ELSEVIER

Physics of the Earth and Planetary Interiors 114 (1999) 141–163

PHYSICS
OF THE EARTH
AND PLANETARY
INTERIORS

Electromagnetic signals generated in the solid Earth by digital transmission of radio-waves as a plausible source for some so-called 'seismic electric signals'

V.-N. Pham [a,*], D. Boyer [a], J.-L. Le Mouël [a], G. Chouliaras [b], G.N. Stavrakakis [b]

[a] *Département de Géomagnétisme (UMR 7577, CNRS), Institut de Physique du Globe de Paris, 4 Place Jussieu, 75252 Paris Cedex 05, France*

[b] *Institute of Geodynamics, National Observatory of Athens, P.O. Box 200, 48 Thissio, 11810 Athens, Greece*

Received 13 January 1999; received in revised form 9 February 1999; accepted 9 February 1999

Abstract

Claims by the VAN group [Varotsos, P., Alexopoulos, K., 1984. Physical properties of the variations of the electric field of the earth preceding earthquakes, I. Tectonophysics 110, 73–98, and later works] to have developed a short-term earthquake prediction technique in Greece continue to arouse contentious debates [Claims of success in using geoelectrical precursors to predict earthquakes are criticized and defended, 1998. Letters, Phys. Today 51 (6), 15–100; Great debates in seismology: the VAN method of earthquake prediction, 1998. Eos 79, 573–580]. This is partly because of the unknown origin of the so-called 'seismic electric signals' (SES) precursors. Their particular characteristics are not those of the usual electromagnetic noise (cultural noise) or of the natural electromagnetic field (magnetotelluric field). In this paper, we show that transient electric signals looking like SES can be generated by digital transmitters of the radio-telecommunication network. Such signals have been observed in different regions of the world, including Greece and Vietnam. Their characteristics have been analyzed in a broad band of frequencies (10^{-3}–10^{3} Hz) in the Ioannina, Greece, site which is considered as the most 'sensitive area' of the VAN network. It is concluded that some of the signals recorded at this site and identified as SES are probably of artificial origin, and that the criteria used by the VAN group are not sufficient to guarantee that the so-called SES are not man-made. Without an extended and thorough study of the ambient electromagnetic noise in a broad band of frequencies and better information about the electrical properties of the deep structure beneath the monitoring station, earthquake predictions issued on the basis of signals recorded by the VAN network are of dubious significance.

Keywords: Seismic electric signals; VAN method; Earthquake prediction; Electromagnetic noise

1. Introduction

For more than a decade Varotsos et al. (commonly called 'VAN group') have been claiming repeated successes in short-term earthquake prediction in Greece. Their method (known as the 'VAN

* Corresponding author. Tel.: +33-144272411; fax: +33-144273373; e-mail: vnpham@ipgp.jussieu.fr

0031-9201/99/$ - see front matter
PII: S0031-9201(99)00050-3

method') is based on the detection of characteristic changes in the geoelectric potential, the so-called Seismic Electric Signals (SES) that are claimed to appear prior to earthquakes.

However, the VAN method remains highly controversial as shown by a recent GRL special issue 'Debate on VAN' (1996) and the book 'A Critical Review of VAN', edited by J. Lighthill (1996). Most of the debates have been focused on the statistical evaluation of VAN predictions and hypothetical physical mechanisms to explain the generation and propagation of SES as earthquake precursors. However very few papers have been devoted to the analysis and discussion of the characteristics of the SES signals themselves. These signals consist of long transient electric signals (duration > 10 s). One of their salient characteristics is that no significant variation of the magnetic field is observed in conjunction with the SES (Varotsos and Alexopoulos, 1984; Park, 1996).

Based on simultaneous observations at stations JAN E and JAN M located near the station IOA of the VAN network in the Ioannina region, Gruszow et al. (1995) confirmed that several long transient electric events were observed during 1993–1994, without any observable correlated transient horizontal magnetic field. But Gruszow et al. (1996) also showed the existence of a correlated transient vertical magnetic field in the case of the anomalous electric signals recorded on April 18 and 19, 1995 (which were claimed by the VAN group to be related to the Kozani earthquake in Northern Greece, Varotsos et al., 1996a), and proposed that they were due to artificial (industrial) sources. However Gruszow et al. acknowledged that they were not able to give a definite proof of this industrial origin. A more recent study of the characteristics of electromagnetic noise in the Ioannina region (Pham et al., 1998) suggests that a possible source of these signals is digital radio-telecommunication transmitters, which can produce long transient electric signals in the ground without observed correlated magnetic signals, like the so-called SES. In this paper we will give more details about these artificial signals not only in the Ioannina region but also in other regions of Greece (Gulf of Corinth) and in another country (Vietnam),

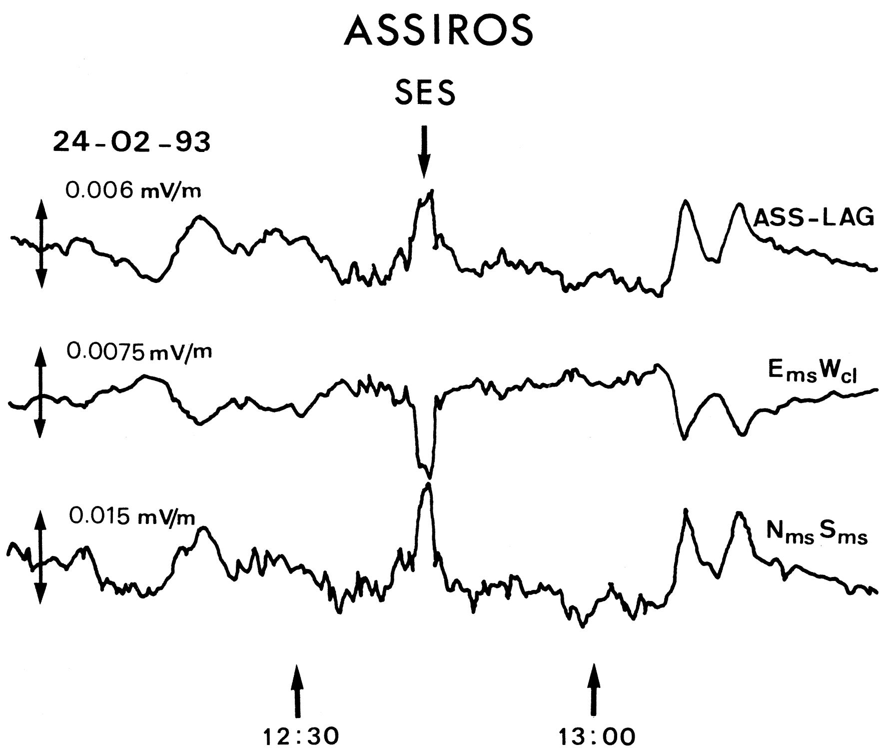


Fig. 1. Typical example of so-called single SES recorded at the Assiros station and corresponding to three configurations of dipoles (redrawn from Fig. 2 in Varotsos et al., 1996b).

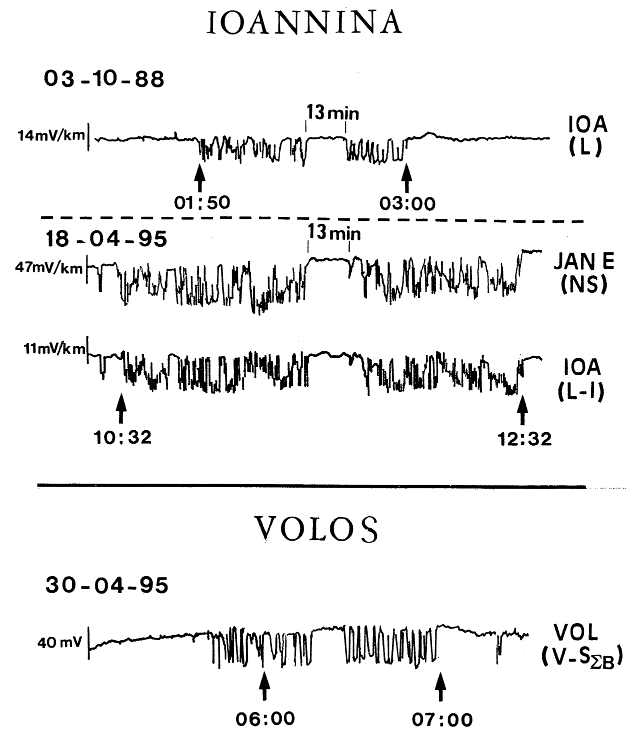


Fig. 2. Typical examples of so-called SESA recorded at the Ioannina and Volos stations (redrawn from Fig. 2 in Gruszow et al., 1996 and from Fig. 10 in Varotsos et al., 1996b).

and will explain theoretically the characteristics of these signals and finally will consider the origin of some signals identified as SES by the VAN group.

2. Characteristics of so-called SES

According to the VAN group (Varotsos et al., 1993), there are three types of SES: single SES, SES Activity (SESA) and Gradual Variation of Electric Field (GVEF). Uyeda (1996) has given a good short description of the characteristics of these signals: ''Single SES is a signal isolated in time having a duration ranging from half a minute to a several hours and precedes a single earthquake, whereas in SES Activity a number of SES appears within a short time, such as in a few hours or a day, and are followed by more than one seismic event.''

Fig. 1 shows a typical example of single SES recorded at the Assiros station of the VAN network on February 24, 1993 (Varotsos et al., 1996b), the duration of which is about 2 min and the amplitude about 10 mV/km. Fig. 2 shows some typical examples of signals labelled as SESA by VAN recorded at Ioannina and Volos stations (Varotsos et al., 1996b; Pham et al., 1998). The SESA have been more frequently observed since 1988, as seen in the summary of the set of predictions issued during the 8-year period (1987–1995) (Varotsos et al., 1996a, Table 1). ''GVEF, having a duration of many hours to days, is reported to appear weeks before a large earthquake. GVEF has amplitude an order of magnitude larger than usual SES... As the VAN group admits, however, GVEF has been observed only rarely, so that its physical nature, such as its duration, lead time, intensity and selectivity is largely still unknown in the present author's view'' (Uyeda, 1996). We think that GVEF, recorded principally during the first period of the VAN experiment, might have been artefacts due to the recording system of the VAN network, which was then equipped with very rudimentary instruments. Hereafter, we will focus on the discussion of the characteristics of signals labelled as single SES and SESA.

In their first paper on SES, Varotsos and Alexopoulos (1984) emphasized that ''no significant variation of the magnetic field is produced by the signal'' (SES). The absence of a magnetic signal correlated with the electric signal has been considered as a firm criterion for discriminating SES from artificial (man-made) noises which ''should have been accompanied by horizontal magnetic field variations'' (Varotsos et al., 1996b), and also from magnetotelluric (MT) signals which present strong horizontal

Table 1
Characteristics of SCM

Type	Frequency range	Sensitivity	Typical noise
CM12	10^{-3} Hz–200 Hz	50 mV/nT	0.33 pT/$\sqrt{\text{Hz}}$ at 0.2 Hz
CM216	1 Hz–2.5 kHz	100 mV/nT	3.3×10^{-3} pT/$\sqrt{\text{Hz}}$ at 700 Hz

magnetic fields (a few nanotesla) in the long period range (> 10 s). Observed SES and SESA have been correlated with subsequent seismic activity, by the VAN group.

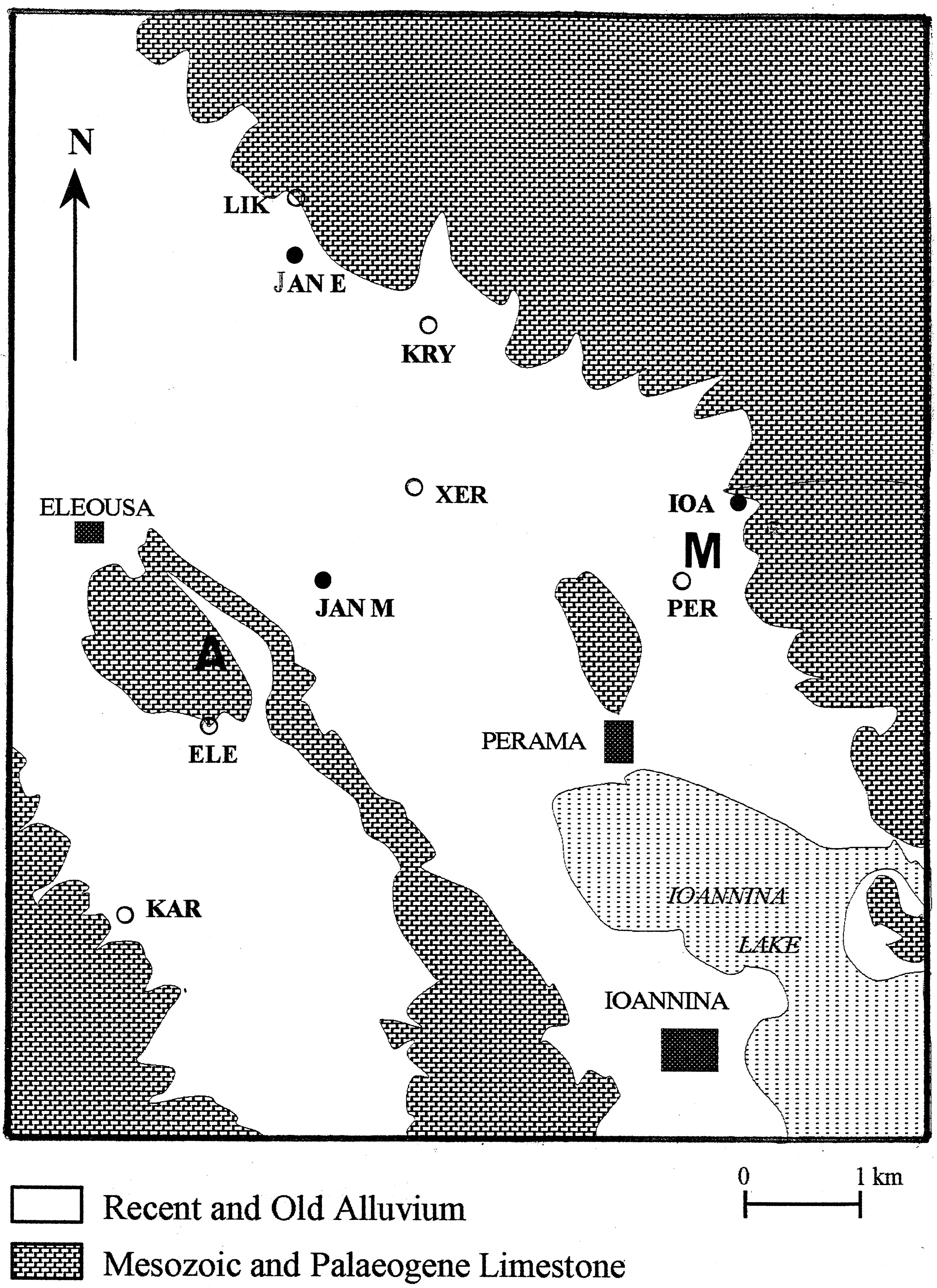


Fig. 3. Location of the six occupied sites (white circles) in the Ioannina region on a simplified geological background adapted from the 1/50 000 geological map of Greece. Black circles are for monitoring stations of the VAN network (IOA) and the IPGP stations (JAN E and JAN M). 'A' symbol represents the location of the transmitter antenna near Eleousa village, and 'M' the military base of Perama.

3. Characteristics of electromagnetic noise in the Ioannina region (NW Greece)

A major element of VAN's prediction method is the so-called 'selectivity': there are particular sites which are claimed to be sensitive only to SES from some specific focal area (Uyeda, 1996). The most sensitive site is claimed to be the IOA station in the Ioannina region (NW Greece) which has been operating continuously for more than 10 years and has recorded the largest number of SES. The selectivity map of this station covers a large area in Western Greece (Fig. 1 in Varotsos et al., 1996a). Note however that the boundaries claimed for the IOA sensitivity region have changed with time.

In order to get more information on the characteristics of the electromagnetic noise in the Ioannina region after 2 years of recording at JAN E and JAN M (Gruszow et al., 1995), the 'Institut de Physique du Globe de Paris' (IPGP) and the Institute of Geodynamics of the National Observatory of Athens (NOA) conducted a short campaign of measurements in the area in June 1997. This study showed the existence of a number of long transient electric signals (duration > 10 s) without measurable correlated magnetic signal, as in the case of so-called SES. These signals have an artificial origin and have been identified as generated by different kinds of digital radio-telecommunication transmitters installed in the Ioannina region. Some typical examples of these signals were presented in our previous paper (Pham et al., 1998). More details on their characteristics are discussed below.

Our data acquisition system was a high sensitivity magnetotelluric (MT) instrument designed for MT survey and covering a broad band of frequencies (10^{-3}–10^{3} Hz) in the ULF band (Pham et al., 1986, 1990). The electric (or telluric) sensors were low noise and stable unpolarizable electrodes of the lead–lead chloride type. The magnetic sensor was a high sensitivity search-coil magnetometer (SCM) with a flux-feedback, giving directly the magnetic field with a flat amplitude response in a large range of frequencies; two types of SCM were used, the CM12 and CM216, the characteristics of which are shown in Table 1. The analog device had five differential input channels, each equipped with an active notch filter of fourth order to eliminate the 50 Hz noise and its harmonics. A set of active high-pass and low-pass filters, with selective cut-off frequencies every decade, allowed us to choose different ranges of frequencies upon request. The digital acquisition was controlled by a portable microcomputer which displayed directly the signals on a screen for control and stored the data.

Six sites were occupied in the Ioannina region in June 1997 (Fig. 3). At each site four components of the electromagnetic signal were recorded: two electric and two horizontal magnetic components, along two perpendicular directions (130°N which corresponds to the general structural direction of the Ioannina basin (Fig. 3) and 40°N). The two electric dipoles were 100 m long. For ease of discussion, the dipoles along 40°N and 130°N directions are called hereafter respectively as NS and EW, and the horizontal magnetic components along these two same directions respectively as H and D. Consequently the two pairs of components of the electromagnetic field are EW–H and NS–D. The electromagnetic field was recorded in five overlapping ranges of two decades of frequencies (or periods) (Table 2).

Let us now present more details about the results from PER station, which is located near IOA station of the VAN network. This station was installed inside the military base of Perama on the football ground about 200 m from the office building.

Fig. 4a shows simultaneous recordings of the four electromagnetic components in the range G1 (10–10^{3} Hz). Despite the high dynamic range of our notch filter, these records only show the presence of the 50 Hz noise and its harmonics, with very strong amplitude: 100–200 mV/km for electric components and about 0.3–0.6 nT for magnetic components. Consequently no other signal can be detected in this range.

In Fig. 4b, corresponding to the range G2 (1–100 Hz), harmonics are filtered out; only the 50 Hz

Table 2
Recorded ranges of frequencies

Range	Cut-off band-pass frequencies (Hz)
G1	10–10^{3}
G2	1–10^{2}
G3	10^{-1}–10
G5	10^{-2}–1
G7	10^{-3}–10^{-1}

signal with a smaller amplitude persists. We can observe the existence of trains of spikes occurring more or less regularly about every 800 ms with a duration of about 300 ms.

Fig. 4c corresponds to the range G3 (0.1–10 s). Here high frequency cultural noise is completely filtered out, and we can clearly observe several trains of very strong spikes. These trains have different

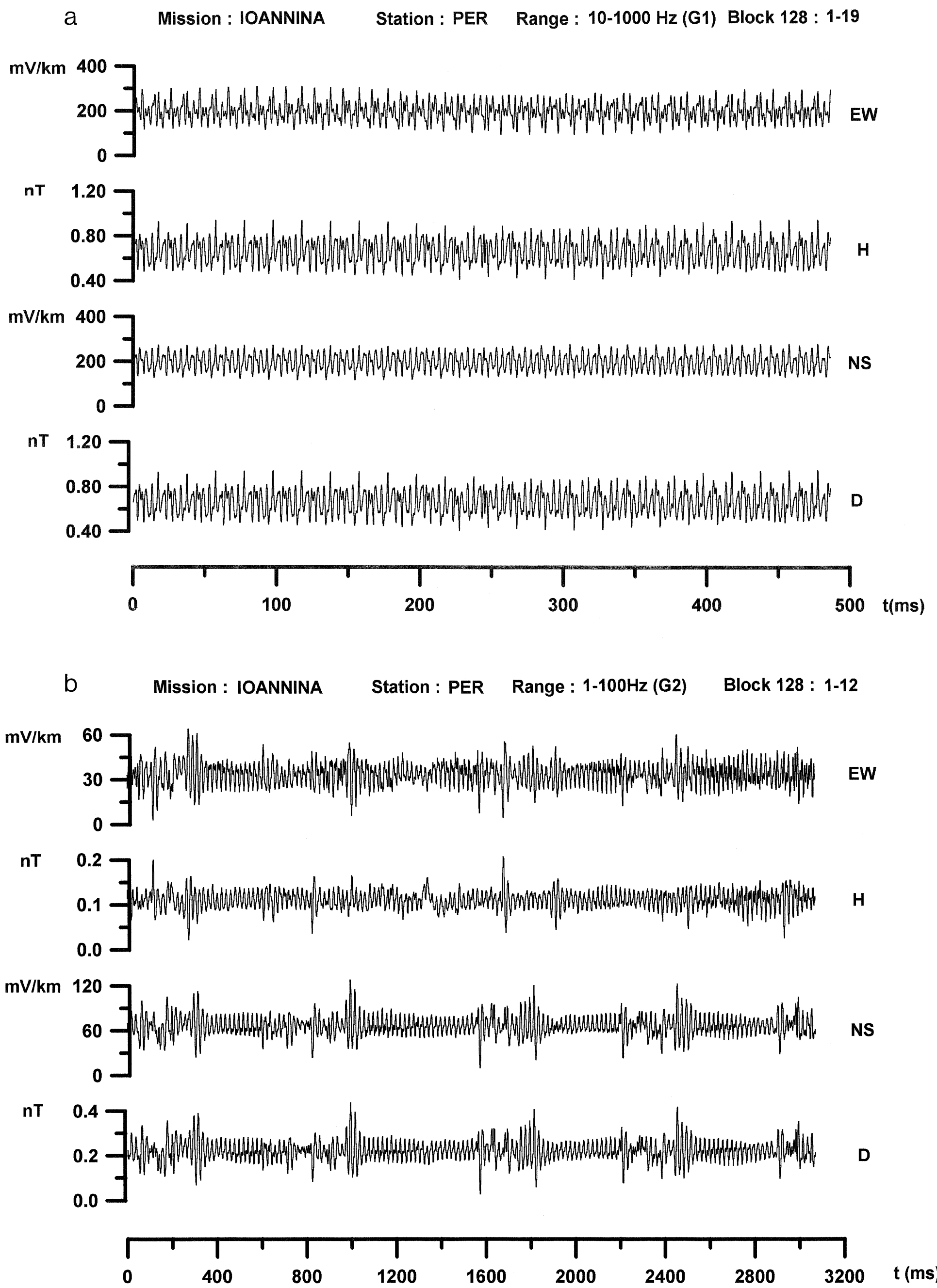


Fig. 4. Examples of simultaneous recording of four electromagnetic components at PER station: two electric components EW and NS, and two magnetic components H and D. The length of the record is specified by the number of 128 samples block in different ranges: (a) range G1; (b) range G2; (c) range G3; (d) range G5; (e) range G7.

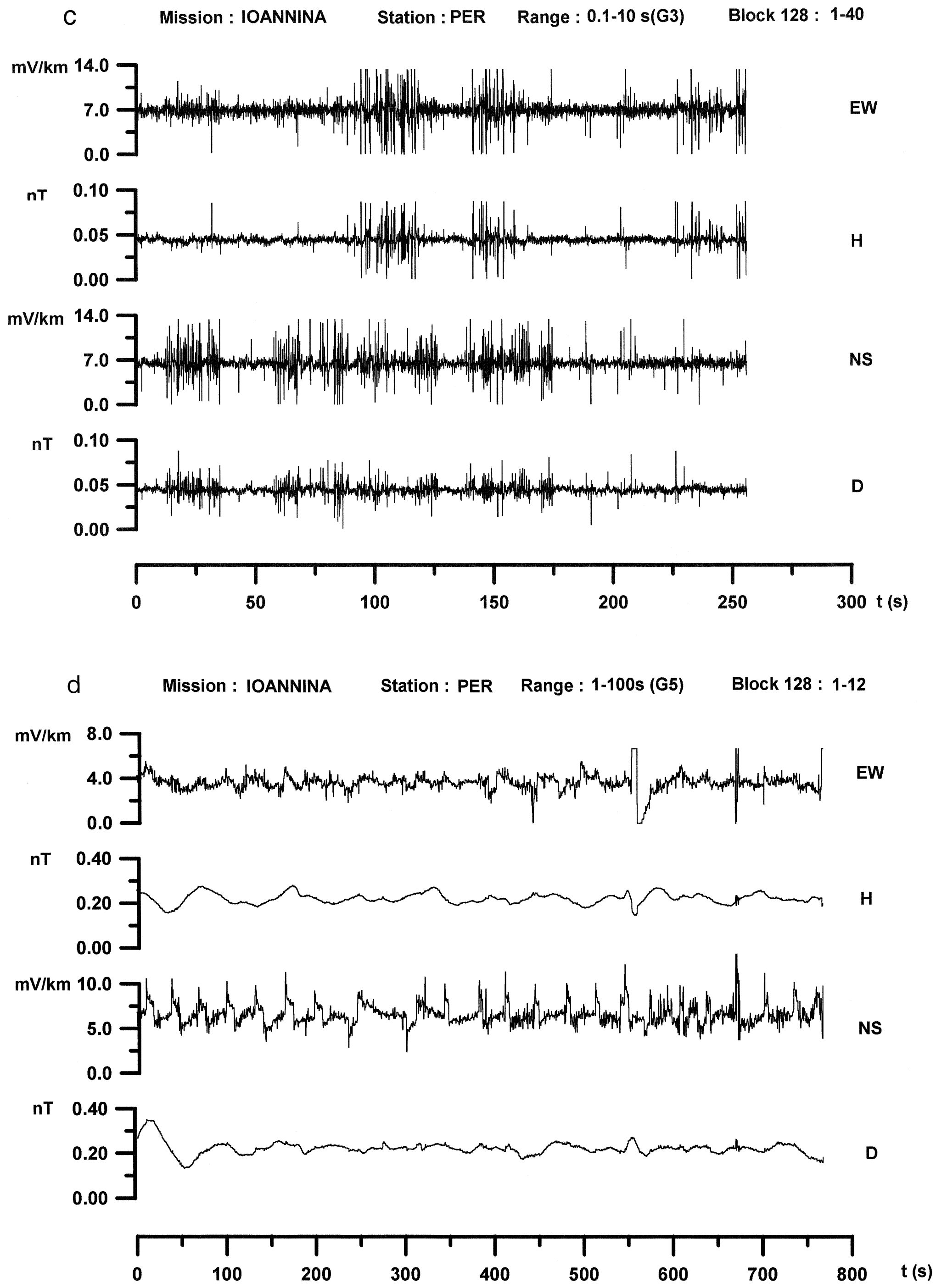


Fig. 4 (continued).

durations, from a few tens of seconds to about 100 s. It is interesting to note that in this range there is a very good correlation between the electric and magnetic components of each pair EW-H and NS-D.

Fig. 4d shows the records in the range G5 (1–100 s). Here the noise appears in the form of a train of long transient electric signals. No clear correlated magnetic component is observed, except for some strong high frequency peaks.

In Fig. 4e corresponding to the range G7 (10–1000 s), we observe the same (but smoothed) long transient electric signals without any clear correlated

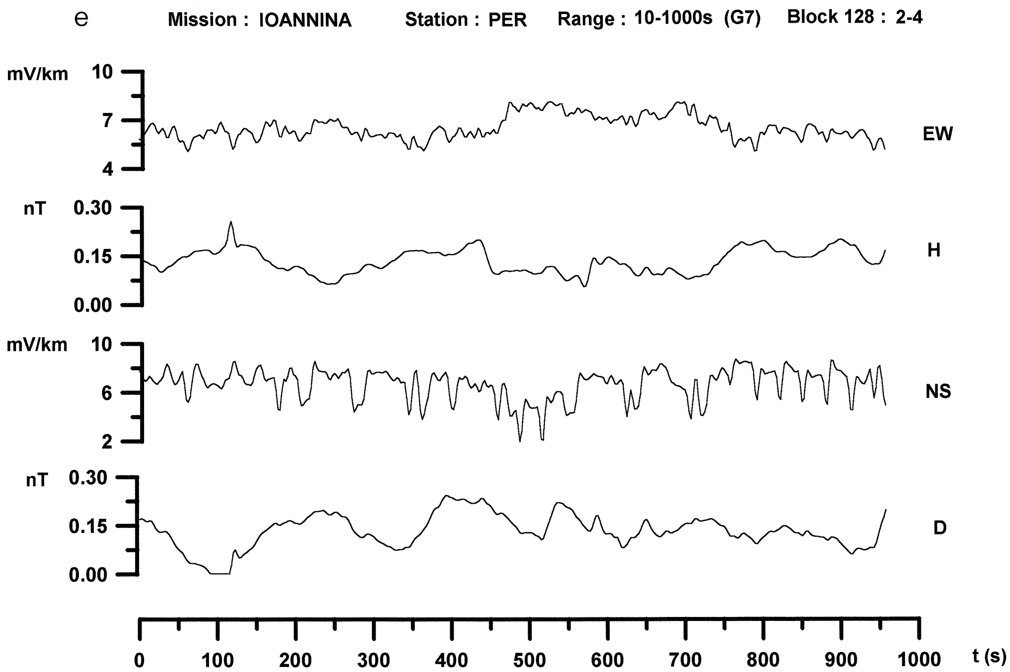


Fig. 4 (continued).

transient magnetic signal. Clearly these signals look like SESA (cf. Fig. 2) according to the VAN's classification.

Another station, ELE, located south of the Eleousa Village and in direct sight ($\sim$ 500 m) of two transmission antennas presents the same features of the electromagnetic signal in the different frequencies ranges. Fig. 5a, corresponding to the range G5, shows a train of spikes and square pulses which looks like a SESA. Fig. 5b, corresponding to the range G7, shows a long square pulse of about 150 s duration which looks like a single SES. Other stations occupied in the Ioannina region confirm that electric transient signals look like single SES or SESA (Pham et al., 1998).

4. Electromagnetic noise in other regions

For several years we have conducted MT surveys in different countries and we have already observed the existence of long transient electric signals without correlated magnetic signals. We show here some examples recorded in another region of Greece, the Gulf of Corinth, and in Vietnam.

4.1. Gulf of Corinth

In order to investigate the crustal structure of the Gulf of Corinth, which is one of the most active tectonic areas of the Mediterranean region, IPGP and NOA conducted a MT survey in the NW part of this region and on both sides of the Gulf (Pham et al., 1996; Chouliaras et al., 1997). In many stations located near important agglomerations, we observed the same characteristics of the electromagnetic noise as in the Ioannina region. We show here only the noise recorded at the station GAL located about 2 km NW of the Galaxidi agglomeration (see Fig. 1 in Pham et al., 1996). Fig. 6 shows an example of a recording corresponding to the range G7. We observe two types of long electric transient signals: square pulses like single SES of a few hundred seconds duration, and a train of spikes like a SESA of about 500 s duration.

4.2. Vietnam

A MT survey was conducted in 1994 in the Yen Bai region located about 120 km NW of Hanoi (Vietnam) in order to investigate the deep structure of the Red River fault zone (Pham et al., 1995). This

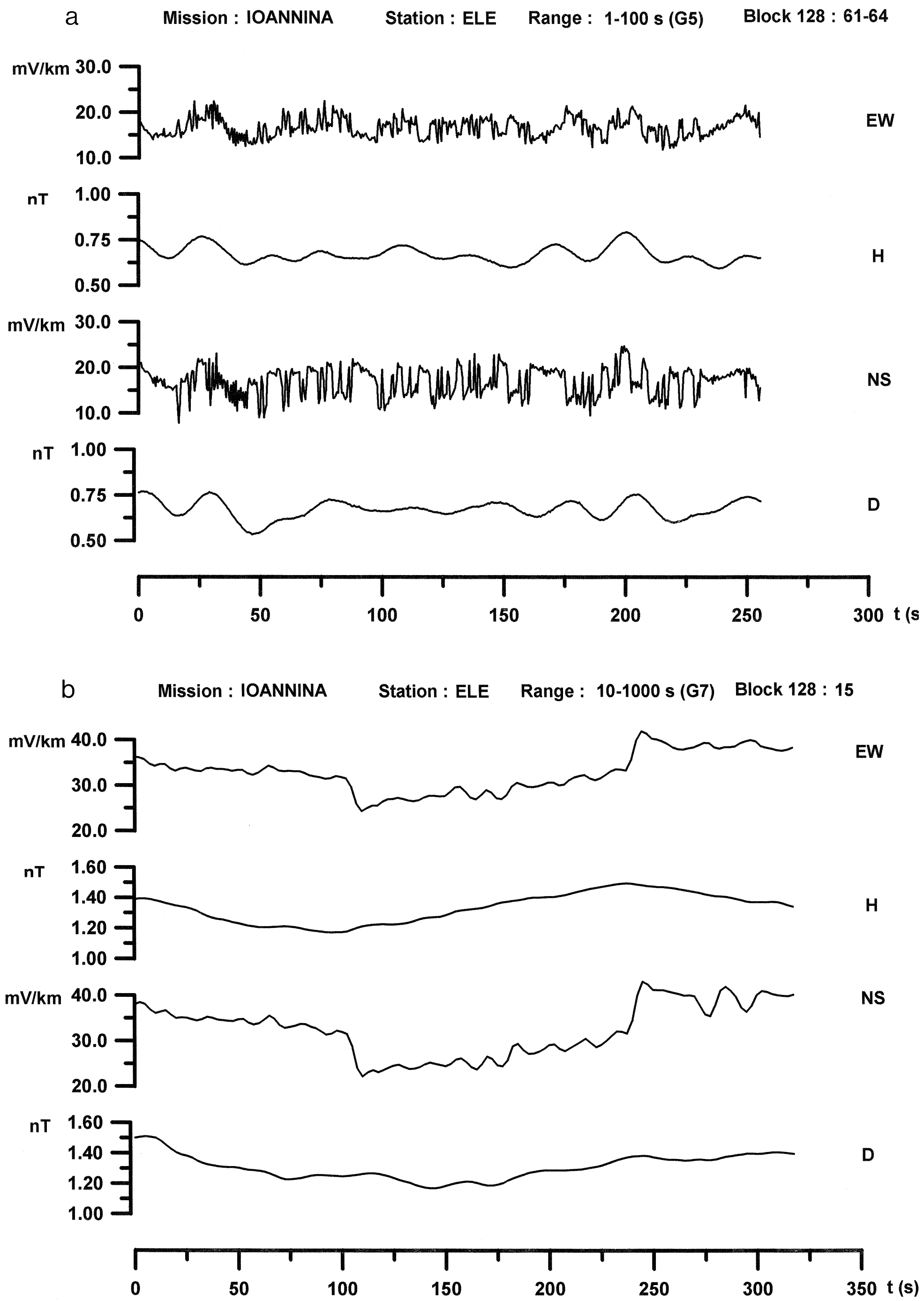


Fig. 5. Examples of recording at ELE station: (a) range G5; (b) range G7.

region is a rural region, there is little industrial noise and the MT signals are generally good, except for one station, TTQ, located near a transmitter. This transmitter worked during the daytime, so that we had to record MT signals during the night in order to obtain good MT results. Fig. 7 shows an example of a day record of a train of spikes and pulses of the electric signal of about 1200 s duration, without any correlated magnetic signal. There is a striking similarity of form between this electric signal and the

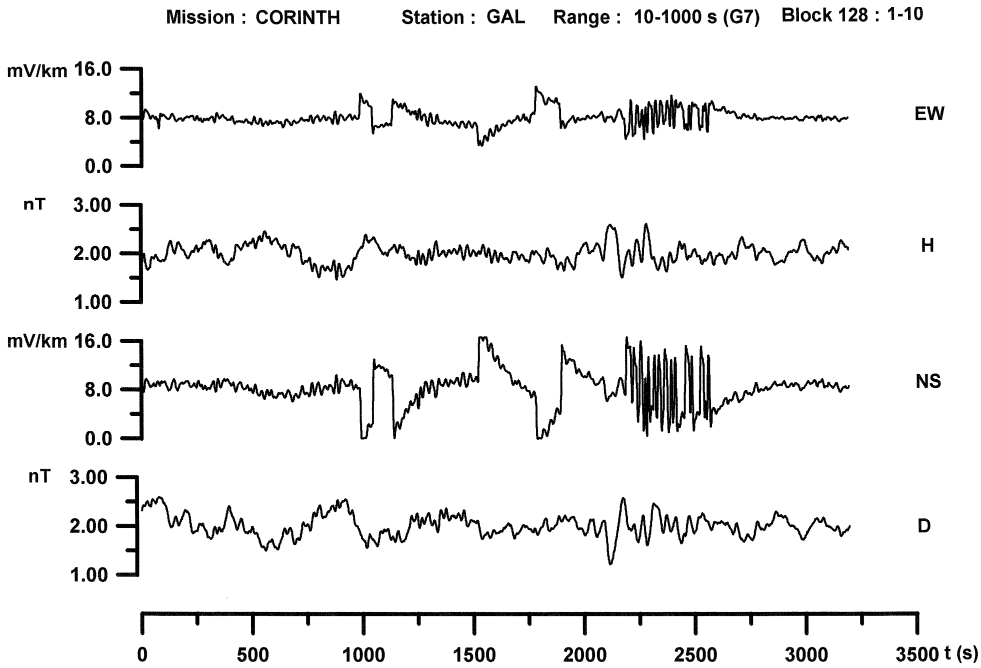


Fig. 6. Example of recording at GAL station (Gulf of Corinth, Greece) in the range G7.

so-called SESA of the Volos station in Greece (see Fig. 2).

5. Radio-wave transmission systems

From the above observations of the electromagnetic noise in different regions, it is clear that abnormal electric transient signals can be related to radio-wave transmission systems in the surrounding area. This is clearly the case for the PER station whose the abnormal electromagnetic signals recorded in different ranges of frequencies (Fig. 4a–e) are generated by the transmitters of the military base of Perama. This is also the case of the ELE station in direct sight of other transmitters, and of the stations in other regions discussed above. In high frequencies ranges (>0.1 Hz), transmitters signals are continuously observed during their emission. In low frequencies ranges (G7), only large amplitude and long duration signals (>10 s) can pass through the low-pass filter of 0.1 Hz cut-off frequency. As the amplitude of the electric signals is smaller in low frequencies ranges than in high frequencies ranges (see further discussion in paragraph 8), and as the large amplitude and long duration signals appear to be rarer, these signals, looking like single SES or SESA, do not continuously occur despite that the transmitters are frequently in activity. At a given station, the amplitude of the recorded signals is not necessarily constant, depending on the activity of one or more surrounding transmitters and their emission power.

There are two types of radio-wave transmitters: analog and digital. The analog type is well known by geophysicists due to the fact that the ground affects the behavior of the radio-waves; the electromagnetic waves transmitted from radio-broadcast stations in the LF frequency band (30–300 kHz) can be used to determine the subsurface electrical properties of the ground. The most popular geophysical survey method using radio-wave propagation is the ‘VLF method’ proposed by Ronka in 1964 (Paterson and Ronka, 1971). This method uses the available worldwide network of high-power VLF transmitters (50–1000 kW) in the 15–25 kHz frequency band planned for marine navigation. These radio-wave methods are used for shallow surveys because of the small penetration depth in LF and VLF bands (from a few meters to a few tens of meters).

Another well-known type of analog transmitter is the ‘Radio-Relay-Link’ (RRL) which appeared in the 1950s. This is a radio-telecommunication system for

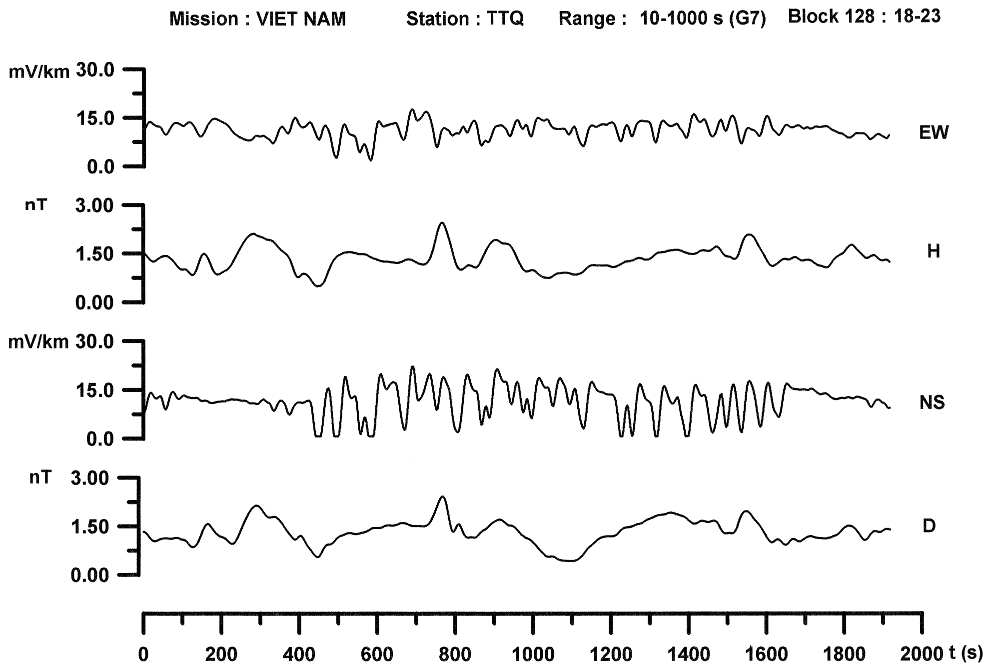


Fig. 7. Example of recording at TTQ station (Vietnam) in the range G7.

transmission of telephone and television signals, in the SHF band (>1 GHz). Beside the RRL network, there is also the analog radio-telephone network which was first proposed in USA by Bell Telephone in 1950 and developed in Europe in the 1970s in the UHF band (450–900 MHz).

These analog transmitters in very high frequency bands have no influence on electromagnetic signals in the ULF band. The pattern of electromagnetic noise discussed here can be generated only by transmitters of digital type. In fact, digital transmission started replacing analog transmission from 1970 for the RRL network, and from 1988 for the radio-telephone network. The new digital mobile telephone network, well known as the GSM (Global System for Mobile communication) is now widely developed in most countries.

The GSM system has a carrier-frequency of 900 MHz, but its radio-transmission quantum is a 'burst' taking place during a time window of about 577 μs. Within this time interval, the signal phase is modulated to transmit a packet of bits. The time unit of the transmission is the 'frame' which is composed of eight bursts and has a 4.615 ms duration. The GSM norm uses different multiples of the frame, the longest being the 'hyperframe' composed of 2,715,648 frames, of a duration longer than 3 h. This short description of the GSM system shows the existence of a great variety of transmission durations depending on the quantity of data to be transmitted. All figures of paragraphs 3 and 4 confirm that the electromagnetic signals generated in the ground by digital transmitters have the form of spikes or pulses of different durations from a few tens of milliseconds to a few tens of seconds. Generally these pulses are not isolated but form trains with different spacings and different durations from a few hundreds of milliseconds to a few thousands of seconds. If the signal is made of a train of spikes or pulses with short spacings between them, it appears as a unique longer pulse on the long periods recordings, as generally observed in the ranges G5 and G7. The different forms of the signals, such as sharp peaks, triangular spikes, square pulses, can be explained by the effect of the low-pass filter corresponding to the recording range.

6. Response of the low-pass filter

Although Varotsos et al. do not give information about their data acquisition system in most of their

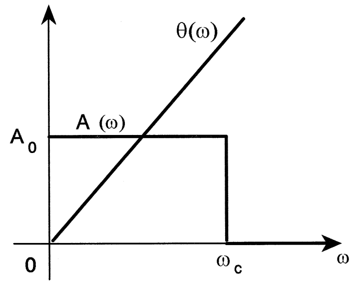


Fig. 8. Ideal low-pass filter with cut-off frequency ω_c and linear phase shift.

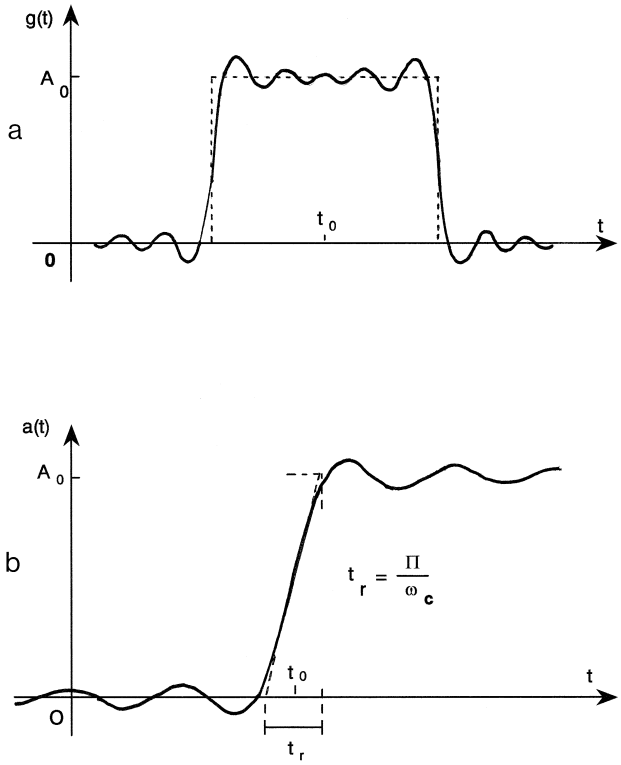


Fig. 10. Responses of an ideal low-pass filter: (a) from a rectangular pulse input signal; (b) from a step input signal.

papers, it has probably a low-pass filter with a cut-off frequency of about 0.1 Hz (Nomicos and Chatzidiakos, 1993), and corresponds to the range G7 of our own data acquisition system.

As the carrier-frequencies of radio-transmitters are generally very high (UHF and SHF band), analog signals at these frequencies are not observable in the G7 range. Only the amplitude-modulated signals with a duration longer than 10 s can pass through the 0.1 Hz low-pass filter. The classical low-pass filter is the ideal low-pass filter which has an amplitude response $A(\omega)$ (Fig. 8):

$$A(\omega) = \begin{cases} A_0 & \text{for } \omega < \omega_c \\ 0 & \text{for } \omega > \omega_c \end{cases}$$

where ω_c is the cut-off angular frequency and a linear phase shift $\theta(\omega) = \omega t_0$.

A real physical low-pass filter is a little different but, in a first approximation, we can assume the filter as ideal for the sake of simplicity. The original elementary input signal emitted by a digital transmitter can be considered as a rectangular pulse $f(t)$ of unit amplitude and of duration $2T$ (Fig. 9). The

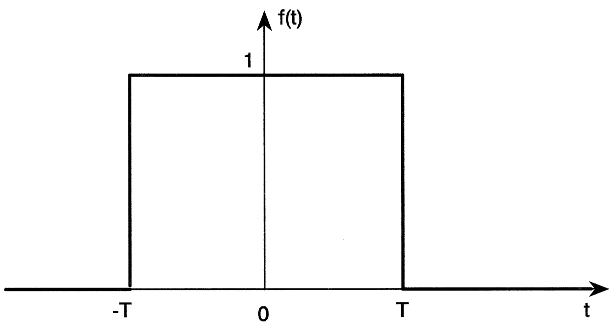


Fig. 9. Rectangular pulse input of duration $2T$.

response $g(t)$ of an ideal low-pass filter to the rectangular pulse $f(t)$ is (e.g., Papoulis, 1962):

$$g(t) = a(t+T) - a(t-T)$$

$a(t)$ is the step response:

$$a(t) = \frac{A_0}{2}\left\{1 + \frac{2}{\pi}\mathrm{Si}[\omega_c(t-t_0)]\right\}$$

where Si[·] is the sine-integral function.

Functions $g(t)$ and $a(t)$ are shown respectively in Fig. 10a and b. The effect of the low-pass filter is to transform the abrupt step variation of the signal into a variation with a finite slope, the rise time being:

$$t_r = \frac{\pi}{\omega_c} = \frac{T_c}{2}$$

and the cut-off period being:

$$T_c = \frac{2\pi}{\omega_c}$$

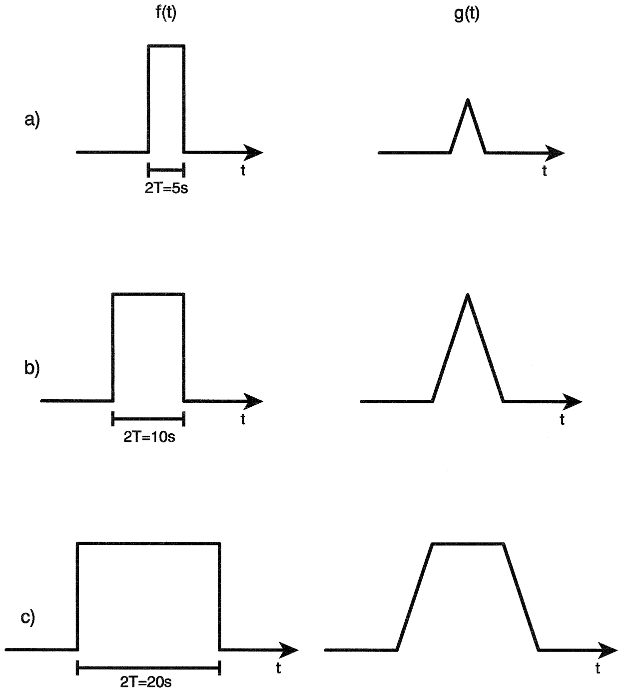


Fig. 11. Different forms of the response signal of an ideal low-pass filter as a function of the cut-off period T_c and the duration $2T$ of a rectangular pulse input.

Consider now the case of $T_c = 10$ s, $t_r = 5$ s. Fig. 11 shows different forms of the response signal $g(t)$ as a function of the duration $2T$ of the input signal:

Case 1: $2T < 10$ s (Fig. 11a)
$g(t)$ = triangular pulse with amplitude < 1
Case 2: $2T = 10$ s (Fig. 11b)
$g(t)$ = triangular pulse with amplitude = 1
Case 3: $2T > 10$ s (Fig. 11c)
$g(t)$ = trapezoidal pulse with amplitude = 1

All forms of SES recorded at Assiros (Fig. 1), Ioannina and Volos stations (Fig. 2) have the same pattern as the responses shown above. Depending on the time-scale, a triangular response can appear as a sharp peak and the trapezoidal response as a square pulse.

7. Electromagnetic field generated in the ground by transmitter

In the following, we will consider that the transmitter emits a succession of rectangular pulses of the same amplitude and with widths varying from 1 ms to—exceptionally—a few hours (Fig. 4b–e). This hypothesis is justified by our discussion in the preceding paragraphs. No interest will be paid to the fine structure of the rectangular pulses which carries information.

The transmitter antenna can be considered as a vertical electric dipole (McNeil and Labson, 1991). The highest frequency we can reach with our recording system is 10^3 Hz. All our ranges, from G1 to G7, are within the ULF band for which the free-space wavelength is larger than 100 km. For horizontal distances from the transmitters $\ll 100$ km, we can use the quasi-static assumption or the near-field solution (Wait, 1982). In the case of a vertical electric dipole of current moment $I_0 h$, located just above the earth surface of homogeneous resistivity ρ, the amplitudes of the tangential magnetic component H_φ and of the radial electric component E_r (in a cylindrical coordinate system, Fig. 12), at radial distances $r \ll 100$ km, are (Wait, 1982):

$$H_\varphi = \frac{I_0 h}{2\pi r^2} \tag{1}$$

$$E_r = \frac{I_0 h \sqrt{\mu_0 \omega \rho}}{2\pi r^2} \tag{2}$$

Both fields H_φ and E_r decrease as r^{-2}. Moreover, at a given distance, E_r increases as $\omega^{1/2}$ and $\rho^{1/2}$ whereas H_φ is independent of both ω and ρ.

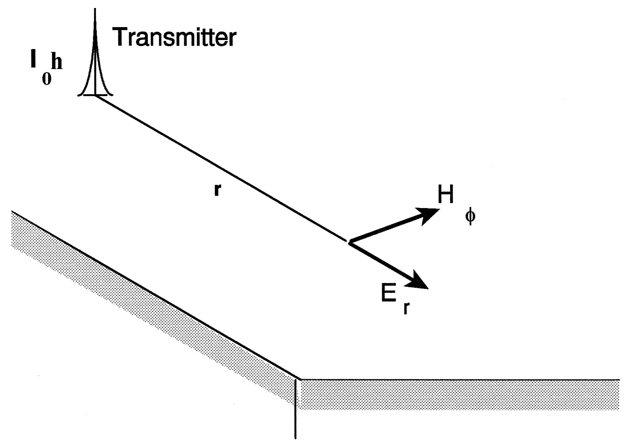
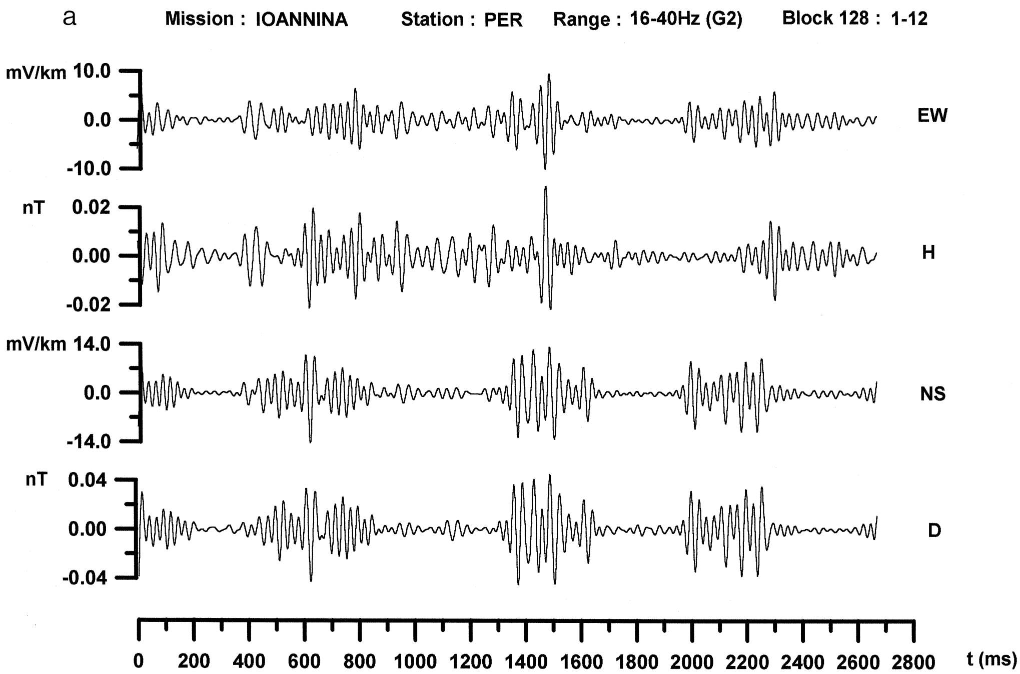


Fig. 12. Electromagnetic field generated in the ground by a vertical electric dipole of current moment $I_0 h$ at a radial distance $r \ll 100$ km (near-field approximation).

8. Verification of the near-field formulas

The near-field formulas (1) and (2) allow to calculate the amplitudes of the electric and magnetic fields generated in the ground by the transmitters. Unfortunately these simple formulas correspond to harmonic solutions, whereas our recorded signals are transient signals covering two decades of frequencies



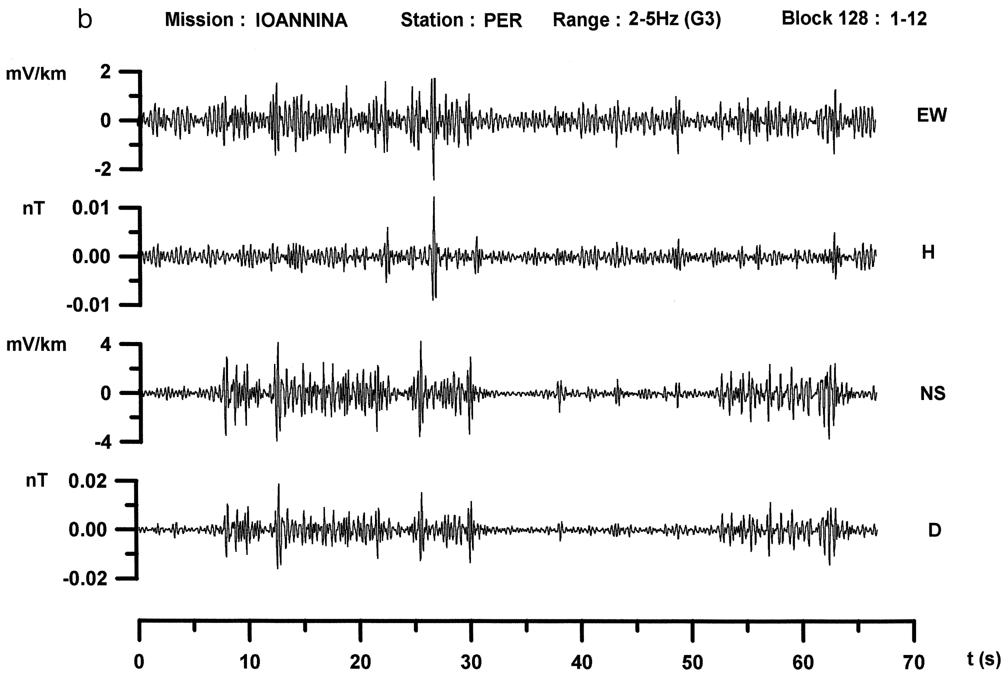


Fig. 13. Filtered signal by narrow band-pass filters at PER station in different ranges: (a) range G2; (b) range G3; (c) range G5; (d) range G7.

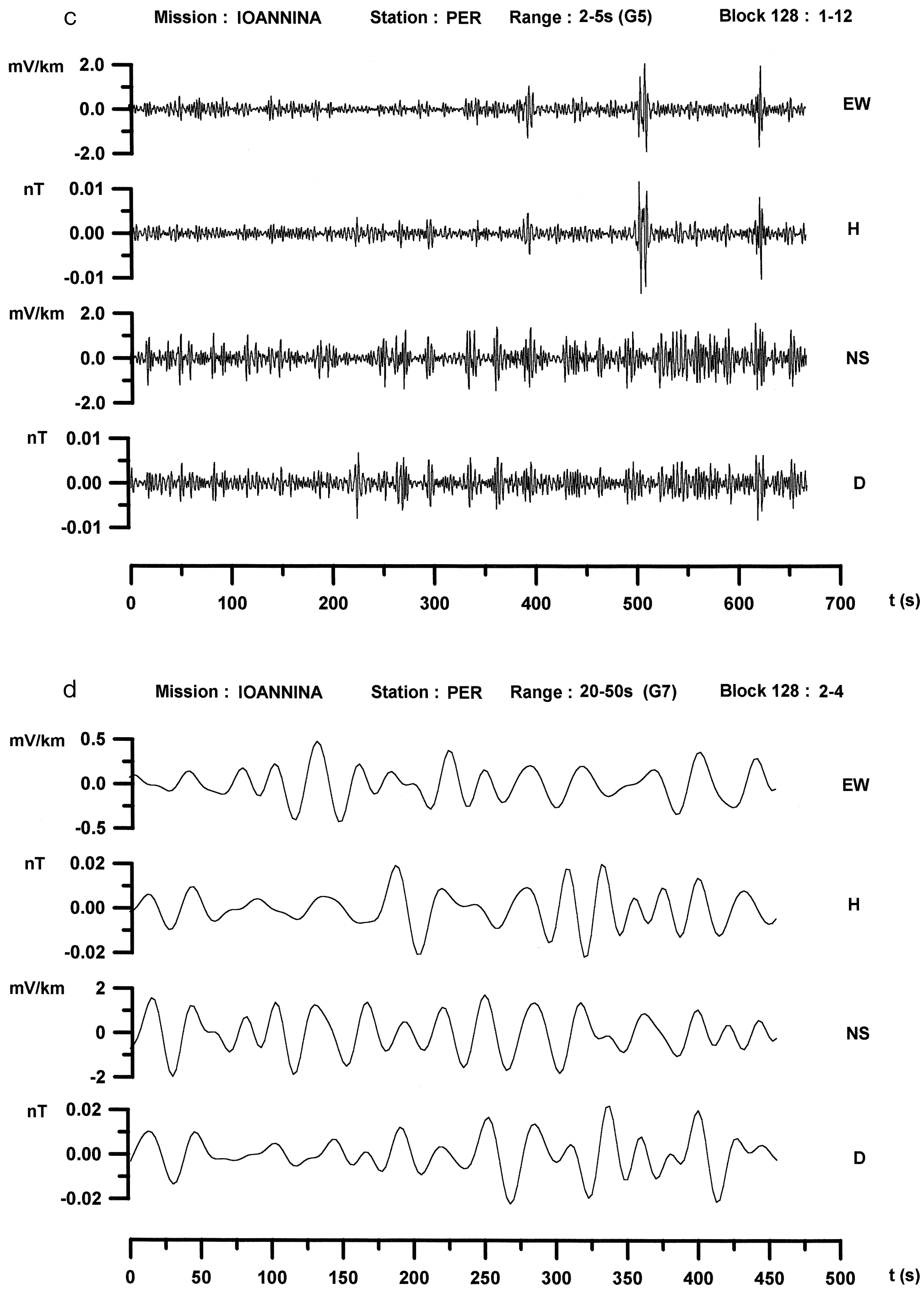


Fig. 13 (continued).

in each range. It is necessary to apply a narrow band-pass filter to obtain quasi-harmonic signals.

Let us consider again the case of the PER station located near the transmitters of the military base of Perama. Except for the high frequencies (range G1) where the level of cultural noise is very high and masks completely the other signals (Fig. 4a), we have selected one center frequency F_0 for each

Table 3
Correction of the influence of the resistivity on the electric field in the formula (2) for PER station

F_0 (range)	H (nT)	ρ_a EW (Ω m)	C_{ρ_a}	EW (mV/km)	EW × C_{ρ_a} (mV/km)
30 Hz (G2)	0.01–0.04	500	4.7	5–15	23.5–70.5
3 Hz (G3)	0.005–0.02	3500	1.8	2–4	3.6–7.2
0.3 Hz (G5)	0.005–0.02	11 000	1	1–3	1–3
0.03 Hz (G7)	0.01–0.04	3000	1.9	0.2–0.6	0.4–1.1

range, respectively 30 Hz for G2, 3 Hz for G3, 0.3 Hz for G5 and 0.03 Hz for G7, corresponding to one decade spacing of the frequencies. The ratio of the bandwidth to the center frequency, $\Delta F_0/F_0$ is chosen approximately constant (~ 0.8) for all the narrow band-pass filters. The filtered signals shown in Fig. 13a to d, corresponding to ranges G2 to G7, are to be compared with the original signals displayed in Fig. 4b to e; trains of transient pulses have been transformed into trains of harmonic oscillations. Let us check that the amplitudes of these harmonic oscillations obey the near-field laws (1) and (2).

The verification of formula (1) is easy because the magnetic field H_φ is independent of both frequency and resistivity. However, as the different ranges of frequencies are not recorded simultaneously, we have to suppose that the transmitters have emitted with the same amplitude and in the same direction during the whole recording time. Within this hypothesis, let us compare the amplitude of one component of the

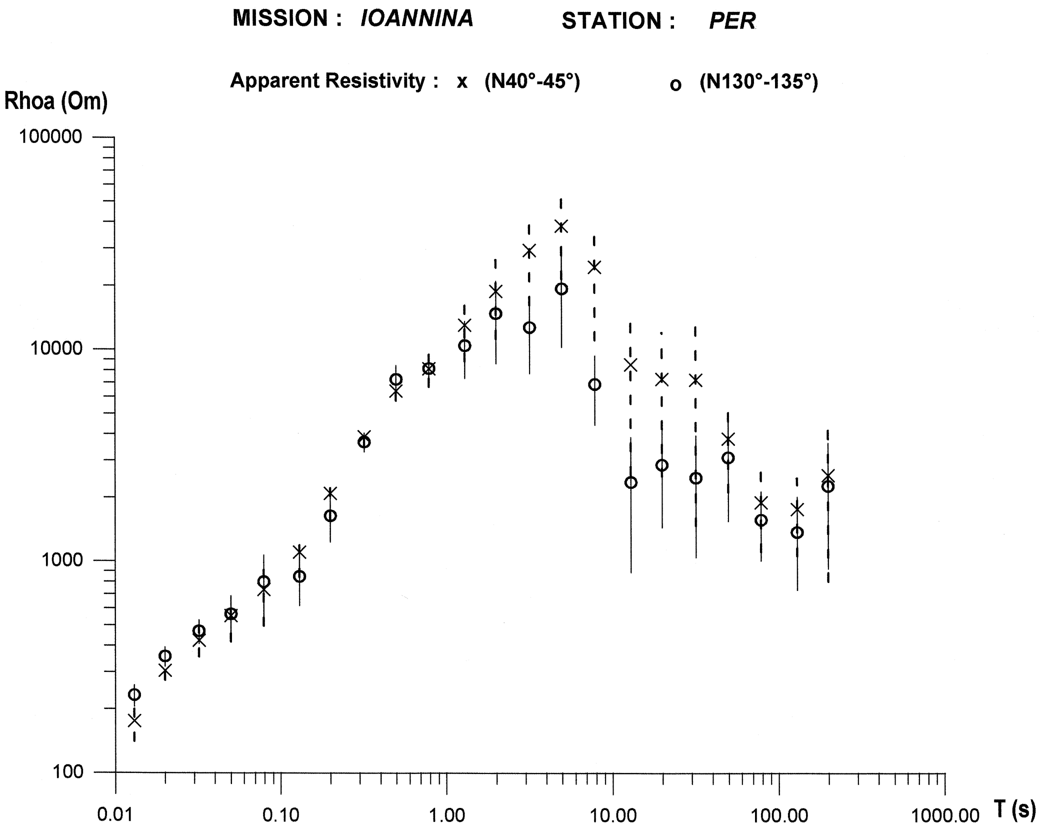
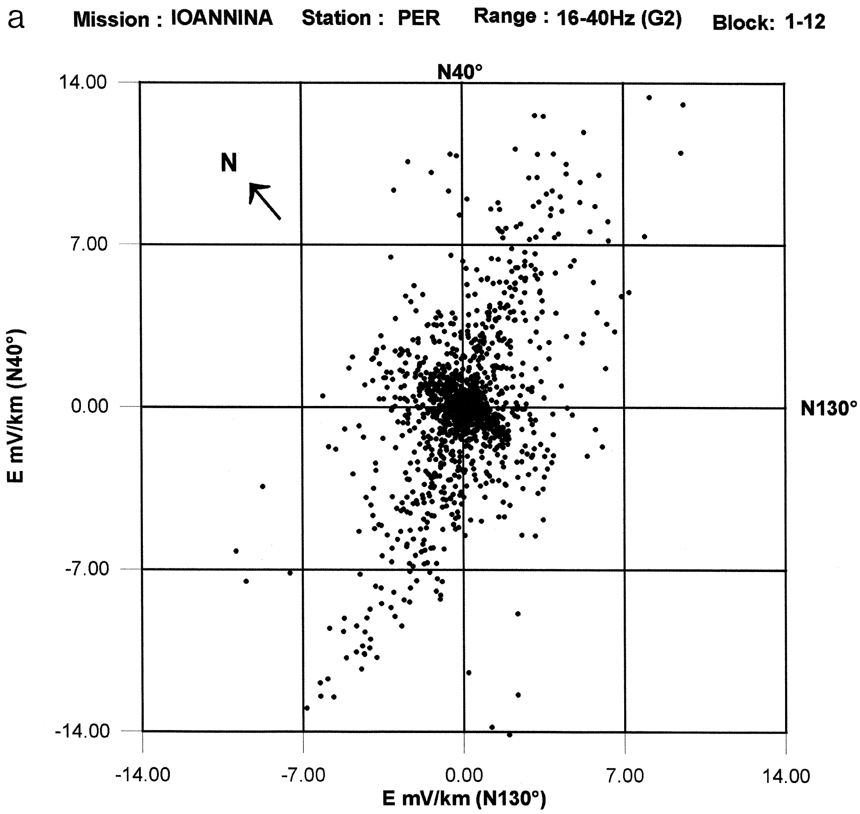
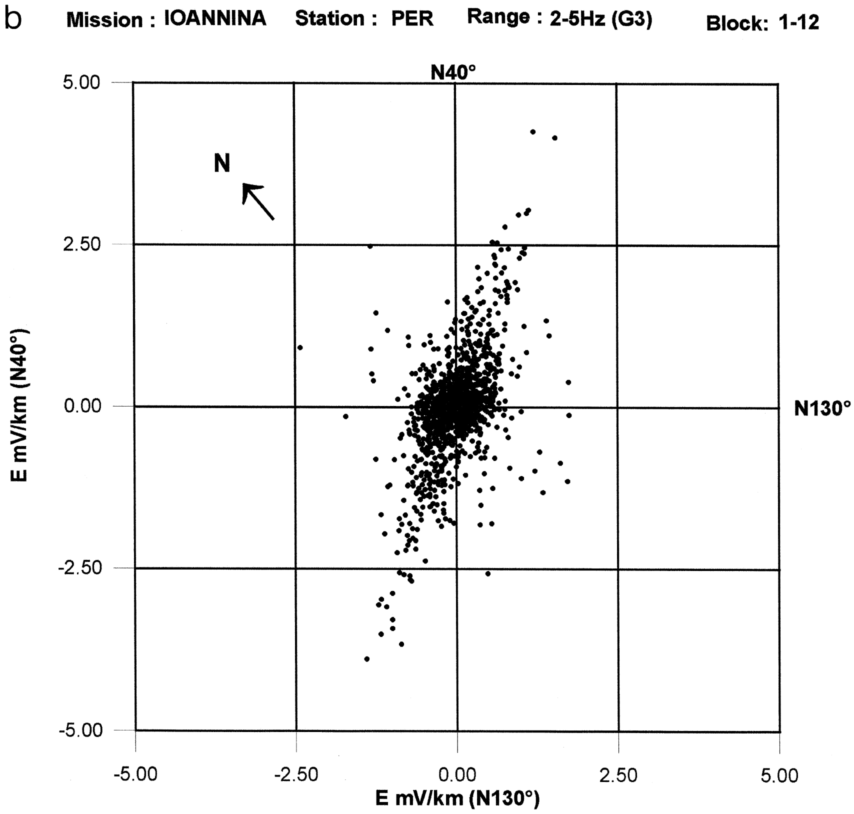


Fig. 14. MT sounding curves along two principal directions at PER station. Full and dashed vertical bars represent the standard deviation corresponding to these two directions.

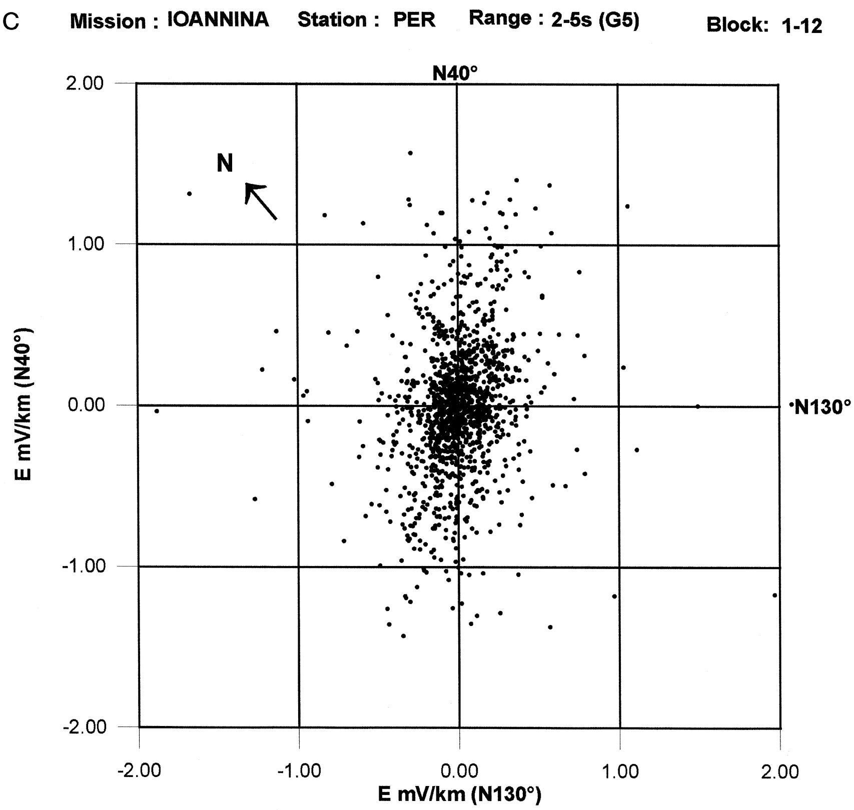
a


Mission : IOANNINA Station : PER Range : 16-40Hz (G2) Block: 1-12
N40°
N
N130°
14.00
7.00
0.00
-7.00
-14.00
E mV/km (N40°)
-14.00
-7.00
0.00
7.00
14.00
E mV/km (N130°)

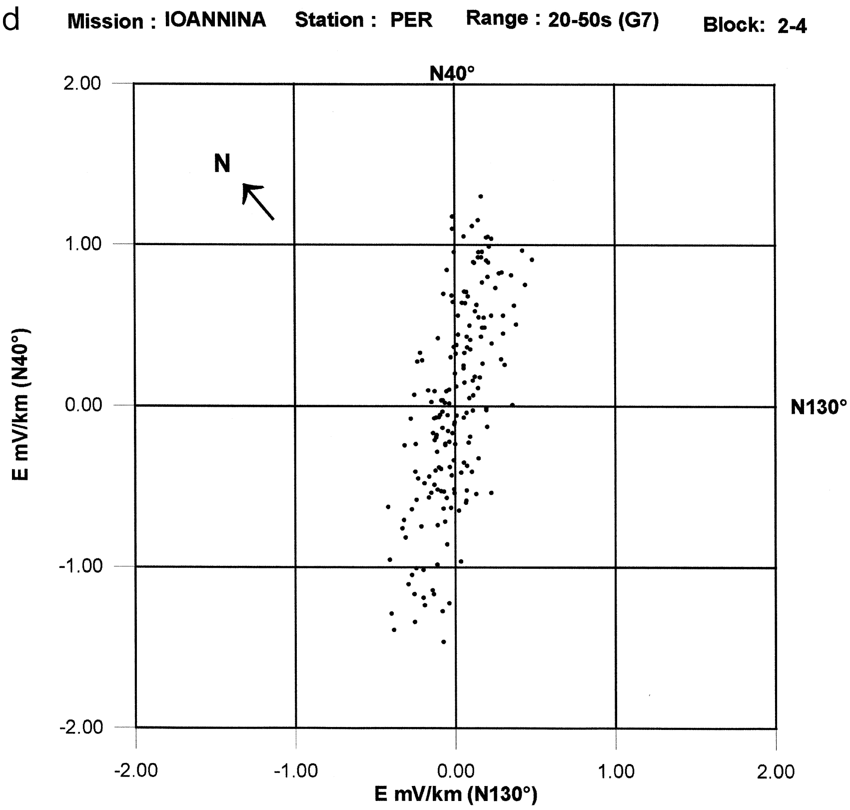
b


Mission : IOANNINA Station : PER Range : 2-5Hz (G3) Block: 1-12
N40°
N
N130°
5.00
2.50
0.00
-2.50
-5.00
E mV/km (N40°)
-5.00
-2.50
0.00
2.50
5.00
E mV/km (N130°)

c


Mission : IOANNINA Station : PER Range : 2-5s (G5) Block: 1-12
N40°
N
N130°
2.00
1.00
0.00
-1.00
-2.00
E mV/km (N40°)
-2.00
-1.00
0.00
1.00
2.00
E mV/km (N130°)

d


Mission : IOANNINA Station : PER Range : 20-50s (G7) Block: 2-4
N40°
N
N130°
2.00
1.00
0.00
-1.00
-2.00
E mV/km (N40°)
-2.00
-1.00
0.00
1.00
2.00
E mV/km (N130°)

magnetic field, for example the H component, of the filtered signals for the different F_0 (Table 3, column 2). The measured amplitudes (on Fig. 13a to d) are more scattered in the G2 range because of the presence of the (50 Hz and harmonics) residual noise (Fig. 4b), and in the G7 range because of the high level of the natural magnetic field (Fig. 4e). Taking into account these limitations, we can consider that the amplitude of the H component is indeed approximately constant, of about 0.01–0.02 nT, for the four frequency ranges.

In order to check formula (2), we must take into account the influence of the variation of the apparent resistivity in the different ranges of frequencies. The signals recorded at the PER station are very noisy, as shown by Fig. 4. Nevertheless, selecting the least noisy data, we have been able to derive two MT sounding curves along the two principal directions 40–45°N and 130–135°N (Fig. 14), using the classical tensorial MT processing (see for example, Pham et al., 1990; Vozoff, 1991). It appears in Fig. 14 that the apparent resistivities are more scattered for periods > 1 s because of the presence of larger electric noises generated by the transmitters in the ranges G5 and G7 (Fig. 4d and e). Nevertheless these MT sounding curves provide approximate values of the apparent resistivities and allow us to evaluate the influence of the resistivity in the formula (2).

From (2), we derive:

$$\frac{[E_r]_1}{[E_r]_2} = \sqrt{\frac{F_1}{F_2}} \sqrt{\frac{\rho_{a1}}{\rho_{a2}}} \tag{3}$$

$[E_r]_1$ and $[E_r]_2$ are the amplitudes of the radial electric field E_r corresponding respectively to frequencies F_1 and F_2, and ρ_{a1} and ρ_{a2} the apparent resistivities corresponding to these frequencies.

Again, as in the case of the magnetic field, we suppose the emission constant in amplitude and in direction during the whole recording time span. In fact we can control the polarization direction for the different ranges of frequencies. Fig. 15a to d show the polarization diagrams of the electric field for ranges G2 to G7. The scattering of the directions is large because of the presence of high frequency noise and low frequency natural signal, but the largest amplitudes allow to estimate the general direction as about 60–70°N. This direction corresponds to the direction, from the recording station, of the transmitters in the military base. Assuming again the stationary condition of the emission, we can consider the amplitudes of one electric component, for example the EW component.

Introducing the correction factor:

$$C_{\rho_a} = \sqrt{\frac{\rho_{a2}}{\rho_{a1}}}$$

we can write from Eq. (3):

$$\frac{[E_r]_1}{[E_r]_2} C_{\rho_a} = \sqrt{\frac{F_1}{F_2}} . \tag{4}$$

The correction factor C_{ρ_a} (Table 3, column 4) can be evaluated from the EW (130–135°N) apparent resistivities curve of Fig. 14 (Table 3, column 3). From the raw amplitudes of the EW component (Table 3, column 5), we can then compute the corrected values (Table 3, column 6) which must verify Eq. (4). This is approximately the case for all ranges except for G2 which shows too strong corrected values because of the presence of 50 Hz residual noise. We do observe approximately an increase of the electric component amplitude going as the square root of the frequency as predicted by formula (2).

At this stage, we can conclude that the abnormal electromagnetic signals recorded at the PER station were generated by the transmitters of the military base; the characteristics of these signals verify approximately the near-field formulas.

A first important consequence of this verification is the frequency independence of the magnetic field generated by the transmitters. As the natural magnetic field (MT field) increases dramatically with the period in the low frequencies ranges (or long periods ranges), especially in the range of periods larger than 10 s, the artificial magnetic fields, even if they exist,

Fig. 15. Polarization diagrams of the filtered electric field at PER station in different ranges: (a) range G2; (b) range G3; (c) range G5; (d) range G7.

are not observable on recordings of long period ranges, because of the high signal/noise ratio of the natural field in these ranges. The absence of apparent transient magnetic signals correlated with the abnormal electric transient signals thus does not constitute a firm criterion to discriminate the so-called SES from artificial noises. This discrimination requires the recording of signals at higher frequencies (> 1 Hz); only such recordings can prove the absence of an artificial magnetic field.

9. A plausible source of SESA recorded simultaneously at the IOA and JAN E stations on April 18 and 19, 1995

The case of the April 18 and 19, 1995 events is very interesting because it is the first time that the signals were recorded simultaneously at two remote stations by two different observers. As these events of SESA type were recorded simultaneously at IOA and JANE E stations, 4.5 km apart and had the same characteristics at both stations (see Fig. 2), according to VAN criterion (Varotsos and Lazaridou, 1991), its source should have been located at a large distance from these two stations (i.e., a distance much larger than 4.5 km). Accordingly, Varotsos et al. (1996a,b) claimed that the remote source was related to the Kozani earthquake, which occurred about 70 km NE of the IOA station on May 1995.

As shown in the preceding paragraphs, digital transmitters can generate electric signals in the ground which may present the same pattern as SESA. Such a transmitter can then be also proposed as a possible source. In this case, as at both stations, on April 18 and 19, 1995, the electric signal is polarized approximately N–NW (Gruszow et al., 1996; Varotsos et al., 1996b), we expect the source to be a remote transmitter located in this direction from the JAN E station.

From Eq. (2), we can write:

$$\frac{E_r(r_1)}{E_r(r_2)} = \sqrt{\frac{\rho_1}{\rho_2}} \left(\frac{r_2}{r_1}\right)^2 \qquad (5)$$

where ρ_1 and ρ_2 are the apparent resistivities of the ground respectively under JAN E and IOA stations, and r_1 and r_2 the respective distances of these stations from the unknown transmitter.

In order to compare the amplitudes of the electric field at the two stations, we must first evaluate the influence of the resistivity, or more precisely, of the apparent resistivity, for periods larger than 10 s, beneath the stations. We have no exact results about the distribution of the resistivity at the IOA and JAN E stations. Nevertheless the MT sounding curves at PER station (Fig. 14), close to IOA station (see Fig. 3), can be assumed to be valid for IOA at long periods (> 10 s). As for the JAN E station, we have the data for the close LIK station (see Fig. 3). Unfortunately, LIK station was located near a factory which generated strong high frequencies noise and was also perturbed by surrounding transmitters. As in the case of PER station, we have selected the least noisy data to compute the MT sounding curves along the two principal directions by the same MT processing method (Fig. 16). The scatter is very large for the 125–130°N direction, but the results are correct for the 35–40°N direction and can be considered as representative of the JAN E station. Comparing the MT sounding curves of Figs. 14 and 16, it appears that for long periods (> 10 s), the apparent resistivity is larger at IOA than at JAN E: $\rho_2 > \rho_1$ in formula (5). The amplitude of the signal is 15 mV/km at IOA and 65 mV/km at JAN E (see Fig. 2 and Pham et al., 1998). The source of the signal could therefore be a digital transmitter located more than 5 km ($\rho_2 > \rho_1$) N–NW from the JAN E station.

The very large amplitude of the April 1995 events recorded at JAN E station (~ 65 mV/km), several times larger than the amplitude of all the signals recorded at different stations reported above, confirms that they are exceptional. The corresponding powerful emissions are rather rare. Indeed, Varotsos et al. (1998a) cited this rarity as evidence for the seismic origin of the exceptional events recorded at IOA station on October 3 and 5, 1997, after 2 years of silence. Moreover, the same authors consider that ''the study of these SES activities revealed that (Varotsos et al., 1998b) the SES sensitive area extends to a zone having a width of the order of a few kilometers and length of ~ 10 km'' (Varotsos et al., 1998c). This extension of the IOA sensitive area (formerly limited to the IOA station) to the entire Ioannina valley could be related to our own observa-

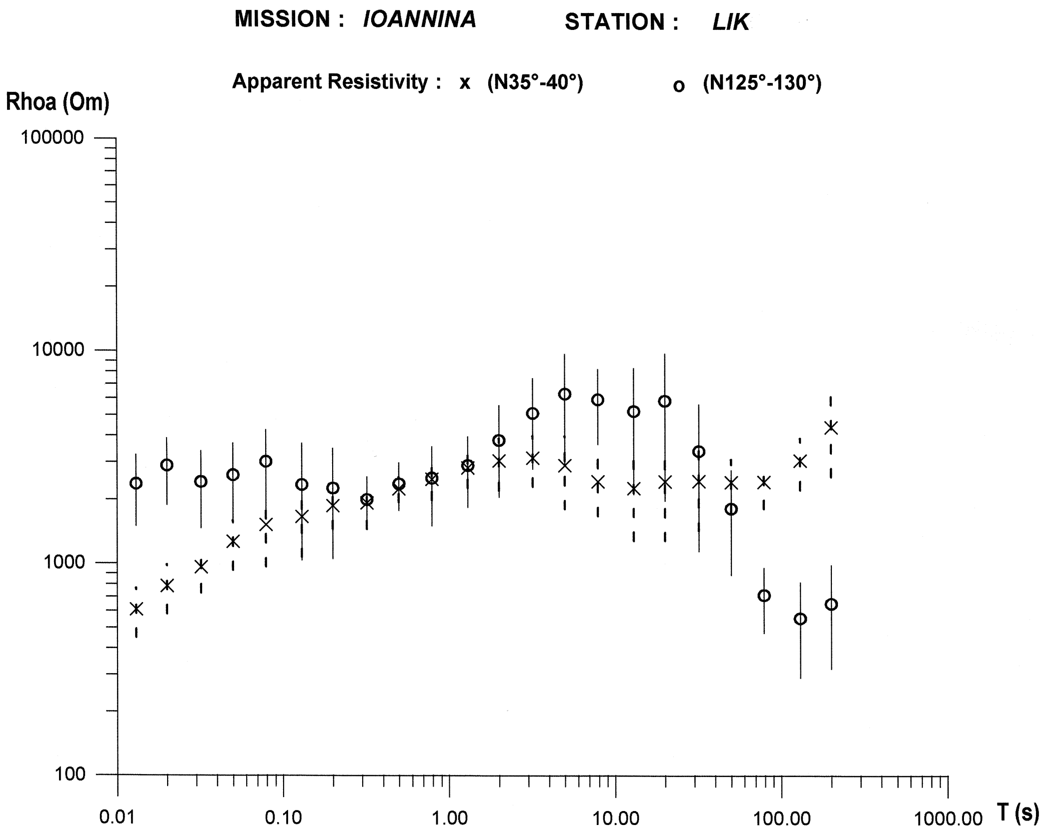


Fig. 16. MT Sounding curves along two principal directions at LIK station. Full and dashed vertical bars represent the standard deviation corresponding to these two directions.

tion that ''there is some evidence that the electric transient signals recorded at these stations are also emitted by transmitters located along the Ioannina valley and the surrounding hills where the most important agglomerations are concentrated'' (Pham et al., 1998). It seems plausible that the extent of the sensitive area corresponds to the extent of the transmitters noises in the Ioannina valley.

Such a situation would of course have nothing to do with VAN's claimed 'selectivity effect' (Varotsos et al., 1998d). In spite of the presence of noise, our broad band MT sounding results at PER and LIK stations (Figs. 14 and 16) clearly show that the crust under the Ioannina basin is very resistive (1000–10 000 Ω m) and that there is no conductive path in the crust beneath the IOA and JAN E stations. Recent results of resistivity mapping around the IOA station (Kanda et al., 1998) can reveal only the heterogeneity of the very superficial layers but give no information on the deep structure of the crust. Another recent study, conducted with the assistance of the VAN group at IOA station, ''suggests that the sources of the SES are in the neighbourhood of the station. It is still unclear how the SES, associated with distant earthquakes, are emitted from the source near the IOA station'' (Uyeshima et al., 1998). During their study Uyeshima et al. also recorded several trains of spikes which have the same form as the signals recorded at PER station (Fig. 4c and d). They attributed the origin of these signals to nearby lightning activity. However, the polarization of these electric signals along the ENE–WSW direction suggests that their origin is also the transmitters of the military base which are indeed located WSW from IOA station (see Fig. 3).

10. Conclusion

In this paper we have shown that transient electric signals looking like single SES and SESA according to the VAN terminology can be generated by digital transmitters at short or longer distances depending on their power. Many typical forms of so-called SES or SESA can be explained simply by the response of a low pass filter to a rectangular pulse. Simple equations are established in order to evaluate the amplitudes of the electric and magnetic fields as functions of period, distance to the transmitter and underground resistivity underneath the recording station; these amplitudes are compatible with the observed ones. Plausible assumptions are proposed for a possible source of the April 18 and 19, 1995 SESA type signal recorded in the Ioannina region. Our study shows that the operating procedure of VAN which consists in recording the signals only in the very low frequency range (< 0.1 Hz), is not sufficient to guarantee that these signals do not have an artificial origin.

The VAN method continues to arouse strong debate as shown by recent discussions in the letters column of Physics Today (1998) and in Eos (1998). We think that the first priority toward resolving this issue is to agree on a monitoring procedure which could determine conclusively whether or not so-called SES are man-made. Special attention should be paid to choosing the location of a monitoring station. The electrical properties of the ground under the station should first be thoroughly studied by an MT sounding campaign over a broad frequency band, in order to determine the structure of the crust from the surface to the Moho. This information is necessary to interpret the characteristics of the recorded electromagnetic signals, either artificial or natural, and to find out whether or not any hypothetical conductive paths exist under the station claimed as 'sensitive' by VAN. If not, as seems to be the case under the IOA station and its neighbourhood, there is no physical possibility that signals emitted from distant earthquakes (> 100 km) could be detected at VAN's observation stations.

A firm criterion for the choice of a monitoring site is a low level of cultural noise, which allows observation of signals at higher frequencies (> 1 Hz). Such observations are very important for discrimination between artificial and natural signals, as reported here. It is clear that the IOA station, and its now extended sensitive area, do not satisfy this criterion, so that all earthquake predictions based on so-called SES signals recorded at this station are highly dubious.

11. Special issues

Measurements and theoretical models of the Earth's electric field variations related to Earthquakes, 1993. Tectonophysics 224, 1–269.

Debate on 'VAN', 1996. Geophys. Res. Lett. 23, 1291–1452.

Lighthill, J. (Ed.), 1996. A Critical Review of VAN. World Scientific, Singapore, 376 pp.

Claims of success in using geoelectrical precursors to predict Earthquakes are criticized and defended, 1998. Letters, Phys. Today 51 (6), 15–100.

Great debates in seismology: the VAN method of Earthquake prediction, 1998. Eos 79, 573–580.

References

Chouliaras, G., Pham, V.-N., Boyer, D., Bernard, P., Stavrakakis, G.N., 1997. Crustal structure of the Gulf of Corinth in Central Greece, determined from magnetotelluric soundings. Ann. Geofis. 40, 61–67.

Gruszow, S., Rossignol, J.-C., Pambrun, C., Tzanis, A., Le Mouël, J.-L., 1995. Characterisation of electric signals observed in the Ioannina region (Greece). C.R. Acad. Sci. Paris 320, 547–554.

Gruszow, S., Rossignol, J.-C., Tzanis, A., Le Mouël, J.-L., 1996. Identification and analysis of electromagnetic signals in Greece: the case of the Kozani earthquake VAN prediction. Geophys. Res. Lett. 23, 2025–2028.

Kanda, W., Uyeshima, M., Makris, J., Orihara, Y., Hase, H., Nagao, T., Uyeda, S., 1998. Directional properties of VAN's SES inferred from a resistivity mapping around Ioannina station, Greece. 14th Workshop on Electromagnetic Induction, Sinaia, Romania. Book of Abstracts, p. 67.

McNeil, J.D., Labson, V.F., 1991. Geological mapping using VLF radio fields. Electromagn. Methods Appl. Geophys. 2, 521–640, SEG.

Nomicos, K., Chatzidiakos, P., 1993. A telemetric system for measuring electrotelluric variations in Greece and its application to earthquake prediction. Tectonophysics 224, 39–46.

Papoulis, A., 1962. The Fourier Integral and Its Applications. McGraw-Hill Electronic Sci. Series, 318 pp.

Park, S.K., 1996. Precursors to earthquakes: seismoelectromagnetic signals. Surv. Geophys. 17, 493–516.

Paterson, N.R., Ronka, V., 1971. Five years of surveying with the Very Low Frequency-Electromagnetics method. Geoexploration 9, 7–26.

Pham, V.N., Boyer, D., Therme, P., Yuan, X.C., Li, L., Jin, G.Y., 1986. Partial melting zones in the crust in Southern Tibet from magnetotelluric results. Nature 319, 310–314.

Pham, V.N., Boyer, D., Cazes, M., 1990. Deep seismic and magnetotelluric sounding in Northern France. In: The Potential of Deep Seismic Profiling for Hydrocarbon Exploration. Ed. Technip, Paris, pp. 105–116.

Pham, V.N., Boyer, D., Nguyen, V.-G., Nguyen, T.-K.-T., 1995. Electrical properties and deep structure of the Red River fault zone in North Vietnam from magnetotelluric sounding results. C.R. Acad. Sci. Paris 320, 181–187.

Pham, V.N., Boyer, D., Chouliaras, G., Bernard, P., 1996. Electrical conductivity and structure of the crust around the Gulf of Corinth (Greece) from magnetotelluric sounding (MTS) results. C.R. Acad. Sci. Paris 323, 651–656.

Pham, V.N., Boyer, D., Chouliaras, G., Le Mouël, J.-L., Rossignol, J.-C., Stavrakakis, G.N., 1998. Characteristics of electromagnetic noise in the Ioannina region (Greece); a possible origin for so-called 'Seismic Electric Signal' (SES). Geophys. Res. Lett. 25, 2229–2232.

Uyeda, S., 1996. Introduction to the VAN method of earthquake prediction. In: Lighthill, J. (Ed.), A Critical Review of VAN. World Scientific, Singapore, pp. 3–28.

Uyeshima, M., Kanda, W., Nagao, T., Kono, Y., 1998. Directional properties of VAN's SES and ULF MT signals at Ioannina, Greece. Phys. Earth Planet. Int. 105, 153–166.

Varotsos, P., Alexopoulos, K., 1984. Physical properties of the variations of the electric field of the earth preceding earthquakes, I. Tectonophysics 110, 73–98.

Varotsos, P., Lazaridou, M., 1991. Latest aspects of earthquake prediction in Greece based on seismic electric signals. Tectonophysics 188, 321–347.

Varotsos, P., Alexopoulos, K., Lazaridou, M., 1993. Latest aspects of earthquake prediction in Greece based on seismic electric signals, II. Tectonophysics 224, 1–37.

Varotsos, P., Lazaridou, M., Eftaxias, K., Antonopoulos, G., Makris, J., Kopanas, J., 1996. Short-term earthquake prediction in Greece by seismic electric signals. In: Lighthill, J. (Ed.), A Critical Review of VAN. World Scientific, Singapore, pp. 29–76.

Varotsos, P., Eftaxias, K., Lazaridou, M., Nomicos, K., Sarlis, N., Bogris, N., Makris, J., Antonopoulos, G., Kopanas, J., 1996b. Recent earthquake prediction results in Greece based in the observation of seismic electric signals. Acta Geophys. Pol. 44, 301–327.

Varotsos, P., Sarlis, N., Lazaridou, M., 1998a. Claims of success in using geoelectric precursors to predict earthquakes are criticized and defended. Phys. Today 51 (6), 96–100, Reply to Letters.

Varotsos, P., Eftaxias, K., Lazaridou, M., Bogris, N., Makris, J., 1998b. Note on the extension of the SES sensitive area at Ioannina station, Greece. Acta Geophys. Pol. 46, 55–60.

Varotsos, P., Bogris, N., Extaxias, K., Hadjicontis, V., Lazaridou, M., Kefalas, M., 1998c. Additional evidence on the extent of the SES sensitive area around Ioannina. Acta Geophys. Pol. 46, 273–275.

Varotsos, P., Sarlis, N., Lazaridou, M., 1998d. Transmission of stress induced electric signals in dielectric media. J. Appl. Phys. 83, 60–70.

Vozoff, K., 1991. The magnetotelluric method. Electromagn. Methods Appl. Geophys. 2, 641–711, SEG.

Wait, J.R., 1982. Geo-Electromagnetism. Academic Press, 268 pp.