



ELECTROSTATIC IMAGING FOR DETECTION OF POSSIBLE EARTHQUAKE PRECURSORY STRUCTURAL CHANGES

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SUMMARY

A network of 14 on-line stations that contains monopolar electric field probes was installed around Northern Anatolian Fault to detect earthquake precursory electrical anomalies beginning from 1999. Electrodes of the probes were intended to measure electrical displacement between the upper lithosphere and the lower atmosphere. We propose a sort of passive electrostatic imaging in time to detect beginning and rate of the structural change. In electrical engineering, "electrostatic imaging" requires a known electrical charge source and a coupling measurement probe. If the probe is mobile in space then the induced electrical charges on the electrode will be a function of dielectric coefficient change of the material between the supply and the scan trajectory. The same feature holds for the lithosphere of the Earth since there is always equivalent internal charge distributed in layers. Non-stationary character of the background electric field is the main problem of passive electrostatic imaging. For this reason we collect long term data from fixed stations instead of mobile measurements. Hence we get the long term development of periodic components and compensate the patterns to be evaluated. Discontinuities and period deflections of the patterns have significant correlation to the seismic events as shown in examples.

1. INTRODUCTION

Electrical connection between the Earth's crust and the atmosphere is a hidden factor that shapes all terrestrial activities. From neural systems of living creatures to thunderstorms, all elements are a part of this coupling. Change of electrical displacement as a precursory seismic event in time and space is investigated in this study.

There have been several research activities for earthquake prediction with a similar approach and new ones including satellite measurements such as Demeter [Parrot and Gwal, 2002] and Quakesat have recently been initiated. Some of these researches depend on evaluation of physical changes on Earth's surface [Ikeya, 1999; Geller, 1996; Varastos et al., 1996; Ikeya et al., 2000]. As an alternative to such physical measurement methods, change of electric field is measured by using a new type of monopolar probe in a common project of Electrical & Electronics Faculty and Faculty of Mines at Istanbul Technical University (ITU). Although time domain measurements at stationary points can be a part of earthquake forecast by using pattern based evaluations [Ozerdem and Ustundag, 2002] another interesting concern is the change of patterns with respect to surface movement of a mobile apparatus that electrically couples to surface.

There are three main possible reasons of change in electrical displacement inside the upper crust as active part. The first one is the stress dependent piezoelectricity due to existence of anisotropic minerals [Cady, 1946]. Piezoelectricity and change of dielectric properties inside the mechanical structures take role in remote diagnostic methods those use electro-potential measurement techniques [Clint, 1999]. On the other hand

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piezoelectricity disappears over Curie temperature and pyroelectricity becomes effective at deeper regions. Another effect that has to be taken into consideration is the electro-chemical process. Besides all these active effects, the upper crust naturally couples to the internal electro-dynamic system of the Earth that generally yields more periodic variations with respect to electrical activity of the upper crust.

Reactive part is another important point for surface measurements. All the active components are connected to the surface through layers of materials such as rock, soil, water, mines etc. Change in structure of the linking system causes variation in surface electric charge. This has been described in Section 2. A monopolar probe system that is used for precision measurement of electric field change related to electromechanical variations is described in Section 3. In Section 4, data acquisition network is shown and typical measurement patterns are evaluated.

2. ELECTRIC FIELD CHANGE IN TIME & SPACE DUE TO VARIATION OF PERMITTIVITY IN A LAYERED STRUCTURE

Let us consider a two-layer physical system made of two different types of materials or mixtures. If this system is electrically connected to a charge pump from one side and to a measurement point at the other side then the measured charge rate will be dependent on displacement due to system capacitance C . This sample system can be illustrated as shown in Figure 1.a where ϵ_{m1} and ϵ_{m2} are average dielectric coefficients of each layer and E_1 & E_2 are electrodes, which connect the system to the source and the measurement points.

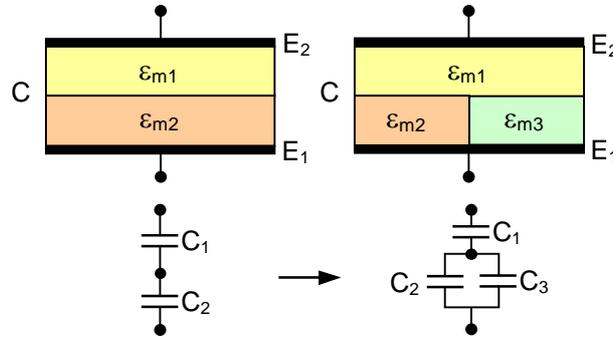


Figure 1: Equivalent capacitive circuit of 2-layer system consisting of a) 2, b) 3 different materials

Even if the equivalent electrical charge source do not change, surface electric field changes if linking capacitance changes due to structural variation because boundary condition of the displacement vector (\mathbf{D}) must be satisfied. Structural variation can be seen both in space (surface movement), if probing location is mobile as shown in Figure 2-a and in time, if probing point is fixed as shown in Figure 3. Although sedimentary layer of the upper crust is quite complex, if average permittivity rate of two neighboring layers at a specified location are represented by coefficients ϵ_{m1} and ϵ_{m2} as shown in Figure 1.a then equivalent electric circuit of the capacitive system will be consisting of two serial capacitors that forms $C = C_a$ where,

$$C_a = \frac{C_1 \cdot C_2}{C_1 + C_2} \quad (1)$$

If one of these layers partially absorbs or replaced by another type of material in some certain proportion then the equivalent circuit becomes two parallel capacitors connected to the serial one. Capacitance of this system $C = C_b$ can be written as

$$C_b = \frac{C_1(C_2' + C_3)}{C_1 + C_2' + C_3} \quad (2)$$

where C_2' depends on remaining rate of material 2 and C_3 is calculated by replacement of new dielectric material ϵ_{m2} . This equivalent circuit approach provides ease for investigation on several cases. As an example, assume that two layers are made of same material, that is a sort of soil, as a singular system where $\epsilon_{m1} = \epsilon_{m2} = 4$. If second half of the volume in vertical axis absorbs 5% water then capacitance change of the system can be found out by 2 layers-3 materials approach as in Figure 1.b. Since $C_1 = C_2$, $C_2' = 0.95C_2$, $C_3 = 0.05 \cdot 80/4 \cdot C_2 = C_2$ then change of C will be, $C_a/C_b = 0.76$ that means overall system capacity dramatically falls as 31.6% although there exist very small volumetric, partial material replacement by water.

It was mathematically shown that if there exists a background charge source over a layered structure then electrostatic image of a closed surface inside the hidden layer is possible to be reconstructed by conformal mapping [Akduman and Kress, 2002]. Here in this study, natural electric field of the upper crust is thought to be the background charge exciter. In this case surface electrical measurements must be affected by the structural changes due to mentioned mathematical inverse problem solution. So our approach is not only based on stress-piezoelectricity relation but it also relies on detection of anomalous patterns due to possible structural changes under excitation of all natural electric charge sources.

The new method is proposed for finding such structure changes as underground water reservoirs by using a mobile measurement system (Figure 2-a). Here, the second layer is consisting of two different materials M1 and M2. ϵ_{M1} , ϵ_{M2} , ϵ_{M3} and ϵ_{M4} denote the permittivity of each material. If $\epsilon_{M4} > \epsilon_{M2}$ and their proportion is approximately same as permittivity proportion of water and rock then Figure 2-b shows the mesh of finite element method (FEM) analysis. The respecting electric field change in space (x-axis) is shown in Figure 2-c. Even finding the geometry of material change is possible to be reconstructed by using inverse problem solution techniques and 2-dimensional surface scan. If the measurement system is stationary and the change of structure occurs in time instead of space, then a simplified model can be considered as shown in Figure 3 in order to explain basic principle of the detection. Figure 4-a, b, c and d shows the arrangement of materials and the probe for FEM solution of electrical displacement variation in time between two stable conditions (a) and (d).

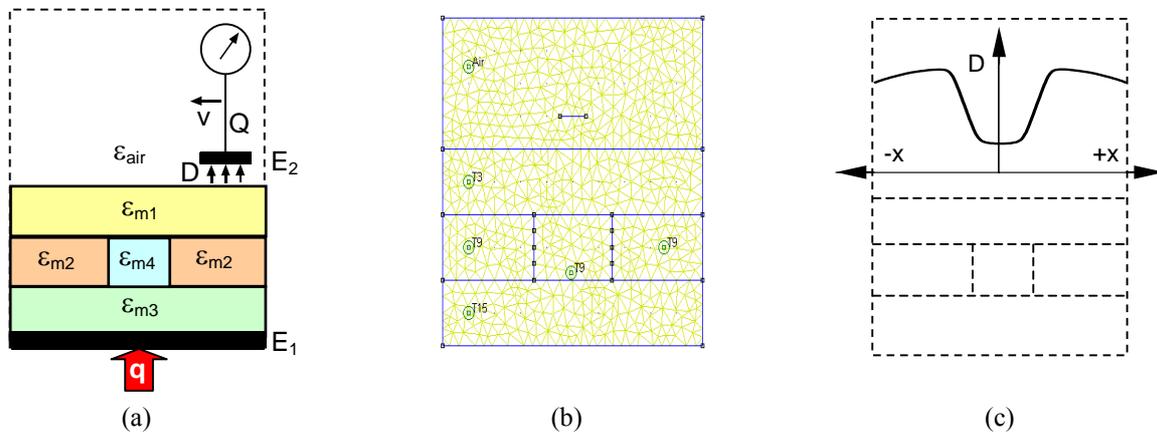


Figure 2: a) Mobile measurement probe to detect change of surface electrical displacement with respect to permittivity change in space; b) Structure used in FEM analysis; c) Electrical displacement change in space (x-axis).

Any material-M4 has not diffused in Figure 4-a yet. Replacement of material-M2 by M4 ends in Figure 4-d when $\frac{3}{4}$ of the central part inside the second layer is filled by M4. Figure 4-e shows that even partial variation of the physical properties inside the hidden layer causes detectable surface electric field change in time. This approach for determination of structural changes can be considered as passive electrostatic measurement.

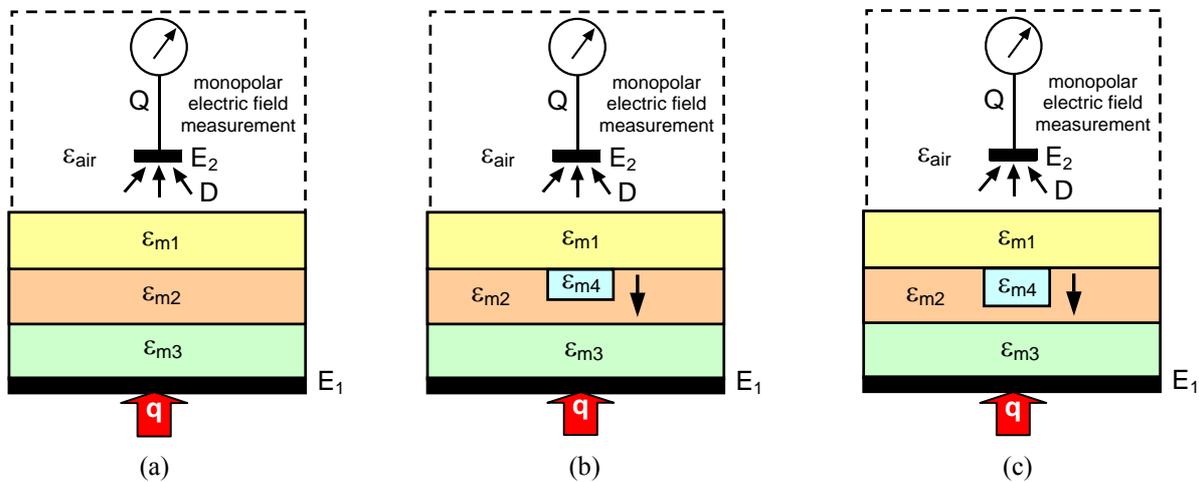


Figure 3: Detection of structural change in time due to material's permittivity variation inside the internal layer

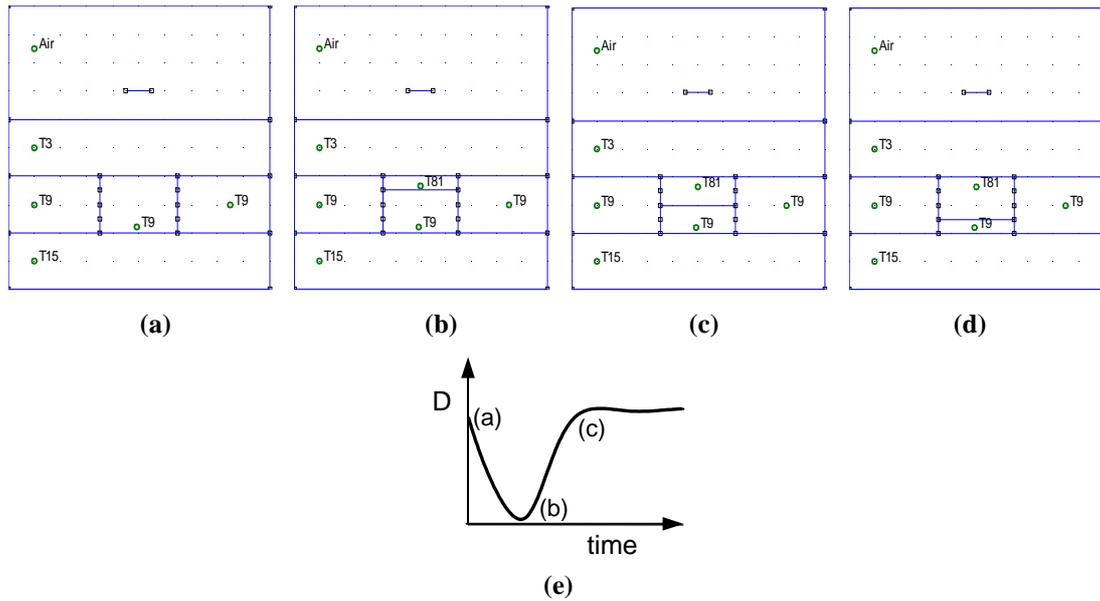


Figure 4: Finite element model of multi-layer system and FEM simulation of electrical displacement (D) change on stationary electrode system with respect to variation of local permittivity in time (e). Case (a) Internal layer is homogenous (no water); (b) Water diffuses upper $\frac{1}{4}$ of central part of the internal layer; (c) Water diffuses upper $\frac{1}{2}$ of central part of the internal layer; (d) Water diffusion stops at $\frac{3}{4}$ of central part of the internal layer after “c”, as final state.

3. MONOPOLAR ELECTRIC FIELD MEASUREMENT METHOD

Maximum electric field strength occurs at the surface of any sphere that is applied a voltage [Ozkaya, 2003] and it decreases inverse-square proportional to the distance from the surface of the source. This is also valid for the Earth as a globe since the upper atmosphere consists negative ions. Detecting the anomalous electric field changes over the surface by using the method described in section 2 requires a single pole sensor mechanism [Canyaran and Ustundag, 1999]. Here, Earth becomes as one part of the sensor mechanism and monopolar electrode is expected to couple it through the air. The monopolar electric field probe shown in Figure 5 was developed for this purpose and it is placed close to the surface of the Earth. Its measurement sensitivity reaches down to 10^{-14} Coulomb levels. The system is consisting of a spherical capacitor as electric charge collector, MOS (metal oxide semiconductor) circuit for charge/bipolar voltage conversion, digital indicator device for amplification, analog to digital conversion, signal processing, telemetric data acquisition and a server for data acquisition and pattern analysis. Electrode of the first stationary probes where spherical and their diameter were just 40 mm. Collected charge is conducted via a high voltage cable to the charge/voltage converter inside the dielectric pot (Figure 5).

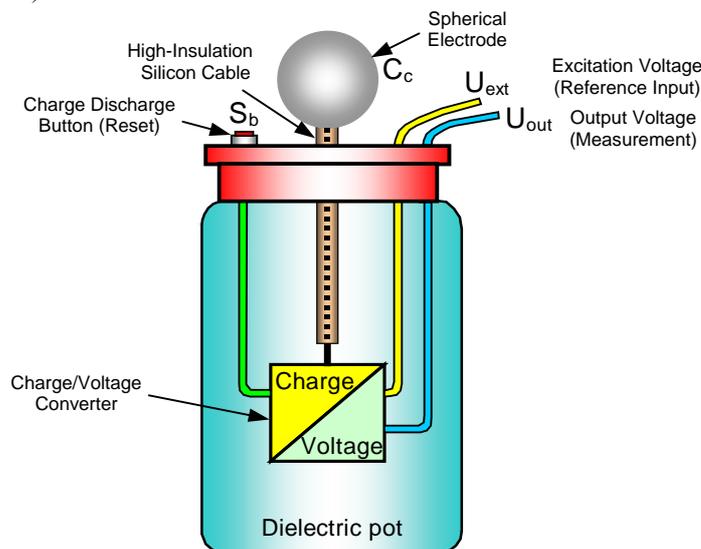


Figure 5: Monopolar electric charge measurement probe.

With respect to Gauss Law, the induced charge amount Q on the electrode is,

$$Q = \oint_S \mathbf{D} \cdot d\mathbf{s} \quad (3)$$

where \mathbf{D} [C/m²] is the electrical displacement vector. The relation between the electric field strength E [V/m] and electrical displacement is,

$$\mathbf{D} = \varepsilon \mathbf{E} \quad (4)$$

ε is the permittivity of the medium here. Since the electrode is spherical the charge amount collected by the probe is,

$$Q = 4\pi r^2 \varepsilon E \quad (5)$$

where r is the radius of the electrode. If the circuit equations of the charge/voltage converter is solved for Q and input charge amount (5) is placed inside then the transfer function of the probe system becomes,

$$T(s) = \frac{U(s)}{E(s)} = k_1 s + k_2 \quad (6)$$

where $k_1 \cong 0.05$ and $k_2 \cong 0.15$ for $r = 40$ mm. Coefficient k_2 determines the steady state accuracy [counts/(V/m)]. It is clear that enlarging the electrode (sphere) surface raises the accuracy. The system was constructed inside the shielded ITU-High Voltage Laboratory in order to experimentally measure and validate transfer function parameters [Ustundag, Kalenderli, and Eyidogan, 2005].

4. STATION NETWORK AND RECORD EXAMPLES CORRELATING TO EARTHQUAKES

An Internet based networking is used for data acquisition. 16 online stations were installed in different locations around North Anatolian Fault (NAF) since 1999 (one test station in 1999, four stations in 2000, eight stations in 2001, 12 stations in 2002 and four temporary stations). 14 of these stations are still active. Both the current and past data can be reached via internet site of the project: <http://www.deprem.cs.itu.edu.tr>. The station locations are shown in Figure 6 on the active fault map of Northwestern Anatolia [Saroglu, Emre, Kucsu-MTA].



Figure 6: Station locations of the monopolar electric field measurements in northwestern Anatolia.

Recorded Signals are evaluated in three ways,

- a) Deviation from daily periodic pattern: Although this was a less used investigation method until now, it is listed here in order to provide a different approach to the used measurement technique. Each station has a unique periodic pattern character. Figure 7 shows an example of three days-record of the stations Sakarya, Yesilyurt (Istanbul) and Canakkale. This daily pattern shows some change in time. The pattern change has predictable continues development at mid term. When there exist deviations out of this development it has been seen that a correlation holds between this phenomena and the seismic events occurred within few days. Green windows in Figure 8 show equivalent time intervals chosen in 4 days record.

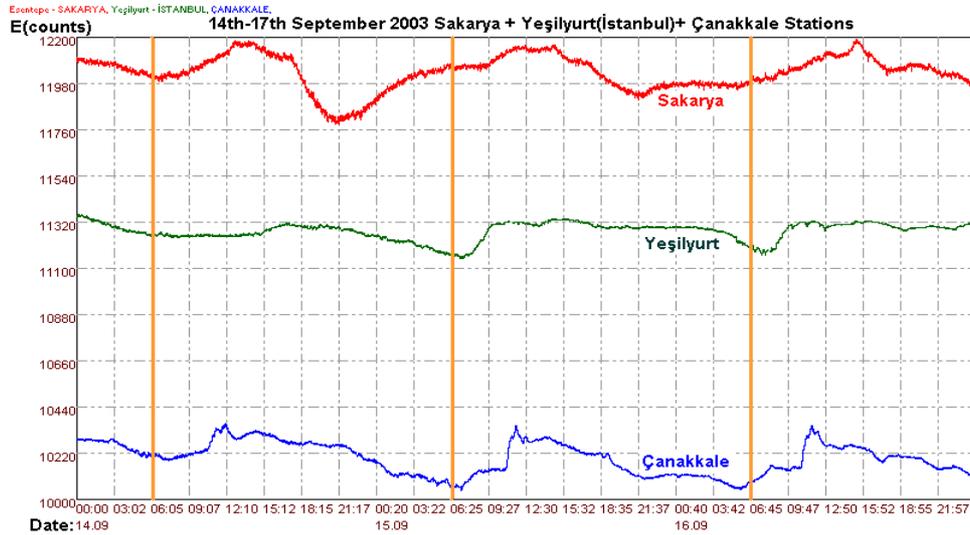


Figure 7: Example to normal periodic variation of three station records in three days.

Discontinuous deviation having higher number of peaks is distinguishable. M4.8 (Richter scale) Earthquake was occurred at 100km distance (at the moment shown by the arrow). More than 50 events (having correlation with $M > 4$ earthquakes) were classified for one or multiple stations in last three years with this approach. Determination and classification of this type anomalous behavior require daily spectral investigation and comparison to average frequency spectrum of the past days. This can be done by FFT (Fast Fourier transformation) in real time but it has to be considered that some other reasons (astronomic, tidal effect etc.) besides the earthquakes have different rate of correlation on this periodic deviation too. Geophysical structure variation related ones can probably be distinguished at most of them but they are not only the earthquakes. For example a higher frequency component is seen when a measurement system calibrated in less seismically active region and moved to a location where spring water activity is high.

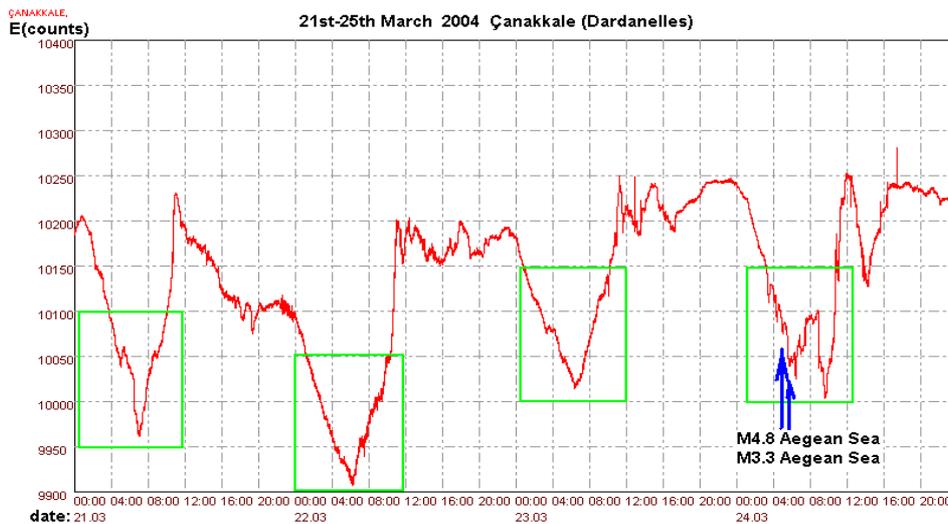


Figure 8: Development of periodic signal and time of M4.8 earthquake (with an aftershock) at approximately 100 km distance.

b) Recognition of statistically classified patterns: Some patterns in 0.1-10 hours time intervals are repetitively recorded before seismic events. These can be classified as: step function, impulse function, impulsive increment followed by negative exponential decrement and exponential increment followed by negative exponential decrement that begins with a discontinuity. Change of envelope level before and after these patterns may have a relation to distance and magnitude of the seismic events. An example pattern is shown in Figure 9. In this example earthquake magnitudes and the pattern amplitudes are proportional. Although correlation of these kind of patterns to the preceding major earthquakes varies around $62\% \pm 5$ at all, unfortunately their amplitudes are not always proportional as given in the example. When this kind of pattern is recognized by the specially developed

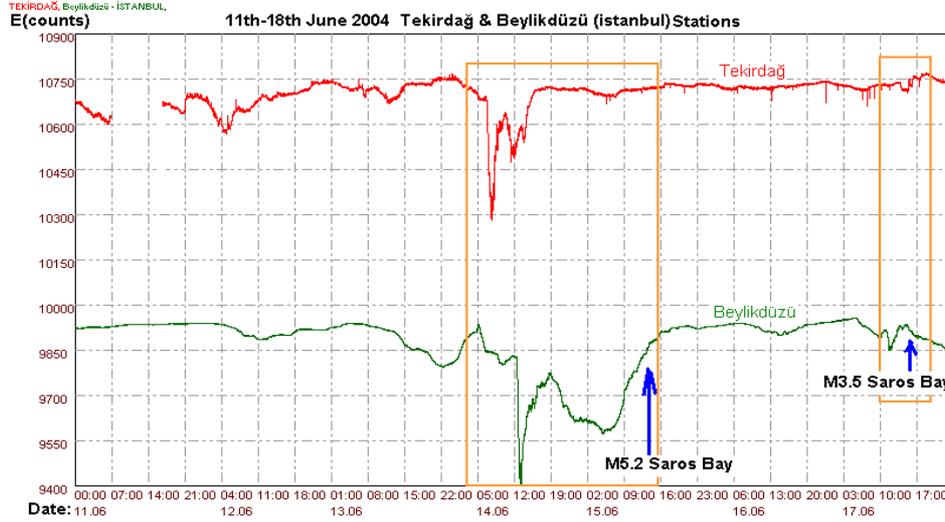


Figure 9: 7-days graph of Tekirdağ and Beylikdüzü stations with M5.2 earthquake in Saros and its aftershock in June 2004

software based on neural networks, probable failure reasons and such other coinciding events as magnetic storms are manually checked and rejected. In order to automate this process and improve correlation with other physical measurements another project enterprise has been initiated for data fusion. Impulsive raise followed by negative exponential settlement is another probable seismic event-precursory pattern [Ustundag, Kalenderli, Eyidogan, 2005]. This impulsive leading edge and negative exponential falling edge character is similar to signals named as SES by VAN group [Varastos, 1996] in Greece.

We determined that weather-originating changes including thunderstorms did not cause such a pattern but they've some other type of negative influence. They especially change the background noise and some different patterns are recorded. Contrary to the seismically correlating signal patterns, the patterns, which hold relation to atmospheric events, have falling edges with positive exponential coefficients. Their short-term amplitude change do not reach the level of amplitude change of seismically correlating signals. An adaptive digital filter inside the signal conditioning system rejects higher frequency noise. All of the recorded signals are in ELF band since they are quasistatic waves.

c) Long term periodic behavior of the signal envelope: A quite interesting finding in the study is the behavior of long-term (weeks) records and the similarity between far station records. 16 days of the record at Yesilkoy-Istanbul before a M4.3 earthquake is shown in Figure 10. Fundamental frequency of the change is 24 hours. On the other hand purple line indicates the envelope. The earthquake that the epicenter was 45 km away from the station followed sudden decrement of the envelope.

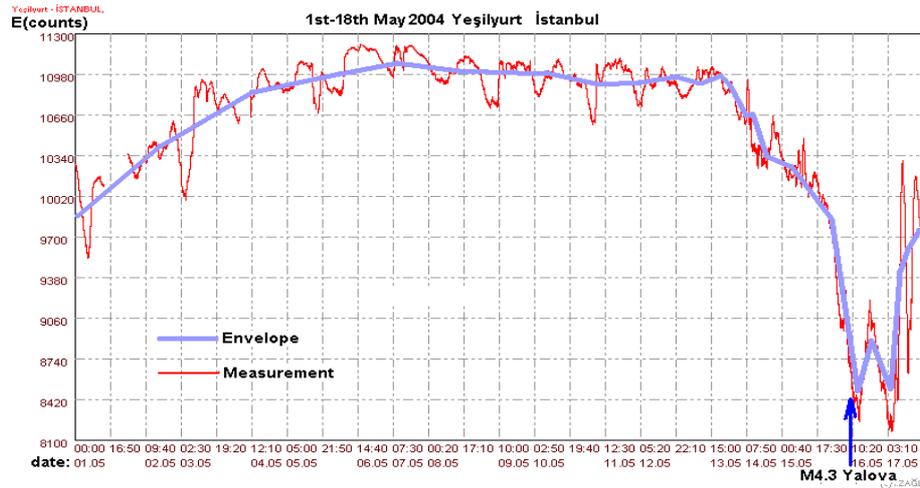


Figure 10: 17-days record of Yesilyurt (Istanbul) station and a seismic event (M4.3) at 45 km distance.

This long-term change and earthquake correlation is not a specific case study since 10s of similar examples recorded in past 5 years. Another well correlating example is shown in Figure 11. All of the earthquakes occurred in the first three months of 2005 in Turkey were indicated by arrows (E1...E6) on Yesilyurt-Istanbul station records. All of them coincide to specific region of the graph which could be mathematically distinguished.

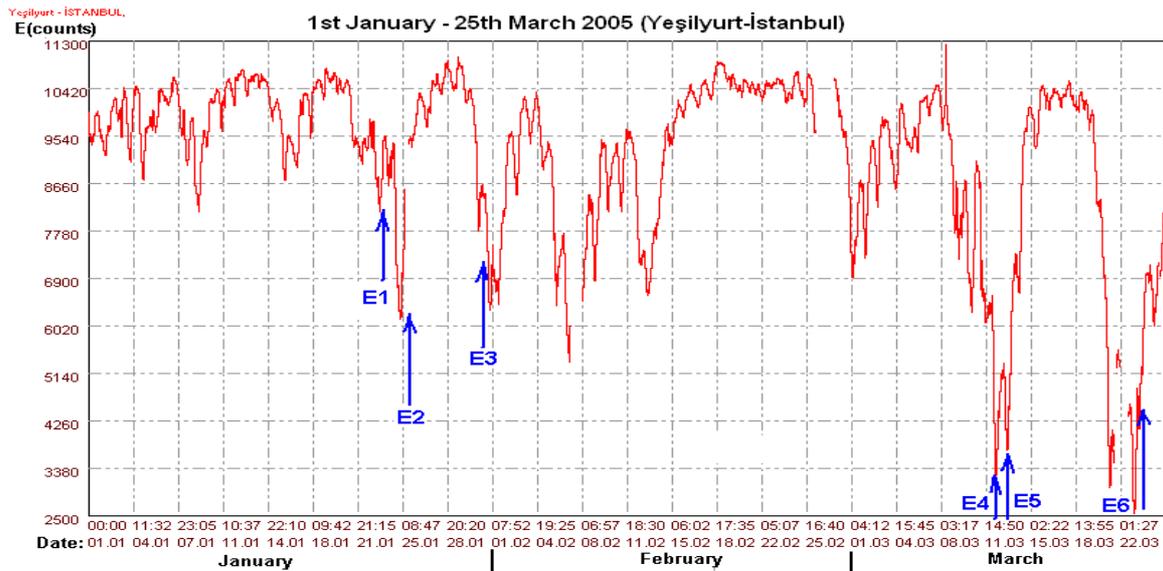


Figure 11: Major earthquakes in Turkey (M > 5) and 3 months record of Yesilyurt-Istanbul.

Table 1. All major events in Turkey between 1st January and 30th March 2005 as indicated in Figure 11.

Event	Magnitude (Richter)	Latitude	Longt.	Location (Turkey)
E1	M5.2	35.7519	29.5737	Rhodes (Med.Sea)
E2	M5.4	37.6435	43.8163	Hakkari (Eastern Turkey)
E3	M5.4	35.9100	29.8400	Mediterranean
E4	M5.6	39.4165	40.8672	Karlioiva-Bingöl (Eastern Turkey)
E5	M5.9	39.4186	40.8183	Karlioiva-Bingöl (Eastern Turkey)
E6	M5.4	39.4164	40.8094	Karlioiva-Bingöl (Eastern Turkey)

Although E4, E5 and E6 occurred at almost the same location (Table 1) an aftershock and foreshock relationship cannot be simply held. Magnitude of E5 is larger than the previous event. On the other hand E6 occurred 10 days after E4 and its magnitude is close to the first one. That region is candidate for earthquakes having magnitude greater than 6.

Time coincidence of these events to the long-term (3 months) change of electric field record is a significant example that shows correlation to the signal envelope. Six events are not enough for severe conclusions but we can also make some mathematical analysis to show detectability of seismically more active terms in time. If we assign a Lipschitz value L for the electric field change in time that sets a boundary to differentiation in time then we can decide if they were predictable or not. This is mainly to find right intervals between the falling edge of the long-term signal envelope and the rising edge of it. Envelope of the signal must be constructed by applying a low pass digital filter first. Cut off frequency can be set around 12 hours to get the envelope.

$$|\Delta E_{\text{Envelope}}/\Delta t| < L \quad (7)$$

If we accept the duration that satisfies condition in 7 as seismically low active region then the remaining parts can be seen as higher probability for major activities. If we apply this L value based criteria for two different values then we get the following parameters:

If $L = 1500$ [counts/time] => Higher risk duration (HRD) rate: 27% (of 88 days)
 Maksimum time interval at each HR period: 4.8 days
 Minimum time interval at HR period: 1.8 days
 False alarm rate (event based): 42%
 Events at HRD: 100%

If $L = 2000$ [counts/time] => Higher risk duration (HRD) rate: 10.5% (of 88 days)
 Maksimum time interval at each HR period: 4.2 days
 Minimum time interval at HR period: 0.4 day
 False alarm rate (event based): 26%
 Events at HRD: 83%

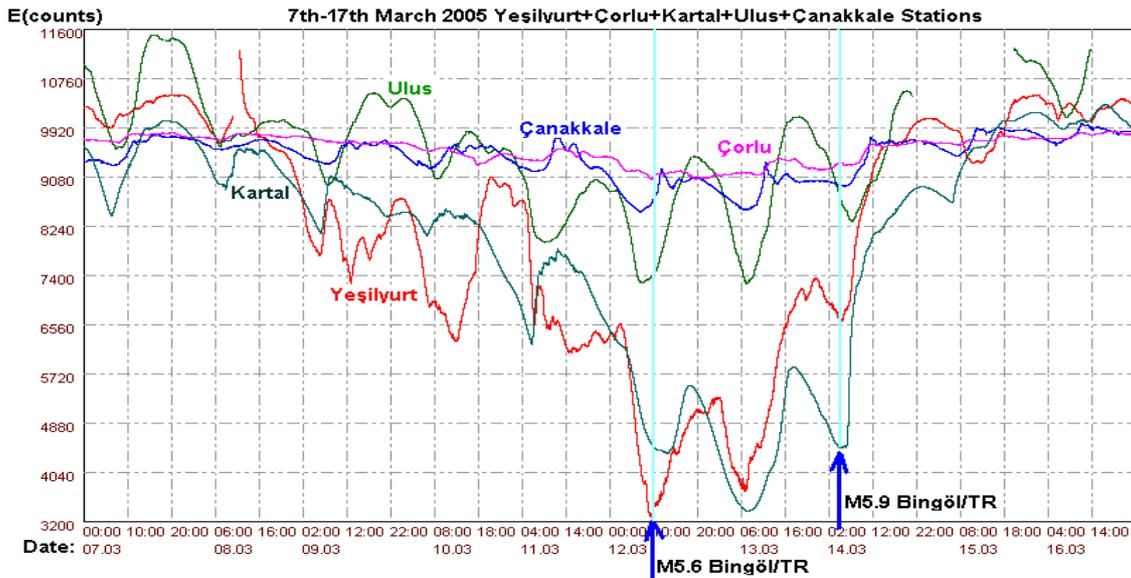


Figure 12: 10-Days record of five stations before and after Bingöl Earthquakes (M5.6 12th, March 2005 and M5.9, 14th March 2005) in Turkey.

Figure 12 shows the 10-days record of five stations that covers the occurrence time of earthquakes listed as E4 and E5 in Table 1. Although distance of some of these recording stations are far to the epicenter of E4 and E5, correlation may depend on some stress transfer effects on two different ends of the North Anatolian Fault system besides the direct electrical reasons. Above explained relationships (a, b, c) were seen in the past earthquakes at the same location too but it has to be considered that they were all in the same fault system even if the distance is high. One of the reasons that Yesilyurt-Istanbul recorded greater amplitude change than the others is that the district of the station is based on alluvium. Alluvium is more conductive and electrically penetrative. Distance of that station to the fault line is also closer than the others. Electrical penetration of the capacitive coupling can be imagined as usage of gel coating for probing the ultrasound on the human skin.

5. CONCLUSIONS

Correlation of measured data patterns to the seismic events can be seen as an indication of macro scale evidence of electrostatic coupling effect in the proposed method. FEM analysis for the basic multi-layer systems indicates that structure variation can be detected from the surface electric field patterns if there exist a charge source in the system. This can be achieved either in time with stationary measurements or in space by mobile measurements. On the other hand it must be considered that equivalent pattern changes are valid for constant excitation level. Unfortunately, this condition is valid only for relatively small time intervals in geophysical measurements because natural electric fields consisting of piezoelectricity, pyroelectricity and electrochemical sources are the charge exciters for passive investigations and they vary in time too. This variation can also be considered as an advantage for long-term macro-seismic analysis since they may have positive addition to the correlation. But the problematic part of this approach is uncontrollability of the field source parameters. Longer-term periodic components as a result of frequency analysis and development of frequency spectrum of the records are other information sources having correlation to activity rates. As a result, pattern based analysis can be a solution for interpretation of passive measurements in long term.

Usage of artificial charge exciters can be thought as a solution for micro-seismic investigations but the exciter must be so dense that it has to be regionally dominant.

As another theoretical approach, an equivalent multi-layer capacitor circuit model of the Earth's upper crust was previously proposed to explain behavior of the measurement patterns in time by using specially developed stationary measurement device; and in space by using mobile version of the system. Proposed probe system is able to measure change of electrical charges with the sensitivity in Femto-Coulomb level. This charge is linked through the electrical displacement over the monopolar electrode. Various electrode geometries in different sizes can be chosen with respect to purpose of the investigation. 40 mm spherical electrodes are used at the pilot network that includes 14 stations in Marmara Region (northwestern Anatolia). On the other hand larger, flat electrodes are better alternatives for smaller scale sedimentary level investigations.

Acquired data had been applied to the input of an artificial self-learning neural network mechanism [Ustundag and Ozerdem, 2002] for recognition and classification of some specific patterns combined inside the envelope of the data. The patterns are classified with respect to the precursory time interval, magnitude and the location of the occurred earthquakes by the network. Three outputs of the network (distance, time interval, magnitude) tend to go 1 as the similar anomalies are received by the system. This training mechanism is seen as a long-term alternative data evaluation method in earthquake forecast research.

The proposed new measurement method has some advantages on detection of deeper anomalous variations those probably lead to seismic events in some cases. Surface capacitive coupling is mainly driven by quasistatic waves and signals in ELF band attenuate much less than higher frequency EM waves inside dense solid mediums. The other advantage is the known fact that satisfying the electromagnetic boundary condition is necessary in layered structures driven by an end-to-end equivalent electro-potential source. This requires change in electric field coupling at the surface due the variation of inner components. Although there are such effects as electro-chemical potentials and conductive natural electric circuits, this boundary condition related effect of deeper components might still have role on surface changes since upper crust has a layered-structure in macro-scale view contrary to complexity and uncertainties of micro and medium scale investigations.

Necessities of long-term multi-point measurements for distinction of periodic events and compensation to other physical influences by using advanced signal processing techniques are the main disadvantages of the proposed method. It is thought that it can be developed by getting more past data in years and signals do not correlate to seismic events can be reduced by applying data fusion techniques with multi-variable measurements.

Since it has been seen that, known material-discontinuities relatively close to surface caused repetitive exponential patterns at mobile measurements, another continuing part of the project is consisting of experiments on known scaled sedimentary models at shielded laboratory conditions. 2D surface measurement patterns received by monopolar electrodes in time and location at the experiments are intended to be used for more reliable evaluation of the field data to explain structural variations of the investigation area.

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