Time-difference between the electric field components of signals prior to major earthquakes

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We present data demonstrating that the electric field components of low-frequency (≤1 Hz) precursory electric signals exhibit markedly different time evolutions. This difference, *if* properly measured, upon considering that the electromagnetic fields obey diffusion-type equations, is of profound importance since it can reveal the distance of the measuring site from the epicenter of the impending earthquake. © *2005 American Institute of Physics*. [DOI: 10.1063/1.1924870]

Electric and magnetic signals have been observed before many geological time events, e.g., volcanic eruptions, in unstable flanks of active volcanoes,[1] landslides, and earthquakes.[2] In the latter case even lightning phenomena have been reported.[3] Here, we focus on the so-called seismic electric signals (SES) activities, which consist of hundreds of pulses and are detected several hours to a few months before major earthquakes (EQs) in Greece[4–6] and Japan.[7,8] These low frequency (≤1 Hz) signals are probably emitted when the stress reaches a *critical* value[9,10] in the focal area, but several other SES generation mechanisms related to the formation and/or motion of defects in the Earth's solid crust have been also proposed.[11–14]

Recent experimental results on the SES activities[6] showed that these electric signals, when transmitted in an inhomogeneous weakly conductive dielectric medium like the Earth, are recorded at distances of the order of 100 km one to two seconds *before* the time derivative of the magnetic field **B**. This lead-time Δt between the electric field **E** and $d\mathbf{B}/dt$ is not *significantly* affected by the orientation (as well as the length L) of the measuring electric dipoles. This article is aiming at studying the time difference between the electric field components themselves. We shall show that two horizontal electric field components, if measured along *appropriate* directions (see below), they exhibit measurable difference in their time-evolutions. This difference can be of major practical importance, because a reliable estimation of the epicentral distance of the impending EQ can be obtained. As an example, we shall consider here, as in Ref. 6, the 6.6 EQ that occurred in northern Greece on May 13, 1995, which was preceded by two SES activities on April 18 and 19, 1995. These SES activities were recorded at Ioannina Station (IOA), which lies in northwest (NW) Greece at an epicentral distance of around 80 km.

We first recapitulate the measuring instrumentation (details can be found in EPAPS Ref. 15). The data of both fields **E**,**B** were simultaneously collected (with a rate F_s =1 sample/s) by the *same* acquisition system. The magnetic field variations were measured by three coil magnetometers, which act as dB/dt detectors for periods larger than around half a second; they are oriented along the three axes: east-west (EW), northsouth (NS), and vertical. Concerning the **E** field variations, they are monitored by several measuring dipoles (pairs of electrodes) with lengths a few to several tens of meters (short dipoles) or a couple of kilometers (long dipoles). Here, among the multitude of electric dipoles, we intentionally select to analyze the data collected by two short electric dipoles, which are oriented along and perpendicular to the (local) current channeling.[16,17] These dipoles of length 50 m are installed at the site "*c*" (see Fig. 1 of Ref. 15) and will be labeled E_c-W_c and N_c-S_c, respectively. It is important to note that this site "*c*" was properly selected, after tedious experimentation, as follows: Since the IOA area is inhomogeneous, we checked several neighboring sites[15] by monitoring (along the directions EW and NS at each site) the so-called magnetotelluric disturbances, which are induced by small changes of the Earth's magnetic field. Among these sites, we selected the one (i.e., the site "*c*") at which the MT electric field component amplitudes exhibit the largest difference (between the two measuring directions), i.e., they have the maximum and minimum (the latter being practically zero within the experimental error) amplitude.[16] Instead of such a selection, one could alternatively do the following: To measure the SES electric field variations with a multitude of short dipoles deployed along several directions, and select the two that exhibit the "slowest" and the "fastest" response in the SES recording, see below. In our measurements, among the aforementioned multitude of dipoles deployed in various directions,[15] the dipoles E_c-W_c and N_c-S_c showed the "slowest" and "fastest" response, respectively, in the SES recordings. The short dipoles are measured by using low pass "10 Hz" filters.[15]

We now proceed to the presentation of the experimental results. The full recording of the SES activity on April 18, 1995, is shown in Fig. 1(a) while the one collected on April 19, 1995, is depicted in Fig. 1 of Ref. 6. Excerpts of these recordings are shown in Figs. 1(b)–1(e) in an expanded time scale. Recalling that the sampling rate is F_s=1 sample/s, an inspection of several cases similar to those of Figs. 1(b)–1(e) reveals that the electric field variations are usually abrupt [i.e., within 1 s, see the channel N_c-S_c in Figs. 1(b)–1(e)]. There are, however, some pulses which exhibit a finite duration of their transition time from the background to the maximum deflection level and vice versa, i.e., sometimes they "need" 2 s to reach the maximum deflection from the background, or 2 s to return from the maximum deflection level to the background; see the channel E_c-W_c in Figs. 1(c) and 1(e). The fact that in most of the 500(=N) pulses collected,

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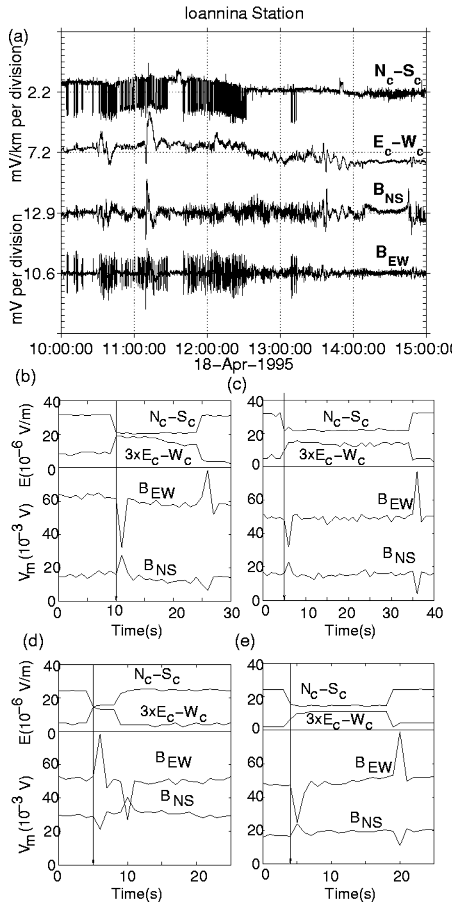

FIG. 1. (a) SES recordings on April 18, 1995 (b)–(e) Excerpts, in an expanded time scale from the recordings on April 18 (b),(c) and April 19, 1995 (d),(e). For the magnetic field variations: 20 mV of V_m correspond to a constantly increasing magnetic field of 0.1 nT/s. The arrows in (b) to (e) are drawn just at the time when the "fast" component N$_c$-S$_c$ reaches its maximum level (lowest in the figure).

the components N$_c$-S$_c$ and E$_c$-W$_c$ have simultaneous initiation and cessation [as in Figs. 1(b) and 1(d)] can be seen when calculating the cross-correlation coefficient ("cr" values[6]) between the time series of the time derivatives, Dt (see Ref. 6), of N$_c$-S$_c$ and E$_c$-W$_c$ (Fig. 2) versus their time-difference Δt. A prominent peak then actually appears at $\Delta t=0$. Beyond this peak, however, a secondary—but still statistically significant—correlation pertains at $\Delta t=1$ s. The latter, which appears as a shoulder in Fig. 2 (shown by the arrows), originates from pulses similar to that depicted in Figs. 1(c) and 1(e). In order to quantify this phenomenon, we

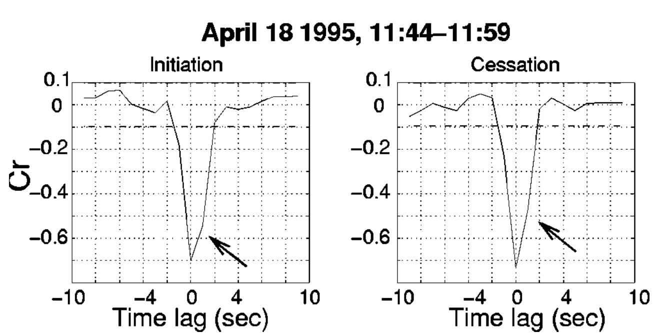

FIG. 2. Calculated "cr" between the derivatives (Dt) of N$_c$-S$_c$ and E$_c$-W$_c$ vs their time-lag Δt on April 18, 1995 for the initiation (left) and cessation (right) of the pulses. Broken horizontal lines correspond to the 99% confidence level.

define here the SES rise time τ_r as the time "needed" for the SES pulse to reach the 85% of its maximum amplitude measured from the moment it has reached 15% (of its maximum deflection). We can obtain an estimation for τ_r as follows: The percentage of pulses N_f/N with finite transition time (i.e., more than one sample) is approximately equal to the ratio of τ_r over the sampling period ($T_s=1/F_s$). Such a procedure reveals that the N_f/N values are (%): 14 ± 6 and 32 ± 5 for the components N$_c$-S$_c$ and E$_c$-W$_c$, respectively. Taking into account the sampling period ($T_s=1$ s), the above N_f/N values lead to the following τ_r estimation: 140 ± 60, and 320 ± 50 ms for the dipoles N$_c$-S$_c$ and E$_c$-W$_c$, respectively. In other words, the component E$_c$-W$_c$, which is parallel to the (local) current channeling, has a τ_r value ($=320\pm50$ ms) markedly larger than that ($=140\pm60$ ms) of the component N$_c$-S$_c$, which is perpendicular to the channeling.

The fact that the aforementioned analysis of a large amount ($N=500$) of pulses can lead to τ_r values smaller than the sampling period (T_s) is further commented in Ref. 15. As explained there, well-known techniques have been recently developed which allow the accurate measurement of the characteristics of a short duration pulse by using *repetitive* sample rate that has a period wider than the pulse.

We now examine whether the above experimental findings can be, in principle, theoretically understood. In a conductive medium, like the Earth, both fields **E** and **B** follow diffusion-type equations in the low-frequency range.[5,18] Let us consider the simplified case of a homogeneous conductive medium of conductivity σ (an alternative case,[5,6] i.e., a conductive cylinder embedded in a medium of smaller conductivity, is discussed in EPAPS Ref. 15), and assume a current density $\mathbf{j}(\mathbf{r},t)=\Theta(t)\delta^3(\mathbf{r})\hat{\mathbf{z}}$, where $\Theta(t)$ is the Heaviside unit-step function, localized at the origin. Then we can calculate the electric field components measured (in two perpendicular directions) at a site located at a distance r. Considering, for example, the simple case of a dipole source being almost parallel to $\mathbf{r}$, and following Refs. 18 and 15, we find[15] that the electric field components have *different* time evolutions, which are described in terms of two functions which both depend[15] on the time-scale $\tau_0=\mu\sigma r^2/4$ (where μ is the magnetic permeability). These functions after considering the "10 Hz" low pass filter (i.e., after their convolution with the filter's impulse response[15]) result in two (new) functions labeled $F_{5/2}$ and $F_{7/2}$ (see Fig. 3 of EPAPS Ref. 15), which correspond to the slow and fast component, respectively.

We now assume, for the sake of simplicity only, that the SES pulses are emitted from the focal area in the form of random telegraph signals (RTS), as discussed in Refs. 10, 19, and 20. We considered a large number ($N=500$) of consecutive boxcar pulses emitted (non-overlapping in time) from the focal area, and simulated their recording at a measuring site lying at some distance from the source. We assumed, that the abrupt edges of these RTS are distorted, for each value of τ_0, and recorded by the measuring system having the feature of $F_{5/2}$ or $F_{7/2}$, respectively. This procedure, repeated 10^3 times via Monte Carlo, leads to the N_f/N values shown in Fig. 3, for both $F_{5/2}$ and $F_{7/2}$.

We now compare the experimental N_f/N values with the calculated ones. In particular, the aforementioned experimental values of E$_c$-W$_c$ (the "slower" component) are compared with the calculated N_f/N values of $F_{5/2}$ in Fig. 3, while those of N$_c$-S$_c$ (the "faster" component) with $F_{7/2}$ (in Fig. 3). In-

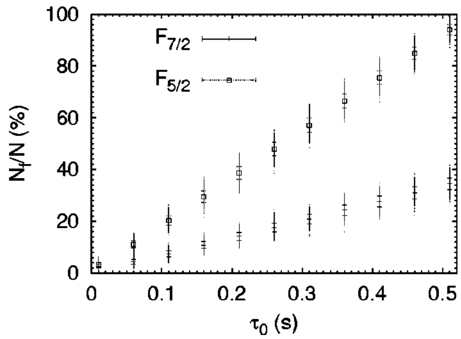

FIG. 3. Calculated values—through Monte Carlo—for the percentage of pulses N_f/N (N=500) with τ_r larger than 1 s vs τ_o (Fs=1 sample/s). The bars correspond to one standard deviation.

terestingly, *both* comparisons point to the *same* τ_0 value, i.e., $\tau_0 \approx 0.18 \pm 0.04$ s. This value, when recalling that $\tau_0 = \mu \sigma r^2/4$ and considering that the resistivity of the medium $\rho = 1/\sigma \approx 10^4\ \Omega m$, leads to an epicentral distance $r \approx 76$ km (ranging from 53 to 107 km, *even if* a wide uncertainty of 50% in the host medium resistivity is assumed), which is comparable to the actual one, i.e., r=80–100 km. In other words, in spite of the simplicity of the theoretical model employed, the experimental N_f/N values (deduced from the analysis of the electric fields components data *alone*) reveal the distance of the emitting source (i.e., the focal area of the impending major EQ) from the measuring site.

In summary, the two components of the electric field detected on the Earth's surface prior to major EQs, *if* measured along appropriate directions, exhibit markedly *different* time evolutions. This stems from the fact that the electric field obeys *diffusion*-type equations (in the low-frequency range only). Even a simplified analysis can reveal the distance of the emitting source from the measuring station, thus leading, if SES recordings at three (at least) noncollinear remote sites are available, to the identification of the EQ epicenter in advance by means of electric field measurements alone.

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