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Electromagnetic control of earthquake dynamics?

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Abstract

Dynamics of earthquakes' temporal distribution at the IVTAN test area in Central Asia undergoes noticeable changes induced by strong EM discharges. We have found that during the period of these discharges (1983–1988) seismic dynamics becomes much more regular compared to the periods before and long after cessation of experiments. These results may serve as an indication of the possible control of dynamics of a complex seismic process by strong EM impacts at least in the temporal domain.

Keywords: Seismicity; Nonlinear analysis; Control of dynamics; Anthropogenic influence

1. Introduction

Recently Russian seismologists reported the triggering effect of MHD soundings, performed by Institute of High Temperatures of Russian Academy of Sciences (IVTAN) in the Central Asia test area on the micro-seismic activity of the region (Tarasov et al., 1999; Jones, 2001). During these experiments deep electrical sounding of the crust was carried out at the Bishkek test site in 1983–1989. The source of electrical energy was a MHD generator, and a load was an electrical dipole of 0.4 Ω resistance with electrodes located at a distance of 4.5 km from each other. When the generator was fired, the load current was 0.28–2.8 kA, the sounding pulses had durations of 1.7–12.1 s, and the energy generated was mostly in the range of 1.2–23.1 MJ (Volykhin et al., 1993). The dipole was installed within Paleozoic crystalline structures in the Northern Tien Shan, which were adjacent to the boundary of Mesozoic/Cenozoic sedimentary deposits in the Chu Valley. A total of 114 firing runs were carried out during the period of operation of MHD generator. Later the laboratory data confirmed the possibility of initiation of mechanical instability of a system that is close to the critical state by strong electromagnetic pulses (Chelidze et al., 2002).

What are the possible physical mechanisms of coupling of EM pulses with the seismic source?

It is well known that the system, which is close enough to the critical state, can manifest anomalous sensitivity to small external impacts. According to recent investigations, Earth's crust in seismically active regions can be in the critical state or in the state of self-organized criticality (Bak et al., 1988; Scholz 1990). This can explain the known phenomenon of seismic activation at filling large reservoirs; this additional loading gives an insignificant contribution to the existing tectonic strains. Another examples are seismicity activation by pumping of water in the boreholes (Sibson, 1994) and remote aftershocks of Landers earthquake. According to King et al. (1994), aftershocks registered far from the epicenter of the earthquake were generated by only one-half bar increment in stress provided by the mainshock.

One of the possible mechanisms can be the direct dielectric breakdown of rocks driven by tectonic stress to the critical state. That means that the EM pulse should be strong enough, which can be expected only in the near-source zone. In the far zone the pulse should be amplified in order to cause dielectric breakdown. Dielectric breakdown as a rule is accompanied by

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emission of elastic waves. This class of models can be called "underground thunderstorms".

The EM field amplification can be realized in following ways:

(i) Amplification of EM field by wedge-type inclusions.

Local electric field near inclusion with conductivity g_2, much larger then conductivity of the host medium g_1, can exceed the intensity of mean macroscopic field. The largest effect is expected for the needle- or lens-shaped inclusions. It is well known that elongated conductive impurities in transformer oil enhance dielectric breakdown (Kharitonov, 1983). As the cracks in rocks are usually saturated with conducting pore fluid and have form of lens or needle, some amplification of the applied field can be expected: theoretically at the tip of the needle, the local field intensity is infinitely high.

(ii) Amplification of EM field in the random lattice model.

Besides above discussed "wedge" model, there is another class of models that also explain local amplification of applied voltage, namely, percolation (random lattice) models. It has been shown (De Archangelis et al., 1986; Benguigi, 1988) that distribution of voltages on the random lattice of resistors and insulators is multifractal and at the percolation threshold p_c, the maximal voltage drop V_{max} occurs on singly connected (so called red) bonds, which carry the total current passing through the network. There are two models of electrical breakdown of the random lattice, dielectric and fuse. In the first model, the system is conductor-loaded insulator. An insulating element becomes conducting (breaks) at the voltage higher than V_{th}. Then, the whole system becomes conducting at the breakdown voltage V_b, which strongly depends on the concentration of conducting bonds p. In the second (fuse) model, the system is insulator-loaded conductor. Here the conducting element is fused, i.e. becomes insulator, if the current, flowing through it is larger than the threshold current J_{th}. Again, the whole system fuses (becomes insulator) at carrying the current J_b which strongly depends on the concentration of conductors p.

Near the percolation threshold p_c when the infinite cluster of conducting bonds spans the whole system, the breakdown voltage V_b has a typical power law form, $V_b = (p - p_c)^v$ and goes to zero as $p \to p_{\tilde{n}}$ (De Archangelis et al., 1986; Benguigi, 1988). Here v is the exponent of correlation length ξ. For two-dimensional systems $v = 4/3$. According to above expression, at $p \to p_{\tilde{n}}$ the system breakdown (applied) voltage becomes very low.

The geological formations can be considered as mosaics of insulating (minerals) and conducting (brine-saturated pores and cracks) components, which in some areas are close to the percolation threshold. This in principle can explain the local breakdown phenomenon, as at $p \to p_{\tilde{n}}$ the intensity of the field, necessary for initiation of breakdown tends to zero. Thus, theoretically the local breakdown voltage can be achieved at very a small applied field if the system is close to the percolation threshold.

EM-activation mechanism can also be related to pore fluid action:

(iii) Seismohydraulic mechanism of activation of seismicity.

We have noted that, in order to initiate fracturing by EM pulses, the system should be close to the critical state; in our case close to the state of mechanical instability. The critical shear stress on the fault $\tau_c = c + \mu(\sigma_n - P_f)$, where c is resistance to fault displacement due to its partial cementation, μ is friction coefficient, σ_n is the stress component normal to the fault plane, P_f is fluid pore pressure. It is evident that, in order to provoke mechanical instability, EM-pulse should affect at least one of parameters of above formula and so change τ_c. It seems that μ, σ_n and P_f can be affected by EM pulse. For example, due to piezoelectric effect μ and σ_n can be favorably changed. The weakening of faults under EM impact can also be connected with interaction of pore fluid and mineral backbone, namely:

(a) Application of EM pulse can drive pore fluid into the "dry" cracks. This decreases surface fracture energy, which means either enhancement of crack growth by Griffith's model of fracture or just decrement of friction coefficient μ.
(b) Electrical impact can provoke electrokinetic flow in the porous rock (electroosmosis) and thus increase pore pressure P_f .
(c) Strong EM impact can generate the so called electrohydrodynamic effect (EHD) which has been discovered in the 1950s (Nesvetailov and Serebryakov, 1966). EHD effect means that water saturated porous solid can be destroyed by strong enough EM pulses; this even has found industrial applications. The mechanism of EHD effect is not known exactly. The most popular explanation is cavitation or generation of small gas bubbles by applied EM pulse; their collapse generates transient stress fields in the fluid, which destroys a solid.

First two mechanisms in principle can explain the considerable time lag between impact and (remote) response as the pore fluid migration or diffusion under electric field is a relatively slow process.

Rigorous quantitative test of above qualitative models is difficult as they all contain some parameters that can not be measured exactly: say, closeness to the percolation threshold of geological formation at the depth 5–10 km, water content, stress state, etc.

In the present study the dynamics of temporal distribution of earthquakes around the IVTAN test area in Central Asia in 1975–1996 is analyzed. For this purpose sequences of time intervals between consecutive earthquakes from the seismic catalogue, compiled by the Institute of Physics of Earth (Moscow) were investigated using tools of nonlinear time series analysis. The main goal was to find out whether strong EM discharges my lead to changes of dynamics of temporal distribution of seismicity. During the last several years Cristian Goltz for Japan (Goltz, 1998) and ourselves for Caucasus and as for Central Asia, have found that the seismic process that is dynamically complex and high dimensional in the energy domain, reveals unexpectedly low dimensional structure, akin to the deterministic chaos, in its temporal domain (Matcharashvili et al., 2000). That is why we have decided to carry out quantitative analysis in the temporal rather than in the high dimensional energetic domain. In its turn, the low-dimensional structure of earthquakes temporal distribution enables us to investigate possible changes in seismic dynamics under strong and brief anthropogenic influence.

2. Methods

Sequences of inter-event time intervals (in seconds) between earthquakes registered around the IVTAN test area in the period of 1983–1996 have been considered. We have analyzed time interval series containing all available earthquakes as well as time interval sequences between earthquakes above the magnitude (M) threshold $M=2$. The minimal magnitude of the catalogue is $M=0.1$.

We have carried out complete qualitative and quantitative nonlinear analysis as described in (Matcharashvili, et al. (2000, 2002)). Namely as qualitative dynamical tools, phase portraits, IFS-clumpiness (Jeffrey, 1992; Sprott and Rowlands, 1995) and recurrence plot analysis (Zbilut and Webber, 1992) tests have been used. Besides the correlation dimension, surrogate time series testing and Lemplel-Ziv algorithmic complexity of interevent time interval series have been calculated (Abarbanel et al., 1993; Kantz and Schreiber, 1997; Hegger and Kantz, 1999; Schreiber and Schmitz, 2000; Lempel and Ziv, 1976).

Often real time series, including seismic ones, are highly corrupted by noise. At the same time it is known that linear filtering leads to distortion of the original dynamical structure of the analyzed complex processes. Consequently, we have used methodology of nonlinear noise reduction, which in fact is phase space nonlinear filtering (Kantz and Schreiber, 1997; Hegger and Kantz, 1999; Schreiber, 2000). Nonlinear noise reduction relies on the exploration of reconstructed phase space of the considered dynamical process, instead of the frequency information of linear filters (Hegger and Kantz, 1999; Schreiber, 1993; Kantz and Schreiber, 1997).

Integral time series were analyzed containing all available data, as well as time series in the periods before (1975–1983), during (1983–1988) and after (1983–1992) EM discharges.

The calculation of a correlation integral of time series and a generation of surrogate data were done using the software developed at our Institute. The program was written in C++. Additionally we applied J. C. Sprott's Chaos Data Analyzer (CDA PRO) professional version 2.1 (Sprott and Rowlands, 1995) and TISEAN package (Kantz and Schreiber, 1997; Hegger and Kantz, 1999).

3. Results and discussion

Firstly we have calculated the correlation dimension (Abarbanel et al., 1993; Kantz and Schreiber, 1997) of the integral time series (14,100 time intervals) for the whole period of observations (1975–1996). In order to avoid frequently encountered error in d_2 calculation caused by false temporal correlations in analyzed data, delay time τ (τ =2–3 for our time series) was calculated based on the mutual information first minimum approach (Hegger and Kantz, 1999).

As for other regions analyzed earlier (Goltz, 1998; Matcharashvili, et al., 2000), our analysis reveals a low correlation dimension (see item E in Fig. 3) of Central Asia earthquakes temporal distribution ($d_2 = 2.40 \pm 0.71$) for the whole observation time period.

Then the sequences of time intervals, corresponding to the different time periods were analyzed. Namely, the time periods before the beginning of the experiment (1975–1983), the time period of EM runs (1983–1988) and the time period immediately after completion of the experiments (1988–1992), as well as the time period long after the experiment (1992–1996) were considered separately. Inter-earthquake time interval sequences, corresponding to these periods, have approximately the equal lengths (about 3660 events).

In Fig. 1 qualitative recurrence plot analysis of time series before, during and after EM experiments are presented. Recurrence quantification analysis (RQA) is an analytical tool developed in the last decade for the study of nonlinear dynamical systems (Zbilut and Webber, 1992; Eckmann et al., 1987). The general idea underlying the recurrence plot analysis is that the considered time series are realizations of some unknown dynamical process. According to the embedding theorem it is possible to recreate a topologically equivalent phase space picture of the original dynamics by using the time series of a single observable variable (Takens, 1981). Recurrent points are selected as Euclidian distances falling within the selected radius. Essentially the recurrence plot is a color-coded or gray scale matrix,

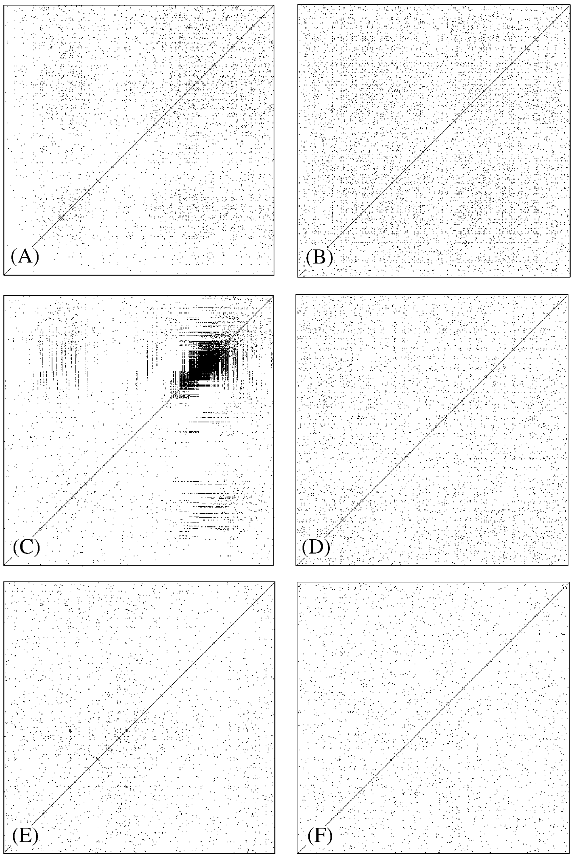

Fig. 1. Recurrence plots of interevent time interval sequences (A, C, E) and their shuffled surrogates (B, D, F) before (A, B), during (C, D) and long after (E, F) experiments.

calculating the distances between all pairs of vectors and coding them as colors. With recurrence plots one can graphically detect hidden structure patterns and their evolution with time. Plots of Fig. 1 show that after the beginning of experiments, the earthquakes' temporal distribution undergoes significant changes. It is especially clear by comparing the RQA of the original time series to the same time series after random shuffling (Fig. 1B, D and F).

The conclusion about noticeable qualitative changes under EM anthropogenic influence is confirmed by the Lempel Ziv algorithmic complexity (LZC) measure analysis (Lempel and Ziv, 1976). This method is based on the transformation of analyzed time series into a finite symbol sequence and further evaluation of the length of the coded sequence. This is a nonparametric and easily to computed, tool for the analysis of relatively short (even for 300–400 data length) time series (Zhang and Thakor, 1999; Matcharashvili and Janiashvili, 2001).

Calculated values of the LZC measure are $C_{LZ} = 0.98 \pm 0.09$; $C_{LZ} = 0.65 \pm 0.05$; $C_{LZ} = 0.99 \pm 0.09$, before, during and long after beginning of experiments. This result confirms the previously mentioned qualitative conclusion about changes in seismic dynamics. Namely, taking into account that $C_{LZ} = 0.04$ for periodic and $C_{LZ} = 1$ for random processes, our result shows the increasing of regularity in earthquakes temporal distribution under EM discharges.

As a main quantitative measure of earthquake temporal distribution dynamics, the correlation integral of time series for separate time periods have been

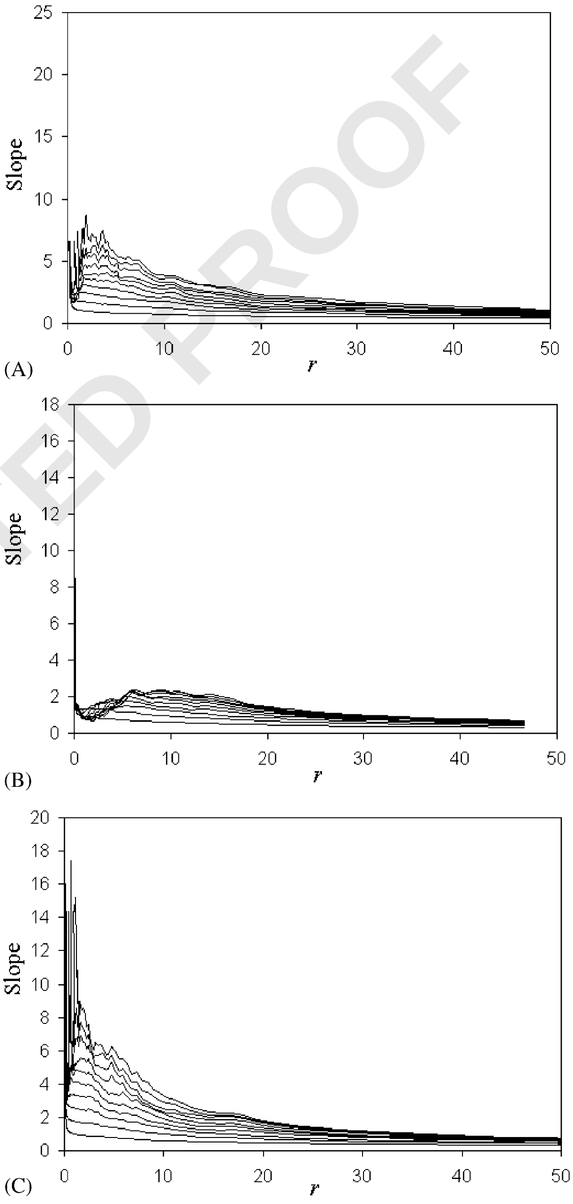

Fig. 2. Dimension estimation for inter-earthquake time intervals time series. Embedding dimension up to 10 is shown. (A) before, (B) during and (C) after EM discharges.

calculated. In Fig. 2, slopes of log $C(r)$-log r plots vs. phase space distance r, evaluated by the Takens estimator (Hegger and Kantz, 1999) are shown. Correlation dimensions vs. embedding dimension are plotted in Fig. 3. It follows from our analysis that before beginning the experiments, the earthquake temporal distribution is characterized by the correlation dimension $d_2 = 3.50 \pm 0.63$ which according to Sprott and Rowlands (1995) is below the low dimensionality threshold ($d_2 = 5.0$). After beginning of experiments (Figs. 2B and 3B) the correlation dimension of the time interval sequence decreases to $d_2 = 1.71 \pm 0.09$. This result together with the qualitative analysis results shown in Fig. 1 provides strong evidence that after the beginning of EM discharges the temporal distribution of earthquakes becomes more regular, or events of corresponding time series become functionally much more interdependent. At the same time, the absence of peculiar for the typical strange attractors phase space and iterated functions system (IFS) (Jeffrey, 1992) (not shown here), as well as recurrence plot analysis patterns, do not allow considering the analyzed process as a deterministically chaotic one.

After the termination of experiments the correlation dimension of inter-earthquake time interval sequences noticeably increases ($d_2 > 5.0$) (Fig. 2C and Fig. 3C and D), exceeding the low dimensionality threshold ($d_2 = 5.0$). It means that after the termination of experiments the extent of determinism in the earthquake temporal distribution decreases considerably. The process becomes much more random both qualitatively (compare Fig. 1E and F) and quantitatively (Fig. 3, diamonds and circles).

In order to avoid effects of possible noise, we have analyzed inter-event time series after applying a multiple noise reduction procedure (Schreiber, 1993; Kantz and Schreiber, 1997; Hegger and Kantz, 1999). We used the methodology of nonlinear noise reduction which preserves the original nonlinear structure of analyzed complex processes (Schreiber, 2000).

The correlation dimension vs. the embedding space dimension of the noise-reduced time series is presented in Fig. 4. As follows from the results, the correlation dimensions are not strongly affected by unavoidable noises. Therefore these results assure us that the observed differences in d_2-phase space dimension before, during and after the experiments are indeed related to the dynamical changes in the temporal distribution of earthquakes due to anthropogenic EM impacts.

Further, in order to have the basis for more reasonable rejection of spurious conclusions, caused by possible linear correlations in considered data sets, we have used the surrogate data approach as described in our previous paper (Matcharashvili, 2002). The main idea of this approach is to test the null hypothesis that time series are generated by a linear stochastic process (Abarbanel et al., 1999; Rapp et al., 1993, 1994). In other words we check the possibility that the revealed dynamics belongs to the colored noise type. Random phase—RP and Gaussian scaled random phase—GSRP surrogates sets were used.

For each of our data sequences we generated 70 of RP and GSRP surrogates. The reliability criterion S,

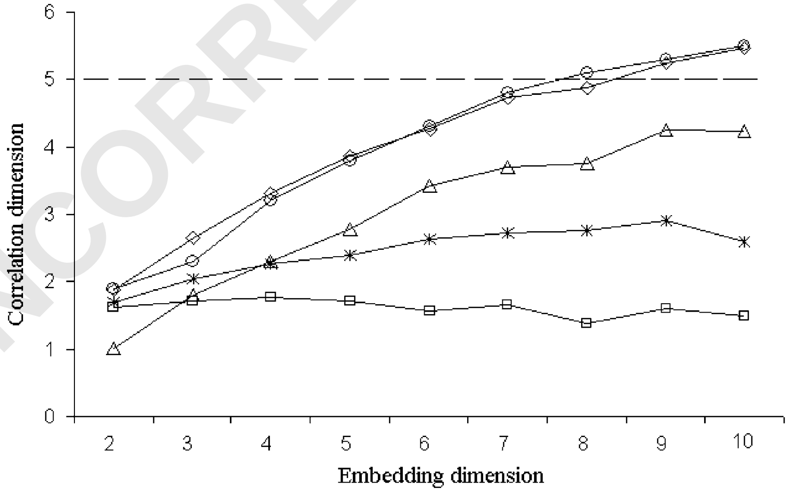

Fig. 3. Correlation dimension versus embedding dimension of inter-event time interval sequences of IVTAN polygon (A) triangles—sequence of 3600 inter-event time intervals before beginning of experiments (1975–1983), (B) squares—sequence of 3600 inter-event time intervals during experiments (1983–1988), (C) circles—sequence of 3600 inter-event time intervals immediately after completion of experiments (1988–1992), (D) diamonds—sequence of 3600 inter-event time intervals long after completion of experiments (1992–1996), (E) whole period of observations (1975–1996).

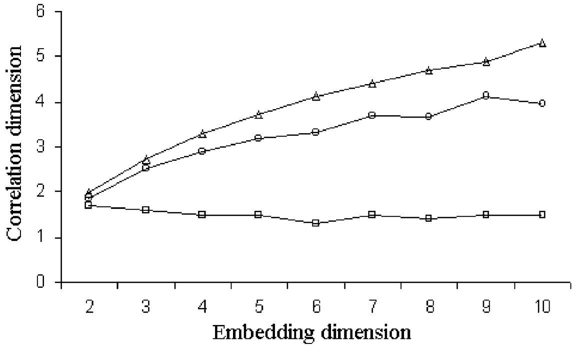

Fig. 4. Correlation dimension versus embedding dimension of noise reduced inter-event time interval sequences: circles—sequence of 3600 inter-event time intervals before beginning of experiments; squares—sequence of 3600 inter-event time intervals during experiments; triangles—sequence of 3600 inter-event time intervals long after completion of experiments.

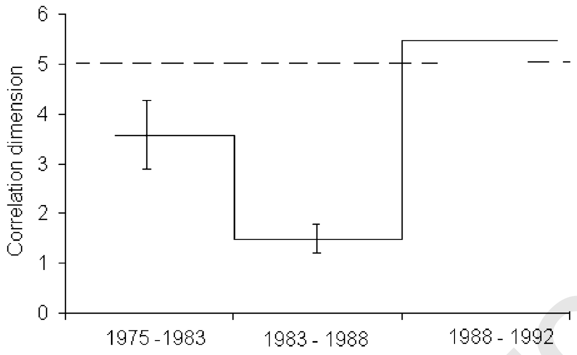

Fig. 5. Variation of inter-earthquake time intervals time series correlation dimension for various periods of observation.

according to Theiler (Theiler et al., 1992) for time series before experiments is significant (i.e. $S > 5$): 32.3 ± 0.2 for RP and 5.1 ± 0.6 for GSRP surrogates. The null hypothesis that original time series during experiments is a linearly correlated noise was rejected with an even larger value of S criterion: 46.2 ± 0.5 for RP and 6.2 ± 0.7 for GSRP surrogates.

The results of all these tests can be considered as strong evidence that the low dimension of analyzed time series are not connected with linear stochastic noise.

Essentially the same conclusions can be drawn from the analysis of catalogue of events of magnitude equal or larger than $M = 2$ (see Fig. 5).

We are examining these results in the light of ideas about chaos control. Indeed, the well known chaos control approach developed by Ott, Grebogy, and Yorke exploits the sensitivity of complex chaotic system to the initial conditions by making small perturbations to an accessible system parameter such that the system's state point is attracted toward the stable direction of any unstable periodic orbits of chaotic attractor (Ott, 1995). Though, this approach was developed for low-dimensional systems, later it was also expanded for high-dimensional systems (e.g. Christini, et al., 1996). In our situation, the energy of EM pulses is about 10^9 J i.e. at least million times lower than released total seismic energy (Jones, 2001). Therefore EM discharges as external impacts may be considered as a really small perturbation leading to the (relative) stabilization of earthquake generating crustal system. In this regard it is possible to assume that the aforementioned changes in earthquakes temporal distribution during strong EM impacts represents an example of control of complex seismic dynamics.

4. Conclusions

In present research we have investigated qualitative and quantitative dynamical characteristics of earthquakes' temporal distribution at the IVTAN test area in Central Asia. It was found that the temporal distribution of earthquakes during a period of strong EM discharges becomes more regular than before. The correlation dimension of inter-event time interval sequences decreases by more than two times. After cessation of EM discharge experiments, the dynamics of the earthquakes temporal distribution of earthquakes becomes more irregular than before the experiments.

Our results may serve as an indication of the possible control of dynamics of a complex seismic process by strong EM impacts, at least in the temporal domain. We suppose that, released by a series of EM discharges, energy my lead to dynamical stabilization of a high dimensional crustal system responsible for the temporal distribution of earthquakes.

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