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Precursory Behaviour of Fractal Characteristics of the Ulf Data Associated With Earthquake

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Abstract :In this paper, we describe fractal method to extract earthquake precursory signatures of the ULF data for moderate earthquake that occurred on 29 July, 2008 having magnitude (M) 4.5, using three-components induction coil magnetometer installed at Shivaji University, Kolhapur (16.40^0 N, 74.15^0 E), India. We have applied FFT procedure to calculate the spectral exponents and fractal dimensions of the ULF time series. We have found specific peculiarities in the behavior of fractal characteristics of the ULF time series one month to several days before the moderate earthquake for 1-5 Hz frequency band. This specific peculiarity in the behavior of fractal characteristics appear to be sharp as compared to ULF time series. Fractal characteristics of ULF data can give important information about earthquake preparation processes and it can be involved in the development of the earthquake prediction methodology.

1. Introduction

It has been recently reported that electromagnetic emissions are observed in a wide frequency range from Direct Current (DC), Ultra-Low Frequency (ULF) to Very High Frequency (VHF) in possible association with earthquakes (Hayakawa 1999, Hayakawa and Molchanov 2002). However, the lower frequency range, i.e. ULF (less than, 10Hz), is the most attractive because it has been deeper skin depth effect and low attenuation than the higher frequency. There are different generation mechanisms of seismo-electromagnetic waves such as piezoelectric effect (Freund, 2000, 2002); electro-kinetic effect (Dragonov *et al.* 1991; Fenoglio *et al.* 1995); tribo-electricity (Brady and Rowell, 1986) and microfracturing processes (Cress *et al.* 1987). Fig. 1 shows the model of generation mechanisms of ULF waves during the earthquake preparation phase. Figure shows that stress builds up or reduced on a fault plane and two plate slides towards or apart from each other until it reaches the breaking strength of the rock and generated microcracks in the rocks. The charge separation at opening microcracks and the radiation of electromagnetic waves from the generated microcurrent in the future focal region could control ULF seismogenic emissions. The sum of current production from many small microcracks has been assuming that they tend to be aligned by large scale stress strain gradients. Then generated ULF waves propagated through conductive lithosphere and reaches to sensors.

The signal processing is essential for detecting changes in seismogenic electromagnetic emissions. Sophisticated signal processing is needed in order to detect and identify weak seismogenic ULF emissions. Therefore, the ULF data has been analyzed by different signal processing techniques such as spectral density, polarization analysis (Hattori *et al*. 2002) and fractal analysis (Hayakawa *et al.* 2007).

Hayakawa *et al.* (1999, 2000) and Smirnova (1999), a fractal analysis has been applied to ULF geomagnetic data to investigate dynamics of their scaling characteristics (spectral exponents, fractal dimensions) depending on seismic and geomagnetic conditions. It has been shown that some specific dynamics of spectral exponents (spectrum slopes) of the ULF emissions were observed in a seismoactive region of Guam Island under the variation of geomagnetic activity and in relation to the large earthquake of 8 August 1993 (M = 8). The concept of self-organized criticality (SOC), which has been originally introduced by Bak *et al.* (1987), is now actively applied to the investigation of behavior of different natural dynamical systems: earthquakes (EQs), landslides, magnetospheric disturbances and space plasmas, (Feder, 1988; Jensen, 1998; Chapman and Watkins, 2001; Chang *et al.,* 2003 and Smirnova *et al*. 2007)

In the present paper, we have discussed observation of fractal characteristic phenomena and it is anomaly behavior associated with seismic activity. We have also observed peculiarities in fractal dimension before the earthquake, which seems to be associated with moderate earthquake, occurred in Koyna-Warna region, India.

2. Possible Generation Mechanism of SEM Waves

The origin of electromagnetic field changes associated with earthquakes has been theoretically investigated by scientists. Although, presented model seems to explain some specific aspects of the ULF observations, no complete theory is so for available.

2.1 ElectroKinetic Effects

The ULF geomagnetic properties associated with 1989 Loma Prieta earthquake by the electrokinetic effect is explained by Fenoglio *et al.* (1995). They determined the electric and magnetic fields generated during failure of faults containing sealed compartments with pore pressures ranging from hydrostatic to lithostatic levels. They showed that electrokinetic effects due to the water flow from higher pressure compartment to low pressure are on several orders of magnitude larger than the piezomagnetic and induced mechanism. If the intermittent movement of ionized under ground water is generated, it is possible to explain anomalous behaviour like ULF emissions. Also, simultaneous measurement with both magnetic and electric fields could provide the apparent anomalous changes of electrokinetic evidences. Mizutani *et al.* (1976) has suggested mechanism of electro-kinetic conversion is due to fluid diffusion in a porous and fractured ground. The basic parameters of the mechanism were also checked in the laboratory experiment (Morgan *et al.* 1989).

2.2 Induced Effects

This model explained that the ULF emissions are caused due to the electric currents induced by conductive material in the geomagnetic field. Draganov *et al.* (1991) conducted a numerical calculation on the induction model to explain the ULF magnetic fluctuation prior to the Loma Prieta earthquake. They concluded that the observed magnetic fluctuation may occur due to the motion of ground water within the crust.

2.3. Microfracturing Effects

Surkov V.V *et al.* (2003) proposed the microfracturing mechanism. The charge separation at opening microcracks and the radiation of electromagnetic waves from the generated microcurrent in the future focal region could control ULF seismogenic emissions. They considered the sum of current production from many small microcracks assuming that they tend to be aligned by large scale stress strain gradients. Each micro-current result from charge relaxation during microcracks opening but the alignment of microcracks should be adequate for the polarity and coherency and then the intensity of current is large enough for intense ULF emissions.

2.4 Piezoelectric Effect

If the rock sample is under pressure, the crystal lattice generates an electrical field around the quartz grains due to the piezoelectric effect. This piezoelectricity is caused by continuous contraction and dilation of the lithospheric layers, which execute elastic vibrations after the release of thermal stress developed by the heat produced due to the annihilation of magnetic field. Possible EM emission by piezoelectric effect occurs due to electrostatic discharge produced by the deformation of piezoelectric minerals or charge separation on fractured surfaces in the earth (Nitsan 1977).

Above discussion gives idea related to the generation mechanism of the ULF emission. Other models will also be helpful to understand the production of electromagnetic waves before the earthquakes.

3. Experimental and Data Analysis Procedure

Seismo-electromagnetic observing system has been installed at low-noise site (such as manmade noise, industrial noise, rail noise etc.) in Shivaji University, Kolhapur (16.40^o N, 74.15^o E), India. Fig. 2 shows the experimental setup for magnetic field observation. Search coil magnetometer (LEMI-30i) with data processing system is used for the collection of the magnetic field variations data in low-noise area. The complete set of the magnetometer consists of three LEMI-30i sensors; the CAM-Unit (Communication and Measuring Unit) consists of ADC (Analog to Digital Converter), GPS (Global Positioning System) timing system RS-232 interface and external PC with data logger. Data collected by the CAM-Unit is transmitted to the PC for storage. Three magnetic field components (B_x, B_y and B_z) are continuously measured using three components induction coil magnetometer, which operate in the frequency range of 0.01-30 Hz. The three sensors of the magnetometer are buried 1m under the ground in orthogonal directions (the X-component along the northï south, Y-component along eastï west, and Z component along vertical directions). The distance between each magnetometer is more than 1m. We built up hut for magnetometers. The hut is made from non-magnetic and non-conductive material such as concrete. Vertical component magnetometer is kept in PVC pipe which is 1.1 min height. Pipe has 1m under the ground and 0.1 m has above the ground. For horizontal component magnetometer, we have used concrete walls and it has 200 mm under the ground and at least 30-50 mm above the ground level in order to protect from water when covered by the hut. Also it provides stable basement for the sensor with concrete plate. There are small gaps between inner part of the hut and the edges of concrete walls in order to allow the outer air to go inside freely. A sensor has covered after installation with waterproof cover. Connection between CAM unit and COM3 port of PC is made by using RS-232 connector. GPS gives information regarding coordinates of the system. The power supply cable is plugged into +12 V socket on the rear panel of the CAM-Unit and connected it to the battery power supply of 12 V.

Spectral density analysis based on Fast Fourier Transform (FFT) method has been applied to raw one hour interval data waveform of three magnetic field components (Smirnova *et al*. 2004). The data from each magnetometer is digitized at the sampling rate of 64 Hz because we are interesting in 0.01 to 30 Hz frequency range. Spectral density analysis has been made with the help of MATLAB software with 1024 data points. Time window 14:00 to 23:00 UT used for the FFT. These are ten hours data (14:00 to 23:00 UT) for one day has been used for analysis. Intensity of magnetic field can be obtained from spectral density analysis. We have analyzed 1-5 Hz frequency range data because we found anomalous behaviour in this frequency range.

Physical interpretation of fractal analysis is not so easy, but it is useful to find out an anomaly. It also increases the reliability of the observational facts. Hayakawa *et al.* (1996) proposed the use of fractal analysis and made the first attempt to estimate the temporal evolution of fractal dimension in case of 1993 Guam and 1996 Biak earthquakes.ULF geomagnetic data are usually represented by irregular time series. To get a quantitative estimation of the time series irregularity, fractal analysis method has been used by Turcotte (1997) and Gotoh *et al.* (2003). The simplicity of this method is that the power spectrum is used for fractal analysis. In this case, when the power spectral density follows a power law, the spectral exponent can be considered as an index of time series irregularity. Here, FFT method is used to calculate the power spectral density of the ULF signals S(ä) for each one hour interval along the preparation phase of the earthquakes. If S(ä) followed a power law behavior $S(f) \propto f^{-\beta}$, we calculate the spectral exponent (ϐ) from the slope of the best-fit straight line in the logï log plot of the spectrum in 1- 5 Hz frequency range. We have observed anomalous enhancement during 1-5 Hz frequency range. Night time observed data has been used for calculation during 14:00 to 23:00 UT because it was free from man made and industrial noises. The power spectrum is plotted in logï log form and the spectrum slope ϐ (spectral exponent) is obtained. Then, the evolution of ϐ has been analyzed during time 14:00 to 23:00 UT. Since the power law behavior of the spectrum is a feature of fractal time series, fractal dimension (D_0) of the ULF time series has been estimated using the well-known Berry equation: D_0 = (5- ϐ)/2 [Berry 1979].

In this study, appropriate fractal methods have been applied for calculation of the spectral exponent ϐ and fractal dimension (D_0) of the ULF emission time series, using FFT method.

4. Results and Discussion of the Fractal Analysis

In this section, fractal analysis method has been applied to extract the earthquake precursory signatures from scaling characteristics of the ULF data, obtained in a seismic active region.

A moderate earthquake occurred on 29th July, 2008 at 19:10:59 UT with magnitude (M) 4.5. Geographic coordinates and depth were (17.64^0N, 74.17^0E) & 5 km, respectively. Fig. 3 shows the locations of the earthquake and induction coil magnetometer indicated by plus and star symbols, respectively. For seismic event, digital records of the magnetic field components B_x (North-South), B_y (East-West) and B_z (vertical) obtained at the nearby geophysical observatory were used for fractal analysis. The data is taken from 14:00 UT to 23:00 UT. Such selection allowed us to separate the local effects from the effects that could be related to earthquake source dynamics. Results obtained by the FFT method for 1-5 Hz frequency band have been presented.

Fig. 4 illustrates the dynamics of the fractal dimensions (D_0) for 29th July earthquake, which was recorded at Kolhapur station during 1 January to 31 December, 2008. The dynamics is presented for 1-5 Hz frequency bands for B_x component. Vertical dotted line indicates the date of the earthquake. Figure shows two panels, lower panel depicts annual day to day variations in fractal dimension and upper panel shows the extended interval around the onset of 29th July earthquake.

Enhancement in fractal dimension of the ULF time series was observed before 29th July earthquake. The ULF time series fractal dimension started to increase 23 days (on 6th July) before the main shock and specific peculiarity appeared to be sharp for 29th July earthquake in comparison with gradual increase of the ULF time series fractal dimension. After the earthquake day, peculiarity in the fractal dimension decreased.

Similar result was observed for the fractal dimensions (D_0) of B_y component. Fig. 5 clearly shows that the enhancement in the fractal dimension started to increase two months before the main shock. Anomalous enhancement was observed one month before the earthquake day.

Fig. 6 illustrates the dynamics of the fractal dimensions (D_0) for 29th July earthquake of the ULF time series for B_z component. Fractal characteristic for B_z component was observed for 29th July earthquake. Special peculiarity in the fractal characteristic of the ULF time series started to increase around two month before the earthquake and it reached to maximum on 5th July and afterwards it decreased. And again, the fractal characteristic increased few days before the earthquake day.

In order to estimate the contribution of geomagnetic activities, the daily variation of ×Kp has been investigated. If, ×Kp > 30; the geomagnetic activity for a particular day is considered to be high. In such cases it becomes difficult to associate the electromagnetic emissions with earthquakes (Hattori *et al*. 2002). Fig. 7 shows daily global geomagnetic activity in terms of ƩKp from 1 January to 31 December 2008. Date of earthquake is indicated by the dotted line. ƩKp was less than 30 during the observation period. Hence, geomagnetic activity during observation period was undisturbed. Therefore, there is no relation between global geomagnetic activity and peculiarity in fractal dimension.

Above discussion for 29th July earthquake shows that peculiarity in fractal dimension were observed before the earthquake for three magnetic field components. Figs. 4 to 6 show the fractal dimension varies consistently with the local seismic activity, which reflects the statistical properties of the random component of the geomagnetic field. Specific peculiarity in the behavior of fractal characteristics of the ULF time series before earthquake noticed for all three B_x, B_y and B_z components for the 29th July earthquake event.

5. Conclusions

From above discussion, we conclude that the fractal analysis of the ULF data could give important information about the earthquake preparation processes and it can be involved in the development of the earthquake prediction methodology. Fractal characteristics of the ULF electromagnetic fields of natural origin registered in seismic active regions tend to exhibit precursory behavior before the earthquake. Such peculiarity in fractal characteristics appears to be one month to several days before the earthquake for 1-5 Hz frequency band. For all components, fractal dimensions of the ULF time series increased and the corresponding spectrum exponents decreased. Above results of fractal dimension analysis is in agreement with that results obtained by Smirnova *et al*. (2004) by ground based observation method.

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FIGURES

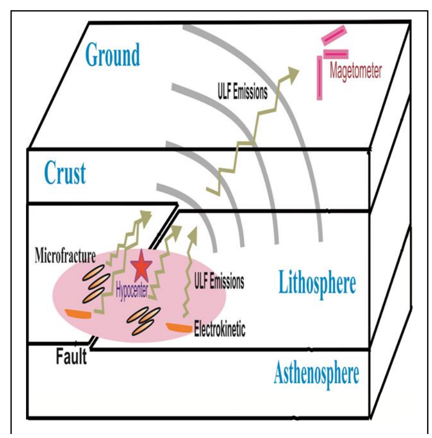

Fig. 1 The model to explain the generation mechanisms of ULF waves during the earthquake preparation phase, Microfracture and Electro-kinetic effects.

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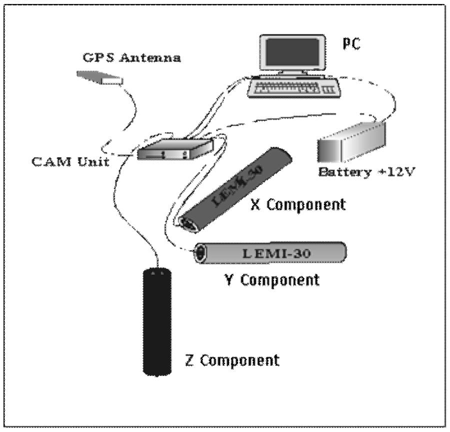

Fig. 2 Experimental setup for magnetic field observation

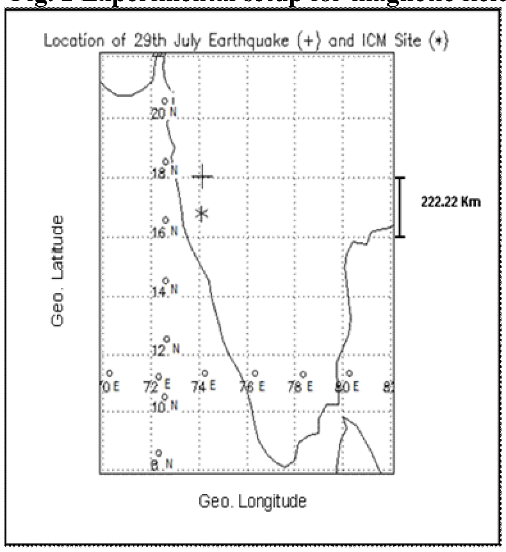

Fig. 3 Locations of the 29th July earthquake and Induction Coil Magnetometer (ICM)

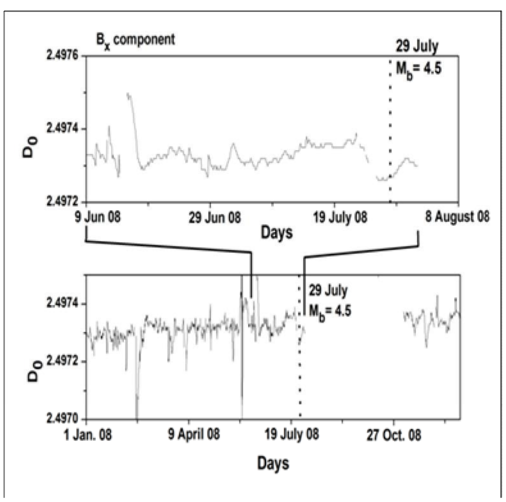

Fig. 4 Dynamics of the fractal dimensions (D_0) of the ULF time series recorded at Kolhapur station during 1 January to 31 December, 2008 for B_x component. The dynamics is presented for 1- 5 Hz frequency band. Lower plot in the frame depicts annual day to day variations. In upper plot the interval around the onset of 29th July earthquake is extended.

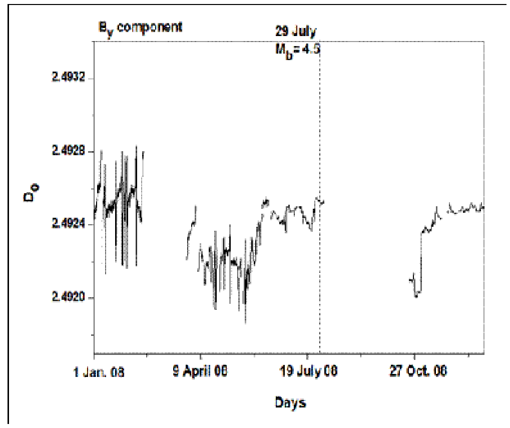

Fig. 5 Dynamics of the fractal dimensions (D_0) for B_y component.

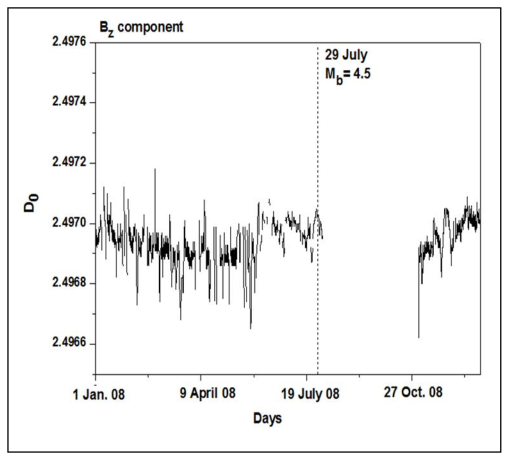

Fig. 6 Dynamics of the fractal dimensions (D_0) for B_z component.

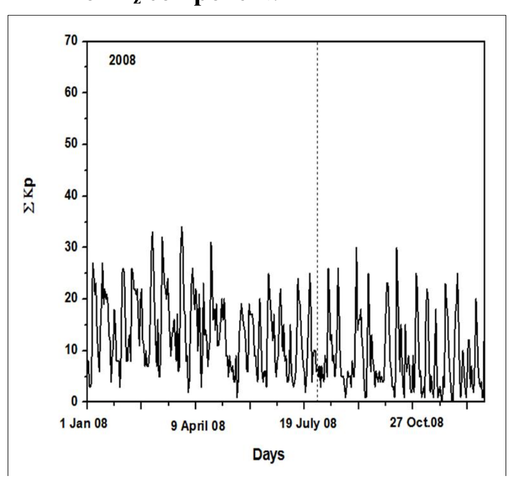

Fig. 7 Geomagnetic activity in terms of ΣKp during 1 January to 31 December, 2008