Fractal ULF signatures related to seismic processes

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Abstract. In order to detect seismo-related patterns that manifest themselves in fractal properties of ULF magnetic field variations, the fractal and multifractal analyses of the ULF data obtained from several stations were performed. As a result, two different behaviors of fractal parameters of the ULF magnetic field variations were detected. The first one has the certain co-seismic character and manifests itself in significant increase in fractal dimension synchronous with the rise of seismic activity. Another pattern can be interpreted as a manifestation of the seismic preparation processes, which is characterized by the significant gradual decrease in fractal dimension during the extended time period of several months.

Also a new procedure of the local geomagnetic activity (LGA) level estimation was proposed. A correlation between the geomagnetic activity and the fractal dimension, and, consequently, the necessity of taking into a consideration the LGA level was demonstrated.

Key words: fractal analysis, ULF variations, seismo-electromagnetic patterns.

1. Introduction

The modern geophysics has several challenging problems. One of those important problems is a possibility to find out some reliable precursor signatures of strong seismic events, and the promising candidate as a role of such a process can be the seismo-electromagnetic coupling. During the last decades several different models describing such a kind of coupling were proposed by different researchers (Molchanov and Hayakawa, 1998, 2008; Molchanov, 1999; Surkov and Pilipenko, 1999; Surkov, 1999; Hayakawa and Molchanov, 2002; Hattori, 2004).

The most promising frequency range of seismogenic emissions is supposed to be ULF because ULF emissions originated from different processes in the focal zone can reach the Earth's surface from the focal depths of several tens kilometers. Different parameters of the ULF signals could be analyzed: polarization ratio, power spectrum, fractal dimension (Hayakawa et al., 1996, 1999; Hattori et al., 2002, 2004; Gotoh et al., 2003; Smirnova et al., 2004; Ida et al., 2005; Ida and Hayakawa, 2006; Molchanov and Hayakawa, 2008).

Hayakawa et al. (1999) carried out the first attempt of fractal analysis for the 1993 Guam earthquake by means of the frequency spectrum slope estimation. Later Smirnova et al. (2004), Gotoh et al. (2004) and Ida et al. (2006) have developed different kinds of fractal estimations and also have extended them from the mono to multifractal analyses (Ida and Hayakawa, 2005). Nevertheless, the number of events analyzed is extremely small, so that we need to increase the amount of analyzed events in order to obtain certain patterns or concrete precursor signatures of earthquakes. In this sense we have performed the fractal analysis of ULF data from several Japanese ULF stations in order to detect any seismo-related patterns and to classify them.

In our analysis we have used the most complete ULF data (with minimal amount of gaps) from nine Japanese ULF stations (Kakioha, Mochikosh, Unobe, Fudago, Iyogatake, Kagoshima, Seikoshi, Kanoya and Kamo) and also from one Taiwan ULF station (Lunping). Notice that if we aim at the detection of some seismo-related patterns, we need notable seismic events located in close vicinity of the station. Otherwise, the desirable component of the analyzed signal, presumably originated from the focal zone processes, will be suppressed by noise. In this sense only two stations, Unobe and Lunping, satisfied this requirement.

As the analysis methods we have used mono and mutifractal analyses. Section 2 contains the detailed description of each method. Section 3 is devoted to the local geomagnetic activity (LGA) and to the correlation between the LGA and fractal parameters of the ULF signal. We have demonstrated the necessity of taking into account the LGA as a significant source of influence on the fractal dimension of the ULF signal. Nevertheless, we could not find any quantitative relations between the LGA and fractal dimension, so that this question requires further investigation. Sections of Analysis results and Discussion contain the description of our results and some speculations on the related problems.
2. Fractal analysis methods

In our investigation we aimed at using the fractal characteristics of the ULF signal: (mono) fractal dimension and multifractal scaling exponents. In order to obtain the monofractal dimension, we have used the power spectral density (PSD) and Higuchi methods. As for the multifractal characteristics, we have used the multifractal detrended fluctuation analysis (MFDFA). Each method has its own peculiarities, its own advantages and disadvantages.

As a first step for all methods we should prepare the initial signal. Usually we use the one-hour windowed piece of the original signal, with or without any preliminary processing. We have used the 2-3 LT one hour window because of the minimal ionospheric and industrial influences and noise during that time period. More exactly, we have used not one hour (3600 s), but 4096 s window, because of technical purposes (for the use of fast Fourier transform and so on).

Common ULF record contains three magnetic field components: $S - N$ (south-north), $W - E$ (west-east) and vertical component. We have analyzed only $S - N$ component as soon as it always demonstrates the most significant dynamics in fractal parameters. Other components are not so informative in comparison with the $S - N$ one.

2.1. PSD method

This method (Gotoh et al. (2004); Smirnova et al. (2004)) requires the preliminary processing of the original signal. It is necessary to remove the linear trend from the signal and to satisfy the zero boundary conditions. As a smoothing function we have used the cosine function with half-period 180 s. After such a kind of preliminary processing we could get the power spectral density and to extract the fractal dimension as described below.

We get the PSD using the standard discrete Fourier transform:

$$F(k) = \sum_{i=1}^{N} X(i)e^{-2\pi i k (i-1)/N}, \quad 1 \leq k \leq N.$$  (1)

That is the Fourier transform $F(k)$ of the signal $X(i)$ (the length of the signal is $N$ s). PSD is a square of the magnitude of $F(k)$:

$$PSD(k) = |F(k)|^2.$$  (2)

After that we approximate the PSD with a power function:

$$PSD(k) \propto k^{-\beta}.$$  (3)

The fractal dimension $D_f$ can be obtained from the spectral slope $\beta$ by using the following Berry’s formula:

$$D_f = \frac{5 - \beta}{2}.$$  (4)

This method has certain advantages and disadvantages. The main advantage of the method is its speed: the method is really fast because it can be realized using only standard functions (like discrete Fourier transform and linear approximation) that work very fast. Also it is possible to find some physical background for the explanation of the results of the method, because it deals with the real physical parameters.

But it is necessary to take into account that because of zero boundary conditions we distort the initial signal. Also there are some uncertainties in the approximation procedure. Exactly, we approximate the PSD with a linear function in double logarithmic scale, so the “tail” of the PSD is extremely “heavy” and it can strongly distort the approximation. Thus, we have to choose not only the scaling interval, but also a set of the approximation points (the weight of a “head” and a “tail” must be equal).

2.2. Higuchi method

This method is a kind of generalized curve length estimation method for the evaluation of the fractal dimension of the curve. It works irrespectively of the real nature of the signal, so it may be difficult to find any physical motivation to explain the results. Nevertheless, this method was used for the fractal analysis of the ULF magnetic variations data (Ida et al. (2006)).

While using this method we do not distort the signal. In the most general sense we calculate the length of our signal for different scales and find the dependence of the length on the scale. Let us describe the procedure.

Initially, we have the time series data $X(i)$ ($i = 1, \ldots, N$). For any given time scale $s$ we can construct a family of $s$ subseries $X_m(i; s)$ of length $[(N-m)/s]$ ($(a/b)$ is the aliquot of division $a/b$):

$$X_m(i; s) = \{X(m + is)\}, \quad 1 \leq m \leq s.$$  (5)
The curve length of each subseries is:

\[ L_m(s) = \frac{1}{s} \sum_{i=1}^{\left\lceil \frac{N-m}{s} \right\rceil} |X(m + is - X((i-1)s))| \left( \frac{N-1}{s} \right) \left( \frac{N-m}{s} \right) \]  

(6)

And the average curve length of the family is:

\[ L(s) = \frac{1}{s} \sum_{m=1}^{\frac{N}{s}} L_m(s). \]  

(7)

So, now we have obtained the dependence of the curve length on the scale: \( L(s) \). And if our signal has fractal properties, it will be possible to approximate \( L(s) \) by a power function:

\[ L(s) \propto s^{-D_f}, \]  

(8)

where \( D_f \) is the fractal dimension of the signal.

The performance (we mean speed) of the realization of this method can be of the same order as the PSD’s realization, i.e. very fast. In this situation we do not have so many scales as in PSD method, so the approximation procedure is more stable. Also there is no need to distort the initial signal (we do not have to satisfy zero boundary conditions). The only disadvantage of this method is in its abstract nature: it is not so easy to find any physical explanation for the results. But just from the computational point of view this method is the best one.

### 2.3. MFDFA method

The MFDFA method (Kantelhardt et al., 2002) is a generalization of the conventional detrended fluctuation analysis (DFA) method (Kantelhardt et al., 2001). We do not discuss here the properties of the signal as a two-dimensional graph, because the time axis and the value axis are not equivalent. We analyze the signal as a one-dimensional structure and consider the multifractality of its values.

The procedure consists of five steps (and first three steps correspond to the usual DFA procedure). Suppose that we have a signal \( X(i) \) of length \( N \). At the first step we determine the profile and remove the constant trend:

\[ Y(i) = \sum_{k=1}^{N} (X(k) - \langle X \rangle). \]  

(9)

At the second step we should divide the integrated signal \( Y(i) \) into \( N_s = \lfloor N/s \rfloor \) non-overlapping segments of length \( s \).

In order not to lose the tail of the signal, we repeat this step starting from the tail downward to the head of the signal. So, we have obtained \( 2N_s \) segments of length \( s \):

\[ Y_s(i; s) = Y((\nu - 1)s + i), \quad 1 \leq i \leq s, \]  

(10)

for \( 1 \leq \nu \leq N_s \) and

\[ Y_s(i; s) = Y((N - (\nu - N_s)s + i), \quad 1 \leq i \leq s, \]  

(11)

for \( N_s + 1 \leq \nu \leq 2N_s \).

As the third step, we should subtract the local trend from each of the \( 2N_s \) segments. We can represent the local trend as a polynomial of order \( m \), getting the MFDFA \( m \)-order procedure. In this paper we have used \( m = 3 \) because of the reasons that we will explain below. After the subtraction of the local trend we define the variance function:

\[ F^2(v, s) = \frac{1}{s} \sum_{i=1}^{s} (Y_v(i; s) - y_v(i))^2, \]  

(12)

where \( y_v(i) \) is the fitting polynomial for the segment \( Y_v(i; s) \).

At the fourth step we should average the variance functions over all segments to obtain the fluctuation function of the \( q \)-th order:

\[ F_q(s) = \left\{ \frac{1}{2N_s} \sum_{v=1}^{2N_s} (F^2(v, s))^\frac{q}{2} \right\}^\frac{1}{q}, \]  

(13)
where the exponent \( q \) can take any real value except \( q = 0 \). For the case of \( q = 0 \) we should employ the logarithmic averaging procedure:

\[
F_q(s) = \exp\left\{ \frac{1}{4N_s} \sum_{n=1}^{2N} \ln(F^2(n, s)) \right\}.
\] (14)

Repeating steps 2 to 4 for different time scales \( s \) we obtain the fluctuation function \( F_q(s) \) dependence on \( s \). Note that \( F_q(s) \) is defined only for \( s \geq m+2 \).

In order to determine the scaling behavior of the fluctuation functions we perform the fifth step that consists of the approximation of the \( F_q(s) \) by a power-law function. If the initial series \( X(i) \) is long-range correlated, \( F_q(s) \) increases for large \( s \) as a power law:

\[
F_q(s) \propto s^{h(q)}.
\] (15)

In our investigation we have used the length of the signal \( N = 4096 \) and the \( s \) values: \( s = 2^k \), where \( k = 4, \ldots, 11 \), so that the minimal value of \( s \) was \( s_{\text{min}} = 16 \) and the maximal value was \( s_{\text{max}} = 2048 \). We have chosen these values because of practical reasons that we will explain below.

For the stationary time series \( h(2) \) is just identical to the Hurst exponent \( H \), so, the function \( h(q) \) is called the generalized Hurst exponent (Kantelhardt et al., 2002).

The relation between the MFDFA and the conventional MF analysis is considered in Kantelhardt et al. (2002), here we only list the results. The relation between the multifractal scaling exponent \( \tau(q) \) and the generalized Hurst exponent \( h(q) \) is:

\[
\tau(q) = q h(q) - 1.
\] (16)

The singularity spectrum can be obtained from the equations:

\[
\alpha(q) = \frac{d\tau(q)}{dq}
\] (17)

and

\[
f(\alpha) = q \alpha - \tau(q).
\] (18)

Here \( \alpha \) is the Hölder exponent and \( f(\alpha) \) is the dimension of the subset of the series that is characterized by \( \alpha \). Using (16) we can relate \( \alpha \) and \( f(\alpha) \) to \( h(q) \):

\[
\alpha(q) = h(q) + q \frac{dh(q)}{dq}
\] (19)

and

\[
f(\alpha) = q(\alpha - h(q)) + 1 = 1 + q^2 \frac{dh(q)}{dq}.
\] (20)

While using the MFDFA method we have found that \( h(q) \) must be a monotonic function of \( q \). Otherwise, the \( a(q) \) can not be the monotonic function of \( q \) and it makes impossible to find the singularity spectrum \( f(\alpha) \). So, we should remember that in a case of non-monotonic \( h(q) \) the singularity spectrum \( f(\alpha) \) can not be determined correctly. In this sense we have found that the use of trend polynomial of order \( m = 3 \) and \( s \) range from 16 to 2048 produces the maximal rate of monotonic \( h(q) \).

We are interested in tracing several parameters: \( \alpha_{\text{max}} = a(-\infty), \alpha_{\text{min}} = a(\infty), a(0) \), Hurst exponent \( h(2) \), and \( h(q) \) for \( q \in [-20, 20] \). We should note that in those cases when it was possible to find the singularity spectrum, values of \( \alpha_{\text{max}} \) and \( \alpha_{\text{min}} \) were obtained from the approximation of the \( f(\alpha) \) by the polynomial of order \( p \). We have used the value \( p = 10 \) for better approximation (\( p < 10 \) did not give sufficiently good approximations, and \( p > 10 \) could not produce the stable one).

For the final results we have used all obtained \( h(q) \) (both monotonic on \( q \) and non-monotonic), but the singularity spectrum parameters were evaluated only in the case of monotonic \( h(q) \).

MFDFA method has several serious disadvantages. First of all, it has a lot of structural parameters that can be estimated only empirically. At the same time the stability of the method is extremely sensitive to these parameters and we could not point out any satisfactory explanation of such a sensitivity. Another serious disadvantage is low speed: since the method requires a huge amount of computations, it is several times slower than the PSD or Higuchi methods.
3. Running average procedure

After obtaining the necessary parameter, for example, the fractal dimension $D_f(t)$ (a set of daily values during the considered time period), it is necessary to apply the running average procedure. Such a kind of procedure is necessary because the daily values of obtained parameters demonstrate a lot of fluctuations. And as we are interested in the considering of more or less smooth evolution of the obtained parameters with the characteristic time-scale about several days, so that it is required to apply some kind of low frequency filtering to smooth the considered parameter. As a rule, the running averaging is used as a filtering procedure. Usually this procedure consists of averaging the signal values during the current date plus-minus several days:

$$\langle S(i) \rangle_{old} = \frac{1}{2n+1} \sum_{k=-n}^{n} S(i+k);$$

here plus-minus $n$ days are used for the averaging. Actually, such an averaging is very rough and distorts the real character of the obtained parameter. Instead of that trivial procedure we have used a more sophisticated one. We have proposed to average the signal using exponentially decreasing weights for the neighbouring values. As a weight we have used the negative powers of 2: $1/2, 1/4, \ldots$:

$$\langle S(i) \rangle_{new} = \frac{S(i) + \sum_{k=1}^{n} (S(i+k) + S(i-k))2^{-k}}{1 + \sum_{k=1}^{n} 2^{1-k}}. \tag{22}$$

In our analysis we have used $n = 5$, i.e., current date plus-minus 5, totally 11 days. Such a kind of improved averaging procedure seems to be more acceptable because of more significant contribution of the current value, and because of the effective suppression of non-current values. In such a way we can filter the common tendency more evidently. Note that as an averaging filter we can use any procedure that provides effective averaging and at the same time effective suppression of non-current values; for example, we can use a Gaussian filter. An example of the obtained fractal dimension (thin line) and both averaging procedures are presented in Fig. 1. The thick blue line refers to the new averaging method, while the thick red line represents the conventional one.

4. Local geomagnetic activity (LGA)

In order to distinguish seismo-related patterns of lithospheric origin from other patterns of solar-terrestrial or artificial nature we have used also the estimation of the LGA level. We should notice here that the $K_p$ or $A_p$ indices of the planetary geomagnetic activity are usually used to recognize the nature of the patterns. However those indices are obtained as a mean value of the geomagnetic activity level estimated for several different stations all over the world. Those reference stations are located at the latitude range from 44 to 60 degrees of northern and southern geomagnetic latitudes. We suppose that the planetary indices can not describe satisfactorily the LGA peculiarities.

The rise of LGA can be caused by different reasons: industrial noise, ionospheric activity, seismic emissions. The industrial noise is supposed to be of the most local character: distant stations should not be affected by such a kind of activity. However, the seismic emissions also reveal the local character and it can be the non-trivial task to ascertain the real nature of LGA spike, if the spike was registered only inside the not so extended area (first hundreds kilometers). Evidently, if the LGA spike was detected in a wide area (thousands kilometers) it can be determined as one of the global, ionospheric nature.

Different methods can be applied for the estimation of the geomagnetic activity level (Zabolotnaja, 2007). For our analyses we have used the 2-3 LT one hour window, because of the minimal influence of industrial noise. The ULF record of the $H$-component during this time interval is characterized by the small amplitude (difference between the maximal and minimal values), the median value of that amplitude for different stations during the long (several years) time period does not exceed 10 $nT$ (usually is about 6 – 7 $nT$). So that we realize that one hour night-time window proposed is really characterized by a quiet geomagnetic activity level. Moreover, the usual daily (24 hours) structure of the signal demonstrates the extended (several hours) plateau during the night-time hours. So that we have proposed to use the amplitude (difference between the maximal and minimal values) of the one hour windowed signal as an estimation of the LGA level. Of course, such a kind of estimation may not be acceptable during the day-time hours and some other kind of estimation should be proposed.

Thus obtained level of the LGA is measured in $nT$. When it was possible we used the ULF data from all available neighbouring stations for the LGA level estimation. In such cases LGA levels obtained for considered and for neighbouring stations were averaged in order to produce the regional geomagnetic activity estimation.
Of course, in order to average LGA level dynamics obtained for different stations, first we should normalize it somehow for each station (for example normalize it by means of the median value), but in such a case the LGA level will be represented in dimensionless units and it is not so suitable. Especially because all the compared stations produced the LGA levels with almost the same median values.

Comparative analysis allows us to distinguish LGA spikes of global (ionospheric) and local (industry, seismic) nature: those spikes that were detected by several stations were supposed to be of ionospheric (solar-terrestrial) origin.

While considering the LGA level in coordination with the obtained fractal parameters, we have supposed patterns (specific significant changes of fractal parameters) that could be correlated with the spikes of the LGA to be of space or artificial nature and those patterns were not taken into account.

The common record of the LGA contains some spikes much greater than the average level. We associated those days with active ones; otherwise, the day was supposed to be quiet. An example of the LGA for the Kamo station is presented in Fig. 2.

Actually, different reasons may cause any spike of the LGA: space, artificial and seismic origins. Space disturbances can be recognized if a spike can be detected by several reference stations in a wide area (hundreds or first
thousands of kilometers). Spikes of artificial nature can be caused by human industry, by trains, and by any other artificial influences near the reference station. Such a kind of spikes could be detected only by a single station.

Seismicity also can be responsible for the LGA spikes. We have detected several LGA spikes that we associated with the seismic swarms near the reference stations. However, such a case is rare and those spikes can be supposed to be caused by other reasons.

As a most significant result of the LGA analysis we should report on an evident correlation between the LGA and fractal peculiarities. For all ULF stations we could detect the following correlation: almost all significant LGA spikes are accompanied by negative spikes of fractal dimension evaluated by means of the PSD and Higuchi methods. That is, the rise of the LGA results in a decrease in fractal dimension. It means, in particular, that if we could detect any pattern based on the rise of fractal dimension, we can be sure that the origin of considered pattern is not the LGA, because the LGA is characterized by a decrease in fractal dimension.

In spite of the evident correlation between strong spikes of the LGA and negative spikes of fractal dimension, we could not obtain any quantitative relation that could describe such a correlation. This point is a subject of further investigations.

We realized that the LGA can affect and even be a reason of the appearance of some fractal patterns. Thus, it is necessary at least to check all obtained patterns for correlation with the LGA in order to remove patterns correlated with (i.e., caused by) the LGA. The example of such a correlation between \( D_f(t) \) and the LGA is presented in Fig. 3. Spikes of the LGA and corresponding negative spikes of \( D_f(t) \) are marked with red circles.

As an example of the LGA-induced pattern we will present one supposed earlier to be a precursor-like pattern in Fig. 4 (Mezentsev et al., 2009). This pattern demonstrates the significant decrease in fractal dimension \( D_f(t) \) and increase in Hölder exponent \( a(q = 0; t) \) 6 weeks before the strong \((M = 7.4)\) earthquake near Kii peninsula occurred on the 5th of September 2004. More detailed analysis allowed us to conclude that this pattern appeared mostly because of the strong negative spike in \( D_f(t) \) which is associated with the strong LGA spike. This spike was detected on 25th of July 2004 at several Japanese stations: Kamo, Fudago, Iyogatake, Moshiri, and also by Indonesia stations: Biak and Kototaban. The distance between the Kamo and Moshiri stations is about 900 km, between Kamo and Biak more than 3800 km, and between Kamo and Kototaban more than 5400 km, so that the considered LGA spike certainly should be related with the global geomagnetic activity.

5. Analysis results

In order to detect the correlation of the estimated parameters with seismicity we have used not only the magnitude representation of the regional seismicity, but also the energy density representation. We have proposed that if the seismic processes cause the EM ULF emissions, such an influence should depend on the cumulated seismic energy. And the seismo-ULF emission intensity should decrease with distance. We have used a rough estimation of such a “seismic energy density” at the observation point: \( E = R^2 \), where \( R \) is the distance between the hypocenter of the considered event and the ULF station, and \( E \) is the seismic energy of the event:

\[
E = 10^{1.5M+4.8}.
\]

Using such a kind of representation of seismicity we can consider only notable events in the vicinity of the ULF station. An example of such a kind of representation for the Lunping station is given in Fig. 5.

We have to point out that other researchers also use the estimations of the seismic energy and related data (e.g., Gladychev et al., 2002). However, those researchers consider the problem of the real seismic energy density at the observation point, they discuss the attenuation and dispersion of seismic waves and define the local seismic index \( K_S \) (Gladychev et al., 2002). But we do not regard the real seismic energy density at the observation point, because we consider the EM ULF emissions from the hypocenter area. It means that we should take into account the attenuation of the EM ULF waves, but not the seismic wave attenuation. That is why we do not use the local seismic index \( K_S \), but a rather simple value: \( E = R^2 \).

We have succeeded in detecting two different types of behaviours in fractal parameters that we can associate with different types of seismic-related lithospheric EM processes. Those processes manifest themselves in significant variations of fractal parameters and the character of those variations is different and specific for different types of seismic related phenomena. We could associate the behaviour of fractal parameters with two distinct types of the lithospheric processes: co-seismic and precursor-like processes.

The first type of the result exhibits evident co-seismic behaviour. We could detect it for the famous seismic swarm in June 2000 near Izu peninsula. The swarm began on the 27th of June 2000 at the area with coordinates 34.1°N, 139.5°E at the shallow depth about 10 km, and continued up to October 2000, including several events with magnitude more than 6. The ULF station Unobe has the coordinates 32.21°N, 140.20°E.
Figure 3: Kamo station. Strong spikes of the LGA are always accompanied with negative spikes in fractal dimension.

Figure 4: Kamo station. A pattern (red partitions) looks as a precursor-like signature, but real nature of such a pattern is the geomagnetic activity (see the text).
We have realized that fractal characteristics of the ULF signal exhibit significant changes synchronously with the rise of seismic swarm activity. Notice that the distance between the swarm focal zone and the station was about 150 km, so that we can exclude the mechanical influence and associate such a behavior of fractal parameters with the co-seismic EM phenomena. We could register a significant increase in the $D_f(t)$ by means of the PSD and Higuchi methods and the synchronous decrease in the multifractal Hurst exponents. The results are plotted in Fig. 6.

Notice that the swarm activity during first three weeks took place at a very quiet LGA level. Moreover, as we realized in Sec. IV, LGA spikes may cause only a decrease in fractal dimension, but we observe an increase. Therefore, geomagnetic activity (as natural, as artificial) could not be the reason of this detected co-seismic pattern.

Another type of the result demonstrates a precursory-like behaviour. We have obtained such a kind of pattern for the strong ($M=7.8$) Chi-chi earthquake (Taiwan) on the 20th of September 1999. The epicentral coordinates were $23.77^\circ N$, $120.98^\circ E$, focal depth was about 33 km. The ULF station Lumping has the coordinates $25.00^\circ N$, $121.20^\circ E$.

In this case we have detected gradual changes of fractal parameters during a long time period (about 20 months) exactly up to the moment of the earthquake. We could register significant gradual decrease of the $D_f(t)$ by means of the PSD and Higuchi methods and increase of the multifractal Hurst exponents.

Evolution of the Higuchi $D_f(t)$ during the time period from September 1997 up to the end of 2000 (more than three years), as given in Fig. 7, demonstrates that changes (significant decrease in $D_f(t)$) started to manifest themselves approximately one year before the main event. Earlier the $D_f(t)$ demonstrated more or less stable behaviour during more than one year. After the main event during the five months of the intense aftershock activity, the $D_f(t)$ continued its gradual decrease. After that the behaviour of fractal parameters looks like the manifestation of the repairing processes.

The behaviour of several fractal parameters is presented in Fig. 8. The distance between the station and hypocenter was about 142 km.

Notice that the multifractal Hurst exponents pattern has a more visual character. The behaviour of Hurst exponents can be associated with gradual “heating” by means of such a visualization, as given in Fig. 9. Here we can observe the evolution of the system from the quiet, “cold” state, through the gradual “heating” up to an “overheated” state just before the main shock.

Theoretically, any decrease in fractal dimension could be due to the rise of the LGA level. But several months before the main event geomagnetic activity demonstrated even a certain decrease as is shown in Fig. 8. Thus, we cannot associate the origin of the considered pattern with any ionospheric nature.

6. Discussion

We have processed a huge amount of available ULF data, but have not succeeded in detecting any significant set of reliable patterns. This situation was caused, as we suppose, by several reasons. First of all, for reliable and stable analysis we strongly need ULF data of good quality. Unfortunately, almost all available data have lots of gaps and artifacts. Data artifacts can be taken into account and their influence can be more or less compensated. But in a case of data gaps the information is lost and it degrades the reliability of detected patterns.

Another reason why it was impossible to detect more patterns, was caused by necessity to associate the variations of fractal parameters with the seismic activity: with notable seismic events that were located not far from the ULF stations. Actually, the amount of such a kind of events is not so big.

Also it is necessary to take into account any probable non-seismogenic nature of the obtained patterns. We should check any probable correlation of detected patterns with the LGA. This procedure also restricts the total amount of registered patterns.

It is interesting that the fractal dimensions $D_f(t)$ obtained by means of different methods: PSD and Higuchi method, — are strongly correlated to the LGA spikes. Of course, such a correlation should be understood and explained. That is a subject for the further research.

As a basic pattern structure we have used the significant changes (increase or decrease) in the fractal parameters, processed by the running average procedure, as it was proposed by earlier works (Hayakawa et al., 1999; Gotoh et al., 2003, 2004; Smirnova et al., 2004; Ida and Hayakawa, 2006; Molchanov and Hayakawa, 2008). It means that patterns can be caused only by long (at least during several days) changes in the average level of considered parameters. This fact shows that such a kind of patterns can be reliable only for the detection of any “slow” seismo-electromagnetic processes that evolve at least during several days. As for the “fast” (several hours or one day) processes — the running average procedure can not resolve such a kind of signatures and it is necessary to involve the more complicated patterns.
Figure 5: Lunping station, “seismic energy density” representation of seismicity.

Figure 6: Unobe station, co-seismic signature. Upper panel: magnitude representation of seismicity. Middle panel: fractal dimensions; lower line (light-blue) is Higuchi fractal dimension, middle line (blue) is PSD fractal dimension, and upper line (green) is the Hurst exponent $h(q = 2)$. Bottom panel: LGA.

Figure 7: Lunping station, Higuchi $D_f(t)$ for the time period from September 1997 up to the January 2001.
Figure 8: Lunping station, precursor-like signature of the Chi-Chi earthquake in September of 1999.

Figure 9: Lunping station, Hurst exponents.
Also it is necessary to take into account that in order to obtain the daily value of any parameter we have used not the whole day signal, but only one hour window, thus we can detect only processes that manifest themselves during that window. The window we have used was 2-3 LT one hour window, contrary to what was proposed by Gotoh et al. (2004) and supported by Ida and Hayakawa (2006). In those works the time window of 14-15 LT was used, because during that time interval fractal parameters demonstrated the most significant changes. However, now we prefer to use the night time window because during this time interval the ionospheric influence and the industrial noises are minimal, so the lithospheric component of the ULF signal should have the maximal intensity.

7. Conclusion

While our investigation we have realized several important points. First of all, we have demonstrated an evident coupling between the LGA and fractal dimension (obtained by means of PSD and Higuchi methods). This fact results in the necessity of taking into account the LGA level during the fractal analyses. It is important because, as we have demonstrated, some patterns can be falsely recognized as of seismic origin, but really be of the ionospheric or artificial nature.

Also we have proposed the improved running average procedure that represents the structure of the initial signal in a more appropriate way.

As a result we have succeeded in identifying two seismogenic patterns of different nature: co-seismic and precursor-like patterns. In case of a precursor-like pattern detected before the Chi-Chi earthquake we can conclude that the accumulation of seismic energy released during the main shock started to manifest itself in the behaviour of fractal parameters several months before the main event, causing the significant decrease of $D_f(t)$ and increase of multifractal parameters.

We can conclude also that co-seismic lithospheric EM activity leads to a rise in $D_f(t)$. At the same time, as we have shown, LGA (as natural as artificial) leads to the decrease of $D_f(t)$. Thus, the real $D_f(t)$ dynamics is represented by a combination of processes of different characters. We can distinguish ”pure” cases, as for Unobe or Lupuning stations, but in a more general situation such a separation is not so evident. So that, some physical procedures should be proposed to provide reliable and stable detection of precursor patterns. In this sense it is necessary to obtain more patterns to perform the analysis of their reasons and to propose any acceptable idea that explains the mechanisms responsible for the appearance of such a kind of patterns and, more generally, the seismo-electromagnetic coupling.

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