SES 2019
Fifteenth International Scientific Conference
SPACE, ECOLOGY, SAFETY
6 – 8 November 2019, Sofia, Bulgaria

SOME RESULTS OF A RETROSPECTIVE MULTIFRACTAL ANALYSIS OF MICROSEISMIC NOISE BEFORE EARTHQUAKES IN BULGARIA AND ADJACENT LANDS

Emil Oynakov, Valentina Protopopova, Emil Botev

National Institute of Geophysics, Geodesy and Geography – Bulgarian Academy of Sciences
e-mail: emil.ilievmg@gmail.com; valya.pr@gmail.com; ebotev@geophys.bas.bg

Keywords: *earthquake indicators, seismic noise, fractal analysis of seismic noise*

Abstract: *For deciphering the structure of micro-seismic noise, the use of multi-fractal analysis proves to be a good enough alternative. If we calculate the spectrum of singularity F (α) in a creeping time window, then changing its parameters gives information about the change of the noise structure, and therefore about the structure of the medium in which it propagates. Such changes in the earth structure are associated with the processes of earthquake preparation and have been established for the periods before several earthquakes in the Central Balkans.*

НЯКОИ РЕЗУЛТАТИ ОТ РЕТРОСПЕКТИВЕН МУЛТИФРАКТАЛЕН АНАЛИЗ НА МИКРОСЕЙСМИЧЕН ШУМ ПРЕДИ ЗЕМЕТРЕСЕНИЯ В БЪЛГАРИЯ И ПРИЛЕЖАЩИТЕ ЗЕМИ

Емил Ойнаков, Валентина Протопопова, Емил Ботев

Национален институт по геофизика, геодезия и география – Българска академия на науките
e-mail: emil.ilievmg@gmail.com; valya.pr@gmail.com; ebotev@geophys.bas.bg

Ключови думи: *индикатори на земетресения, сеизмичен шум, фрактален анализ на сеизмичния шум*

Резюме: *За разшифроването на структурата на микросеизмичния шум, използването на фракталния анализ се оказва една достатъчно добра алтернатива. Ако изчисляваме спектъра на сингулярност F(α) в пълзящ времеви прозорец, то промяната на неговите параметри дава информация за промяната на структурата на шума, и оттам за структурата на средата в която той се разпространява. Такива изменения в земната среда се свързват с процесите на подготовка на земетресенията и са установени за периодите преди няколко земетресения в Централни Балкани.*

Introduction

The development of new methods for earthquake forecasting based on data from geophysical and, in particular, seismic monitoring is one of the priority goals of Earth science. Seismic records of twenty-three Balkan Peninsula broadband stations were analyzed, at distances of 1 to 500 km far from the earthquake on 28.10.2018 with magnitude 5.5 in seismic zone Vranchea. For the analysis, the Lubusin method was used for fractal analysis of scalar time series.

A scientific goal is to detect common signals based on different earthquakes focal mechanisms and ignore the "individual" behavior of the elements of the monitoring systems.

Determination of the clear signs for future strong earthquakes on Bulgarian territory and the neighboring countries is a main task for the project "Exploration of changes in some geophysical fields preceding the occurrence of earthquakes in the Balkans", Grant DN 14-1/11.12.2017, financed by Bulgarian National Science Fund.

The present paper generalizes the experience accumulated in studies of microseismic background in the (LF) range of periods from 1 to 300 min observed in time interval preceding the earthquake on 28.10.2018 with magnitude 5.5 in seismic zone Vranchea. This frequency range is the least studied and occupies an intermediate position between LF seismology and investigations of slow geophysical processes such as gravity field variations, crustal strain, and tilt variations, and so on. In the present paper, the main attention is given to the background behavior of microseisms. Note that this background contains continuous arrivals from near weak and far strong and moderate earthquakes.

The joint effect of atmospheric and oceanic processes, tidal deformations of the crust, and the global seismic process, as well as difficultly identifiable and poorly studied processes in the crust related to accumulation and slow dissipation of tectonic energy in the lithosphere results in a random process the study of which by the traditional technique of spectral analysis is ineffective. The methods of identifying periodicities in an event flow, orthogonal wavelet decompositions, estimates of multifractal spectra of singularity, and multidimensional measures of coherent behavior were applied to the study of LF microseismic background in [Sobolev, 2004; Sobolev et al., 2005; Sobolev and Lyubushin, 2006, 2007; Lyubushin and Sobolev, 2006; Lyubushin, 2007].

Method and Theory

Let *F* be some random fluctuations in the time interval $[t-\delta / 2, t + \delta / 2]$ (Figure 1) with duration δ and the reach of the random process for this interval - $\mu (t, \delta)$ (difference between the maximum and minimum amplitude values) and calculate the mean value of its power degree q:$M(\delta, q)=[(\mu_x(t, \delta))^q]$. A random signal is scale-invariant [Taqqu, 1988] if $M (\delta, q) \sim \delta^{(q)}$ when $\delta \rightarrow 0$, that is, the following limit exists:

(1) $$(q)=\lim_{\delta\rightarrow 0}(\ln(M(\delta,q))/\ln(\delta)),$$

If $\rho (q)$ is a linear function $(q) = Hq$, where $H = const$, $0 < H <1$, the process is called monofractal. In the case where $\rho (q)$ is a nonlinear concave function of *q*, the signal is called multifractal. To estimate the value of $\rho (q)$ using a finite sample $x(t)$, $t = 0,1,...,N -1$ we used the method, which is based on the approach of detrended fluctuation analysis (DFA) [Kantelhardt et al., 2002]. Let us split the entire time series into non-overlapping intervals of length *s*:

(2) $$I_k^{(s)} = \{t: 1 + (k-1)s \leq t \leq ks, k = 1, \ldots\ldots, \left[\frac{N}{s}\right]\}$$

and let

(3) $$y_k^{(s)}(t) = x\big((k-1)s + t\big), t = 1, \ldots\ldots, s$$

be a part of the signal *x(t)* , corresponding to interval $I_k^{(s)}$. Let $p_k^{(s,m)}(t)$ be a polynomial of the order *m*, best fitted to the signal $y_k^{(s)}(t)$. Let us consider the deflections from the local trend:

(4) $$\Delta y_k^{(s,m)}(t) = y_k^{(s)}(t) - p_k^{(s,m)}(t), t = 1, \ldots, s$$

and calculate the values

(5) $$Z^{(m)}(q,s) = \left(\frac{\left(\sum_{k=1}^{\left[\frac{N}{s}\right]}(\max_{1\leq t\leq s} \Delta y_k^{(s,m)} - \min_{1\leq t\leq s} \Delta y_k^{(s,m)}(t))^q\right)}{\frac{N}{s}}\right)^{\frac{1}{q}}$$

that can be regarded as the estimate of $(M(\delta_s,q))^{\frac{1}{q}}$. Let us define the function *h(q)* as a coefficient of linear regression between $\ln\big(Z^m(q,s)\big)$ and *ln(s)*: $Z^{(m)}(q,s) \sim s^{h(q)}$ fitted for scales range $s_{min} \leq s \leq s_{max}$. It is evident that $(q) = qh (q)$ and, for a monofractal signal, $h(q) = H = const$. The multifractal singularity spectrum *F(α)* is equal to the fractal dimensionality of the set of time moments *t* for which the Hölder – Lipschitz exponent is equal to *α* i.e. for which

$|x(t+\delta)-x(t)|\sim|\delta|^{\alpha}$, δ→0 [Feder, 1988]. The singularity spectrum can be estimated using the standard multifractal formalism, which consists in calculating the Gibbs sum: multifractal formalism, which consists in calculating the Gibbs sum:

$$W(q,s)=\sum_{k=1}^{N/s}\left(\max_{1\leq t\leq s}\Delta y_k^{(s,m)}(t)-\min_{1\leq t\leq s}\Delta y_k^{(s,m)}(t)\right)^q \tag{6}$$

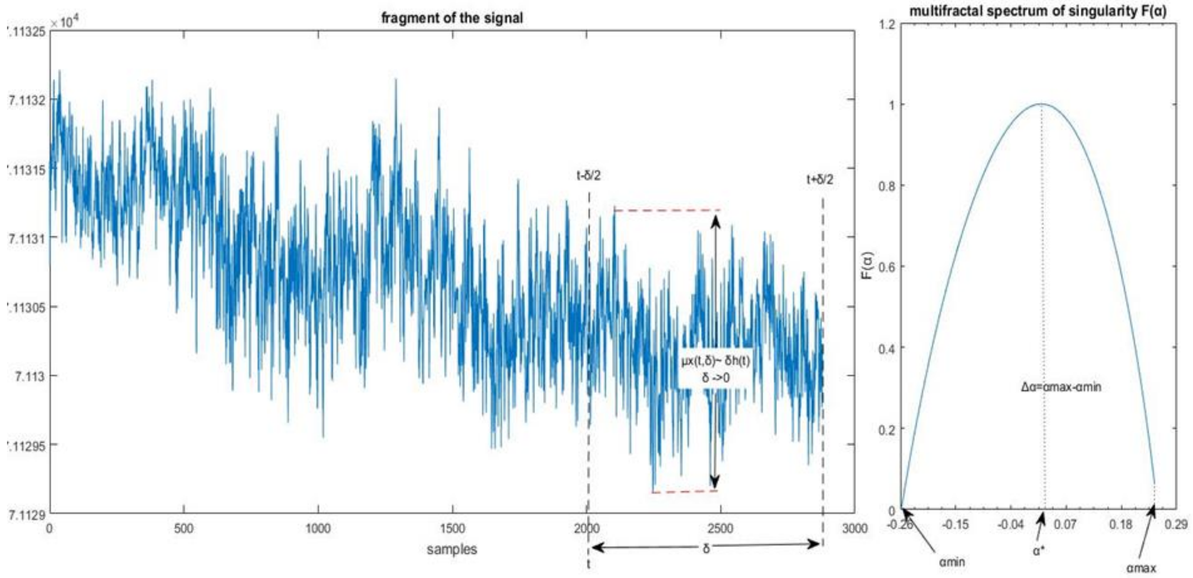

Fig. 1. Illustration of the multifractal spectrum of the singularity, where: F (α) - the multifractal spectrum of the singularity or fractal dimension of the set of times t; Δα - width of the carrier of F (α); α* - a general exponent Hearst.

and in estimating the mass exponent τ *(q)* from the condition $W(q,s)\sim s^{\tau(q)}$. From (6) it follows that $\tau(q)=\boldsymbol{\rho}(q)-1=qh(q)-1$. In the next step, the spectrum $F(\alpha)$ is calculated with the Legendre transform:

$$F(\alpha)=\max\{\min_q(\alpha q-\tau(q)),0\} \tag{7}$$

If the singularity spectrum $F(\alpha)$ is estimated in a moving window, its evolution can give useful information on the variations in the structure of the “chaotic” pulsations of the series. In particular, the position and width of the support of the spectrum $F(\alpha)$, i.e., the values $\alpha_{\min}$, $\alpha_{\max}$, $\Delta\alpha=\alpha_{max}-\alpha_{min}$, and α^* , such that $F(\alpha*)=\max_{\alpha}F(\alpha)$, are characteristics of the noisy signal. The value α^* can be called a generalized Hurst exponent and it gives the most typical value of Lipschitz-Holder exponent. Parameter $\Delta\alpha$, singularity spectrum support width, could be regarded as a measure of variety of stochastic behavior. In the case of a monofractal signal, the quantity $\Delta\alpha$ should vanish and $\alpha^* = H$. Usually $F(\alpha^*) = 1$, but there exist time windows for which $F(\alpha^*) < 1$. Estimates of minimum Hölder-Lipschitz exponent min a are mainly positive. Nevertheless negative values of min a are quite possible as well [Telesca et al., 2005; Currenti et al, 2005; Telesca, Lovallo, 2011; Chandrasekhar et al., 2016] for time fragments which are characterized by high-amplitudes spikes and steps.

Used data

This article explores the time interval of 06.10.2018–30.10.2018, preceding the Vrancea earthquake on 28.10.2018; 00:38:15 GMT; with coordinates 45.7 oN / 26.4 ^{o}E; M_w = 5.5; h = 150 km. For the study, vertical component records (BHZ) of 23 seismic stations (Table 1), with records of 100 reports per second (i.e., 8 640 000 reports for 24 hours) are used. In order to obtain 1/2-minute low-frequency noise time series, the average values of the original recordings at successive time intervals of 3000 reports calculated for each station — 1/2 minute time series are obtained for all 23 stations.

Eight of the seismic stations – PLOR, PLOR1, PLOR2, PLOR3, PLOR4, PLOR5, PLOR6 and PLOR7 (Local Ploeschina network), located in the epicentral region (average 20 km from the epicentres of the two earthquakes) of the Vrancea seismic zone, VRI and DRGR stations are located at distances of 30 and 450 km respectively from the earthquake epicentres. All ten listed seismic stations are part of the seismic network of Romania. The seismic stations PRD, AVR, BOZ, DOB, NEF, and ROIA, are part of the Provadia Local Seismic Network (LSN-Provadia). They are at an average distance of 400 km from the epicenters of the two earthquakes, the PSN, PVL, MPE, SZH, ORH and VLD seismic stations are part of the seismic network of Bulgaria and located at approximately 370 km, 430 km, 470 km, 380 km, 420 km and 460 km from the epicenters, respectively. The DJES seismic station is part of the seismic network of Serbia and is at approximately 470 km from the epicenters.

Table 1. Seismic stations used in the study. The last 3 columns represent the time intervals and the number of 24-hour seismic records, used in the research.

сеизм. станции	дигитайзер	геогр. дължина	геогр. ширина	надморско ниво	сензори	период 06.10.18 до 30.10.18 брой 24 ч. записи
AVR	DAS 9AF3	27,6685	43,1178	513	GEOPHON	24
BOZ	DAS 98B6	27,4786	43,1044	31	GEOPHON	24
DOB	DAS 9C9D	27,4628	43,1790	230	GEOPHON	24
PRD		27,4099	43,1602	128		24
NEF	DAS 986E	27,2753	43,2644	343	S13	24
ROIA	DAS 9913	27,3778	43,0934	353	GEOPHON	24
PSN	DAS A646	28,1359	43,6376	182	KS2000/60s	24
PVL	DAS 990C	25,1732	43,1227	210	CMG 3ESPC/120	24
MPE	DAS A625	23,7401	43,3560	342	S13	24
SZH	DAS 9901	25,9762	43,2653	329	CMG 3ESPC/120	24
ORH		23,9664	43,7263	231	S13	24
VLD		23,4356	43,6899	95	S13	24
VRI	Altus-K2	26,2764	45,8665	472	CMG3ESP	24
DRGR	Altus-K2	22,7111	46,7917	921	KS54000	24
PLOR	Q330	45,8512	26,6498	680	STS2	24
PLOR1	Q330	26,6466	45,8520	706	CMG-40T	24
PLOR2	Q330	26,6437	45,8502	702	CMG-40T	24
PLOR3	Q330	26,6454	45,8539	722	CMG-40T	24
PLOR4	Q330	26,6498	45,8512	730	CMG-40T	24
PLOR5	Q330	26,6635	45,8455	720	CMG-40T	24
PLOR6	Q330	26,6415	45,8419	720	CMG-40T	24
PLOR7	Q330	26,6405	45,8603	831	CMG-40T	24
						552

With the used methodology, three informative fractal statistics are estimated at consecutive time intervals of 2880 report (1 day) for 1/2-minute time series for each station. The estimation of the values of the noise statistics is made after the separation of the low-frequency trend using an 8th-order polynomial. Trend filtering is required to eliminate the effects of tidal and temperature deformations of the Earth's crust in the seismic noise variations and also represents a necessary procedure for studying the noise's statistical characteristics. The usage of an orthogonal polynomial enables the stability of the trend evaluations at the reading points. In this case, the order of the polynomial (8th) was chosen as the smallest one after numerical experiments, thus allowing the elimination of the day-to-day variations for the intervals of one-day duration (Lyubushin, A. A. 2007). The question of the regularity of the transition in such a low-frequency domain of seismic signal recordings naturally arises.

It should be noted that the development of broadband seismological apparatus did not consider its use for continuous seismic recording over a more extensive frequency range beyond the earthquake signal frequencies, and is not assumed that seismic sensors could also be used as the usual inclinometer, i.e., to register the change of signal in the tidal band frequencies. Following numerical experiments (Lyubushin A. A, 2008), we believe that in solving geophysical monitoring tasks and investigating earthquake preparation processes, there is a theoretical possibility for broader use of broadband seismological equipment that exceeds the formal operating frequency limitations, which is traditionally used to study individual earthquakes. Fig. 2 shows the graphs, illustrating this consideration. Continuous, uninterrupted seismic noise recordings of the taken eight stations and a 1-hour discretization step are made. From the initial recordings at a sampling rate of 100 Hz, the average value was calculated at consecutive time intervals with a length of 360,000 reports, which is 1 hour. In this way, the traditional for gravimetry frequency range is provided. If adhering to the traditional view of such a procedure, the transition to an hourly discretization step seems unacceptable. The graphs of the time series of Fig. 1a in their behavior do not differ externally from similar graphs of the readings of the inclinometers.

Moreover, if we look at the power spectra of the temporal variations of the seismic noise, recorded with the instrumentation used (Table 1), we see the manifestation of tidal 12 and 24-hour spectral extremum, even separation of different tidal harmonics at sufficient length of time series. This example shows that the signal, recorded with modern broadband seismometers, contains low-frequency components, significantly exceeding the formal limits, specified in their technical passports by the manufacturer. It is these undocumented and poorly understood capabilities of broadband seismometers that could be used in this study.

It should also be pointed out that all of the used noise statistics are dimensionless and do not depend on the scale of the output data. That significantly reduces their dependence on the fact that different seismometers have been installed at the seismic stations.

Results

The interest towards the positive value of the Hurst exponent estimate (H > 0) is related to the fact that for self-similar processes it is in the interval $0 < H < 1$ (Kantelhardt, Jan W., et al., 2002). Therefore, H (τ) > 0 represents a sign of self-similar fractal behavior of low-frequency seismic noise, indirectly. It is of our interest to separate those time windows, as for all simultaneously analyzed processes, the Hurst exponent is positive, which is a sign of low-frequency synchronization – a possible sign of a future earthquake.

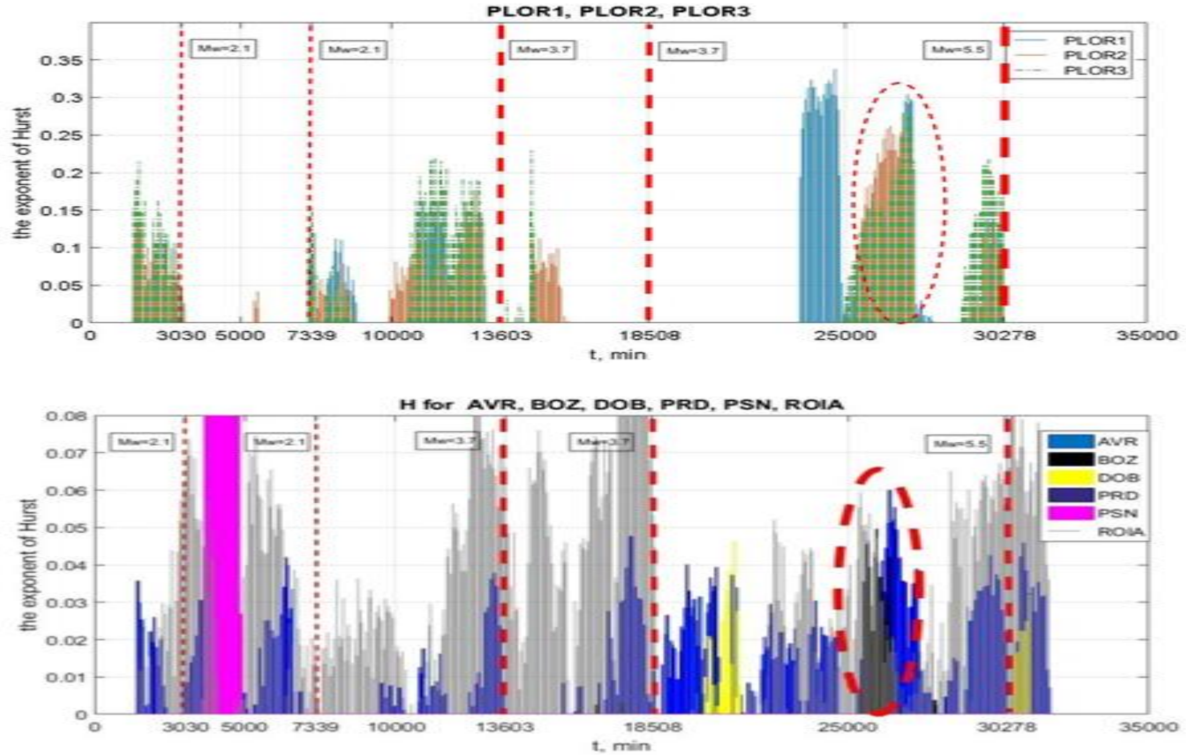

Fig. 2. Graphs of the change in the Hearst (H) metric for different stations combination, calculated in a time window 1 day and 1 hour displacemen; the red dotted line shows the moment of the earthquake - 28.10.2018 (Vrancha, 00:38:15; 45.7 / 26.4; M = 5.5) and the earthquakes that occurred in the analysed area

The results obtained show that 2 to 4 days before the earthquake on October 28, 2018, with Mw = 5.5 and 2 to 3 days before the earthquake on October 18.2018 with MW = 3.7, the Hurst index has a high value (Fig. 2).

The parameter $\Delta\alpha = \alpha_{max} - \alpha_{min}$ (Feder E., 1991), also called the width of the singularity spectrum, represents one of the important multifractal characteristics and assessments for the variety of random signal behavior. The statistically significant decrease in the average value of Δα reflects the decrease in the degrees of system's freedom, generating a signal and thus enables the determination of the time of preparation of an earthquake.

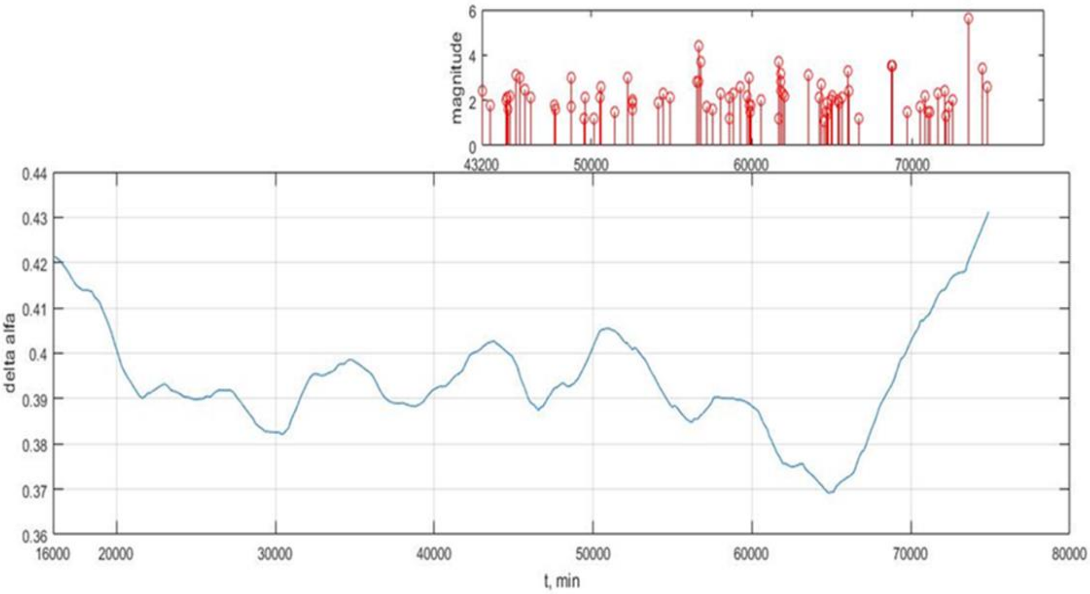

Fig. 3. Diagram of the mean values of parameter Δα, for stations - DJES, DOB, DRGR, MPE, ORH, PVL, SZH, VLD, VRI, between 06.09 and 28.10.2018. Combined with the graphs of all the earthquakes that occurred in the Balkan Peninsula in the period 06.10–28.10.2018.

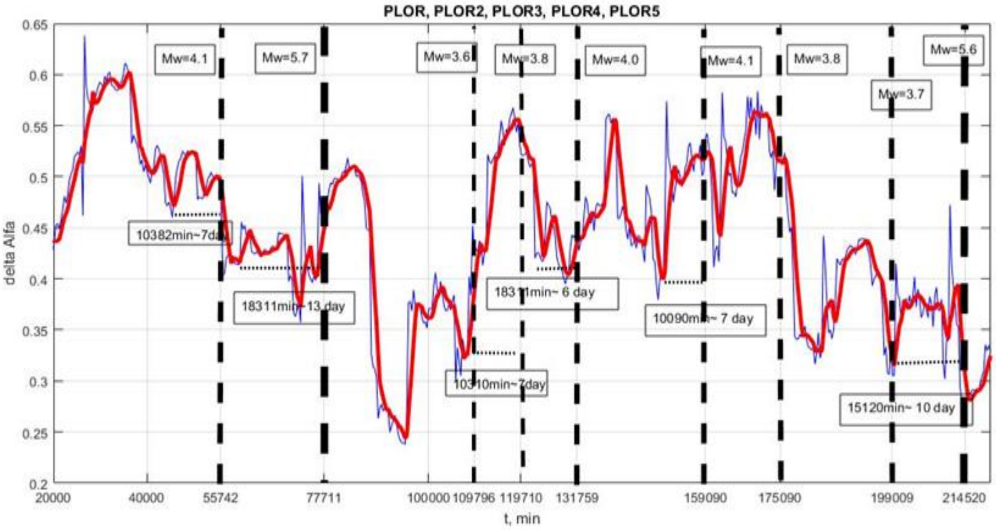

Fig. 4. Graph of the average values of the parameter Δα, for stations from the local area network Ploeschina. The dashed line indicates all earthquakes, occurrences in the analyzed area for the period. The beginning of the abscissa is 06.10.2018–00:00 hours (GMT).

Fig. 3 and 4 presents a graph of the overall assessment of the parameter Δα for stations DJES, DOB, DRGR, MPE, ORH, PVL, SZH, VLD, VRI, and all stations on the network PLOR (i.e., the average value of Δα). For each station, Δα is calculated in consecutive non-intersecting windows with a length of 24 hours and a shift of 1 hour over the entire time interval (01.08–30.12.2016, 22 days), after which the average value for the local area network is obtained. One feature of the smoothed Δα schedule are the minimums in the 59400 and 199700 minutes, 13 and 10 days before the earthquakes on 23.09.2016 and 27.12.2016. The other earthquakes in the analyzed time interval are preceded by a minimum of the width index of the singularity spectrum from 6 to 7 days. We may also note a large minimum of Δα at 95040 minutes, which precedes the earthquakes at 109796, 119710, and 131759 minutes, and can be assumed to be related to them.

For assessing the synchronization effects of the results, measuring of the low-frequency microseismic background for several seismic stations, is used the spectral measure of coherence, proposed by Lyubushin (1998). It is constructed as a module of the product of the component canonical coherence.

(8) $$\lambda(\tau,\omega) = \prod_{j=1}^{m} |\upsilon_j(\tau,\omega)|,$$

where $m \geq 2$ is the total number of jointly analyzed time series (the dimension of the multidimensional time series), ω is the frequency, τ is the time coordinate of the right edge of the scandent time window, $\upsilon_j(\tau,\omega)$ is the canonical coherence of the jth scalar time row that describes the relationship between that row and the other ones. The inequality $0 \leq |\upsilon_j(\tau,\omega)| \leq 1$ is satisfied. The closer the value of $|\upsilon_j(\tau,\omega)|$ is to one, the higher linearly are connected the variations of the jth order of frequency ω in the time window with coordinate τ to the similar variations in other lines studied. Accordingly, measure $0 \leq \lambda(\tau,\omega) \leq 1$ describes the effect of the overall coherent (synchronous, collective) behavior of all signals.

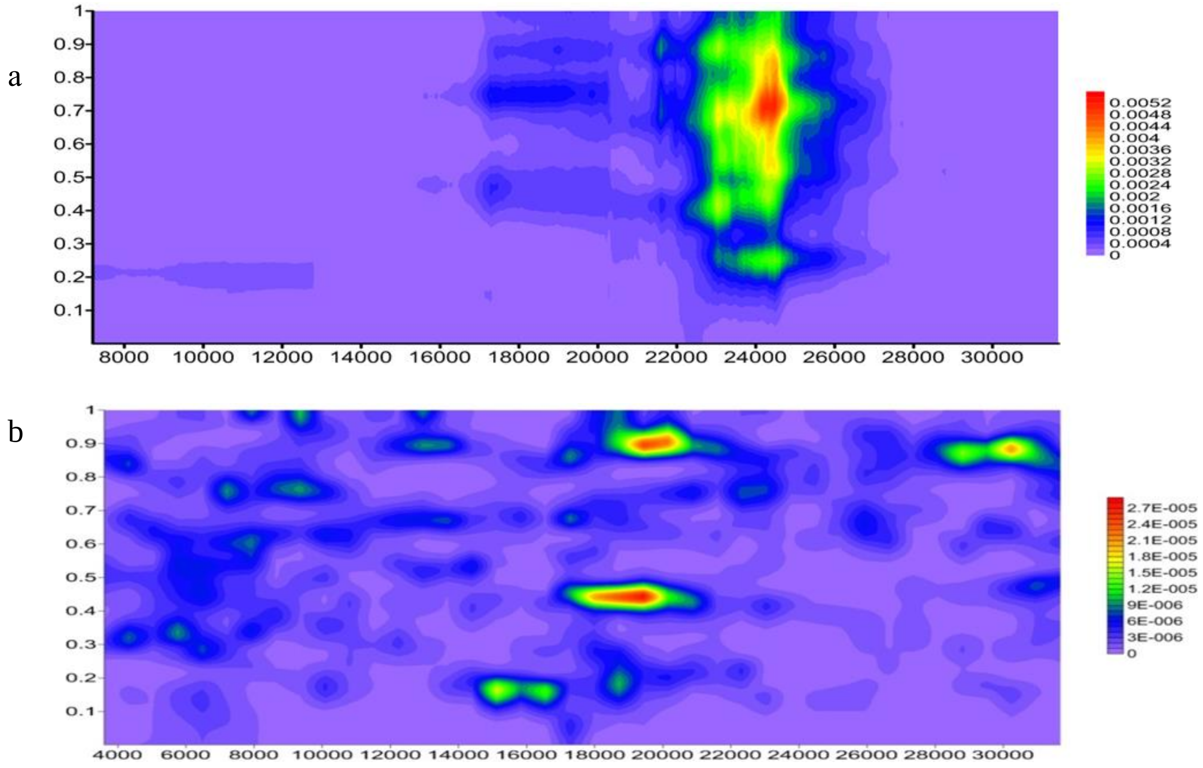

Fig. 5. Frequency-time diagram of the evolution of λ (τ, ω) (spectral measure of coherent behaviour) for PLOR1-PLOR7 stations a); end MPE; NEF; ORH; PSN; PVL; ROIA; SZH ; VLD stations b).

Fig. 5 a) shows the behaviour of the spectral measure of coherent behaviour λ(τ, ω) of the seismic signal for stations PLOR1-PLOR7, in a time window 20160 half minute reports (7 days) with 720 reports (6 hours) shift for the time interval 06.09.2018–30.10.2018 (the abscissa timestamps indicate the right end of the time window). From the result we can conclude that the signal synchronization of all stations has a maximum of all frequencies in 24000 minutes, which is ~ 5 days before the earthquake which is in 30278 minutes (28.10.18, Mw = 5.5) and b) shows the behaviour of the spectral measure of coherent behaviour λ(τ, ω) of the seismic signal for stations MPE; NEF; ORH; PSN; PVL; ROIA; SZH ; VLD. From the result we can conclude that the signal synchronization of all stations has a maximum from 19000 to 21000 minutes, which is ~ 9 to 7 days before the earthquake..

Conclusion

An attempt to predict strong earthquakes shows insufficient reliability of forecasts only on seismic catalogues. To increase the effectiveness of traditional forecasting methods, they need to be supplemented by analysing the multi-dimensional uninterrupted data flow of monitoring networks.

The search for qualitatively new earthquake predictors such as the effect of increasing synchronization (coherent behaviour) of scalar components of multi-dimensional time series of monitoring systems is one of the most pervasive directions in earthquake forecasting.
It is necessary to develop and improve software that can simultaneously analyse hundreds of hundreds of millions of reports in each signal.

Acknowledgements

This study has been carried out within the framework of the National Scientific Program "Young Scientists and Postdoctoral Fellows", approved by Council of Ministers Decision No 11/ 17.08.2018 and the project “Exploration of changes in some geophysical fields preceding the occurrence of earthquakes in the Balkans”, Grant DN 14-1/11.12.2017, financed by Bulgarian National Science Fund.

References:

1. Любушин, А. А. "Модель сейсмического процесса в блоковой среде." Современные методы интерпретации сейсмологических данных. (*Вычислительная сейсмология*, выпуск 24). М., *Наука*, 1991.
2. Любушин, А. А. Анализ данных систем геофизического и экологического мониторинга. *Наука*, 2007.
3. Ойнаков, Е., Александрова, И., **–** Сеизмични характеристики на земетресението от 28.10.2018 г., генерирано в сеизмогенна област Вранча, Румъния. *Проблеми на географията*, Книга 1, София 2019.
4. Benoit, B., B. B. Mandelbrot, J.W. van Ness. 1968. Fractional Brownian Motions, Fractional Noises and Applications. SIAM Review, Vol. 10, No. 4 : pp. 422–437.
5. Feder, J. 1988. Fractals. Plenum, New York.
6. Feder, E**.** 1991. Fractals. M.: Mir, 254 p. (Ru)
7. Huang, K. 1967. Statistical Mechanics. John Wiley & Sons, New York.
8. Hurst, H. E. 1951. Long-term storage capacity of reservoirs. Trans. Am. Soc. Eng. 116, 770-99. Kac, M. & Pollard, H. (1950). The distribution of the maximum of partial sums of independent random variables. Can. J. Math. 2, 375–384.
9. Kantelhardt, J. W., S. A. Zschiegner, E. Konscienly-Bunde, S. Havlin, A. Bunde, H.E. Stanley. 2002. Multifractal detrended fluctuation analysis of nonstationary time series // Physica A. № 316.
10. Kantelhardt, J. W., R. Sven et al. 2002. Fuc (α1→ 3) GalNAc-: the major antigenic motif of Schistosoma mansoni glycolipids implicated in infection sera and keyhole-limpet haemocyanin cross-reactivity. *Biochemical Journal*, 366.1 (2002): 217–223.
11. Lyubushin, A. A. G. A. Sobolev. 2006. Multifractal Measures of Synchronization of Microseismic Oscillations in a Minute Range of Periods, Fiz. Zemli, no. 9, pp. 18–28 [Izv. Phys. Earth (Engl. Transl.), 2006, vol. 42, no. 9, pp. 734–744.
12. Lyubushin, A. A. 2008. Microseismic Noise in the Low Frequency Range (Periods of 1–300 min): Properties and Possible Prognostic Features, Fiz. Zemli, no. 4, pp. 17–34 [Izv. Phys. Earth (Engl. Transl.), 2008, vol. 44, no. 4, pp. 275–290].
13. Mandelbrot, B. B., J.R. Wallis. 1969. Water Resources Research.
14. Mandelbrot, B. B. 1982. Fractal Geometry of Nature, Freeman, San Francisco.