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EXPERIMENTAL INVESTIGATION OF ELECTROTELLURIC FIELD PERIODIC ANOMALIES IN WESTERN GREECE AND THEIR POSSIBLE RELATION TO SEISMICITY DURING A FIVE-YEAR PERIOD

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Abstract

Results from a five-year experimental investigation of electrotelluric field variations in Western Greece are presented in this paper. The data have been collected by the earthquake prediction section of the University of Patras Seismological Laboratory (UPSL). During the evaluation period, 18 earthquakes with magnitude $M_s > 4.8$ took place within 200 km of the monitoring station. The emphasis in this work was given towards the investigation of low frequency periodicities superimposed on the telluric data and a probable correlation between seismicity and 24-h periodic oscillations of the Earth's electric field.

Key words: earthquake prediction, geoelectric potential, precursor signals.

1. INTRODUCTION

Many researchers have studied the correlation between the variation of certain physical parameters and the occurrence of strong earthquakes. The study of anomalous behaviour of the electrotelluric field (ETF) *prior* to significant seismic events has attracted most of the scientific attention in recent years, although precursor signals characteristics vary considerably and their association to the impending seismic event is not an easy task.

Electrical precursors are considered to be related to stress or strain variations in the focal area generated during the earthquake preparation process. There are different theories accounting for the generating mechanism. It is also believed that during transmission through the crust, these signals are further modulated by periodic and non-periodic mechanisms within the Earth. Detection is hindered by many disturbing parameters like natural and man-made noise, transmission medium anisotropy and attenuation. The ionosphere is also contributing to noise due to the electromagnetic coupling between the ionosphere and the underlying geological formations.

Precursor signals vary in duration, pattern and have special features and spectral characteristics, so in each case proper noise rejection and processing techniques have to be employed. Additionally, almost all geophysical fields are subject to considerable temporal variations in a wide range of periods. Thus, the association of a specific time behaviour to earthquakes is not an easy task. Emphasis in the present work is given into validating previous observations that the electrotelluric field presents low frequency variations before strong earthquakes.

There are two major families of signals reported: (i) Electrical signals that extend up to several days, weeks, or even months before the event (Kawase *et al.*, 1993; Moroz, 1995; Fedotov *et al.*, 1997; Tselentis and Ifantis, 1993; Sobolev, 1975; Myachkin *et al.*, 1972; Ifantis *et al.*, 1993; Meyer and Pirjola, 1986; Karakelian *et al.*, 2000; Telesca, 2001); these are usually referred as "very low frequency signals" (VLF) and (ii) signals of relatively short duration, several minutes up to a few hours (Varotsos and Alexopoulos, 1984; Hadjicontis and Mavromatou, 1994; Economou *et al.*, 1996) known as "seismic electrical signals" (SES).

It is interesting to give a brief reference of some previous similar investigations. The appearance of 24-h periodic anomalies superimposed on a large variation of geoelectric potential difference starting a couple of days before the earthquake was reported in the Kamchatka Peninsula for a ten-month period (Meyer, 1984; Meyer and Ponomarev, 1987; Meyer and Teisseyre, 1988). Thanassoulas and Tselentis (1986), observed 24-hour periodic oscillations prior to large earthquakes in Greece. Their work included three tectonically active regions in Greece and their investigation extended a few days prior to the event. In a similar research,Tselentis and Ifantis (1996), and Ifantis *et al.* (1997) present characteristic ETF periodic anomalies during a 3-year independent investigation.

In order to further investigate the phenomenon, we conducted a similar ETF-seismic monitoring experiment in the vicinity of Patras (Western Greece), where the surrounding area is known for its high seismic activity and an 18-station seismological network is continuously operated by UPSL. During this time, significant seismic events took place both in the close vicinity and further away of the measuring site.

The novel feature of this work is the long and continuous observation period: five years. This is helpful in establishing a better and more reliable picture of the behaviour of ETF variations as related to seismicity in the area. In contrary, most of previous research works were usually related to a single event and the time window was restricted to a certain period prior and after the earthquake.

As mentioned previously, the time scale of reported electrical precursors is very wide, with frequencies ranging from DC to VHF. In order to reveal all possible signal anomalies, a detailed examination of the ETF time series records requires a multiresolution analysis. The present study was mainly initiated to investigate any possible relation of 24-h anomalies of the ETF field prior to significant earthquakes.

2. MONITORING STATION AND OBSERVED SIGNALS

The electrotelluric field measurement took place on the outskirts of the University of Patras (Western Greece), in Rio at a distance of approximately 1 km from the seashore. The geological background is a Pleistocene compact conglomerate. Four sets of non-polarized lead electrodes buried to a depth of not less than 1.5 m are used to sense the geoelectric potential difference which is measured relative to a common ground for all electrodes (Fig. 1).

Two sets of the electrodes have a separation distance of 100 m and are laid out in geographic directions N-S (Ch1) and E-W (Ch2), perpendicular one to each other. The third set (Ch3) has an electrode separation of 300 m and is directed towards the NE-SW. The fourth one has an electrode separation of 3000 m in the direction NW-SE (Ch4).

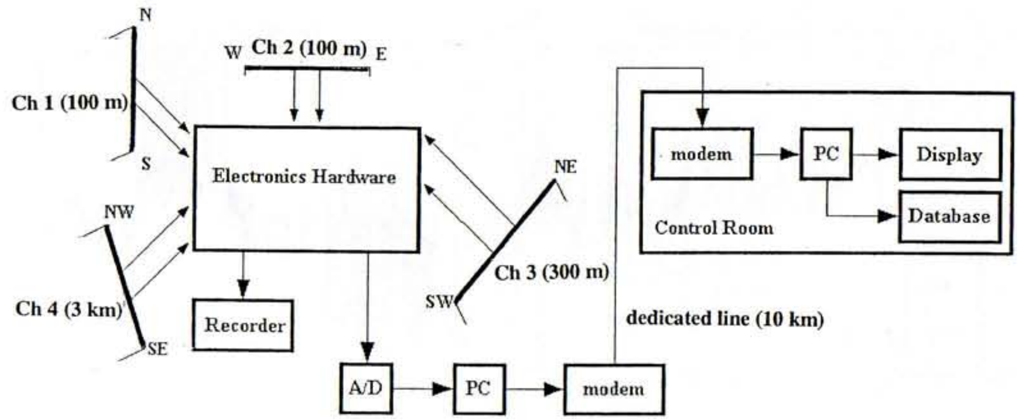

Fig. 1. Monitoring station diagram with the system of the recording lines.

Collected signals are in the mV range and are used as input to an analog signal-conditioning unit. The filtered signals are directed to an A/D converter and digitized with an 8-bit accuracy at a rate of 3 sample/min. The signals are also connected to an analog pen-chart recorder, in order to have an easy visual inspection. Subsequently the digitized signals are stored into a PC and once a day transmitted via a dedicated line to the control room of UPSL. The arrangement of electrodes is done so as to provide signal orientation selectivity and noise discrimination capability. It should be mentioned that the station was operated continuously over the five-year period 1993-1997. Nevertheless, due to several reasons (high voltage electrical damage, electronic failure, power cuts, etc.) there were some time periods during which the station was not functioning. These time intervals correspond to continuous flat lines in the displayed signals and account for about 12% of the total time of measurement.

Collected data over the five-year observation period 1993-1997, are displayed in Fig. 2. There are a total of 43 600 samples per channel, each sample corresponding to

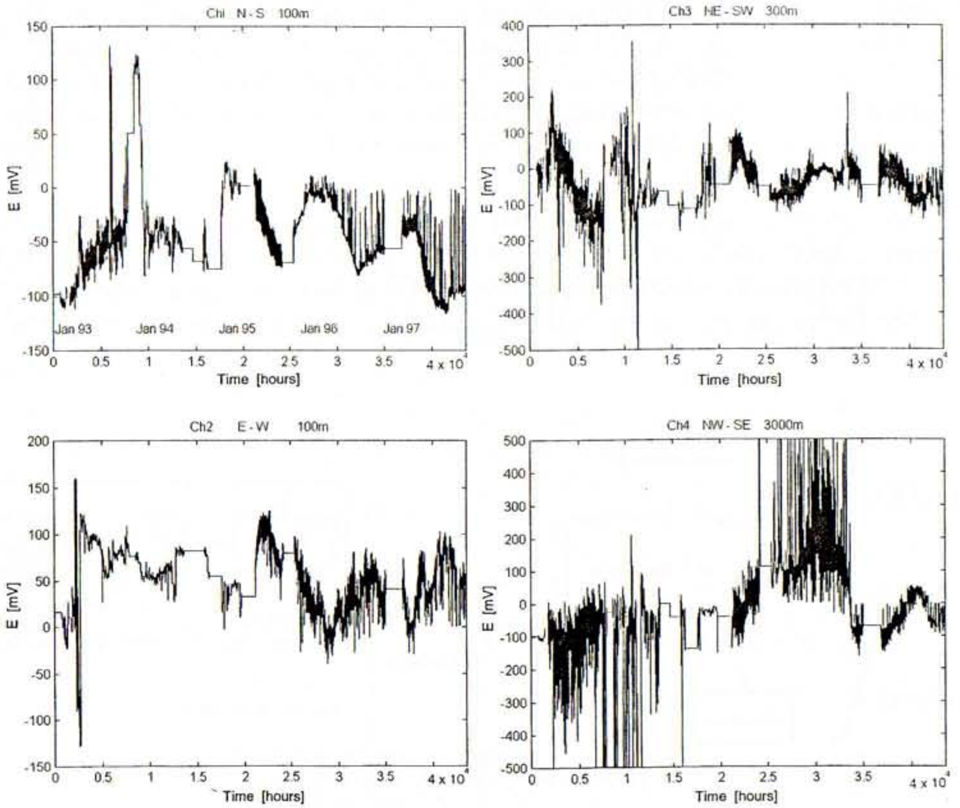

Fig. 2. Electrotelluric field variation over the five-year period 1993-1997 for the four channels.

the hourly average of 180 measurements. The range of amplitude variations for the four channels is in the mV area and is approximately of the same order as that of similar experiments. All earthquakes with magnitude $M_s > 4.8$ which occurred within an epicentral distance of 200 km in the duration of the experiment are shown in Fig. 3. Table 1 depicts all the earthquake parameters, while Fig. 4 displays the earthquake epicenters. The most important events were the 26 March 1993, $M_s = 5.0\,R$ earthquake (No. 3), which devastated the city of Pyrgos, the 14 July 1993, $M_s = 5.1\,R$ earthquake (No. 5), which damaged many buildings in the city of Patras and the 15 June 1995, $M_s = 5.6$ and $M_s = 5.1$ earthquakes (Nos. 10 and 11), which caused casualties to the city of Egio, all of which were at a distance of less than 80 km from the ETF recording site.

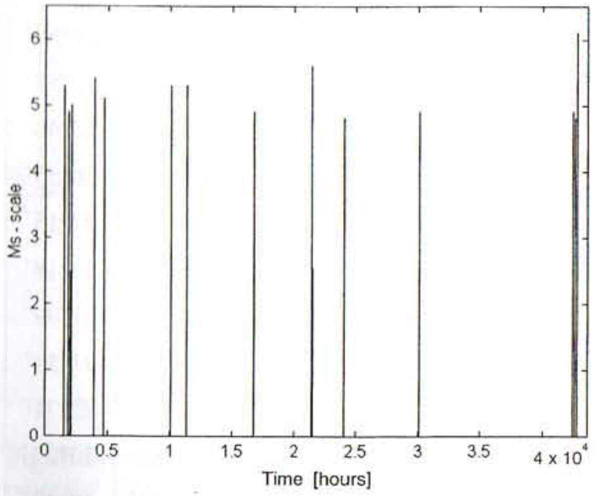

Fig. 3. Magnitudes of the significant earthquakes ($M_S > 4.8$) over the five -year period.

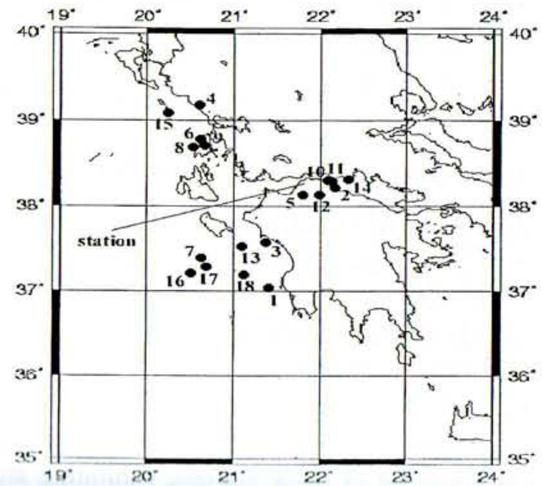

Fig. 4. Area map and the significant seismic events that took place during the observation period (see Table 1).

Table 1

Major earthquakes that occurred in Western Greece during the period 1993-1997

Event no.	Time [hours]	Magni-tude	Distance [km]	Date	Origine time [h:m]	Depth [km]	Coordinates	
							φ	λ
1	1543	5.3	176	05 Mar 93	06:55	6.4	37°07′	21°46′
2	1863	4.9	44	18 Mar 93	15:47	1.5	38°26′	22°20′
3	2055	5.0	100	26 Mar 93	11:58	18.3	37°65′	21°44′
4	3960	5.4	192	13 Jun 93	23:26	40.0	39°25′	20°57′
5	4700	5.1	15	14 Jul 93	12:31	50.2	38°16′	21°76′
6	10082	5.3	147	25 Feb 94	02:30	49.7	38°73′	20°58′
7	11304	5.3	182	16 Apr 94	23:09	36.4	37°43′	20°58′
8	16744	4.9	159	29 Nov 94	14:30	28.2	38°66′	20°46′
9	16783	4.8	148	01 Dec 94	07:17	35.8	38°69′	20°55′
10	21505	5.6	42	15 Jun 95	00:15	50.9	38°36′	22°15′
11	21506	5.1	43	15 Jun 95	00:31	3.7	38°33′	22°18′
12	24030	4.8	29	28 Sep 95	06:17	30.4	38°15′	21°99′
13	30064	4.9	130	06 Jun 96	16:25	35.8	37°55′	21°11′
14	42453	4.9	55	05 Nov 97	21:10	28.3	38°34′	22°31′
15	42616	4.8	200	12 Nov 97	16:26	56.6	39°10′	20°27′
16	42757	6.1	206	18 Nov 97	13:07	36.9	37°26′	20°49′
17	42758	5.6	183	18 Nov 97	13:13	48.3	37°36′	20°65′
18	42759	5.0	209	18 Nov 97	15:23	32.4	37°25′	21°16′

3. DATA PROCESSING AND ANALYSIS

The recorded signals reveal similar characteristics to those described by other researchers (e.g., Moroz *et al.*, 1999), such as high frequency noise and slow annual variations.

Low pass filtering removes noise so the relative phase variations between channels can be clearly seen in Fig. 5. In order to remove high frequencies, data were filtered using a Butterworth digital filter.

Next we concentrate on the study of the high frequency part of the signal. A typical spectrum of these signals, exhibiting strong periodicities, is illustrated in Fig. 6,

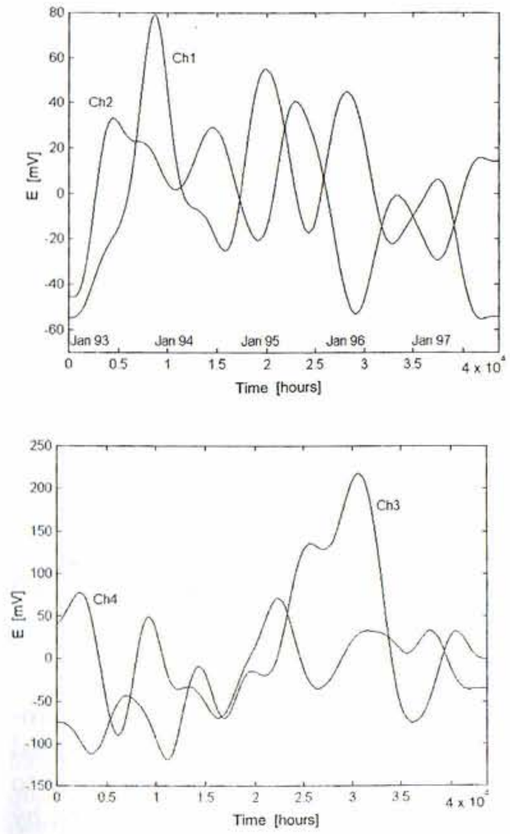

Fig. 5. Long term behaviour of the geoelectric potential after low pass filtering: Ch1 and Ch2 (upper panel), Ch3 and Ch4 (lower panel).

part of what looks like high frequency noise is due to hidden periodicities, among which the dominant one is the 24-h periodicity. Its origin is attributed to the modulation of Earth's geophysical fields by its daily rotation. The time window of the Fourier transform was selected so as to coincide with a signal section exhibiting high variance. The strong 24-hour period oscillation is evident as well as other harmonics. According to Thanassoulas and Tselentis (1993), the amplitude of this oscillation is changing due to stress built up at the earthquake preparation zone and is expected to reach its peak at the time of the earthquake. In this work we will try to investigate any possible relation of precursor amplitude A with earthquake magnitude M.

In order to estimate the 24-hour oscillations amplitude and time of occurrence, the power spectrum of the signals is examined. Limitations of the Fourier transform when applied to nonstationary signals are well known. To deal with the problem of varying frequency content with time, the **S**hort **T**ime **F**ourier **T**ransform STFT (t,f) is used. It employs a sliding time window $g(t)$ which emphasizes "local" frequency properties. Although the actual signal is far from stationary, when divided into small enough segments some degree of stationarity can be assumed over this time period. Thus, a sliding ten-day window is applied over each sample and the power spectrum is estimated locally. The operation is repeated for the next signal sample. The peak amplitude related to the 24-hour period oscillation is searched in each frame and the maximum of the signal energy, contained within a narrow band around this frequency is registered. Thus, the amplitude variation of the 24-hour period oscillation of the ETF over the whole signal is obtained as output result.

Using Matlab's implementation, the power spectrum estimation is based on the Welch's averaged periodogram method. The signal is divided into overlapping sec-

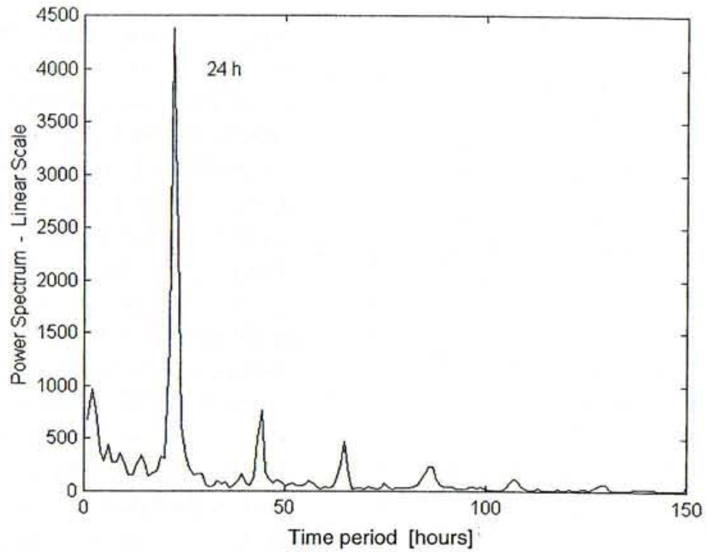

Fig. 6. Power spectrum of signal Ch1, sample points [21450:24000], showing a strong, 24-h periodic component.

tions, each being linearly detrended, weighted by a Hamming window and zero-padded. The squared magnitudes of the sections DFTs are averaged to form the final power spectral density. As mentioned before, telluric signals are extremely prone to noise thus in order to exclude an increase of the 24-h component that is produced by an overall increase in the signal variance (that is spread equally over all frequencies), the 24-h component is normalized by the total variance. As an example, the variation in amplitude level of the 24-hour periodic component in the power spectrum of Ch1, over the five-year period, is illustrated in Fig. 7. The corresponding moving window size used is 512 h (21.3 days).

Although the signal-processing task described in the previous part was rather straightforward, it is not the same for the seismic signals. The usual time chart indicating earthquake's time of occurrence and magnitude has to be modified so as to display better the influence and relation that each of the seismic events is expected to have on the electrotelluric precursors. In doing so, the possible correlation of the two signals will be more easily substantiated. In order to account for the influence of the occurring earthquakes on the measured ETF signal, we have to accept certain more or less well established hypothesis about the relation of ETF precursors and seismic events. These findings are integrated in order to create a continuous model signal, indicative of the overall seismic activity. A direct cross-correlation of the seismicity related signal with the processed precursor will determine the possible relation of the two.

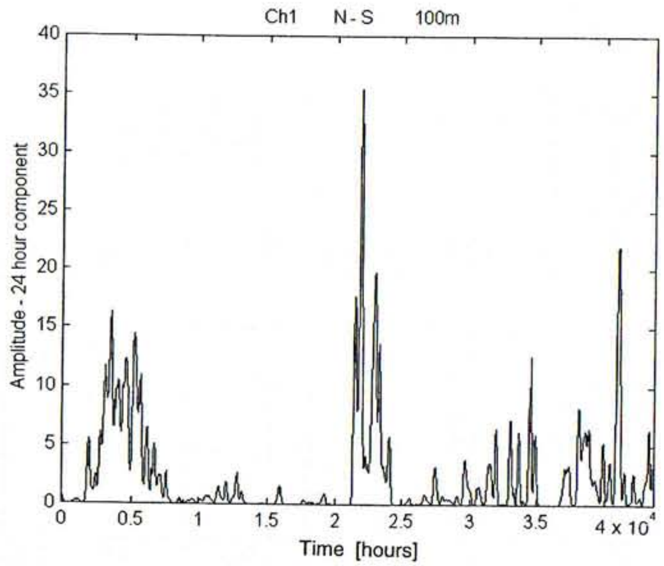

Fig. 7. Variation with time (5-year period) for the amplitude of the 24-h component.

Assuming that the origin of electromagnetic signals is due to mechanical disturbances in the Earth's crust and that they obey the scaling laws that are a direct consequence of their generation, it sounds reasonable to correlate the precursor signal to the earthquakes total energy. Thus, the main seismological parameters of interest in relation to the precursor signal strength are: the earthquake's magnitude and time of occurrence, the epicenter distance, and the electrical parameters of the geological medium between the focal region and the measuring site (Papanikolaou, 1993).

Another basic assumption made here is that the earthquake is not considered as an abrupt event as far as its influence to the precursor signal is concerned. A certain build up time is allowed for the earthquake preparation process, during which the precursor signal is also expected to be present. In order to model its influence to the precursor signal, an exponentially increasing and decreasing time behavior before and after the event, respectively, with different time constants is assumed. It is reported in the literature that the onset of the oscillations can take place up to a month prior to the earthquake. So, we construct our crude model using an exponential increase with a time constant of 30 days and we allow 10% of it, that is 3 days, for the decay time. This time pattern is considered independent of magnitude. The total area under the curve for each event is normalized to represent the emitted seismic energy. Effectively we are distributing the seismic energy over a certain time period before and after the event. Regarding signal transmission characteristics, a unidirectional homogeneous medium is assumed and precursor signal attenuation with distance from the epicenter

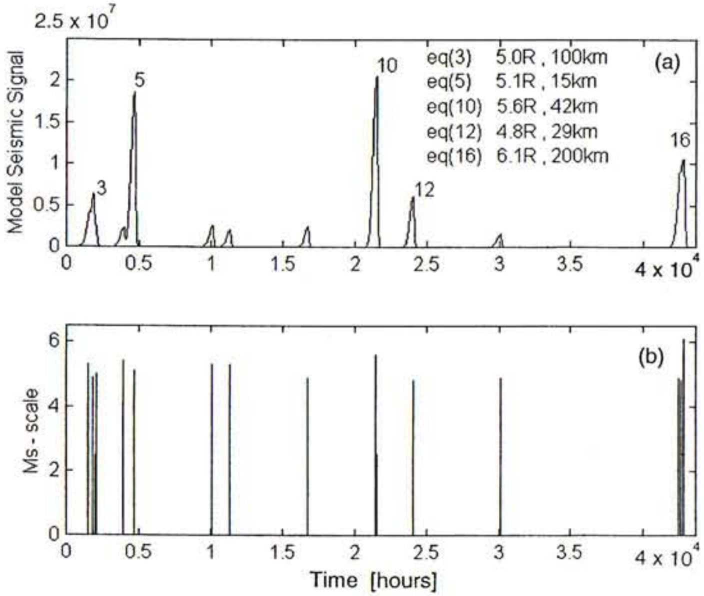

Fig. 8: (a) Expected seismic influence to precursor signals, and (b) earthquakes.

is considered analogous to $1/r$. Thus, the distance to the station also scales the total area of each event.

Taking into account the above assumptions and accepting the principle of superposition (all recorded seismic events are considered independent), the resulting model seismic signal is illustrated in Fig. 8a. The vertical lines in the diagram below (Fig. 8b) once again represent the seismic events in M_S scale. Significant and close to the ETF recording site earthquakes are considered only.

In the first of the above graphs, the "modified seismicity diagram", it is easier to identify significant earthquakes (as far as the measurement site is concerned), which are expected to influence the measurements. Also, it gives an estimate of the time over which precursor signals are expected to correlate with earthquakes.

In order to process all of the signals, a 256-hour window, approximately 10 days long, was selected. Results were similar and in the case of using a window with double size (512 h), the only difference was, as expected, signal smoothing and reduced variability. The smaller window was chosen because it permitted identification of sharper peaks in the oscillations. This also determines the method's time resolution. The variations with time of the 24-hour oscillations for the two sets of channels Ch1-Ch2 and Ch3-Ch4, are illustrated in Figs. 9 and 10, respectively. The model seismic signal is also included in both figures to assist inspection.

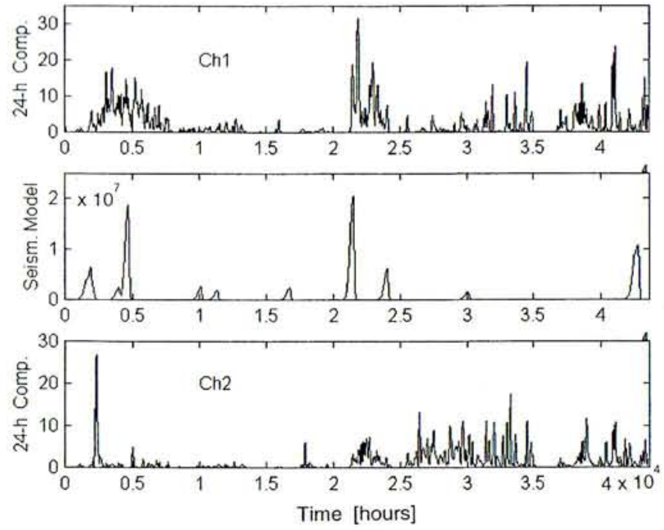

Fig. 9. Variation of the 24-h oscillation amplitude for the channels Ch1 and Ch2. To facilitate inspection, the middle panel presents the modified diagram of seismic events.

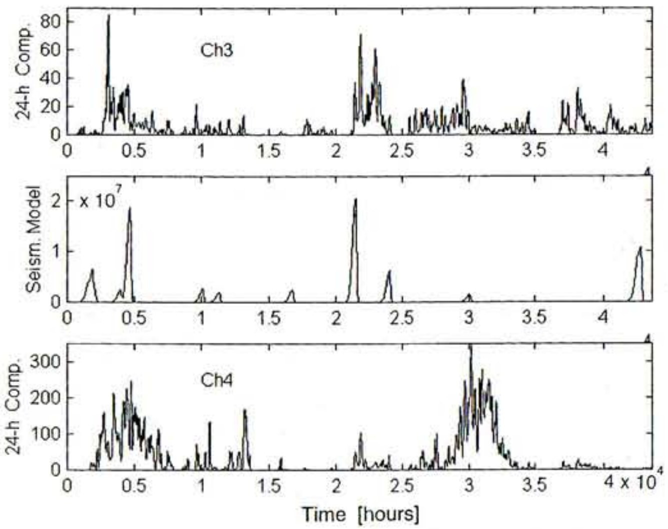

Fig. 10. Variation of the 24-h oscillation amplitude for the channels Ch3 and Ch4. The modified diagram of seismic events is again given in middle panel.

Further to a visual evaluation, a direct multiplication of the model seismic signal and 24-hour periodic oscillations shows the strength of the correlation for each event. Results and the modified seismic signal are shown in Fig. 11.

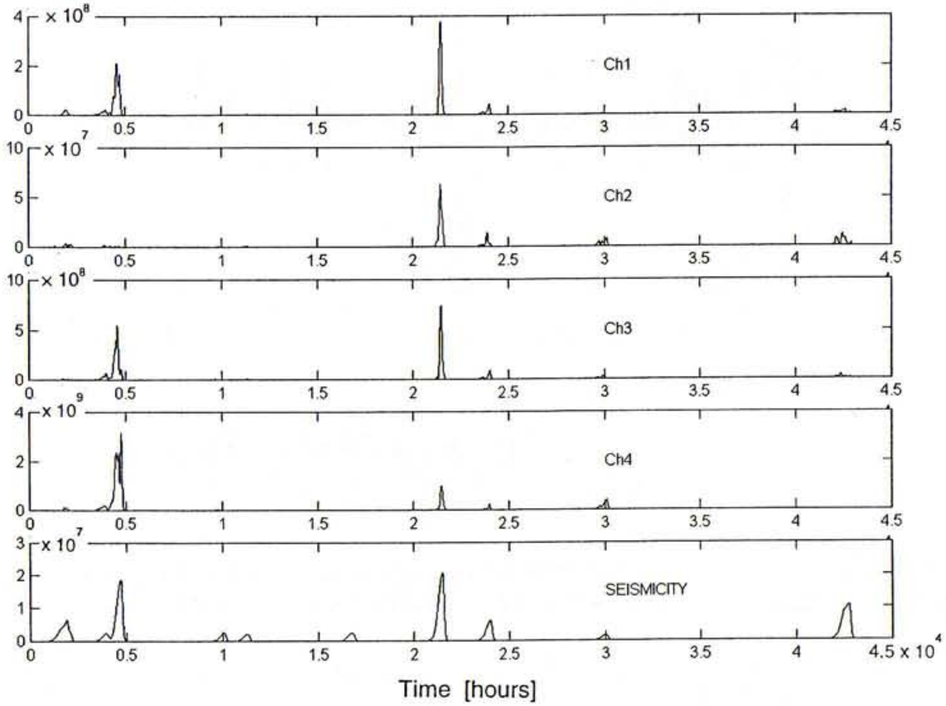

Fig. 11. Correlation between seismic activity and electrotelluric field's 24-hour periodicity.

4. DISCUSSION OF THE RESULTS – CONCLUSIONS

The spectral analysis of all recordings revealed that the 24-hour oscillation is the dominant periodic disturbance, and is present to all channels. During the five-year recording period, 18 significant seismic events with magnitude $M_s \geq 4.8\ R$ and an epicenter distance < 200 km from the monitoring station took place.

We start our discussion from the last result of Fig. 10, which is rather striking. It is observed that whenever there was a significant event, at close distance, there was a correlation with the periodic oscillations of the electrotelluric field. Oscillation with 24-hour periodicity did exist on other occasions as well, but there was no significant earthquake without oscillations. Additionally, since our experiment spanned over a great length of time, the element of randomness and the bias caused by few events was minimized. The assumptions and the model used for the seismic signal are rather straightforward and somehow widely accepted. Thus, it is our belief that this correlation is well substantiated.

Ch1 (N-S) shows a strong 24-h period oscillation of geoelectric field that appeared at the same time interval when three major earthquakes occurred in the close

vicinity of the geoelectric dynamic monitoring station. These were: earthquake No. 2, West Corinthian Gulf; No. 3, which devastated the city of Pyrgos; and No. 5, which damaged many buildings in the city of Patras. We observed the same behaviour, with very strong 24-h period oscillations, when earthquakes Nos. 10-11 occurred. These caused severe damages to the city of Egio and the death of 40 people. Ch1 also sustained quite strong oscillations at the time interval when the very strong but distant from the station earthquakes Nos. 16-17 (Strofades island) occurred. It is interesting to observe that this channel had an oscillatory behaviour with medium magnitude earthquakes, Nos. 13-14-15, the epicentral points of which are quite far from the station. In all these cases, the epicenters of the earthquakes are not in the N-S geographic direction of the Ch1 dipole and probably that explains the greater sensitivity of this channel. Thus, it is probable that a directional sensitivity of the dipole is also indicated.

The behaviour of Ch2 (dipole E-W) is similar. It has strong disturbances of oscillations for the earthquakes Nos. 3, 5, 10, 11, 12, 13, 14, 16, 17. Channel 3, with geographic direction NE-SW and electrode spacing of 300 m, has strong disturbances at earthquakes Nos. 3, 5, 10, 11, 12, 13, 14, 16, 17. Finally, Ch4 with geographic direction NS-SE and distance between the poles of 3000 m, shows strong oscillations at earthquakes Nos. 3, 5, 10, 11, 12, 13, but the oscillations disappear at the strong events Nos. 16, 17.

Summarizing, it is obvious that Ch1 demonstrates a strong correlation for earthquakes Nos. 3, 5, 10, 11 (strong and damaging) and a weak correlation for earthquakes Nos. 16, 17 (very strong but at a long distance). Ch2 has a good correlation for the strong and damaging earthquakes (Nos. 10, 11) and a weak correlation for the very strong but far away earthquakes (Nos. 16, 17) and for the earthquakes the epicentral points of which are relatively near the station (Nos. 3, 5). The reason probably is the E-W direction of Ch1 dipole.

Chapter 3 has a very good correlation only for the strong and damaging earthquakes (Nos. 5, 10, 11) and has no correlation for the very strong but far away earthquakes (Nos. 16, 17) and for earthquake No. 3, which is relatively near the station. The NE-SW direction of Ch2 dipole is a possible reason.

Finally, Ch4 has a good correlation for the strong and damaging earthquakes (Nos. 5, 10, 11) and has not got any correlation for earthquakes Nos. 16, 17 (very strong but far away), and for earthquake No. 3, which is relatively near the station (probably due to the NW-SE direction of Ch4 dipole).

From these results we can conclude that for strong earthquakes, at short epicentral distance (Nos. 5, 10 and 11), a strong 24-h period oscillation appears at all channels. This realization does depend neither on the geographical direction of the dipoles nor on the distance between the poles. In all other cases, the appearance of a strong 24-h period oscillation depends on (a) the magnitude of earthquake, (b) the distance and the geological medium between the earthquakes epicentral points and the geoelectric potential measurement station and (c) the geographical direction of the measuring dipoles.

The systematic investigation of the Earth's electric field over the five-year period indicates a correlation between the 24-h period oscillation in the monitoring field and seismic activity, which starts to develop a few days or weeks prior to earthquake occurrence.

The accuracy and reliability of the results can be improved by geolectric characterization of the area and measurements at multiple locations. Using a single station, it cannot be verified whether the observed variations of geoelectric field are local in nature, caused by physical/chemical processes in the direct vicinity of the observation site. In terms of processing, a better approach would be to use a fuzzy expert system where the input parameters will be given according to their degree of certainty. Finally, since the observed signals are hidden into noise, more advanced signal detection techniques are required as well as a better study of the influence of man made electrical noise.

Concluding we believe that there is substantial evidence that there is some relation of the local seismic activity with the disturbance of the electrotelluric field potential.

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