DETERMINATION OF STRUCTURAL VARIATONS IN TIME AND SPACE BY CAPACITIVE COUPLING

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ABSTRACT

Effect of regional change in dielectric constant (permittivity) of the upper crust on surface electric fields due to probable structural deformations has been investigated in this study. A method has been proposed to determine structural changes in time by using specially developed stationary measurement device; and in space by using mobile version of the system. In the proposed method, one part of the sensor mechanism is the Earth's upper crust that couples to the monopolar electrode through the air. Maximum electric field strength occurs at the surface of any sphere that is loaded by a voltage source and the electric field 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. A high sensitive monopolar electric field probe has been developed which is to be installed close to the surface of the earth for this reason. We assume that change in charge induction at the probe should be related to the change in regional resultant stress as an electric potential source or change of permittivity due to structural variations in time or space. Although there also exist atmospherically electric field changes as noise, they can be filtered since the frequency range and the signal patterns are different from the change in surface connection. On the other hand superposition of the attenuated electric field changes from further regions should be considered. These two facts require vectoral measurement using a group of stations and adaptive filtering for the removal of the atmospheric noises.

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 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 [1] and Quakesat have recently been initiated. Some of these researches depend on evaluation of physical changes on Earth's surface [2 - 5]. As an alternative to such physical measurement methods, change of electric field is measured by using a new type of monopolar probes in a common project of Electrical & Electronics Engineering Faculty and Faculty of Mines at Istanbul Technical University. Although time domain measurements at stationary points can be a part of earthquake forecast by using pattern based evaluations [6] 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 [7]. Piezoelectricity and change of dielectric properties inside the mechanical structures take role in remote diagnostic methods those use electro-potential measurement techniques [8]. On the other hand piezoelectricity disappears over Curie temperature and pyroelectricity become 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 change of electric fields related to electromechanical variations is described in section 3.

An equivalent multi-layer capacitor circuit model of the Earth's upper crust is proposed to determine structural changes in time by using specially developed stationary measurement device in section 4.

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

Let us consider a two layer physical system made of two different type 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 capacity C. This sample system can be illustrated as shown in figure1.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.

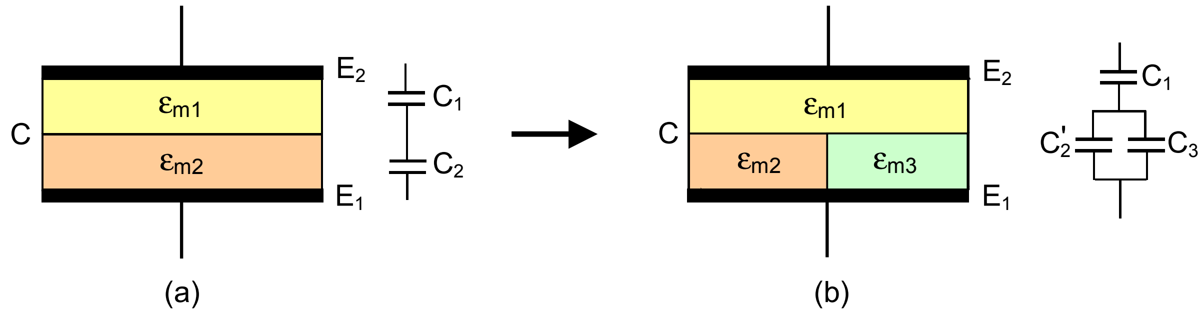


Figure 1. Equivalent capacitor circuit of two layer system consisting of a) two different materials b) three different materials

Even if the equivalent electrical charge source do not change, surface electric field changes if linking capacity changes due to structural variation since boundary condition of the displacement vector must be satisfied. Structural variation can be seen both in space (surface movement), if probing location is mobile as shown in figure 2 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 figure1-a then equivalent electric circuit of the capacitive system will be consisting of two serial capacitors that forms $C = C_a$ where,

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

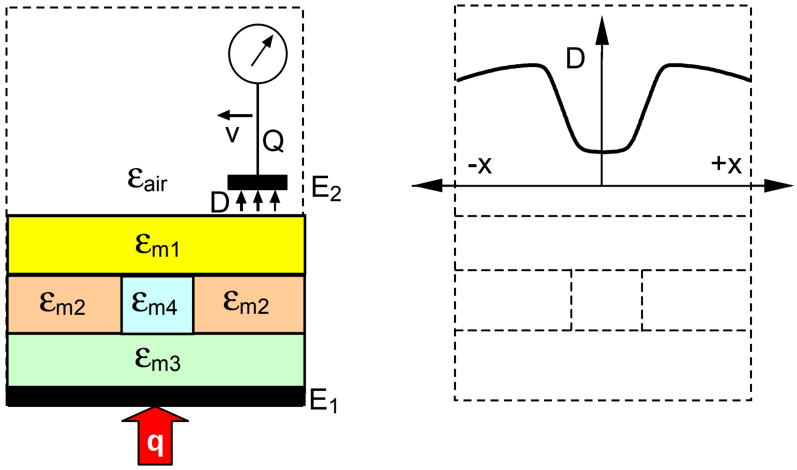


Figure 2. Change of surface electrical displacement to permittivity change in space

If one of this 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. Capacity of this system C = C_b can be written as

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

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.

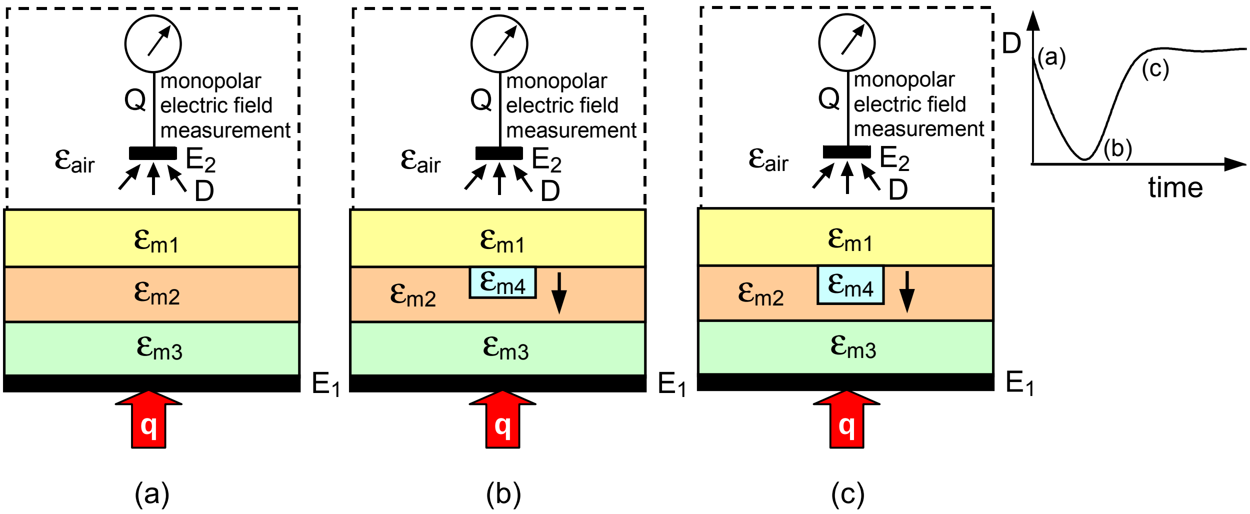


Figure 3. Change of electrical displacement on stationary electrode system due to variation of local permittivity in time (a, b, c).

As an example, assume that two layers are made of same material, that is a sort of soil, as a singular system where $\varepsilon_{m1} = \varepsilon_{m2} = 4$. 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.

A measurement method is proposed for finding the structure changes as underground water reservoirs with a mobile system (figure 2) and earthquake precursory changes as deeper and larger scale events by using this fact. Since electrode of monopolar electric field measurement system [9] couples to the surface through air, shape and distance of the probe affects the measurement pattern in time and space. Expected character of this combination is explained in section 4 where air is taken into consideration as an additional layer.

3. MONOPOLAR ELECTRIC FIELD MEASUREMENT

In the proposed method, one part of the sensor mechanism is the Earth that is coupled to the monopolar electrode through air. Maximum electric field strength occurs at the surface of any sphere that is loaded by a voltage source (figure 4) [10]. The electric field 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. A high sensitive monopolar electric field probe has been developed and patented which is to be installed close to the surface of the earth for this reason.

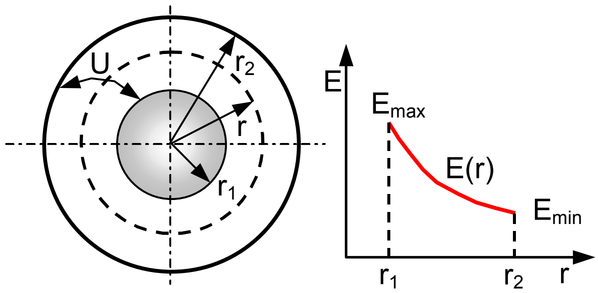


Figure 4. Electric field variation with respect to distance ($r - r_1$) outside a charged sphere

Charge induction at the probe should possibly be related to a) the change in regional resultant stress and b) local electrochemical processes as electric potential sources c) such structural changes as fractures and leakages d) charge coupling of deeper Earth components. Although there also exist atmospherically electric field changes as noise, they can be filtered since the frequency range and signal patterns are different from the seismic components. On the other hand superposition of the attenuated electric field changes from further regions should be considered. These two facts require vectoral measurement using a group of stations and adaptive filtering for the removal of the atmospheric noises.

The system consists of a spherical capacity as electric charge collector, MOS (Metal oxide semiconductor) circuit as monopolar charge/bipolar voltage converter, indicator device for amplification, analog to digital conversion, signal processing, telemetric data acquisition and a server for pattern analysis. Electrode of the first stationary probes where spherical and where diameter was just 40 mm. Collected charge is conducted via a high voltage cable to the charge/voltage converter, that is placed in a dielectric pot as shown in figure 5. The measurement sensitivity reaches down to 10^{-14} Coulomb level.

Collected charge amount from the air is calculated with respect to Gauss Law,

$$Q = \oint_S \vec{D} \cdot d\vec{s} \tag{3}$$

Since the relation between the electric field strength and electrical displacement is,

$$D = \varepsilon E \tag{4}$$

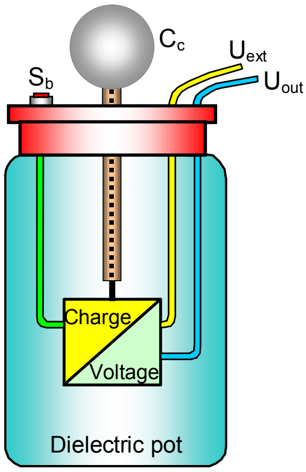


Figure 5. Monopolar electric charge measurement probe.

the amount of charge collected by the probe's sphere is,

$$Q = 4\pi \, r^2 \, \varepsilon \, E \tag{5}$$

where r is the radius of the sphere on the probe. Dynamic behavior of the charge/bipolar voltage converter is in the form of

$$V_{out}(t) = k_1 \, [dE(t)/dt] + k_2 \tag{6}$$

where k_1 = 0.05 and k_2 = 0.186. Transfer function of the monopolar probe can be written as,

$$T(s) = k_1 \, s + k_2 \tag{7}$$

which means that steady state accuracy is 0.186 [counts/(V/m)]. It is clear that accuracy can easily be raised by enlarging the electrode (sphere) surface.

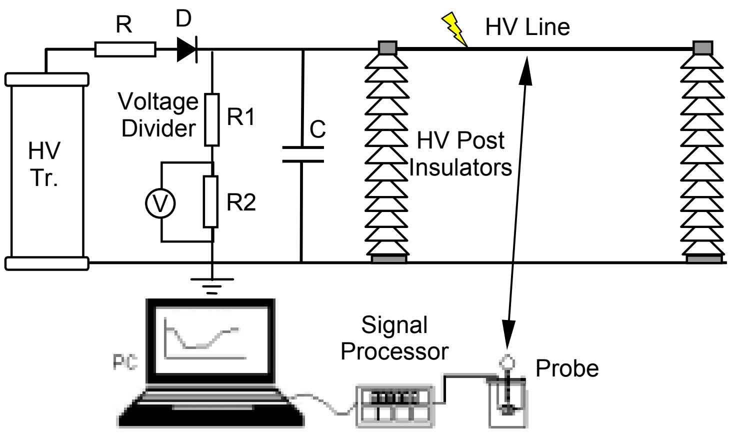
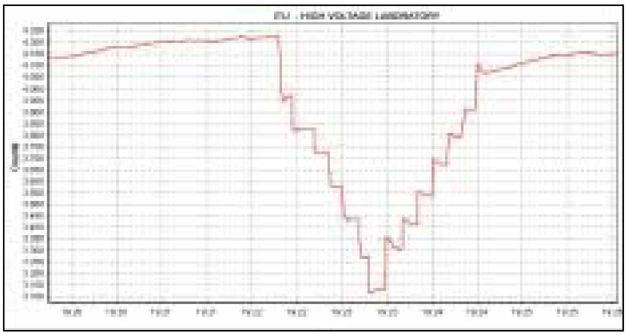


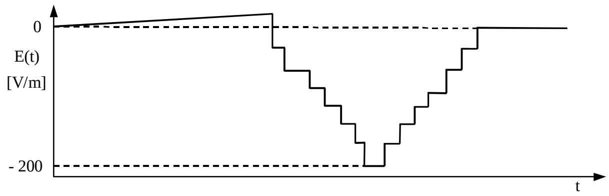
Figure 6. Electric field source and position of monopolar electric field probe for experimental determination of device parameters.

A test system shown in figure 6 is used to determine the transfer function parameters of the measurement device. This system is constructed inside the Faraday caged ITU-High Voltage

Laboratory. Experimental results shown in figure 7 verifies the calculated transfer function T(s) with respect to the relation between the applied electric field pattern and the output data pattern.



(a)



(b)

Figure 7. a) Change of electric field strength during the experiment [V/m].
b) Response of the monopolar measurement system with respect to change in electric field in (a)

Finding the direction and the strength of the electric field source has an important role in geophysical measurement since it is theoretically possible to determine exact location of the source of an observed pattern when triangular intersection method is used.

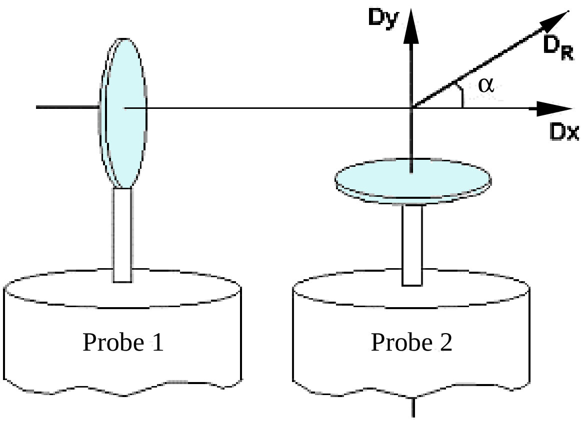


Figure 8. Two dimensional field measurement using plate type electrodes

Magnitude and the direction of the resultant electric field or respecting displacement can be calculated using the following equations in a two dimensional measurement system,

$$\alpha = \tan^{-1}\left(\frac{Dy}{Dx}\right) \tag{8}$$

$$D_R = \sqrt{Dx^2 + Dy^2} \tag{9}$$

Triangular intersection method in coordinate calculation requires three one-dimensional monopolar probes. D_R for 3D measurement can be expressed as a function of Dx, Dy and Dz similar to that in (9). On the other hand, unfortunately, it has to be noticed that mechanical structure of the fault lines is not homogenous and induced charge at a point has several different type of mechanisms.

4. EFFECT OF LIQUID DILATENCY TO PERMITTIVITY AND SURFACE ELECTRIC FIELD

Three different models (liquid dilatency, non-liquid dilatency, long-term elasto-plastic instability) were proposed for the evaluation of real data of monopolar electric field measurements [11]. These proposed explanatory models are used for characteristic classification of the anomalies. On the other hand, variations and cooperative usage of these simplified models may take role in more realistic explanations. Although most parts of this section 4 were previously explained at previous conference papers of the project, permittivity effect of the liquid dilatency has taken place here again for the integrity of the subject.

In order to explain the behavior of the patterns measured by monopolar electric field probes, charged sphere approach for the Earth has been used here. Earthquake process has precursory, instantly and posterior effects on the fault structure. Since the occurrence time of the earthquake indicates a definite phase of this process, it provides experimental view to long term observations for structural analysis too. Let the depth of a probable earthquake be $d_{hypocenter}$. Since $d_{hypocenter}/r_{earth} << 1$ parallel plate equivalent circuit can be used for multilayer capacitor approach instead of spherical layers. This approach also gives the ability of adding regional parameters that can probably be used in seismo-tectonic analysis using the spatio-temporal data. The parameters seen in the models (figure 9 and figure 10) are as follows,

ε_a is the dielectric coefficient (permittivity) of the air,
ε_1 is dielectric coefficient of the sedimentary layer,
$\varepsilon_{2,3}$ is dielectric coefficient of upper crustal granitic layer,
R_s represents equivalent reservoir output resistance of the leakages. It determines the time constant of liquid dilatency,
C_4 couples the circuit model to the lower layers of the crust where piezoelectricity is negligible beside the affects such as pyroelectricity,
U_p is the local stress dependent equivalent voltage source,
q_E is the equivalent charge flow supplied by coupled deeper layers

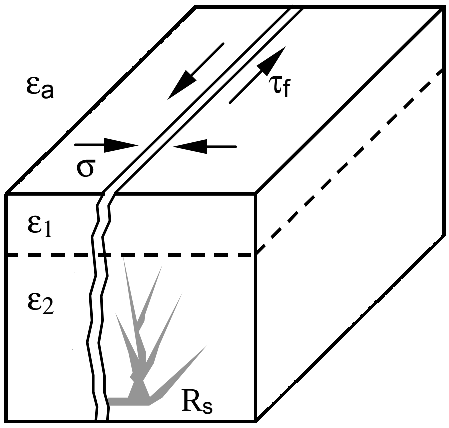


Figure 9. The elements of earthquake occurrence model having dielectric and mechanical parameters including liquid dilatency.

The rectangular block in the model is exposed to the shear force τ_f that causes mechanical energy cumulation at either horizontal or the vertical directions. Raise amount of the charged energy is generally expressed in terms of equivalent yearly displacement [centimeters] in Earth sciences. σ is the normal stress that is a factor bonding the fault surface and it is also used in explanation of friction and instability models [12].

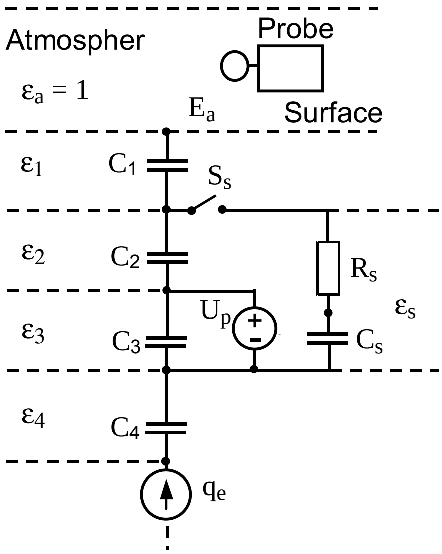


Figure 10. Equivalent circuit model of dilatency and piezoelectricity of a multi-layer system.

Equivalent electric circuit model of the upper crust that is used for explanation of the effect of dilatency on surface electric fields is shown in figure 10. The proposed circuit model is as multilayer capacitor system having stress dependent voltage source. Upper crustal granitic layer is reduced into two different layers having pure piezoelectric material and non-piezoelectric material for the simplicity of the simulations. Dielectric coefficient $\varepsilon_{2,3}$ is replaced by ε_2 and ε_3 respectively. ε_3 represents the dielectric coefficient of the layer consisting of pure piezoelectric material.

Capacity of each layer in an n-layer capacitive system is,

$$C_1 = \frac{\varepsilon_1 \cdot S}{a_1} \qquad C_2 = \frac{\varepsilon_2 \cdot S}{a_2} \qquad \cdots \qquad C_n = \frac{\varepsilon_n \cdot S}{a_n} \tag{10}$$

where S is the surface and a_n is the thickness of the n^{th} layer [12].

$$C = \frac{S}{\frac{\varepsilon_1}{a_1} + \frac{\varepsilon_2}{a_2} + \ldots + \frac{\varepsilon_n}{a_n}} \tag{11}$$

Since the charge of each layer is equivalent

$$Q = C \cdot U = C_1 U_1 = C_2 U_2 = \ldots = C_n U_n \tag{12}$$

voltage drop over the layer can be expressed as,

$$U_k = \frac{a_k}{\varepsilon_k} \frac{U}{A} \qquad\qquad k = 1, 2, \ldots, n \tag{13}$$

where,

$$A = \sum_{i=1}^{n} \frac{\varepsilon_i}{a_i} = \frac{\varepsilon_1}{a_1} + \frac{\varepsilon_2}{a_2} + \ldots + \frac{\varepsilon_n}{a_n} \tag{14}$$

and the electric field strength inside each layer is,

$$E_k = \frac{U}{\varepsilon_k A} \qquad k = 1, 2, \ldots, n \tag{15}$$

which means that electric field strength is independent from the surface and varies with dielectric coefficient if we assume that the electric potential is constant.

$$E_a = \frac{E_3 \, \varepsilon_3}{\varepsilon_a} \tag{16}$$

stress dependent voltage source due to piezoelectricity can be expressed as,

$$U_p = 0.25 \; l \; p \; d \; [V] \tag{17}$$

where p is σ oriented pressure [bar], d is the anisotropic mineral ratio and l is average fault gouge. 0.25 is valid only under the assumption that stress sensitivity of all piezoelectric minerals are same as quartz for the simplicity.

$$E_p = \frac{Up}{l} = 0.25 \cdot p \cdot d \;\; [V/m] \tag{18}$$

Since pure piezoelectric portion is represented with a different capacitive layer d ratio is 1 for C_4. If the change of pressure due to stress drop during the stress weakening and earthquake process is p = 200 bars as an example then the change in electric field strength will be

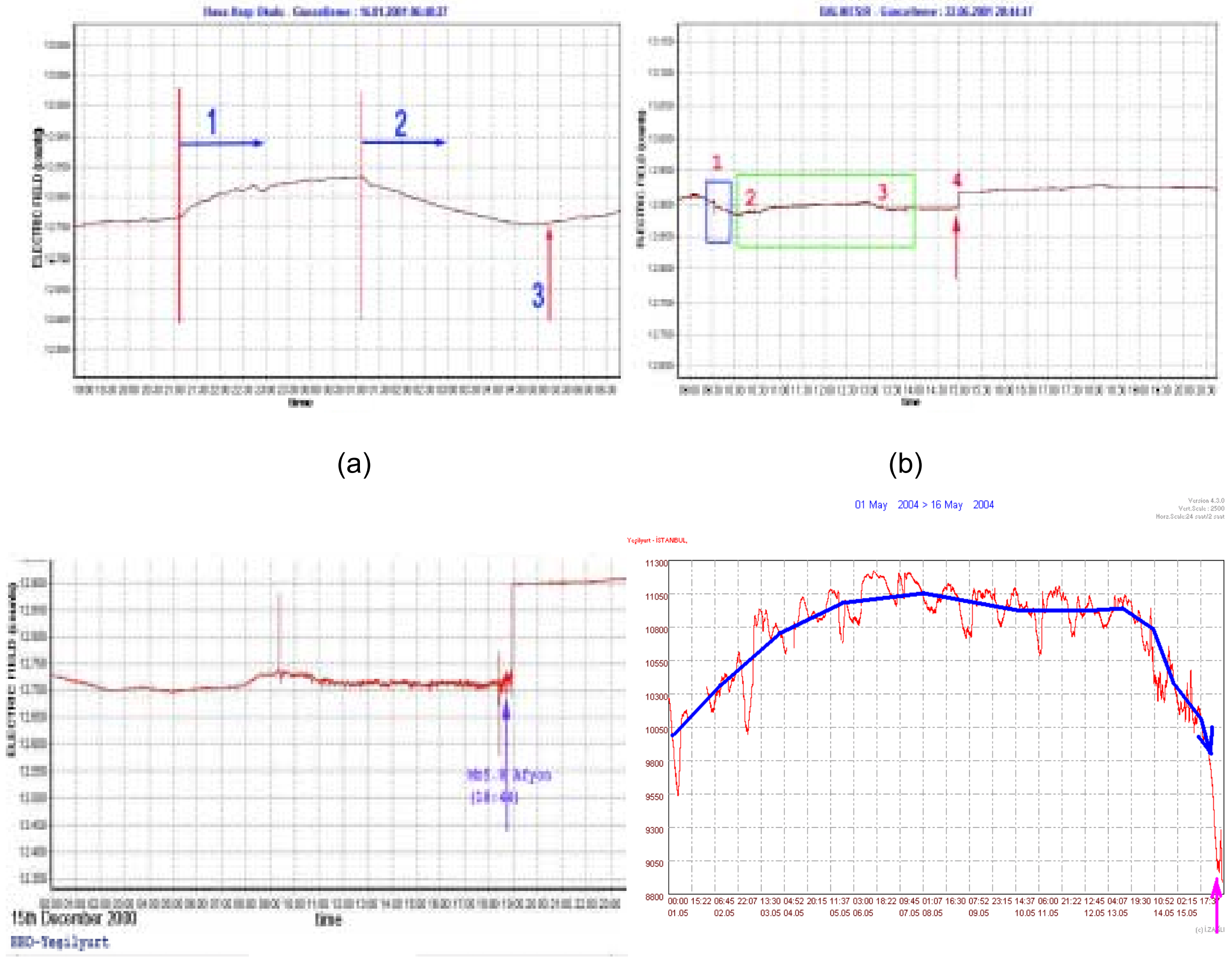
$$E_a = \frac{50 \cdot 5}{1} = 250 \text{ V/m}$$

without liquid dilatency.

On the other hand equation (16) shows that change in permittivity of the deeper layers affect the surface electric field as much as the stress dependent electric field variation. This can only be possible if there is a structural change or deformation.

In case of liquid dilatency, change in E_a will also be a function of change in voltage Up because of the new shunt capacitor representing the dielectric coefficient of the fluid. The dilatency process begins with the switch Ss in the equivalent circuit and the time constant is determined by $\tau = R_s C_s$. The expected behavior of E_a will be $\Delta E \cdot \exp(-t/\tau)$ which is observed in many record examples before the earthquakes. Although the volume filled by the fluid inside the crack is relatively low, change in E_a is still effective since $\varepsilon_s = 81$ which is much greater than $\varepsilon_3 = 4$ and $\varepsilon_4 = 5$.

Anomaly pattern examples those can mathematically be distinguished from the regular daily behavior are shown in figure 11. Earthquakes occurred at the time of minimum transition in more than 4/5 of similar cases. This can also be considered as an evidence to a precursory stress weakening process.



(a) (b) (c) (d)

Figure 11. Different type anomalous ELF electric field pattern examples and the preceding earthquakes (record time is UTC+2)

- **a)** Deflection of electric field pattern outside the daily period before the earthquake (red arrow) having magnitude 4.2 in 16th January 2001, Kartal-Istanbul/Turkey.
- **b)** Change of electric field before an earthquake (red arrow) with magnitude 5.1 in 22nd June 2001, Balıkesir/Turkey.
- **c)** An example for a probable stress weakening process prior to the earthquake in Afyon Mb5.8/Turkey (December 15th, 2000).
- **d)** 15 days record of station in Yesilyurt station in Istanbul preceded by M4.2 (vertical arrow) earthquake in Yalova-Marmara/Turkey (May 16th, 2004).

5. CONCLUSIONS

In this study, a method that uses monopolar electric field measurements to determine structural variations with respect to time and location has been proposed. A multi-layer capacitor circuit model of the upper crust is used to explain behavior of the measurement patterns in time by applying specially developed stationary measurement device; and in space by implementation of 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 15 stations in Marmara Region (Northwestern Anatolia). On the other hand larger, flat electrodes are better alternatives for smaller scale sedimentary level investigations. Inspection of time domain patterns are more meaningful than the level based evaluations because of periodic components. Acquired data had been applied to the input of an artificial self-learning neural network mechanism [6]. The patterns are classified with respect to the precursory time interval, magnitude and the location of the occurred earthquakes by the network. 3 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.

Direction of the electric field can approximately be determined by using multi directional, plate type electrodes instead of a single spherical electrode. Contrary to caged laboratory conditions, measurement device is exposed to several uncertain electric field sources at geophysical measurement environments. Because of this reason, pattern and model based investigations are preferred in order to construct relationships to geophysical events. Distinction of the direction was not precise (up to 30 degrees) even in the laboratory conditions because of the movement of free air ions away from the origin. Another continuing part of the project is consisting of experiments on known scaled sedimentary models at shielded laboratory conditions. 2D surface measurement patterns scanned 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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