Fractal dimension variability in ULF magnetic field with reference to local earthquakes at MPGO, Ghuttu

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ABSTRACT
Ultra-low frequency (ULF) geomagnetic data recorded during 1 January 2010 to 31 December 2010 at multi-parametric geophysical observatory (30.53°N, 78.74°E) in Garhwal Himalaya region of Uttarakhand, India, are analyzed. From the temporal variation of polarization ratio, the presence of seismo-magnetic disturbances superposed upon background geomagnetic variations are inferred. Considering earthquake process as a self-organized critical system based on flicker noise characteristics, fractal dimension for each day is estimated using two methods namely power spectral (FFT) method and Higuchi method. Variability in fractal dimension is studied in the background of local earthquakes (M ≥ 3.5) within a zone of radius 150 km from observing station multi-parametric geophysical observatory (MPGO), Ghuttu. Fractal dimension variability indicates that average fractal dimension for first half of the year is increased as compared to average fractal dimension of second half of the year and there is gradual increase in the fractal dimension before earthquakes. It is also observed that during the first half of the year, there is seismic activity within zone of 150 Km radius centred at around MPGO, Ghuttu. There are no earthquakes during the second half of the year. Gradual increase in the fractal dimension before earthquakes, observed elsewhere in the world, is considered precursory signature of seismo-electromagnetic field emissions.

1. Introduction
Amidst the pessimism for realization of earthquake prediction, growing evidences of electromagnetic (EM) anomalies before the earthquakes suggested the possibility of short-term earthquake prediction at some stage. EM emissions emerged as one of the most promising candidate for precursory signals of the earthquakes. Various studies in the globe indicate that during the earthquake preparation process, EM phenomena could appear in wide frequency range from DC to MHz frequencies (Molchanov et al. 2003; Ida & Hayakawa 2006; Hayakawa et al. 2007; Chauhan et al. 2012; Arora et al. 2012; Kumar et al. 2013; Rawat 2014). Although there is no uniformly accepted model for the generation of this EM field during seismogenic processes, electro-kinetic theory and peizo-magnetic effect are advocated to explain the origin of seismo-electromagnetic (SEM) field (Fitterman 1978; Yoshida 2001; Fedorov et al. 2001; Uyeda et al. 2009).

Discrimination of weak SEM signals from the background EM signals and identifying source location of SEM signals are two important aspects of earthquake precursory studies in EMs that
should lead to short-term earthquake prediction. The first problem is critical due to the presence of EM field generated through complex interaction of Sun-ionosphere. SEM signals are weak and their detection depends upon various aspects of source receiver location. Methods like polarization ratio based on planar wave concept, principal component analysis, wavelet analysis and fractal analysis (Uyeda et al. 2002; Harda et al. 2004; Hattori et al. 2004; Gotoh et al. 2004, 2003; Hayakawa et al. 2007) provide some insights on the presence of EM field of tectonic origin. Efforts for locating source location of SEM signals or finding its direction are also in progress, as evident from proposed methods in literature based on time lag or phase difference (Ismaguilov et al. 2003; Kopytenko et al. 2006, 2001) and polarization ellipse (Schekotov et al. 2008, 2007; Dudkin et al. 2010) utilizing simultaneous observation at two or more stations.

In a different approach of studying seismogenic process, temporal variability of fractal dimension is used to analyze the dynamics of natural hazards system, based on the consideration of self-organized critical (SOC) system. The theory of SOC was first introduced by Bak et al. (1988, 1987) for the explanation of 1/f noise and scale-invariant structure. The primary characteristic of the SOC dynamics is a power law distribution (or fractal organization) of the system parameters both in space and time. Therefore, a nonlinear dynamics occurring in the earth crust towards the rupture can be investigated with the use of fractal method (Gotoh et al. 2003; Smirnova et al. 2004; Yonaiguchi et al. 2007). Hayakawa et al. (1999) first time used this technique on ultra-low frequency (ULF) data and found that a few days to weeks before the occurrence of the earthquake, there are significant changes in the spectral slope. Later, many researchers calculated the fractal dimension of ULF time series in order to examine the precursory signatures of earthquakes (Gotoh et al. 2004; Smirnova et al. 2004; Varotsos, 2005). Three methods (Varlamov et al. 2012) are widely used for estimating the fractal dimension of ULF band EM signals. These three methods are power spectral density (PSD) method (Feder 1988; Turcotte 1997), Burlaga-Klein method (Burlaga & Klein 1986) and Higuchi method (Higuchi 1990, 1988). Gotoh et al. (2003) have calculated the fractal dimension of ULF geomagnetic time series corresponding to a swarm of earthquakes nearby Izu Peninsula region using all these three methods. They have reported increasing trend in the fractal dimensions of ULF time series before the seismic events. Similarly, Smirnova et al. (2004) have reported an increase in the fractal dimension or decrease in the spectral exponent as an earthquake precursory signature. Ida and Hayakawa (2006) presented their findings related to Guam earthquake (M = 8.2) of 8 August 1993 using ULF geomagnetic data and stated that the fractal dimension of ULF time series, obtained using Higuchi method, exhibited five maxima 9—4 days before the occurrence of main shock of the earthquake. Varlamov et al. (2012) have done fractal analysis of magnetic data for five stations, located along the 210 magnetic meridian. They investigated the dependency of fractal dimension and spectral exponent on geomagnetic activity. They found that the fractal dimension decreases and spectral exponent increases with increasing geomagnetic activities at all the stations. This observation is significant as an increased fractal dimension before earthquake is widely reported and may, therefore, indicate the presence of SEM signal.

In this paper, we discuss our observations at multi-parametric geophysical observatory (MPGO) at Ghuttu (Tehri Garhwal, India) indicating the existence of SEM signals in the ULF band magnetic field variations. We have analyzed fractal characteristics of ULF band geomagnetic variations for the year 2010 using PSD method and Higuchi method. The data used in our study are recorded at MPGO, Ghuttu (geographic lat.30.53°N, long.78.74°E). We analyzed the results in the background of earthquake events occurred within 150 km radius from MPGO, Ghuttu. The location of MPGO, Ghuttu and epicentres of the earthquakes within a distance of 150 km from MPGO, Ghuttu are shown in figure 1. In this study, we have found that the fractal dimensions obtained using Higuchi method are more stable whereas the fractal dimension obtained using PSD method is more variable. Procedures similar to Smirnova et al. (2004) are used while calculating the fractal dimension and the spectral exponent using PSD method. The ULF time series shows an irregular behaviour and if the PSD $S(f)$ of a time series follows a power law behaviour $S(f) \propto f^{-\beta}$, the spectral exponent ($\beta$) can be considered as an index of irregularity of the time series.
2. Data analysis and methodology

An MPGO at Ghuttu in Garhwal Himalaya region of Uttarakhand is established with an objective of establishment and integration of earthquake precursors in different geophysical parameters, if any. Three orthogonal components of ULF band geomagnetic variations are being continuously recorded at MPGO using lemi 30i search coil induction magnetometer from Lviv centre of Institute for space research, Ukraine (ISR, Lviv Ukraine). The continuous analogue data from each sensor is digitized at a sampling rate of 64 Hz and recorded for offline analysis. Induction coils are calibrated in ISR, Lviv Ukraine and calibration functions are incorporated in the data logger and in the software of data retrieval from CAM unit (data logger and digitizer).

In this study, we have used hourly data from 1900—2000 hrs (UT) corresponding to local midnight (0030—0130 hrs) for each day of the year 2010. The 64 Hz time series is resampled at 1 Hz by averaging. The selection of midnight data is to have minimum influence of ionospheric origin signals and signals generated due to human activity, called cultural disturbances. For the PSD method, the hourly 1 Hz time series is detrended, then divided into segments of 1024 data points with 50% overlapping to previous segment. Each segment is subjected to fast Fourier transform (FFT). Power spectrum of five segments in one hour were then averaged to obtain the most coherent and persistent spectral characteristics. Slope (β) of averaged power spectrum is then estimated using linear fit to the...
spectrum plotted on log–log scale (figure 3) in the frequency band 0.03–0.1 Hz. Seismic activity in North West (NW) Himalaya is limited to upper crustal depths and delimited by the geometry of detachment in this part of Himalaya (Kayal et al. 2003). Considering the geoelectrical structure of Garhwal Himalaya (Rawat et al. 2014; Israil et al. 2008), frequency band 0.03–0.1 Hz corresponds to upper crustal and mid-crustal depth. We, therefore, limited our data analysis for this frequency band in order to obtain signatures from depths where seismogenic processes dominates in NW Himalaya.

Spectral mean in the frequency band 0.03–1 Hz is calculated for three components of ULF band magnetic field variations. From this spectral mean, polarization ratio \( \frac{S_Z}{S_H} \) (Hayakawa et al. 1996) is calculated, where \( S_Z \) and \( S_H \) are the spectral densities of vertical and total horizontal field component, respectively. Temporal variations of polarization ratio enable us to distinguish seismo-magnetic signals from the background geomagnetic field fluctuations of space origin. This method is based on the concepts that waves from far distance (approximately thousands km) are planar and therefore do not have vertical component whereas field of near source origin is non-planar and have vertical component. Therefore, increased \( \frac{S_Z}{S_H} \) ratio indicates the presence of near source field. Along with the polarization ratio, we have also calculated ratio of \( \frac{S_Z}{S_X} \) and \( \frac{S_Z}{S_Y} \) to show the dominance of vertical field to either of horizontal components (N–S or E–W).

For calculating fractal dimension from spectral slope (\( \beta \)), fractal dimension (FD) \( D \) is computed using the Berry’s equation (Berry 1979), i.e. \( D = (5-\beta)/2 \). Evolution of fractal dimension with time is seen in the background of earthquakes occurred within 150 km radius of MPGO Ghuttu (figure 3). Due to the superimposition of noisy fluctuations on power law spectrum, there are limitations of accuracy in the computation of spectral exponent (Smirnova et al. 2004). Considering this limitation of PSD method in the estimation of FD, we have also calculated fractal dimension using Higuchi method (figure 4). The Higuchi method is robust and is considered suitable for estimating fractal dimension for short segment of time series and therefore it can be used for the estimation of fractal dimension of non-stationary signals by dividing the signal into short length (Raghavendra & Dutt 2010). In the Higuchi method, the original time series \( y(1), y(2), y(3) \ldots \ldots \ldots y(N) \) is subdivided into \( k \) new time series \( y_{m}^{n} \), each time series is defined as \( y_{m}^{n} = \{ y(m), y(m+\tau), y(m+2\tau), \ldots \ldots \ldots \ y(m+M\tau) \} \), \( m=1,2,\ldots \ldots \tau \) where \( m \) and \( \tau \) are integers indicating an initial time and an interval time, respectively. Length of each sub-time series is expressed as \( L(\tau) \propto \tau^{-D} \) where \( D \) is the fractal dimension of time series.

The earthquake data used in this paper is collected from website of Indian Meteorological Department (IMD) (www.imd.gov.in). Global geomagnetic activity using \( K_p \) indices is considered with variation of polarization ratio and temporal evolution of fractal dimension. \( K_p \) indices are obtained from World Data Centre, Kyoto, Japan (http://wdcddb.kugi.kyoto-u.ac.jp). We have considered earthquakes within 150 km radius from MPGO, Ghuttu. The list of earthquakes occurred within 150 km radius from MPGO Ghuttu is shown in table 1.

### Table 1. List of earthquakes within 200 km radius from MPGO, Ghuttu.

| S. No. | Date       | Julian day | Time (UTC) | Lat.     | Long. | Depth (km) | Magnitude | Epicentral distance (km) |
|-------|------------|------------|------------|----------|-------|------------|-----------|--------------------------|
| 1.    | 22.02.2010 | 53         | 17:23:43   | 30.0°N  | 80.1°E| 02         | 4.7       | 143.29                   |
| 2.    | 01.05.2010 | 121        | 22:36:25   | 29.9°N  | 80.1°E| 10         | 4.6       | 148.27                   |
| 3.    | 03.05.2010 | 123        | 17:15:08   | 30.4°N  | 78.4°E| 08         | 3.5       | 35.65                    |
| 4.    | 22.06.2010 | 173        | 23:14:08   | 29.6°N  | 79.7°E| 18         | 4.7       | 138.67                   |
| 5.    | 10.07.2010 | 191        | 03:16:20   | 29.9°N  | 79.6°E| 10         | 4.1       | 108.33                   |

### 3. Results and discussion

From the polarization analysis plot in figure 2, we observed that the vertical magnetic field variations are considerably increased three times during early January, February and April month and marginally increased during few days in the month of February, March, April and June. Increased
polarization ratio \((Z/H)\) is an indicator of presence of seismo-magnetic field variations. Polarization ratio, based on planar wave field approximation for signals generated at far off distance and non-planar for near field, is used to isolate near field, non-planar seismogenic ULF emissions (Hayakawa et al. 2007; Rawat 2014). It may also be noted that this increase in the polarization ratio is also observed in the first half of year 2010 when there are earthquakes within 150 km radius from MPGO observatory. After 10 July 2010 earthquake of magnitude 4.1, there is no earthquake within 150 km radius and polarization ratio also remain below 1.0 during remaining period of the year. Observation of increased polarization ratio before earthquakes suggests the presence of precursory signature of SEM. However, it will be difficult to associate these increases with particular earthquake at this stage. In order to associate the variations with particular earthquake or to infer about the directionality of anomalous source zone, synchronous observations from more than one location are required (Dudkin et al. 2010). Variation of \(Z/X\) and \(Z/Y\) may signify directional dependency of source region of earthquakes. It may also be noted that \(Kp\) variations plotted for 1800—2100 hrs UTC, signifying global geomagnetic activity shown in the bottom panel of figure 2, do not show any one-to-one correlation of increased polarization ratio with global geomagnetic activity. Further

**Figure 2.** Ratio of vertical to horizontal components (upper two panels) and Polarization ratio \((Z/H)\) (third panel) and for the year 2010. Vertical arrows mark the days of earthquakes as per table 1. \(Kp\) variations during 1800—2100 hrs for year 2010 (bottom panel).
from the bottom panel of figure 2, it may be observed that during May 2010 when there is highest
$Kp$, signifying dominant geomagnetic activity, the polarization ratio is quite lower.

Fractal dimension obtained using FFT method in figure 3 shows large variability and variation
ranges from 0.2 to 2.5 whereas fractal dimension obtained using Higuchi method has less variability
and varies from 1.6 to 1.8. The difference in the fractal dimensions from both methods is primarily due
to the difference in time series used. In FFT method, fractal dimension is calculated for frequency band
of 0.03—0.1 Hz, whereas with Higuchi method we have considered unfiltered time series. Large variabil-
ity in fractal dimension from FFT method is due to the limitation of FFT method. Despite of the differ-
ences in the fractal dimension variability from both methods, there are distinctly two divisions in both
the time series of fractal dimension variations (figures 3 and 4) for the year 2010. Average fractal
dimension in the first half of the year is more as compared to average fractal dimension of the second
half of the year and from mid July 2010 to onward, the range of variation is reduced.

If we observe the features of fractal dimension variability, there are three things to notice, (i) sharp
daily variations, (ii) five-day running mean variations and (iii) gradual increase in the fractal dimension
variability in the first half of year 2010. Sharp daily variations of fractal dimension show antipersistent
behaviour and can be attributed to daily dynamics of solar ionospheric interaction. Similarly, five-day
running mean shown with the dashed curve in figure 4 has variation of 30 days which can also be
related to magnetosphere—ionosphere disturbances due to its proximity to the period of sun rotation.
In order to highlight the gradual increase in the fractal dimension variability, we plotted 31-day
As it can be observed from Figure 5, the fractal dimension is higher in the first half of the year as compared to the second half of the year 2010. There is a gradual increase in the fractal dimension till the June and July earthquake after which there is a decrease in the fractal dimension. The gradual increase in the fractal dimension, therefore, can be related to earthquake preparation processes. An increase in the fractal dimension before earthquakes is widely reported (Hayakawa et al. 1999; Molchanov et al. 2003; Gotoh et al. 2004; Ida & Hayakawa 2006; Rawat 2014). Further, to show that the observed gradual increase is not related with geomagnetic variations and solar-ionosphere interaction dynamics, we plotted those days which are having $K_p$ variation less than 3. The resulting plot is shown in Figure 6 and the same behaviour is observed in this plot also.

Further, in Figure 7, we have shown fractal dimension (Higuchi) variability from July 2009 to May 2011, extending observation period to six months at both ends. Extending observation beyond this period is not possible as there is a data gap of almost six months before July 2009 and May 2011 due to some technical problem in the instrument. Rawat (2014) has shown increased fractal dimension in the month of June 2011 before the earthquakes occurred in this month using Digital Fluxgate data of MPGO observatory. Therefore, the decay in fractal dimension during the second half of the year 2010 is not a cyclic phenomenon as can be observed from Figure 7. Therefore, it will be worthwhile to relate this gradual increase in fractal dimension of ULF geomagnetic variation to the preparatory process of earthquakes. Increased fractal dimension during earthquakes within 150 km radius of observation may be associated with the different stages of self-organized criticality in the crust or lithosphere associated with the earthquake cycle.
4. Conclusion

Polarization ratio along with ratio of vertical to horizontal field is an important method for the discrimination of weak precursory signatures from the naturally occurring EM field variations. Increased polarization ratio during the first half of the year before earthquakes within 150 km radius of MPGO observatory indicates the presence of SEM signals for earthquake process. It also indicates that the effective area of seismogenic processes leading to earthquake is limited and the extent of this area depends upon the earthquake parameters. Therefore, signify the need of network of monitoring stations. Simultaneous monitoring of ULF geomagnetic variations will not only help to reduce the effect of solar-ionospheric contributions but also help to relate such changes with the directionality and size of the earthquake. Higuchi method for estimating fractal dimension is robust and provides stable and consistent estimates of fractal dimension as compared to FFT method. It is interesting to note that the fractal characteristics of ULF band geomagnetic variations can exhibit precursory behaviour and the behaviour is attributed to gradual increase in fractal dimension before earthquakes as observed elsewhere also. Different variability in different components of EM field indicates directional dependence of source zone with respect to observing station. Dudkin et al. (2010) have demonstrated the localization of anomalous source zone of ULF emission associated with earthquake processes using two station observations in Koyna region. If network of ULF

Figure 5. Fractal dimensions using Higuchi method with 31 days running mean (red line). To view this figure in colour, see the online version of the journal.
Figure 6. Fractal dimensions during days when $Kp$ is less than 3.

Figure 7. Higuchi Fractal dimension variability from Jul 2009 to May 2011. Vertical arrows mark the days of earthquakes within 150 km radius from MPGO, Ghuttu.
monitoring station is used in a region, source localization of anomalous zone corresponding to earthquake sources can be done utilizing Dudkin et al. (2010) method and ULF emission associated with particular earthquake may be traced.

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**Disclosure statement**

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**References**

Arora BR, Rawat G, Kumar N, Choubey VM. 2012. Multi-Parametric geophysical observatory: gateway to integrated earthquake precursory research. Curr Sci India. 103:1286–1299.

Bak P, Tang C, Wiesenfeld K. 1987. Self-organized criticality: an explanation of 1/f noise. Phys Rev Lett. 59:381–384.

Bak P, Tang C, Wiesenfeld K. 1988. Self-organized criticality. Phys Rev. 38:364–374.

Berry MV. 1979. Diffractals. J Phys A Math Gen. 12:781–797.

Burlaga LF, Klein LW. 1986. Fractal structure of the interplanetary magnetic field. J Geophys Res. 91:347–350.

Chauhan V, Pandey U, Singh OP, Singh B, Arora BR, Rawat G, Pathan BM, Sinha AK, Sharma AK, Patil AV. 2012. A search for precursors of earthquakes from multi-station ULF observations and TEC measurements in India. Indian J Radio Space. 41:543–556.

Dudkin F, Rawat G, Arora BR, Korepanov V, Leontyeva O, Sharma AK. 2010. Application of polarization ellipse technique for analysis of ULF magnetic fields from two distant stations in Koyna-Warna seismoactive region, West India. Nat Hazard Earth Sys. 10:1513–1522.

Feder J. 1988. Fractals. New York (NY): Plenum Press. p. 283.

Fedorov E, Pilipenko V, Uyeda S. 2001. Electric and. magnetic fields generated by electrokinetic processes in a conductive crust. Phys Chem Earth. C26:793–799.

Fitterman DV. 1978. Electrokino and magnetic anomalies associated with dilatant regions in a layered earth. J Geophys Res. 83:5923–5928.

Gotoh K, Hayakawa M, Smirnova N. 2003. Fractal analysis of the ULF geomagnetic data obtained at Izu Peninsula, Japan in relation to the nearby earthquake swarm of June–August 2000. Nat Hazard Earth Sys. 3:229–236.

Gotoh K, Hayakawa M, Smirnova N, Hattori K. 2004. Fractal analysis of seismogenic ULF emissions. Phys Chem Earth. 29:419–424.
Harada M, Hattori K, Isezaki N. 2004. Transfer function analysis approach for anomalous ULF geomagnetic field change detection. Phys Chem Earth. 29:409–417.

Hattori K, Serita A, Gotoh K, Yoshino C, Harada M, Isezaki N, Hayakawa M. 2004. ULF geomagnetic anomaly associated with 2000 Izu islands earthquake swarm. Phys Chem Earth. 29:425–435.

Hayakawa M, Kawate R, Molchanov OA, Yamuro K. 1996. Results of ultra-low-frequency magnetic field measurements during the Guam earthquake of 8 August 1993. Geophys Res Lett. 23:241–244.

Hayakawa M, Tetsuya I, Smirnova N. 1999. Fractal analysis of ULF geomagnetic data associated with the Guam earthquake on August 8, 1993. Geophys Res Lett. 26:2797–2800.

Hayakawa M, Hattori K, Ohta K. 2007. Monitoring of ULF (ultra-low-frequency) geomagnetic variations associated with earthquakes. Sensors. 7:1108–1122.

Higuchi T. 1988. Approach to an irregular time series on the basis of fractal theory. Physica D. 31:277–283.

Higuchi T. 1990. Relationship between the fractal dimension and the power-law index for a time series: a numerical investigation. Physica D. 46:254–264.

Ida Y, Hayakawa M. 2006. Fractal analysis for the ULF data during the 1993 Guam earthquake to study prefracture criticality. Nonlinear Proc Geophys. 13:409–412.

Ismaguilov V, Kopytenko Y, Hattori K, Hayakawa M. 2003. Variations of phase velocity and gradient values of ULF geomagnetic disturbances connected with the Izu strong earthquake. Nat Hazard Earth Sys. 3:211–215.

Israil M, Tyagi D, Gupta PK, Sri Niwas. 2008. Investigations for imaging electrical structure of Garhwal Himalaya corridor, Uttarakhand, India. J Earth Syst Sci. 117:189–200.

Kayal JR, Ram S, Singh OP, Karunakar G. 2003. Aftershocks of the March 1999 Chamoli Earthquake and seismotectonic structure of the Garhwal Himalaya. B Seismol Soc Am. 93:109–117.

Kopytenko Y, Ismagilov V, Hayakawa M, Smirnova N, Troyan V, Peterson T. 2001. Investigation of the ULF electromagnetic phenomena related to earthquakes: contemporary achievements and the perspectives. Ann Geofis. 44:325–334.

Kopytenko YA, Ismagilov VS, Hattory K, Hayakawa M. 2006. Determination of earth position of a forthcoming strong EQ using gradients and phase velocities of geomagnetic disturbances. Phys Chem Earth. 31:292–298.

Kumar N, Rawat G, Choubey VM, Hazarika D. 2013. Earthquake precursory research in western Himalaya based on the MPGO data. Acta Geophys. 61:977–999.

Molchanov O, Schekotov A, Fedorov E, Belyaev G, Gordeev E. 2003. Preseismic ULF electromagnetic effect from observation at Kamchatka. Nat Hazard Earth Sys. 3:203–209.

Raghavendra BS, Dutt N. 2010. Computing fractal dimension of signals using multiresolution box-counting method. World Acad Sci Eng Technol. 61:1223–1238.

Rawat G. 2014. Characteristic ULF band magnetic field variations at MPGO, Ghuttu for the 20 June 2011 earthquake in Garhwal Himalaya. Curr Sci India. 106:88–93.

Rawat G, Arora BR, Gupta PK. 2014. Electrical resistivity cross-section across the Garhwal Himalaya: proxy to fluid-seismicity linkage. Tectonophysics. 637:68–79.

Schekotov AY, Molchanov OA, Hayakawa M, Fedorov EN, Chebrov VN, Sinitsin VI, Gordeev EE, Belyaev GG, Yakova NV. 2007. ULF/ELF magnetic field variations from atmosphere induced by seismicity. Radio Sci. 42RS6S90:1–13.

Schekotov AY, Molchanov OA, Hayakawa M, Fedorov EN, Chebrov VN, Sinitsin VI, Gordeev EE, Andreesky, SE, Belyaev GG, Yakova NV, et al. 2008. About possibility to locate an EQ epicenter using parameters of ELF/ULF pre-seismic emission. Nat Hazard Earth Sys. 8:1237–1242.

Smirnova N, Hayakawa M, Gotokh M. 2004. Precursory behavior of fractal characteristics of the ULF electromagnetic fields in seismic active zones before strong earthquakes. Phys Chem Earth. 29:445–451.

Turcotte DL. 1997. Fractals in geology and geophysics. 2nd ed. Cambridge: Cambridge University Press.

Uyeda S, Nagao T, Hattori K, Noda Y, Hayakawa M, Miyake K, Molchanov O, Gladychev V, Baransky L, Schekotov A, et al. 2002. Russian–Japanese complex geophysical observatory in Kamchatka for monitoring of phenomena connected with seismic activity. In: Hayakawa M, Molchanov O, editors. Seismo electromagnetics: lithosphere-atmosphere -ionosphere coupling. Tokyo: TERRAPUB; p. 413–420.

Uyeda S, Nagao T, Kamogawa M. 2009. Short term earthquake prediction: current status of seismo-electromagnetics. Tectonophysics. 470:205–213.

Varotsos P. 2005. The physics of seismic electric signals. Tokyo: TERRAPUB. p. 338.

Varlamov A, Smirnova N, Hayakawa M, Yumoto K. 2012. Fractal characteristics of the ULF emissions along a meridian profile based on the 210 MM stations data. Acta Geophys. 60:928–941.

Yonaiguchi N, Ida Y, Hayakawa M, Masuda S. 2007. Fractal analysis for VHF electromagnetic noises and the identification of preseismic signature of an earthquake. J Atmos Sol-Terr Phy. 69:1825–1832.

Yoshida S. 2001. Convection current generated prior to rupture in saturated rocks. J Geophys Res. 106:2103–2120.