

Flicker-noise spectroscopy: a new approach to investigate the time dynamics of geoelectrical signals measured in seismic areas

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Abstract

The Flicker-Noise Spectroscopy (FNS) is an innovative method of extracting quantitative dynamical information from time series. The method represents the signal as sequences of irregularities (spikes, jumps, discontinuities of derivatives), derived on the basis of power spectra and structural functions of different orders. By means of this method we investigated one-year hourly geoelectrical data measured during 2002 in the station Giuliano, southern Italy, one of the most seismically active areas of Mediterranean region. The analysis performed seems to reveal the potential of the FNS to identify seismic precursors.

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1. Introduction

Searching for intermediate and short term seismic precursors has recently favored the dynamical investigation of time series of several geophysical parameters, e.g. local fluid flows (water, saline components, gases), medium electrochemical variables, geoaoustic and geoelectromagnetic streams, geophysical ground fields, whose anomalous variations have been interpreted as precursors of earthquakes. Field measurements in seismic areas have documented anomalous patterns in geophysical parameters attributed to stress and strain changes which were followed by earthquakes (i.e. Rikitake, 1988; Chu et al., 1996). In particular, geoelectrical parameters measured in seismic areas can give a useful contribution to the understanding various seemingly complex phenomena correlated with seismic activity (Park, 1997; Johnston, 1997). As an example, variations in the stress and fluid flow fields can produce changes in the geoelectrical field, in resistivity, and in other electrical parameters (Scholz, 1990), so that investigating

these induced fluctuations may give information on the governing mechanisms both in normal conditions and during intense seismic activity.

At present, the use of electrical precursors in earthquake prediction is to a large extent still empirical, due to difficulties in understanding the physics underlying the source mechanisms of geophysical precursory phenomena. In order to assess the use of geoelectrical signals as indicators of earthquake preparation (Hayakawa and Fujinawa, 1994; Hayakawa, 1999), the fundamental issue to address is if these parameters are able to reveal dynamical characteristics of active tectonics, and we have to understand if there is a significant correlation between seismic events and geoelectrical temporal fluctuations. Obviously, the existence of such a correlation can be established only after a dynamical characterization of the geoelectrical signals is performed. In a previous paper Cuomo et al. (1998) analyzed the geoelectrical daily means in order to give information about the statistical features of the geoelectrical background noise and the inner dynamics of geophysical processes producing the electrical phenomena observed on earth surface in seismic areas. They discussed the statistical analysis of dynamical systems based on the estimation of their degree of predictability, distinguishing

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randomness from chaos and providing a parsimonious representation in terms of autoregressive models of observations, by means of the only information coming from the time series itself. Hayakawa et al. (1999) proposed a fractal analysis of ULF electromagnetic data obtained at the Guam observatory during a strong ($M_s = 8.0$) earthquake occurred on August 8, 1993 near Guam island. They found that the spectrum of emissions exhibited a power-law behaviour $1/f^\alpha$ which is typical for self-organized critical dynamics; furthermore the exponent α was observed to decrease during the process of earthquake preparation. The analogous behaviour was observed in the ULF electromagnetic emissions associated with a large earthquake that occurred at Biak Island, Indonesia ($M_w = 8.2$) on February 17, 1996 (Hayakawa et al., 2000). Gotoh et al. (2003) have obtained the same results for a swarm of Japanese earthquakes of June–August 2000. Nagao et al. (2000) reported co-seismic geoelectric potential changes in Japan, that, however, can be used to extract information on the crustal EM phenomena. Uyeda et al. (2000) observed slow geoelectric potential changes before several earthquakes in Japan. Other electromagnetic anomalies were observed in Greece (Tzanis et al., 2000; Vallianatos and Nomikos, 1998). Telesca et al. (2001) proposed a new approach to correlate geoelectrical signals with earthquakes, analyzing the correlation between two parameters strongly connected with the inner dynamics of electrical signals and seismicity, the spectral exponent and the Hurst exponent, respectively; furthermore, they found a decrease of the spectral exponent before the occurrence of the major seismic event during the period of observation.

In this work the Flicker-Noise Spectroscopy (FNS) method is discussed concerning with the identification of earthquake precursors. The FNS method was proposed to analyze chaotic series of different nature (in time, space and energy domains) (Timashev, 2000a). The method represents the signals as sequences of irregularities (spikes, jumps, discontinuities of derivatives of different orders) that are considered to have recognizable information. The method has been firstly used for the dynamical analysis of several physico-chemical processes, such as the fluctuations of voltage in electrochemical systems (the porous silicon formation under conditions of anode polarization, molecular hydrogen formation on platinum under conditions of cathode polarization, initiation of hydrodynamic instability in an overlimiting current density region in electromembrane systems), the fluctuations of solar activity and the variations of velocity components in turbulent flows (Timashev et al., 2000; Parkhutik and Timashev, 2000; Timashev and Vstovsky, 2003; Kostuchenko and Timashev, 2000; Letnikova et al., 2001).

In this paper the FNS approach is performed to the analysis of non-stationary time series, obtained by

observational geoelectrical measurements carried out in a seismically active area of southern Italy, aiming to identify possible earthquake precursors. The data present gaps, but their number allows us to reliably perform the FNS analysis.

2. Method

The FNS is based on the concept of high informative content of the sequences of irregularities—spikes (bursts), jumps, and discontinuities of derivatives of different orders—of some dynamic variable $V(t)$. The structural function $\Phi^{(p)}(\tau)$ of order p is defined as

$$\Phi^{(p)}(\tau) = \langle [V(t) - V(t + \tau)]^p \rangle, \quad (1)$$

where τ is the delay time. We will show that $\Phi^{(p)}(\tau)$ is given exclusively by the jumps of the dynamic variable, described by the Heaviside's θ -functions (Timashev et al., 1999).

Let us consider a system, whose dynamic variable $V(t)$ evolves as depicted in Fig. 1. This type of evolution is characterized by relatively low-amplitude variations over relatively long time intervals (laminar periods) with characteristic time T_0^i and by sharp spikes (bursts) of duration τ_0^i ($\tau_0^i \ll T_0^i$). Note that the spikes are characterized by sharp changes of the variable $V(t)$ at the subsequent laminar intervals, which are accompanied by the emergence of discontinuities in derivatives. The sharp jump-like changes of the laminar background can be characteristic of the variable $V(t)$ during short time intervals τ_1^i . Let us denote the characteristic time intervals between the sharp jumps as T_1^i ($\tau_1^i \ll T_1^i$). We assume that the main information about the system

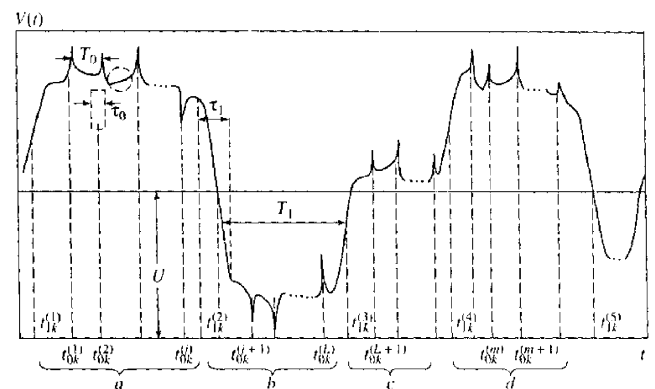


Fig. 1. Behaviour of a hypothetical dynamic variable $V(t)$. This type of evolution is characterized by relatively low-amplitude variations over relatively long time intervals (laminar periods) with characteristic time T_0^i and by sharp spikes (bursts) of duration τ_0^i ($\tau_0^i \ll T_0^i$). The sharp jump-like changes of the laminar background can be characteristic of the variable $V(t)$ during short time intervals τ_1^i . Let us denote the characteristic time intervals between the sharp jumps as T_1^i ($\tau_1^i \ll T_1^i$).

evolution is given by these singularities. According to Timashev (2000c) and Timashev and Vstovsky (2003), let us rewrite Eq. (2) in the following form

$$\Phi^{(p)}(\tau) = \left\langle \left| \int_t^{t+\tau} \frac{dV(y)}{dy} dy \right|^p \right\rangle. \quad (2)$$

Since δ -functions singularities do not give any contribution to the structural function $\Phi^{(p)}(\tau)$, after differentiation, the main contribution is given by the θ -functions, which are transformed in δ -functions after differentiation, and are located at the points $t_{0k}^{(j)}$ and $t_{1k}^{(j)}$ (Fig. 1). By considering the contribution from these θ -functions and taking into account the presence of the smaller jumps at the $t_{0k}^{(j)}$ points, we obtain:

$$\Phi^{(p)}(\tau) = \left\langle \left| \sum_{k=1}^{N_0(\tau)} q_{0,k} \right|^p \right\rangle, \quad (3)$$

where the quantities $q_{0,k}$ characterize the amplitudes of the k th jump, and whose dimension is $[V^2]$. The sum is computed over the total number $N_0(\tau)$ of the jumps in every interval τ within the total period T . We suppose that $N_0(\tau) \gg 1$, that is $\tau/T_0^i \gg 1$. Introducing a new variable $\xi = (T_0^i k)/\tau$, so that $(T_0^i N_0)/\tau = 1$ and $d\xi = (T_0^i \Delta k)/\tau \ll 1$ if $\Delta k = 1$. Then

$$\Phi^{(p)}(\tau) = \left\langle \left| \frac{\tau}{T_0^i} \int_0^1 Q_{01} \left(\frac{\tau}{T_0^i} \xi \right) \rho \left(\frac{\tau}{T_0^i} \xi \right) d\xi \right|^p \right\rangle, \quad (4)$$

where $Q_{01}(\tau\xi/T_0^i)$ and $\rho(\tau\xi/T_0^i)$ are the amplitudes and probability density function of the jumps in the interval $[0, \tau]$ respectively. In the stationary case the outer brackets in Eq. (4) can be omitted.

Let us introduce the function $\Phi_{01}^i(z) = Q_{01}(z)\rho(z)$ which characterizes the jump density during the evolution. Since the dimension of $\Phi_{01}^i(z)$ is $[V^2]$, we can write:

$$\Phi_{01}^i(z) = G_{01} b_{01}^i \chi_{01}(b_{01}^i z), \quad (5)$$

where $\chi_{01}(b_{01}^i z)$ is a dimensionless function, b_{01}^i is a dimensionless scaling factor and G_{01} is a constant whose dimensionality is $[V^2]$. Then

$$\Phi^{(p)}(\tau) = \left| G_{01} \int_0^{K_{01}\tau} \chi_{01}(x) dx \right|^p, \quad K_{01} = \frac{b_{01}^i}{T_0^i}. \quad (6)$$

In the simplest case we choose:

$$G_{01} \chi_{01}(x) = g_{01}^{1/p} \cdot \sigma \cdot \lambda_{01}^H \cdot \Gamma^{-1}(H) \cdot x^{H-1} \exp(-\lambda_{01} x), \quad H > 0, \quad (7)$$

where g_{01} , H and λ_{01} are the phenomenological parameters, and σ is the variance of the dynamic variable.

Substituting (8) in (7) we obtain

$$\Phi^{(p)}(\tau) \approx g_{01}(p) \cdot \sigma^p \cdot [1 - \Gamma^{-1}(H) \cdot \Gamma(H, \tau/T_{01})]^p, \quad T_{01} = (\lambda_{01} K_{01})^{-1}, \quad (8)$$

where $\Gamma(s)$ and $\Gamma(s, x)$ are the gamma function and incomplete gamma function, respectively ($x \geq 0$ and

$s > 0$); σ is the variance of the measured signal; H is the Hurst constant, which characterizes the “memory” of the variable, T_{01} is the correlation time of the process, and $g_{01}(p)$ is the parameter, that characterizes asymptotic behaviour of $\Phi^{(p)}(\tau) \rightarrow 2\sigma^2$, that is $g_{01}(2) = 2$. Therefore, the structural functions $\Phi^{(p)}(\tau)$ expressed by the Eq. (1) are fitted with the formula in Eq. (8).

Before applying the FNS method, the low frequency component $V_R(t)$ has to be removed from the signal. A new method, based on a “relaxation procedure”, has been developed to extract the high frequency component $V_F(t)$.

This method is analogous to the solution of diffusion (heat conductivity) equation

$$\frac{\partial V}{\partial \tau} = \chi \frac{\partial^2 V}{\partial t^2}, \quad (9)$$

that, in the form of a finite difference equation, is given by

$$\frac{V_k^{j+1} - V_k^j}{\Delta \tau} = \chi \frac{V_{k+1}^j + V_{k-1}^j - 2V_k^j}{(\Delta t)^2}. \quad (10)$$

This equation leads to

$$V_k^{j+1} = V_k^j + \frac{\chi \Delta \tau}{(\Delta t)^2} (V_{k+1}^j + V_{k-1}^j - 2V_k^j). \quad (11)$$

Assuming $\omega = \frac{\chi \Delta \tau}{(\Delta t)^2}$, Eq. (11) can be rewritten as

$$V_k^{j+1} = \omega V_{k+1}^j + \omega V_{k-1}^j + (1 - 2\omega) V_k^j, \quad (12)$$

which is absolutely stable for $\omega < 1/2$. The boundary conditions of Eq. (12) ($k = 1$ and $k = N$, where N is the length of the time series) are calculated by

$$\begin{aligned} V_1^{j+1} &= (1 - 2\omega) V_1^j + 2\omega V_2^j, \\ V_M^{j+1} &= (1 - 2\omega) V_M^j + 2\omega V_{M-1}^j. \end{aligned} \quad (13)$$

Therefore, calculating iteratively V_k^{j+1} from V_k^j , we obtain the low frequency component V_R . The high frequency component V_F is simply obtained by subtraction of V_R from the original signal. Up to now, many methods have been used to filter low frequency components, e.g. by using smoothing polynomials, wavelets, etc. This method of extracting high frequency components from a signal has the main advantage that it does not require to set any a priori form of the trend line to calculate the low frequency component V_R .

To investigate non-stationary processes, we need to analyze the time variation of $\Phi^{(p)}(\tau)$, which is calculated within an averaging interval $[k\Delta T, t_k]$ of duration T , shifting through the entire observation period by ΔT . The time variation of $\Phi^{(p)}(\tau)$ could be characterized by sharp changes, due to signal fluctuations (i) in the beginning of the averaging interval ($k\Delta T$) and at (ii) the end (t_k) of the same averaging interval T . Calculating the time variation of $\Phi^{(p)}(\tau)$, for different values of T it is shown that the first changes depend on T and appear simply shifted between each other, while the second

changes are invariant respect to T and can convey a well time-located information of non-stationarity (Deshchevsky et al., 2003).

Let us finally introduce the criterion of non-stationarity based on the time variation of $\Phi^{(p)}(\tau)$ (Timashev and Vstovsky, 2003):

$$C_F^{(p)}(t_{k+1}) = \frac{\int_{(k+1)\Delta T}^{\alpha T + (k+1)\Delta T} \Phi^{(p)}(\tau) d\tau - \int_{k\Delta T}^{\alpha T + k\Delta T} \Phi^{(p)}(\tau) d\tau}{\int_{k\Delta T}^{\alpha T + k\Delta T} \Phi^{(p)}(\tau) d\tau} \left/ \frac{\Delta T}{T} \right., \quad (14)$$

where $\Phi^{(p)}(\tau)$ is the structural function calculated for the the high frequency component of the signal and $\alpha \leq 0.5$. The introduced quantity characterizes a “measure of non-stationarity” of the signal. Evidently, $C_F^{(p)}(t_{k+1}) = 0$ for stationary processes.

3. Geological and seismological settings

The measuring station is located on the Southern Apennine chain whose framework consists of a pile of thrust sheet forming a complex system orogenically transported over the flexured south-western margin of the Apulia foreland. It is the result of a complex sequence of tectonic events associated with the collision between Africa and Europe (Pantosti and Valensise, 1990).

Starting in the middle Miocene up to upper Pliocene, five or more compressional tectonic phases caused progressive thrusting and piling of different tectonic units, corresponding to different paleogeographic domains, toward stable external domains of the Apulo-Adriatic foreland. During the Quaternary, the Southern Apennines have been affected by an important extensional tectonic phase, with NE-SW extensional trend, that caused further chain fragmenting into several isolated blocks (Doglioni et al., 1996).

The Southern Apennine chain is one of the most active area of the Mediterranean region. In this area on November 23, 1980 ($M_s = 6.9$), a large normal-faulting earthquake occurred (Pantosti and Valensise, 1990). One of the most historically relevant events, the December 16, 1857 normal-faulting earthquake, occurred in Val d’Agri. Seismic activity occurred after the 1980 event consisted of medium intensity events ($M < 5.0$) located close to the border between Campania and Basilicata regions. The May 5, 1990 ($M_D = 5.0$) and the May 26, 1991 ($M_D = 4.7$) earthquakes may be considered the strongest events after the Irpinia 1980 earthquake occurred in this area. These events have been followed by aftershocks sequences that identify a fault structure located near the Potenza town. The seismological analysis of the above-mentioned remarkable events demonstrated that such earthquakes have been generated by a strike-slip fault in WE direction,

perpendicularly oriented toward the Apennine chain (Ekström, 1994). This fault lies north of Potenza town and it is located in such a way to limit toward north and south two great seismogenetic faults that caused the 1857 Val d’Agri and 1980 Irpinia earthquakes respectively. The fault area outlined by the aftershocks extends approximately 20 km in length and 10 km in depth, making it significantly larger than what is expected for a $M_L = 5.0$ earthquake. The aftershocks were concentrated between 15 and 25 km depth, which is deeper than over well determined focal depth in the central and Southern Apennines (Ekström, 1994).

The geological and seismological settings allow us to consider the investigated area an ideal outdoor laboratory to study the possible correlations between tectonic activity and anomalous patterns in the geoelectrical signals.

4. Results

In this work we analyze the time series of hourly geoelectrical means recorded at the station Giuliano during 2002. The station Giuliano (40.688N, 15.789E) is located just on a strike fault. It measures two SP signals. The dipoles are located parallel and perpendicular to the strike-fault. The distance between the probes is 100 m for the dipole oriented along the strike-fault direction (EW), and 80 m for the other dipole (NS) perpendicular to the fault. In the present study, we analyze the time dynamics of the SP signal recorded along the NS direction. Fig. 1 shows the location of the station. Technically, a geoelectrical or self-potential time series is a sequence of voltage differences measured with a selected sampling interval using a receiving electrode array. During the geoelectrical soundings, where a current is injected into the ground, the self-potential represents the noise. On the other hand, when we record using a passive measurement technique (i.e. without an energizing system), we measure the signal. To avoid some self polarizing effects, we used ceramic electrodes built of ceramic vessels filled with a saturated solution of copper sulphate.

Fig. 2 shows the hourly time variation $V(t)$ of the geoelectrical signal measured at the station Giuliano during January–September 2002. Fig. 3 shows the low frequency component V_R and the high frequency component V_F obtained as outlined in the previous section. Fig. 4 shows the criteria C_F calculated for two averaging intervals $T = 720$ h and $T = 1080$ h with $\Delta T = 24$ h. The parameters $\alpha = 0.5$ and $p = 2$ have been used. The figure shows a strong variability of the criterion C_F , denoted by the presence of several sharp changes, indicating a strong variability of the non-stationarity of the signal. Furthermore, the negative spikes for $T = 720$ are simply shifted with respect to the negative spikes for $T = 1080$,

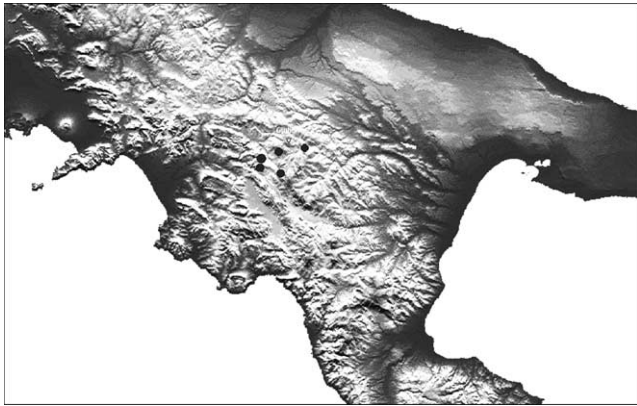


Fig. 2. Location of the geoelectrical station Giuliano in southern Italy (\blacktriangle) and the earthquakes (\bullet) occurred during the period of observation and satisfying the Dobrovolskiy's rule.

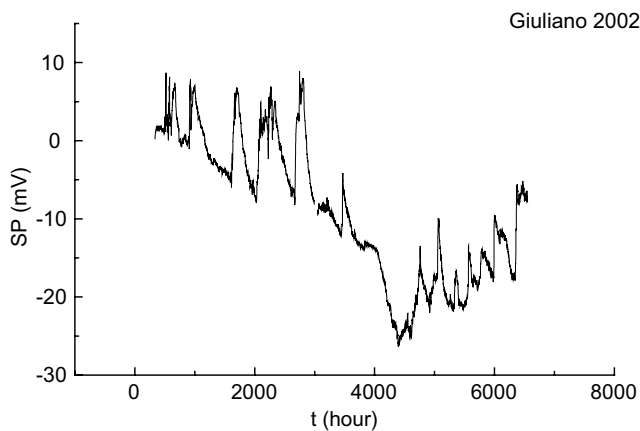


Fig. 3. Geoelectrical signal variation recorded at station Giuliano during 2002.

and therefore they are related to the duration of the averaging interval T . But, the time position of the positive spikes is invariant with respect to the averaging interval T and depends on the signal. We consider the second type of spikes, that are invariant with respect to T , as informative of non-stationarity behaviour of the signal.

In order to find correlations with the earthquakes, we need to select the only seismic events that could be responsible of significant changes in the time dynamics of the geoelectrical signal. Therefore we selected only earthquakes that could be responsible for strain effects in the investigated area. The stress field produces cracks on the rock volumes triggering fluid pressure variations. As a result of this process we have an underground charge motion and, subsequently, we observe anomalies in the electrical field on the surface only if the preparation region is near the measuring station. It is necessary to discriminate the useful events (i.e. earthquakes responsible for significant geophysical variations in a rock volume of the investigated area) from all the seis-

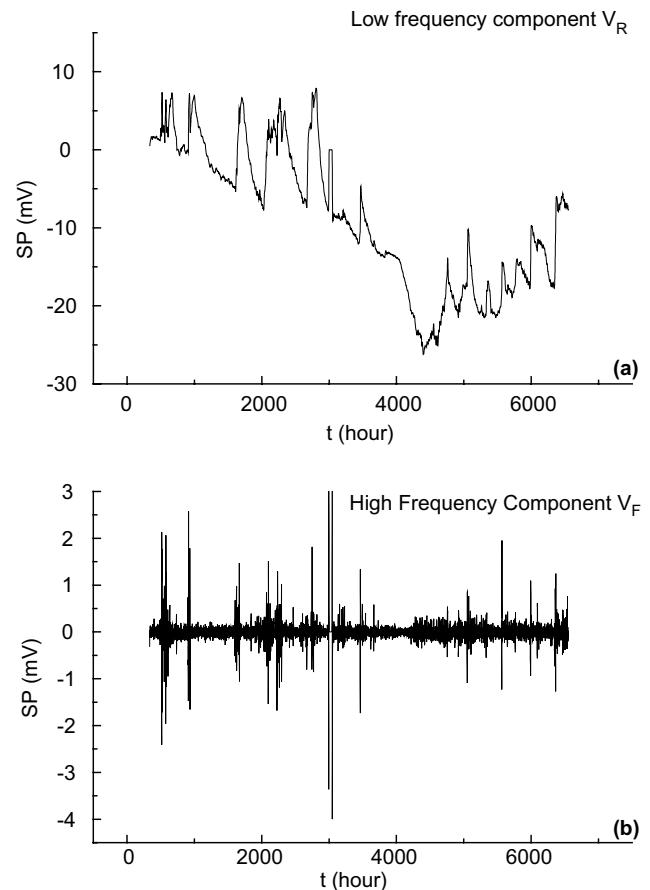


Fig. 4. Low V_F (a) and high V_F (b) frequency component of the signal plotted in Fig. 3.

mic sequences that occurred in the area surrounding the measuring station. To this purpose an empirical formula introduced by Dobrovolskiy (Dobrovolskiy et al., 1979; Dobrovolskiy, 1993) is used:

$$r = 10^{4.3M}, \quad (10)$$

where M is the magnitude and r (km) the radius of the area in which the effects of the earthquake are detectable. We considered only the earthquakes with r greater than the distance between the epicenter and the measuring station.

Fig. 5 shows the criteria C_F along with the seismic events (extracted by the INGV catalogue), occurred in the investigated area and satisfying the Dobrovolskiy's rule. Also the mean and the 1σ range of the criteria are plotted. It seems very clear that correlation between the positive spikes in the criterion C_F and earthquakes exists. In particular, the positive sharp changes of the criterion seem to precede the occurrence of a seismic event, selected by means of the Dobrovolskiy's rule (Fig. 6). Furthermore, no significant strong variation of C_F has been detected during the largest interevent time period between the fourth and the fifth earthquake, this corroborating the correlation found.

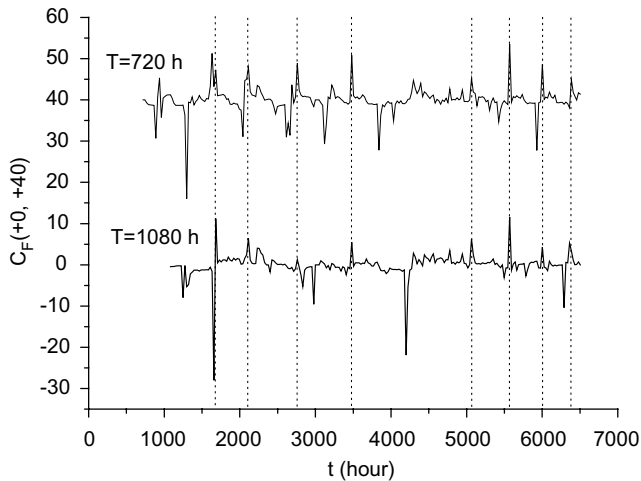


Fig. 5. Criterion C_F for two values of the averaging interval $T = 720$ h and $T = 1080$ h and $\Delta T = 24$ h for both cases. Strong sharp positive and negative changes are clearly visible, indicating a strong variability of the non-stationarity of the signal. The negative spikes relate to the duration of the averaging interval T and appears shifted between each other, while the positive spikes are independent on the interval T and are informative of the dynamics of the signal.

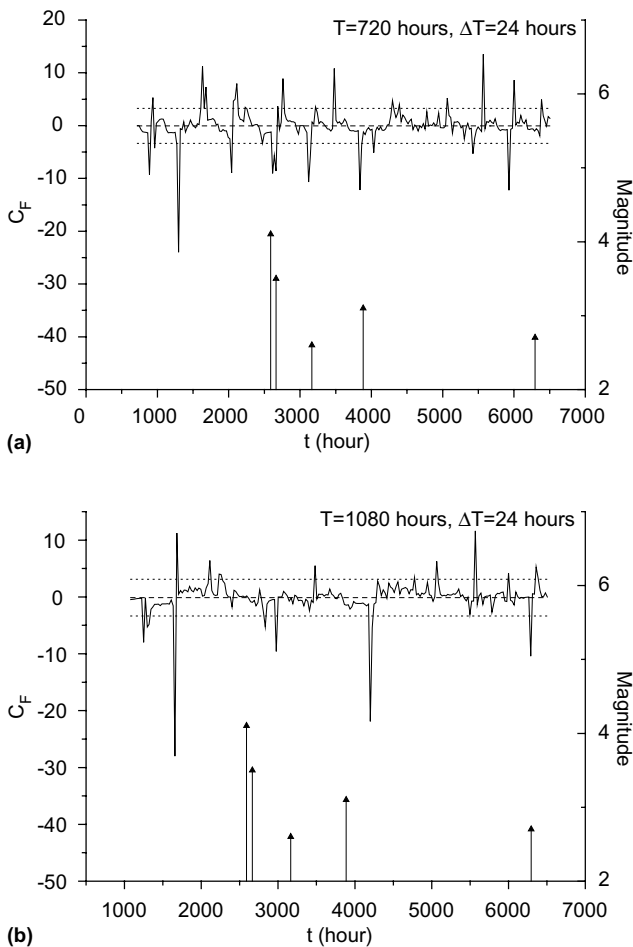


Fig. 6. Criterion C_F of Fig. 5 plotted along with the earthquakes, occurred in the investigated area during the observation period and selected by the Dobrovolskiy's rule. (a) $T = 720$ h, (b) $T = 1080$ h.

5. Conclusions

The earthquake prediction research evidences that deterministic concept has exhausted its capabilities. By means of this concept, observed geophysical variations are determined by the medium passive response to its deformation due to certain external forces. The crisis of the deterministic paradigm of earthquake prediction has allowed the growth of other models. In particular, a model of the medium as an active discrete hierarchically structural geophysical system has received wide recognition (Scholz, 1990; Turcotte, 1994; Lukk et al., 1996; Deshcherevsky et al., 2000). The main characteristics of this model is that the medium can actively redistribute and release the energy. Due to additional input of external energy (tidal motions, tectonic shifts etc.) some elements of the medium could reach an unstable state and throw off the energy surplus, which is absorbed by neighboring fragments or separate pieces. Such processes of accumulation and redistribution of this energy could gradually lead the whole system to instability and ultimately seismic large earthquakes (Sadovsky and Pissarenko, 1989). Following this perspective, the paradigm of earthquake prediction research has to be changed: The preparation of a large seismic event is reflected in non-stationarities of geophysical signals. A degree of non-stationarity of geophysical medium can be evaluated analyzing the temporal variations of geophysical signals, in particular, geoelectrical, as it has been performed in the present study.

The FNS methodology yields the total information contained in geophysical signals to be classified discernibly in the most general phenomenological form. The FNS, representing a signal as a sequence of irregularities, allows us to deeply analyze the non-stationarity properties of a time series. In our case, it has been observed that the non-stationarity behavior of geoelectrical signals measured in seismically active areas is characterized by a strong variability, that may be put in significant relation with the seismic activity of the area investigated. This approach could be useful in identifying a new type of seismic precursor.

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References

- Chu, J.J., Gui, X., Marone, C., Spiegelman, M.W., Seeber, L., Armbruster, M., 1996. Geoelectric signals in China and the

- earthquake generation process. *J. Geophys. Res.* 101 (B6), 13869–13882.
- Cuomo, V., Lapenna, V., Macchiato, M., Serio, C., Telesca, L., 1998. Linear and non linear dynamics in electrical precursory time series: implications with earthquake prediction. *Tectonophysics* 287, 279–298.
- Deshcherevsky, A.V., Lukk, A.A., Sidorin, A.Ya., 2000. Evidences of self-organization in geophysical fields' temporal variations. *Phys. Chem. Earth (A)* 25 (12), 775–779.
- Deshcherevsky, A.V., Lukk, A.A., Sidorin, A.Ya., Vstovsky, G.V., Timashev, S.F., 2003. Flicker-noise spectroscopy in earthquake prediction research. *Nat. Haz. Earth Syst. Sci.* 3, 159–164.
- Dobrovol'skiy, I.P., 1993. Analysis of preparation of a strong tectonic earthquake. *Phys. Solid Earth* 28 (6), 481–492.
- Dobrovol'skiy, I.P., Zubkov, S.I., Miachkin, V.I., 1979. Estimation of the Size of Earthquake Preparation Zones. *Pageoph* 117, 1025–1044.
- Doglioni, C., Harabaglia, P., Martinelli, G., Mongelli, F., Zito, G., 1996. A geodynamic model of the Southern Apennines accretionary prism. *Terra Nova* 8, 540–547.
- Ekström, G., 1994. Teleseismic analysis of the 1990 and 1991 earthquakes near Potenza. *Annali di Geofisica XXXVII* (6), 1591–1599.
- Gotoh, K., Hayakawa, M., Smirnova, N., 2003. Fractal analysis of the ULF geomagnetic data obtained at Izu Peninsula, Japan in relation to the nearby earthquake swarm of June–August 2000. *Nat. Haz. Earth Syst. Sci.* 3, 229–236.
- Hayakawa, M. (Ed.), 1999. *Atmospheric and Ionospheric Electromagnetic Phenomena Associated with Earthquakes*. Terra Sci. Pub. Co, Tokyo, p. 997.
- Hayakawa, M., Fujinawa, Y. (Eds.), 1994. *Electromagnetic Phenomena Related to Earthquake Prediction*. Terra Sci. Pub. Co, Tokyo, p. 667.
- Hayakawa, M., Ito, T., Hattori, K., Yumoto, K., 2000. ULF electromagnetic precursors for an earthquake at Biak, Indonesia on February 17, 1996. *Geophys. Res. Lett.* 27, 1531–1534.
- Hayakawa, M., Ito, T., Smirnova, N., 1999. Fractal analysis of ULF geomagnetic data associated with the Guam earthquake on August 8, 1993. *Geophys. Res. Lett.* 26, 2797–2800.
- Johnston, M.J.S., 1997. Review of electric and magnetic fields accompanying seismic and volcanic activity. *Survey Geophys.* 18, 441–475.
- Kostuchenko, I.G., Timashev, S.F., 2000. The comparative analysis of dynamic characteristics of solar-terrestrial processes. In: Gurzadyan, V.G., Ruffini, R. (Eds.), *The Chaotic Universe: Proceedings of the Second ICRA Network Workshop*, 10. Singapore, World Scientific, pp. 579–585.
- Letnikova, A.F., Vstovsky, G.V., Timashev, S.F., 2001. Formation of anisotropic fractal structures during dissolution of LiF monocrystals. *Mater. Sci. (Medziagotyra)* 7 (2), 98–103.
- Lukk, A.A., Deshcherevsky, A.V., Sidorin, A.Ya., Sidorin, I.A., 1996. Variation of geophysical fields as a manifestation of determinate chaos in fractal medium, Moscow. *UIPE Russ. Acad. Sci.* 210 (in Russian).
- Nagao, T., Orihara, Y., Takahashi, I., Hattori, K., Noda, Y., Sayanagi, K., Uyeda, S., 2000. Co-seismic geoelectric potential changes observed in Japan. *Geophys. Res. Lett.* 27, 1535–1538.
- Pantosti, D., Valensise, G., 1990. Faulting mechanism and complexity of the November 23, 1980, Campania Lucania earthquake, inferred from surface observations. *J. Geophys. Res.* 95 (B10, 15), 329–341.
- Park, S.K., 1997. Monitoring resistivity change in Parkfield, California: 1988–1995. *J. Geophys. Res.* 102 (B11), 24545–24559.
- Parkhutik, V., Timashev, S.F., 2000. Informative essence of noise: new finding in the electrochemistry of silicon. *Russ. J. Electrochem., Engl. Transl.* 34, 1221–1235.
- Rikitake, T., 1988. Earthquake prediction: an empirical approach. *Tectonophysics* 148, 195–210.
- Sadovsky, M.A., Pissarenko, V.F., 1989. Randomness and instability in geophysical processes, *Izvestiya. Earth Phys.* 25 (2), 79–85.
- Scholz, C.H., 1990. *The Mechanics of Earthquakes and Faulting*. Cambridge University Press. p. 439.
- Telesca, L., Cuomo, V., Lapenna, V., Macchiato, M., 2001. A new approach to investigate the correlations between geoelectrical time fluctuations and earthquakes in a seismic area of southern Italy. *Geophys. Res. Lett.* 28 (25), 4375–4378.
- Timashev, S., Budnikov, Y., Klochikhin, V., Kostuchenko, I., Lakeev, S.G., Maximychev, A., 1999. In: Uvarova, L. (Ed.), *Mathematical Models of the Non-linear Dynamics and Control in Condensed Systems and Other Media*. Plenum Press, New York, p. 1999.
- Timashev, S.F., 2000a. A new dialogue with nature. In: Broomhead, D.S., Luchinskaya, E.A., McClintock, P.V.E., Mulin, T. (Eds.), *Stochastic and Chaotic Dynamics in the Lakes, STOCHAOS AIP Conference Proceedings*. Melville, New York, pp. 238–243.
- Timashev, S.F., 2000b. Self-similarity in nature. In: Broomhead, D.S., Luchinskaya, E.A., McClintock, P.V.E., Mulin, T. (Eds.), *Stochastic and Chaotic Dynamics in the Lakes, STOCHAOS AIP Conference Proceedings*. Melville, New York, pp. 562–566.
- Timashev, S.F., 2000c. Science of complexity: phenomenological basis and possibility of application to problems of chemical engineering. *Theoret. Foundat. Chem. Eng.* 34, 301–312.
- Timashev, S.F., Kotova, S.N., Solovieva, A.B., Timashev, P.S., Luzgina, V.N., Rummyantseva, T.N., Evstigneeva, R.P., 2000. Deterministic quantum chaos in the system of vibration-rotation levels of porphyrin molecules according to IR spectroscopy data. *Russ. J. Phys. Chem., Suppl. 1, Engl. Transl.* 74, S1–S12.
- Timashev, S.F., 2001. Flicker-noise spectroscopy in analysis of chaotic flow in distributed dynamic dissipative systems. *Russ. J. Phys. Chem., Engl. Transl.* 75 (11), 1742–1749.
- Timashev, S.F., Vstovsky, G.V., 2003. Flicker-noise spectroscopy in analysis of chaotic time series of dynamic variables and a problem of signal-noise ratio. *Electrochemistry, Engl. Transl.* 39 (2), 149–162.
- Turcotte, D.L., 1994. Crustal deformations and fractals, a review. In: Kruhl, J.H. (Ed.), *Fractals and Dynamic Systems in Geoscience*, pp. 7–23.
- Tzani, A., Vallianatos, F., Gruszow, S., 2000. Identification and discrimination of transient electric earthquake precursors: Fact, fiction and some possibilities. *Phys. Earth Planet. Int.* 121, 223–248.
- Uyeda, S., Nagao, T., Orihara, Y., Yamaguchi, T., Takahashi, I., 2000. Geoelectric potential changes: Possible precursors to earthquakes in Japan. *Proc. US Nat. Acad. Sci.* 97, 4561–4566.
- Vallianatos, F., Nomikos, K., 1998. Seismogenic radioemissions as precursors to earthquakes in Greece. *Phys. Chem. Earth* 23, 938–944.