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THE MUTUAL INFORMATION AS A TOOL FOR THE RECOGNITION OF A PRESEISMIC ELECTROMAGNETIC ANOMALY

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ABSTRACT

Recent observations suggest that electromagnetic anomalies could be used as precursors to earthquakes. The recognition of such signal is up to now mainly empirical. In the present work we use the concept of mutual information as a working index for the recognition of an abnormal electromagnetic signal. To demonstrate the results we use the horizontal components of electromagnetic field in 3 and 10 kHz recorded from the "Crete electromagnetic network".

ΠΕΡΙΛΗΨΗ

Πρόσφατες παρατηρήσεις συνηγορούν υπέρ της άποψης ότι ηλεκτρομαγνητικές διαταραχές προηγούνται των σεισμών. Η αναγνώριση της παρουσίας των βασίζεται κυρίως στην εμπειρία. Στην παρούσα εργασία η έννοια της αμοιβαίας πληροφορίας χρησιμοποιείται σαν ένας κατάλληλος δείκτης για την αναγνώριση ανώμαλης ηλεκτρομαγνητικής συμπεριφοράς. Με τη βοήθεια του παραπάνω δείκτη αναλύονται δεδομένα από τις οριζόντιες συνιστώσες του ηλεκτρομαγνητικού πεδίου στα 3 και 10 kHz και δείχνουν ότι η μέθοδος αυτή είναι αποτελεσματική. Τα δεδομένα αυτά έχουν καταγραφεί από το Τηλεμετρικό Δίκτυο Κρήτης.

KEY WORDS : mutual information, preseismic electromagnetic signals

1. INTRODUCTION

In Geophysical literature a number of preseismic electromagnetic anomalies have reported (Gokhberg et al., 1982; Fraser-Smith et al., 1990; Yoshino, 1991; Nomikos et al.,1995; 1997; Vallianatos and Nomikos 1997). The approach used for the recognition of a preseismic anomaly is mainly empirical (Park et al., 1993). A more objective approach using Artificial Intelligence techniques has been recently presented (Yialouris et al., 1996). In the frame of the latter approach certain statistical and probabilistic methods are applied to detect abnormal signals.

In the present paper we introduce a new statistical approach for the recognition of a preseismic electromagnetic anomaly. The technique is based on the treatment of the signal as a stochastic variable. It also uses the mutual information of a set of variables as an objective index of the presence of an abnormal behaviour. We estimate the limiting values of the aforementioned quantity during the presence or absence of an anomalous signal. These limiting values are possible working indexes for the recognition of a preseismic anomaly.

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The applicability of the aforementioned approach, is tested by the application of electromagnetic data recorded from the "Crete electromagnetic network" (Nomikos et al., 1997). This network is installed along Crete island (South Aegean, Greece). In each field station, among other electromagnetic parameters, the two horizontal components EW and NS of the electromagnetic field in 3kHz and 10kHz are measured, using tuned loop antennas. A detailed analysis of experimental setup is given in Nomikos et al. (1995).

2. THE INDEX OF MUTUAL INFORMATION

Let X be a stochastic discrete variable with values x_i. If p_i is the probability $P(X=x_i)$ we define the entropy H(X), (Papoulis, 1991), of the stochastic variable X as

$$H(X)= -\Sigma\, p_i \ln(p_i).$$

For a continuous stochastic variable X it may be shown that H(X) could be defined as:

$$H(X) = - \quad Z_i = \frac{X_i - X_m}{S} \quad = \hat{E}\{-\ln(f(x))\}$$

where f(x) is the probability density function and $\hat{E}$ is the expectation value operator (Scharf, 1984). The definition of entropy H(X) of a distribution gives a measure of the spread of the distribution or, equivalently, the uncertainty of the stochastic variables drawn from it. Assuming that the stochastic variable X follows the normal distribution $N(\mu_x,\sigma_x)$ with average μ_x and standard deviation σ_x, it is not difficult to show that

$$H(X) = \ln(\sigma_x \quad). \tag{1}$$

We proceed now to the definition of joint entropy H(X,Y) of two stochastic variables X and Y. If X and Y are discrete variables with $P(X=xi, Y=yi)=p_{ij}$, then the joint entropy is defined as

$$H(X,Y)= - \Sigma\, p_i \ln(p_{ij})$$

In a similar way for two continuous variables the joint entropy is given by

$$H(X)= - \qquad \log\left(\frac{2H}{r}\right) \quad = \hat{E}\{-\ln(f(x,y))\},$$

where f(x,y) is the joint distribution function. For a joint normal distribution function $N(\mu_x,\mu_y,\sigma_x,\sigma_y,r)$, (r is the correlation coefficient between the variables X and Y) it is shown that (see Papoulis, 1991)

$$H(X,Y)= \ln(2\pi e \quad),$$

where $D= \sigma_x\, \sigma_y\, (1-r^2)$.

In order to define the "informatic correlation" between the stochastic variables X and Y the mutual information is defined as

$$I(X,Y)=H(X)+H(Y)-H(X,Y)$$

If the variables X, Y are uncorrelated, then I(X,Y)=0. Furthermore, for two stochastic variables, with normal joint distribution function, the mutual information is given as :

$$I(X,Y)= - \sqrt{\frac{1}{\;}} \ln(1-r^2).$$

The latter expression implies that if the stochastic variables X and Y are uncorrelated then r=0 andI(X,Y)=0. Furthermore the mutual information attains high values as the correlation coefficient approaches unity.

We now proceed to generalise the above for the case of a set of N stochastic variables. Let us assume that $\underline{X}=(X_1,X_2,\ldots,X_N)$ represent an array of N stochastic variables. The probability characteristics of the N variables are described by the joint probability distribution function $f(\underline{X})=f(X_1,X_2,\ldots,X_N)$. The joint entropy is (Papoulis, 1991),

$$H(\underline{X})=H(X_1,X_2,\ldots,X_N)= \hat{E}\,[-\ln(f(\underline{X}))].$$

If the stochastic bility function

$$f(X)= \quad K_s = \pi^2 \cdot r_0 \cdot \frac{\tau_{max}}{8 \cdot \tau_{(D)}} \quad (5)$$

where $\underline{M}=(\mu_i)= \hat{E}(X)$ is an array in which the elements are the expectation value of the variable X_i and **C** is the covariance matrix with elements $c_{ij}= \hat{E}[(x_i-\mu_i)(x_j-\mu_j)]$. Then, the joint entropy of H(X) is:

$$H(X)=\ln(\qquad \tau = 1 + \qquad (2)$$

In a similar way we define the generalisation of mutual information

$$I(X) = \sum H(Xi) - H(X). \qquad (3)$$

Substituting equations(1) and (2) in (3) we obtain

$$I(X)=\sqrt{\frac{1}{}}\ln(\qquad \sqrt{3}) \qquad (4)$$

If the variables X_i are independent, i.e. uncorrelated, then the covariance matrix is diagonal so that $c_{ij}=\sigma_i^2$, if i=j and $c_{ij}=0$ if i=j, and, as a consequence, I(X)=0.

4. APPLICATION OF MUTUAL INFORMATION INDEX IN VLF ELECTROMAGNETIC DATA

In this section we present an analysis of the electromagnetic time series recorded from the Crete Network in 3 and 10kHz in the EW and NS directions, using the index of mutual information. The four stochastic variables used herein are $X_1=X_{ew3}$, $X_2=X_{ns3}$, $X_3=X_{ew10}$ and $X_4=X_{ns10}$, where the subscripts indicate the measured directions and the observed frequencies. We note that any preseismic electromagnetic anomaly appears simultaneously in the frequencies of 3 and 10 kHz (Nomikos et al., 1997; Vallianatos and Nomikos, 1997). The latter implies that in this case the four recorded stochastic variables are strongly correlated and the mutual information must yield high values.

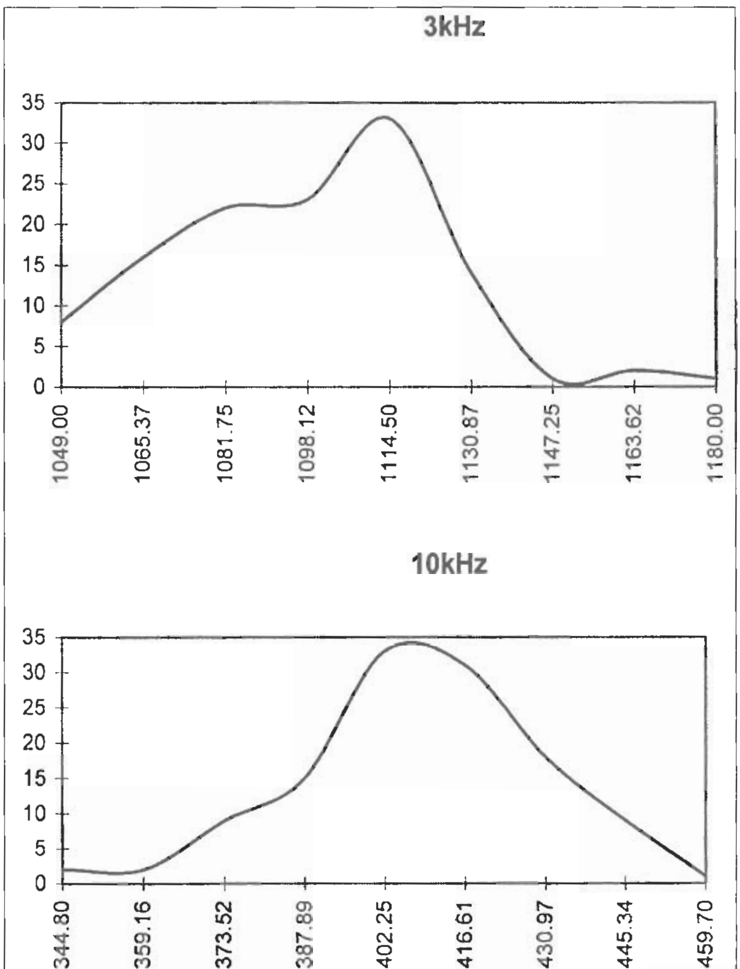


Figure 1: Probability distribution of the background values of the electromagnetic field in 3 and 10 kHz, recorded in field stations of "Crete Electromagnetic Network".

Taking into account that the values of our variables are normally distributed, (figure 1) we use equation (4) for the calculation of mutual information taking a time window of 100 samples and a window step of 10 samples. Figures 2 and 3 present two typical examples of the time dependence of mutual information. As we can see in figure 2, a high value of mutual information appears. This value is correlated with a preseismic electromagnetic anomaly recorded in all channels at the same time period (see Nomikos and Vallianatos, 1996; Nomikos et al., 1997). On the other hand figure 3 does not present any unusually high value of I(X), since the electromagnetic time series contain only background noise in the vicinity of the field station. A detailed examination, using an electromagnetic time series with almost a year duration, indicates that the presence of an abnormal electromagnetic signal leads to mutual information values grater than 6. In contrast, the values I(X) corresponding to electromagnetic background does not exceed 4. We point out that the index of mutual information is in logarithmic scale. The latter means that, in the aforementioned case, the argument of logarithm in equation 4 varies at least five orders of magnitude.

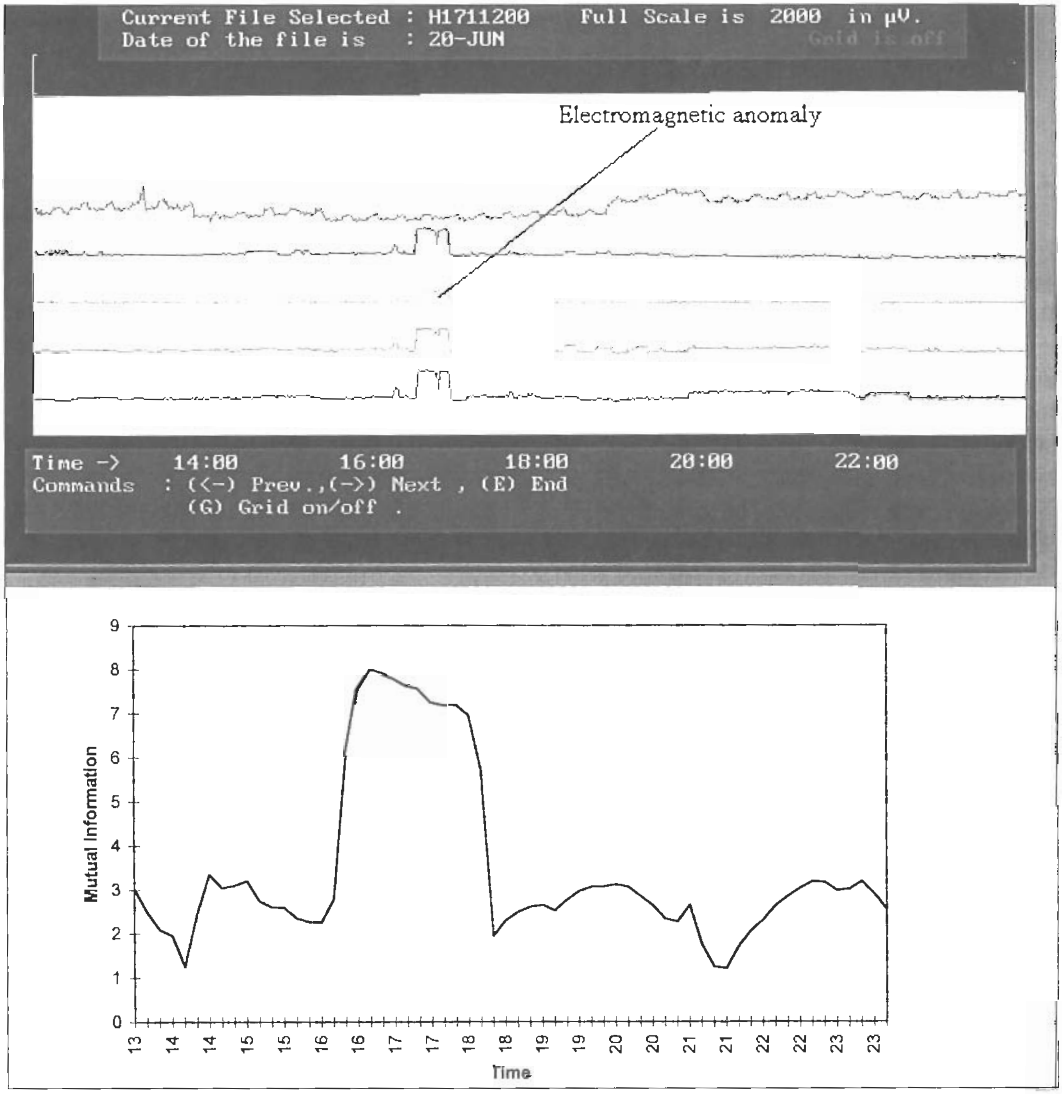
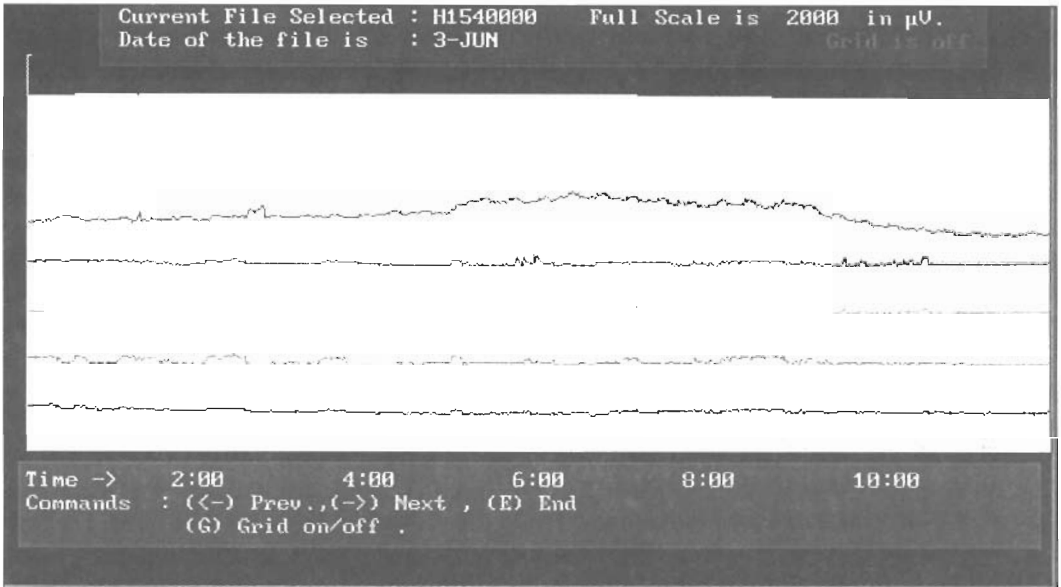


Figure 2: Time dependence of mutual information in the presence of a preseismic electromagnetic anomaly. The calculation is based on four stochastic variables (i.e on electromagnetic variation at 3 and 10 KHz in EW and NS direction)



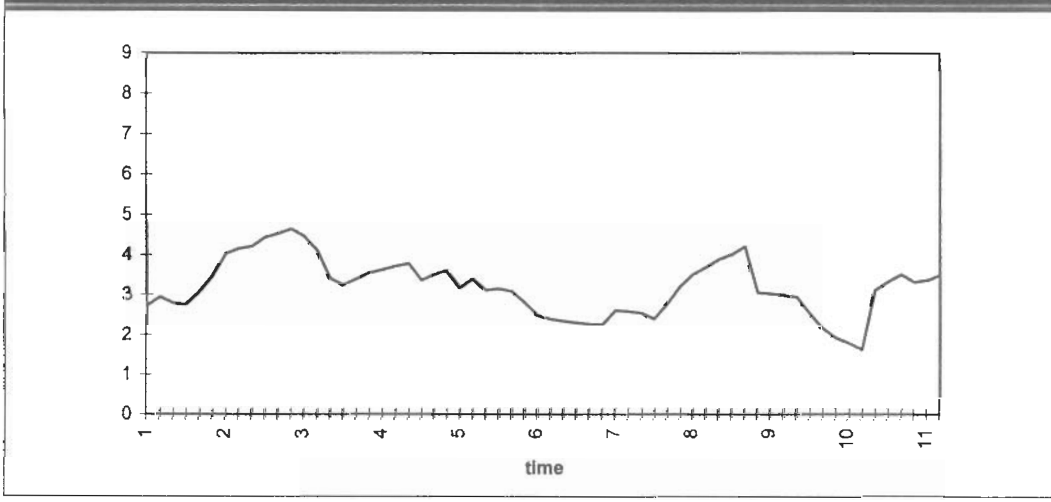


Figure 3: Time dependence of mutual information taking into account only the presence of the natural electromagnetic background. The calculation is based on four stochastic variables (i.e on electromagnetic variation at 3 and 10 KHz in EW and NS direction)

The presented results, from the physical point of view, are straightforward, since the presence of a preseismic signal in all the measured time series increases their correlation. Hence the values of mutual information increases significantly. In the presence of only the electromagnetic background, the recorded time series are highly independent and the mutual information attains lower values.

5. CONCLUDING REMARKS

We have attempted to define an objective criterion for the recognition of a preseismic electromagnetic anomaly. We have suggested that a working index is the mutual information. The presence of an abnormal electromagnetic signal simultaneously in all the recorded time series leads to high values of the mutual information. The latter index could be used in the future as a part of an expert system appropriate for an objective recognition of a preseismic anomaly.

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STUDY OF SPATIAL DISTRIBUTION OF CODA Q WITH RESPECT TO THE SEISMICITY IN CENTRAL GREECE

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ABSTRACT

The spatial distribution of coda attenuation parameter Q_c was studied in the eastern part of central Greece. Attenuation parameters were estimated by applying the single isotropic scattering model to the time decay of coda waves. Analysis was performed as a function of lapse time and frequency. In order to investigate the regional distribution of Q_c values we separate the objective area into many grid points, homogeneously distributed. Then at each grid point we calculate the average of the observed Q_c values from each station-event pair. The smoothed spatial distribution of Q_c at low frequency range shows a remarkable correlation with seismically active areas, the main low Q_c spots appear on or very close to specific strong seismic sources. At the higher frequency band (8-12Hz), spatial Q_c distribution seem to be uncorrelated with seismicity. Such distribution may be controlled by the deeper structure of the examined area.

KEY WORDS: Coda Q, Greece, seismicity

1. INTRODUCTION

Recently there has been a growing interest in the study of seismic wave attenuation in the earth. The observations show both large and small scale regional differences of the attenuation properties. The desirability of using all available data to study those properties, makes models of coda excitation an important tool. Coda attenuation Q_c is a parameter which can be easily estimated by applying one of several coda scattering models. Estimation of the Q_c factor and its time and frequency dependence indicates how heterogeneous the areas under study are.

A widely accepted hypothesis on the nature of coda waves of local earthquakes was developed by Aki (1969), and Aki and Chouet (1975), and was later extended by Sato (1977). Thus coda is considered to be waves scattered by randomly distributed heterogeneities in the lithosphere and Q_c is a parameter which phenomenologically characterizes the coda amplitude decay gradient. Q_c is then assumed to be expressed in terms of scattering Q_{sc} and intrinsic Q_i in the form $Q_c^{-1} = Q_{sc}^{-1} + Q_i^{-1}$ (Dainty, 1981). In the single scattering model, however, we cannot separate Q_{sc} from Q_i. Separation of intrinsic from scattering attenuation was attempted by Fehler et al., (1992).

The mean value estimated from coda decay reflects an average Q_c within a certain volume which includes source and receiver.

It is well known local seismotectonic features can have a significant effect on the amplitude decay and the shape of locally recorded earthquakes. Many investigators have measured Q_c in a number of areas and correlated the results with the nature of geotectonic features (Aki and Chouet, 1975; Singh and Herrmann, 1983; Jin and Aki, 1988; Sato, 1984; Matsumoto and Hasegawa, 1989).

In the present study we estimated spatial distribution of Q_c values in the lithosphere in central Greece. Then we examined these results in terms of the shallow seismic activity within the extent of a local seismic

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