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ORIGINAL ARTICLE

Discrimination of earthquakes and explosions using multi-fractal singularity spectrums properties

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Abstract A new method of discrimination of seismic records from earthquakes and explosions is proposed which is based on using properties of their multi-fractal singularity spectrums. The efficiency of the method is illustrated by analysing seismic records from the region of Aswan Dam in Egypt. Current pattern of seismicity in the Upper Egypt is composed by three types of records: tectonic earthquakes, reservoir-induced earthquakes and seismic events generated by quarry blasts. To discriminate quarry blasts from earthquakes of both natures, multi-fractal analysis of records were used. Singularity spectrum support width and multi-fractal generalised Hurst exponents were calculated for all seismic events in the selected data set from a given area. The linear Bayesian discriminator using these characteristics of seismic records provides correct classification for 93 % of earthquakes records and for 99 % of quarry blasts records.

Keywords Multi-fractal parameters · Singularity spectrum · Bayesian discriminator · Aswan Dam · Upper Egypt · Seismic event discrimination

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1 Introduction

Classification of recorded seismic events is one of the most frequent problems for seismologists in observatories around the world. Separation of artificial events, first of all nuclear blasts and explosions in quarries, and natural earthquakes is solved with different degree of reliability. This problem occurs especially in countries where the database of quarries is incomplete. This problem of seismic records discrimination is rather interesting from the point of view of signal analysis. A variety of waveform-based discrimination methods have been developed and investigated over the last five decades (see Stump et al. 2002 for a recent review). These methods can be roughly divided into (1) determining amplitude ratios between seismic phases (Dahy 1997), (2) spectral methods (Dahy and Hassib 2010) and (3) coda studies (Allmann et al. 2008).

Problem of discrimination between explosions in quarries and earthquakes is also solved in records provided by seismic networks operated by National Research Institute of Astronomy and Geophysics, Helwan, Cairo, and Aswan Earthquake Research Center, Aswan, Egypt (see Fig. 1). It is possible to present as examples the discrimination quarry blasts from earthquakes using amplitude ratio of P and S waves (Dahy 1997). A simple method using spectral analyses of records was tested for fast decision in Haggag et al. (2008a). The main difference was found in a narrow interval of low values of frequency from a broadband spectrum of explosions and earthquakes (Haggag et al. 2008b). Similar results were obtained by Dahy and Hassib (2010) who also documented the discrimination between natural earthquakes and quarry blasts at regional distances using spectra of records.

Here, we propose a new method for solving the seismic discrimination problem which is based on using two parameters of their multi-fractal singularity spectrums. The method turns to be rather fast and it does not require preliminary seeking for the working frequency bands, which usually is one of the main problems and necessary to solve before the discrimination. The test set consists of data from the vicinity of Aswan reservoir in the Upper Egypt recorded at seismic stations of two local networks.

2 Seismicity in Egypt

Analysing the earthquake catalogue of the Upper Egypt area since 1982, some interesting characteristics of seismicity were found. Seismic activity is concentrated in different seismic zones from the east to the west. Construction of a seismicity map according to the seismicity level in Upper Egypt showed 14 seismic zones, and the seismic activity is intense around the strait of the Gulf of Suez, along the Red Sea axis, Abu Dabbab and the Aswan area (Haggag et al. 2008a). This zone map shows higher activity from the Red Sea towards the Nile River and Aswan area, while it is lower in the west and very low in the far west, partially due to the lack of seismic stations that can monitor small magnitude events in far areas.

The detailed study of Aswan area shows eight seismic zones and the activity is concentrated in and around the Gable Marawa area. Wider surroundings of the southern part of Aswan High Dam are known as a low natural seismicity natural region from historical data. After the main shock of November 14, 1981 with a magnitude 5.3, it was of great importance to monitor and to study the seismic activity in this area, particularly for the safety and stability of the Aswan High Dam. Therefore, the first regional seismic stations were installed since 1982; later, this network was completed and reconstructed. More detailed information about the Aswan seismic network and local seismicity can be obtained from several papers (Kebeasy et al. 1987; Mohamed 1997; Selim et al. 2002; Dahy and Hassib 2010). The main purpose of this network was to monitor the seismic activity along the Kalabsha fault which crosses the whole area. The activity in Kalabsha area in general can be also divided according to the focal depth into two seismic zones with different focal depths as follows: a zone with focal depth less than 12 km and another one with focal depth greater than 12 km (Haggag et al. 2008a).

3 Description of elaborated data set

All data used in this investigation are taken from the records of both networks mentioned in Fig. 1. Data from four seismic stations (ADN, KFR, MSM and SGH) of the Tushka network (Egyptian national seismic network) located near Aswan reservoir are used; data from Aswan seismic network (Fig. 1). In 2004–2007, seismic recorders by Nanometrics Inc. with SS1 sensors were operated the most. Many of these seismic stations recorded only vertical component of ground velocity; therefore, only this component was selected for mathematical analysis. In the monitoring period, 12 earthquakes and 10 quarry blasts from 2004 till 2007 were selected for compiling the wave pattern data set. The database set of wave patterns consists of 68 records of earthquakes and

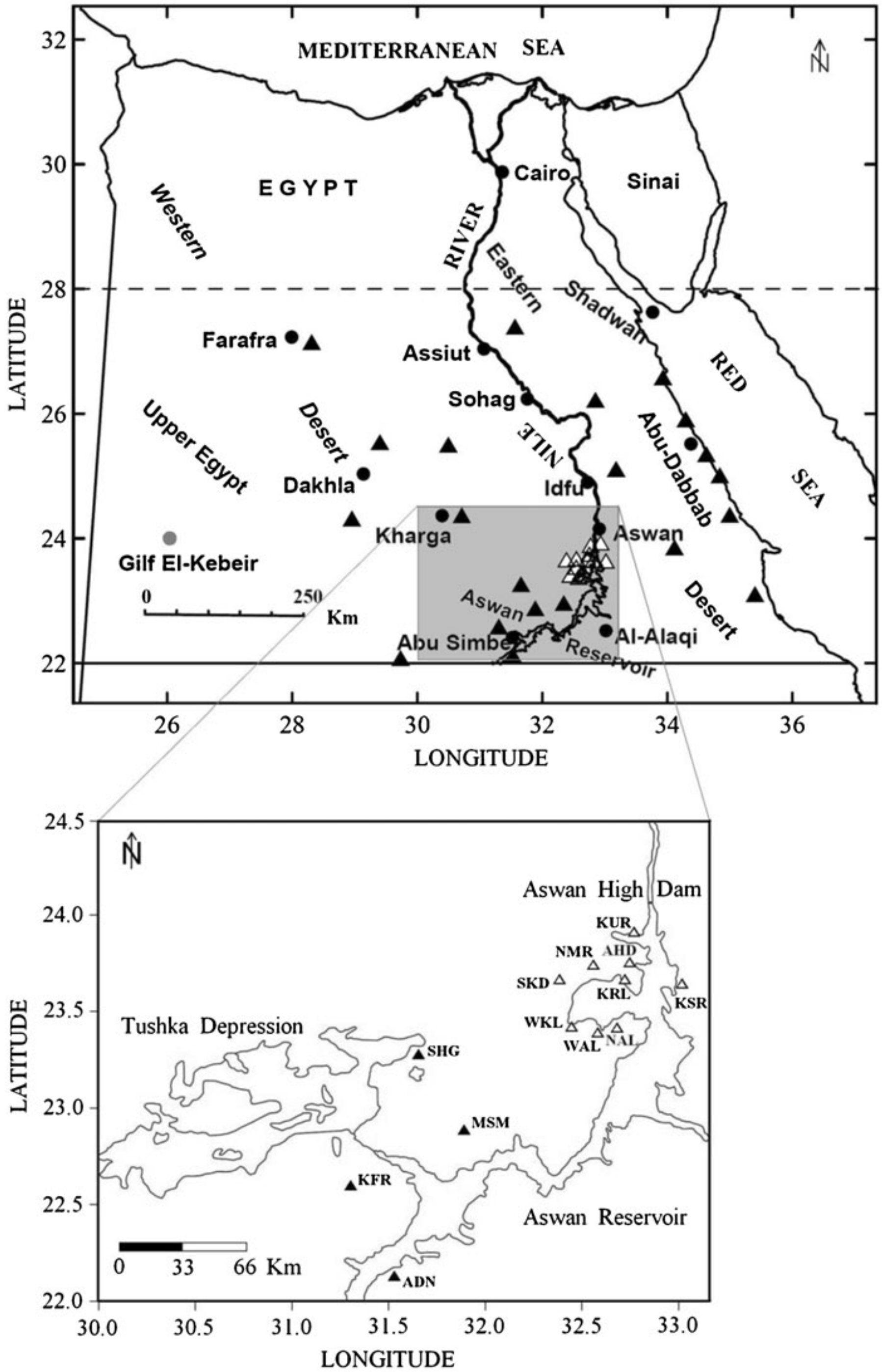

Fig. 1 Location map of the Upper Egypt area, Tushka seismic network (*black triangle*) and Aswan seismic network (*empty triangle*), according Haggag et al. (2008a)

75 records of explosions in quarries recorded on above-mentioned seismic stations (database owner is Aswan Earthquake Research Center). Tables 1 and 2 contain information about used seismic events waveforms.

4 Singularity spectrums of seismic records

Let $X(t)$ be a random process. Define the range $\mu_X(t,\delta) = \max_{t \le s \le t+\delta} X(s) - \min_{t \le s \le t+\delta} X(s)$ as the measure $\mu_X(t, \delta)$ of the behaviour of the signal $X(t)$ in the

Table 1 Information about 12 earthquakes

Serial no.	Date_time (GMT)	Latitude, N, deg	Longitude, E, deg	Magnitude, m_b	Number of waveforms
1	13 Jan 2004_12:13:00.0024	22.05	31.58	4.2	13
2	06 June 2004_17:45:00.0001	22.84	31.44	1.6	1
3	28 July 2004_20:22:10.0001	22.71	31.54	1.2	2
4	02 Aug 2004_08:06:00.0001	22.23	31.65	2.1	6
5	30 Aug 2004_14:24:00.0001	22.11	31.64	2.2	6
6	20 Dec 2004_08:18:00.0001	22.07	31.66	2.7	2
7	25 Feb 2007_12:28:40.0001	22.15	31.24	3.6	10
8	23 March 2007_22:36:20.0001	21.88	31.60	2.6	5
9	17 May 2007_16:02:20.0001	22.63	31.35	1.7	5
10	17 May 2007_22:10:00.0001	22.13	31.25	2.0	5
11	25 Aug 2007_12:39:50.0001	22.18	31.34	2.0	5
12	19 Sept 2007_03:55:00.0001	22.05	31.65	1.5	8

interval $[t, t+\delta]$ and calculate the average modulus of such measures raised to the power q:

$$M(\delta, q) = M\{(\mu_X(t, \delta))^q\} \qquad (1)$$

A random process is scale-invariant, if $M(\delta, q) \sim |\delta|^{k(q)}$, i.e., there exists the limit:

$$\kappa(q) = \lim_{\delta \to 0} \frac{\ln M(\delta, q)}{\ln|\delta|} \qquad (2)$$

If the dependence $\kappa(q)$ is linear, $\kappa(q)=Hq$, where H=const, $0<H<1$, then the process is mono-fractal (Taqqu 1988).

For calculating the function $\kappa(q)$ from a finite sampling from the time series $X(t)$, $t=1, \ldots, N$, it is possible to apply the detrended fluctuation analysis method (Kantelhardt et al. 2002). Let s be the number of samples associated with the varied scale δ_s: $\delta_s = s \cdot \Delta t$. We divide the sampling into non-overlapping small intervals s samples in length,

$$I_k^{(s)} = \{t : \; 1 + (k-1) \cdot s \leq t \leq k \cdot s, \quad k = 1, \ldots, [N/s]\} \qquad (3)$$

and let

$$y_k^{(s)}(t) = X((k-1)s + t), \quad t = 1, \ldots, s \qquad (4)$$

be the part of the time series $X(t)$ corresponding to the interval $I_k^{(s)}$. Let $p_k^{(s,m)}(t)$ be a polynomial of order m fitted by the least squares method to the

Table 2 Information about 10 explosions

Serial no.	Date_time (GMT)	Latitude, N, deg	Longitude, E, deg	Magnitude, m_b	Number of waveforms
1	21 Feb 2007_06:01:00.0044	23.02	31.43	1.1	4
2	22 Feb 2007_07:03:25.0001	23.12	31.43	2.0	6
3	22 Feb 2007_09:41:50.0001	23.09	31.42	1.3	6
4	05 April 2007_09:37:00.0001	23.08	31.46	2.1	10
5	07 April 2007_07:42:00.0001	23.08	31.44	2.3	8
6	20 May 2007_10:49:00.0001	23.08	31.46	2.1	6
7	27 May 2007_07:05:30.0001	23.08	31.44	2.6	9
8	12 June 2007_07:42:50.0001	23.08	31.44	2.6	10
9	19 June 2007_07:33:00.0001	23.08	31.40	2.3	8
10	23 June 2007_05:53:00.0001	23.01	31.46	2.1	8

signal $y_k^{(s)}(t)$. Consider deviations from the local trend

$$\Delta y_k^{(s,m)}(t) = y_k^{(s)}(t) - p_k^{(s,m)}(t), \quad t = 1, \ldots, s \tag{5}$$

and calculate the value

$$Z^{(m)}(q,s) = \left(\sum_{k=1z}^{[N/s]} \left(\max_{1 \le t \le s} \Delta y_k^{(s,m)}(t) - \min_{1 \le t \le s} \Delta y_k^{(s,m)}(t) \right)^q / [N/s] \right)^{1/q} \tag{6}$$

which will be regarded as an estimate for $(M(\delta_s, q))^{1/q}$. Now, we will define the function $h(q)$ as the coefficient of linear regression between the values ln $(Z^{(m)}(q, s))$ and ln (s): $Z^{(m)}(q, s) \sim s^{h(q)}$. It is evident that $\kappa(q)=qh(q)$, and for a mono-fractal process $h(q)=H=$const.

After the determination of the function $h(q)$, the next step in the multi-fractal analysis (Feder 1989) is the calculation of the singularity spectrum $F(\alpha)$, which is the fractal dimension of the time moments τ_α, which have the same value of the local Holder–Lipschitz exponent: $\lambda(t) = \lim_{\delta \to 0} \frac{\ln(\mu(t,\delta))}{\ln(\delta)}$, i.e. $\lambda(\tau_\alpha)=\alpha$. The standard approach consists in the calculation of the Gibbs statistical sum

$$W(q,s) = \sum_{k=1}^{[N/s]} \left(\max_{1 \le t \le s} \Delta y_k^{(s,m)}(t) - \min_{1 \le t \le s} \Delta y_k^{(s,m)}(t) \right)^q \tag{7}$$

and the determination of the mass indicator $\tau(q)$ from the condition $W(q, s) \sim s^{\tau(q)}$, after which the spectrum $F(\alpha)$ is calculated by the formula

$$F(\alpha) = \max \left\{ \min_q (\alpha q - \tau(q)),\ 0 \right\} \tag{8}$$

Comparing (6) and (7), it is easy to see that $\tau(q)=\kappa(q)-1=qh(q)-1$.

Thus, $F(\alpha) = \max \left\{ \min_q (q(\alpha - h(q)) + 1,\ 0 \right\}$.

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^* $\left(F(\alpha^*) = \max_\alpha F(\alpha)\right)$ are the characteristics of noise. The quantity α^* is called the generalised Hurst exponent. For a mono-fractal signal, the value of $\Delta\alpha$ must be 0, and $\alpha^*=H$. Usually, $F(\alpha^*)=1$, but there exist windows, for which $F(\alpha^*)<1$. In the general case, $F(\alpha^*)$ is equal to the fractal dimension of the multi-fractal measure support (Feder 1989).

In the calculation of $\Delta\alpha$ and α^*, we were guided by the following considerations. The exponent q was varied within the interval $q \in [-Q, +Q]$, where Q is a certain sufficiently large number, for example, $Q=10$. For each value of α within the interval $\alpha \in [A_{\min}, A_{\max}]$, where $A_{\min} = \min_{q \in [-Q,+Q]} \frac{d\tau(q)}{dq}$, and $A_{\max} = \max_{q \in [-Q,+Q]} \frac{d\tau(q)}{dq}$, we calculated the value $\tilde{F}(\alpha) = \min_{q \in [-Q,+Q]} (\alpha q - \tau(q))$. If the value of α is close to $A_{\min}$ then $\tilde{F}(\alpha) < 0$, and this value is unsuitable as an estimate of the singularity spectrum, which must be non-negative. However, beginning from a certain α, the value $\tilde{F}(\alpha)$ becomes non-negative, and this condition defines the $\alpha_{\min}$ value. At a further α increase, the value $\tilde{F}(\alpha)$ increases, reaches its maximum when $\alpha=\alpha^*$, then begins to decrease, and finally, attains a certain value $\alpha_{\max}<A_{\max}$, at which $\tilde{F}(\alpha)$ again becomes negative, if $\alpha>\alpha_{\max}$. Thus, $F(\alpha) = \tilde{F}(\alpha)$ provided that $\tilde{F}(\alpha) \ge 0$, which determines the interval of the singularity spectrum support $\alpha \in [\alpha_{\min}, \alpha_{\max}]$. The derivative $\frac{d\tau(q)}{dq}$ is calculated numerically from the values $\tau(q)$, $q \in [-Q, +Q]$, and the accuracy of its calculation is of little significance because this derivative is used for a rough determination of an a priori interval of possible exponents q. Usually, local trends (formula (5)) are removed by polynomials of some order which is more than 1. Here, we take the minimum order 0, i.e. local mean values were removed only. This order turns to be the better choice for discrimination of blasts and earthquakes. Minimum value of scale s within formula (6) had chosen 20 samples, maximum scale equals $N/5$.

The singularity spectrum $F(\alpha)$ could be characterised by the following parameters: $\alpha_{\min}$, $\alpha_{\max}$, $\alpha = \alpha_{\max} - \alpha_{\min}$ and α^*—argument providing maximum to singularity spectra, $F\left(\alpha^*\right) = \max_\alpha F(\alpha)$. Parameter α^* could be called a generalised Hurst exponent and it gives the most typical value of Lipschitz–Holder exponent. Parameter $\Delta\alpha$ could be regarded as a measure of variety of stochastic behaviour. It should be noticed that usually $F(\alpha^*)=1$—maximum of singularity spectra equals to the dimensionality of an embedding set, i.e. to dimensionality of time interval.

Earlier, the estimates of multi-fractal singularity spectra for geophysical time series were used in Currenti et al. (2005), Ramirez-Rojas et al. (2004)

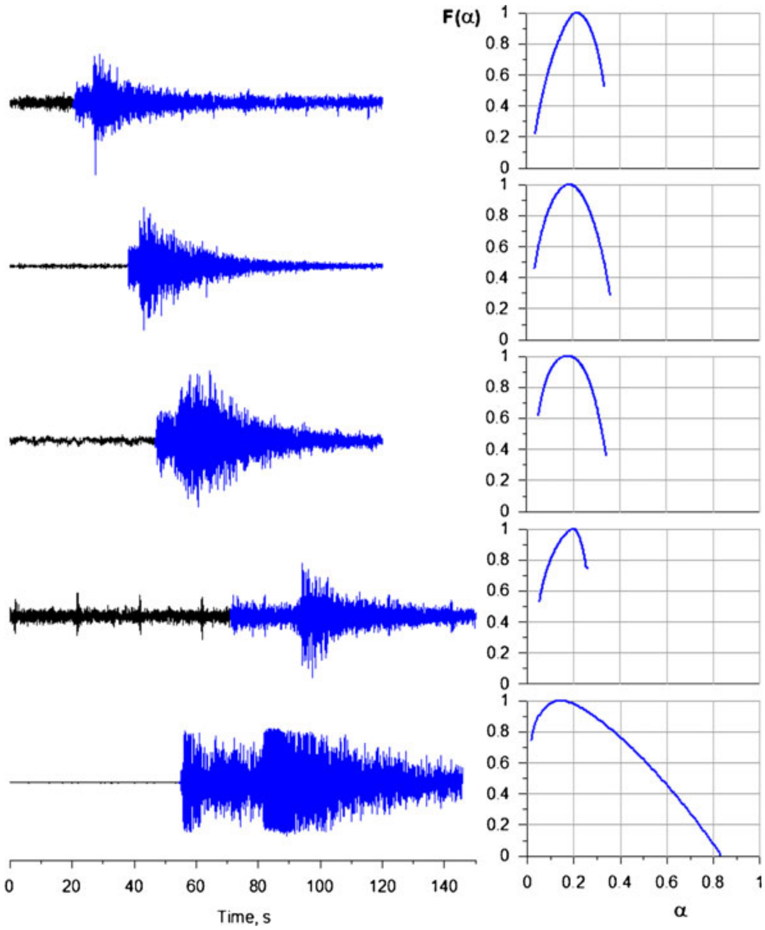

Fig. 2 *Left-hand panel* of graphics presents earthquakes waveforms, *blue lines* correspond to the parts of waveforms after P wave onsets for which multi-fractal singularity spectrums are estimated (*right-hand panel* of graphics)

and Telesca et al. (2005). The multi-fractal analysis of low-frequency seismic noise waveforms from broadband seismic network F-net in Japan for the period from the beginning of 1997 up to the middle of May 2012 was performed in the papers (Lyubushin 2009, 2010, 2012). It was shown that decreasing of multi-fractal singularity spectrum support width $\Delta\alpha$ ("the loss of multi-fractality") is a precursor which allows to make a prediction of the Great Japanese earthquake 11 of March 2011, and creating maps of spatial distribution of $\Delta\alpha$ within moving time window provides a new tool for dynamic estimate of seismic hazard. These results (with all references concerning the history of prediction publications since the middle of 2008) are summarised in the paper (Lyubushin 2012). In the paper (Lyubushin et al. 2012), the multi-fractal analysis of geomechanical monitoring time series was applied for its fragmentation into intervals with different behaviour.

Figures 2 and 3 present examples of graphics of seismic records from earthquakes (Fig. 2) and explosions (Fig. 3) in parallel with graphics of their multi-fractal singularity spectra estimates by the method which was described above. The signal to noise ratio (defined as the ratio of variance after P wave onset to the variance before the onset) for the seismic records varies from 1.5 up to few hundreds.

5 Result of multi-fractal singularity spectra properties of the seismic records

Figure 4 presents the result of discrimination of earthquakes and industrial explosions seismic records by using their multi-fractal parameters.

Discrimination of earthquakes and quarry blasts on the 2D plane of parameters ($\Delta\alpha$, α^*) was performed using linear discriminator $\alpha^* = u \cdot \Delta\alpha + w$ where (u, w) are

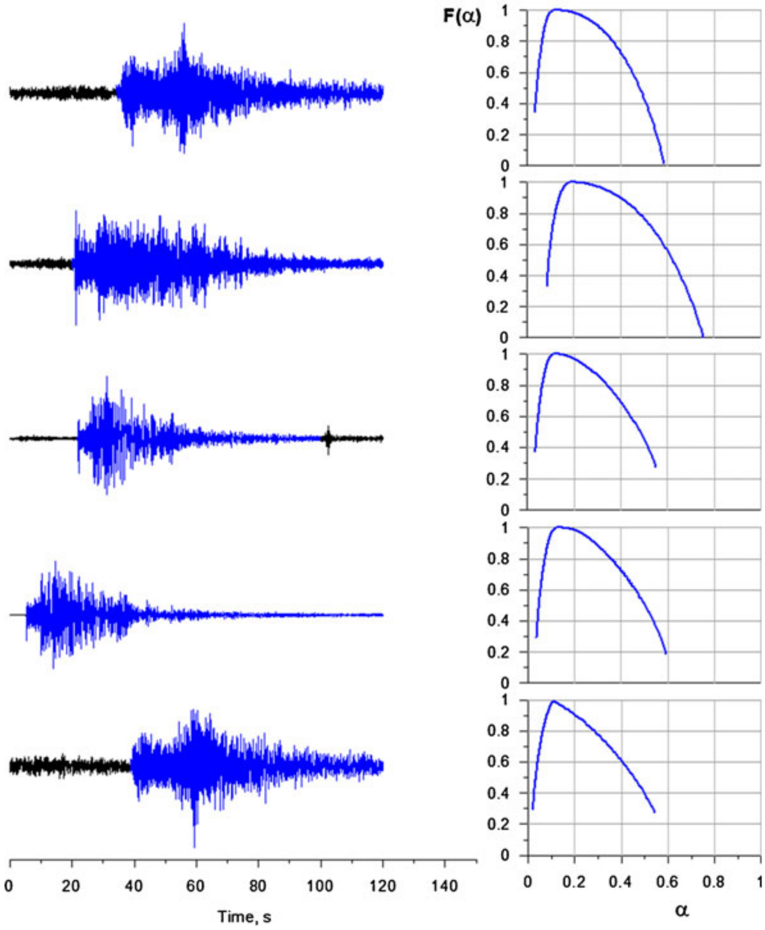

Fig. 3 *Left-hand panel* of graphics presents explosions waveforms, *blue lines* correspond to the parts of waveforms after P wave onsets for which multi-fractal singularity spectrums are estimated (*right-hand panel* of graphics)

unknown parameters which should be found from minimising Bayesian criterion (Duda and Hart 1973):

$$P^{(a)}_{\mathrm{EQ}} \cdot P^{(\mathrm{Err})}_{\mathrm{EQ}} + P^{(a)}_{\mathrm{EXP}} \cdot P^{(\mathrm{Err})}_{\mathrm{EXP}} \rightarrow \min_{u,w} \tag{9}$$

where:

$P^{(a)}_{\mathrm{EQ}} = \frac{N_{\mathrm{EQ}}}{(N_{\mathrm{EQ}}+N_{\mathrm{EXP}})} = 0.476$ is an a priori probability of earthquake records;

$P^{(a)}_{\mathrm{EXP}} = \frac{N_{\mathrm{EXP}}}{(N_{\mathrm{EQ}}+N_{\mathrm{EXP}})} = 0.524$ is an a priori probability of explosion records;

$N_{\mathrm{EXP}} = 75$, $N_{\mathrm{EQ}} = 68$ are the numbers of explosions and earthquakes records; and

$P^{(\mathrm{Err})}_{\mathrm{EQ}}$ and $P^{(\mathrm{Err})}_{\mathrm{EXP}}$ are probabilities of discrimination errors for earthquakes and explosions records for current values of parameters (u, w).

After minimising Bayesian criterion, the following parameters of linear discriminator were found: $u = 0.760$, $w = -0.236$. This linear discriminator provides correct classification for 93 % of earthquakes records and for 99 % of explosions records. Results are presented at the Fig. 4.

6 Discussion

Many authors and papers deal with solution of wave patterns discrimination, especially in the case of earthquakes and quarry blasts (Allmann et al. 2008; Dahy 1997; Dahy and Hassib 2010; Haggag et al. 2008a, b; Kebeasy et al. 1987; Mohamed 1997; Selim et al. 2002; Stump et al. 2002). In this paper, multi-fractal singularity spectrum (Feder 1989) support width $\Delta\alpha$ and multi-fractal generalised Hurst exponents α^* were used for the discrimination of wave patterns recorded on the seismic stations in the vicinity of Aswan reservoir in the Upper Egypt. One of the positive feature of the proposed method is absence of necessity of preliminary seeking for working frequency bands which is necessary for traditional spectral methods of seismic

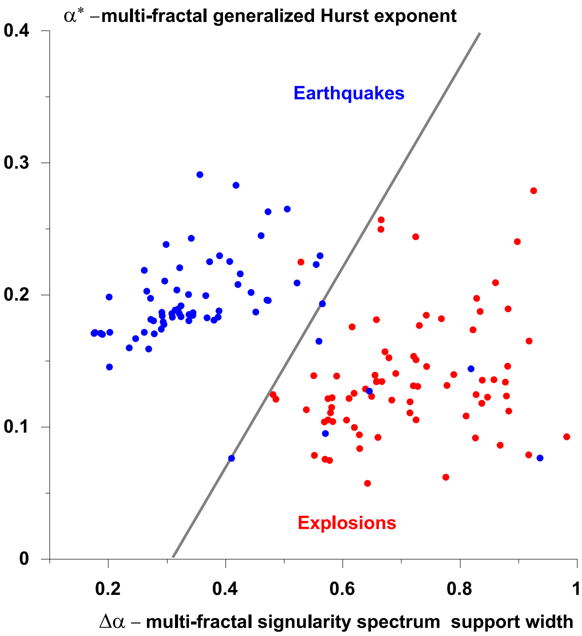

Fig. 4 Discrimination of earthquakes and quarry blasts. The discrimination line has an equation $\alpha^* = u \cdot \Delta\alpha + w$, where coefficients u=0.760, w=−0.236 were found from minimising Bayesian risk (formula (9))

records discrimination. Cross-diagram of $\Delta\alpha$ and α^* enables to discriminate records by minimising of linear Bayesian criterion into two parts that represent information from database about nature with high probability. This discriminator provides correct classification for 93 % of earthquakes records and for 99 % of explosions records.

The proposed discrimination method is quite new and we have not enough experience to claim that it is better than more traditional methods which are based on estimating power spectrums of seismic records. This method is proposed just as some alternative. The results of the experiment with seismic records of blasts and earthquakes from Upper Egypt provide some optimism that the method could be useful. A lot of questions must be answered before this method becomes a reliable tool for solving the discrimination problem. In particular, the choice of polynomial order for removing local trends within formula (5) turns to be rather important. This problem is known in the analysis of meteorological and hydrological data (Kantelhardt et al. 2002). The fact that the best result corresponds to the minimum polynomial order 0 is rather surprising and needs additional investigations and experiments.

The outliers of points at the Fig. 4 for earthquakes from discriminating line occur for the seismic records with high signal to noise ratio which contain "fresh" information about peculiarities of the process within seismic source. These records preserve information of different mechanisms of seismic waves radiation from earthquake source and they have a wide singularity

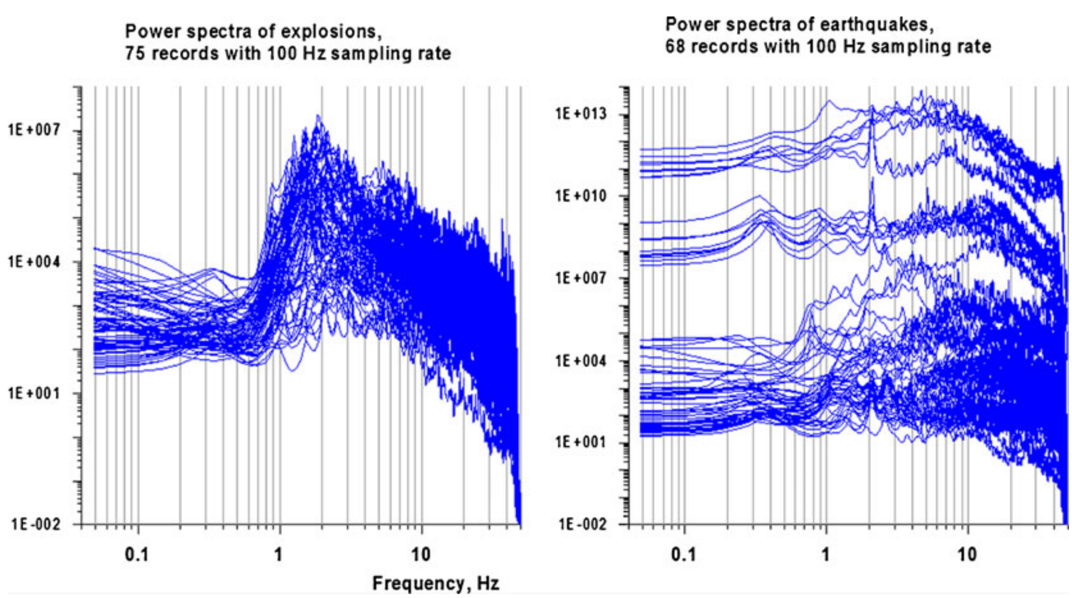

Fig. 5 *Left-hand panel* presents graphics of power spectra estimates for all seismic records from industrial explosions, whereas *right-hand panel* presents estimates of seismic records from earthquakes

spectrum support width what reflects a large variety of stochastic behaviour. In general, Fig. 4 illustrates that earthquakes seismic records are “less multi-fractal” (Lyubushin 2009, 2010, 2012), i.e. they have more simple stochastic structure than records from blasts.

Figure 5 presents graphics of power spectra estimates of all seismic records which were analysed in this paper. A glance view at these graphics confirms opinion that there must be physical meanings which could help to discriminate records from earthquakes and from industrial explosions. But the main difficulty in such analysis is to find formal quantitative parameters of the records which provide efficiency for such discrimination. We suppose that using of multi-fractal parameters could provide such tool.

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