Indexing of ULF Electromagnetic Emission to Search Earthquake Precursors

ULF電磁放射を用いた地震前兆の探査

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Abstract

Three possible indices are examined to isolate precursory seismo-EM signals of moderate earthquakes from the natural ULF variations of solar-terrestrial origin recorded in the seismoactive Koyna-Warna region, western India. The temporal variations of polarization ratios as well as fractal dimensions/spectral exponent (ß) in the power law relation $S(f)= f^{\beta}$, which have been used with success in discriminating the seismo-EM signals of strong earthquakes, fail to reveal any perturbation which can unambiguously be related with the occurrence of two moderate earthquakes studied here. Instead, both indices are negatively correlated with solar/geomagnetic activity, a manifestation of the solar modulated solar wind-magnetosphere-ionosphere interactions. A new index defined by the ratio of major axis of the polarization ellipse (PE) traced out by vector magnetic field components at two stations, provides a quantitative mode to distinguish ULF signals dominated by seismo-EM origin from those associated with solar-terrestrial origin. The numbers of ULF events qualifying as seismo-EM exhibit a pattern similar to that deciphered in the spectral exponent before the large earthquakes. Seismo-EM origin of such qualified ULF events is further corroborated by observation as intersections plane of polarization ellipses, which at any instant contains the source of the EM fields, clutter in the source region of the Koyna seismic activity. Further, the orientation of seismogenic ULF signals in the Koyna-Warna corresponds well with a causative fault zone inferred from long-term earthquake data as well as fault plane solutions of the two earthquakes discussed here. Thus, potential seismo-EM precursory signals isolated with the help of polarization could be a suitable index for integration with other geophysical parameters.

アブストラクト

地震活動の高いインドの西部Koyna-Warna地域で観測された超高層起源の自然ULF変動を用いて、地震に伴う電磁信号を分離する三つの手法を調査した。大きな地震の電磁気信号を分離するのに成功している偏波比とフラクタル次元という従来の手法を試したが、二つの中規模地震に対しては明瞭な異常を検出することができなかった。しかし、その二手法で得られた指標が太陽/地磁気活動と負の相関を示したことから、観測された電磁信号は太陽を起源とした太陽圏ー磁気圏ー電離圏相互作用の帰結であると考えられる。そこで、二つ

の観測点で観測された磁界３成分により描かれた偏波楕円の主軸の比によって定義される新しい指標を第３手法として提案し、これが太陽地球起源のULF変動と地震ULF変動とを定量的に分離できることを示す。地震に関係すると考えられるULF放射の頻度は、大地震の時のフラクタル次元の時間変化と同様の変化を示し、本手法の有用性を証明することができた。

1. Introduction

With the hope that earthquake (EQ) precursors could well lay the roadmap for short-term EQ prediction, monitoring of precursory phenomena have continued for more than half of the last century [Rikitake, 1982; Bakun and Lindh, 1985; Lomnitz, 1994; Silver and Wakita, 1996]. Amongst the wide variety of precursors, the anomalous electromagnetic (EM) emission in ultra low frequency (ULF) band (0.001-10 Hz) have received large attention and considered potential candidate for short-term EQ prediction [Park et al., 1993; Hayakawa et al., 1996, 2000, 2007; Molchanov et al., 2004; Molchanov and Hayakawa, 2008]. Despite some important leads, there is wide spread skepticism about their applications to real time prediction. Uyeda et al. (2009), in a lucid review, have traced factors responsible for the prevailing skepticism about EQ precursors as a whole and seismo-EM precursors in particular. The skepticism is basically rooted in: (i) there are no proven physical mechanisms or even when plausible physical explanations or models are provided, there are many free parameters in the model that are poorly constrained. Although various mechanisms including (a) movement of conductive medium in the Earth's permanent magnetic field [Surkov et al., 2003, 2004]; (b) displacements of boundaries between high and low conductive crustal blocks [Dudkin et al., 2003]; (c) electrokinetic effect [Fedorov et al., 2001]; (d) piezoelectric or piezomagnetic effects [Ogawa and Utada, 2000] and (e) microfracture electrification [Molchanov and Hayakawa, 1995] etc. are advanced, the effectiveness of specific mechanism to explain particular features of field observations in varied tectonic settings are yet to be established; (ii) the size of the area around an eventual EQ epicenter where precursory signals could be observed is an open unresolved issue. Controlled by the scaling relationship of fault length and EQ magnitude, the anomalies generally are confined to a small area around the epicenter and identification of some anomalous phenomena prior to an EQ usually depends on the luck of having good experiment in operation [Ciceron et al., 2009]. In another extreme, some of the anomalously large signal, like recorded in association with M7.1 Loma Prieta EQ [Fraser-Smith et al., 1990; Bleier et al., 2009] may well be cases of chance detection due to the proximity of the magnetometer to the epicenter. However, underground seismo-EM emission generated by any of the above mechanisms attenuates only little in crustal material and hence on theoretical considerations field can be detected on ground to large distances up to 100-150 km [Hayakawa et al., 2007] whereas the emission emanating successfully from surface can propagate unabatedly to ionospheric heights and thereby facilitating their large-scale detection by satellite based sensors [Hattori, 2004; Parrot et al., 2007]. This is a unique advantage of EM precursors over the other class of precursors. (iii) various geophysical time series searched for EQ precursors have characteristic time variability related to inter-planetary, terrestrial, hydrological, environmental, tectonic sources etc. The successful isolation and documentation of weak precursory signals are, therefore, largely controlled by the extent to which these background variations can be estimated and eliminated. The applications of data adopted numerical techniques are critical to understand the sources and nature of the time variability of different geophysical time series. Often when recordings are not especially designed for EQ precursory research, due to the paucity of long length of data prior to an EQ, less vigorous tools are adopted, casting doubts on the characterization and isolation of EQ precursors. Therefore, development of strategies and methodologies to document and validate of EQ precursors is an area of current active interest [Ouzounov et al., 2011].

The EM emissions in ULF band are primarily of solar-terrestrial origin resulting from solar wind-magnetosphere-ionosphere interactions, and attain high variability following an increased activity on the Sun. Therefore the discrimination of weak seismo-EM signals from the background natural EM fields of ionospheric and magnetospheric origin is fundamental requirement. The polarization ratio [Hayakawa et al., 1996; Hirano and Hattori; 2011] and fractal dimension [e.g., Hayakawa et al., 1999, 2007; Ida and Hayakawa, 2006] are used effectively to isolate seismo-EM signals for strong EQs. In the present study, we apply these widely used formulations to search and isolate seismo-EM signals of moderate magnitude EQs in the Koyna-Warne region, western India, known for prolonged reservoir triggered seismicity. In addition, we propose a new index defined by the ratio of major axis of the polarization ellipse traced out by time varying magnetic data at two simultaneously operating stations, one within the seismic zone and second a few tens of km away.

2. Study Area, Seismic History and Experiment Design

In the seismicity map of the world, the Koyna-Warna region in the southern part of Deccan Volcanic Province, Western India has attracted attention as a classical seat of reservoir triggered seismicity in Fig. 1 [for review see Gupta, 2002 and references therein]. The largest triggered EQ of M 6.3 occurred here on 10 December 1967, and since then the area has remained seismoactive [Gupta, 2005]. During the past four and half decades, 19 EQs of $M_L \geq 5$ and about 170 EQs with $M_L \geq 4$ have occurred, all confined to a well defined belt of roughly 20x30 km2 with hypocentres $h \leq 12$ km [Gupta et al., 2007]. Such features make the area unique for studying peculiarities of ULF magnetic field during EQ preparation process.

Since 1993, seismic activity in Koyna-Warna region is being monitored by a closely spaced network of seven modern 3-component seismometers [Gupta, 2002]. During the present observation campaign of April-May, 2006, more than 700 EQs with magnitude in the range of M_L= 0.5-4.7 were recorded. The spatial distribution of these EQs with M_L>2.5 (Fig. 1) completely overlapped with the area outlined by seismic activity over the past 45 years. During our observation campaign, 2 largest EQs recorded included; EQ1 on 17 April 2006 (M_L=4.7, h=3.9 km, 17.13 N, 73.78 E, UT 16.39.59.4) and EQ2 on 21 May 2006 (M_L=4.2, h=5.1 km, 17.17 N, 73.77 E, UT 20.29.01.2) and their fault plane solutions as determined by NGRI are shown as inset in Fig.1. The examination of ULF magnetic activity in relation to these 2 modest magnitude EQs is a central goal of the present report.

To study the nature of seismo-EM activity in the Koyna-Warna sector, a station was established at Koyna within the limits of focused seismic zone. Another station, ~100 km away from Koyna station, was functional in the campus of the Shivaji University, Kolhapur (Fig. 1). Extremely low-noise (0.2pT/

Hz$^{0.5}$ at f=1Hz) 3-component LEMI-30 magnetometers were deployed at both stations. The LEMI-30 magnetometers operate in the frequency range of 0.001-32 Hz and are ideally suited to record the most promising EQ magnetic precursors in ULF band, which are found dominant below 0.1 Hz [Hayakawa et al., 2004, 2007]. Magnetometers measured variations in 3-orthogonal components in geomagnetic coordinates at sampling rate of 64 samples per second over the entire observational campaign period of April 1- May 31, 2006. Since the absolute value of declination is less than 1 degree, the measured fields were transformed to geographic north-south (X), east-west (Y) and vertical (Z) components without much loss of precision. The continuous data were re-sampled to create new time series with sample interval of 1s by averaging measured 64 samples per second. This re-sampled time series formed base for further processing to derive different index parameters to isolate seismo-EM signals from background natural fluctuations.

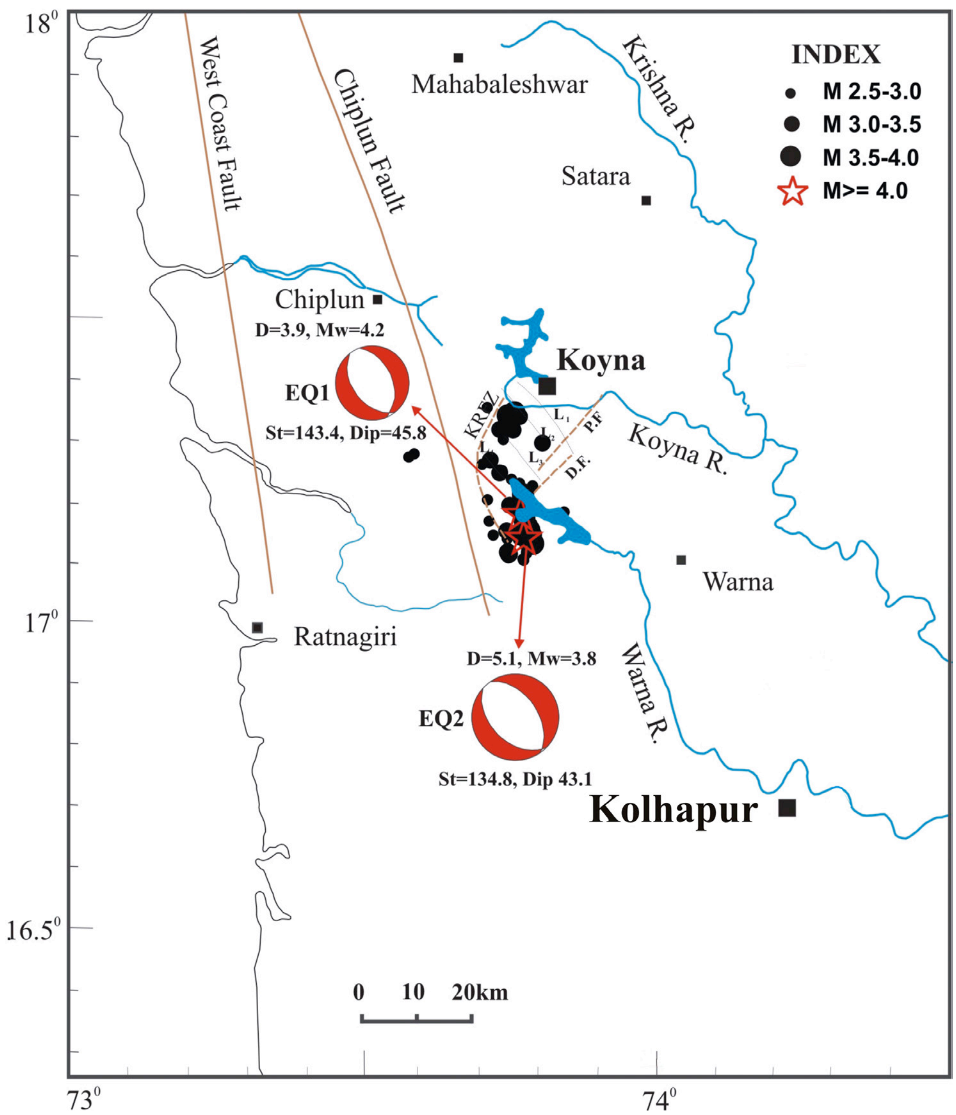


Figure 1 Map of western India showing locations of ULF magnetometers established at Koyna and Kolhapur to monitor EM emission related to reservoir triggered seismicity associated with Koyna-Warna reservoirs. Black dots represent epicentres of EQs recorded during the period of March-June 2006. Fault plane solutions of two moderate EQs (M_L>4) are also shown.

3. Analysis and Results

3.1 Polarization Analysis

Polarization analysis incorporating the ratio S_Z/S_H, where S_Z and S_H are the spectral densities of vertical and horizontal magnetic field components in the select frequency band was introduced and used with some success in distinguishing seismo-EM signals from the background geomagnetic field fluctuations [Hayakawa et al., 1996]. The basic physical rationale of this approach is that the frequency range of seismo-EM signals in ULF magnetic band overlaps with the Pc3-Pc5 band of micropulsations [Hayakawa et al., 2007; Kopytenko et al., 2001; Molchanov et al., 2004]. The sources of these pulsations are dominantly of magnetospheric origin related to field line resonance or large-scale cavity oscillations [Waters et al., 1994]. The spatial scale-length of these magnetospheric current system, except in polar regions, are typically several thousand kilometers, and therefore permits plane wave approximation for natural electromagnetic waves [Cagnaird, 1953]. A net consequence of the plane wave approximation is that the amplitude of vertical field tends to be zero. In contrast, characteristics spatial scale-length of the ULF signal emanating from within the focal zones is no more than few hundred km [Hayakawa et al., 2007], producing substantial vertical fields. The dominance of the later would result in highly non-zero S_Z/S_H ratio.

In addition to the presence of magnetospheric component in the measured magnetic field, a weak secondary ionospheric contribution arises due to instantaneous penetration of the magnetospheric inducted polar electric field to low and middle latitude [Trivedi et al., 1997], to minimize the influence of ionospheric part on the polarization ratio we confined our analysis to only one hour each day centered at local night. Fig. 2 gives the histogram of daily S_Z/S_H ratio, averaged over 5 spectra computed using selected hour data with overlapping time windows, each of 1024s. The plots are shown for a representative frequency band of 0.03-0.1 Hz because seismo-EM signals dominate in this frequency band. The magnetic field compositions in this band also display power law and are later used to compute the fractal dimension (Fig. 3b). The observed S_Z/S_H ratio shows significantly variability with mean value of 0.62±0.27 statistically different from zero. As noted earlier, in the event of magnetospheric origin (plane wave approximation), the more anticipated value of the ratio is expected to be close to zero at any station, provided the electrical conductivity distribution in the crust beneath the measuring site varies only as a function of depth (1-D approximation). Any lateral variation in conductivity can cause a local perturbation in induced currents causing local scale anomalies in time varying vertical magnetic fields and, thus producing non-zero S_Z/S_H ratio. This in essence forms the working principle of geomagnetic deep sounding designed to map geoelectrical structures marked by later conductivity contrast [Gough and Ingham, 1983]. Since such induction effects controlled by the orientation of lateral conductivity heterogeneity, may be differently reflected in the S_Z/S_X and S_Z/S_Y ratios, to understand the influence of induction effects the nature of variability of S_Z/S_H ratio is examined in relation to S_Z/S_X and S_Z/S_Y ratios.

This simple mode of presentation shows that despite the small differences in the mean values, polarization ratios obtained by normalizing the vertical fields with respect to S_H, S_X and S_Y, exhibit similar temporal variability. The temporal variability of ratios, particularly S_Z/S_H and S_Z/S_X , shows a strong negative correlation with global geomagnetic index Kp (Table 1). An important feature of this correlation is that as the geomagnetic activity increases, the polarization ratio tends to be the expected value close to zero, validating an implicit assumption of near plane wave approximation for the source currents in ULF band and thus facilitating use of polarization parameters in distinguishing seismo-EM signals from background geomagnetic activity. Given the high sensitivity of the LEMI-30 search coil magnetometer used here, magnetic signals with amplitude as low as 1-80 pT are well resolved in individual field component but not many individual ratios when seen in relation to EQ occurrences do not reveal any strong perturbation which can be classified as seismo-EM precursor candidate (see Fig. 2). The only exception is S_Z/S_H as well as other ratios on April 3, 2006, which may qualify to be seismo-EM precursor to a moderate EQ of April 17, 2006 (EQ1). In order to check whether the variability of polarization ratio in any way is controlled by background seismic activity, the upper panel in Fig. 2 gives the daily plot of cumulative energy (E) released by EQs/micro EQs, computed using the following relation:

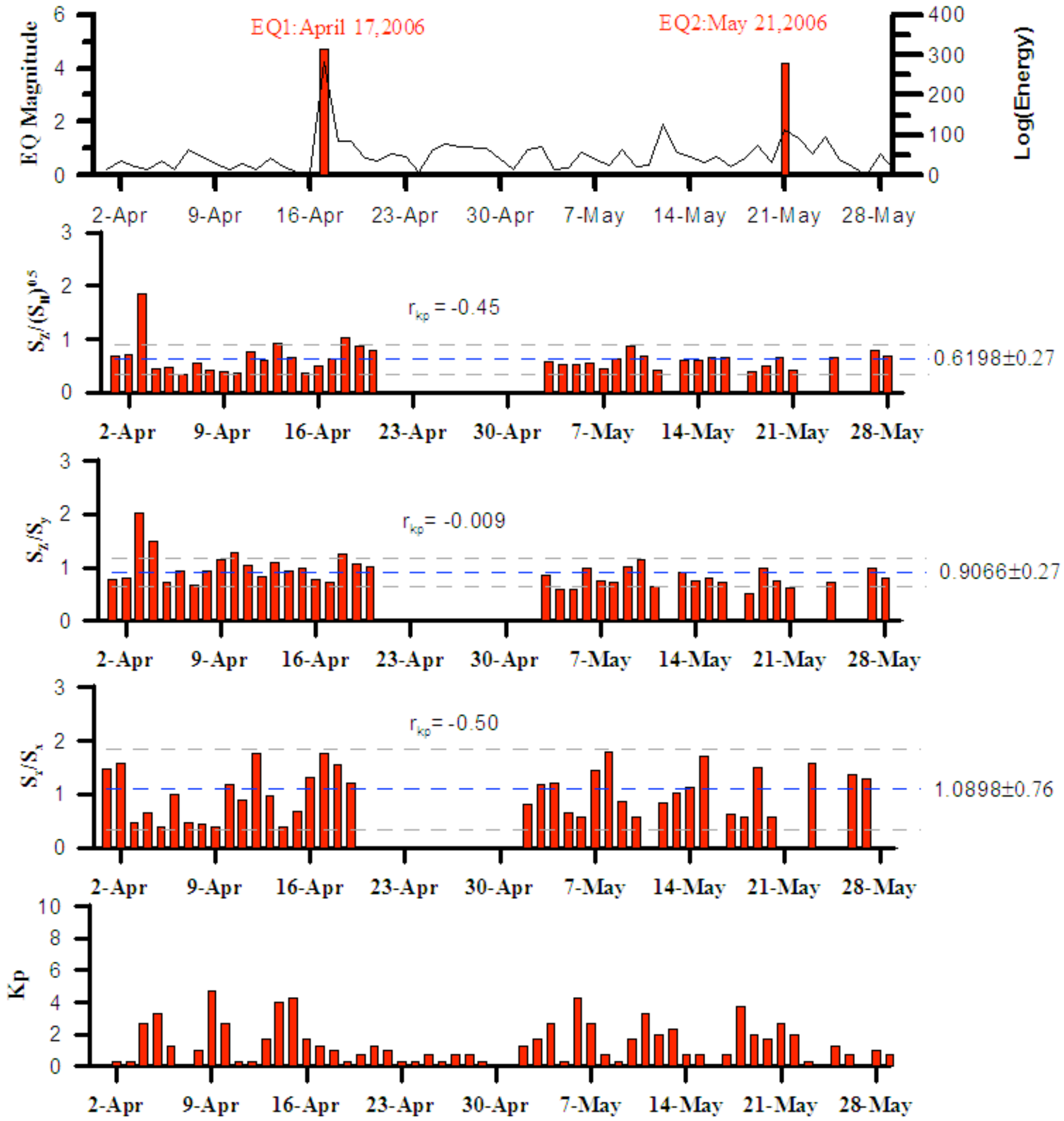


Figure 2 Variation in polarization ratios obtained by normalizing the spectral density in vertical component (S_Z) with respect to horizontal components in north-south (S_X), east-west (S_Y) and total horizontal field (S_H) in the frequency range of 0.03-0.1 Hz. The lower panel gives a plot of geomagnetic activity index, Kp sums, and the top panel gives a daily plot of seismic energy (E) released by local EQs during April-May 2006. The gaps in data are related to days of power failure.

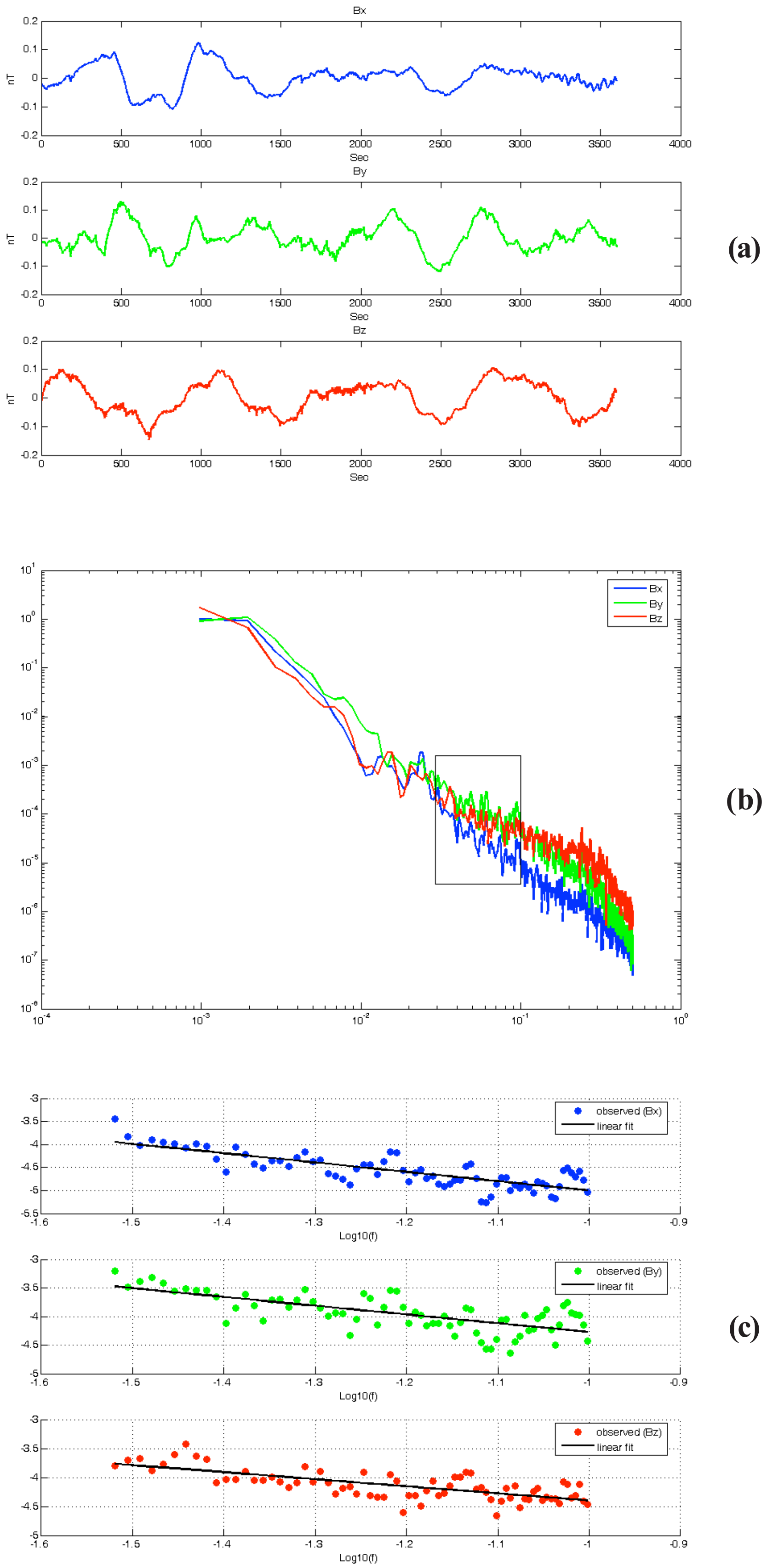


Figure 3 (a) Typical examples of ULF geomagnetic variations in north-south (Bx) , east-west (By) and vertical (Bz) components during the local mid-night (1800-1900 UT) at Koyna station (Fig. 1), (b) stacked plot of the power spectrum for the variations shown in (a). Note the exponential decay of power in the ULF frequency band (0.03-0.1), (c) best fit line estimating the spectral slope ß for the frequency band 0.03-0.1 Hz.

Parameter	$1=S_z/S_x$,	1=Sz/Sy	1=Sz/SH
r_{12}	-0.5031	-0.1798	-0.4156
r_{13}	0.003	-0.1220	-0.0359
r_{23}	-0.0136	-0.0136	-0.0136
$r_{12,3}$	-0.5031	-0.1829	-0.1829
$r_{13,2}$	-0.0045	-0.01265	-0.1265

Table 1 Correlation and Partial Correlation Coefficient : Various Polarization (1), Ratios with Kp Indices (2), Earthquake Energy (3)

$$\mathrm{Log}_{10}\, E = 4.8 + 1.5\, M_L$$

where M_L is local magnitude of recorded EQ.

The plots as well as correlation coefficients between E and different polarization ratios do not indicate any statistically significant relation (Table 1). In the statistical sense this correlation does not improve as partial correlation between E and polarization ratios when the effect of solar/geomagnetic activity variability is kept constant. It seems likely that small amplitude EQ precursory seismo-EM signals, even if present in relation to the moderate magnitude EQ occurrences, are completely masked by much stronger variability of background geomagnetic field to stand out clearly in S_Z/S_H plot.

3.2 Fractal Analysis

It is now widely accepted that the dynamics of the EQs manifest the state of the system driven to the point of self-organized criticality [Bak, 1997]. Since in this state, the system is highly sensitive to any external perturbation whose time response exhibits characteristic of flicker noise or 1/f noise. Therefore, fractal properties by investigating the scaling characteristics of signals from sub-critical level to a self-organized criticality state could give us information on the EQ processes [Hayakawa et al., 1999]. This has been the motivation to apply fractals method to extract the seismo-EM precursory signals from scaling characteristics of the ULF geomagnetic time series [Gotoh et al., 2003; Smirnova et al., 2004]. Here, we analyze the data set from seismically active Koyna region to check how the fractal dimensions corroborate the polarization or provide additional information to isolate precursory seismo-EM signals.

The analysis procedure followed is similar to that adopted by Hayakawa et al. [1999] to search peculiarities in ULF data in association with the Ms=8 Guam EQ. We analyzed the data of one-hour each day over the entire period of observation campaign. The interval of one-hour selected for analysis was centered at local mid-night in order to exclude effect of ionospheric component. Each of 5 overlapping time sections from one-hour data (Fig. 3a), each of 1024s, were de-trended, smoothened with Hanning window and finally subjected to FFT. The resulting power spectra, S(f), for five sections were overlapped and those displaying power law $S(f)= f^{\beta}$ were averaged to obtain the most coherent decay pattern of amplitude with frequency (Fig. 3b), which is the characteristics of fractal time series. The slope ß of the spectrum is next estimated using the best fit approximation to the spectrum plotted on log-log scale for the frequency range of 0.03-0.1 Hz (Fig 3c). This frequency band is invariably best defined by the linear segment. Since the slope ß is related to the fractal dimension 'D' through the relation (ß=5 -2D), we preferred to examine directly the time evolution of ß over the entire period of observation. Since we have measured 3-orthogonal component of the geomagnetic field, we have three independent time series of slopes, one each corresponding to X, Y and Z (Fig. 4).

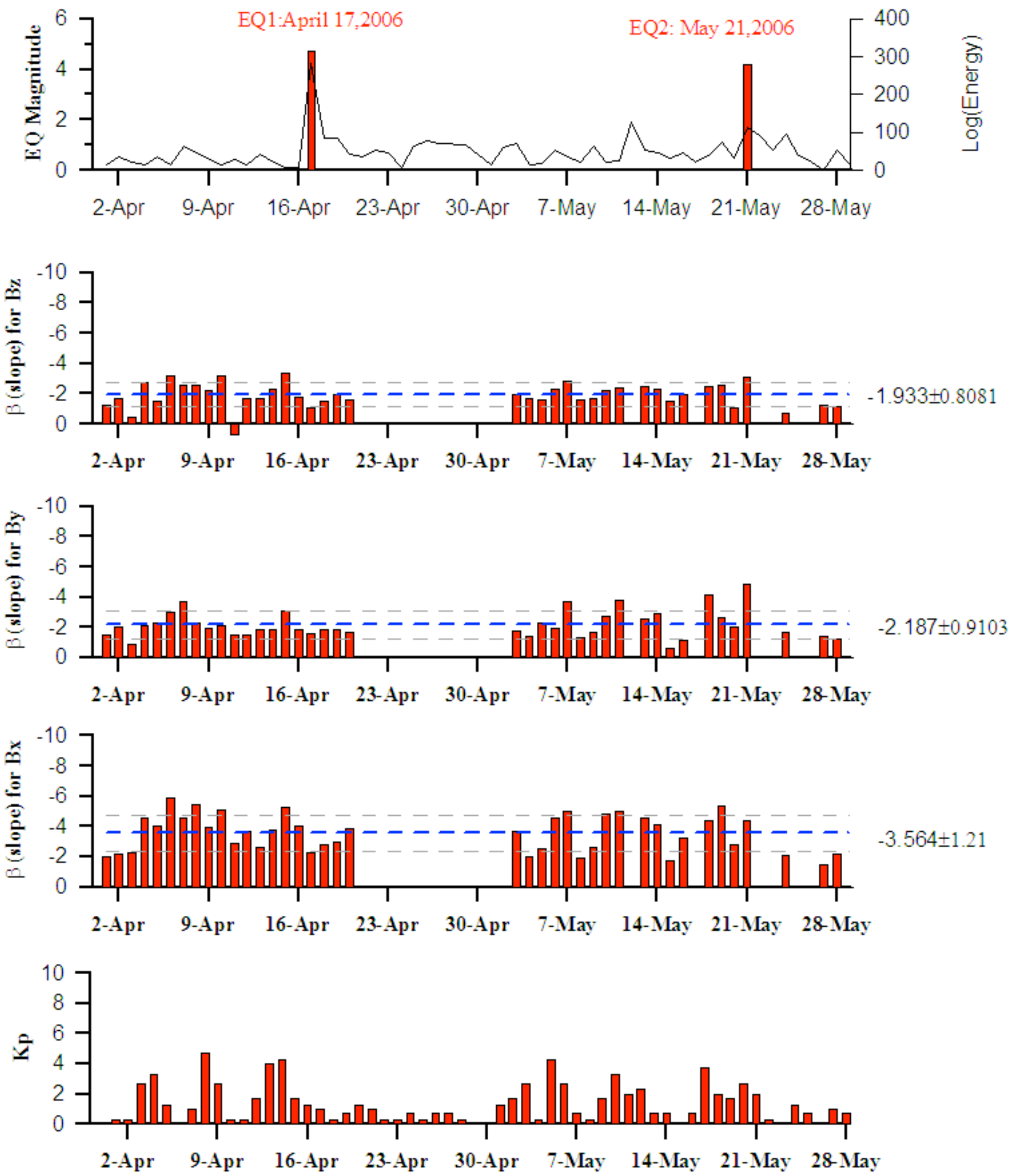


Figure 4 Histogram showing the time evolution of spectral slope ß of ULF emissions recorded in various geomagnetic components during April-May, 2006 at Koyna component. The lower panel gives a plot of geomagnetic activity index, Kp sums, and the top panel gives a daily plot of seismic energy (E) released by local earthquakes during April-May 2006. The gaps in data are related to days of power failure.

Parameter	1= βx	1= βy	1=βz
r_{12}	-0.5352	-0.4141	-0.5211
r_{13}	0.1472	0.0270	0.1329
r_{23}	-0.0133	-0.0133	-0.0133
$r_{12,3}$	-0.5392	-0.4139	-0.5241
$r_{13,2}$	0.1658	0.0236	0.1476

Table 2 Correlation and Partial Correlation Coefficient: Spectral Exponent (1) in Different Magnetic Components with Kp Indices (2), Earthquake Energy E(3)

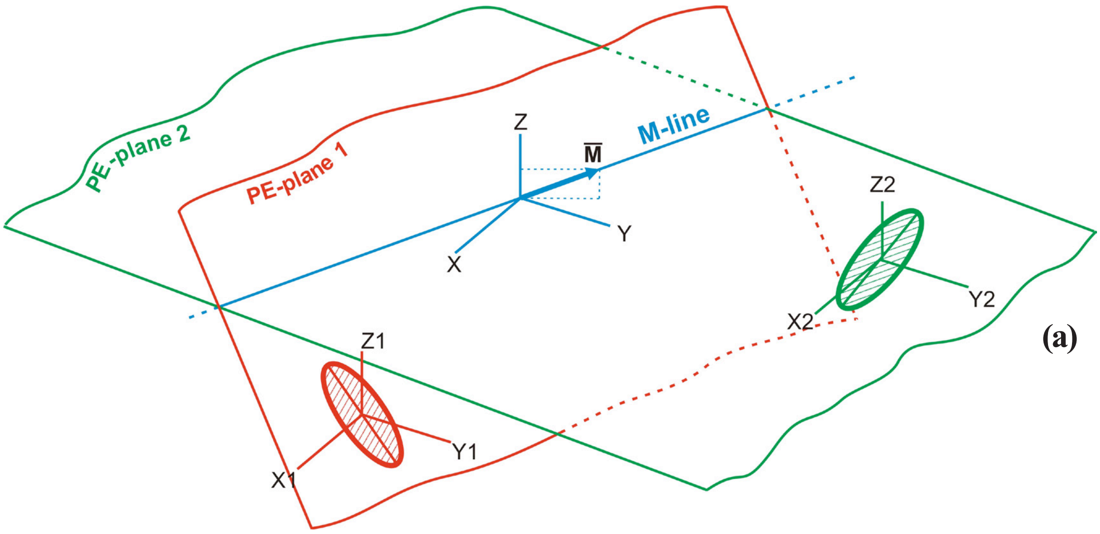
The fractal dimension as represented by the slope of the spectrum of ULF time series is found to be highly variable. The mean of each component differs but when normalized with respect to the standard deviation the degree of variability is comparable in each component. More striking is that the temporal variations in each component over the entire period of observation are identical and show a strong negative correlation with geomagnetic activity index Kp (Table 2). The time sequence of ß neither depict any rapid change related to occurrences of two modest EQs EQ1 and EQ2 on April, 17 and May 21, 2006 nor any organized trend can be inferred 10-15 days prior to the EQs. More significantly the value of ß does not attain a value close to one, the later being characteristic feature of flicker noise and hence indicator of self organized system reaching the point of critical state [Bak, 1997]. Statistically also the time evolution of ß does not depict any significant relation with energy released by local EQs whether the effects of geomagnetic activity are statistically eliminated or not (Table 2).

3.3 Polarization Ellipse Method

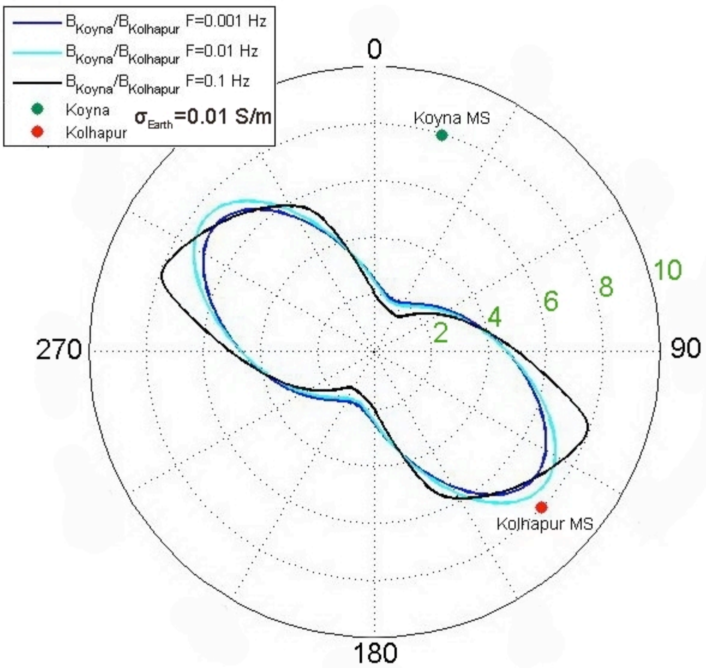
The geomagnetic field variations in ULF band can be represented by harmonic (periodic) function and as a consequence the locus of time varying magnetic fields in 3-orthogonal components traces out the polarization ellipse (PE) in space. The PE plane at any time contains the source of magnetic field, and this property of the PE is exploited to extract information on the source azimuth (direction) and location of seismo-EM signals [Du et al., 2002; Schekotov et al., 2007, 2008; Ismaguilov , 2003; Surkov et al., 2004]. If synchronous observations at two or multiple recording sites are available, the intersection line of PE planes from distant stations (Fig. 5a), locate the source region of magnetic fields. Taking advantage of this property, a new method of source location has been proposed and was test applied to the data of the present pilot experiment in Koyna-Warna region [Dudkin et al., 2010]. Since details of the formulation and applications are already discussed in Dudkin et al. [2010], here we shall only focus on the merit of this formulation in discriminating signals of seismo-EM origin from those of magnetospheric/ionospheric origin.

To have larger data base, the dynamic Fourier spectra (DFS) for all 24 hours of the day were calculated, each time using a sliding window of 1024 points with sampling interval of 1s. Then in each

DFS, the amplitude and phase in X, Y and Z for a pre-defined frequency band (0.001-0.5 Hz) were used to calculate the parameters of PE for both measuring site at Koyna and Kolhapur. As the PE plane at any time contains the source of magnetic field, the intersection line of PE planes from observations at two distant stations (Fig. 5a), locate the source region of magnetic fields. Assuming the magnetic-dipole type configuration, the magnetic moment of an elementary magnetic dipole placed at the intersection of the PE planes was calculated from the field components at the measurement points. Further taking cognizance of the large differences in dimension of the two sources, seismo-EM sources and natural background variations, we calculated the ratio of PE major axes at Koyna and Kolhapur measuring sites



(a)



(b)

Figure 5 (a) Intersection plane that contains the magnetic source represented by PE of ULF signals recorded at two synchronous stations (Adopted from Dudkin et al., 2010).
(b) PE major axes ratio at two recording stations, e.g. Koyna and Kolhapur, along the direction of the magnetic dipole placed at the intersection plane of PEs.

against the orientation of horizontal magnetic dipole placed in EQ hypocentres. The results of calculation are shown in Fig. 5b, where the minimal ratio of PE major axes is about 2. Therefore, it appears that for long wave-length current systems associated with background geomagnetic variations, the major axis ratios of less than 2 can be attributed to fields dominated by magnetospheric origin whereas magnetic dipoles with PE major axes ratio exceeding the threshold value 2 can be ascribed to the possible seismo-EM precursory signals.

The number of magnetic dipoles qualifying, based on above criterion, as seismo-EM and magnetospheric dominated signals per day are plotted in Fig. 6a, b with daily Kp-index as well as with occurrence of EQs with local magnitude >2.5 during the observation campaign interval. The good correlation between the numbers of signals of the ionospheric origin and the value of Kp-index is clearly seen. The number of seismo-EM signals increase before EQ1 (M_L=4.7) up to 11 April and then approaches to zero level. After EQ1 very low seismo-EM activity in the region of interest is observed. For EQ2 (M_L=4.2) the number of magnetic precursors is maximal on May, 17 and then drop rapidly to a small value. Then on May, 23 the signals classified as seismo-EM origin rise again, which apparently is

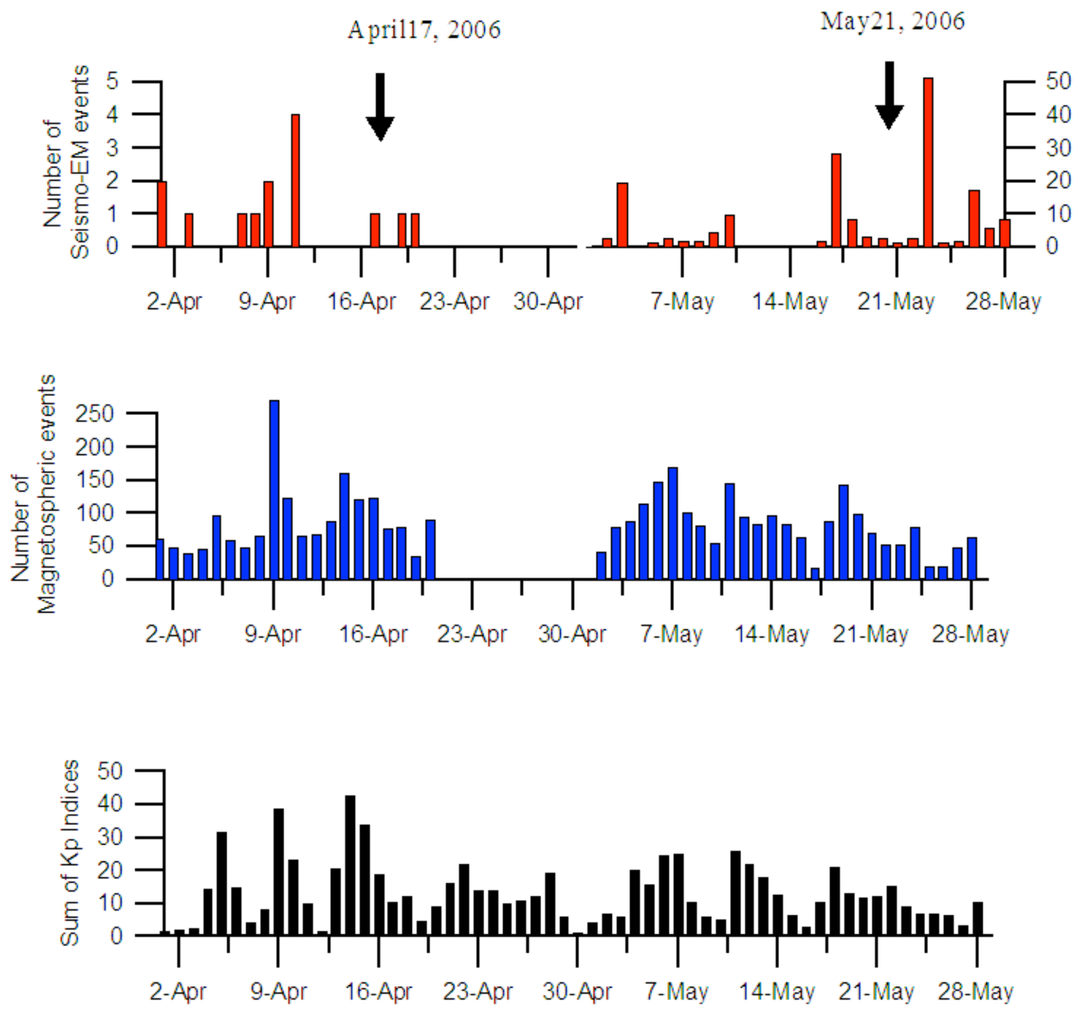


Figure 6 Time relation of the number of detected seismo-EM and magnetospheric signals with the Kp-index values and during the time of observation. Red bars are numbers of seismo-EM precursors, and blue bars are numbers of magnetospheric signals.

neither related to any abnormal seismic activity nor marked by intense solar/magnetic disturbances. However, given that this time interval is marked by moderate values of Kp, it seems possible that these seismo-EM signals may be related to the release of residual mechanical stresses following EQ2. It can be surmised that the ratio of major axes of PE at two distant sites proves effective in isolating seismo-EM signals from those of inospheric/magnetospheric origins (Figs. 6).

4. Discussion and Summary

Given that the intensity of anticipated seismo-EM signals in the ULF band is very low, their accurate isolation from the natural background ULF signals of magnetospheric/ionospheric origin is prerequisite of any experiment designed to study seismo-EM precursors. Here we have examined the relative efficiency of three different approaches. The temporal variations of polarization ratios as well as spectral slope ß determining fractal dimension are found to be negatively correlated with solar/geomagnetic activity. Analyzing the long time series of geomagnetic data in the ULF band at Guam Island, Hayakawa et al. [1999] noted that the temporal evolution of slope ß is modulated by the quasi-periodic variations of 27 days. Further these long-term background variations in ULF activity were seen to vary in-phase with similar variation in geomagnetic activity index Kp. The well-known 27-day recurrence tendency in the geomagnetic storm is caused by the corotating stream of energetic particles in the solar wind injected from Coronal holes on the Sun [Campbell, 2003]. The observed variation in ULF activity correlated with solar/geomagnetic can be considered to be the manifestation of the solar modulated solar wind-magnetosphere-ionosphere interactions.

Hayakawa et al. [1999] also noted that superimposed on these long-term slow variation in the slope, there is a gradual increasing trend (ß becoming less negative) few days to few weeks prior to the occurrence of the Ms=8 Guam EQ when ß jumps to attain a value of 1, characteristic of flicker noise. Contrary to these earlier observations, the commonly employed polarization analysis (S_Z/S_H ratio) as well as fractal dimension analysis fails to reveal any precursory and/or co-seismo-EM signals which can unambiguously be related with the occurrence of two moderate EQs studied here. The absence of any conspicuous co- or precursory ULF signals, despite the fact that highly sensitive and low noise magnetometers can resolve ULF magnetic signals with amplitude as low as of few pT, has two possible implications; First that such signals, even if present, are completely masked by the much stronger signals of natural ionospheric/magnetospheric origin. Second, it raises a question whether small magnitude EQs do not derive the dynamic system to the point of self-organized criticality to produce seismo-EM emission characterized by flicker noise behaviour. Such inference may not be surprising as almost all reported anomalies are in relation to large EQs of M> 5, whereas the only two EQs searched here have magnitude M_L >4. However, when we have used the ratio of major axis of PE at two sites, it provides a quantitative mode to distinguish ULF signals dominated by seismo-EM origin from those associated with magnetospheric origin. The numbers of ULF events classified to be dominated by magnetospheric part vary in unison with geomagnetic activity index Kp providing independent confirmation to their magnetospheric origin. On the other hand, the ULF events that qualify as seismo-EM grow in numbers for several days and vanish immediately prior to the occurrence of largest EQ recorded during observation period. In terms of time evolution, the pattern is similar to the gradual increase in ß values that culminate in flicker noise just prior to an EQ [Hayakawa et al., 1999]. seismo-EM origin of such qualified ULF events is further corroborated by the observation as an intersected plane of polarization ellipses defined by magnetic field components at Koyna and Kolhapur cluttered in localized zone of 20 × 30 km^2 [Dudkin et al., 2010], identified as the source region of the Koyna seismic activity [Gupta et al., 2007]. Approximating the plane of intersection as an elementary magnetic dipole, the magnetic moment and orientation of magnetic dipole is determined by the inversion of observed magnetic field. The computed azimuth of the seismo-EM fields invariably align in the NNW-SSE direction. This orientation of seismogenic ULF signals in the Koyna-Warna corresponds well with the causative fault zone inferred from long-term EQ data as well as fault plane solutions of the two EQs discussed here. The already available knowledge on the role of high pressure fluids in generating the EQs [Talwani, 1997a,b] favoured electrokinetic effect to be one of the possible source mechanisms for seismo-EM fields [Dudkin et al., 2010].

Since at this stage no EQ precursor is definite prognostic value, the present focus is on cross-examined variety of precursors and on making collective assessment to validate the EQ precursors [Cicerone et al., 2009; Yuce et al., 2010]. This integration exercise would be benefitted if some index parameters are derived from each geophysical time series wherein precursory signals, if present, are enhanced against the natural time variability. It is demonstrated that the ratio of major axis of PE is more effective in discriminating the seismo-EM signal particularly of moderate magnitude EQs. The isolation or absence of such signals in commonly used polarization ratios may be due to the masking effects from terrestrial signals whereas the absence of flicker noise characteristics in fractal dimension results may suggest that moderate magnitude EQs may not derive the dynamic system to the point of self-organized criticality. Thus, seismo-EM precursory signals isolated by comparing the PE parameter at neighbouring sites could be a suitable index for integration with other geophysical parameters. In the present case, this threshold is fixed at 2, corresponding to the minimum value of the ratio recorded between Koyna and Kolhapur. This choice of the value of cutoff threshold adopted here would be a function of station spacing and hence can be constrained better with long term data.

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References

Bak, P., *How nature works: the science of self-organised criticality*, Oxford University Press, Copernicus, NY, 210pp, 1997.

Bakun, W.H. and Lindh, A.G., The Parkfield, CA earthquake prediction experiment, *Science*, 229, 619-624, 1985.

Bleier, T., Dunson, C., Maniscalco, M., Bryant, N., Bambery, R., and Freund, F., Investigation of ULF magnetic pulsations, air conductivity changes, and infra red signatures associated with the 30 October Alum Rock M5.4 earthquake, *Nat. Hazards Earth Syst. Sci.*, 9, 585–603, 2009.

Cagniard, L., Basic theory of the magnetotelluric method of geophysical prospecting, *Geophysics*, 18, 605-635, 1953.

Campbell, W.H., *Introduction to Geomagnetic Fields*, Cambridge University Press, pp337, 2003.

Cicerone, R.D., Ebel, J.E. and Britton, J., A systematic compilation of earthquake precursors, *Tectnophysics*, doi:10.1016/j.tecto.2009.06.008, 2009.

Du, A., Huang, Q., and Yang, S., Epicenter location by abnormal ULF electromagnetic emissions, *Geophys. Res. Lett.*, 29 (10), 1455-1458, 2002.

Dudkin, F., De Santis, A., and Korepanov, V., Active EM sounding for early warning of earthquakes and volcanic eruptions, *Phys. Earth Planet. Inter.*, 139 (3, 4), 187-195, 2003.

Dudkin, F., Rawat, G., Arora, B.R., Korepanov, V., Leontyeva, O. and Sharma, A.K., Application of polarization ellipse technique for analysis of ULF magnetic fields from two distant stations in Koyna-Warna seismoactive region,West India, *Nat. Hazards Earth Syst. Sci.*, 10, 1–10, 2010, doi:10.5194/nhess-10-1-2010

Fedorov E., Pilipenko V., and Uyeda S., Electric and magnetic fields generated by electrokinetic processes in a conductive crust, *Phys. Chem. Earth (C)*, 26 (10-12), 793-799, 200l.

Fraser-Smith, A.C., Bernardi, A., McGill, P.R., Ladd, M.E., Helliwell, R.A., and Villard Jr., O.G., Low-frequency magnetic field measurements near the epicenter of the Ms 7.1 Loma Prieta earthquake, *Geophys. Res. Lett.*, 17, 1465-1468, 1990.

Gotoh, K., Hayakawa, M., and Smirnova, N., Fractal analysis of the ULF geomagnetic data obtained at Izu Peninsula, Japan in relation to the nearby earthquake swarm of June-July, 2000, *Nat. Hazards Earth Syst. Sci.*, 3, 229-236, 2003.

Gough, D.I. and Ingham, M.R., Interpretation methods for magnetometer arrays, *Rev. Geophys.*, 21, 805-827, 1983.

Gupta, H.K., A review of recent studies of triggered earthquakes by artificial water reservoirs with special emphasis on earthquakes in Koyna, India, *Earth-Science Reviews*, 58 , 279–310, 2002.

Gupta, H.K., Artificial water reservoir-triggered earthquakes with special emphasis at Koyna, *Current Science*, 88 (1), 1628-1631, 2005.

Gupta, H., Shashidhar, D., Pereira, M., Mandal, P., Purnachandra, Rao N., Kousalya, M., Satyanarayana, H.V.S., and Dimri, V.P., Earthquake forecast appears feasible at Koyna, India, *Current Science*, 93 (6), 1628-1631, 2007.

Hattori, K., ULF geomagnetic changes associated with large earthquakes, *Terrestrial, Atmospheric and Oceanic Sciences*, 15, 329–360, 2004.

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

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

Hayakawa, M., Itoh, T., Hattori, K., and Yumoto, K., ULF electromagnetic precursors for an earthquake in Biak, Indonesia on 17 February 1966, *Geophys. Res. Lett.*, 27, 1531–1534, 2000.

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

Hirano, T., and Hattori, K., ULF geomagnetic changes possibly associated with the 2008 Iwate–Miyagi Nairiku earthquake, *J. Asian Earth Sci.*, 41 , 442–449, 2011.

Ida, Y., and Hayakawa, M., Fractal analysis for the ULF data during the 1993 Guam earthquake to study prefracture criticality, *Nonlin. Processes Geophys.*, 13, 409–412, 2006.

Ismaguilov, V.S., Kopytenko, Yu.A., Hattori, K., and Hayakawa, M., Variations of phase velocity and gradient values of ULF geomagnetic disturbances connected with the Izu strong earthquakes, *Nat. Hazards Earth Syst. Sci.*, 3, 211–215, 2003.

Kopytenko, Yu.A., Ismaguilov, V.S., Hayakawa, M., Smirnova, N., Troyan, V., and Peterson, T., Investigation of the ULF electromagnetic phenomena related to earthquakes: contemporary achievements and perspectives, *Annali di Geofisica*, 44 (2), 325-334, 2001.

Lomnitz, C., *Fundamentals of Earthquake Prediction*, John Wiley and Sons, New York, pp 326, 1994.

Molchanov, O.A., and Hayakawa, M., Generation of ULF electromagnetic emissions by microfracturing, *Geohpys. Res. Lett.*, 22, 3091–3094, 1995.

Molchanov, O.A., Schekotov, A.Yu., Fedorov, E., Belyaev, G.G., Solovieva, M.S., and Hayakawa, M., Preseismic ULF effect and possible interpretation, *Ann. Geophysics*, 47 (1), 119-131, 2004.

Molchanov, O.A., and Hayakawa, M., *Seismo-electromagnetics and Related Phenomena: History and results*, TERRAPUB, Tokyo, 189pp, 2008.

Ogawa, T., and Utada, H., Coseismic piezoelectric effects due to a dislocation. 1. An analytic far and early-time field solution in a homogeneous whole space, *Phys. Earth Planet. Inter*., 121, 273–288, 2000.

Ouzounov, D., Hattori, K. and Liu, J.Y. (Eds), Validation of earthquake precursors—VESTO , *J. Asian Earth Sci*., 41, 369–370, 2011.

Park, S.K., Johnston, M.J.S., Madden, T.R., Morgan, F.D., and Morrison, H.F., Electromagnetic precursors to earthquakes in the ULF band – a review of observations and mechanisms, *Rev. Geophysics*, 31, 117–132, 1993.

Parrot, M. (Ed), First results of the DEMETER micro satellite, *Planet Space Sci*., 54(5), 411-458, 2007.

Rikitake, T., *Earthquake Forecasting and Warning*, Elseveir, 402pp, 1982.

Schekotov, A.Y., Molchanov, O.A., Hayakawa, M., Fedorov, E.N., Chebrov, V.N., Sinitsin, V.I., Gordeev, E.E., Belyaev, G.G., and Yagova, N.V., ULF/ELF magnetic field variations from atmosphere induced by seismicity, *Radio Sci*., 42, RS6S90, doi:10.1029/2005RS003441, 2007.

Schekotov, A.Y., Molchanov, O.A., Hayakawa, M., Fedorov, E.N., Chebrov, V.N., Sinitsin, V.I., Gordeev, E.E., Andreevsky, S.E., Belyaev, G.G., Yagova, N.V., Gladishev, V.A., and Baransky, L.N., About possibility to locate an EQ epicenter using parameters of ELF/ULF preseismic emission, *Nat. Hazards Earth Syst. Sci*., 8, 1237–1242, 2008.

Silver, P.G. and Wakita, H., A search for earthquake precursors, *Science*, 273, 77-78, 1996.

Smirnova, N., Hayakawa, M. and Gotoh, K., Precursory behaviour of fractal characteristics of the ULF electromagnetic field in seismic active zones before strong earthquakes. *Phys. Chem. Earth*, 29, 445-451, 2004.

Surkov, V.V., Molchanov O.A., and Hayakawa M., Pre-earthquake ULF electromagnetic perturbations as a result of inductive seismomagnetic phenomena during microfracturing, *J. Atmos. Sol.-Terr. Phys*., 65 (1), 31-46, 2003.

Surkov, V.V., Molchanov, O.A., and Hayakawa, M., A direction finding technique for the ULF electromagnetic source, *Nat. Hazards Earth Syst. Sci*., 4, 513–517, 2004.

Talwani, P., On the nature of reservoir-induced seismicity, *Pure Appl. Geophys*., 150, 473–492, 1997a.

Talwani, P., Seismotectonics of the Koyna-Warna Area, India, *Pure Appl. Geophys*., 150, 511–550, 1997b.

Trivedi,N.B., Arora B.R., Padilha A.L., Da Costa J.M. and Dutra S.L.G., Global Pc5 geomagnetic pulsations of March 24, 1991, as observed along the American sector, *Geophys. Res. Lett*., 24, 1683-1686, 1997.

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

Yuce, G., Ugurluoglu, D.Y., Adar, N., Yalcin, T., Yaltirak, C., Streil, T. and Oeser, V., Monitoring of earthquake precursors by multi-parameter stations in Eskisehir region (Turkey), *Applied Geochemistry*, 25, 572-579, doi:10.1016/j.apgeochem.2010.01.013, 2010.

Waters, C.L., Menk, F.W., and Fraser, B.J., Low latitude geomagnetic field line resonance: Experiment and modeling, *J. Geophys. Res*., 99 (A9), 17,547-17,558, 1994.