Supplementary information on: Electric pulses some minutes before earthquake occurrences

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Abstract

Here, in Section I, we recapitulate the instrumentation used along with relevant maps showing the sites of the electrodes at IOA and the location of three (out of 10) operating stations. Furthermore, in Section II, we present an electric pulse observed at two remote stations almost $7\frac{1}{2}$ minutes before a magnitude 6.6 earthquake that occurred in the Aegean sea in 2001.

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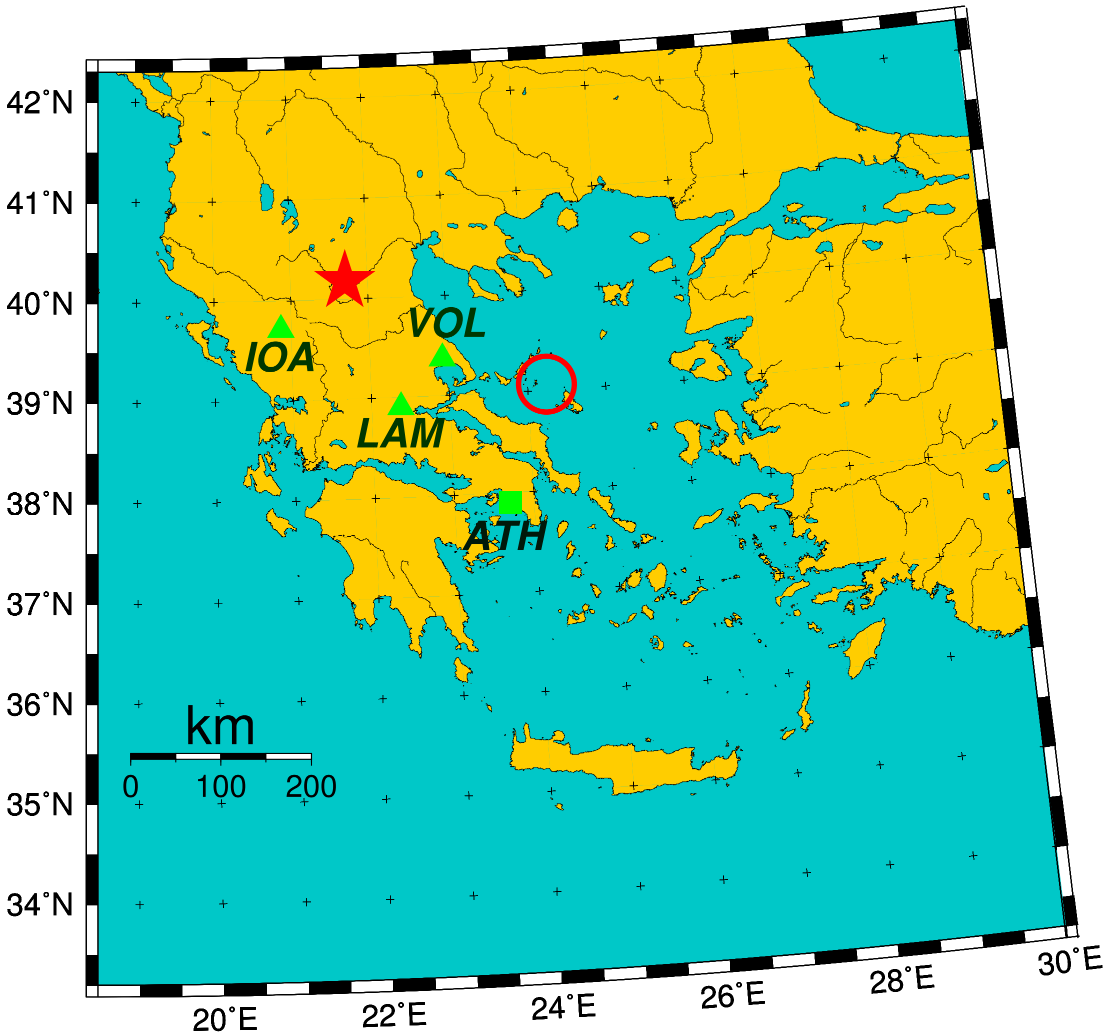

FIG. 1: A map of Greece depicting the location (green) of three (out of 10) measuring stations, i.e., IOA, VOL and LAM, and the central station ATH. Furthermore, the epicenters(red) of the Grevena-Kozani 6.8 EQ(star) in 1995 and the Aegean sea 6.6 EQ(circle) in 2001 are shown.

I. THE INSTRUMENTATION

Figure 1 provides a map of Greece depicting the location of three (out of 10) measuring stations, i.e., IOA, LAM and VOL, along with that of the central station ATH of the telemetric network. Furthermore, in the same figure, the epicenters of the M6.8 Grevena-Kozani EQ in 1995 and the M6.6 Aegean sea EQ in 2001 are shown.

A schematic diagram of the measuring system used for the digital/analog collection of the data presented in the main text, is shown in Fig.2.

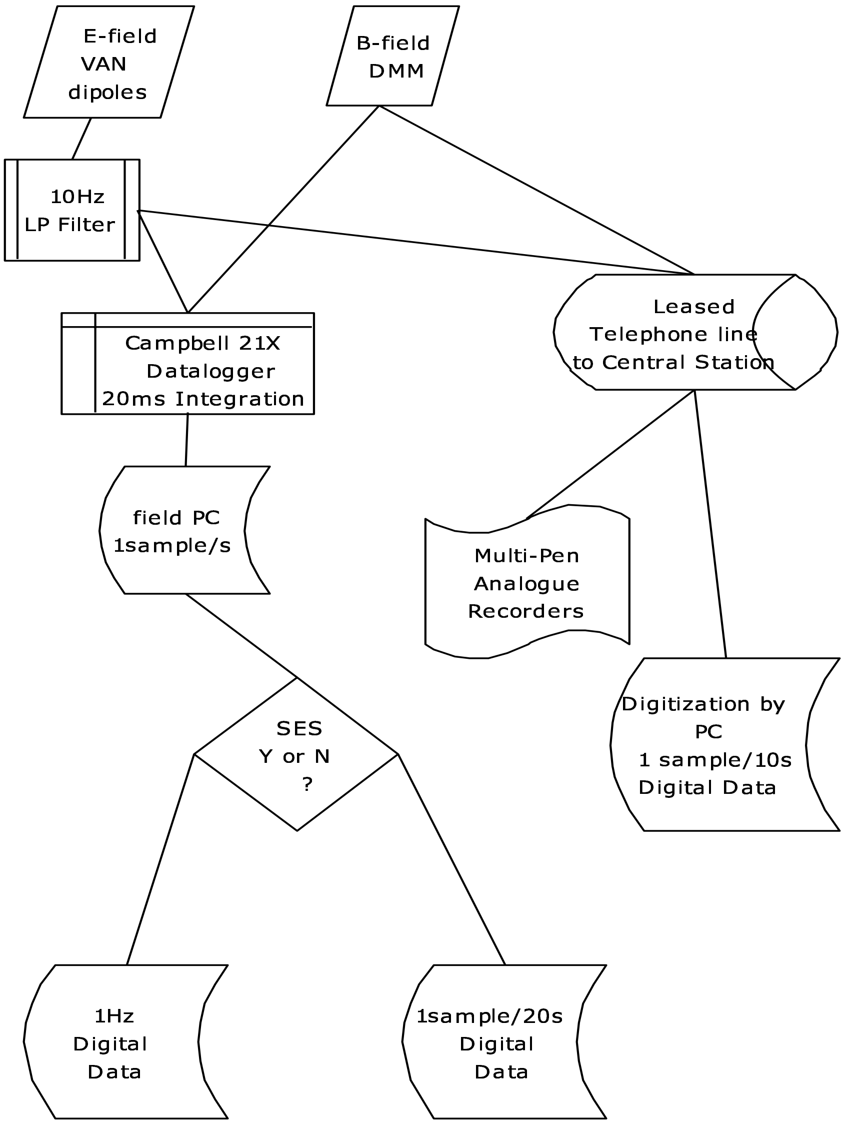

FIG. 2: Schematic diagram of the measuring system used for the digital/analog data collection.

A. The sites of the electrodes at Ioannina (IOA) station

The electric field (E) measurements at IOA have been carried out by several dipoles with lengths a few to several tens of meters(short dipoles) or a couple of kilometers (long dipoles). The short- and long- dipoles are measured by 10Hz and 1Hz low pass filters, respectively. A map of all these dipoles is given in Fig.3. Only the data of the dipoles $E_c - W_c$ and $N_c - S_c$,

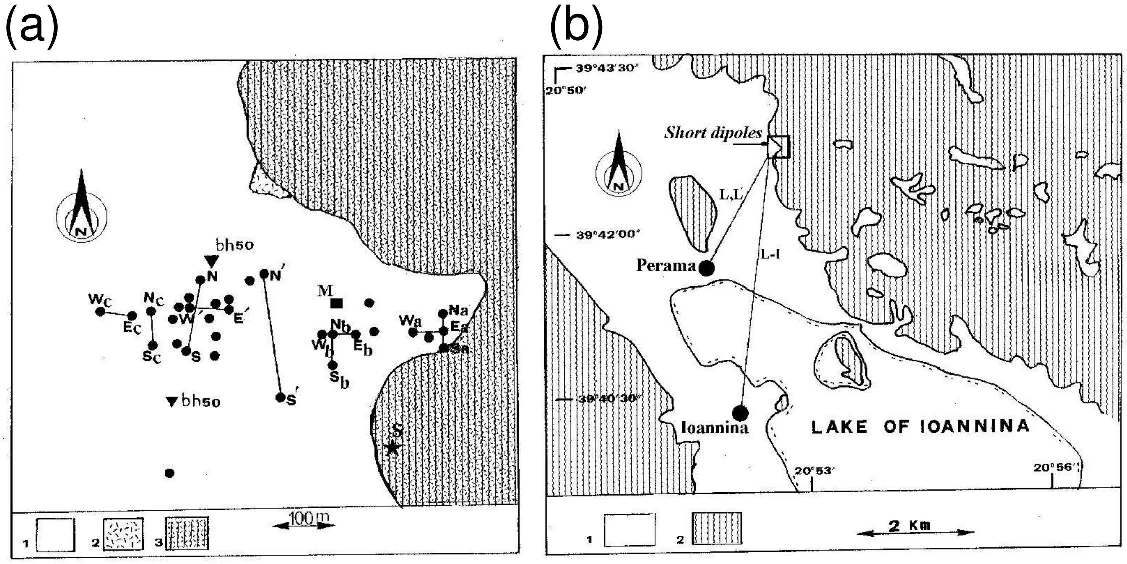

FIG. 3: (a)Configuration of short dipoles at IOA. The dipoles with subscripts c are those located at the site 'c' which have been analyzed in the main text. Concerning the geology: (1) alluvial deposits, (2) flysch of the Ionian unit, (3) limestones. The geographical coordinates of the station are $39^o 42.6' N, 20^o 51.4' E$(Northwestern Greece). (b)The same as in (a) but for the long dipoles at IOA.

i.e., the two dipoles to the left of Fig.3(a), are discussed in the main text.

B. The magnetometers used for the magnetic field measurements at IOA

In 1995, the permanent recording of the magnetic field variations at IOA was carried out by three DANSK coil magnetometers (DMM). These magnetometers were located close to the middle of the dipole labelled $N'S'$, which lies between the sites 'b' and 'c' in Fig.3(a). Furthermore, since 1996 the MT-1 system of Electro-Magnetic Instruments (EMI) has been also used. Concerning the calibration of DMM, in addition to a laboratory calibration, an in situ (i.e., at IOA) calibration was performed[1] by comparing the DMM recordings $V_m(t)$ to those of EMI-magnetometers (hereafter called EMM) and relying on the accurate laboratory calibration[2] of the latter. This calibration led to a Heaviside (or unit step) response function $H(t)$:

$$V_m(t) = \int_{-\infty}^{\infty} H(\xi) \frac{dB}{dt}(t - \xi) d\xi, \qquad (1)$$

TABLE I: The amplification A, the 3dB frequency corner f_p, the time delay τ_d, and the characteristic "period" T_p for the low-pass "10Hz" filters used in the field experiments[3].

A	f_p(Hz)	τ_d(ms)	T_p(ms)
1.015±0.024	15.4±0.4	1.5±0.4	14.6±0.4

that vanishes for $t < 0$, while for $t \geq 0$

$$\begin{aligned} H(t) &= A\frac{\tau_d^4}{(\tau_d-\tau_r)^4}\left[\exp\left(-\frac{t}{\tau_d}\right)-\exp\left(-\frac{t}{\tau_r}\right)\right] \\ &- A\frac{\tau_d^3}{(\tau_d-\tau_r)^3}\frac{t}{\tau_r}\exp\left(-\frac{t}{\tau_r}\right) \\ &- \frac{A}{2}\frac{\tau_d^2}{(\tau_d-\tau_r)^2}\left(\frac{t}{\tau_r}\right)^2\exp\left(-\frac{t}{\tau_r}\right) \\ &- \frac{A}{6}\frac{\tau_d}{(\tau_d-\tau_r)}\left(\frac{t}{\tau_r}\right)^3\exp\left(-\frac{t}{\tau_r}\right) \end{aligned} \tag{2}$$

with $\tau_d \approx 0.025$s and $\tau_r \approx 0.007$s (see [1]).

This calibration showed that, for periods larger than around half a second, DMM magnetometers act as dB/dt detectors. Their output is "neutralized" after 200ms from the "arrival" of a Heaviside unit step magnetic variation, i.e, $B(t) = B_0\Theta(t)$, where $\Theta(t)$ is the Heaviside (or unit step) function.

C. The filters for the electric field measurements[3]

The low pass "10Hz" filters used[3], are fourth order active low pass filters, having two symmetric second order poles in the complex ($i^2 = -1$) f-plane with a frequency response:

$$R(f) = \frac{A\exp(-2\pi i f\tau_d)}{[1-(f/f_p)^2+i\sqrt{2}(f/f_p)]^2}, \tag{3}$$

where A is the amplification, f_p is the 3dB frequency corner of the filter, and τ_d is the time delay of the filter. The expression (3) was applied to the laboratory measured data for both amplitude and phase, and a non-linear least squares fitting was performed(see Fig.4) using the constant chi-square($p = 95\%$) boundaries for the determination of the errors in the fitting parameters (see Table I).

Finally, Eq.(3) leads to an impulse response:

$$I(t) = 2\frac{A}{T_p}\exp\left[-\frac{(t-\tau_d)}{T_p}\right]\left[\sin\left(\frac{t-\tau_d}{T_p}\right)-\left(\frac{t-\tau_d}{T_p}\right)\cos\left(\frac{t-\tau_d}{T_p}\right)\right]\Theta(t-\tau_d), \tag{4}$$

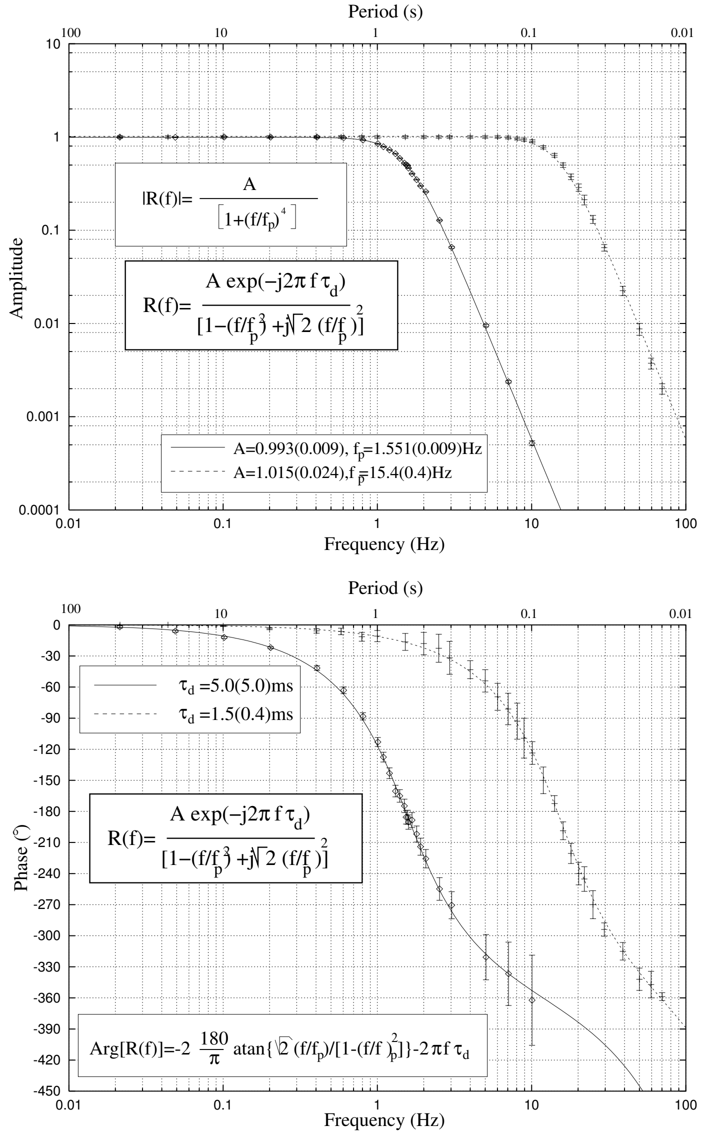

FIG. 4: The frequency response of the "10Hz"(broken lines) and "1Hz"(solid lines) low-pass filters[3].

where $T_p = 14.6 \pm 0.4$ms and $\tau_d = 1.5 \pm 0.4$ms, determined by the aforementioned laboratory calibration see Fig.4.

II. EXAMPLE OF AN ELECTRIC PULSE BEFORE AN M6.6 EARTHQUAKE RECORDED AT TWO REMOTE STATIONS

As mentioned in the main text, electric pulses were recorded before all five EQs(see Table II) with magnitude M$\geq$ 6.5 that occurred in Greece within $N_{35}^{41}E_{19}^{27}$ during the period

TABLE II: All earthquakes during 1995-2005 within $N_{35}^{41}E_{19}^{27}$ with magnitude larger than (or equal to) 6.5 according to NEIC/USGS.

Year	Month	Date	Origin Time (UT)	Lattitude	Longitude	Depth (km)	Magnitude
1995	May	13	08:47:12.73	40.15	21.69	14	6.80 MSBRK
1995	June	15	00:15:48.73	38.40	22.28	14	6.50 Ms GS
1997	October	13	13:39:37.49	36.38	22.07	24	6.60 Ms GS
1997	November	18	13:07:41.73	37.57	20.66	33	6.60 MwHRV
2001	July	26	00:21:36.92	39.06	24.24	10	6.60 Ms GS

1995-2005.

The case of the first EQ of Table II was already discussed in the main text. Let us now focus on the last EQ of Table II, which occurred at 00h:21m:36.92s on July 26, 2001 in the Aegean sea (epicenter 39.06^{o}N 24.24^{o}E). Here, we present in Fig.5 the electrical recordings of some electric dipoles operating at two remote stations, namely VOL and LAM, which are the closest stations of our telemetric network -consisting of 10 stations- to the EQ epicenter. (The configuration of all the operating dipoles at these two stations, i.e., 48 in VOL and 16 in LAM, can be seen in Figs.6 and 7, respectively, where the geology is also shown.) An almost simultaneous pulse can be clearly seen at both stations approximately $7\frac{1}{2}$ minutes before the origin time (OT) of this M6.6 EQ. This is marked by an arrow in Fig.5(a) and 5(b) for VOL and LAM, respectively. The following remarks are in order:

First, the electric pulse is *not* recorded at all electric dipoles at a given station. This is reminiscent of the fact mentioned in the discussion of Fig.1 in the main text that the pulses "b" and "d" are *non* visible on the NS component (but they do so in the EW component). Hence, it is important to use a multitude of electric dipoles oriented in different directions in order to detect the electric pulse (dipoles should be installed in a variety of local geological conditions, since the influence of the geology on the pulse detectability is still unknown).

Second, the simultaneous recording of the electric pulse at two remote stations (cf. the distance between VOL and LAM is around 65km) excludes any possibility of attributing it

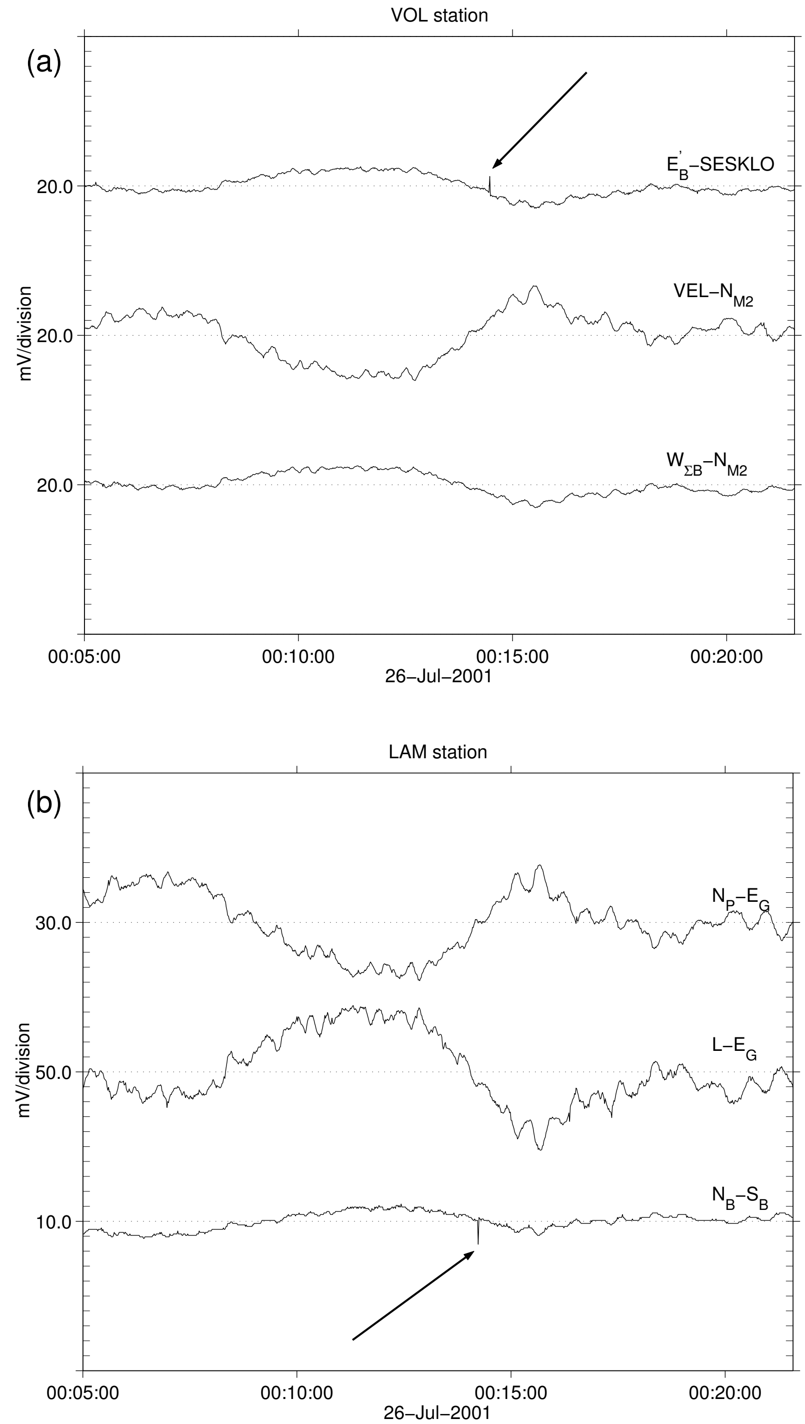

FIG. 5: Electrical recordings at VOL(a) and LAM(b) from 00:05:00 UT until the origin time (00:21:37) of the M6.6 EQ in the Aegean sea on July 26, 2001. The arrows show the electric pulse detected almost $7\frac{1}{2}$ minutes before the origin time.

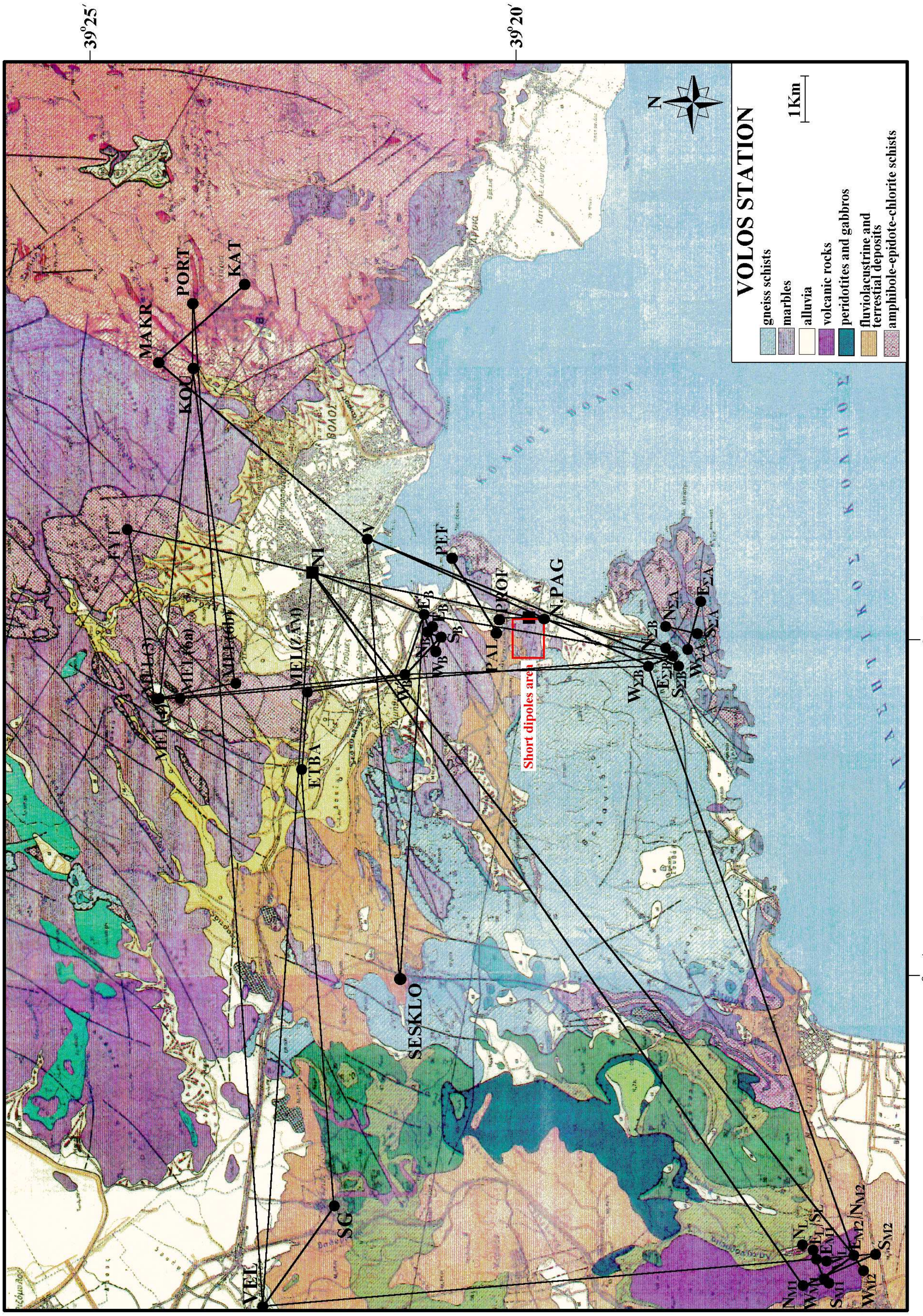

FIG. 6: Configuration of the measuring dipoles at VOL.

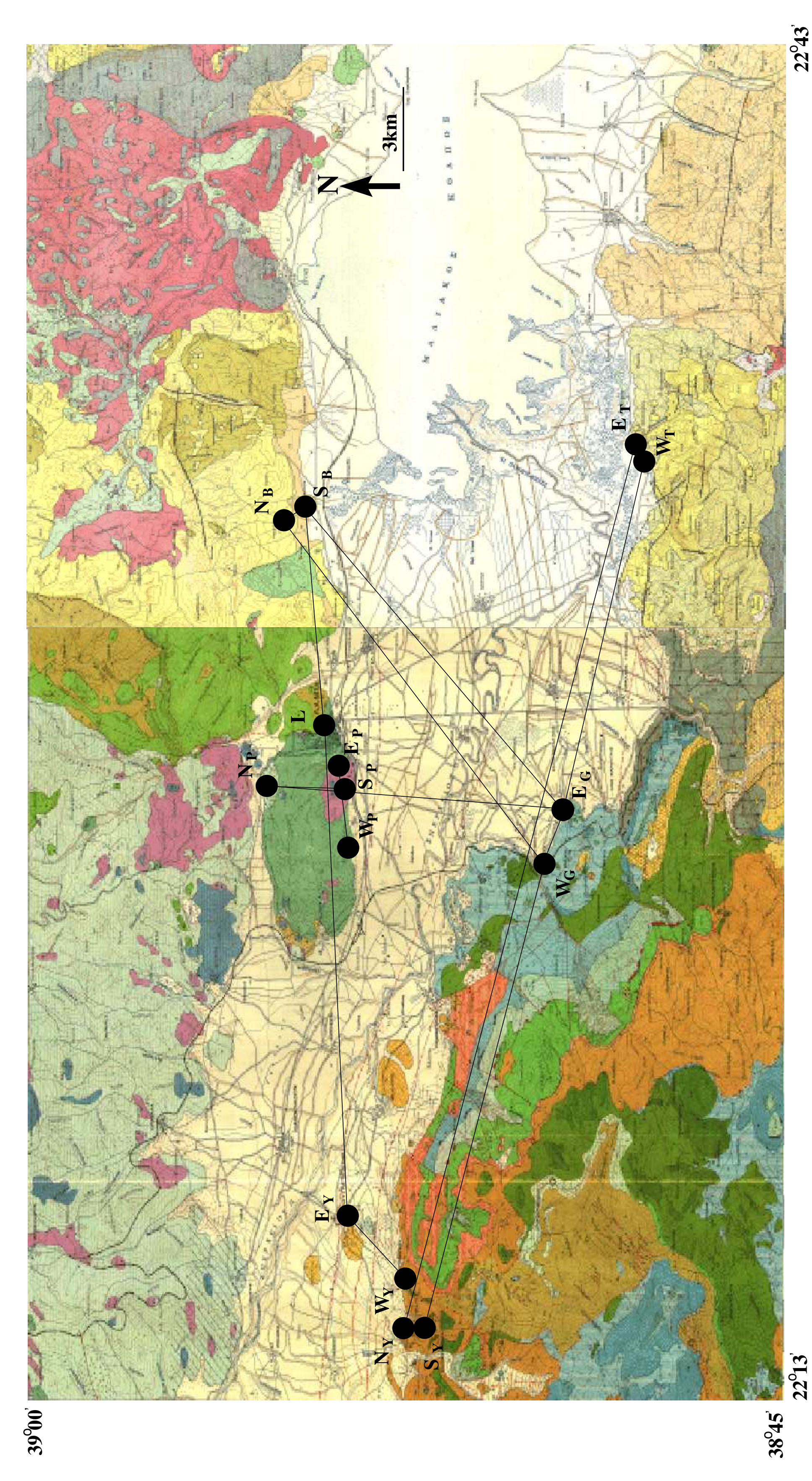

FIG. 7: Configuration of the measuring dipoles at LAM.

to a local man-made source.

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[2] EMI, *MT-1, A mobile System for MT Measurements* (Electro Magnetic Instruments, Berkeley, CA, 1995).

[3] See EPAPS Document No. E-APPLAB-86-100519 for additional information, originally from P. A. Varotsos, N. V. Sarlis, E. S. Skordas, Appl. Phys. Lett. **86**, 194101 (2005). For more information on EPAPS, see `http://www.aip.org/pubservs/epaps.html`.