On the recent seismic activity in North-Eastern Aegean Sea including the $M_w$5.8 earthquake on 8 January 2013

By Nicholas V. SARLIS*1,†

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Abstract: In the last week of November 2012, we announced that a strong electrotelluric disturbance, which we judged to be a Seismic Electric Signal (SES) activity, was recorded at station Assiros located in Northern Greece. This disturbance was actually followed by an $M_w$5.8 earthquake on 8 January 2013 in North-Eastern Aegean Sea. Here we show that, by analyzing this SES activity and employing the natural time analysis of subsequent seismicity, we estimated the epicentral location, magnitude and occurrence time which are reasonably compatible with those of the $M_w$5.8 event.

Keywords: Seismic Electric Signals, natural time, epicentral location, earthquake magnitude, time-window

1. Introduction

Recent studies1–3 have strengthened the importance of general seismo-electromagnetics in earthquake (EQ hereafter) prediction. There have been suggested1–3 various promising candidates for EQ prediction, the measurement4–7 of Seismic Electric Signals is one of them for which their correlation with EQs has been intensively studied4–13 with positive results, e.g. for a recent review see Ref. 14. In this paper, we intend to report on the possible relationship between the Seismic Electric Signals observed at Assiros station in Northern Greece on 13 July 2012 (see Fig. 1) and an $M_w$5.8 EQ which occurred on 8 January 2013 in North-Eastern Aegean Sea. We shall show that the epicenter, magnitude and occurrence time of the impending EQ estimated before its occurrence conform to those of the actual EQ.

Continuous measurements of the electric field of the Earth in Greece4–9 (see Fig. 2) and Japan1,10–12 revealed that transient variations of the electric field of the Earth, called Seismic Electric Signals (SES), precede major EQs. When several SESs occur within a short time like a few hours or so, they are called SES activity. The lead time of SES activity varies between a few weeks and five months or so.13 The current configuration of the telemetric network comprising 9 field stations, in each of which a multitude of measuring short and long electric dipoles of length ($L$) has been installed, can be seen in Fig. 2. The discrimination of SES from noise is based on the four criteria suggested in Ref. 6. Briefly, an electric disturbance is classified as SES if: (a) it is not recorded simultaneously at all stations, (b) at a station, it exhibits an almost constant value of $\Delta V/C_1$, where $\Delta V$ is the potential difference observed for almost parallel short measuring dipoles, (c) it appears simultaneously in both short and long dipoles, and (d) the $\Delta V$ values of long and short dipoles are compatible. A sensitive station can record SES only from some specific seismic areas (selectivity effect). A map showing the seismic areas that emit SES detectable at a given station is called selectivity map of this station. For example, the three grey shaded areas of Fig. 2 are the selectivity map of Assiros station (ASS) which was known to us before 8 January 2013 (the day of the $M_w$5.8 EQ).

The above physical properties of SES have been theoretically explained15,16 — for a recent review see Ref. 13.

The magnitude of the expected EQ can be estimated by the relation:5,12

$$\log_{10}(E \times r) = aM + b$$  \[1\]
Fig. 1. Recordings of the SES activity at Assiros station at 13 July 2012 at the three — out of sixteen — independent dipoles of different lengths (varying between 500 to 900 m) with true headings $H_1$, $H_2$ and $H_3$ as shown in the legend.

Fig. 2. Map showing the operating field stations (blue triangles) and the central station (blue square). The selectivity map of ASS is also shown; the three areas ‘a’, ‘b’, and ‘c’ may be joined$^{13}$ to a single larger area as indicated by a thick solid black curve. The EQs that occurred after the initiation of the SES activity at ASS until 6 January 2013 within the area $N^{41.5}E^{22.7}$ (blue broken rectangle) are depicted by red circles. The area $N^{41.5}E^{22.7}$ originally used for the estimation of the occurrence time-window of the forthcoming EQ is shown by the green rectangle bounded with dotted lines. The orange star shows the epicenter of the $M_w5.8$ EQ that occurred on 8 January 2013 whereas its mechanism (USGS Body-Wave Moment Tensor Solution) is the depicted by the beachball. The proposed selectivity map of ASS is bounded with the red dashed-dotted line while the EQs that lie inside it are marked with the blue plus symbols. The cyan and the yellow stars show the epicenters of the $M_w5.6$ EQ on 30 April 1985 and the $M_w5.3$ EQ on 4 May 1995, respectively, also discussed in the text.
where \( E = \Delta V/L \) is the amplitude of the SES, \( r \) is the focal distance from the station, \( b \) a station dependent constant, and \( a \) a constant lying in the range 0.32–0.37 related with the fractal properties of the SES emitting source, e.g. see Ref. 17.

2. Natural time analysis. Background

The analysis of SES was significantly advanced in the new time-domain, termed natural time domain.\(^{13,18} \) The real time collection of SESs and their analysis allow announcement of prediction well before the EQ occurrence.

In a time series consisting of \( N \) events, the natural time \( \chi_k = k/N \) serves as an index\(^{18} \) for the occurrence of the \( k \)-th event. In natural time analysis\(^{13} \) the evolution of the pair \( (\chi_k, Q_k) \) is studied, where \( Q_k \) denotes a quantity proportional to the energy released in the \( k \)-th event. In the case of seismicity,\(^{13,19} \) \( Q_k \) is given by

\[
Q_k \propto 10^{1.5M}
\]

where \( M \) stands for the moment magnitude.

It was shown\(^{13,20} \) that when the system enters the critical stage, the variance

\[
\kappa_1 \equiv \sum_{k=1}^{N} \chi_k^2 p_k - \left( \sum_{k=1}^{N} \chi_k p_k \right)^2
\]

of natural time \( \chi \) weighted by \( p_k \equiv Q_k / \sum_{n=1}^{N} Q_n \) approaches the value

\[
\kappa_1 = 0.070.
\]

The experiences showed\(^{13,19,21} \) that when analyzing the small EQs that occurred after the SES activity initiation in natural time the main shock occurs within a week or so after Eq. [4] is realized, thereby making the time window of prediction appreciably narrower.

3. Comparison of the actual EQ epicenter and magnitude with those estimated from the SES

Figure 2 shows the selectivity map of ASS (grey shaded areas ‘a’, ‘b’ and ‘c’) available to us before the date of the 8 January 2013 \( M_{W} 5.8 \) EQ which is also shown by an orange star. The beachball depicts the EQ mechanism by the United States Geological Survey (USGS). Based on this selectivity map, we expected the epicenter of the coming EQ may be in one of the areas ‘a’, ‘b’ and ‘c’. We observe that the actual EQ epicenter lies about 40 km southeast of area labeled ‘a’. This may be regarded as reasonably confirming the prediction.

Moreover, we exclude the area ‘c’ from the candidate area by the recordings of the long and the short dipoles operating at ASS (for geographic distribution of dipoles, see Figs. 1.1.4, 1.4.1 and 4.2.3 of Ref. 22) as follows. By considering the value of the ratio \( E_{EW}/E_{NS} \) of the two SES components (as measured by the short dipoles along the directions EW and NS), we could select the regions from the selectivity map which might have emitted the observed SES. Detailed studies\(^{23} \) (see also p. 15 of Ref. 22) have shown that a sensitive measure of \( E_{EW}/E_{NS} \) is the ratio \( \Delta V_{long} / \Delta V_{short} \) where \( \Delta V_{long} \) and \( \Delta V_{short} \) stand for the \( \Delta V \) values of the SES measured on a long and a short dipole, respectively (cf. this ratio, which is termed “directional parameter” in Ref. 23, was found to change from one epicentral region to another). In particular, in the case of ASS a long dipole 10 km long is operating which connects the location where the short dipoles are deployed with the nearby village of Lagada (see Figs. 4.2.3 and 1.4.1(b) of Ref. 22). Considering the value \( \Delta V_{long} \) measured at this dipole (cf. \( \Delta V_{long} \approx 20 \mu V \), see the lowest panel of Fig. 1(b) of Ref. 24) we find that the ratio \( \Delta V_{long}/\Delta V_{short} \) in the present case (e.g. \( \Delta V_{short} \approx 1.5 \mu V \) when \( L_{short} = 100 \text{ m} \), see the first line of Table 1 where \( E_{short} = E = 15 \mu V/m \)) differs significantly from the ones observed in the past before EQs coming from the area ‘c’ of the selectivity map. For example, compare the SES activity under discussion (announced in Ref. 24) with the one recorded on 6 April 1995 at ASS—depicted in Fig. 4.2.2 of Ref. 22—with \( \Delta V_{long} \approx 13 \mu V \) and \( \Delta V_{short} \approx 0.4 \mu V \) that preceded the \( M_{W} 5.3 \) EQ on 4 May 1995 at 40.7°N, 23.5°E (marked with the yellow

| Table 1. The occurrence date, location and magnitude of the two mainshocks in the areas ‘a’ and ‘b’ discussed in the text along with the parameters (SES initiation date, SES amplitude \( E \) and focal distance \( r \)) of their preceding SES recorded at ASS |
|------------------|--------|--------|-----------------|------------------|
| SES date         | \( E (\mu V/m) \) | \( r (\text{km}) \) | EQ date          | EQ location      | \( M_{W} \) |
| 13 July 2012\(^a\) | 15     | 250    | 8 January 2013  | 39.66°N,25.54°E  | 5.8 |
| 25 April 1985\(^b\) | 14     | 195    | 30 April 1985   | 39.06°N,23.15°E  | 5.6 |

\(^{a}\)See the lowest panel of Fig. 1(b) of Ref. 24.

\(^{b}\)See Fig. 4 of Ref. 6.
As mentioned in Section 2, it has been observed that when the system enters the critical stage, the variance \( \kappa_1 \) calculated using a seismic catalogue approaches the value \( \kappa_1 = 0.070 \) provided that the calculation is started at the initiation time of SES. If major EQs are critical phenomena, this property should be observed in a wide spatial range due to the unavoidable development of long range correlations, e.g. see Ref. 20. Thus, once an SES activity has been recorded at a station we start studying the seismicity in the area to suffer a mainshock based on the selectivity map of the station. In this area, hereafter labelled A, we examine the small events (EQs) — with magnitudes greater or equal to a threshold \( M_{thres} \) — that occur after the initiation of the SES activity. Analyzing in natural time this subsequent seismicity as it evolves event by event in area A as well as in all the possible subareas of A (cf. practically we use only rectangular subareas delimited by the epicenters of small EQs as an approximation as shown in Fig. 4, see also Fig. 1 of Ref. 21) we can obtain a multitude of \( \kappa_1 \) values that enable the construction of the distribution of \( \kappa_1 \), labeled \( \text{Prob}(\kappa_1) \). When the critical stage is approached the condition \( \kappa_1 = 0.070 \) should exhibit spatial invariance leading to a maximum of \( \text{Prob}(\kappa_1) \) at \( \kappa_1 \approx 0.070 \). Moreover, the scale invariance associated with critical phenomena implies that the same picture is expected to hold if we also vary the magnitude threshold. Thus, the simultaneous observation of maxima of \( \text{Prob}(\kappa_1) \) at \( \kappa_1 \approx 0.070 \) for various magnitude thresholds can indicate that the critical stage has been approached and the mainshock is imminent. It was found\(^{[13,21]}\) that such a behavior usually occurs a few days to around one week before the mainshock, making the time window of prediction to the order of a week or less as already mentioned in Section 2.

Figure 2 depicts with red circles all the small EQs that occurred after the SES and before the \( M_{5.8} \) event within the area \( N_{a}^{1.7}E_{21.9}^{38.4} \) (blue dashed rectangle) that surrounds the Assiros selectivity map. We observe that during this period a series of small EQs occurred close to Lamia city (LAM): these EQs cannot be related with SES at Assiros because they lie well outside the already known selectivity map (areas ‘a’, ‘b’, ‘c’) and if they were related to some SES, the corresponding SES should have been recorded according to our experience\(^{[13,22]}\) at the nearby LAM station and not at ASS. In order to exclude the majority of them from the calculation without missing events that occurred within the selectivity map of ASS, we moved the Western star in Fig. 2), i.e., 40 km ESE of ASS. Thus, the area ‘c’ was excluded in the present case as a candidate area for the EQ epicenter.

We now turn to the magnitude of the EQ. This can be investigated on the basis of Eq. [1] by referring to an earlier SES recorded at ASS having an amplitude \( E_2 (= 14 \mu V/m) \) comparable with that of the SES activity under discussion (see the second line of Table 1) and a focal distance \( r_2 \) (= 195 km). This was the case of the SES recorded on 25 April 1985 which preceded an \( M_{5.6} \) EQ (Harvard reported \( M_{5.6} \) that occurred close to Volos city in central Greece on 30 April 1985, see the cyan star in Fig. 2. Using Eq. [1], we estimated the magnitude \( M_x (= \log_{10}(r_2 E_1/r_2 E_2)/a + M_z) \) versus the focal distance \( r_2 \) from ASS as shown in Fig. 3. We observe that for \( r_2 \) in the range 120 to 260 km (cf. area ‘c’ was already excluded as mentioned) \( M_x \) varies between 5 to 6 magnitude units. The actual focal distance \( r_2 \) was 250 km leading to \( M_x \approx 6.0 \). The latter value compares favourably with the observed \( 5.8 M_w \) EQ if we also take into account a plausible estimation error.

4. Identifying the EQ occurrence time on the basis of natural time analysis

A procedure to identify the time window of an impending mainshock has been developed\(^{[13,19,21]}\) based on the hypothesis that the occurrence of a mainshock can be considered as a critical point (e.g. Ref. 25, see also Ref. 26 and references therein). As mentioned in Section 2, it has been observed that when the system enters the critical stage, the variance \( \kappa_1 \) calculated using a seismic catalogue approaches the value \( \kappa_1 = 0.070 \) provided that the calculation is started at the initiation time of SES. If major EQs are critical phenomena, this property should be observed in a wide spatial range due to the unavoidable development of long range correlations, e.g. see Ref. 20. Thus, once an SES activity has been recorded at a station we start studying the seismicity in the area to suffer a mainshock based on the selectivity map of the station. In this area, hereafter labelled A, we examine the small events (EQs) — with magnitudes greater or equal to a threshold \( M_{thres} \) — that occur after the initiation of the SES activity. Analyzing in natural time this subsequent seismicity as it evolves event by event in area A as well as in all the possible subareas of A (cf. practically we use only rectangular subareas delimited by the epicenters of small EQs as an approximation as shown in Fig. 4, see also Fig. 1 of Ref. 21) we can obtain a multitude of \( \kappa_1 \) values that enable the construction of the distribution of \( \kappa_1 \), labeled \( \text{Prob}(\kappa_1) \). When the critical stage is approached the condition \( \kappa_1 = 0.070 \) should exhibit spatial invariance leading to a maximum of \( \text{Prob}(\kappa_1) \) at \( \kappa_1 \approx 0.070 \). Moreover, the scale invariance associated with critical phenomena implies that the same picture is expected to hold if we also vary the magnitude threshold. Thus, the simultaneous observation of maxima of \( \text{Prob}(\kappa_1) \) at \( \kappa_1 \approx 0.070 \) for various magnitude thresholds can indicate that the critical stage has been approached and the mainshock is imminent. It was found\(^{[13,21]}\) that such a behavior usually occurs a few days to around one week before the mainshock, making the time window of prediction to the order of a week or less as already mentioned in Section 2.

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boundary by 0.6° to the East (as well the Eastern boundary 0.1° to the West so that it coincides with the Eastern boundary of the selectivity map) and applied the aforementioned procedure for the natural time analysis assuming that area A is $N^{41.2}_W E^{25.0}_S$ (drawn with a green dotted rectangle in Fig. 2) which practically surrounds the ASS selectivity map excluding its Western part.

Here, in our analysis we used the local magnitudes ($M_L$) reported by the seismic catalogue of the Institute of Geodynamics of the National Observatory of Athens (www.gein.noa.gr). A major improvement of the seismological network of this Institute has been recently completed.27–31

Figure 5 shows that on 5 January 2013, upon the occurrence of the $M_L = 2.9$ event at 05:55 UT, $\text{Prob}(\kappa_1)$ for $M_{\text{thres}} = 2.9$ maximized at $\kappa_1 \approx 0.070$. This behavior also exhibits magnitude threshold invariance since it holds for magnitude thresholds $M_{\text{thres}} = 2.9, 2.8$ and 2.7. As said, the fulfillment of the condition $\kappa_1 \approx 0.070$ signals that the system has approached the critical point and actually the $M_{L}5.8$ EQ occurred on 8 January 2013.

5. Construction of a new selectivity map for ASS

The fact that the epicenter of the 8 January 2013 EQ lies just outside the existing selectivity map of ASS prompted us to improve it (cf. it has been already suggested13 that areas ‘a’, ‘b’ and ‘c’ may be interconnected into a single large region but since no large EQs had occurred in the intermediate region no significant SES has been correlated to them so far). To this end, we depict in Fig. 2 with the red dashed-dotted curve the proposed new selectivity map of ASS—in which the natural time analysis of seismicity should be performed—and mark with blue plus symbols the small EQs that occurred inside it after the SES initiation and before the $M_{L}5.8$ EQ.

If the proposal is correct, the exclusion of small EQs not related with the SES at Assiros (e.g. see the events that occurred in the South-Southeastern part of the original area $N^{41.2}_{W} E^{25.0}_{S}$) will lead to a more evident correlation between the EQs studied and hence the results of Fig. 5 should be improved. The results of this analysis for $M_{\text{thres}} = 3.0$ are shown in Fig. 6. We observe a clearly better shape of the peak at $\kappa_1 \approx 0.070$ upon the occurrence of the $M_L = 3.0$ EQ on 27 December 2012, which is the last one (for this magnitude threshold) before the $M_{L5.8}$ EQ. Moreover, the peak at $\kappa_1 \approx 0.070$ is also observed upon the occurrence of the aforementioned $M_L = 2.9$ event on 5 January 2013 at 05:55 UT.
Prob($\kappa_1$) for $M_{\text{thres}} = 2.9$, 2.8 and 2.7. We note that both the $M_L = 3.0$ and the $M_L = 2.9$ EQs occurred very close in space with epicenters at 39.81°N, 24.45°E and 39.87°N, 24.50°E (cf. the latter epicenter is marked with a green circle in Fig. 2 and lies 92 km west of the epicenter of the $M_w 5.8$ EQ on 8 January 2013).

6. Conclusions

By analyzing in natural time the seismicity that occurred inside a rectangular region surrounding the already known ASS selectivity map after the initiation of the SES activity recorded at ASS on 13 July 2012, we identified that the condition $\kappa_1 \approx 0.070$ was fulfilled on 5 January 2013 and hence a major EQ would be imminent. Actually on 8 January 2013 an $M_S(ATH) = 6.2$ ($M_w = 5.8$) EQ occurred close to the eastern edge of this rectangular region. Moreover, the properties of the SES activity allows the determination of the epicentral location and magnitude which are reasonably compatible with those of the $M_w 5.8$ event. In short, all the parameters (epicenter, magnitude and time-window) of this EQ could be estimated on the basis of the SES properties together with natural time analysis. This strengthens the view that SES measurements are valuable for short-term EQ prediction. In addition, the present results indicate that the selectivity map of Assiros station should be augmented to include also the epicenter of the last EQ.
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Fig. 6. The same as in Fig. 5, but by considering only the EQs — marked with blue plus symbols in Fig. 2 — that lie inside the proposed selectivity map of ASS. The figure depicts the histograms of $\text{Prob}(\kappa_1)$ versus $\kappa_1$ for $M_{thres} = 3.0$. 

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