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Multifractal analysis for the ULF geomagnetic data during the 1993 Guam earthquake

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Abstract. In our previous papers we have shown that the fractal (monofractal) dimension ($D_o$) showed a significant increase before the Guam earthquake occurred on 8 August, 1993. In order to have a further support to this precursory effect to the general rupture (earthquake) we have carried out the corresponding multifractal analysis (by means of detrended fluctuation analysis) for the same data to study the statistical self-similar properties in a wide range of scales. We have analyzed the ULF geomagnetic data (the most intense $H$ component) observed at Guam observatory. As the result, we have found that we could observe significant changes in the multifractal parameters at Guam such that $\alpha_{\text{min}}$ showed a meaningful decrease about 25 days before the earthquake and correspondingly $\Delta \alpha$ increased because $\alpha_{\text{max}}$ exhibited no significant change at all. The most sensitive parameter seems to be non-uniformity factor $\Delta$. Correspondingly, the generalized multifractal dimension $D_q$ ($q>1$) showed a significant decrease (whereas $D_q$ ($q<0$) showed no change) and $D_0$ ($=D_q$ ($q=0$)) (as already found in our previous papers) is reconfirmed to increase before the earthquake. These multifractal characteristics seem to be a further support that these changes are closely associated with the earthquake as a precursor to the Guam earthquake, providing us with appreciable information on the pre-rupture evolution of the earthquake.

1 Introduction

An important question in geophysics and in material science is to investigate whether any precursory signature exists or not before a macroscopic rupture or an earthquake and then to identify such an earthquake precursor if it exists.

We understand that when a heterogeneous material is strained, its evolution toward the final breaking is characterized by the nucleation and coalescence of microcracks before the final rupture. The two physical quantities are recognized as being most indicative of microfracturing process in the focal zone; that is, (1) ULF electromagnetic emissions and (2) acoustic emissions (Hayakawa, 2001; Hayakawa et al., 2004). There have recently been found a lot of convincing evidences on the electromagnetic emissions in a wide frequency range from DC, ULF to VHF associated with earthquakes, which are known to take place prior to the final breakup (e.g. Hayakawa and Fujinawa, 1994; Hayakawa, 1999; Hayakawa and Molchanov, 2002). Our main tool in this paper is to monitor the microfractures which are known to occur before the final breakup in the focal zone of an earthquake, by recording the ULF emissions. The presence of precursory signature of earthquakes is clearly identified in the ULF range for large (magnitude greater than 7) earthquakes such as Spitak, Loma Prieta, Guam, Biak etc. (Fraser-Smith et al., 1990; Mochanov et al., 1992; Kopytenko et al., 1993; Hayakawa et al., 1996, 1999, 2000).

The ULF emissions are found to take place from a few weeks to a few days prior to large destructive earthquakes (including Spitak, Loma Prieta, Guam etc.), which are considered as the so-called precursors of the general fracture. The emissions in the higher frequency range (like, VLF and HF/VHF) (Kapiris et al., 2004) are likely to be occurring in the focal zone of an earthquake, but they cannot be detected on the Earth’s surface because of their extremely severe attenuation in the crust. So, those higher frequency emissions might be generated as secondary effect near the Earth’s surface, and their generation mechanism is very unclear at the moment. In comparision with this, the ULF emissions are very definite to have been generated in the focal zone and to have propagated up to the subsurface ULF sensors. We can list the following reasons for this.

(1) When we estimate the skin-depth for ULF waves (period: 0.1 to 200 s) for the earthquake source depths from 5 km to 100 km, it will be less than 100 km. Hence, we can expect that those ULF waves are definitely coming from the source region.

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(2) Dynamic process in seismo-active areas can produce current systems of different kinds (see e.g. Molchanov and Hayakawa, 1995; Vallianatos and Tzanis, 1999 and references therein), which can be local sources for electromagnetic waves at different frequencies. The ULF range is the most possible to come from the source region with the least attenuation.

Based on these arguments, we can consider that those ULF emissions would carry the information on the microfracturing taking place near the focal zone. For example, as already mentioned before, Molchanov and Hayakawa (1995) proposed the generation mechanism of seismogenic ULF emissions on the basis of microfracturing.

One more important notice for those ULF emissions is the necessity of sophisticated signal processing. Signal processing is found to be of potential significance in finding out weak seismogenic ULF emissions especially in the general case when the observatory is located relatively away from the epicenter, so that the seismogenic emission is embedded in the noise. We have proposed so far several possible methods, including the polarization analysis method (using the ratio of vertical to horizontal magnetic field components) (Hayakawa et al., 1996), fractal (mono-) analysis (Hayakawa et al., 1999), principal component analysis (PCA) (Gotoh et al., 2002) etc. The first and third methods are simply mathematical, but the second is a physical analysis method, which was exactly the first step of this paper.

Because the dynamics of earthquakes is well known to exhibit properties which are characteristics for the self-organized criticality (SOC) state (e.g. Bak et al., 1987; Bak, 1997), we have made the first attempt to use the fractal analysis to the seismogenic ULF emissions for the Guam earthquake (Hayakawa et al., 1999). Since the principal feature of the SOC state is a fractal organization of the output parameters both in space (scale-invariant structure) and in time (flicker noise or 1/f noise). If the time series of ULF data is a temporal fractal, we expect a power-law spectral density of the recorded time series: $S(f) \propto f^{-\beta}$ ($\beta$: spectral exponent).

Hayakawa et al. (1999) have found a significant change in this spectral exponent ($\beta$) just before the Guam earthquake in such a way that the value of $\beta$ is approaching unity (becoming flicker noise) before the rupture, and later the similar behavior has also been confirmed for another large earthquake at Biak (Hayakawa et al., 2000). This estimation of fractal dimension was based on the spectral slope, $\beta$ in the spectral analysis, but later Smirnova et al. (2001) and Gotoh et al. (2003, 2004) have compared different analysis methods in estimating the fractal dimension (spectral slope, Burlaga and Klein (1986) and Higuchi (1988) methods). Their conclusion is that the Higuchi method provides us with the most reliable value of the fractal dimension. The seismicity spatial and temporal distribution is known to reveal statistically self-similar properties in a wide range of scales and can be treated as multifractal (e.g. Turcotte, 1997). Our previous studies are just a monofractal analysis, but we are interested in examining the multifractal nature of the ULF electromagnetic data for the same Guam earthquake.

This paper is a further extension of our previous papers dealt with the monofractal analysis (Hayakawa et al., 1996, 2000; Smirnova et al., 2001; Gotoh et al., 2003, 2004). We have already found a significant precursory change in the monofractal dimension before the Guam earthquake (Hayakawa et al., 1999; Smirnova et al., 2001; Gotoh et al., 2003, 2004). This data set is also studied in this paper, to which we have applied the multifractal analysis, and this will be the first attempt in seismogenic ULF data.

2 Experimental ULF data and analysis procedure

The details of the ULF data for the Guam earthquake have already been given in Hayakawa et al. (1999), but we have to repeat only the important points as follows. The Guam earthquake with magnitude $M_s=8$, occurred on 8 August 1993 at 08:34 UT suddenly and without any foreshock. Its epicenter was located in the sea near the Guam island (geographic coordinates: 12.98° N, 144.80° E), and its depth was 60 km. The Guam observatory where the ULF data were recorded, is located at ~65 km from the epicenter. Figure 1 illustrates the relative location of our ULF observatory with respect to the epicenter. A regular magnetic observation is maintained there using a three-axis ring-core-type fluxgate magnetometer (Hayakawa et al., 1996). Three components of magnetic variations are usually recorded on a digital cassette tape with a sampling rate of 1 s, but we use only the $H$ component (which is the most intense) (though Gotoh et al., 2004 have already found the similar behavior in the monofractal dimension for the $Z$ component as well). We analyze the data.
during one whole year of 1993, and we analyze the data during daytime (LT=14:00–15:00), because Gotoh et al. (2004) have found that the most significant change in the monofractal dimension was observed for the Guam earthquake during daytime. One hour data are treated, so that the number of data is 3600 points per day.

We now describe the multifractal analysis. The general description can be found in Feder (1988) and Mandelbrot (1989). There have been developed a few methods for multifractal analysis, but we have adopted the MFDFA (multifractal detrended fluctuation analysis) (Kanterhardt et al., 2002). The MFDFA is apparent to be much more accurate than the conventional box counting, and the detrended fluctuation analysis (DFA) has become a widely-used technique for the determination of fractal scaling properties and the detection of long-range correlations in noisy, nonstationary time series (Gotoh et al., 2004). One reason to employ the DFA procedure is to avoid spurious detection of correlations that are artifacts of nonstationarities in the time series. The data used are not filtered by using any filter before the multifractal analysis. We followed the analysis of DFA method developed by Kantelhardt et al. (2002). Let us suppose that \( x_\lambda \) is a time series of length \( N \) (\( N=3600 \) points for one hour every day), and we first determine the profile

\[
Y(i) \equiv \sum_{k=1}^i (x_k - \langle x \rangle)(i = 1, \cdots, N)
\]

(where \( \langle x \rangle \) is the mean over our relevant one-hour interval), which means that we remove the DC bias. Next we divide the profile \( Y(i) \) into \( N_s=\text{int} (N/s) \) (\( N/s \) means integer) non-overlapping segments of equal length \( s \). Since the length \( N \) of the series is often not a multiple of the considered time scales, a short part at the end of the profile may remain. In order not to disregard this part of the series, the same procedure is repeated starting from the opposite end. Thereby, \( 2N_s \) segments are obtained altogether. Then, we calculate the local trend for each of the \( 2N_s \) segments by a least-square fit of the series and we determine the variance;

\[
F^2(v, s) \equiv \frac{1}{s} \sum_{i=1}^s \left[ Y[(v-1)s+i] - y_v(i) \right]^2
\]

for each segment

\[
v(v = 1, \cdots, N_s)
\]

and

\[
F^2(v, s) \equiv \frac{1}{s} \sum_{i=1}^s \left[ Y[(v-1)s+i] - y_v(i) \right]^2
\]

for \( v=N_s+1, \cdots, 2N_s \). Here, \( y_v(i) \) is the fitting polynomial in segment \( v \). We have used the sixth-order \((m=6)\) polynomials in the fitting procedure. In the paper by Kantelhardt et al. (2002) they have used the values of \( m=2 \) or 3, but we could not get sufficient fitting for these \( m \) values. Simply increasing \( m \) value, we have found that \( m=6 \) gave sufficient fitting. We then average over all segments to obtain the \( q \)th order fluctuation function.

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

Of course, \( F_q(s) \) depends on the DFA order \( m \), and by construction \( F_q(s) \) is only defined for \( s \geq m+2 \). Kantelhardt et al. (2002) have suggested the value for \( s \) in such a way that \( s < N/4 \). So that we have adopted a reasonable range of \( s = 10 - 300 \), and so the obtained results are acceptable. We show one example of \( F_q(s) \) \((q=-0.5, 0, +0.5) \) on a particular day of 12 March 1993 in Fig. 2. This figure shows the \( s \) dependence of \( F_q \), which indicates that \( F_q(s) \) decreases as a power law for large values of \( s \) if the series \( x_k \) are long-range power-law corrected, and we can estimate the \( h(q) \), the generalized Hurst exponent. It is seen that \( F_q(s) \) can be approximated as \( \propto s^{\tau(q)} \), so that we can estimate the \( \tau(q) \). Here we had better comment on how good the fitting of the fluctuation function \( F_q(s) \) by a linear approximation is. One way to estimate this is the use of \( r^2 \) values as the square of the correlation coefficient. The \( r^2 \) values are found to be over 0.8 in Fig. 2, which are not so bad as compared with the corresponding values on the monofractal estimation by Gotoh et al. (2004).

Fig. 2. Examples of \( F_q(s) \)–\( s \) curves on a particular day of 12 March 1993, for a few selected \( q \) values \((q=-0.5, 0, +0.5)\).
Fig. 3. An example of (a) $D_q-q$ curve and (b) $f(\alpha)-\alpha$ curve on the same day of 12 March 1993.

be interpreted as follows: The spectrum which looks like an upside-down parabola, peaks at $f_{\text{max}}$ (at $\alpha(f_{\text{max}})$) and stretches from $\alpha_{\text{min}}$ to $\alpha_{\text{max}}$. That is, the range $w$ ($\alpha_{\text{min}}$ to $\alpha_{\text{max}}$) quantifies the non-uniformity of the fractal, while $f(\alpha)$ tells how frequently events with scaling exponent $\alpha$ occur.

Figure 4 illustrates the whole-one year plot of the variations of those multifractal parameters. The thin lines are the daily variations (the corresponding value for one particular day), and the full lines indicate the running average over $\pm 5$ days on a current day (+5 days including the current day and $-5$ days including the current day; Total 9 days). The vertical line in all the plots (as shown as 8/8) indicates the date of the Guam earthquake (i.e. 8 August). The top panel is the temporal evolution of geomagnetic activity expressed by the $A_p$ index. The multifractal parameters are given from top; $\Delta$, $\alpha(f_{\text{max}})$, $f_{\text{max}}$, $w$, $\alpha_{\text{max}}$, and $\alpha_{\text{min}}$. By means of a close look at Fig. 4, we can notice the following important findings for the multifractal parameters.

1. The temporal variations of bottom three panels ($\alpha_{\text{min}}$, $\alpha_{\text{max}}$, and $w$) has indicated a significant change (increase) in $w$ about 30 days before the earthquake. This is entirely dependent on the significant decrease in $\alpha_{\text{min}}$, because $\alpha_{\text{max}}$ is not found to exhibit any obvious changes.

2. $\alpha(f_{\text{max}})$ seems to show no significant change, but $f_{\text{max}}$ itself is found to indicate a significant decrease before the earthquake.

3. The most pronounced effect is clearly seen in the temporal evolution of the non-uniformity factor, $\Delta$. That is, the value $\Delta$ of is found to show a significant increase about 30 days before the earthquake and remain at a high value until a few days before the earthquake. This $\Delta$ value is seen to be back to the background value a few months later than the earthquake.

4. Significant changes (increase) in $\Delta$ before the earthquake are apparent to have no correlation with the geomagnetic activity because we are during geomagnetically quiet period.

In order to give some more quantitative estimate on the significant change in $\Delta$ (conclusions (3) and (4)), we have plotted the mean value (over the whole period) (horizontal line) and the corresponding 1$\sigma$ ($\sigma$: standard deviation (over the whole year)). Even the running mean (over 9 days) of $\Delta$ is found to exceed the mean plus one standard deviation, and the daily $\Delta$ is seen to fluctuate at a high level (like the mean plus 2$\sigma$). This behavior is apparent to be very abnormal.

Another form of presentation is the use of $D_q(q)$ curve for the same one year of 1993, including the earthquake day of 8 August. The result is given in Fig. 5, in which the ordinate is the value of $q$ and the value of $D_q$ is indicated in different color. We can notice the following facts.

(1) As for $D_o$ (capacity dimension) we find a significant increase about 30 days before the earthquake, which seems to support the previous works by Hayakawa et al. (1990) and Gotoh et al. (2004) based on the monofractal analysis. The most significant effect is seen for $q=0.5$.

(2) In the region of $q>1$, $D_q$ is found to decrease about 30 days before the earthquake, while $D_q (q<0)$ did not show any particular changes.

3 Discussion and conclusion

In our previous monofractal analyses by Hayakawa et al. (1999) and Gotoh et al. (2004), we have already found that the monofractal dimension (corresponding to $D_o$ in this analysis) showed a significant increase before the Guam earthquake, which seems to be a precursor (Hayakawa et al., 1999) to the Guam earthquake (Hayakawa et al., 1999). In addition to this monofractal analysis, our first attempt of multifractal analysis (by means of MFDFA) in this paper...
Our multifractal analysis has yielded a significant insight into the precursory effects of earthquakes. It seems clear that the temporal variations in $w$ and $\Delta f$ provide some message for medium-term forecast of earthquakes. Especially, the non-uniformity factor, $\Delta$ has indicated a significant increase starting about 30 days before and lasting just before the earthquake. This $\Delta$ value is normalized by the denominator $(f_{\text{max}})$. The most influential point is the shift of $\alpha_{\text{min}}$ to the left, which indicates that the clustering within the most clustered areas becomes more intense (the local fractal dimension increases within these vicinities). The corresponding increase in $w$ indeed means a transition from homogeneous (random, space filling) to heterogeneous (ordered, complex, clustered) patterns.

We here comment on the 25–30 days precursory warning. The presence of ULF signatures in this period has already been found for a few large earthquakes like Loma Prieta and some others. This kind of temporal evolution has been attempted to explain by means of the microfracturing model by Molchanov and Hayakawa (1995) based on a space-time model of microfracture progression.

While the multifractality of earthquake patterns has been firmly established by now (Goltz, 1997), there have been very few reports on the use of multifractal spectral change as a precursor to earthquakes. Only a few sources are known to us; Jiang (1993) and Hirabayashi et al. (1992). Jiang (1993) was interested in the change in multifractal parameters for moderately large earthquakes (long-term variation of the order of a year) and he concludes that the temporal variations in $w$ and $\Delta f$ provide some message for medium-term forecast of earthquakes. Then, the main focus of Hirabayashi (1992)’s paper was on showing that seismicity from three major regions (California, Greece and Eastern Japan) constitutes multifractal measures. But, they analyzed the temporal behavior of the spectrum of generalized dimensions (the $D_q$ curve) obtained from the epicenter distributions. The similar work to these has been recently published by Kiyaschenko et al. (2003) in order to find out some medium-term earthquake precursors. The epicenter distributions analyzed by Jiang (1993) and Hirabayashi et al. (1992) are known to be useful for the medium-term prediction, but the short-term earthquake prediction seems to be possible only with the use of electromagnetic phenomena (Hayakawa and Molchanov, 2002). Our multifractal analysis for the geomagnetic ULF data is found to be of great potential in short-term earthquake prediction. Also, we will take into account the multifractal changes as obtained in this paper in the improvement of our previous generation mechanism (Molchanov and Hayakawa, 1995).

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