Fractal analysis of Ultra Low Frequency magnetic field emissions observed at Agra associated with two major earthquakes occurred in Pakistan

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Abstract. Fractal analysis has been applied to the ultra-low frequency (ULF) magnetic time series data to study the critical behaviour of impending earthquake preparation zone. Burlaga Klein method has been adapted. The ULF time series data have been prepared from the routine recordings of ULF magnetic field emissions at Agra station in India with the help of 3-component search coil magnetometers for the month of September 2013 in which two large earthquakes of magnitudes M=7.4 and 6.8 occurred in Pakistan. The two important parameters namely fractal dimension D and fractal exponent β are calculated which are found to vary abnormally before the occurrence of earthquakes. From a detailed amplitude-time analysis of ULF data precursory period of anomalies in amplitude has been found of the order of 16 days. The fractal dimension and fractal exponent show complementary behaviour with each other and they are found to vary abnormally around the observed precursory period in the normal analysis of the data. This month is free from geomagnetic disturbances and hence the analysis is not contaminated from the effects of such disturbances.

Keywords: ULF, Earthquakes, Fractal analysis

1. Introduction

Many workers have done a lot of efforts in the field of earthquake prediction in the earlier years employing seismo-electromagnetic techniques, details of which are available in a number of monographs (Hayakawa and Fujinawa 1994; Hayakawa 1999; Hayakawa and Molchanov 2002; Molchanov and Hayakawa 2008; Singh 2008; Hayakawa 2012, 2015; Pullinets and Ouzounov 2018). Monitoring of ULF magnetic field emissions recorded from the lithosphere directly is one of the many seismo-electromagnetic techniques employed extensively. The reason behind choosing ultra-low frequency (f= 0.01-10 Hz) is that it is characterised by large skin depth, low attenuation, less contamination and penetration through ionosphere and magnetosphere etc. Different kinds of analysis methods have been employed to detect anomalies in seismogenic ULF signals in order to find out earthquake precursors. One such method is fractal analysis which helps to detect
ULF precursor signals at higher magnitudes and correlate the results of analysis in support of findings (Gotoh et al., 2003, 2004; Smirnova et al., 2004; Varatsos, 2005). This analysis can be done in three ways: - Power Spectrum Analysis, Higuchi method and Burlaga-Klein method. Hayakawa et al., (1999) applied fractal analysis on ULF data for the first time related to the Guam earthquake for a period of four months before and after the earthquake. It was found that the spectrum of emissions exhibited a power law behaviour $f^{-\beta}$ which is critical for self-organized critical dynamics. Since then several workers have applied mono and multi fractal analysis techniques to study the criticality in the time series data related to different earthquakes (Smirnova 2001, 2004; Gotoh et al., 2003, 2004; Ida et al., 2005; Ida and Hayakawa, 2006; Yonaiguchi 2007a,b, Hayakawa and Ida , 2008; Ida et al., 2008, 2012).

Routine monitoring of ULF magnetic field emissions at Agra station in India (Geograph. lat. 27.2°N, long. 78°E) has been in progress ever since the year 2002 except for large period gap between 2013 and 2015 due to replacement of sensors and other hardware by new units. The new system has been working regularly since November, 2016. The ULF data obtained at this station has been utilized by many researchers for the study of earthquake precursor (Kushwah et al., 2005; Chauhan et al., 2009, 2010). Fractal analysis has been earlier applied by Chauhan et al., (2010) on GPS TEC data at Agra station and promising results have been found.

In this paper we analyze the ULF data recorded at our station for the month of September 2013 in which two major earthquakes occurred in the neighbouring country of Pakistan and apply fractal analysis using Burlaga Klein method to study the critical behaviour of the impending earthquake zone. Two important parameters fractal dimension $D$ and fractal exponent $\beta$ are calculated which vary abnormally before the occurrence of earthquakes. The work presented here is different from earlier work in the sense that the fractal analysis has been applied in ULF data which are associated with two major earthquakes occurred in the same month and also there was no geomagnetic activity in the whole month to contaminate the ULF time series data. The results are very convincing and informative which describe the critical behaviour of earthquakes.

2. Experimental Setup

We have employed the experimental setup similar to that used by our group earlier for monitoring the ULF magnetic field emissions at Agra station (Kushwah et al. 2005, 2009; Chauhan et al. 2009; Singh et al. 2014; Singh and Pundhir, 2014). The whole setup is shown in Fig. 1. In brief, it comprises of 3-component search coil magnetometer ($f=0.01$-$30$ Hz), communication and data acquisition unit (CAM unit), and Lemi30i software imported from Lviv centre of Institute of Space Research, Ukarine. The three sensors of the magnetometer are buried 1.5m underground in orthogonal directions such that X component is oriented along North-South, Y component along East-West and Z component along vertical directions in the agriculture fields of the college where local electric and electromagnetic disturbances are low. The data from the three sensors are carried to the CAM unit which is placed in a room 200 m away from sensors through cables. It stores data at the rate of 256 samples per second. These samples are averaged by
summing and dividing using Lemi30i software such that 64 samples are stored in computer every second. The software processes 1024 data points at the sampling rate of 64 Hz in a time of 16 sec (1024/64). In this method the spectrum is obtained per hour by taking the average of 450 spectrum with 1024 data points.

3. Details of earthquakes and geomagnetic activity

The details of the earthquakes which occurred in Pakistan in the month of September 2013 are taken from United States Geological Survey (USGS) website http://earthquake.usgs.gov/earthquakes/ and are given in Tab. 1 and their locations are shown in Fig. 2.

| EQ No. | Date of earthquake | Time (UT) | Latitude (Deg.) | Longitude (Deg.) | Depth (km.) | Magnitude | Region | Distance from Agra (km) | Radius of the influence zone (km) |
|--------|--------------------|-----------|-----------------|------------------|-------------|-----------|--------|------------------------|---------------------------------|
| 1.     | 24/09/2013         | 11:29:48  | 27.0°N          | 67.7°E           | 10          | 7.4       | Pakistan | 1217                   | 1520.5                           |
| 2.     | 28/09/2013         | 07:34:10  | 27.2°N          | 65.9°E           | 20          | 6.8       | Pakistan | 1196                   | 839.5                            |
Table 1 shows the details of the earthquakes such as location, depth, magnitude and distances from Agra etc. The last column shows the radius of influence zone. The location of these earthquakes and observing station are shown in the map of Fig. 2 by solid circles and open squares respectively. The radii of influence zones $R$ are calculated by using the relation $R=10^{0.43M}$ km where $M$ is the magnitude of earthquake (Dobrovolsky et al., 1979). The relation is valid for determining the radius of influence zone of the earthquakes both on the ground and ionosphere (Pullinets and Boyarchuk, 2004). As shown in the table, the radius of the influence zone calculated for the earthquake occurring on 24 September ($M=7.4$) covers the observing station very well, but the same for other earthquake occurring on 28 September ($M=6.8$) does not. However, the later one occurs just after four days only and may be after shock of the first one. Hence, in spite of being out of influence zone literally, it may have profound impact of its own and also as joint with the other one.

The geomagnetic data (Dst and $\sum Kp$) are taken from website http://omniweb.gsfc.nasa.gov/form/dx1.html and their variations in the month of September 2013 is shown in Fig.3. As it may be seen from the figure, the whole month is free from severe magnetic storms as the Dst is always less than $-25$ and $\sum Kp$ is always less than 30.
4. Results and discussions

4.1. Experimental data

The ULF time series data are obtained from the routine recording of ULF magnetic field emissions for the month of September 2013 in which two major earthquakes occurred in Pakistan. The reason for choosing only one month data is two-fold. Firstly, the Agra station is only 400 km away from Himalaya where there exists a Main Boundary Fault (MBF) extending from North east in India to North-west in Pakistan and Afghanistan which is characterised by frequent occurrence of low magnitude earthquakes. The consideration of a long data set might be contaminated by the effects of such earthquakes also which may cause the analysis difficult. Secondly, the fractal analysis of many Japanese workers earlier (Ida et al., 2008, 2012) have been questioned by Masci (2010, 2013) and Masci and Thomas (2013) on the ground that the fractal anomalies are related to geomagnetic activity and ULF emissions of magnetospheric origin. In order to take care of such remarks in our analysis we have considered one month data only of September 2013 in which no geomagnetic activity occurred as can be seen from Fig.3. In Fig 4(a,b,c) we show Y component amplitude time records of ULF data which are available on all days of month in contrast to X and Z components where data are either limited or noisy. The days of occurrence of the two earthquakes are shown by downward arrows. As
per our experience of working with ULF data analysis for long we have found that the effect of earthquakes occurs on ULF data in the form of bursts usually (Kushwah et al., 2005, 2009, Chauhan et al., 2012). Such bursts also occurred in the existing data which are encircled in Fig.4. An interesting result obtained from the detailed examination of these bursts (temporal expansion) is that they contain electromagnetic pulses of periods $10^{-15}$ s ($f=0.06-0.1$ Hz). An example of such pulse is shown in Fig. 4(d). It may be noticed here that against the earthquakes occurred on September 24 and 28 such bursts appeared in the data from 8 September 2013 itself showing a precursory period of about 16 days and these are not correlated with other events. These bursts appear as precursors because of intermittent occurrence of microfracturing before the main shock.

The ULF time series data are formed by considering six hour night time data (12:00-18:00 UT, LT= UT+ 5.5h), to avoid daytime local noise interference. As it has been mentioned above, time series data obtained here are neither influenced by magnetic storms nor by the influence of any other earthquakes.

4.2. Fractal Analysis

The fractal analysis method adapted here has been used by other researchers who have found convincing results (e.g. Gotoh et al. 2004; Chauhan et al. 2010). In order to provide a stable estimation of fractal characteristics i.e. fractal dimension ($D_o$) and fractal exponent ($\beta$) from a time series geophysical data, Burlaga Klein (1986) defined the length of the curve representing a geophysical time series $B(t_k) (k = 1,2,3, \cdots ,n)$ between time interval $0\leq t \leq T_o$ (where $T_o= n\tau$) as follows:

$$L_{BK}(\tau ) = \sum_{k=1}^{n} \frac{|B(t_k + \tau) - B(t_k)|}{\tau}$$

where $\overline{B(t_k)}$ represents the mean value of $B(t)$ between $t=t_k$ and $t_k+\tau$. This length of the curve is a function of $\tau$. For statistically self-affine (fractal) curves length is given by the relation $L_{BK}\propto \tau^{D_o}$. Using this relation fractal dimension ($D_o$) can be calculated as the log-log plot of the length $L_{BK}(\tau)$ versus the time interval. Then fractal exponent is computed using Berry equation (Berry, 1979)

$$\beta = 5-2D_o. \quad \quad \quad (2)$$

Using Eq. (1) the length of the curve is calculated for six different intervals and then log-log plot of length and time by using hourly (averaged) data for a day has been plotted. This shows a straight line, the slope of which gives fractal dimension ($D_o$). An example of this log-log plot on a particular day (1 September) is shown in Fig 5. Same methodology is applied on the remaining days and the fractal dimension for the whole month is calculated. In order to make a statistical study of the fractal dimension of the ULF data we have adopted the mean ($m$) and standard deviation around the mean ($m \pm \sigma$) approach. Such an approach has been adopted by Ida and Hayakawa (2006) also. The horizontal lines in Fig.6 show the limits of $m$ and $m \pm \sigma$. Daily variation of fractal dimension
Figure 4a

Figure 4b
Figure 4d

Figure 4 (a, b, c). Daily amplitude time record of Y component for the whole month of September, 2013. Two arrows indicate the occurrence date of two earthquakes analysed. In Fig. 4d. An electromagnetic pulse present in ULF burst on 8 September 2013.
of ULF data for the month of September 2013 has been shown by the solid curve with square points in the upper panel of Fig. 6. The anomalous peak in fractal dimension on 15 September 2013 above $m \pm \sigma$ line and its increasing tendency after this day may indicate the critical behavior in relation with two earthquakes. Fractal exponent ($\beta$) is computed by using Berry Eq. (2) for each day and its daily variation is shown in the lower panel of Fig. 6. As stated above, $m \pm \sigma$ are the thresholds for normal variations of $D_o$ and $\beta$. Hence, any outward departure from the thresholds may indicate the critical behavior of the data. Since both $D_o$ and $\beta$ are related linearly by Eq. (2) (one increases while the other decreases simultaneously) their behavior is very well visible from Fig 6. Here it may be seen that fractal exponent shows a complimentary behavior with that of fractal dimension as expected. From this figure it may also be seen that the fractal dimension and fractal exponent show a large enhancement and depletion 9-16 days before the earthquakes.

Our findings that the fractal dimension of ULF data increases and fractal exponent decreases before the occurrence of the earthquakes are consistent with the result of the earlier workers also. These results are also validated by Eq. (2). The fractal analysis demonstrates clearly the critical behavior in the time series data originating from the preparation zones of the earthquakes (Smirnova et al., 2001; Gotoh et al., 2003; Yonaiguchi et al., 2007b; Chauhan et al., 2010).

In order to support the results of fractal analysis applied on the ULF data obtained at Agra station (Fig. 6) we repeat the same analysis on the ULF data collected from another station in India, namely Shillong (Geograph. Lat. 25.92°N, long. 91.88°E). This station is located at distances of 2411 km and 2588 km from the two Pakistan earthquakes and 1390 km from Agra station. The data for the same month of September, 2013 shows similar bursts also except some minor variations in the amplitude of the bursts and the duration of occurrence. The results of variation of fractal dimension and fractal exponent are shown in the two panels of Fig. 7. The variation is almost similar except that the precursory days lie between 10 and 15 days.

![Figure 5. Log plot for 1 September 2013.](image-url)
Now we look for ULF data pertaining to the same months of September but occurring in other years in which no earthquakes occurred. Unfortunately, we could not find such months without the occurrence of earthquake. However, we show here fractal analysis on the ULF data obtained at Agra for the months September, 2014 and September, 2017. In September, 2014 several low magnitude (M<6) earthquakes occurred whereas in September, 2017 two low magnitude earthquakes occurred.
The fractal analysis on the ULF data corresponding to the month of September, 2014 is shown in Fig. 8a and that of September, 2017 is shown in Fig. 8b. The downward arrows and magnitude of earthquakes indicating the days of occurrence of earthquakes are shown in the figures. Here, in Fig. 8a we find anomalous sharp enhancements and depletion in fractal dimension and exponent respectively, possibly due to combined effect of the low magnitude earthquakes but with small precursory periods. In Fig. 8b, we find similar results with coseismic and precursory effects. These results confirm the critical behaviour of the data in the preparation zones of the earthquakes.

Figure 8a. Same as Figure 6 but for the month of September, 2014.

Figure 8b. Same as Figure 6 but for the month of September, 2017.
The earthquakes related ULF anomalies described in this paper may be questioned on the ground that epicenters of earthquakes are located at large distances from the observing station at Agra (see Tab. 1). Many workers (Hobara et al., 2004; Hattori et al., 2004; Hayakawa et al., 2007; Molchanov and Hayakawa, 2008) have inferred from two decades of their ULF observations that the ULF anomalies can be detected in an area of radius 100 km for earthquakes of magnitude M=7.0 and 70-80 km for magnitude M=6.0. On the basis of these results the anomalies observed by us may be questionable because we observed them at large distances ranging from 1196 km-1217 km (See Tab. 1). In order to answer this we may like to bring these points in focus firstly, the earthquakes considered by us are of very large magnitude (M=6.8-7.4) so that our observing station is within the radius of their influential zone. Secondly, while the short distance propagation maybe true for homogenous earth in which electromagnetic signal may decay exponentially, it is not true in real sense because the earth is highly inhomogeneous in which ULF signals can propagate to long distance (Varostos et al., 1998; Huang and Ikeya, 1998). Several authors have reported ULF anomalies at long distances of 500 km and more (Du et al., 2002), more than 600 km (Kushwah et al., 2009) and 2000 km (Ohta et al., 2002) for this reason. Hence the distance factor in observing ULF anomalies in present studies does not arise.

5. Conclusion:

We have analyzed the ULF data for the month of September 2013 in which two major earthquakes of magnitude M=7.4 and M=6.8 have occurred in Pakistan. Fractal analysis method is applied for studying the critical behavior of impending earthquake preparation zone to ULF time series in which two important parameters fractal dimension (Df.) and fractal exponent (β) are calculated. The two parameters show complementary behavior to each other and are found to vary abnormally 9-16 days before the dates of the earthquake and also show increasing and decreasing trends in enhancement and depletion respectively before the main shocks. The period of anomaly matches very well with those observed in the amplitude-time records of the data. No contamination in the fractal analysis exists as the whole month is free from geomagnetic disturbances. The results of the analysis are supported by carrying out similar analysis on the data obtained at another station for the same month and also on the data for the same month but different years.

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