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On the Problem of Identification and Discrimination of Electrical Earthquake Precursors

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Abstract. The possibility of electrical precursors to earthquakes has long been appreciated, but to date there still exists neither a solid theory to describe the expected precursory waveforms, nor proven techniques to identify and discriminate precursors from noise. In addressing the latter problem, the only published approach and criteria involve simultaneous observations on elaborate arrays of short and long dipoles (e.g. Varotsos & Lazaridou, *Tectonophysics, 188*, 321, 1991). It is shown that these techniques are ineffective and can easily be deceived by local noise into identifying it as a distant signal. As an alternative approach, we discuss that some problems in identifying local, anthropogenic noise can be addressed with simultaneous measurement in a number of simple and inexpensive distributed stations operating as a network. In support of this point we present an example from an experiment in Ioannina : we have been able to successfully identify local noise with a single station recording the horizontal components of the telluric field in a two point configuration.

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1 Introduction.

A number of authors have studied electric and magnetic signals that might be associated with seismic or volcanic activity (Sobolev, 1975; Rikitake, 1987; Park et al., 1993; and many others) but, in most cases, they correspond to isolated events whose precise relationship to tectonic movements has not yet been demonstrated (except for precursory and co-seismic resistivity variations, e.g. Yamazaki, 1975). The origin of these electrical earthquake precursors (EEP) is not yet well understood. As a consequence, several cardinal questions remain unanswered. A number of different approaches exist, which attempt to explain the signal (e.g. Varotsos et al, 1993, Lazarus, 1993; Slifkin, 1993; Dobrovolsky et al., 1989; Bernard and LeMouël, 1996; Nomicos and Vallianatos, 1997). These provide for different generation mechanisms, all of which should yield different source geometries and, therefore, different propagation/decay laws and received waveform characteristics. The difficulty in understanding what produces the EEP and how it reaches the observer, raises a more important question: how can we tell what is an EEP from what isn't ?

The only research group which has attempted a systematic resolution of this question is the VAN team in Greece (Varotsos and Alexopoulos, 1984a,b; Varotsos and Lazaridou, 1991, Varotsos et al., 1993). Note however, that signals similar to those reported in Greece have not been unambiguously observed elsewhere (e.g. Maron et al., 1993; Kawase et al., 1993) and the VAN method remains highly controversial (e.g. Mulargia and Gasparini, 1992; Drakopoulos et al., 1993; Geller, 1996; Special issue on VAN, 1996). It is precisely the question of how the VAN team authenticates an EEP (Seismic Electric Signal - SES in their terminology), that initiated the investigations reported in this paper.

The VAN team has designed a number of *ad hoc* rules for identifying an EEP or SES, which can be summarized as follows (e.g. see Varotsos an Lazaridou, 1991):

1. Magnetotelluric noise is easy to eliminate because it appears at all stations simultaneously.
2. An SES must appear simultaneously on all of the short and long dipoles at the station or stations concerned.
3. An SES must satisfy the relationship $\Delta V/L$=constant for the short dipoles in both the EW and NS directions, provided that the ground is homogeneous over the area spanned by the arrays of short dipoles.
4. The polarity and amplitude of the SES on the short and long dipoles must be compatible with the distant source assumption : the projection onto the long dipole of the $\Delta V/L$ vector calculated from the short dipoles must have the same polarity and similar amplitude to the observed change on the long dipole. Specifically :

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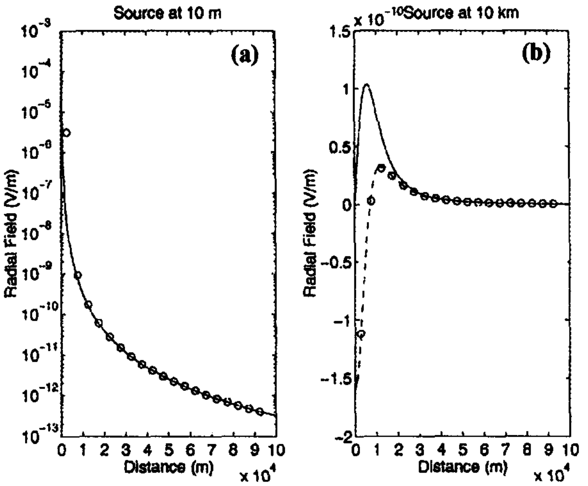

Fig. 1 The theoretical radial field (continuous line), and surface horizontal difference field ($\Delta V/L$) for electrode spacings L=0.1 km (dashed line) and L=5km (open circles), for a horizontal, y-directed dc dipole source, of unit current moment in a homogeneous lower halfspace with conductivity σ=0.001 S/m. **(a)** The field of a shallow source, (d=10m); **(b)** the field of a deep source (d=10000m). $\Delta V/L$ values are plotted at the midpoint of the 'dipoles'.

a) If the source is distant, then $\Delta V/L$ should be constant or at least comparable over dipoles of unequal lengths, otherwise the source may be local/nearby and the inequality of $\Delta V/L$ will be due to the steep gradients of the near field conditions.
b) If the source is distant, then the signal arrives at the station unilaterally and the polarity of the voltage variation between the short and long dipoles will be the same. Otherwise, if the source is local and located *within* the span of the long dipoles but *without* the span of the short dipoles, the polarity will be different and the locality of the source may be acknowledged.
Rules 2 and 3 are useful in rejecting the effects of electrode instabilities due to rainfall and noise from nearby sources, i.e. within a few hundred meters. For instance, Varotsos and Lazaridou (1991, p 328) state that : "When short dipoles (for a homogeneous area) are found to obey the rule $\Delta V/L$=constant, two possibilities exist for the interpretation of a voltage variation: either it's due to a noise source located at a distance appreciably larger than the length of the short dipoles, or it is an SES". Rule 4 has been designed to resolve this ambiguity in determining the distance of the source (4a) and be effective in rejecting noise from sources at distances comparable to the length of the long dipole, i.e. within a few kilometers (4b). Rule 4 has been used rigorously by VAN and co-workers and comprises the main tool by which they authenticate an SES (e.g. Varotsos and Lazaridou, 1995). Rules 3 and 4a are collectively termed *'the ΔV/L criterion'*, and rule 4b is *'the polarity criterion'*.

The VAN criteria have never been rigorously tested for their limitations. As Nagao et al (1996) state, "the physical meaning of these rules is straightforward" and as such they have been adopted by many researchers of electrical earthquake precursory phenomena. For instance, Nagao et al (1996), did not examine the physical background of the criteria, they were only concerned with how well can a signal be authenticated as SES by using these rules. Indeed, both criteria appear to be physically and intuitively straightforward and reasonably founded on well understood properties of the electromagnetic field. The '$\Delta V/L$ criterion' is similar in concept and expands on the differences known to exist for near and far field EM waves. It does not cater for the fact that in a finite conducting medium and at ranges of a few hundreds of kilometers from the source, one will always be in the near field conditions. The polarity criterion is straightforward and, at first sight, it is hard to see where it may fail. Yet, it does not take into account the possibility of lateral resistivity changes *within* the span of the long dipoles. In fact, neither criterion considers the influence of inhomogeneous earth structure, either within or without the span of the long dipoles. With such questions in mind, we set out to investigate and test these rules.

2 Discrimination capability of the ΔV/L criterion.

Consider a horizontal, y-directed dc dipole source, of unit current moment Il, embedded in a homogeneous lower halfspace with conductivity σ=0.001 S/m. An appropriate scalar potential is $V = Il\cos(\theta) / 4\pi r^2$ where $r=(d^2+y^2)^{1/2}$ and θ is the polar angle. Due to the spherical symmetry of the source, the electric field (**E**=-gradV) has only radial and azimuthal components. Image theory can be used to evaluate potential and fields at the surface of the halfspace.

Fig. 1 illustrates the theoretical radial field (continuous line) over a range R=100 km. Fig. 1a is the field of a shallow source (d=10m), taken to represent superficial anthropogenic noise. Fig. 1b is the field of a deep source (d=10000m), which assumes the role of an earthquake. The potential differences (ΔV) are calculated over lengths of L=0.1 km (dashed line) and L=5km (open circles). $\Delta V/L$ values are plotted at the midpoint of the 'dipoles'.

The horizontal difference field ($\Delta V/L$) of the shallow source (Fig. 1a), is a good approximation to the radial field; $\Delta V/L_{0.1km}$ is apparently different than $\Delta V/L_{5km}$ only in the first 10km from the source. The difference field of the deep source (Fig. 1b) is a poor approximation to the radial field at R≈30-40 km from the source (high polar angles) and a fair or good approximation at greater distances (low polar angles). The differences between $\Delta V/L_{0.1km}$ and $\Delta V/L_{5km}$ are very small for the scale of this figure and as will be shown, limited to the first 10 km from the epicenter. We investigate the relative amplitudes between the difference fields in short and long dipoles by constructing the ratio $(\Delta V/L_{0.1km})/(\Delta V/L_{5km})$ for three different cases: (a) The short and long dipoles share a common electrode at the beginning of the long dipole - crosses in Fig. 2a,b; (b) the short and long dipoles have a common midpoint - open circles in Fig. 2a,b; (c) The short and long dipoles share a

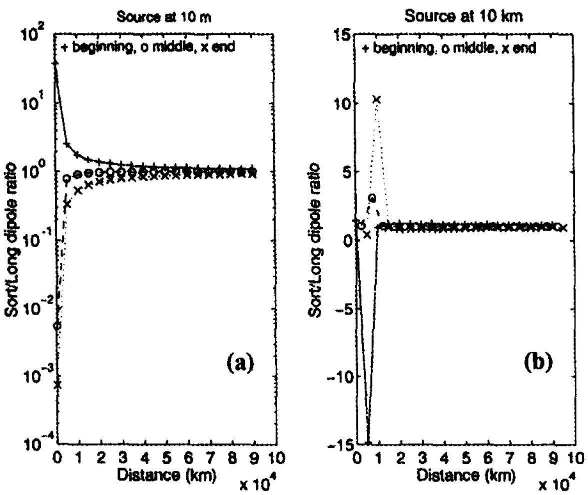

Fig. 2. The ratio $(\Delta V/L_{0.1km})/(\Delta V/L_{5km})$ between short and long dipoles by constructing for three cases: (1) crosses : the short and long dipoles share a common electrode at the beginning of the long dipole; (2) open circles : the short and long dipoles have a common midpoint; (3) x's : the short and long dipoles share a common electrode at the end of the long dipole. (a) the case for the shallow source of Figure 1a. (b) the case for the deep source of Fig. 1a

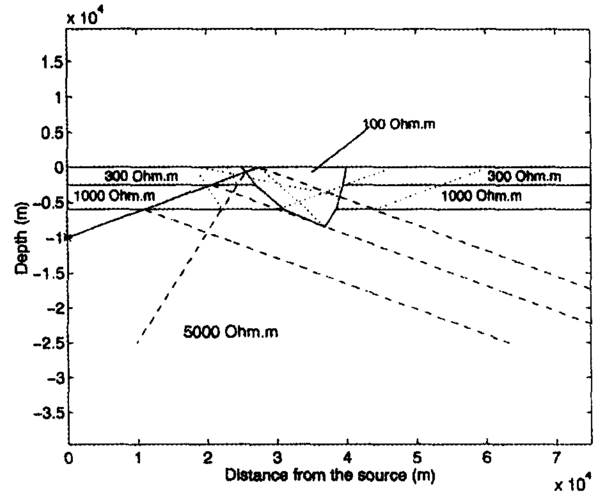

Fig. 3a. The geometry of potential transmission by image theory and the geoelectric structure producing the results of Figures 3b,c. Continuous lines are the direct 'rays'; dashed lines are the primary reflections; dotted lines are the first multiples. Second multiples have not been drawn to avoid confusion.

common electrode at the end of the long dipole - x's in Fig. 2a,b. In this way, we attempt to summarize the entire range of changes registered by the short dipoles within the span of one long dipole. The results are as follows :

Shallow source (noise) : Differences as high as 10^3 can be observed at the beginning of the long dipoles. These attenuate rapidly by a factor of 2.5-4 at a distance of only 5-10 km from the source and disappear at ranges longer than 10km. The differences maximize at the beginning and end of the long dipoles, where ΔV are also maximal. Note that Nagao et al (1996) maintain that experimental error and other uncertainties render acceptable differences of the order of 4-5 between short and long dipoles. According to this rationale, the relatively small differences observed at distances greater than 5-6 km may be taken to indicate a distant source. In short, the effectiveness of the $\Delta V/L$ criterion is limited to no more than 1-1.5 long dipole lengths from a noise source in its immediate vicinity. The criterion may misinterpret a local noise source as an 'SES' at ranges as short as 1.5-2 long dipole lengths from the source. In this case the polarity criterion will assist in the misinterpretation : both the short and long dipoles arrays will exhibit the same polarity because the source is one sided.

Deep source (earthquake) : There are no differences observed within the first 5km (1 long dipole length) from the epicenter of the source. However, the differences rise to a factor of 15 at distances of 5-10 km, only to disappear again at R > 10km. The reason for this behaviour can easily be seen in the shape of the expected radial field and the observed $\Delta V/L$ in Fig. 2b. The insignificant differences observed at R>10km are due to the low potential gradient generated by a deep and, therefore, relatively distant source. In this case, the $\Delta V/L$ criterion indicates a distant source and identifies an 'SES', but only by chance! At distances of only 5-10km from the earthquake source, it misguides the observed into assuming a local noise origin of the observed perturbation.

These results have been obtained for a dipole source with very fast decay. It may be shown that conditions are similar (or worse), when slower varying sources are considered, as for instance are point sources with r^{-2} and line sources with r^{-1} dependence, respectively. Our simple simulation indicates that any differences observable in real circumstances, at distances of a few tens of km from the source, may be a consequence of the inherent inhomogeneity of the Earth's crust and the omni-present natural potentials. Let us, now, investigate this possibility.

Method of analysis: Potential, the EM equivalent of mechanical stress, is absolutely continuous across interfaces, even in cases of oblique incidence. In the static (DC) case, matters are quite simple because many complications associated with wave propagation are canceled. When only piecewise planar interfaces are considered, and providing that the source is not located on one of them, image theory comprises a simple and effective tool to numerically evaluate the transmission of potential across a resistivity discontinuity. We implement a 'ray tracing' approach, in which a 'potential ray' departing from the source is transmitted and reflected across plane interfaces until it emerges to the surface. The algorithm also traces the reflected rays. An example of how this concept works can be seen in Fig. 3a. The emerging reflected 'rays' are grouped together according to their surface of origin and interpolated to equally spaced intervals. Finally, the emergent groups are superimposed to provide a measure of the total potential observed on the surface. We only consider reflections up to second multiple, because they comprise the main contributions to the total observed potential - higher order multi-

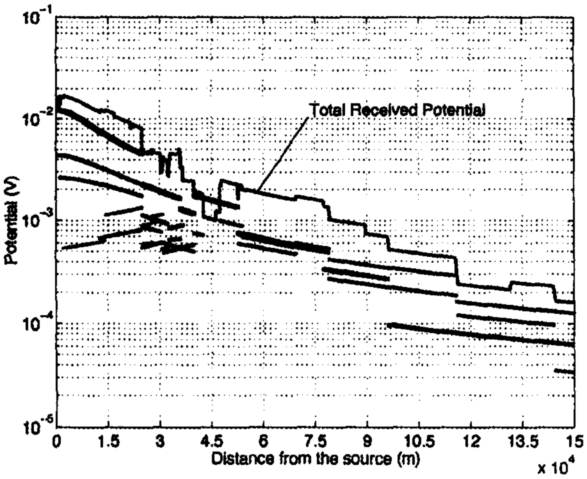

Fig. 3b. The total observed potential at the surface of the geoelectric structure of Fig. 3a, computed with potential transmission using image theory. The direct all positive reflected arrivals are also shown (negative polarity arrivals are excluded due to the logarithmic scale).

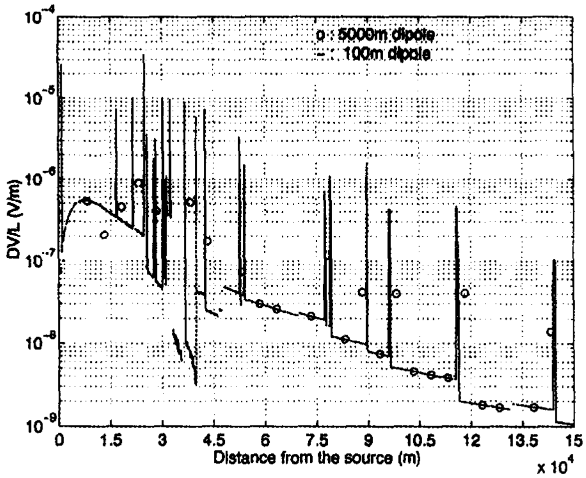

Fig. 3c. The horizontal difference field ΔV/L of the potential in Fig. 3b, in logarithmic scale for better scrutiny (negative values are not plotted). The continuous line corresponds to potential differences over dipole lengths L=0.1km. The open circles correspond to L=5km

ples are severely attenuated. Only a point source is considered herein, because of its simplicity. The procedure however is directly extendible to dipole and line sources.

Results. We present the case of a simple layered structure over a resistive basal half-space including an embedded, asymmetric conductive basin (Fig. 3a). Note that resistivity decreases towards the surface. The source is located at the origin and at d=10km. The total observed potential at the surface is shown in Fig. 3b, which also depicts several reflected components (albeit only those with positive polarity due to the logarithmic scale). The potential at the surface of this relatively simple structure is quite complex and exhibits a number of breaks and steps, as a result of the superposition of several discontinuous reflected arrivals. This is particularly true in the far side of the basin (R>40km). A remarkable observation is the build-up of potential within the boundaries of the basin due to the focusing of reflections from its portside walls.

Fig. 3c illustrates the horizontal difference field. The horizontal potential differences (ΔV) are calculated over dipole lengths of L=0.1 km (continuous line) and L=5km (open circles). ΔV/L values are plotted at the midpoint of the 'dipoles'. The dependence of ΔV/L on the inhomogeneity of the structure is apparent. In general, $\Delta V/L_{0.1km}$ is a rough function of distance. At epicentral distances 15-40 km, where the surface potential is a very rough function of distance due to the large number of reflections from the basin structures, $\Delta V/L_{5km}$ and $\Delta V/L_{0.1km}$ are very different, practically everywhere, and yet the distance from the source is relatively short. At epicentral distances 45km<R<100km, at the far side of the basin, $\Delta V/L_{5km}$ and $\Delta V/L_{0.1km}$ are different only where ΔV changes abruptly due to the onset or termination of reflected arrival(s). Here, the short dipole difference field ($\Delta V/L_{0.1km}$) is still a rough function, especially at distances < 80km, as a result of the corresponding roughness of the potential (steps and breaks). $\Delta V/L_{5km}$ is a considerably smoother function. In consequence, ΔV/L can be up to a few orders of magnitude different between short and long dipoles. For instance at distances 87-90 km, $\Delta V/L_{0.1km}=-1.6\times10^{-6}$ V/m and $\Delta V/L_{5km}=-4\times10^{-8}$ V/m. *In both cases, the observation sites are located over homogeneous ground.* Thus, if tested against the ΔV/L criterion these differences would be interpreted in terms of a source in the immediate vicinity of the observation sites, or at least within a few long dipole lengths, certainly not as much as 90 km away.

A final observation is that the superposition of primary and reflected arrivals *enhances* the amplitude of the total observed potential, with respect to the direct (primary) arrival, by a considerable factor (1-2 orders of magnitude at places), and at large distances from the source. This increases the chances of observing an electrical disturbance with fewer requirements of amplification by some particular or bizarre local properties (e.g. Bernard, 1992). Another 'amplification' effect takes place at locations where lateral variations of the structure, or steps and breaks of the potential-distance function generate high potential differences and hence high amplitude local electric fields, thus improving the chances to observe a variation at great distances from the source. It must be emphasized that this is *not* a 'selectivity effect' as defined in Varotsos et al, (1984a,b), because it does not depend on local structure, but is a consequence of the propagation of the electric field.

3 Discrimination capability of the polarity criterion.

Consider a geoelectric structure comprising a N-S lower quarter-space with resistivity contrast ρ_1/ρ_2, a network of long and short dipoles W-E and w-e respectively, with the long dipole traversing the discontinuity and a point source N lying in the domain ρ_1 and within the span of W-E (Fig. 4). The potential due to N at electrodes W and E can be evaluated by means of image theory:

$$V_W = \frac{\rho_1 I}{2\pi r_1} + \frac{\rho_1 I'}{2\pi r_2}, \qquad V_E = \frac{\rho_2}{2\pi r_3} \cdot \frac{2\rho_1 I}{(\rho_1 + \rho_2)}$$

where r_1 is the distance W-N, r_2 is the distance between N and the resistivity interface, r_3 in the distance N-E, I is the current at N and I′ is the image current of N. From the above we obtain: $I'=-kI$, $r_2=(D-r_1-\alpha)+(D-\alpha)=2D-r_1-2\alpha$, $r_3=D=r_1$, where k is the reflection coefficient and D, a are distances as defined in Fig. 4. With this simple configuration we can evaluate the potential difference ΔV_{W-E} between electrode W and the resistivity interface.

The results are shown in Fig. 5 for different resistivity contrasts. The polarity of ΔV_{W-E} changes sign from positive to negative within the distance r_1 and the location of sign conversion is absolutely dependent on the magnitude of the resistivity contrast. Now consider that for the configuration of Fig. 4, the polarity of the potential difference ΔV_{w-e} at the short dipole will be constant and positive ($V_w > V_e$). Therefore, if a point source of noise is located within the area where $\Delta V_{W-E}>0$, then according to the polarity criterion its signal will be interpreted as arriving from beyond W-E, specifically, from the far side of electrode W. We call the area of polarity criterion failure *the G-domain* and the location of sign conversion *the G-boundary*. It is interesting to note that the G-boundary is closer to electrode W when $\rho_1/\rho_2 \ll 1$ and moves eastwards to coincide with the resistivity interface when $\rho_1/\rho_2 \gg 1$, in which case, the polarity criterion will always fail.

This simple simulation shows the profound effects of resistivity inhomogeneities between the span of the long dipole. In the case treated herein, the criterion may identify a local noise source if and only if it is located in a *part* of the area spanned by the long dipole, or if the source is known *and* the effect of the resistivity contrast is known and compensated for. In the latter case however, a slight shift of the source or the electrode configuration may invalidate it. The example presented here for the simpler case of a point source, is directly extendible to other types of sources.

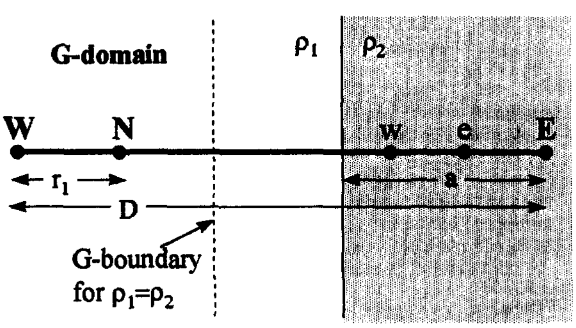

Fig. 4. The set of parameters used to test the polarity criterion and calculate the position of the G-boundary. W-E is the long dipole; w-e the short dipole; N is the noise source.

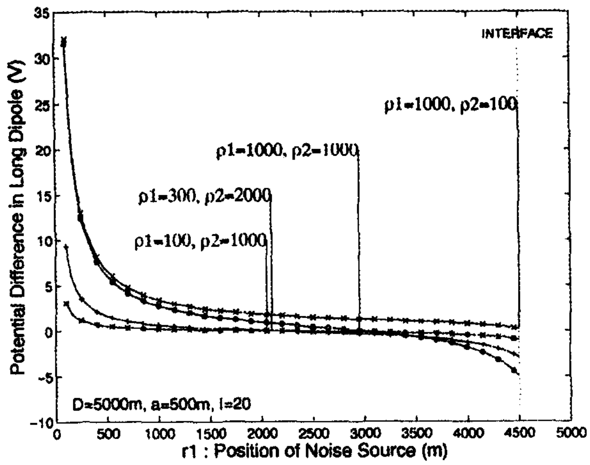

Fig. 5. Position of the G-boundary as a function of resistivity contrast.

4 Discussion

In testing the performance of the VAN 'SES validation criteria', we consider only a handful of the innumerable possible combinations between the long and short dipole networks and geoelectric structures. The behaviour of ΔV/L and polarity criteria is expected to be different for each one of them, due to their dependence on the geoelectric structure of the path from the source to the observer. As we also have shown, the ratio ΔV/L for two dipoles of unequal length may not always depend on local geoelectric structure; it may be influenced by features embedded at any place along the propagation path. For distant/deep sources, this dependence is unknown and will probably remain so forever. Thus, existing noise/EEP discrimination practices with long and short dipole combinations can be misleading and unreliable. A remedy may be to calibrate the short/long dipole array using powerful nearby and distant grounded sources. However, the feasibility of such an undertaking is questionable, particularly when it comes to simulating deep seated earthquake sources. Given the poor reliability of the criteria, it appears that their only unquestionable usefulness of the short/long dipole combinations is the identification of electrode noise. This task, however, does not necessarily require long *and* short dipoles - it may as well be done with a distributed array of short dipoles.

The question of how to discriminate a genuine EEP from noise is still open. In our opinion, the most solid approach would be to build appropriate physical models for the generation and propagation of EEP and simulate their received characteristics in cases of non-trivial geoelectric structures. The comparison and possible agreement of theory with observations may provide a basis for the recognition of some classes of EEP. We shall not be expand on this problem herein.

From a practical point of view, a very solid criterion would be the simultaneous appearance of a signal in more than one, mutually separated stations. This alone would be sufficient to account for local noise sources. On a more local scale however, we propose that some noise terms may be identified with a small number of distributed stations. Our experience arises from an experiment in Ioannina basin, NW Greece, which has been described in detail by Gruszow et al (1995).

This involves observations of the telluric field with two adjacent sets of orthogonal electric lines, laid down in a NS-EW configuration, their centres being 30 m apart; these are complemented by a high sensitivity (0.25 nT) observatory-type, fluxgate variometer. The different components of the electric signal recorded at this installation may be distinguished into: **a)** A class of signals which can be attributed to natural EM induction (MT signals), and which can, in general, be removed analytically (e.g. Tzanis, 1994). **b)** A class of signals comprising powerful transient events with amplitudes varying from five to a few tens of mV/km; apparently, these arrive from the same repeating sources because they are consistently polarised in the same directions over extended periods of time. The waveforms of signals with similar polarisations are also similar. These observations indicate nearby, anthropogenic sources, therefore it is possible to eliminate local noise by comparing the received characteristics of signals simultaneously recorded at the two adjacent sets of electrodes. **c)** Low amplitude (<3 mV/km) background noise including electrode instabilities.

In addition, we have identified some sporadic events which cannot be assigned to any of the above classes. These are usually polarised in the same general direction as class (a), but cannot be correlated with any observable magnetic field variations; their amplitudes vary between a few and a few tens of mV/km. Because some of these events coincided with 'SES activity' announced by VAN (e.g. 22/8/1993, 11:40 GMT; B. Massinon, personal communication), the conclusion of Gruszow et al. (1995) concerning their origin was rather circumspect: "they may be generated by some industrial source, but it cannot be excluded, at the present state of the analysis, that they might as well be tectonoelectric effects".

Using such techniques we have identified noise waveforms on the basis of their received characteristics (shape and patterns of occurrence) and *not* their amplitudes. Electrode noise could be identified by comparison of records from adjacent arrays. Our single station may be effective in eliminating local sources, but is certain to fail in the case of noise sources at distances of a few hundred meters to a few km. The concept however can be expanded with installation of more that one observation posts (a small local network of distributed stations) : Noise sources with ranges comparable to the size of the network may, then, be identified and located on the basis of their received characteristics and patterns of occurrence. We have attempted to explore this possibility by installing a second station a few km away. The data at the second station could identify MT and local sources in a similar manner, but during its short period of operation we did not observe an anomalous signal simultaneously at both stations

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