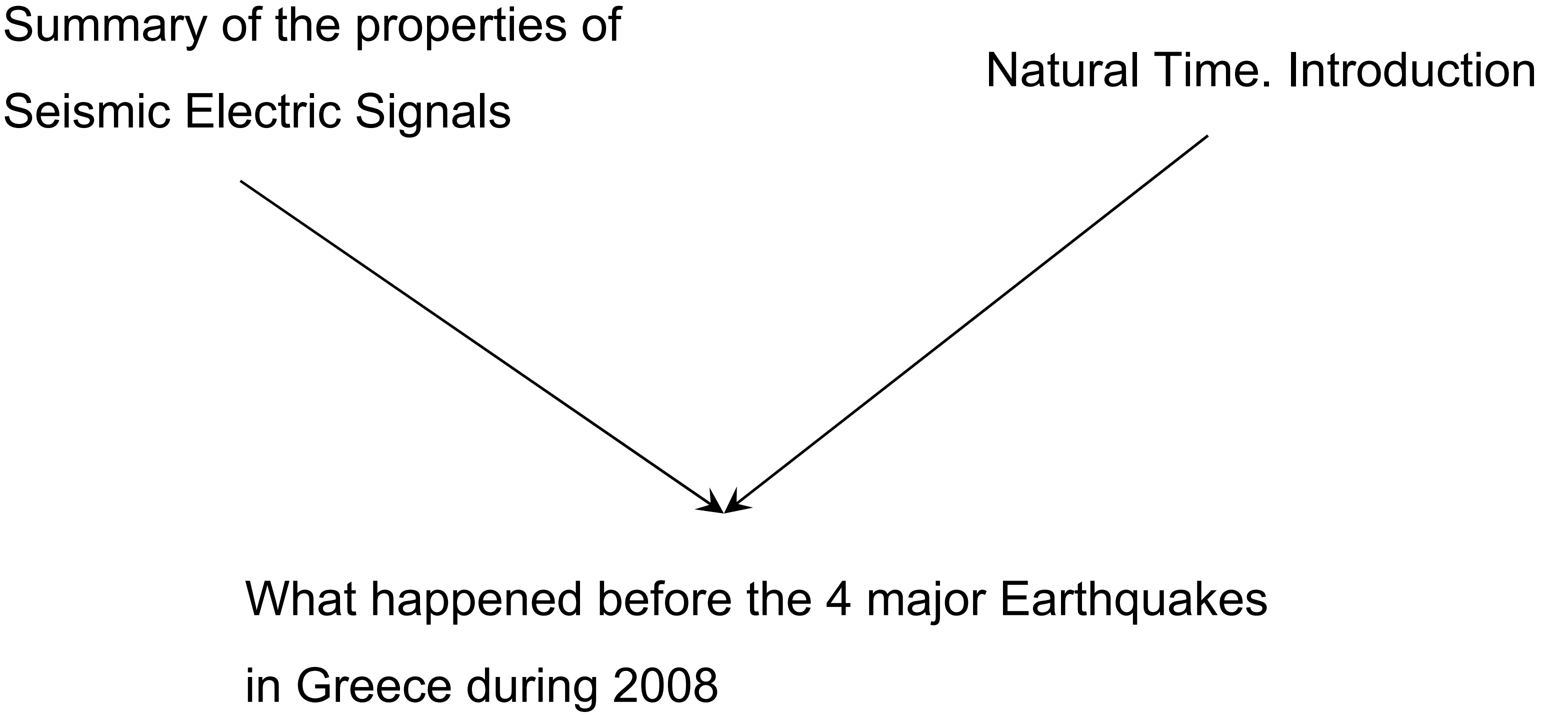
NATURAL TIME AND SEISMIC ELECTRIC SIGNALS

P.A. Varotsos, N.V. Sarlis, E.S. Skordas and M.S. Lazaridou

Solid State Section and Solid Earth Physics Institute, Department of
Physics, University of Athens, Panepistimiopolis, Zografos 15784,
Athens, Greece. Email: pvaro@otenet.gr



Summary of the properties of
Seismic Electric Signals

Natural Time. Introduction

What happened before the 4 major Earthquakes
in Greece during 2008

Seismic Electric Signals (SES)

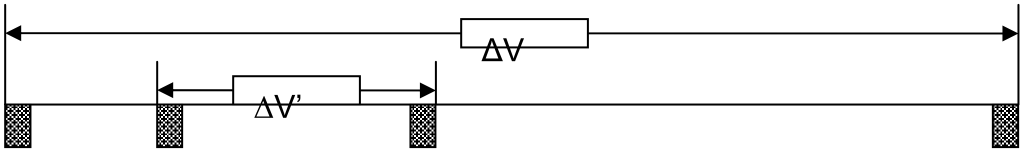
(VAN method, 1981)

1. We measure *both* the electric field and the magnetic field ≤1Hz

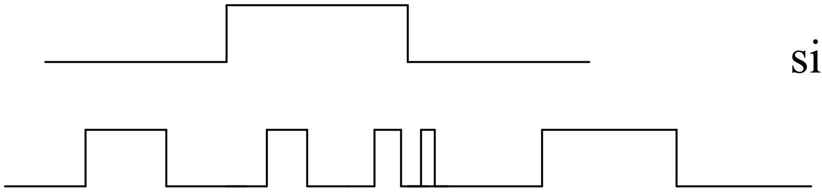
2. Several measuring dipoles (pairs of electrodes, ~2m)

   L ≈ a few tens of meters (short dipoles)

   to a few tens of kilometers (long dipoles)

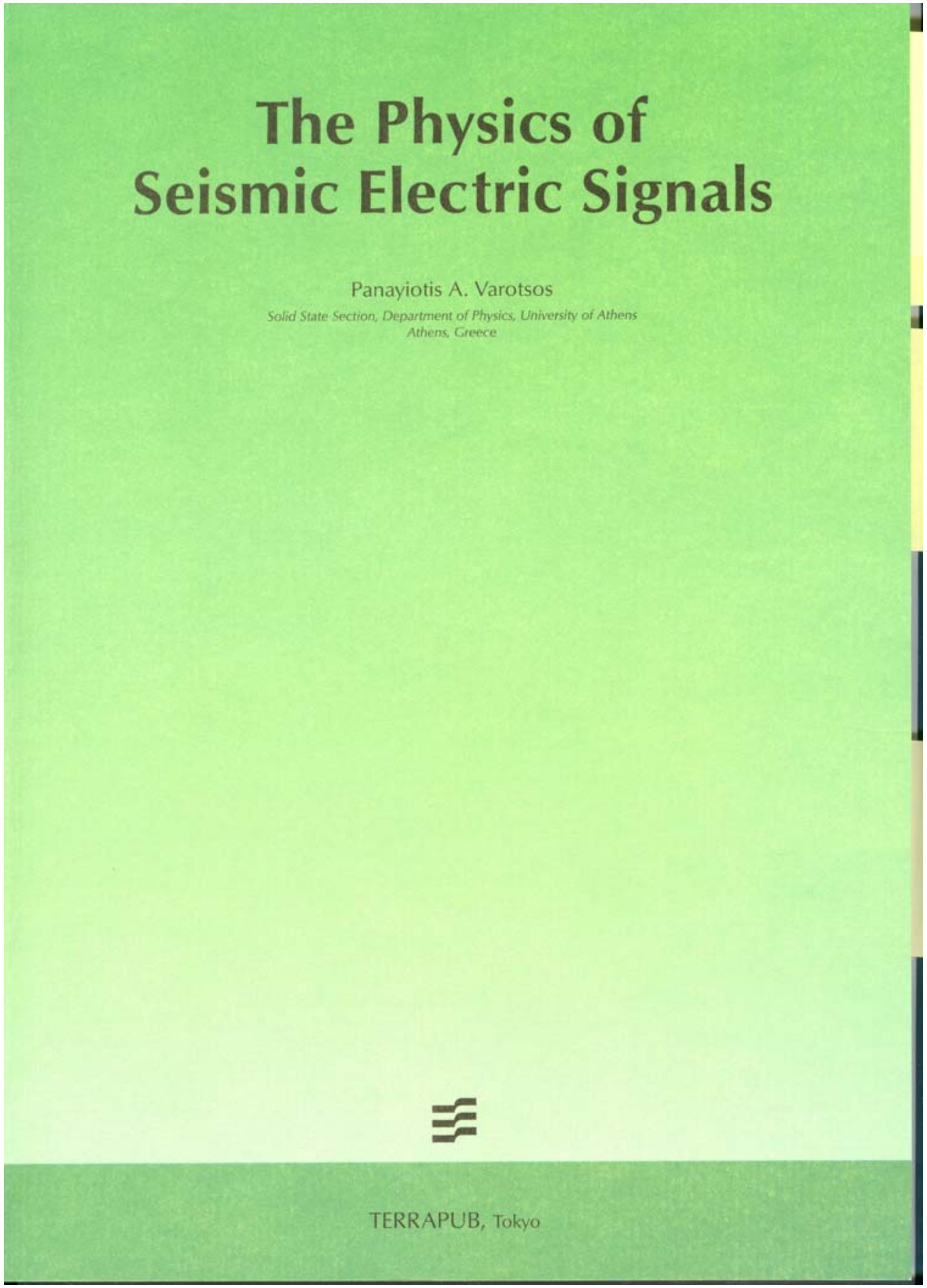


ΔV/L ≈ constant



single SES

SES activity



The Physics of Seismic Electric Signals

Panayiotis A. Varotsos

Solid State Section, Department of Physics, University of Athens
Athens, Greece

TERRAPUB, Tokyo

SES physical properties

since 1984, P. Varotsos & K. Alexopoulos *Tectonophysics* **110,** 73-125 (1984)

1. **Sensitive points**

SES are recorded *only* at certain sites of the Earth's surface …. detailed experimentation is necessary.

2. **Selectivity**

…Each sensitive site records SES *only* from certain seismic areas (selectivity map)

3. For a given pair: "SES station – seismic region":

$$E_{EW} / E_{NS} = const$$

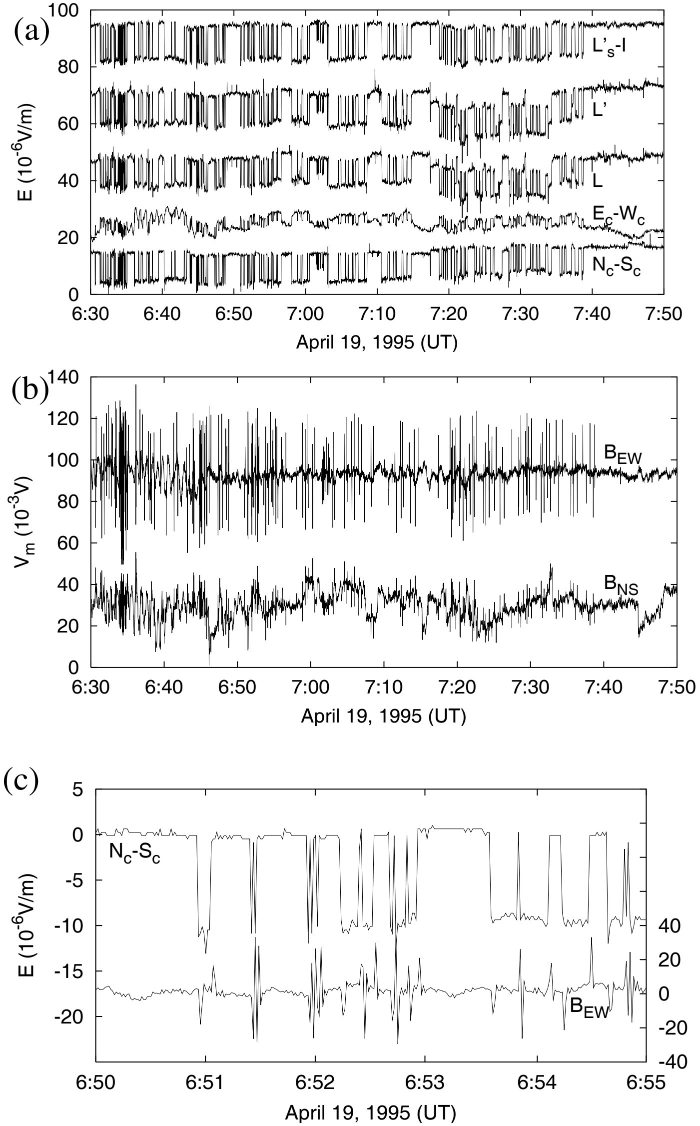
(polarity: constant)

(2) + (3) → epicentral determination

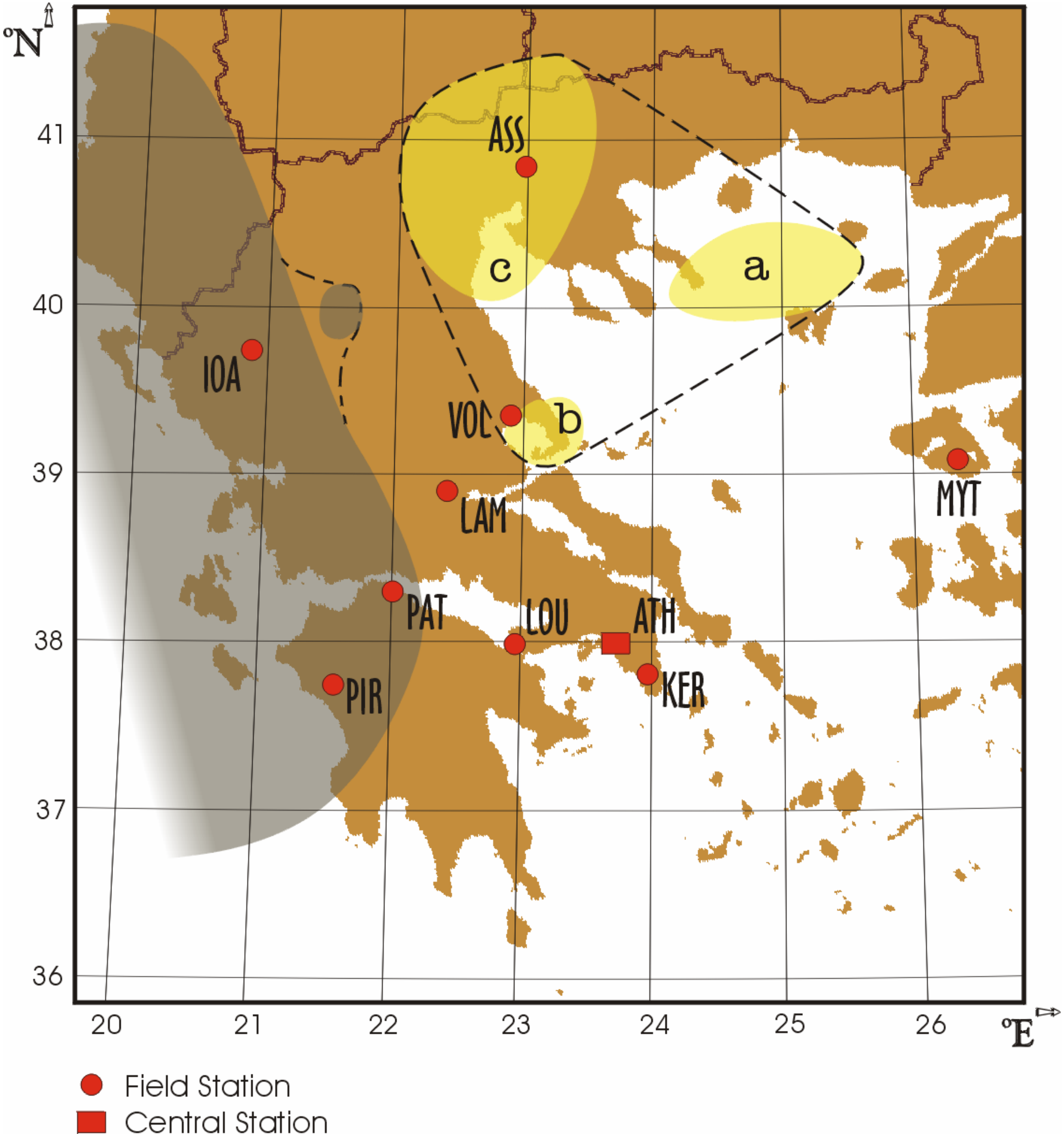
4.

$$\log\left(\frac{\Delta V}{L}\right) \approx (\underline{0.3 - 0.4})\, M + const$$

which leads to the determination of magnitude



Varotsos, P., Sarlis, N. and E. Skordas, Electric fields that “arrive” before the time-derivative of the magnetic field prior to major earthquakes, *Phys. Rev. Lett.* **91**, 148501 (2003)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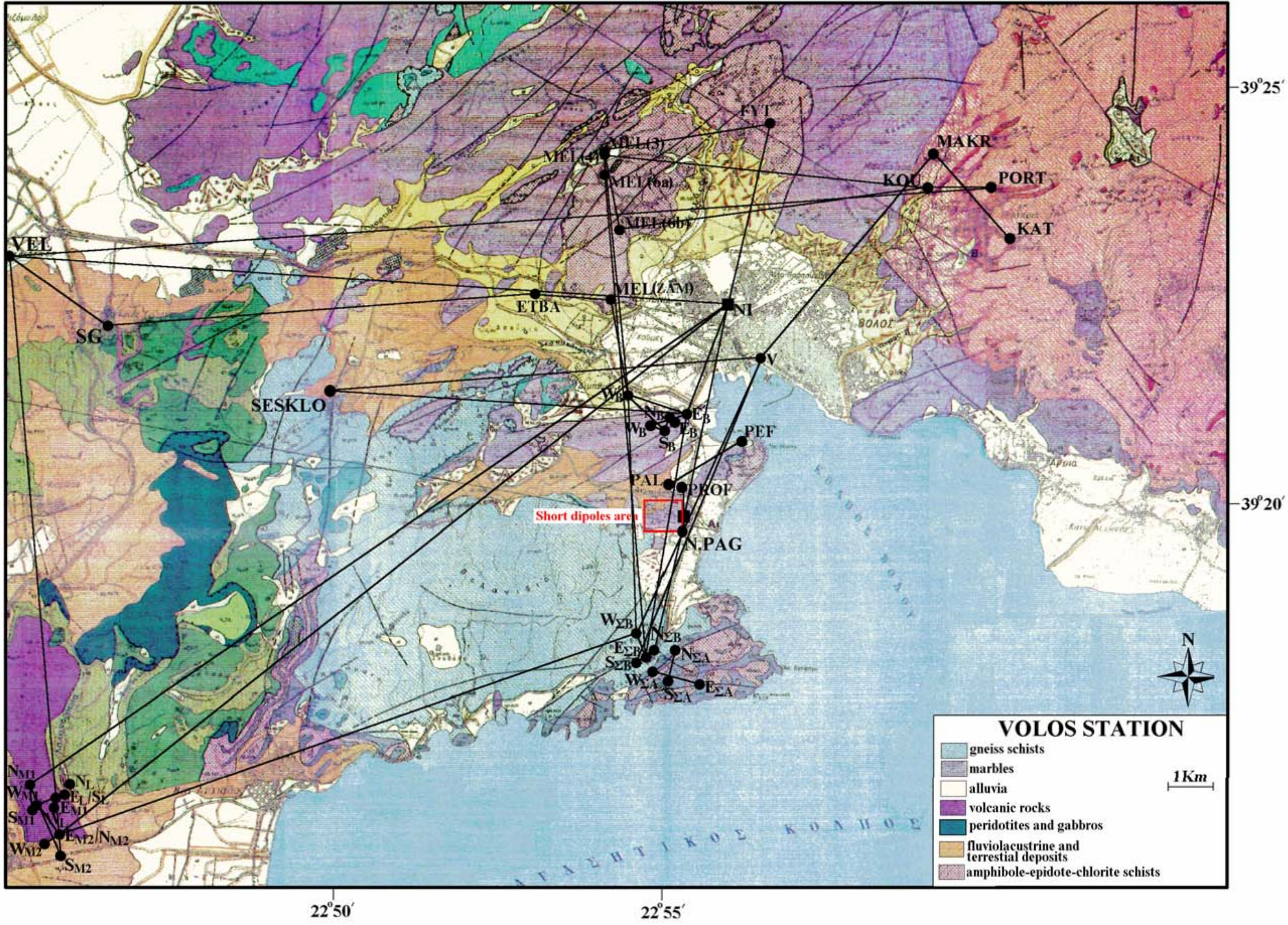
● Field Station
🟥 Central Station

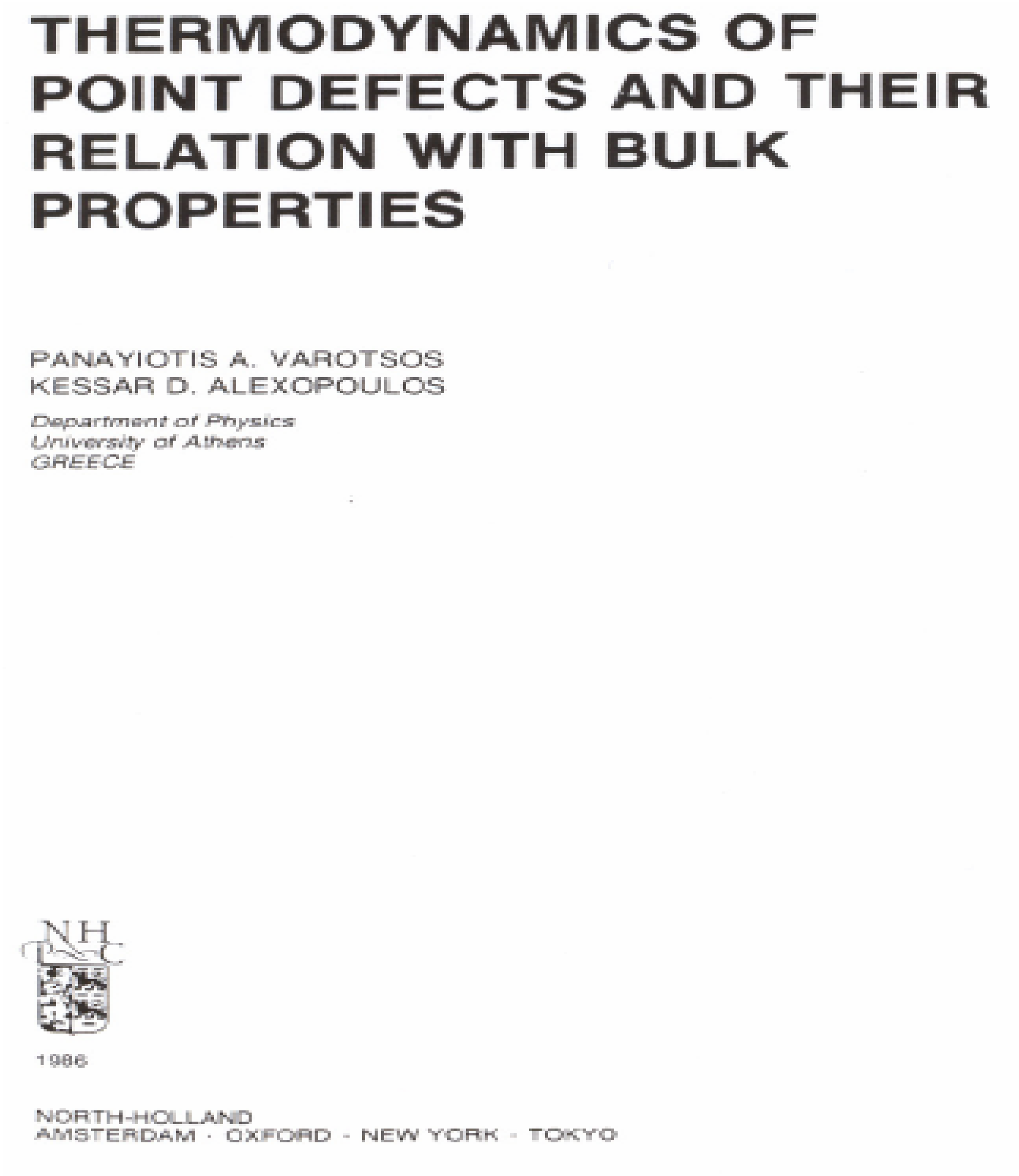
During the last decade:

When the expected magnitude is around 6.0 or larger, the SES activities are submitted for publication to International Journals well in advance

Dipoles at Volos Station



P. Varotsos, N. Sarlis, and E. Skordas, " A note on the spatial extent of the Volos SES sensitive site", *Acta Geophysica Polonica*, Vol. **49** (2001), 425-435.

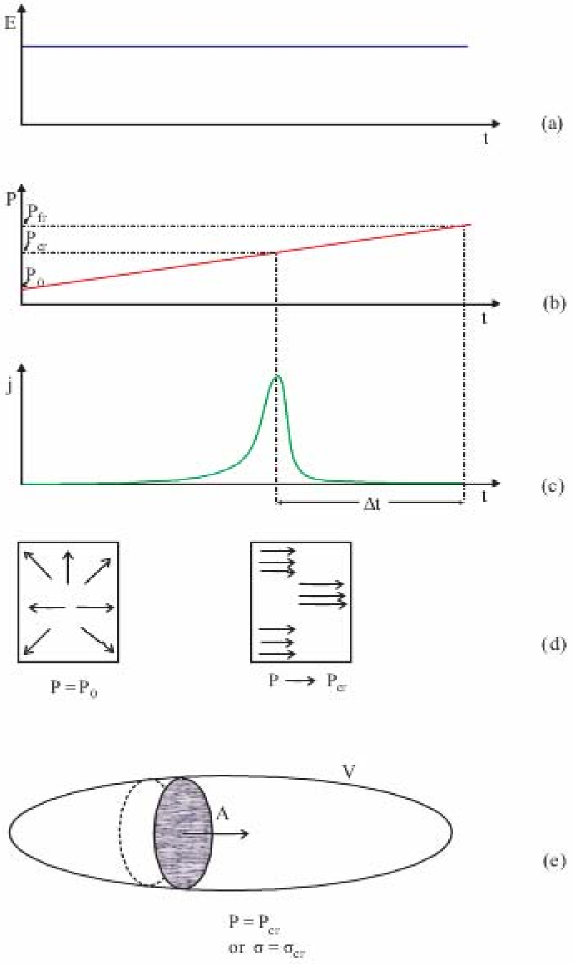


THERMODYNAMICS OF POINT DEFECTS AND THEIR RELATION WITH BULK PROPERTIES

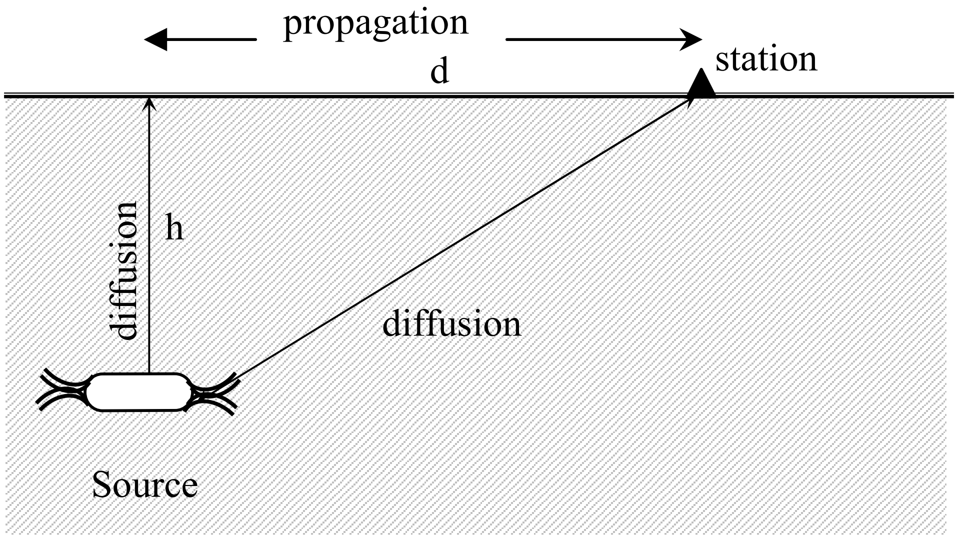
PANAYIOTIS A. VAROTSOS
KESSAR D. ALEXOPOULOS
Department of Physics
University of Athens
GREECE

1986

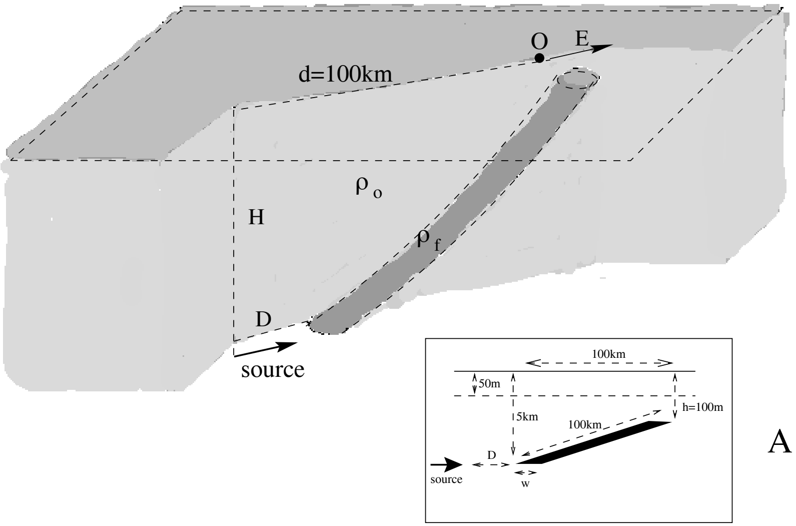
NORTH-HOLLAND
AMSTERDAM · OXFORD · NEW YORK · TOKYO



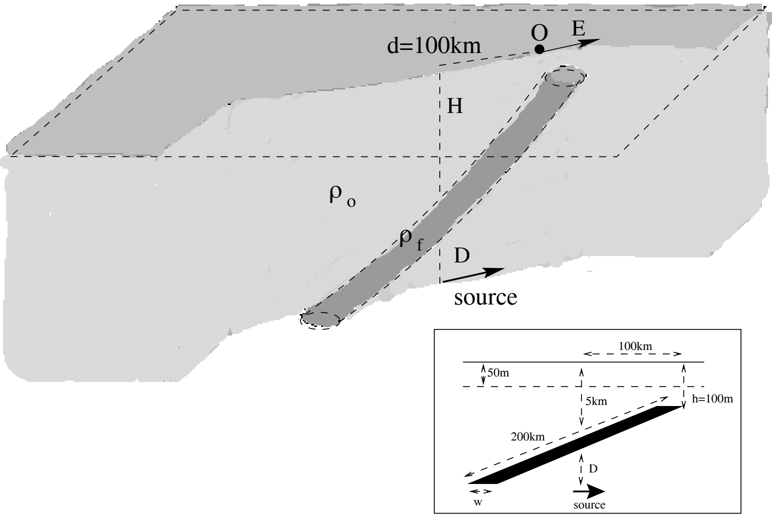
Attention 2nd order phase transition



See page 184 of P. Varotsos, *The Physics of Seismic Electric Signals*, TerraPub, Tokyo, 2005



A



B

SES transmission model suggested by *Varotsos and Alexopoulos* [1986]

The dipole source may be parallel (B) or perpendicular to the neighbouring conductive path.

The case A exhibits “over-amplification”.

Varotsos and Alexopoulos [1986] suggested that A is more probable than B; this seems to coincide with the recent aspects that there is always a significant component of the emitting dipole perpendicular to the conductive path

When the SES is emitted, the current follows the most conductive channel through which most of this current travels; since the emitting source lies near a channel of high conductivity, if the measuring station lies at a site close to the upper end of the conductive channel, the observed electric field (E) is order(s) of magnitude stronger than in the case of a homogeneous or horizontally layered earth.

Actually, numerical solutions of Maxwell equations (Sarlis et al., , *Geoph. Res. Lett.* **26**, 3245, 1999), being in full agreement with analytical solutions (Varotsos et al. *J. Appl. Phys*. **83**, 60, 1998), indicate that, within a certain region (i.e., above the end of the channel), at distances r ~ 100km from EQs of magnitude M 5.5-6.0, the electric field may reach detectable values (5-10 mV/km). This explains why the SES observations revealed the so called *selectivity* effect.

NATURAL TIME (*φυσικός χρόνος*)

It was suggested by P. Varotsos, N. Sarlis and E. Skordas, *Practica of Athens Academy* **76**, 294 (2001). It extracts signal information as much as possible *Phys. Rev. Lett*. **94**, 170601 (2005)

Ion current fluctuations in membrane channels.

All **SES activities** fall on a universal curve (critical dynamics)

Phys.Rev.E **66**, 011902 (2002)

Analysis of electrocardiograms in natural time:

The **sudden cardiac death** individuals are distinguished from the truly healthy ones as well as from patients.

Phys. Rev. E **70**, 011106 (2004)

Phys. Rev. E **71**, 011110 (2005)

Appl. Phys. Lett. **91**, 064106(2007)

The **entropy** S changes to S- **under time reversal**.

*Phys.Rev.E***71**, 032102 (2005)

Discrimination of SES activities (strongest memory) from **noise** emitted from nearby artificial sources

*Phys.Rev.E***67**, 021109 (2003)

Earthquakes:

- The seismicities of various countries fall on a universal curve.
- Order parameter
- Studying the seismicity after an SES activity, we can determine **the time-window of the impending mainshock** with good accuracy of a few hours to a few days.

Phys. Rev. E **72**, 041103 (2005); *Phys. Rev. E* **73**, 031114 (2006); *Phys. Rev. E* 74, 021123 (2006); *Journal of Applied Physics* **103**, 014906 (2008)

Similar looking signals that are emitted from systems **with different dynamics** can be distinguished.

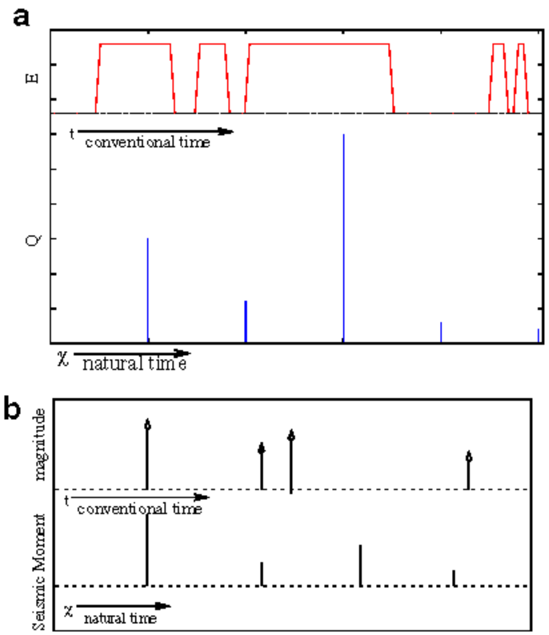
Modern techniques of statistical physics, e.g., Hurst Analysis, Wavelet transform, Detrended Fluctuation Analysis (DFA) etc. should be better made in natural time.

Phys. Rev. E **68**, 031106 (2003)

- High **Tc-superconductors**
- Small changes in the magnetic field can result in large rearrangements of fluxing the sample, known as flux avalanches
- **Rice piles**

(**S**elf **O**rganized **C**riticality)

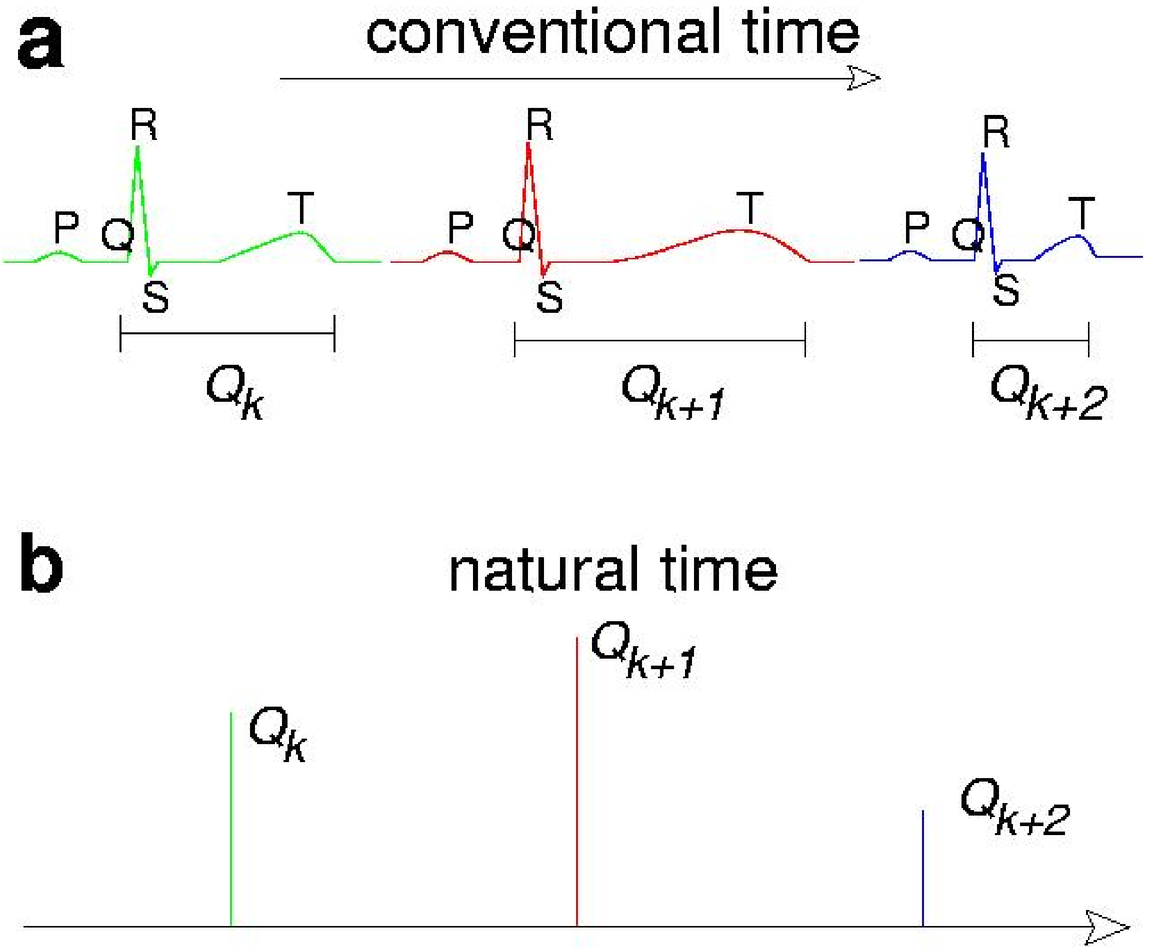
Phys.Rev.B **73**, 054504 (2006)



For example, we refer to the analysis of dichotomous electric signals (Fig.1(a)) where we consider E_k as being proportional to the duration of the *k*-th pulse. As another example, to perform the analysis of seismic events (Fig.1(b)), we consider the time evolution of the pair (χ_k, M_{0_k}) where M_{0_k} stands for the seismic moment of the *k*-th event, since M_{0_k} is proportional to the energy emitted in that earthquake (cf. M_{0_k} differs essentially from the magnitude M, but they are interconnected).

P. Varotsos, N. Sarlis, and E. Skordas, *Practica of Athens Academy* **76**, 294 (2001)

Physical Review E **70,** 011106 (2004) & *Physical Review E* **71,** 011110 (2005)



Schematic diagram of a three heartbeat excerpt of an ECG in the usual (conventional) time–domain (a), and the QT–interval time–series of (a) read in the natural time (b). The vertical bars are equally spaced, but the length of each bar denotes the duration of the corresponding QT–interval marked in (a).

In a time series comprising N events, the ***natural time*** is defined as

$$\chi_k = \frac{k}{N}$$

and serves as an index for the occurrence of the k-th event

In natural time analysis the evolution of the pair of two quantities (χ_k, E_k) is considered, where E_k denotes in general a quantity proportional to energy of the individual event.

For the purpose of analysis, the following *continuous* function $\Phi(\omega)$ was introduced

$$\Phi(\omega) = \frac{\sum_{k=1}^{N} E_k \exp(i\omega \frac{k}{N})}{\sum_{n=1}^{N} E_n} = \sum_{k=1}^{N} p_k \exp(i\omega \frac{k}{N})$$

where $$p_k = \frac{E_k}{\sum_{n=1}^{N} E_n}$$

and $\omega = 2\pi\phi$ and ϕ stands for the frequency in natural time, termed *natural* frequency.

We then compute the power spectrum $\Pi(\omega)$ of $\Phi(\omega)$ as

$$\Pi(\omega) = |\Phi(\omega)|^2$$

If we regard p_k as a probability density function, $\Phi(\omega)$ may be justified to be treated mathematically as a *characteristic* function in analogy with the probability theory. Then, the properties of the distribution of p_k can be estimated by the expansion of this characteristic function for $\omega \to 0$.

Practica of Athens Academy **76**, 294 (2001)

The Taylor expansion, around $\omega = 0$, of the relation $\Pi(\omega) = |\Phi(\omega)|^2$ reveals that

$$\Pi(\omega) = 1 - \kappa_1\omega^2 + \kappa_2\omega^4 + \kappa_3\omega^6 + \kappa_4\omega^8 + \ldots\ldots,$$

where

$$\kappa_1 = -\frac{1}{2}\frac{d^2\Pi(\omega)}{d\omega^2}|_{\omega=0}$$

we now consider

$$\frac{d^2\Pi(\omega)}{d\omega^2} = \Phi^*(\omega)\frac{d^2\Phi(\omega)}{d\omega^2} + \Phi(\omega)\frac{d^2\Phi^*(\omega)}{d\omega^2} + 2\frac{d\Phi(\omega)}{d\omega}\frac{d\Phi^*(\omega)}{d\omega}$$

and taking into account that $\Phi(\omega) \equiv \sum_k p_k \exp(i\omega\chi_k)$, with $\Phi(0) = 1$, we find:

$$\kappa_1 = -\frac{1}{2}\left[-\sum_k p_k\chi_k^2 - \sum_k p_k\chi_k^2 + 2(\sum_k p_k\chi_k)^2\right] = \langle\chi^2\rangle - \langle\chi\rangle^2,$$

where $\langle\chi^n\rangle = \sum_k p_k\chi_k^n$.

Thus:

$$\kappa_1 = \langle\chi^2\rangle - \langle\chi\rangle^2$$

Practica of Athens Academy **76**, 294 (2001)

Criticality

When the system enters the critical stage, the following relation holds

$$\Pi(\omega) = \frac{18}{5\omega^2} - \frac{6\cos\omega}{5\omega^2} - \frac{12\sin\omega}{5\omega^3}$$

For $\omega \to 0$, this equation leads to $\Pi(\omega) \approx 1 - 0.07\omega^2$

which reflects that the variance of χ is given by

$$\kappa_1 = \langle \chi^2 \rangle - \langle \chi \rangle^2 = 0.07,$$

where $\langle f(\chi) \rangle = \sum_{k=1}^{N} p_k f(\chi_k)$.

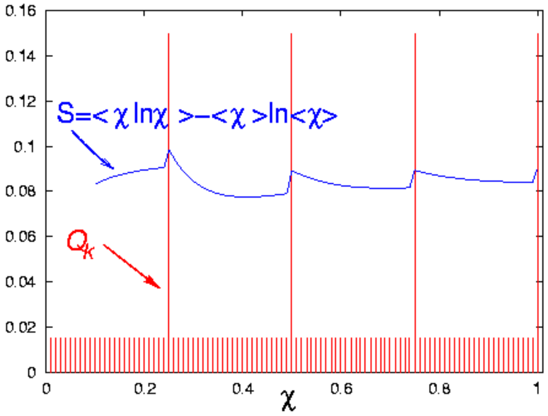
Since, at $\omega \to 0$, κ_1 is linearly related to $\Pi(\phi)$ (because $\Pi(\phi) = 1 - 4\pi^2\phi^2\kappa_1$ for $\phi \to 0$) one can study, instead of $P[\Pi(\phi)]$, the PDF of κ_1, i.e., $P(\kappa_1)$

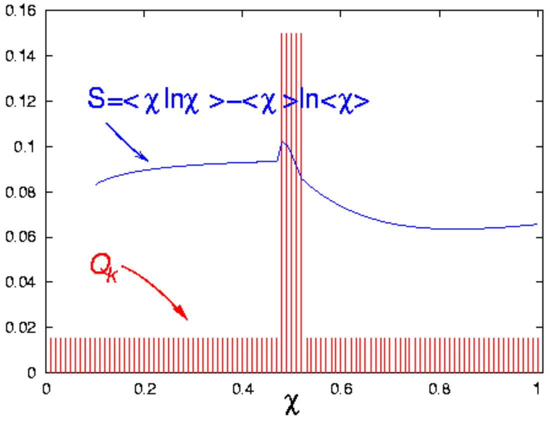
Practica of Athens Academy **76**, 294 (2001)

The entropy in natural time

$$S \equiv \langle \chi \ln \chi \rangle - \langle \chi \rangle \ln \langle \chi \rangle$$

(*Varotsos et al., Practica of Athens Academy* ***76***, *294* (2001); *Phys. Rev. E.* **68**, 031106 (2003); *ibid* ***70***, 011106 (2004))





S is a dynamic entropy and hence differs essentially from the usual static entropy:

Shannon: $-\Sigma p_i \ln p_i$

When reversing the time arrow, S changes to S- (*casual* operator)

Varotsos et al., *Phys. Rev. E* 71, 032102 (2005)

For *criticality*: *Both* S and S- are smaller than that of a "uniform" distribution $S_u = (\ln 2)/2 - 1/4 = 0.0966$

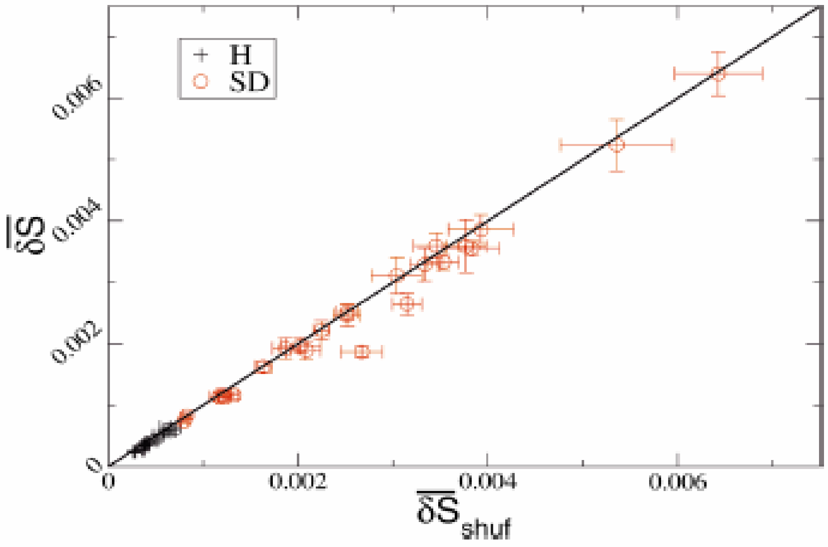


FIG. 6. (Color) The $\overline{\delta S}$ value, in each of the 10 H (black) and 24 SD (red), for the QT intervals versus $\overline{\delta S}_{\mathrm{shuf}}$ (time-window range 3–10 beats). Note that the values of the ordinates are appreciably smaller than the δS value ($\approx 2\times 10^{-2}$) of the Markovian time series (10^3 events) depicted in Fig. 2.

Varotsos et al., *Phys. Rev. E* **70**, 011106 (2004)

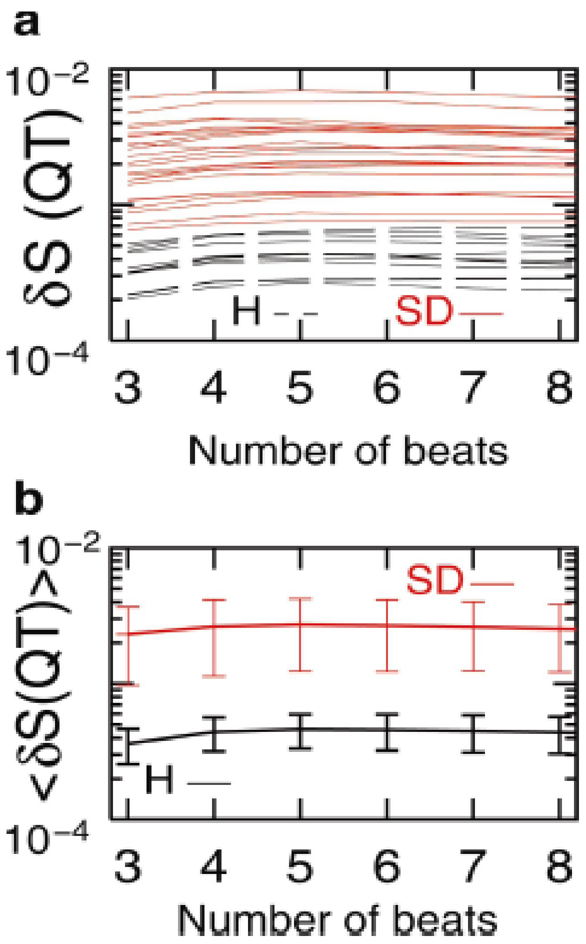
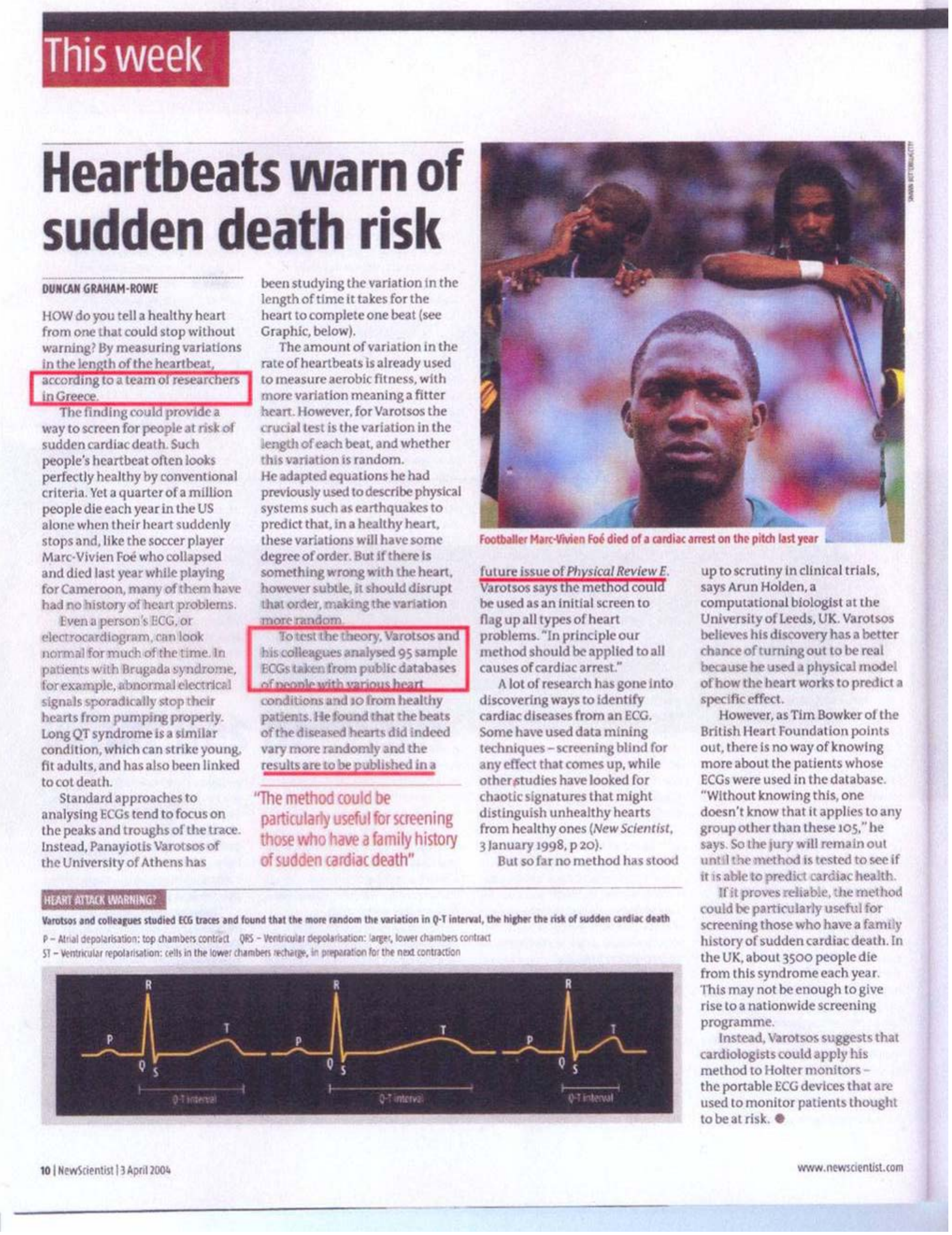


FIG. 2. (Color) (a) The δS(QT) value for each of the 24 SD and 10 H (see Table I) and (b) the average of the δS(QT) values—designated by $\langle \delta S(\mathrm{QT})\rangle$—along with their standard error deviation for each of the two groups SD and H vs the time-window length.

Varotsos et al., *Phys. Rev. E* **71**, 011110 (2005)



This week

Heartbeats warn of sudden death risk

DUNCAN GRAHAM-ROWE

HOW do you tell a healthy heart from one that could stop without warning? By measuring variations in the length of the heartbeat, according to a team of researchers in Greece.

The finding could provide a way to screen for people at risk of sudden cardiac death. Such people's heartbeat often looks perfectly healthy by conventional criteria. Yet a quarter of a million people die each year in the US alone when their heart suddenly stops and, like the soccer player Marc-Vivien Foé who collapsed and died last year while playing for Cameroon, many of them have had no history of heart problems.

Even a person's ECG, or electrocardiogram, can look normal for much of the time. In patients with Brugada syndrome, for example, abnormal electrical signals sporadically stop their hearts from pumping properly. Long QT syndrome is a similar condition, which can strike young, fit adults, and has also been linked to cot death.

Standard approaches to analysing ECGs tend to focus on the peaks and troughs of the trace. Instead, Panayiotis Varotsos of the University of Athens has been studying the variation in the length of time it takes for the heart to complete one beat (see Graphic, below).

The amount of variation in the rate of heartbeats is already used to measure aerobic fitness, with more variation meaning a fitter heart. However, for Varotsos the crucial test is the variation in the length of each beat, and whether this variation is random. He adapted equations he had previously used to describe physical systems such as earthquakes to predict that, in a healthy heart, these variations will have some degree of order. But if there is something wrong with the heart, however subtle, it should disrupt that order, making the variation more random.

To test the theory, Varotsos and his colleagues analysed 95 sample ECGs taken from public databases of people with various heart conditions and 10 from healthy patients. He found that the beats of the diseased hearts did indeed vary more randomly and the results are to be published in a future issue of *Physical Review E*.

"The method could be particularly useful for screening those who have a family history of sudden cardiac death"

Footballer Marc-Vivien Foé died of a cardiac arrest on the pitch last year

Varotsos says the method could be used as an initial screen to flag up all types of heart problems. "In principle our method should be applied to all causes of cardiac arrest."

A lot of research has gone into discovering ways to identify cardiac diseases from an ECG. Some have used data mining techniques – screening blind for any effect that comes up, while other studies have looked for chaotic signatures that might distinguish unhealthy hearts from healthy ones (*New Scientist*, 3 January 1998, p 20).

But so far no method has stood up to scrutiny in clinical trials, says Arun Holden, a computational biologist at the University of Leeds, UK. Varotsos believes his discovery has a better chance of turning out to be real because he used a physical model of how the heart works to predict a specific effect.

However, as Tim Bowker of the British Heart Foundation points out, there is no way of knowing more about the patients whose ECGs were used in the database. "Without knowing this, one doesn't know that it applies to any group other than these 105," he says. So the jury will remain out until the method is tested to see if it is able to predict cardiac health.

If it proves reliable, the method could be particularly useful for screening those who have a family history of sudden cardiac death. In the UK, about 3500 people die from this syndrome each year. This may not be enough to give rise to a nationwide screening programme.

Instead, Varotsos suggests that cardiologists could apply his method to Holter monitors – the portable ECG devices that are used to monitor patients thought to be at risk. ●

HEART ATTACK WARNING?

Varotsos and colleagues studied ECG traces and found that the more random the variation in Q-T interval, the higher the risk of sudden cardiac death

P – Atrial depolarisation: top chambers contract QRS – Ventricular depolarisation: larger, lower chambers contract
ST – Ventricular repolarisation: cells in the lower chambers recharge, in preparation for the next contraction

10 | NewScientist | 3 April 2004

www.newscientist.com

1st usefulness of Natural Time

Several Modern Procedures to distinguish true preseismic signals (*critical* dynamics) from “artificial” noise:

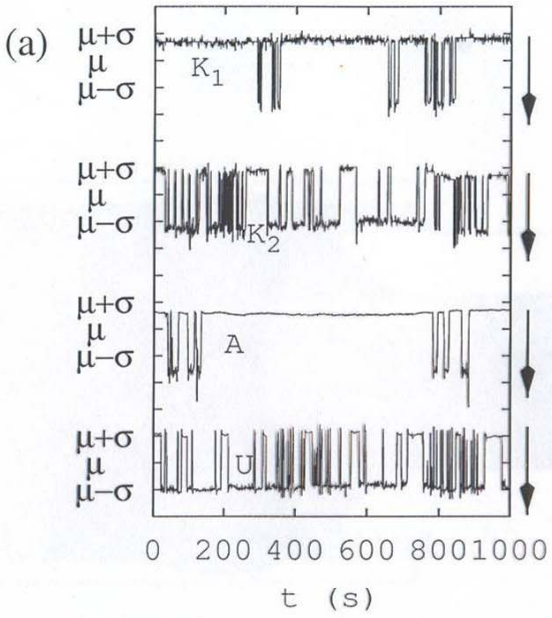
- Normalized power spectrum Π(ω) (*or* $\kappa_1 = \langle \chi^2 \rangle - \langle \chi \rangle^2$)
- Hurst
- Detrended Fluctuation Analysis (DFA)
- Multifractal DFA
- Wavelet Transform
- Entropy

ATTENTION: *All* the above in natural time

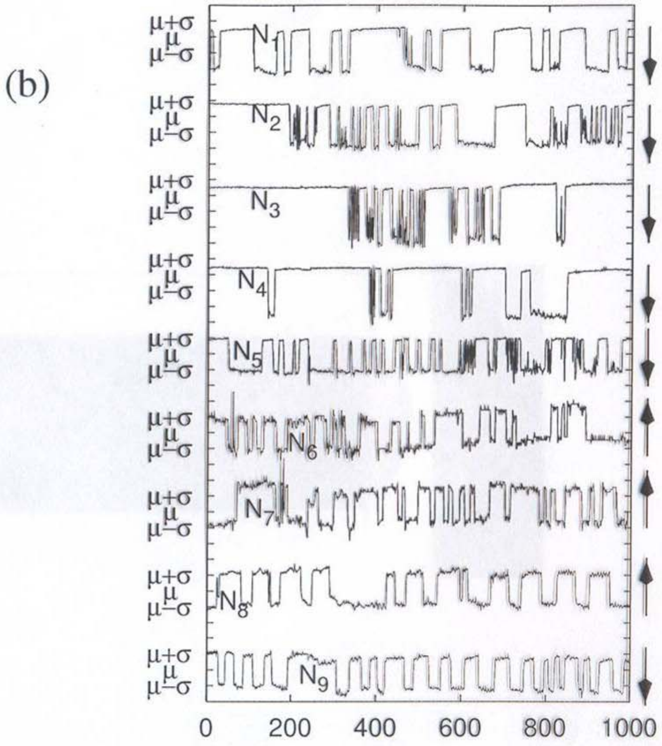
Apart from SES activities one usually also records artificial noises

SES activities

(satisfying the well known criteria*)

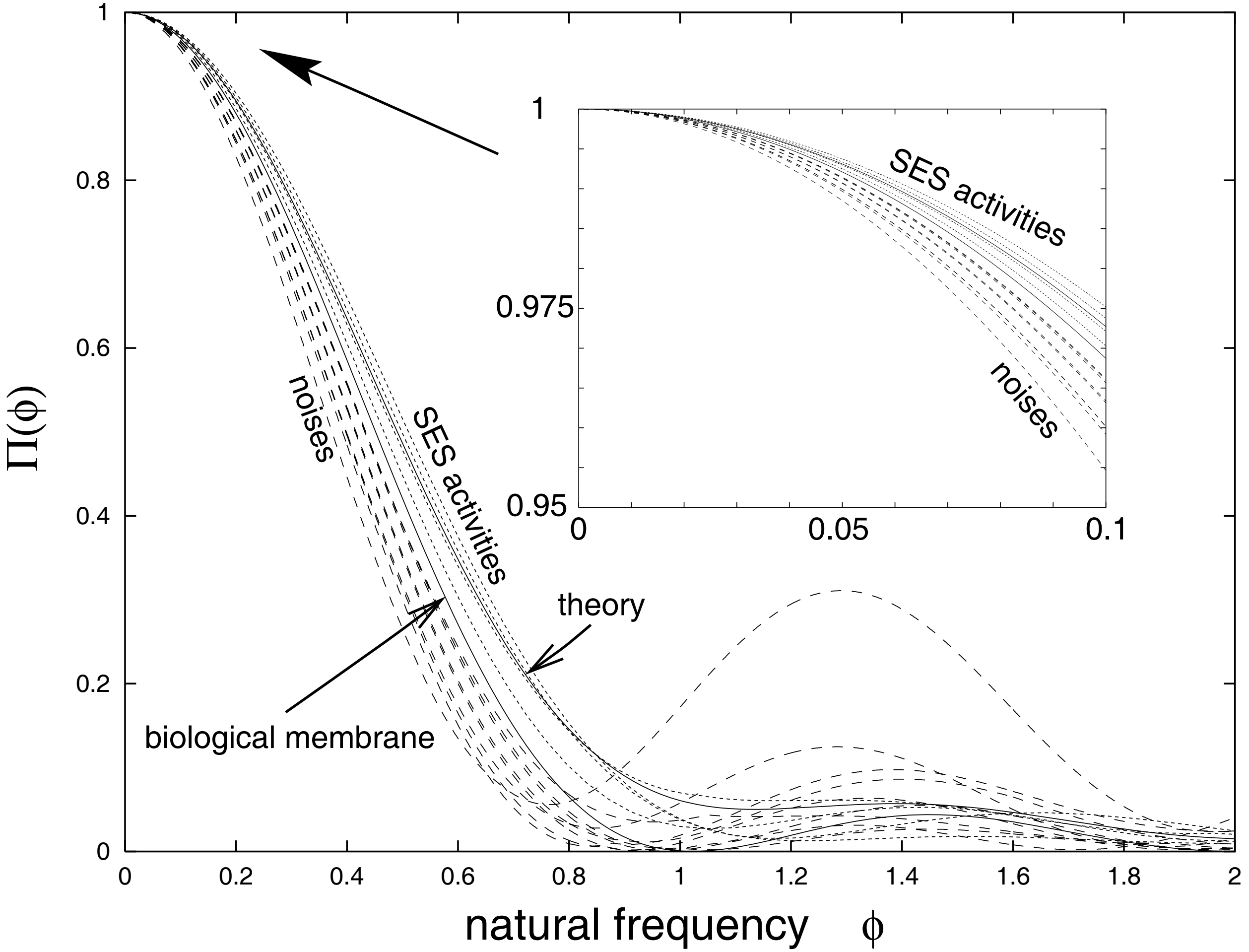


Artificial noises



P.Varotsos, N. Sarlis, E.Skordas, Phys. Rev. E, 67, 021109,2003

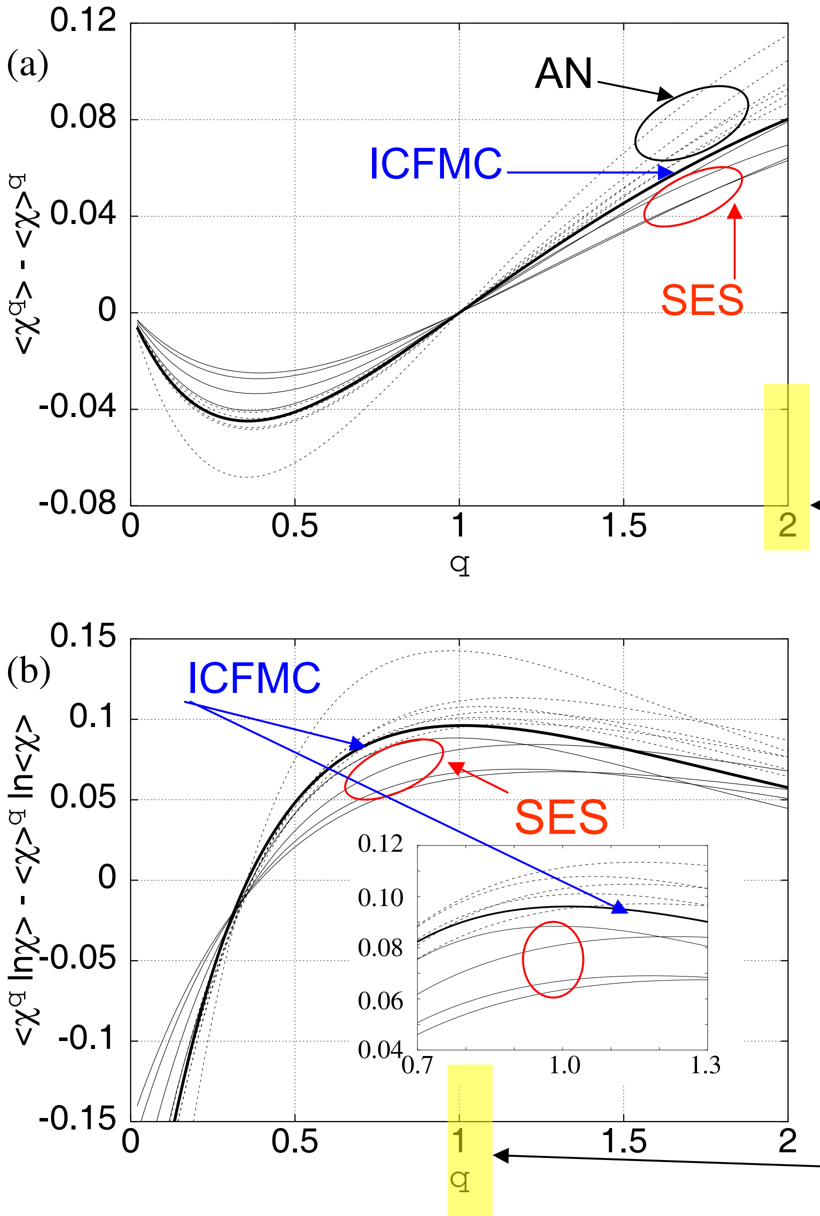
**P. Varotsos and M. Lazaridou, Tectonophysics 188,321, 1991*
**P. Varotsos, K. Alexopoulos and M. Lazaridou, Tectonophysics 224, 1, 1993*



The normalized power spectra $\Pi(\phi)$ for SES activities (dotted lines) and artificial noises (broken lines). They correspond to $\kappa_1 \approx 0.07$ and $\kappa_1 \leq \frac{1}{12} \approx 0.0833$, respectively. The lower solid curve corresponds to the ICFMCs (labeled biological membrane), while the upper solid curve to the theoretical estimation for critical phenomena. For the sake of clarity, the curve corresponding to the "uniform" distribution ($\kappa_1 = \kappa_u = \frac{1}{12}$) was not drawn: this lies very close and only slightly below the ICFMCs. The inset refers to the range $0 \leq \phi \leq 0.1$.

SES activities Universality!!! Universality!!!

Entropy in natural time



$$\kappa_1 = \langle \chi^2 \rangle - \langle \chi \rangle^2$$

$q=2$

Entropy $q=1$

Varotsos et al., *Phys. Rev. E* **68**, 031106 (2003)

2^{nd} usefulness of Natural Time

How the time of occurrence of the impending mainshock is estimated

We study how the seismicity evolved after the recording of the SES activity by considering two areas A and B to check the spatial invariance (criticality).

If we set the natural time for seismicity zero at the initiation of the SES activity, we form time series of seismic events in natural time for various time windows as the number N of consecutive (small) EQs increases. We then compute the normalized power spectrum in natural time $\Pi(\varphi)$ for each of the time windows. We investigate when the power spectrum obeys the relation

$$\Pi(\omega) = \frac{18}{5\omega^2} - \frac{6\cos\omega}{5\omega^2} - \frac{12\sin\omega}{5\omega^3}$$

which holds when the system enters the *critical* stage ($\omega = 2\pi\phi$)

This *coincidence* between the theoretical and the computed curve occurs roughly a few days before the strong EQ. To ensure that this coincidence is a true one we also calculate the evolution of the quantities.κ_1, S and S_-

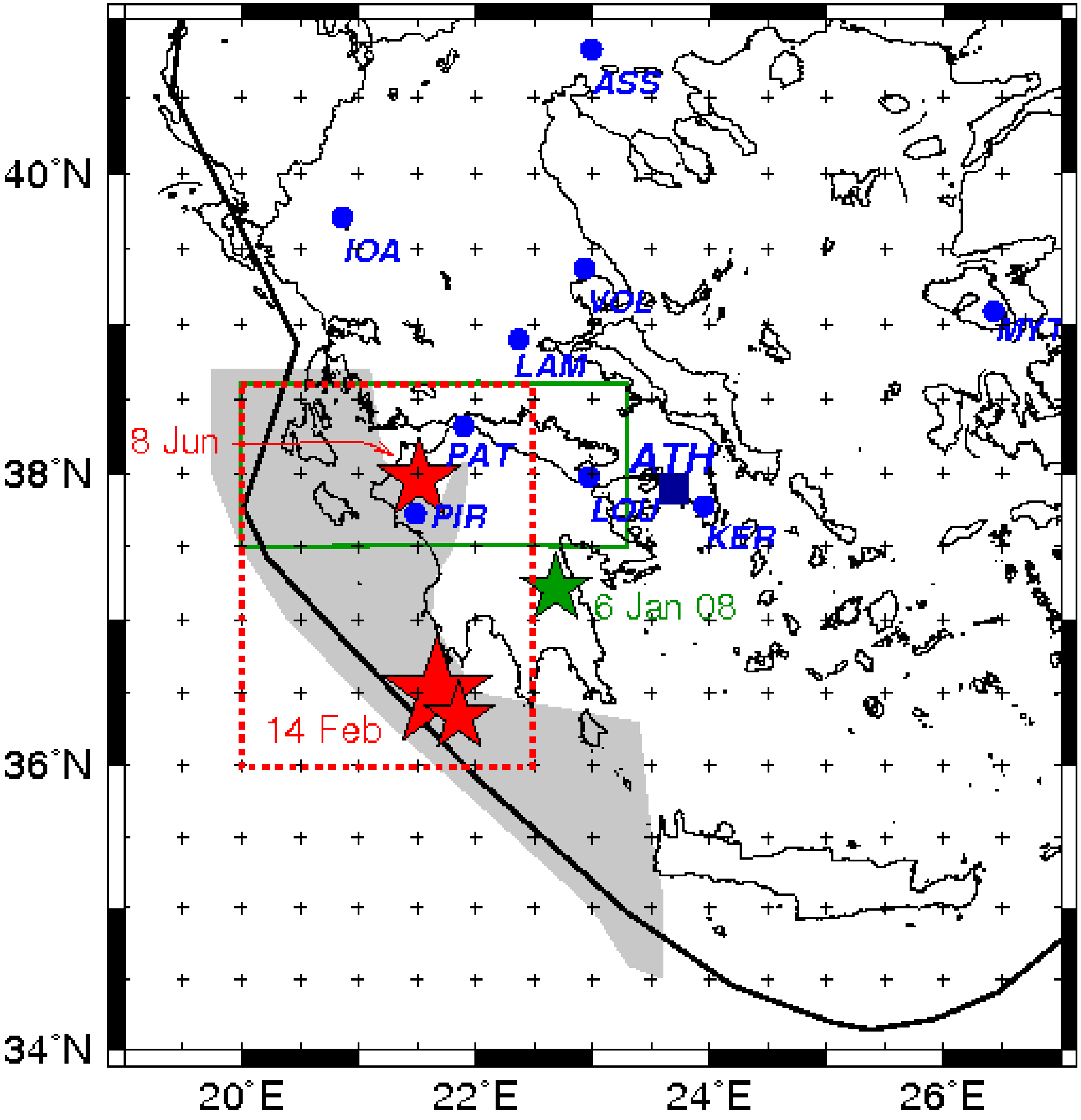
The conditions for a coincidence to be considered as *true* are the following:

First, the `average' distance $<D>$ between the empirical and the theoretical $\Pi(\varphi)$ (i.e., the red and the blue line, respectively) should be smaller than 10^{-2}.

Second, in the examples observed to date, a few events *before* the coincidence leading to the strong EQ, the evolving $\Pi(\varphi)$ has been found to approach the theoretical one, i.e., the blue one from *below* (cf. this reflects that during this approach the κ_1-value decreases as the number of events increases).

In addition, both values S and S- should be smaller than Su at the coincidence. Finally, since the process concerned is self-similar (*critical* dynamics), the time of the occurrence of the (true) coincidence should *not* change, in principle, upon changing either the (surrounding) area or the magnitude threshold used in the calculation.

$K_1=0.070$, $S, S_- < S_u$ (=0.0966)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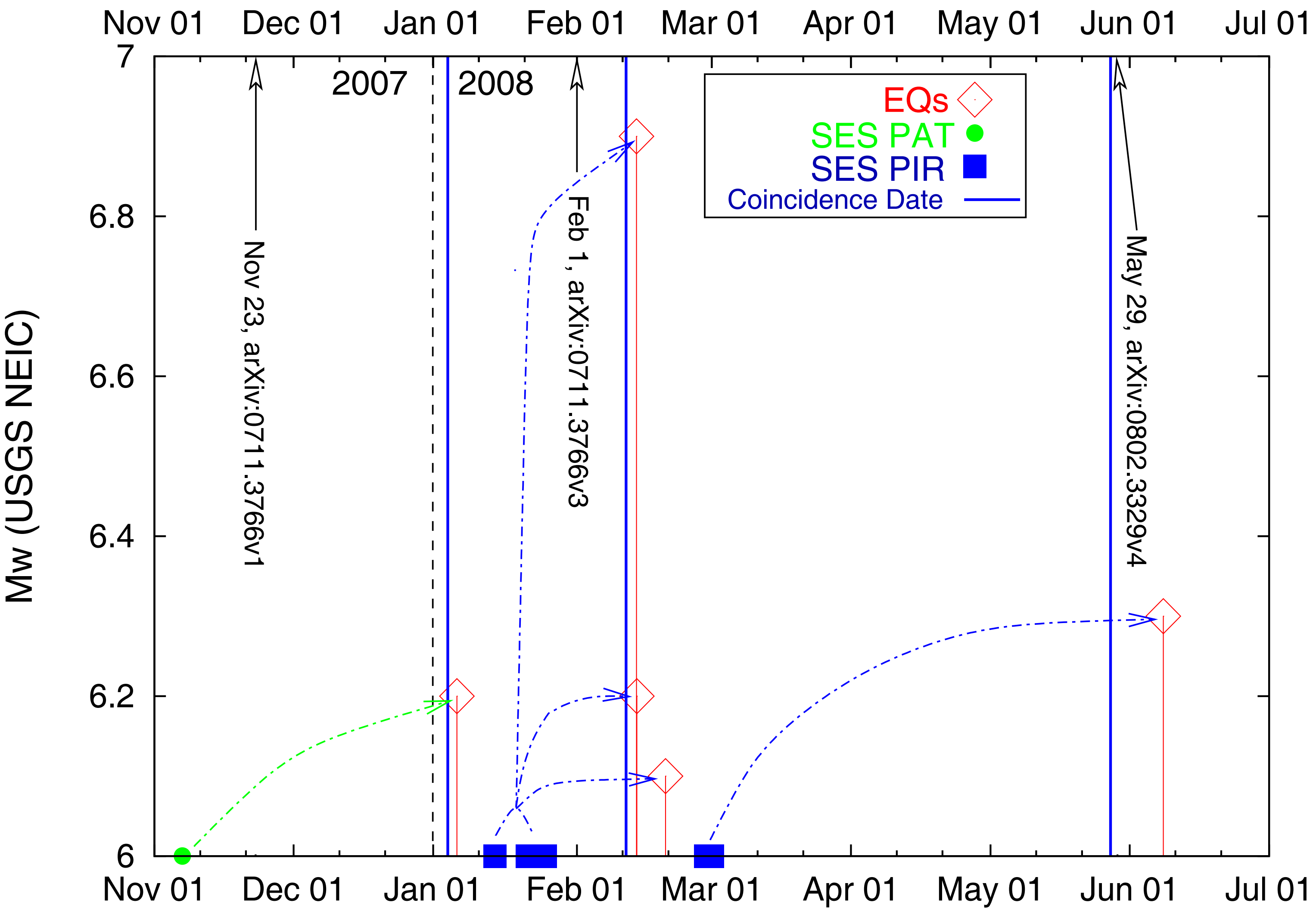
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Nov 23, arXiv:0711.3766v1
Feb 1, arXiv:0711.3766v3
May 29, arXiv:0802.3329v4
EQs ◇
SES PAT ●
SES PIR ■
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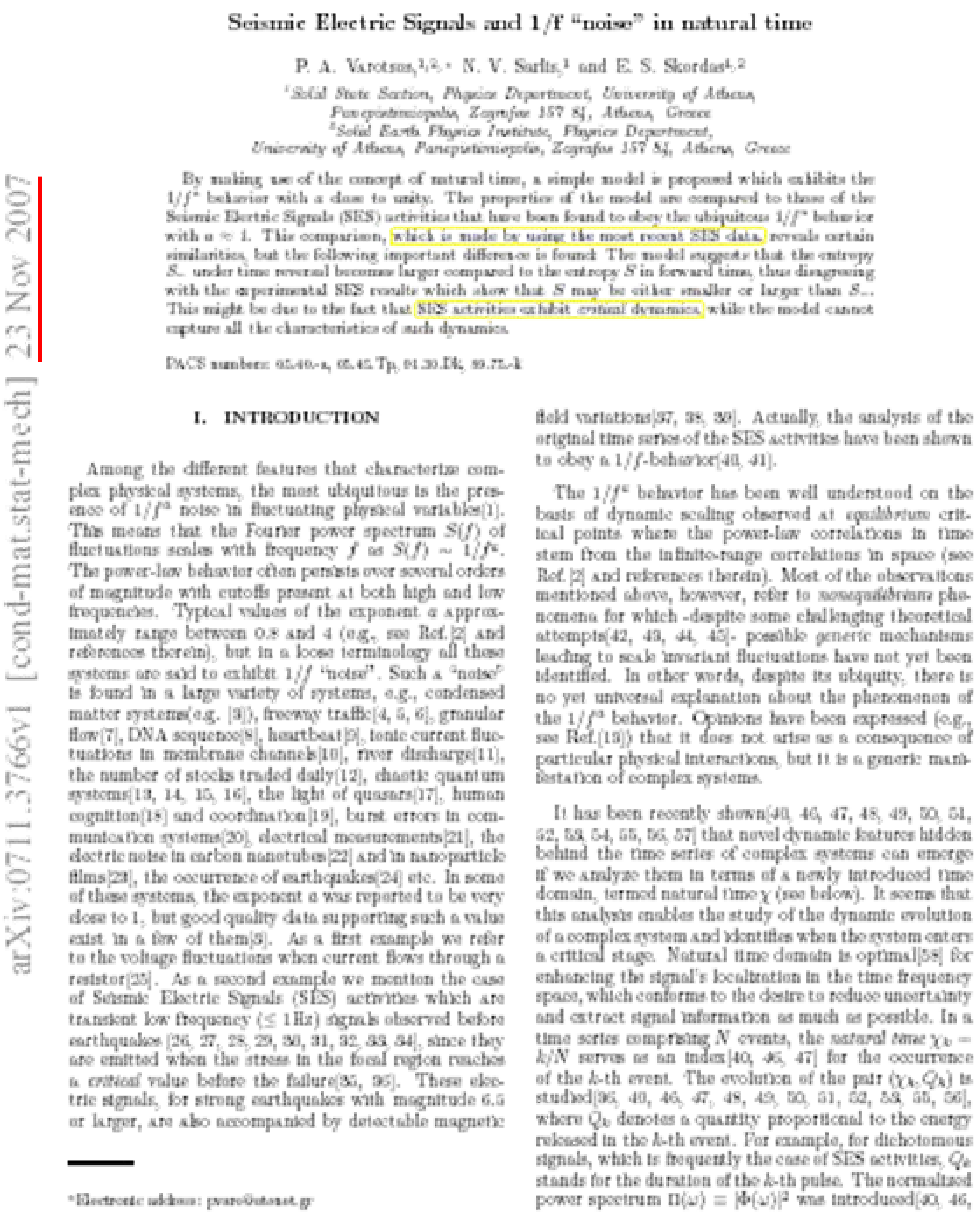

Seismic Electric Signals and 1/f "noise" in natural time

P. A. Varotsos,[1,2,*] N. V. Sarlis,[1] and E. S. Skordas[1,2]

[1]Solid State Section, Physics Department, University of Athens,
Panepistimiopolis, Zografos 157 84, Athens, Greece
[2]Solid Earth Physics Institute, Physics Department,
University of Athens, Panepistimiopolis, Zografos 157 84, Athens, Greece

By making use of the concept of natural time, a simple model is proposed which exhibits the $1/f^a$ behavior with a close to unity. The properties of the model are compared to those of the Seismic Electric Signals (SES) activities that have been found to obey the ubiquitous $1/f^a$ behavior with $a \approx 1$. This comparison, which is made by using the most recent SES data, reveals certain similarities, but the following important difference is found: The model suggests that the entropy S_- under time reversal becomes larger compared to the entropy S in forward time, thus disagreeing with the experimental SES results which show that S may be either smaller or larger than S_-. This might be due to the fact that SES activities exhibit *critical* dynamics, while the model cannot capture all the characteristics of such dynamics.

PACS numbers: 05.40.-a, 05.45.Tp, 91.30.Dk, 89.75.-k

I. INTRODUCTION

Among the different features that characterize complex physical systems, the most ubiquitous is the presence of $1/f^a$ noise in fluctuating physical variables[1]. This means that the Fourier power spectrum $S(f)$ of fluctuations scales with frequency f as $S(f) \sim 1/f^a$. The power-law behavior often persists over several orders of magnitude with cutoffs present at both high and low frequencies. Typical values of the exponent a approximately range between 0.8 and 4 (e.g., see Ref.[2] and references therein), but in a loose terminology all these systems are said to exhibit $1/f$ "noise". Such a "noise" is found in a large variety of systems, e.g., condensed matter systems(e.g. [3]), freeway traffic[4, 5, 6], granular flow[7], DNA sequence[8], heartbeat[9], ionic current fluctuations in membrane channels[10], river discharge[11], the number of stocks traded daily[12], chaotic quantum systems[13, 14, 15, 16], the light of quasars[17], human cognition[18] and coordination[19], burst errors in communication systems[20], electrical measurements[21], the electric noise in carbon nanotubes[22] and in nanoparticle films[23], the occurrence of earthquakes[24] etc. In some of these systems, the exponent a was reported to be very close to 1, but good quality data supporting such a value exist in a few of them[3]. As a first example we refer to the voltage fluctuations when current flows through a resistor[25]. As a second example we mention the case of Seismic Electric Signals (SES) activities which are transient low frequency ($\leq$ 1Hz) signals observed before earthquakes [26, 27, 28, 29, 30, 31, 32, 33, 34], since they are emitted when the stress in the focal region reaches a *critical* value before the failure[35, 36]. These electric signals, for strong earthquakes with magnitude 6.5 or larger, are also accompanied by detectable magnetic field variations[37, 38, 39]. Actually, the analysis of the original time series of the SES activities have been shown to obey a $1/f$-behavior[40, 41].

The $1/f^a$ behavior has been well understood on the basis of dynamic scaling observed at *equilibrium* critical points where the power-law correlations in time stem from the infinite-range correlations in space (see Ref.[2] and references therein). Most of the observations mentioned above, however, refer to *nonequilibrium* phenomena for which -despite some challenging theoretical attempts[42, 43, 44, 45]- possible *generic* mechanisms leading to scale invariant fluctuations have not yet been identified. In other words, despite its ubiquity, there is no yet universal explanation about the phenomenon of the $1/f^a$ behavior. Opinions have been expressed (e.g., see Ref.[13]) that it does not arise as a consequence of particular physical interactions, but it is a generic manifestation of complex systems.

It has been recently shown[40, 46, 47, 48, 49, 50, 51, 52, 53, 54, 55, 56, 57] that novel dynamic features hidden behind the time series of complex systems can emerge if we analyze them in terms of a newly introduced time domain, termed natural time χ (see below). It seems that this analysis enables the study of the dynamic evolution of a complex system and identifies when the system enters a critical stage. Natural time domain is optimal[58] for enhancing the signal's localization in the time frequency space, which conforms to the desire to reduce uncertainty and extract signal information as much as possible. In a time series comprising N events, the *natural time* $\chi_k = k/N$ serves as an index[40, 46, 47] for the occurrence of the k-th event. The evolution of the pair (χ_k, Q_k) is studied[36, 40, 46, 47, 48, 49, 50, 51, 52, 53, 55, 56], where Q_k denotes a quantity proportional to the energy released in the k-th event. For example, for dichotomous signals, which is frequently the case of SES activities, Q_k stands for the duration of the k-th pulse. The normalized power spectrum $\Pi(\omega) \equiv |\Phi(\omega)|^2$ was introduced[40, 46,

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[*] Electronic address: pvaro@otenet.gr

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Panepistimiopolis, Zografos 157 84, Athens, Greece
[2] *Solid Earth Physics Institute, Physics Department,*
University of Athens, Panepistimiopolis, Zografos 157 84, Athens, Greece

Abstract

By making use of the concept of natural time, a simple model is proposed which exhibits the $1/f^a$ behavior with a close to unity. The properties of the model are compared to those of the Seismic Electric Signals (SES) activities that have been found to obey the ubiquitous $1/f^a$ behavior with $a \approx 1$. This comparison, which is made by using the most recent SES data, reveals certain similarities, but the following important difference is found: The model suggests that the entropy S_- under time reversal becomes larger compared to the entropy S in forward time, thus disagreeing with the experimental SES results which show that S may be either smaller or larger than S_-. This might be due to the fact that SES activities exhibit *critical* dynamics, while the model cannot capture all the characteristics of such dynamics.

PACS numbers: 05.40.-a, 05.45.Tp, 91.30.Dk, 89.75.-k

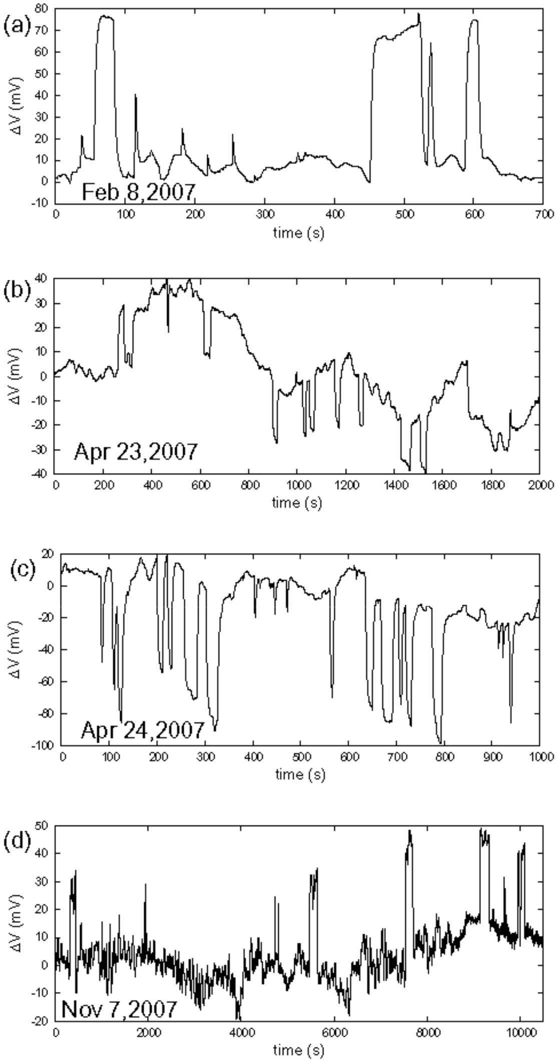


FIG. 5: Four electric signals recorded at PAT(sampling rate f_{exp}=1 sample/sec) on February 8, 2007(a), April 23, 2007(b), April 24, 2007(c) and November 7, 2007(d).

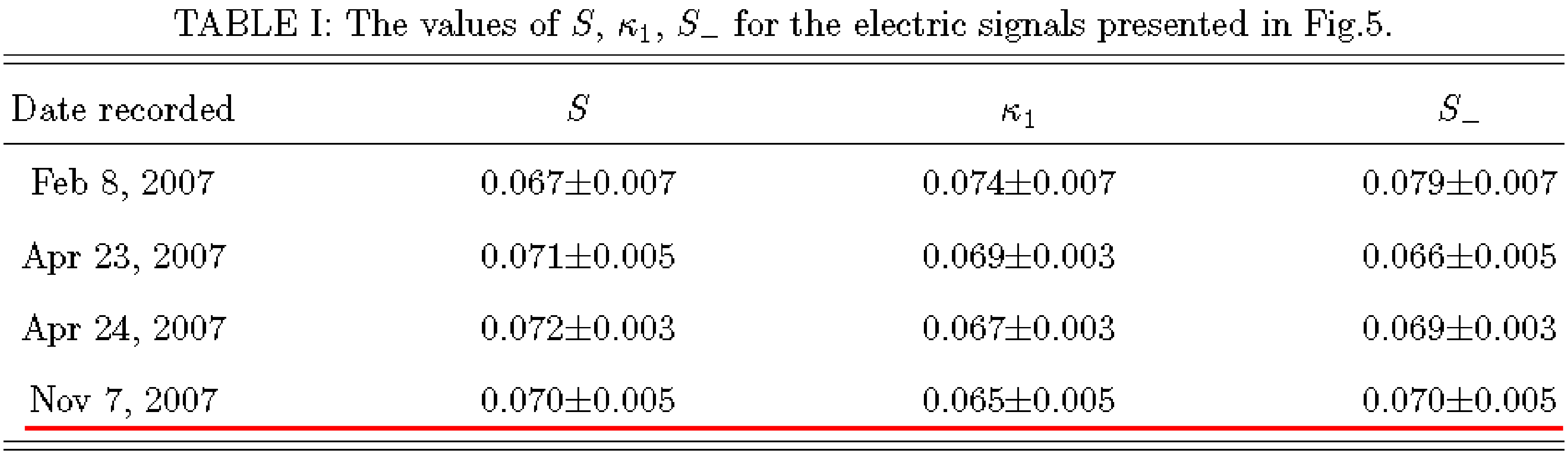


TABLE I: The values of S, κ_1, S_- for the electric signals presented in Fig.5.

Date recorded	S	κ_1	S_-
Feb 8, 2007	0.067±0.007	0.074±0.007	0.079±0.007
Apr 23, 2007	0.071±0.005	0.069±0.003	0.066±0.005
Apr 24, 2007	0.072±0.003	0.067±0.003	0.069±0.003
Nov 7, 2007	0.070±0.005	0.065±0.005	0.070±0.005

IV. CONCLUSIONS

In summary, using the newly introduced concept of natural time:(a) A simple model is proposed that exhibits $1/f^a$ behavior with a close to unity. (b) Electric signals, recorded during the last few months in Greece, are classified as SES activities since they exhibit *infinitely* ranged temporal correlations.

……

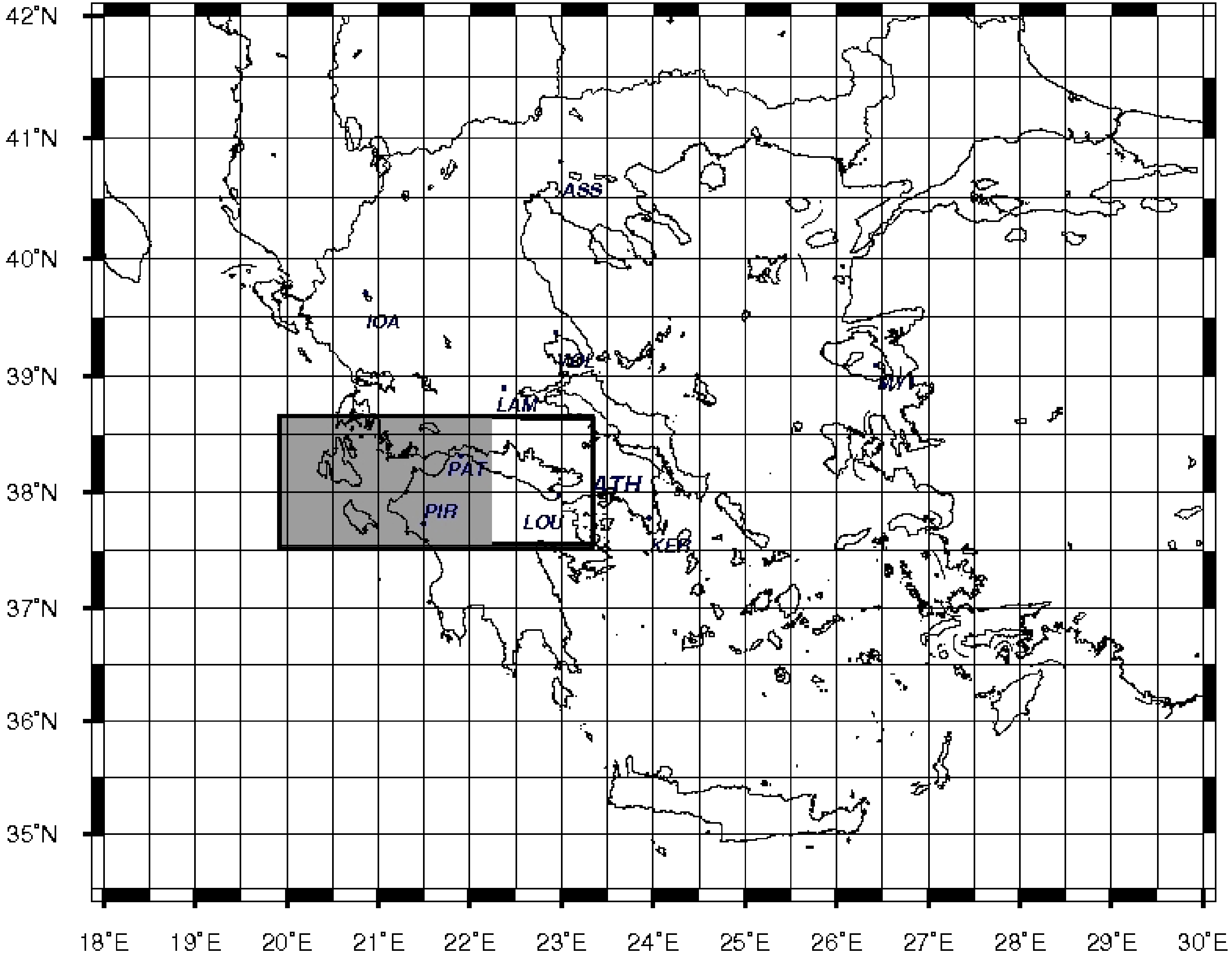
APPENDIX: WHAT HAPPENED AFTER THE SES ACTIVITIES DEPICTED IN FIG.5

We clarify that, during the last decade, preseismic information[65] based on SES activities is issued *only* when the magnitude of the strongest EQ of the impending EQ activity is estimated -by means of the SES amplitude[26–30] to be comparable to 6.0 units or larger[36].]

……

3. Study of the seismicity after the SES activity on November 7, 2007

This study (along the lines explained above) is still in progress by investigating the seismicity in the area B of Fig.8 as well as in the larger area, i.e., $N^{38.6}_{37.6}E^{20.0}_{23.3}$.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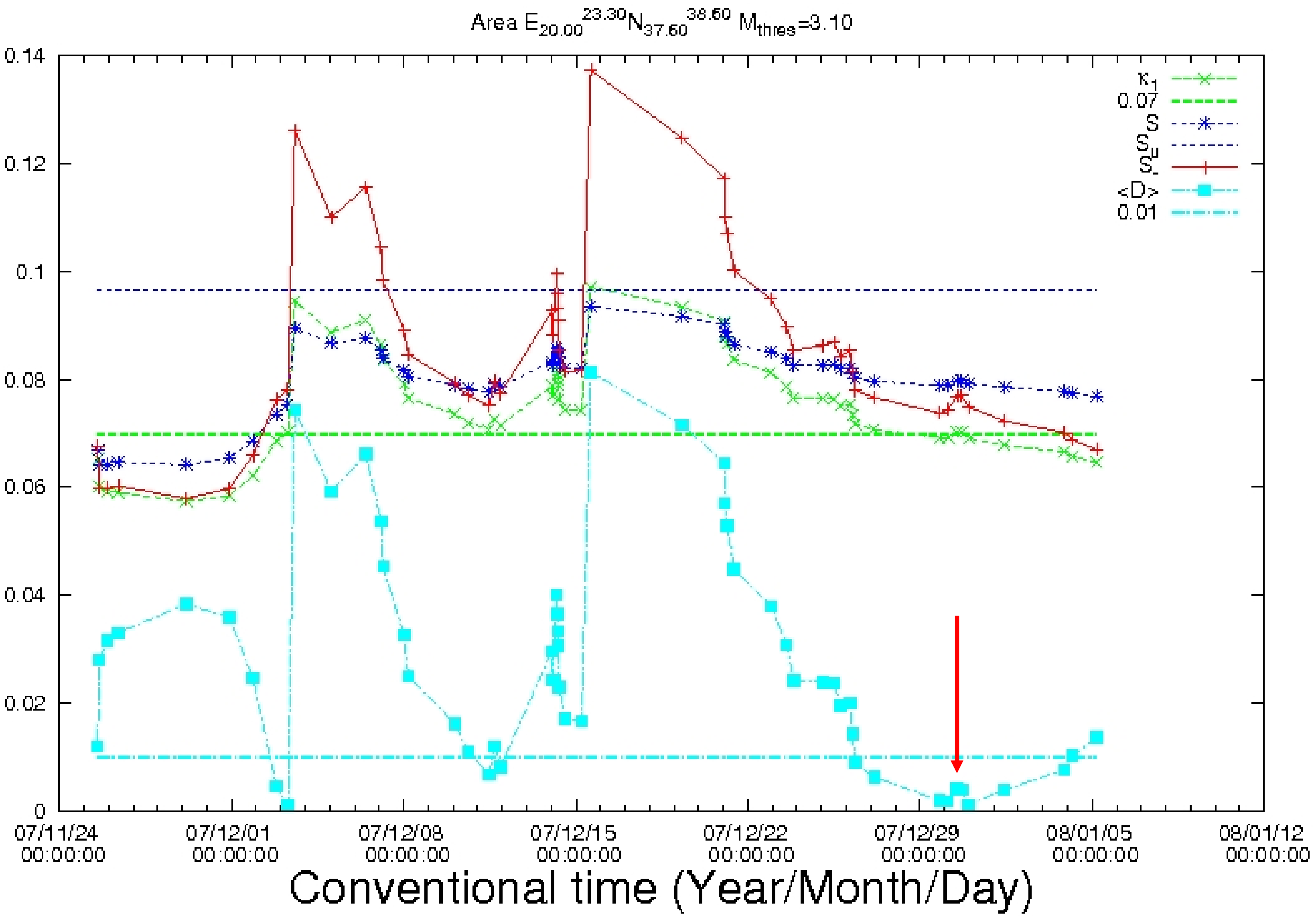
Area E20.00 23.30 N37.60 38.60 Mthres=3.10
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
κ1
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S
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S-
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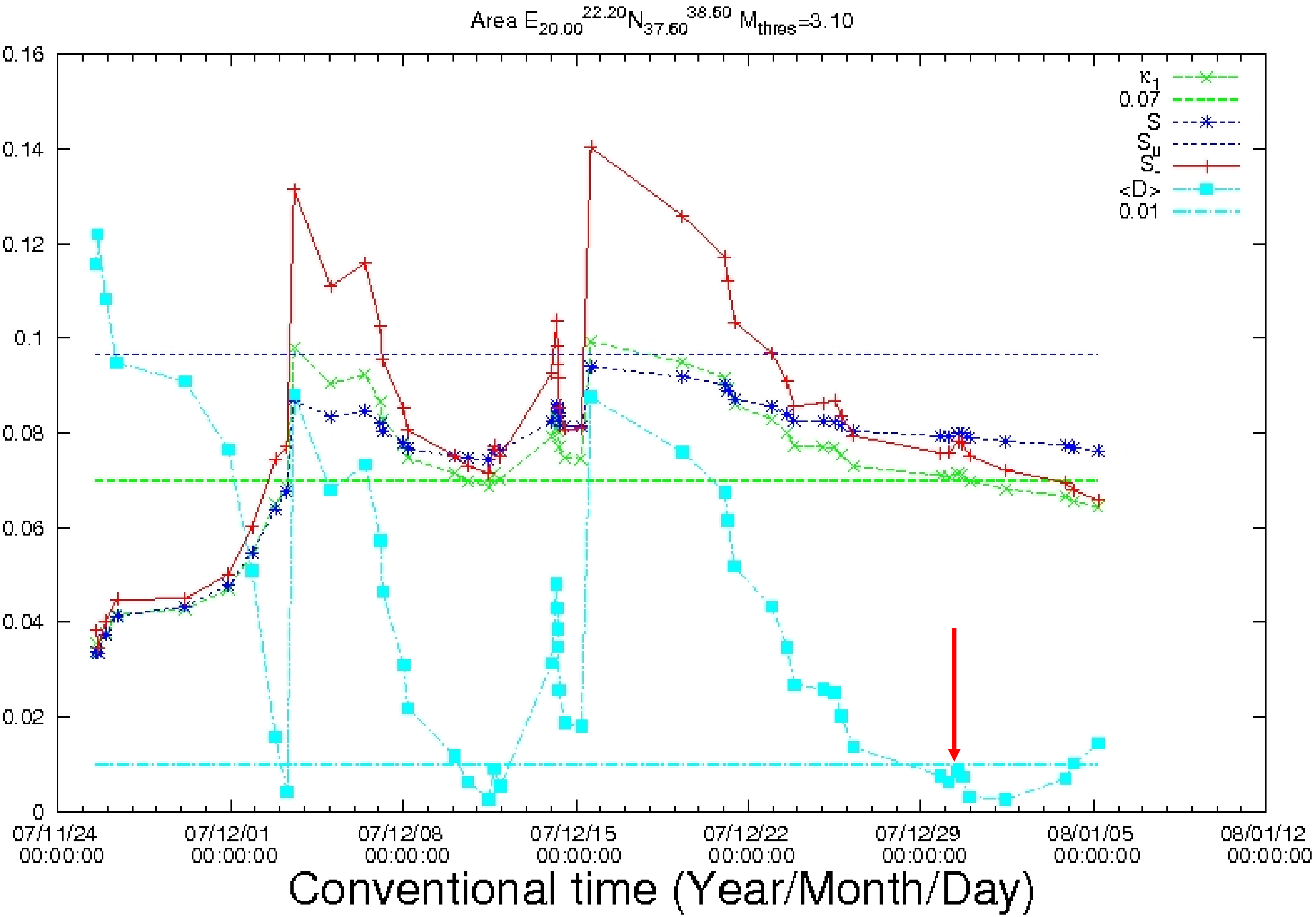
07/11/24 00:00:00
07/12/01 00:00:00
07/12/08 00:00:00
07/12/15 00:00:00
07/12/22 00:00:00
07/12/29 00:00:00
08/01/05 00:00:00
08/01/12 00:00:00
Conventional time (Year/Month/Day)

Large Area



Area $E_{20.00}^{22.20} N_{37.60}^{38.60}$ M_{thres}=3.10
0.16
0.14
0.12
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0.08
0.06
0.04
0.02
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κ_1
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S_u
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07/12/22 00:00:00
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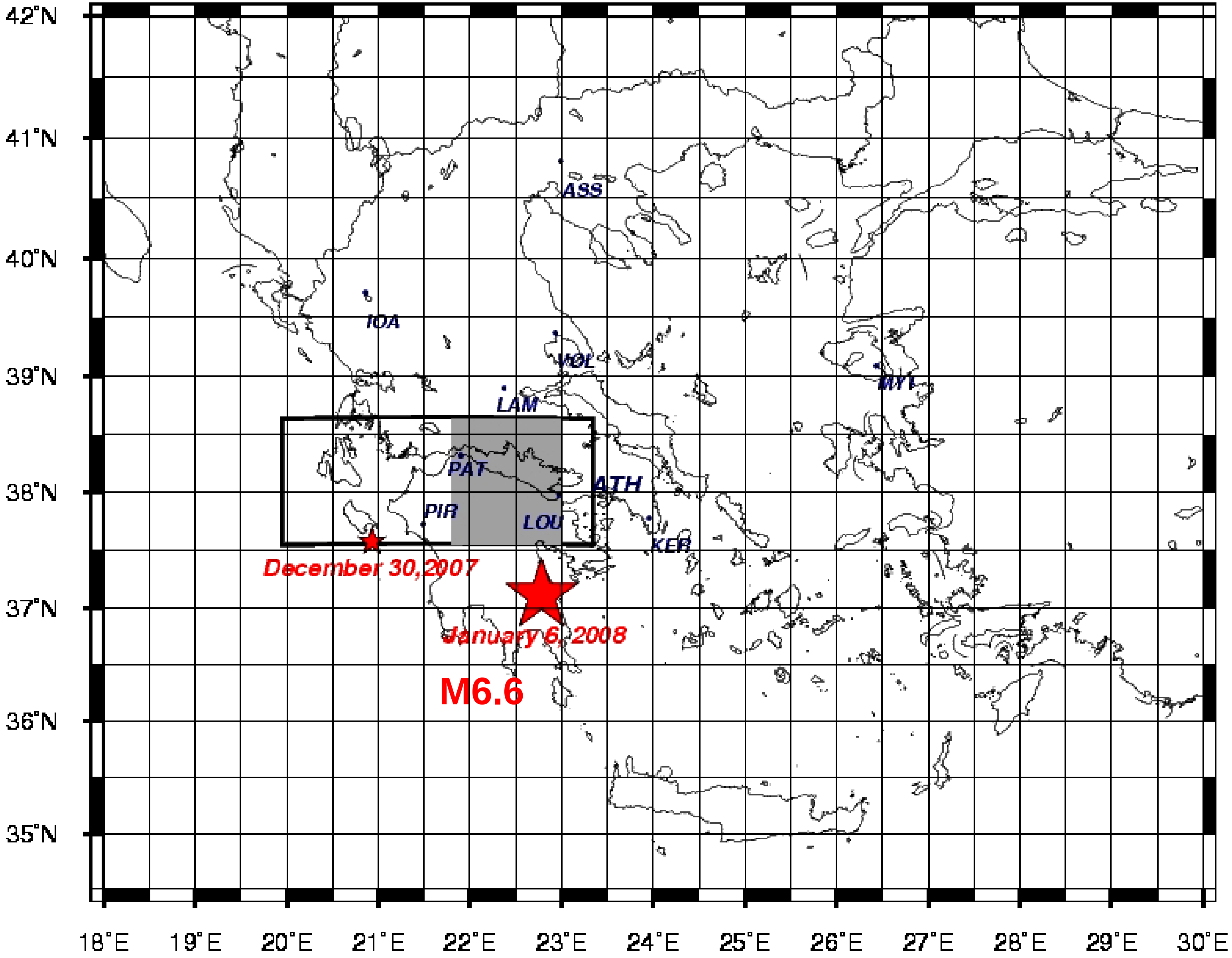
08/01/12 00:00:00
Conventional time (Year/Month/Day)

Small Area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December 30,2007
January 6, 2008
M6.6

Seismic Electric Signals and 1/f "noise" in natural time

P. A. Varotsos,[1,*] N. V. Sarlis,[1] and E. S. Skordas[1]

[1]*Solid State Section and Solid Earth Physics Institute, Physics Department,*
University of Athens, Panepistimiopolis, Zografos 157 84, Athens, Greece

By making use of the concept of natural time, a simple model is proposed which exhibits the $1/f^a$ behavior with a close to unity. The properties of the model are compared to those of the Seismic Electric Signals (SES) activities that have been found to obey the ubiquitous $1/f^a$ behavior with $a \approx 1$. This comparison, which is made by using the most recent SES data (that were followed by three magnitude 6.0-class earthquakes), reveals certain similarities, but the following important difference is found: The model suggests that the entropy S_- under time reversal becomes larger compared to the entropy S in forward time, thus disagreeing with the experimental SES results which show that S may be either smaller or larger than S_-. This might be due to the fact that SES activities exhibit *critical* dynamics, while the model cannot capture all the characteristics of such dynamics.

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It has been recently shown[41, 50, 51, 52, 53, 54, 55, 56, 57, 58, 59, 60, 61] that novel dynamic features hidden behind the time series of complex systems can emerge if we analyze them in terms of a newly introduced time domain, termed natural time χ (see below). It seems that this analysis enables the study of the dynamic evolution of a complex system and identifies when the system enters a critical stage. Natural time domain is optimal[62] for enhancing the signal's localization in the time frequency space, which conforms to the desire to reduce uncertainty and extract signal information as much as possible. In a time series comprising N events, the *natural time* χ_k =

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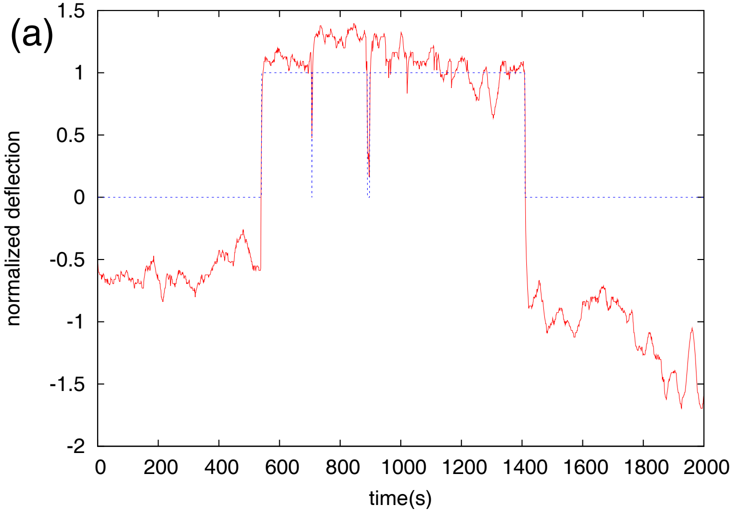
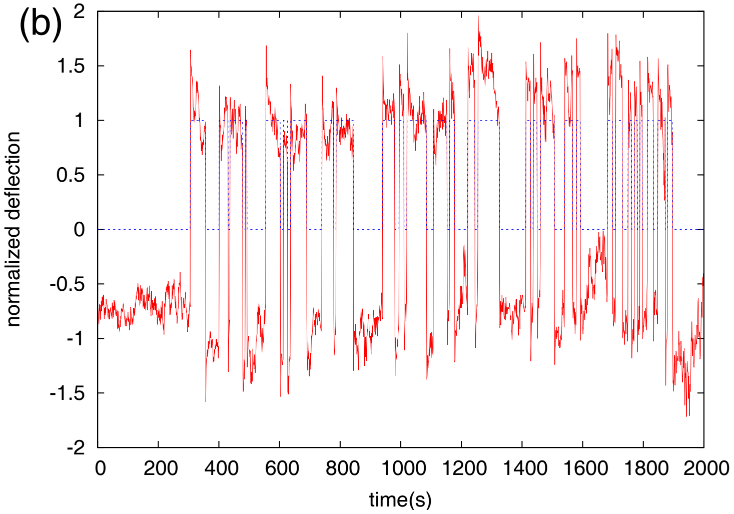
[*] Electronic address: pvaro@otenet.gr



10 January 2008 at PAT



14 January 2008 at PIR

(and additional ones on 21-24 Jan.)

Page 12 of the arXiv paper on February 1, 2008

…………One SES activity at PAT on 10 January, 2008 and another one on 14 January, 2008 at the station PIR located in western Greece, see Fig.13 (cf. The configuration of the measuring dipoles in the latter station is described in detail in the EPAPS document of Ref.[60]). Their subsequent seismicities are currently studied along the lines explained above considering the evolving seismicity in the following areas: Concerning the former SES activity at PAT the areas depicted in Fig.13, while for the one at PIR on 14 January, 2008, the subsequent seismicity is studied in the area B of Fig.9 as well as in the larger area $N_{36.0}^{38.6}E_{20.0}^{22.5}$ and in the one surrounding the epicenter[69] (36°N 23°E).

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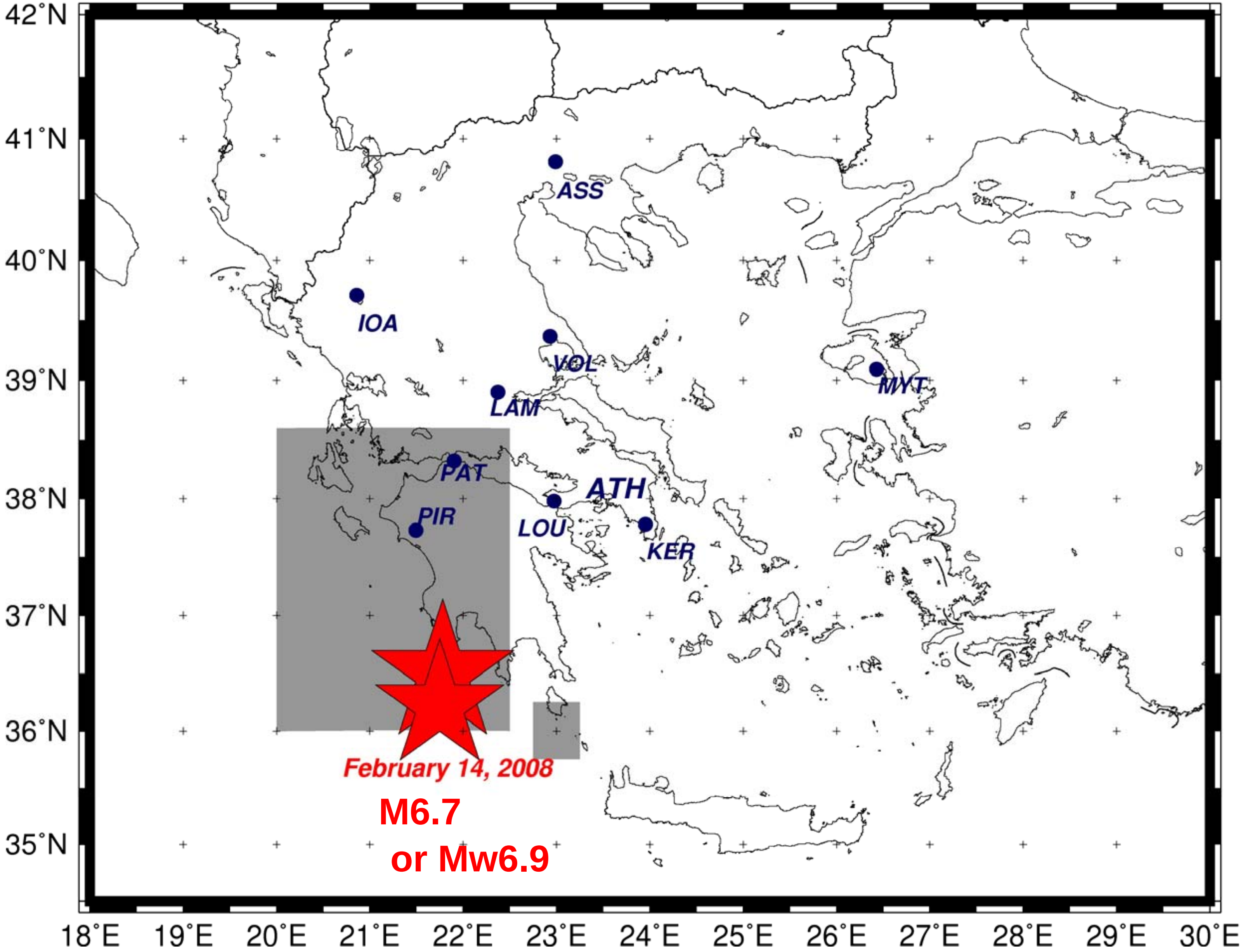
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February 14, 2008

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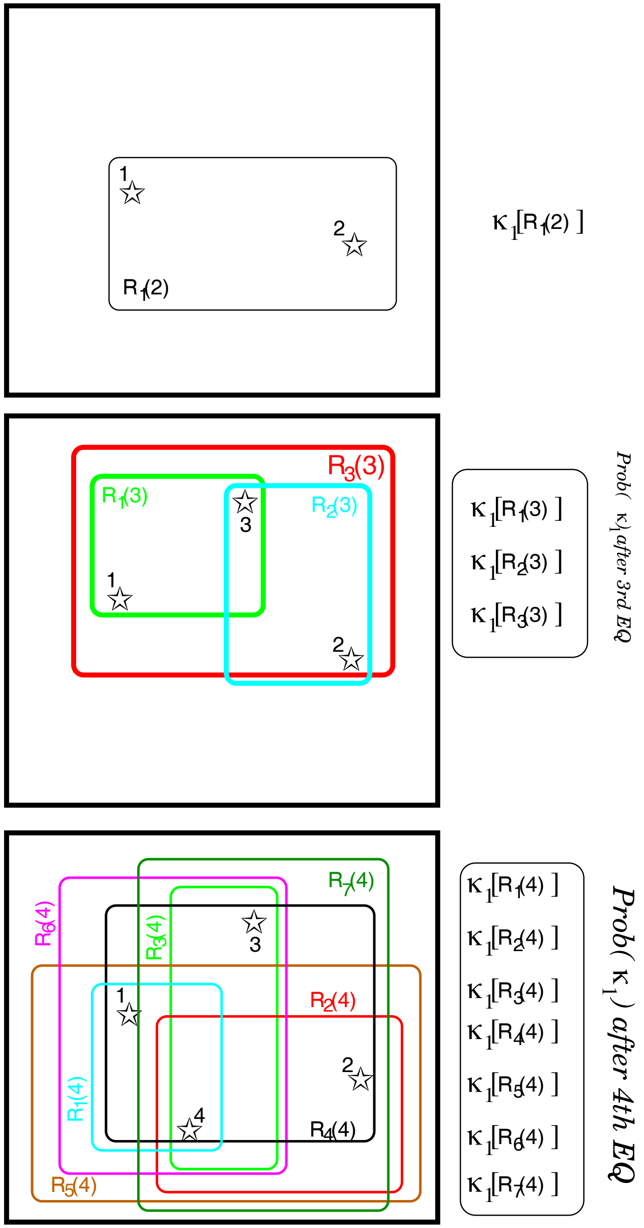
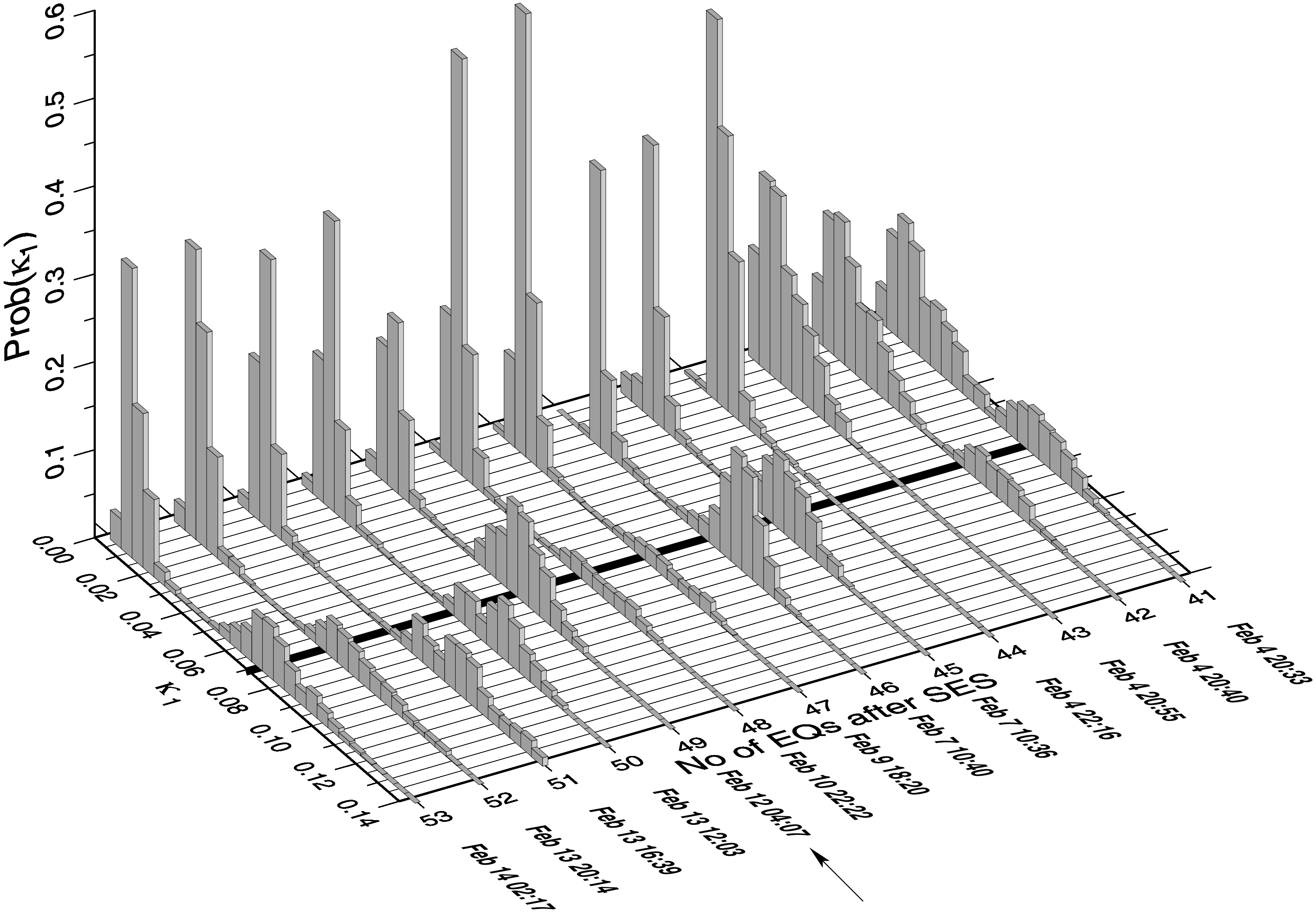
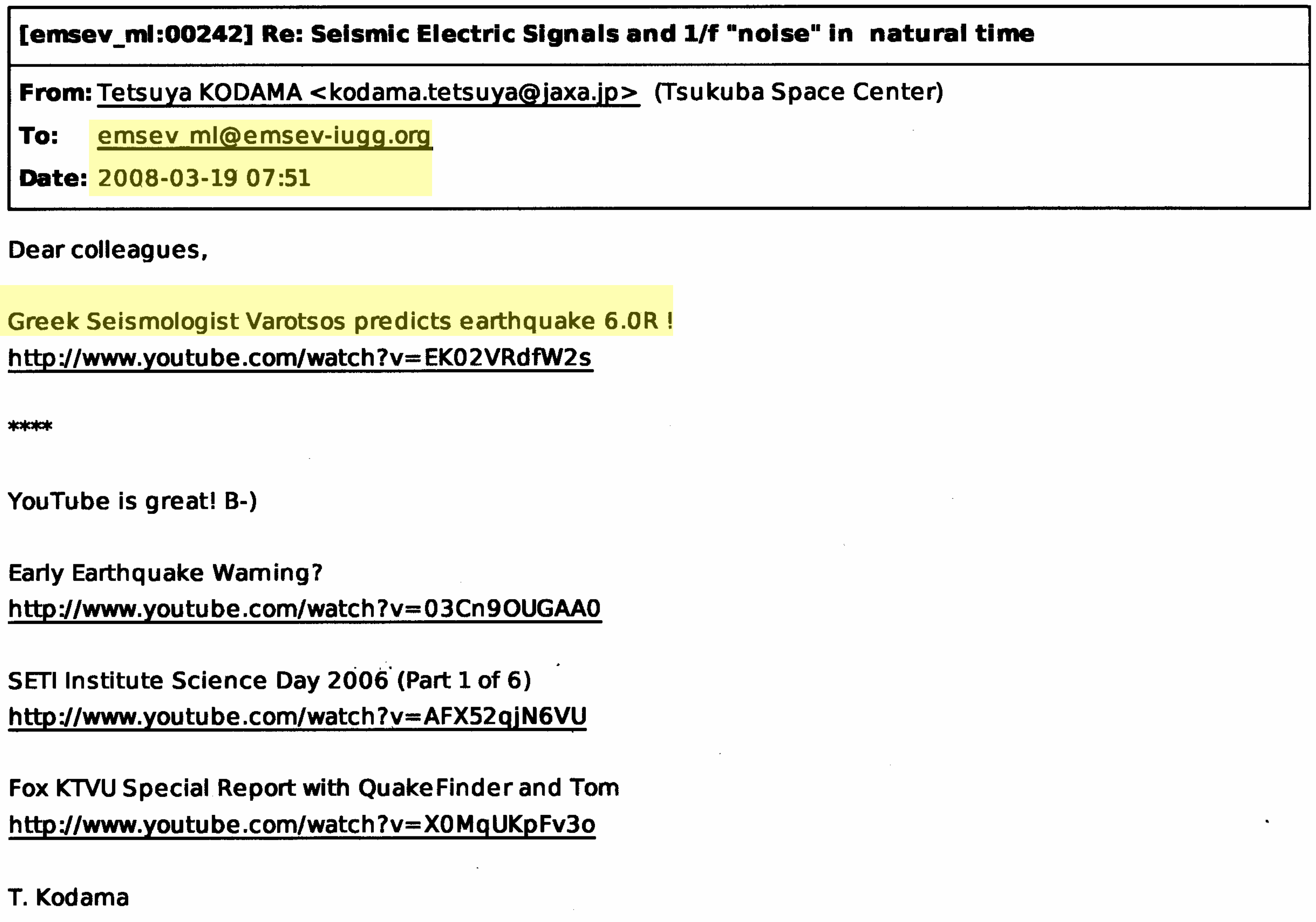


Fig. 1: The area A (in thick black rectangle) and its rectangular subareas $R_j(i)$, corresponding to the proper subsets immediately after the occurrence of the second EQ “2” (upper panel), the third EQ “3” (middle panel) and the fourth EQ “4” (bottom panel). The location of each EQ is shown by an open star. Right column shows that values can be obtained for each subset



Study of the Prob(κ_1) for the seismicity ($M_{thres}=3.2$) that occurred within the area $N_{36.0}^{38.6}E_{20.0}^{22.5}$ after the SES activity at PIR on Jan. 14, 2008.



[emsev_ml:00242] Re: Seismic Electric Signals and 1/f "noise" in natural time

From: Tetsuya KODAMA <kodama.tetsuya@jaxa.jp> (Tsukuba Space Center)
To: emsev_ml@emsev-iugg.org
Date: 2008-03-19 07:51

Dear colleagues,

Greek Seismologist Varotsos predicts earthquake 6.0R !
http://www.youtube.com/watch?v=EK02VRdfW2s

****

YouTube is great! B-)

Early Earthquake Warning?
http://www.youtube.com/watch?v=03Cn9OUGAA0

SETI Institute Science Day 2006 (Part 1 of 6)
http://www.youtube.com/watch?v=AFX52qjN6VU

Fox KTVU Special Report with QuakeFinder and Tom
http://www.youtube.com/watch?v=X0MqUKpFv3o

T. Kodama

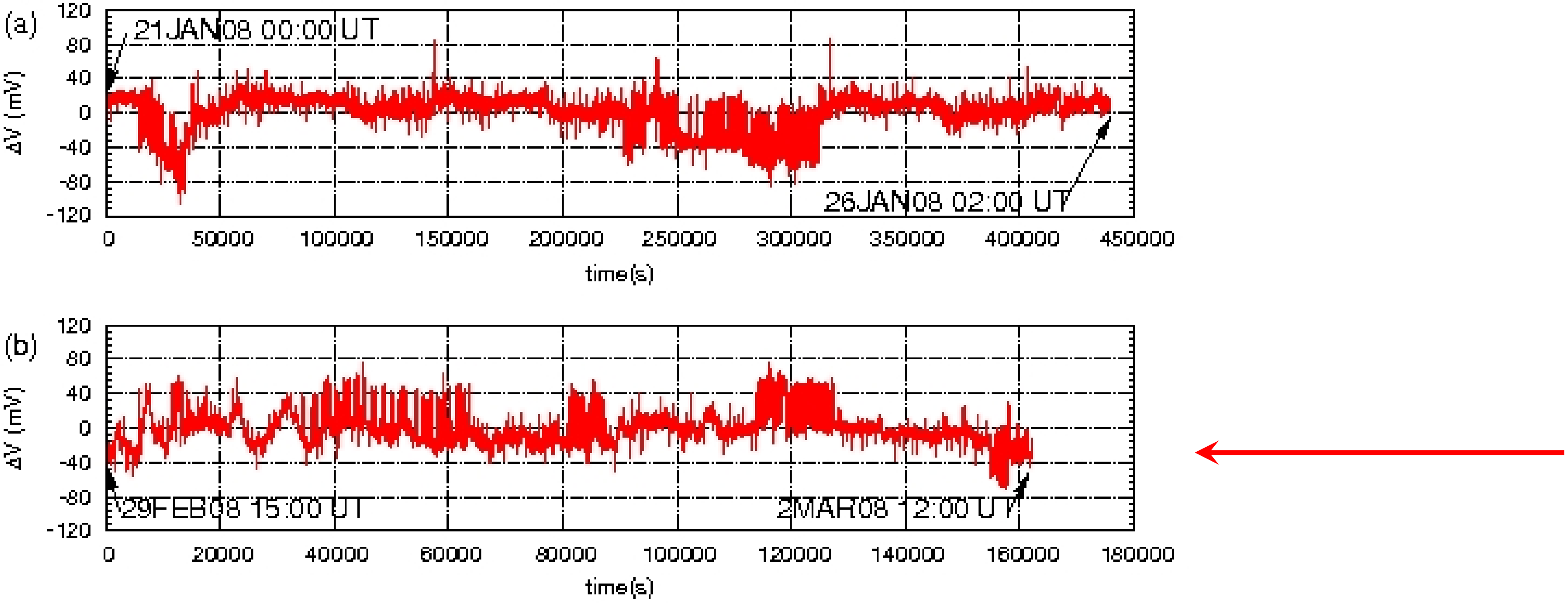
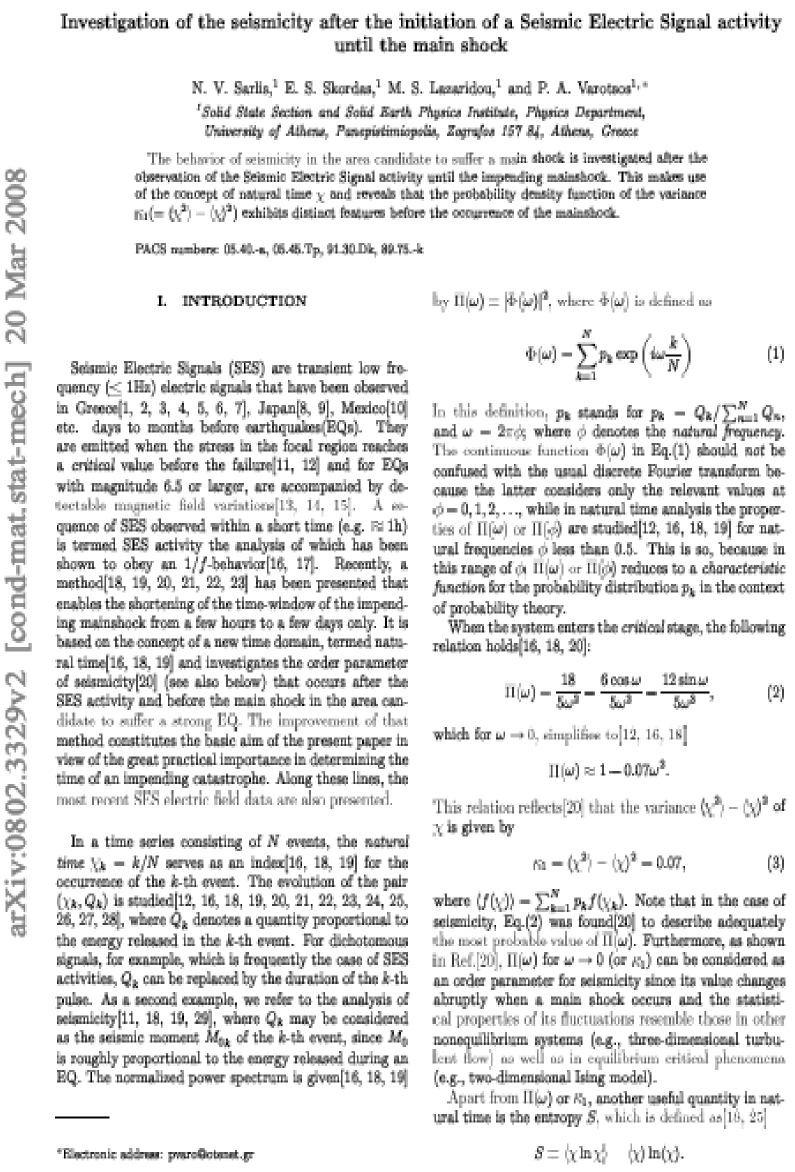


Fig.3 The most recent long duration SES activities recorded at PIR: (a) Jan. 21 – 26, 2008, (b) Feb. 29-March 2, 2008



Investigation of the seismicity after the initiation of a Seismic Electric Signal activity until the main shock

N. V. Sarlis,[1] E. S. Skordas,[1] M. S. Lazaridou,[1] and P. A. Varotsos[1,*]
[1] *Solid State Section and Solid Earth Physics Institute, Physics Department,*
University of Athens, Panepistimiopolis, Zografos 157 84, Athens, Greece

The behavior of seismicity in the area candidate to suffer a main shock is investigated after the observation of the Seismic Electric Signal activity until the impending mainshock. This makes use of the concept of natural time χ and reveals that the probability density function of the variance $\kappa_1 (= \langle \chi^2 \rangle - \langle \chi \rangle^2)$ exhibits distinct features before the occurrence of the mainshock.

PACS numbers: 05.40.-a, 05.45.Tp, 91.30.Dk, 89.75.-k

I. INTRODUCTION

Seismic Electric Signals (SES) are transient low frequency ($\leq$ 1Hz) electric signals that have been observed in Greece[1, 2, 3, 4, 5, 6, 7], Japan[8, 9], Mexico[10] etc. days to months before earthquakes(EQs). They are emitted when the stress in the focal region reaches a critical value before the failure[11, 12] and for EQs with magnitude 6.5 or larger, are accompanied by detectable magnetic field variations[13, 14, 15]. A sequence of SES observed within a short time (e.g. $\approx$ 1h) is termed SES activity the analysis of which has been shown to obey an $1/f$-behavior[16, 17]. Recently, a method[18, 19, 20, 21, 22, 23] has been presented that enables the shortening of the time-window of the impending mainshock from a few hours to a few days only. It is based on the concept of a new time domain, termed natural time[16, 18, 19] and investigates the order parameter of seismicity[20] (see also below) that occurs after the SES activity and before the main shock in the area candidate to suffer a strong EQ. The improvement of that method constitutes the basic aim of the present paper in view of the great practical importance in determining the time of an impending catastrophe. Along these lines, the most recent SES electric field data are also presented.

In a time series consisting of N events, the *natural time* $\chi_k = k/N$ serves as an index[16, 18, 19] for the occurrence of the k-th event. The evolution of the pair (χ_k, Q_k) is studied[12, 16, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28], where Q_k denotes a quantity proportional to the energy released in the k-th event. For dichotomous signals, for example, which is frequently the case of SES activities, Q_k can be replaced by the duration of the k-th pulse. As a second example, we refer to the analysis of seismicity[11, 18, 19, 29], where Q_k may be considered as the seismic moment M_{0k} of the k-th event, since M_0 is roughly proportional to the energy released during an EQ. The normalized power spectrum is given[16, 18, 19] by $\Pi(\omega) = |\Phi(\omega)|^2$, where $\Phi(\omega)$ is defined as

$$\Phi(\omega) = \sum_{k=1}^{N} p_k \exp\left(i\omega \frac{k}{N}\right) \qquad (1)$$

In this definition, p_k stands for $p_k = Q_k / \sum_{n=1}^{N} Q_n$, and $\omega = 2\pi\phi$, where ϕ denotes the *natural frequency*. The continuous function $\Phi(\omega)$ in Eq.(1) should *not* be confused with the usual discrete Fourier transform because the latter considers only the relevant values at $\phi = 0, 1, 2, \ldots$, while in natural time analysis the properties of $\Pi(\omega)$ or $\Pi(\phi)$ are studied[12, 16, 18, 19] for natural frequencies ϕ less than 0.5. This is so, because in this range of ϕ, $\Pi(\omega)$ or $\Pi(\phi)$ reduces to a *characteristic function* for the probability distribution p_k in the context of probability theory.

When the system enters the *critical stage*, the following relation holds[16, 18, 20]:

$$\Pi(\omega) = \frac{18}{5\omega^2} - \frac{6\cos\omega}{5\omega^2} - \frac{12\sin\omega}{5\omega^3}, \qquad (2)$$

which for $\omega \rightarrow 0$, simplifies to[12, 16, 18]

$$\Pi(\omega) \approx 1 - 0.07\omega^2.$$

This relation reflects[20] that the variance $\langle \chi^2 \rangle - \langle \chi \rangle^2$ of χ is given by

$$\kappa_1 = \langle \chi^2 \rangle - \langle \chi \rangle^2 = 0.07, \qquad (3)$$

where $\langle f(\chi) \rangle = \sum_{k=1}^{N} p_k f(\chi_k)$. Note that in the case of seismicity, Eq.(2) was found[20] to describe adequately the most probable value of $\Pi(\omega)$. Furthermore, as shown in Ref.[20], $\Pi(\omega)$ for $\omega \rightarrow 0$ (or κ_1) can be considered as an order parameter for seismicity since its value changes abruptly when a main shock occurs and the statistical properties of its fluctuations resemble those in other nonequilibrium systems (e.g., three-dimensional turbulent flow) as well as in equilibrium critical phenomena (e.g., two-dimensional Ising model).

Apart from $\Pi(\omega)$ or κ_1, another useful quantity in natural time is the entropy S, which is defined as[16, 25]

$$S = \langle \chi \ln \chi \rangle - \langle \chi \rangle \ln \langle \chi \rangle.$$

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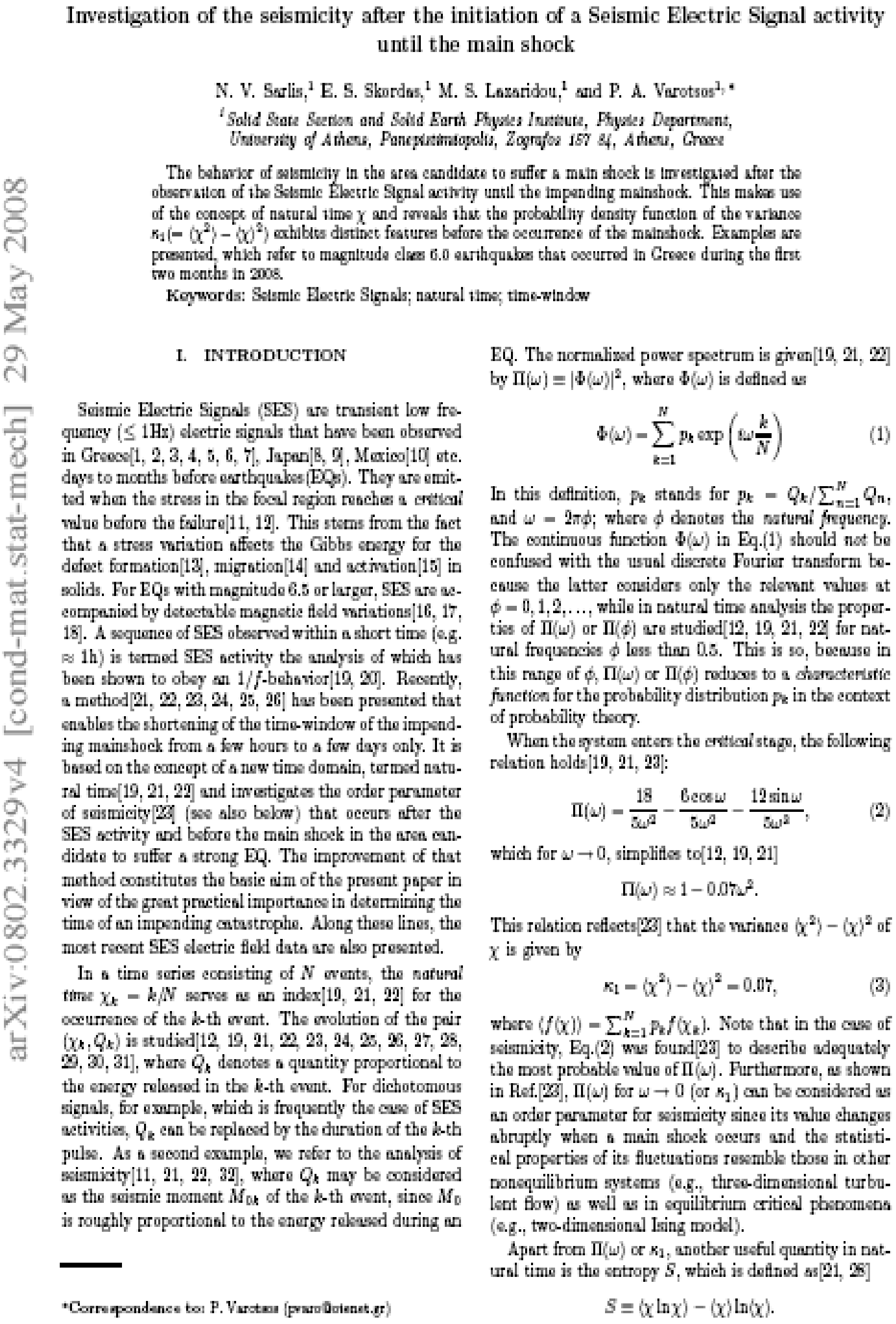
[*] Electronic address: pvaro@otenet.gr

No true coincidence yet



Investigation of the seismicity after the initiation of a Seismic Electric Signal activity until the main shock

N. V. Sarlis,[1] E. S. Skordas,[1] M. S. Lazaridou,[1] and P. A. Varotsos[1, *]

[1] *Solid State Section and Solid Earth Physics Institute, Physics Department, University of Athens, Panepistimiopolis, Zografos 157 84, Athens, Greece*

The behavior of seismicity in the area candidate to suffer a main shock is investigated after the observation of the Seismic Electric Signal activity until the impending mainshock. This makes use of the concept of natural time χ and reveals that the probability density function of the variance $\kappa_1 (= \langle\chi^2\rangle - \langle\chi\rangle^2)$ exhibits distinct features before the occurrence of the mainshock. Examples are presented, which refer to magnitude class 6.0 earthquakes that occurred in Greece during the first two months in 2008.

Keywords: Seismic Electric Signals; natural time; time-window

I. INTRODUCTION

Seismic Electric Signals (SES) are transient low frequency ($\leq$ 1Hz) electric signals that have been observed in Greece[1, 2, 3, 4, 5, 6, 7], Japan[8, 9], Mexico[10] etc. days to months before earthquakes(EQs). They are emitted when the stress in the focal region reaches a *critical* value before the failure[11, 12]. This stems from the fact that a stress variation affects the Gibbs energy for the defect formation[13], migration[14] and activation[15] in solids. For EQs with magnitude 6.5 or larger, SES are accompanied by detectable magnetic field variations[16, 17, 18]. A sequence of SES observed within a short time (e.g. $\approx$ 1h) is termed SES activity the analysis of which has been shown to obey an $1/f$-behavior[19, 20]. Recently, a method[21, 22, 23, 24, 25, 26] has been presented that enables the shortening of the time-window of the impending mainshock from a few hours to a few days only. It is based on the concept of a new time domain, termed natural time[19, 21, 22] and investigates the order parameter of seismicity[23] (see also below) that occurs after the SES activity and before the main shock in the area candidate to suffer a strong EQ. The improvement of that method constitutes the basic aim of the present paper in view of the great practical importance in determining the time of an impending catastrophe. Along these lines, the most recent SES electric field data are also presented.

In a time series consisting of N events, the *natural time* $\chi_k = k/N$ serves as an index[19, 21, 22] for the occurrence of the k-th event. The evolution of the pair (χ_k, Q_k) is studied[12, 19, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31], where Q_k denotes a quantity proportional to the energy released in the k-th event. For dichotomous signals, for example, which is frequently the case of SES activities, Q_k can be replaced by the duration of the k-th pulse. As a second example, we refer to the analysis of seismicity[11, 21, 22, 32], where Q_k may be considered as the seismic moment M_{0k} of the k-th event, since M_0 is roughly proportional to the energy released during an EQ. The normalized power spectrum is given[19, 21, 22] by $\Pi(\omega) = |\Phi(\omega)|^2$, where $\Phi(\omega)$ is defined as

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This relation reflects[23] that the variance $\langle\chi^2\rangle - \langle\chi\rangle^2$ of χ is given by

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where $\langle f(\chi)\rangle = \sum_{k=1}^{N} p_k f(\chi_k)$. Note that in the case of seismicity, Eq.(2) was found[23] to describe adequately the most probable value of $\Pi(\omega)$. Furthermore, as shown in Ref.[23], $\Pi(\omega)$ for $\omega \to 0$ (or κ_1) can be considered as an order parameter for seismicity since its value changes abruptly when a main shock occurs and the statistical properties of its fluctuations resemble those in other nonequilibrium systems (e.g., three-dimensional turbulent flow) as well as in equilibrium critical phenomena (e.g., two-dimensional Ising model).

Apart from $\Pi(\omega)$ or κ_1, another useful quantity in natural time is the entropy S, which is defined as[21, 28]

$$S \equiv \langle\chi\ln\chi\rangle - \langle\chi\rangle\ln\langle\chi\rangle.$$

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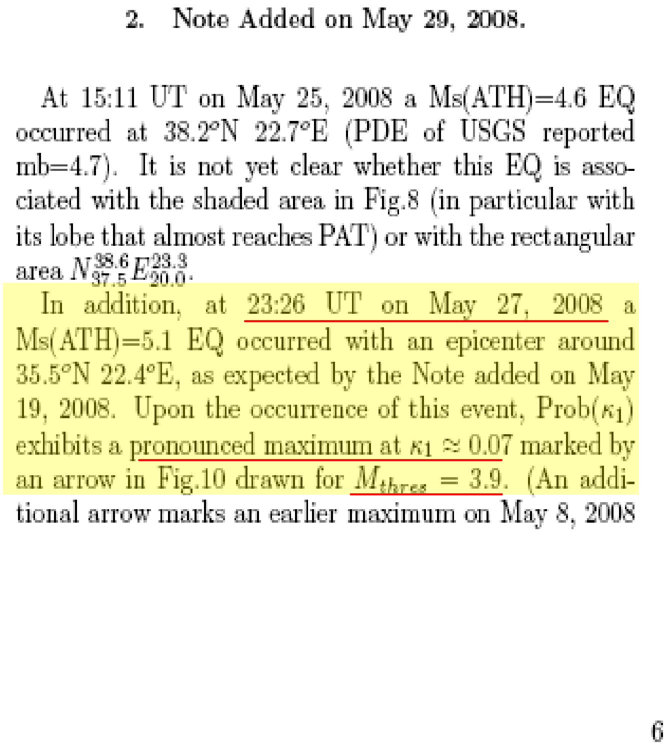
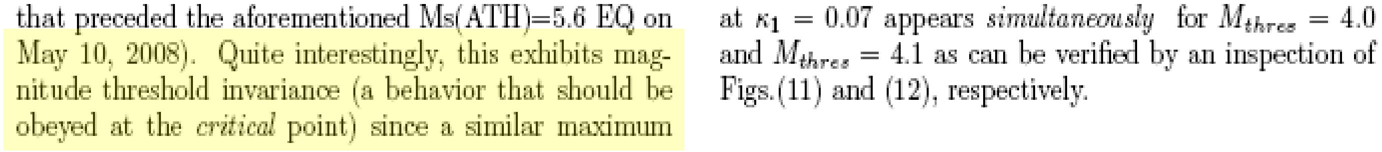
[*] Correspondence to: P. Varotsos (pvaro@otenet.gr)



2. Note Added on May 29, 2008.

At 15:11 UT on May 25, 2008 a Ms(ATH)=4.6 EQ occurred at 38.2°N 22.7°E (PDE of USGS reported mb=4.7). It is not yet clear whether this EQ is associated with the shaded area in Fig.8 (in particular with its lobe that almost reaches PAT) or with the rectangular area $N^{38.6}_{37.5}E^{23.3}_{20.0}$.

In addition, at 23:26 UT on May 27, 2008 a Ms(ATH)=5.1 EQ occurred with an epicenter around 35.5°N 22.4°E, as expected by the Note added on May 19, 2008. Upon the occurrence of this event, Prob(κ_1) exhibits a pronounced maximum at $\kappa_1 \simeq 0.07$ marked by an arrow in Fig.10 drawn for $M_{thres} = 3.9$. (An additional arrow marks an earlier maximum on May 8, 2008



that preceded the aforementioned Ms(ATH)=5.6 EQ on May 10, 2008). Quite interestingly, this exhibits magnitude threshold invariance (a behavior that should be obeyed at the *critical* point) since a similar maximum at $\kappa_1 = 0.07$ appears *simultaneously* for $M_{thres} = 4.0$ and $M_{thres} = 4.1$ as can be verified by an inspection of Figs.(11) and (12), respectively.

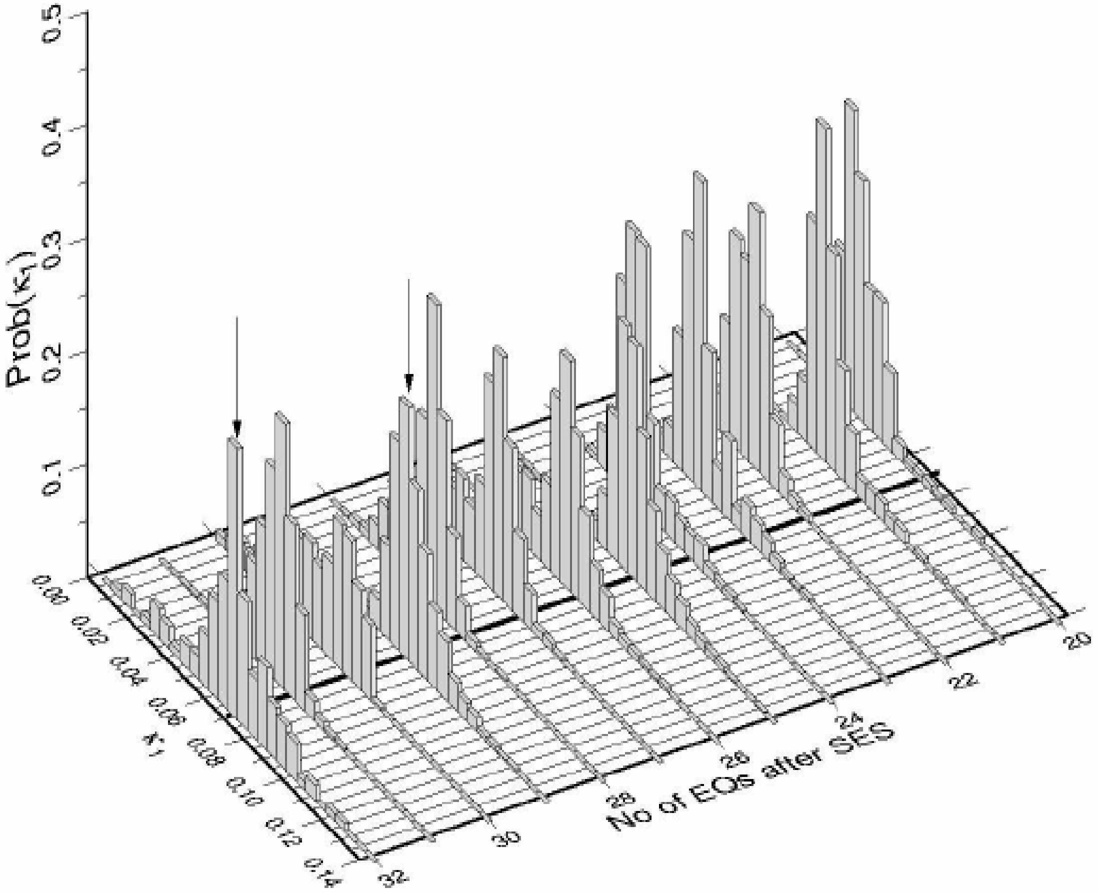


FIG. 10: Prob(κ_1) versus κ_1 of the seismicity, for $M_{thres} = 3.9$, (subsequent to the long duration SES activity recorded at PIR during February 29 to March 2, 2008) within the shaded area shown in Fig.8. The two arrows mark the maxima at $\kappa_1 = 0.07$ that occurred on May 8, 2008 (i.e., on the occurence of the 29th event after the SES) and on May 27, 2008 (i.e.,on the occurence of the 32nd event after the SES). The first maximum has been followed by the 5.6EQ on May 10, 2008, as described in the Appendix.

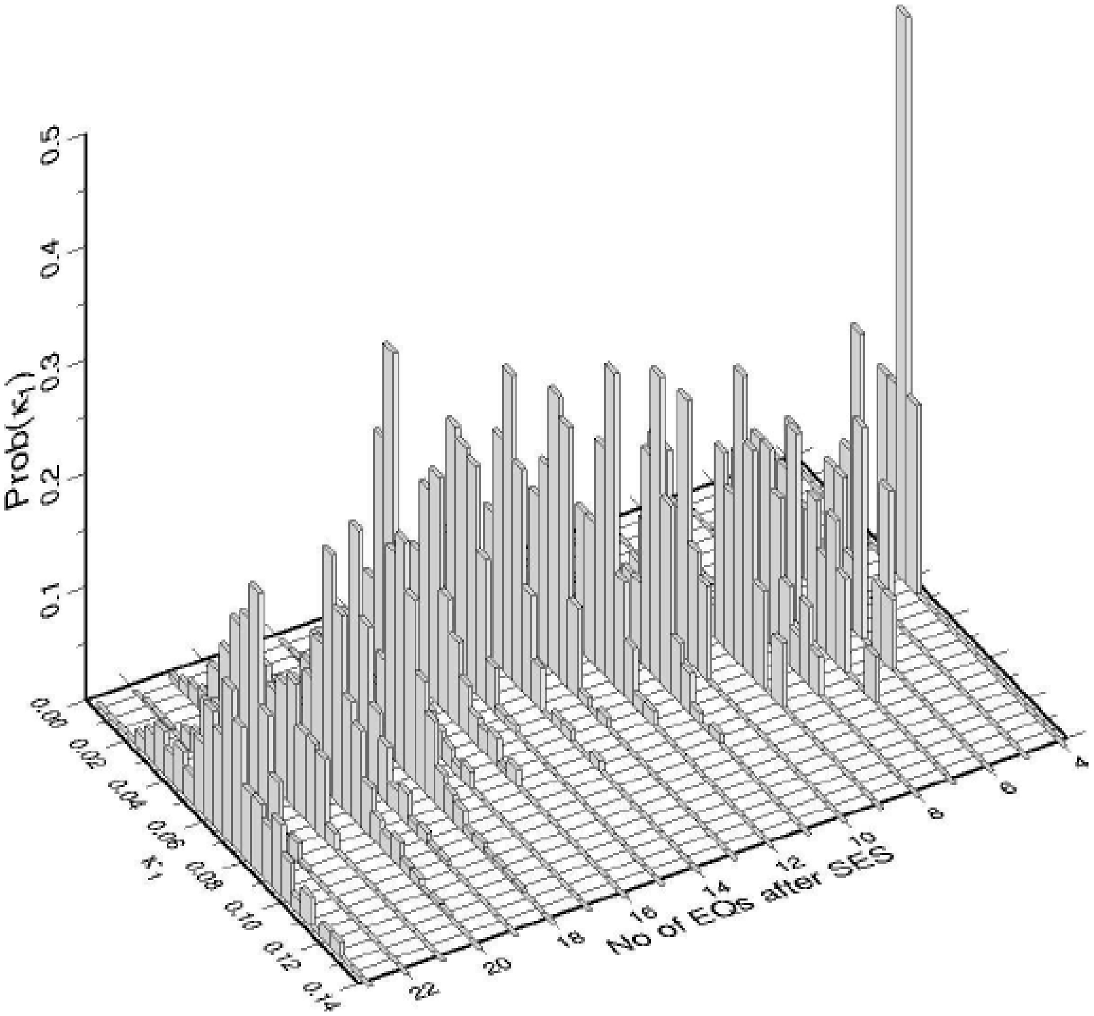


FIG. 11: The same as Fig.10, but for $M_{thres} = 4.0$. The last histogram corresponds to the 5.1 event on May 27, 2008 and exhibits a maximum at $\kappa_1 = 0.07$.

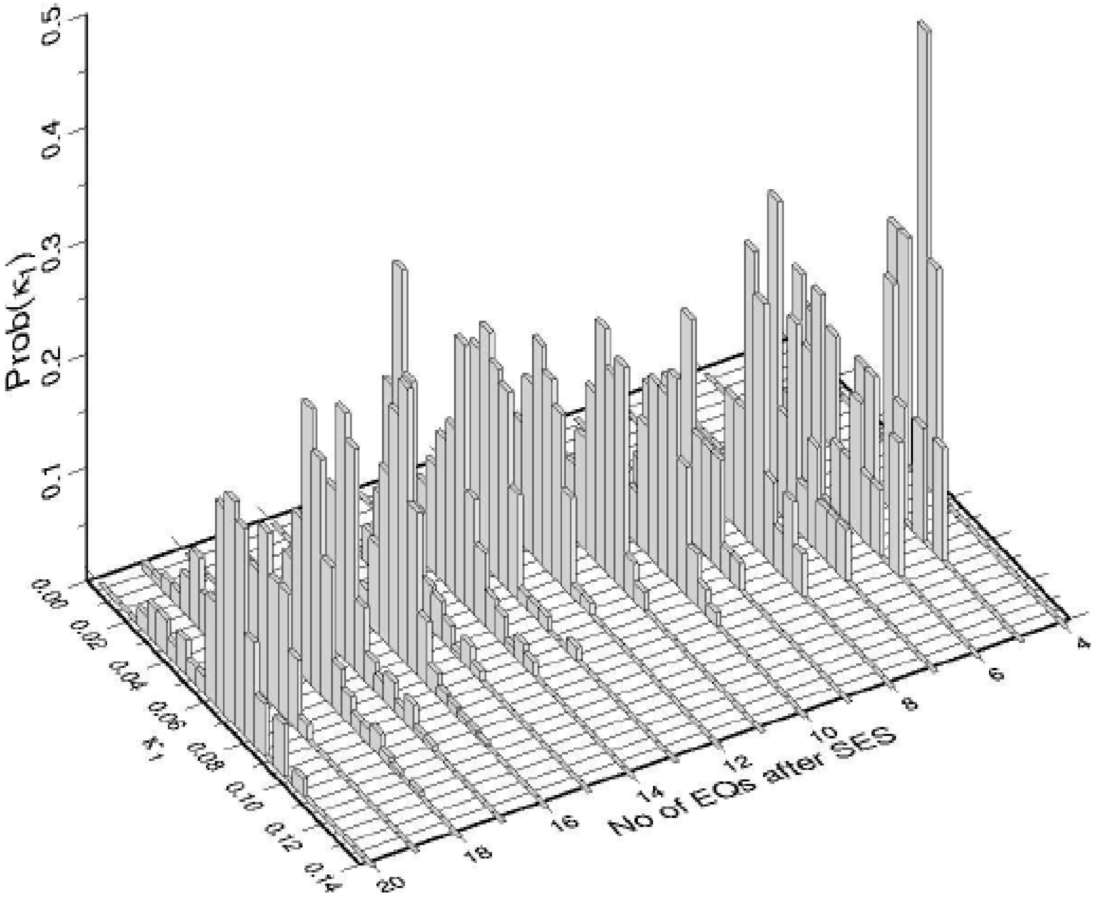
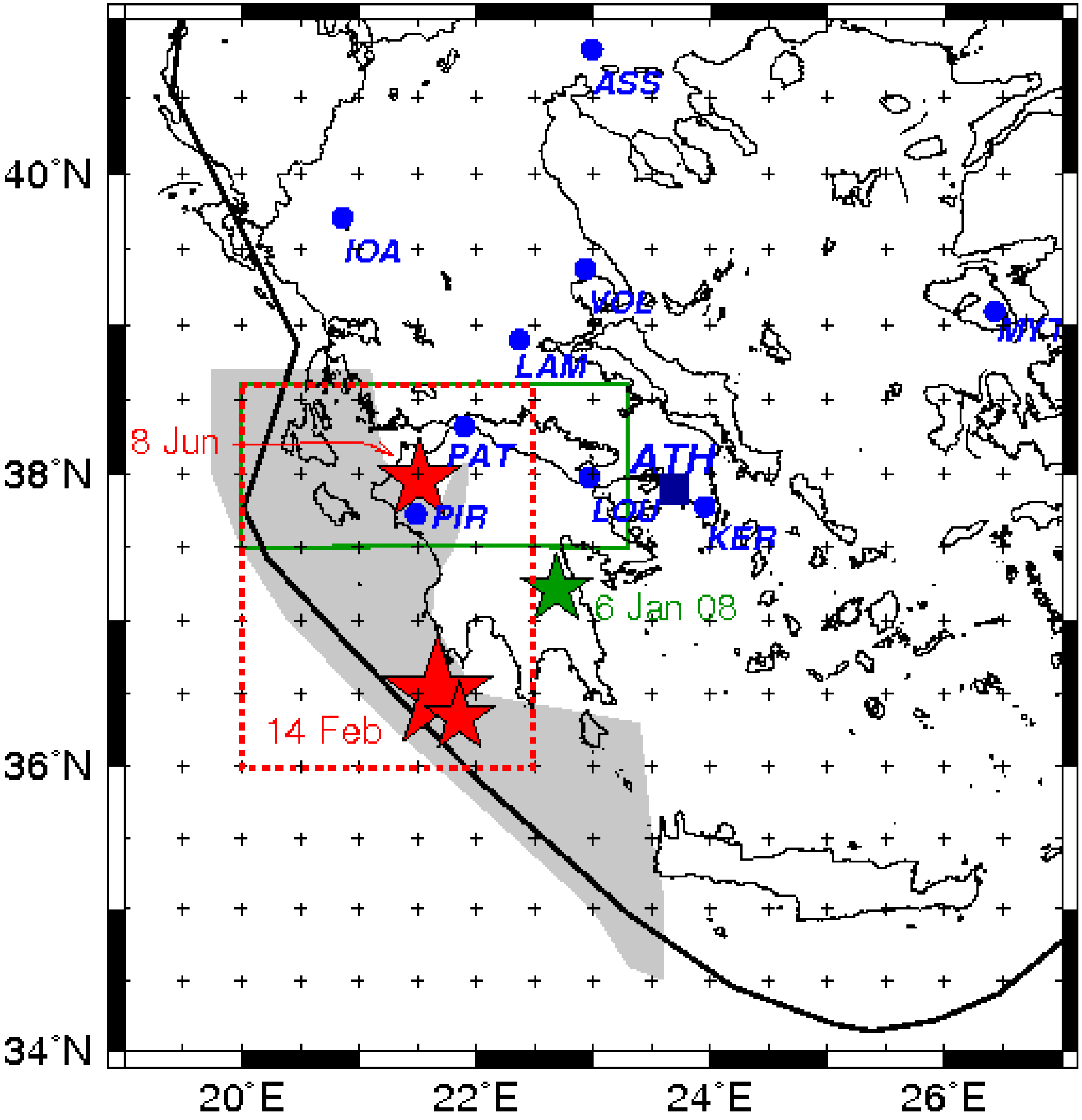


FIG. 12: The same as Fig.10, but for $M_{thres} = 4.1$. The last histogram corresponds to the 5.1 event on May 27, 2008 and exhibits a maximum at $\kappa_1 = 0.07$.



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