 4.8R. At the processing stage, spectral analysis has been carried out using the non-linear fractal method revealing a scaling behavior for the recorded signals of the Long-Term Geoelectric Potential (LTGP). Results were obtained using a fixed time window shifting through the entire 5-year time period and not for intervals at time periods just before and after the events. The spectral analysis revealed a scaling behavior for the recorded geoelectrical signal, with $a \approx 1.05$ for the 18 significant earthquakes and $a2 \approx 1.1$ for the whole seismic activity. In fig. 3, the results of this analysis are presented after the investigation of the time variations of H and $a1$ calculated for the 18 significant earthquakes. The outcome of H and $a2$ after the same analysis can be found in fig. 4 when the entire seismic activity is employed.

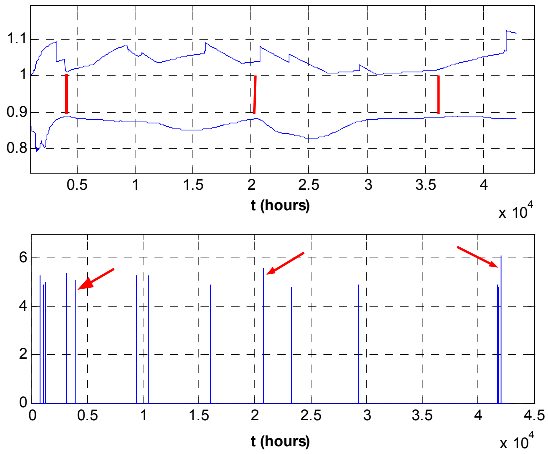

Figure 3: Correlation of H-coefficient and α-parameter for the 18 most significant earthquakes.

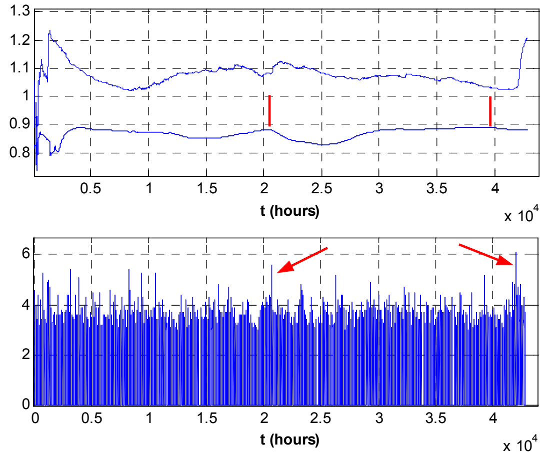

Figure 4: Correlation of H-coefficient and α-parameter for the entire seismic activity signal.

The standard deviations of parameters H and a are in both cases very small, ($H \approx 0.02$ and $a \approx 0.05$). The values of $a1$ and $a2$ vary approximately from 1.01 to 1.13 and from 1.02 to 1.21, with mean values 1.04 and 1.07 respectively. The values of H range from 0.5 (at the very beginning) to 0.89, with average 0.86. It is obvious that a and H tend to decrease and increase respectively during the progress of the preparation of the major earthquakes. Specifically, this behaviour is apparent just before the occurrence of the major earthquake, which respectively occurred nearby the geoelectric dynamic monitoring station (No.5 of the Table 1 which caused damages in the city of Patras). The same behavior appears at the time interval about 3 weeks before the earthquakes No 10-11which destroyed the city of Aigio causing 40 deaths, as it is shown in fig. 3 and fig.4. Finally, a and H approach unity about 6 weeks before the major but far away from the station event in the area (No.16-17 Strofades island). It is noteworthy that similar behavior was observed at the time interval four weeks before the big magnitude earthquake (No.6), the epicentral point of which was far from the station. All these cases of earthquakes are in the same geotectonic area and that explains the greater sensitivity of the channel for every earthquake disturbance. The aforementioned sensitivity is due to the similar behavior of the dipole to an antenna sensor. These results are in agreement with the behavior of the Long-Term Geoelectric Potential spectral exponent observed in Hayakawa [8] and Telesca [10,11].

5. CONCLUSIONS

In this work we investigated the possible relation between the behavior changes of a and H. The experimental results indicate the existence of good correlation between a and H. The increase of H exponent as well as its converge toward unity indicates the respective persistence of the seismic process to the earthquake event. In addition, the decrease of a-coefficient toward unity is consistent with the appearance of small- scale fractal structures in the focal zone. This is possibly due to the evolution of the earth's crust toward the self-organization at the critical point and involves the formation of fractal structures in the fault zone. This procedure results in the observed geoelectrical signal. The presented results indicate that the degree of correlation between seismic sequences and geoelectrical fluctuations can provide evidence for upcoming earthquake events. However, the prediction error seems to increase for the cases of earthquakes with small magnitude or epicenter far from the station monitoring of the geoelectric signal. This means that the earthquake generation process affects the LTGP dynamics in a manner dependant upon many parameters (e.g. geological composition, location of epicenter).

Future work remains to understand better the relations between the behavior changes of a and H. The consideration of many LTGP channels at the training algorithm could provide more information and can improve both the accuracy and the reliability of this method. The measures of the changes of a and H gives promising results that can be used together with other pre-seismic signals to solve the difficult problem of short time earthquake prediction**.**

6. ACKNOWLEDGEMENTS

This work was supported by the National Ministry of Education, under the project entitled "Soft computing techniques for multichannel processing", in the context of the program "Archimidis". The authors wish to thank *Mr. Dimitris Petropoulos* for his contribution to this work.

REFERENCES

[1] P. Varotsos and K. Alexopoulos, "Physical properties of the variations of the electric field of the earth preceding earthquakes I & II", *Tectonophysics*, vol. 110, pp. 73-125, 1984.

[2] K. Meyer and R. Pirjola, "Anomalous electrotelluric residuals prior to a large imminent earthquake in Greece", *Tectonophysics*, vol. 125, pp. 371-378, 1986.

[3] T. Kawase, S. Uyeda, M. Uyeshima and M. Kinoshita, "Possible correlation between geoelectric potential change in Izu-Oshima Island and earthquake swarm off the East Izu Peninsula Japan", *Tectonophysics*, vol. 224, pp. 83-93, 1993.

[4] G-A. Tselentis and A. Ifantis, "Geoelectric variations related to earthquakes observed during a 3-year independent investigation", *Geophysical Research Letters*, vol. 23, pp. 1445-1448, 1996.

[5] D. Karakelian, S. Klemperer, A. Fraser-Smith and G Beroza, "A Transportable System for Monitoring Ultra low Frequency Electromagnetic Signals Associated with Earthquakes", *Seismological Research Letters*, vol. 71, pp. 423-436, 2000.

[6] A. Ifantis, G. Economou and G. A. Tselentis, "Experimental Investigation of Electrotelluric Field Periodic Anomalies in Western Greece and their Possible Relation to Seismicity during a Five – Year Period", *Acta Geophysica Polonica*, vol. 51 (3), pp. 291-305, 2003.

[7] G. Economou, A. Ifantis and D. Sindoukas, "Multichannel distance filtering of seismic electric signals", *Proc. EUSIPCO 1996,* Trieste, Italy, Sept. 1996, pp. 10-13.

[8] M. Hayakawa, T. Ito and N. Smirnova, "Fractal analysis of ULF geomagnetic data associated with the Guam earthquake on August 8", *Geophysical Research Letters*, vol. 26, pp. 2797-2800, 1999.

[9] S. Uyeda, T. Nagao, Y. Orihara, T. Yamaguchi and I. Takabashi, "Geoelectric potential changes: possible precursors to earthquakes", *Proc. US Nat. Acad. Sci. 97*, pp. 4561-4566, 2000.

[10] L. Telesca, V. Cuomo, V. Lapenna and M. Macchiato, "Identifying space-time clustering properties of the 1983-1997 Irpinia-Basilicata (Southern Italy) seismicity", *Tectonophysics*, vol. 330, pp. 93-102, 2000.

[11] L. Telesca, V. Cuomo, V. Lapenna, "A new approach to investigate the correlation between geoelectrical time fluctuations and earthquakes in a seismic area of southern Italy", *Geophysical Research Letters*, vol. 28(23), pp. 4375-4378, 2001.

[12] H. E. Hurst, R. P. Black and Y. M. Simaiki, "Long-term Storage: An Experimental Study", London: Constable, 1965.

[13] B. Mandelbrot, "Fractals: Form, Chance and Dimension", San Francisco: W.H. Fridman and Co., 1977.

[14] J. B. Bassingthwaighte, L. S. Liebovitch and B. J. West, "Fractal Physiology", *Oxford University Press*, 1994.