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Ultra Low Frequency (ULF) amplitude anomalies associated with the recent Pakistan earthquake of 8 October, 2005

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ABSTRACT

Employing a system of 3- component search coil magnetometer (f=0.01 -30 Hz), ULF magnetic field emissions associated with earthquakes have been monitored at Agra since September 2002. The bulk of the data shows that normally the amplitudes of the three components (Bx, By, Bz oriented toward north-south, east-west, and vertical directions respectively) are low between 0.01 and 0.3 nT. However, By and Bz components are found to be enhanced considerably in the range of 0.3 – 2 nT (Bx being the smallest) occasionally. Such enhancements are correlated mostly to occurrence of earthquakes where enhancements in By and Bz correspond to earthquakes mostly in North-East (or North- South) and Northwest direction from Agra respectively. Recently, one such correlation has been found between the enhancements in Bz components and large magnitude earthquake (M=7.7) that occurred in Muzaffarabad (Pakistan) about 900 km northwest from Agra on 8 October, 2005. We have examined the amplitude enhancements in the light of solar flares and magnetic storms during the whole month of October, 2005 and found a negative correlation with these events. An interesting result obtained was that the enhancements occurred as precursors, first about 10 days before between 27 and 30 September, and then 3 days before on 05 October, 2005. The precursory characteristics of the signal is confirmed by a statistical analysis of the data for a period of fifteen days before and fifteen days after from 17 Sept., 2005- 29 Oct.,2005 by employing mean (m) and mean around standard deviation ($m \pm 2\sigma$) approach. The enhancements in the intensity of the precursory signals are also observed from a wavelet analysis of the data. The frequency –time spectrogram and power spectrum analysis of the data show the enhancements around 2 Hz and 7-8 Hz and polarization analysis of the data shows that the signals propagated from below.

INTRODUCTION

Besides some very well known ULF amplitude anomalies associated with large earthquakes like Spitak (Kopytenko et al., 1990), Loma-Pieta (Fraser –Smith et al., 1990, Molchanov et al., 1992) and Guam (Hayakawa et al., 1996, Kawate, Molchanov & Hayakawa 1998) there are growing evidences of such anomalies reported recently (Hayakawa et al., 2000, Gotoh et al., 2002, Hattori et al., 2002, Kushwah & Singh 2004, Kushwah et al., 2005). These experimental results have been supported by theoretical work also, in which attempts have been made to explain the generation and propagation mechanism of such emissions. In particular, it has been shown that microfracturing of rocks is a potential mechanism for the generation of such emissions (Molchanov, Hayakawa & Rafalsky 1995) and that the generated emissions can penetrate the crust and propagate through the ionosphere and magnetosphere (Molchanov & Hayakawa 1995). Further, it has been found that emissions in ULF band can produce more convincing precursors of earthquake in comparison with higher frequency band owing to its inherent characteristics of large skin depth, less contamination, and low attenuation involved (Park et al., 1993, Hayakawa, Ito & Smirnova 1999, Kopytenko et al., 2001). Recently, some efforts have also been made to utilize ULF data for direction finding of emitted signals from epicenter regions (Kopytenko et al., 2002, Ismaguilov et al., 2003, Huang 2004). The Pakistan earthquake of 8 October, 2005 was one of the most

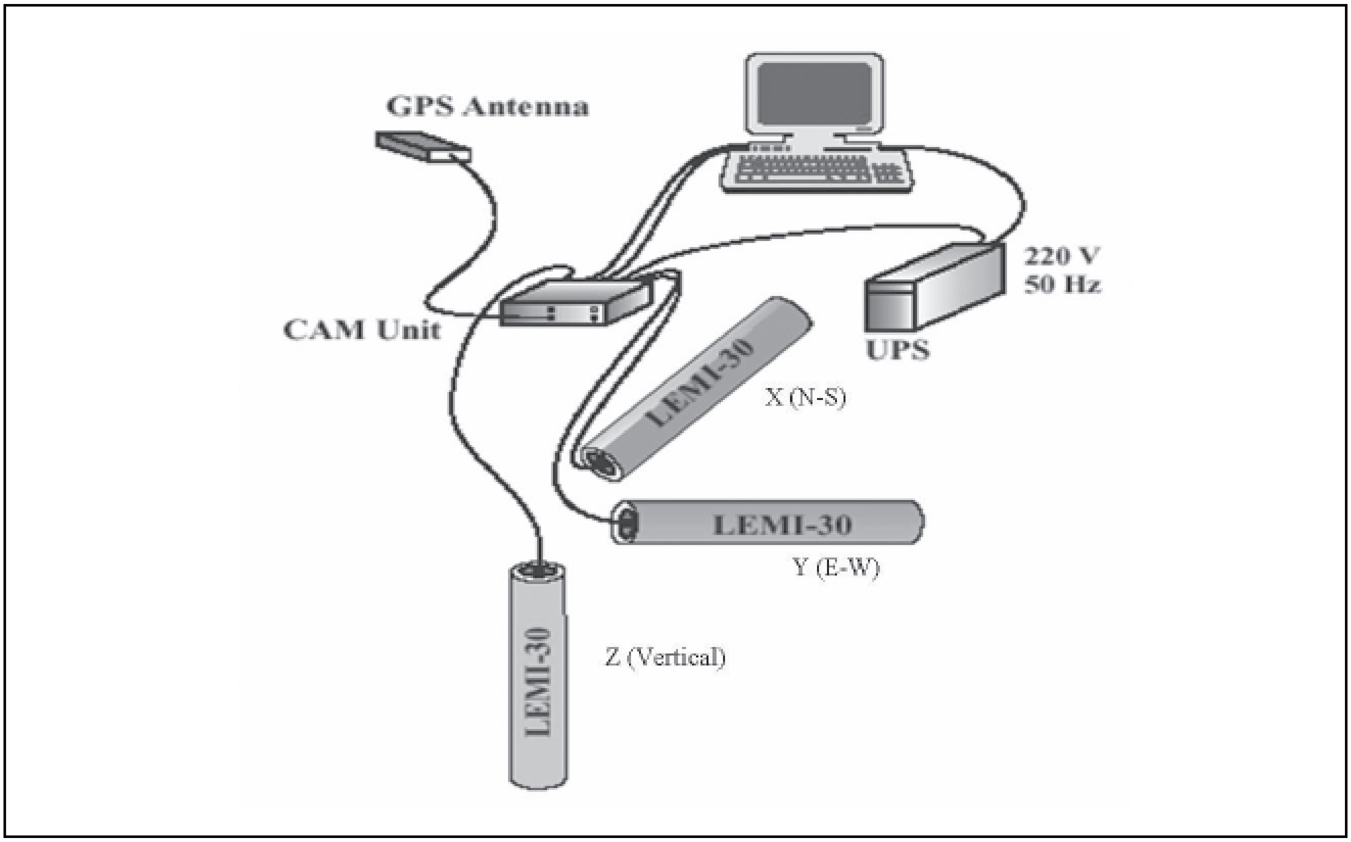

Figure 1. Experimental setup for Ultra Low Frequency observations at Agra using Lemi 30 search coil sensors in orthogonal directions buried 1m under ground

devastating earthquakes (M=7.7) of the region in which more than 70000 people were killed across the Pakistan – India border as seen from newspaper reports. The epicenter of this earthquake was near Muzaffarabad (Lat. 34.53^{0}N, Long. 73.58^{0}E), Kashmir (Under Pakistan) and its focal depth was 26 Km. There was 156 aftershocks (M= 4-5.9), which occurred on the same day and nearly at the same place.

We have reported the results of ULF amplitude anomalies related to some moderate earthquakes in India and around observed at Agra (Lat.27.2^{0}N, Long. 78^{0}E(Kushwah & Singh 2004, Kushwah et al., 2005). In the present paper we report the ULF amplitude anomalies related to Pakistan earthquake mentioned above. We also carry out statistical analysis of the data including polarization and wavelet analysis to confirm that signals are related to earthquakes. We also make a spectrum analysis of the data and determine the frequency and relative strength of the signal.

EXPERIMENTAL SETUP

The experimental setup for monitoring the ULF emissions is shown in Fig.1, which is similar to those of Kushwah & Singh (2004) and Kushwah et al., (2005). Briefly, it consists of 3- component search coil magnetometer (f= 0.01-30 Hz) imported from Lviv centre of Institute of Space Research, Ukraine. The three sensors of the magnetometer are buried 1m under ground in orthogonal directions such that X-component is oriented in north-south, Y-component in east-west, and Z-component in vertical directions. The data from each sensor are digitized at a sampling rate of 60 Hz and recorded on a hard disc. They are analyzed by using FFT available in the MATLAB software with 1024 words of data length at a time.

The observations are taken round the clock at Bichpuri, a rural area about 12 Km west of Agra city where local electric and electromagnetic disturbances are low.

Earthquake and magnetic storm data

The details of the Pakistan earthquake, were taken from United States Geological Survey (USGS, website, http://neic.usgs.gov). The sensors of the magnetometer also respond to ULF signals generated from the ionosphere and magnetosphere during solar flares (or magnetic storm) and known popularly as "micropulsations". To verify that the observed anomalies are not due to such factors, we study the variations of magnetic storms ($\sum Kp$) data of which were obtained from the website (http://swdcdb.kugi.kyoto-u.ac.jp). According to the world data center at Boulder, Colorado, a magnetic storm may be classified as minor, major, or severe depending upon whether the value of Kp lies between 0 and 4, 5 and 6, and 6 and 9, respectively. The $\sum Kp$ is the sum of Kp values between 0 and 9 for each day. The $\sum Kp \geq 30$ indicates usually a severe magnetic storm.

RESULTS AND DISCUSSION

The monitoring of ULF emissions by employing the experimental setup of Fig.1 was started at Bichpuri in September, 2002. In our earlier publications (Kushwah & Singh 2004, Kushwah et al., 2005), we have reported that normally the ULF amplitudes recorded by the three ensors are low, in the range of 0.03-0.3 nT, but they are enhanced to much higher values in the range of 0.3-3nT occasionally. We have found that these occasional enhancements are mostly related to the occurrence of earthquakes in India and around. Further, we have observed empirically that earthquakes occurring in the east direction from Agra in the northeast region of India and around give rise to enhancement in amplitude of magnetic field emissions recorded by Y component of the sensor, whereas earthquakes occurring in the north-south direction produce similar enhancement in the X component of the sensor. The enhancement in the Z component of the emissions is interpreted in terms of location of the hypocenter. If it is below the sensor, or if the direction of emitted radiation is inclined in the X-Z (or Y-Z) plane more towards the Z direction such that the component of the magnetic field vector along the Z direction is strong enough to produce enhanced amplitude in the Z component.

The locations of the Pakistan earthquakes, which occurred in northwest direction at Muzaffarabad, 908 Km from Agra, are encircled in the map of Fig.2. The ULF monitoring station of Agra is indicated by a rectangle in the map. Since the amplitude enhancement occurred in Z-component during this earthquake, we show in Fig.3 the amplitude variation of the Z-component for a period of 16 days between 25 September 2005 and 10 October 2005, during which the effect of the earthquakes is reflected very well on the data. The data on 07 October 2005 is not available because of power failure at the campus. Here, the amplitude variation is shown in the nighttime 2230hrs – 2430hrs on each day. The purpose for

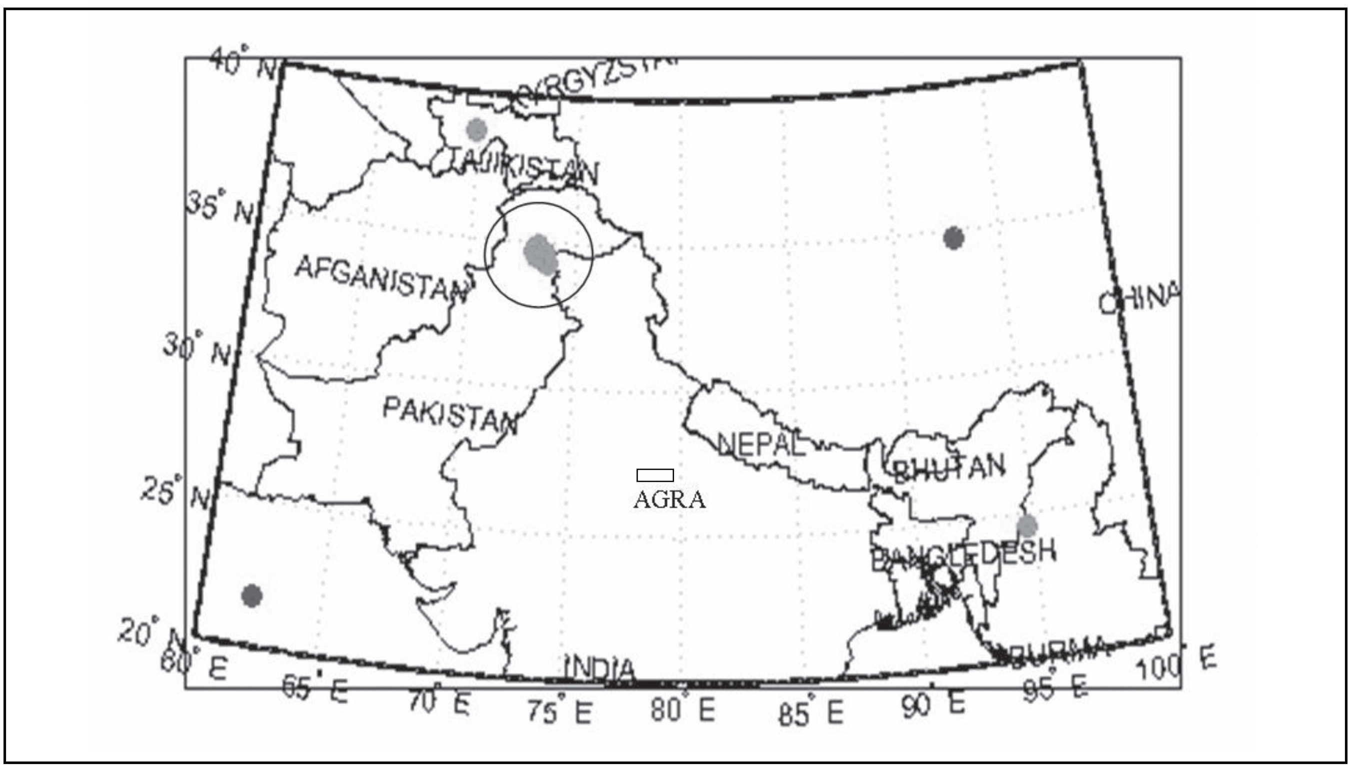

Figure 2. Map showing the location of earthquakes (encircled solid points) of 08 October, 2005 in Muzaffarabad (Pakistan) near India-Pakistan border. The location of observating station Agra is indicated by open rectangle.

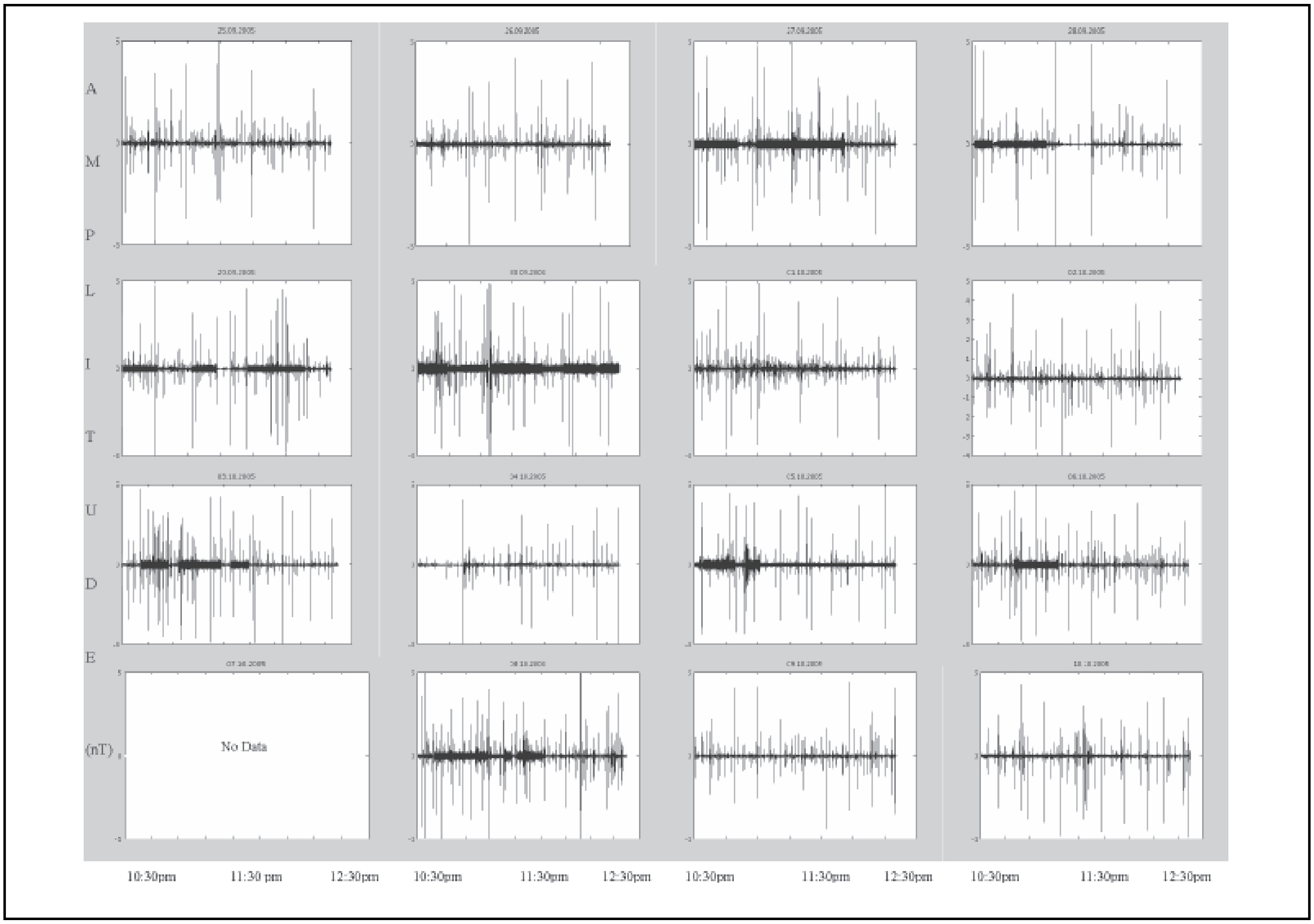

Figure 3. The amplitude-time record during nighttime (1000-1200hrs, LT) of the Bz component from 25 September, 2005 to 10 October, 2005.

Table.1 ULF Precursors associated with different large earthquakes

Region of the Earthquakes	Date	Ms	Observed Precursors before the main shock		Depth Km	Distance of monitoring station (Agra) from epicenters Km	References
			I	II			
Spitake Arminia	07.12.88	6.9	3-5 days	4 h	6	140	Fraser-Smith et al., 1990
Loma Prita California	18.10.89	7.1	12 days	3 h	15	7	Kopytenko et al., 1990
Guam Japan	08.08.93	7.1	10-15 days	3 days	60	65	Hayakawa et al., 1993
Muzaffarabad Pakistan	08.10.05	7.7	11 days	5 days	10	908	This study

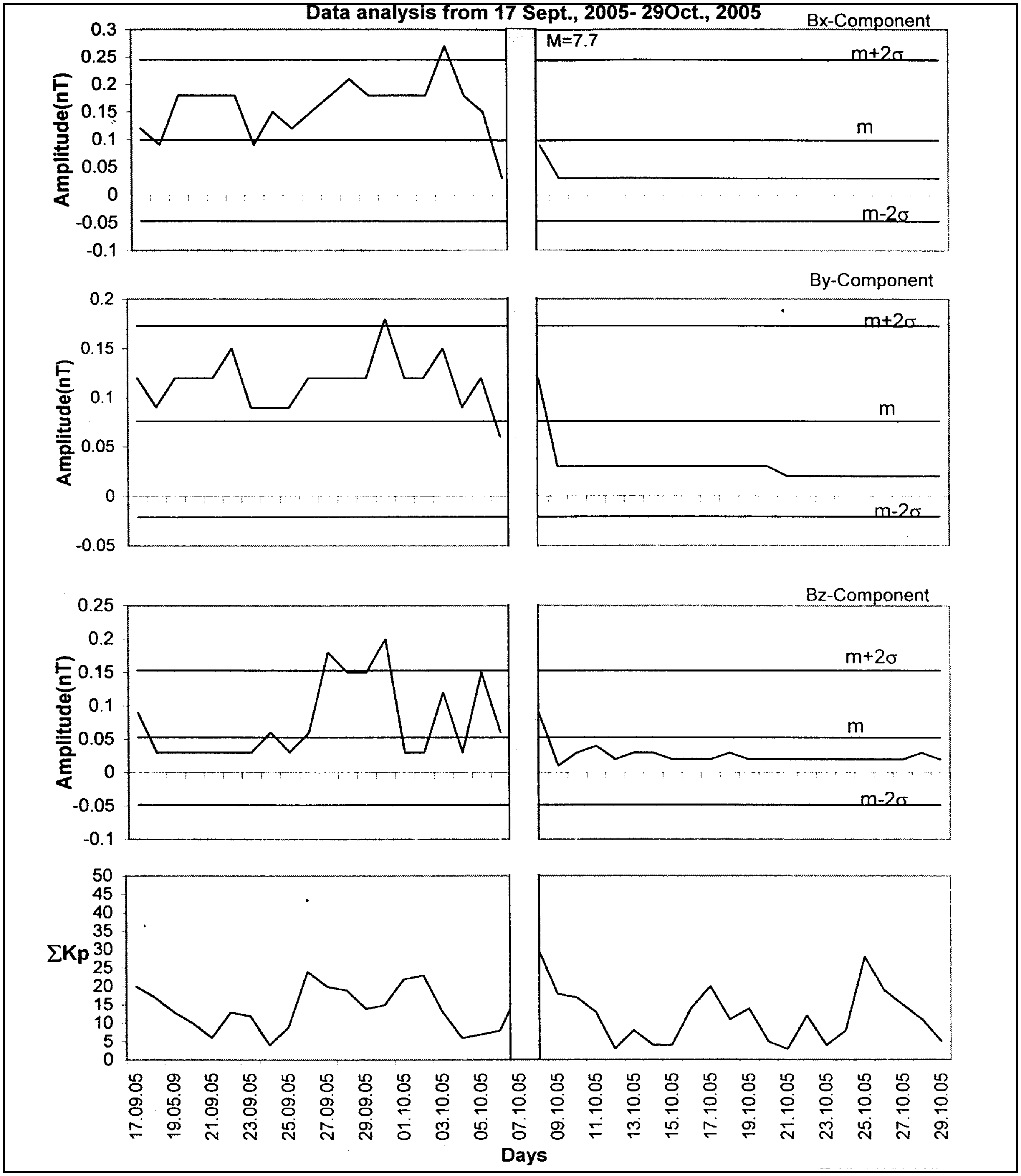

Figure 4. The amplitude variation of the three components from 17 September, 2005 to 29 October, 2005.The first three panels correspond to X-,Y-, and Z-components of the magnetic field in which mean (m) and standard deviation($m \pm 2\sigma$) are shown by straight lines and the amplitude data are shown solid curves and vertical shaded block shows the occurrence of the earthquake(m=7.7). The Magnetic Storm(ΣKp) for the same period is shown in the bottom panel.

choosing the nighttime data only is because electric and electromagnetic disturbances are very low during this time. Although, the ULF signals from magnetospheric origin are of less amplitude and they are detected even during daytime the question may be asked why not the electromagnetic signals from earthquake origin are recorded during daytime. The simple answer is the location of our sensors. Here we have our sensors installed at the university campus where there are so many sources of electric and electromagnetic noises during daytime due to which even the seismogenic ULF signals are masked. Such noises are considerably reduced during nighttime. Considerations of nighttime data have also been emphasized by other workers (Saito, 1969, Akinaga et al., 2001, Kopytenko et al., 2002). In the figure the time is shown on the X-axis and the amplitude is shown on the Y-axis. The horizontal dark bands indicate the amplitude and vertical spikes are due to local noise. It may be seen from the figure that the amplitude is enhanced significantly on 27, 28 and 30 September and then on 5 October, i.e. 10 and 3 days before the main shock of 8 October, 2005 respectively. The amplitude level is normal after 8/9 October suggesting that the above enhancenments are precursors to the earthquake. It may be noted here that the data on 29 September, 2005 show enhanced amplitude for a short period, and also there is an erratic behavior in the increase of amplitude like on 04 October, 2005 which is much silent than 30 September, 2005. These unusual data are explained ahead. The question of occurrence of significant amplitude enhancements 10 and 3 days before the main shock may be explained in terms of space-time model of micro fracture progression (Molchanov & Hayakawa 1995). Microfracturing electrification is suggested as a possible mechanism for explaining ULF electromagnetic emissions observed before and after the earthquakes. This effect appears as fast fluctuation of micro-cracks and leads to the origination of wide band electromagnetic noise. The fluctuation in emission process in time scale depends upon the

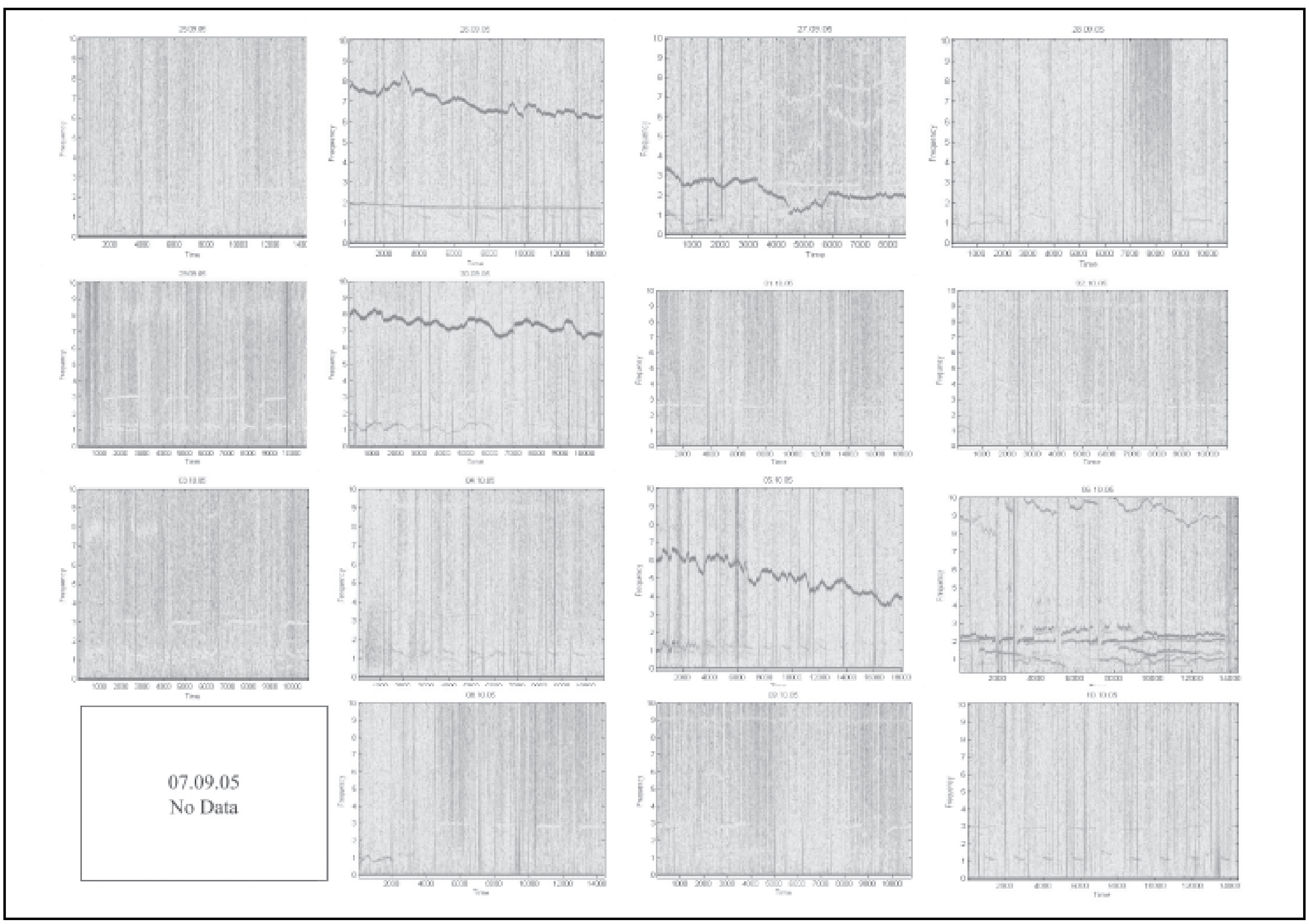

Figure 5. Frequency-time spectra of the Bz component from 25 September, 2005 to 10 October, 2005 showing signals between 0 to10 Hz.

distribution of micro-cracks, their fast opening and healing (Intermittence), and average size progression due to stress corrosion. Similar intermittent emissions before the main shock have also been observed during other prominent earthquakes (see Table 1).

In order to support the above result we carry out a rigorous statistical analysis of the data in which we determine the mean (m) and standard deviation (s) around the mean of the amplitude of the three components for a period of 15 days before and 15 days after between 17 September 2005- 29 October 2005. The amplitude data show 7 to 8 nT peak-to-peak spikes as mentioned earlier. These are produced by local noises and have been removed from the data before attempting for the statistical analysis. The amplitude given by the horizontal thick bands are considered in the analysis only. For a high degree of confidence the variation around the mean is taken to be m±2σ. A 2σ approach has also been considered to interpret LF data related to Slovenio earthquakes (Biagi & Hayakawa 2002). The result of our analysis is shown in Fig.4. The first three panels of the figure show the result for Bx, By and Bz component in which the three dashed horizontal lines correspond to mean and standard deviation around the mean and the solid curves show the variation of the amplitude. The bottom panel shows the variation of ∑Kp for the whole period of one month. The vertical shaded block indicates the day of occurrence of earthquake (M=7.7) in Muzaffarabad near India–Pakistan border. As seen from the variation of the amplitudes in the three panels the Z component of the ULF emissions show significant enhancement on 30 September and 05 October 2005 as the amplitude cross and touch the 2σ lines. These enhancements are not caused by magnetic storm because the ∑Kp is less than 25 as shown by the variation in the bottom panel on these days and hence they may be attributed to earthquake effect only. There are enhancements in X and Y components around these days also but the effect is reflected more in the Z component. The highest peak (>0.25 nT) in X component on 04 October, 2005 is due to an earthquake of magnitude 5.5 (depth 30 km) which occurred in the Indonesian region (lat 5.51^{0}N,

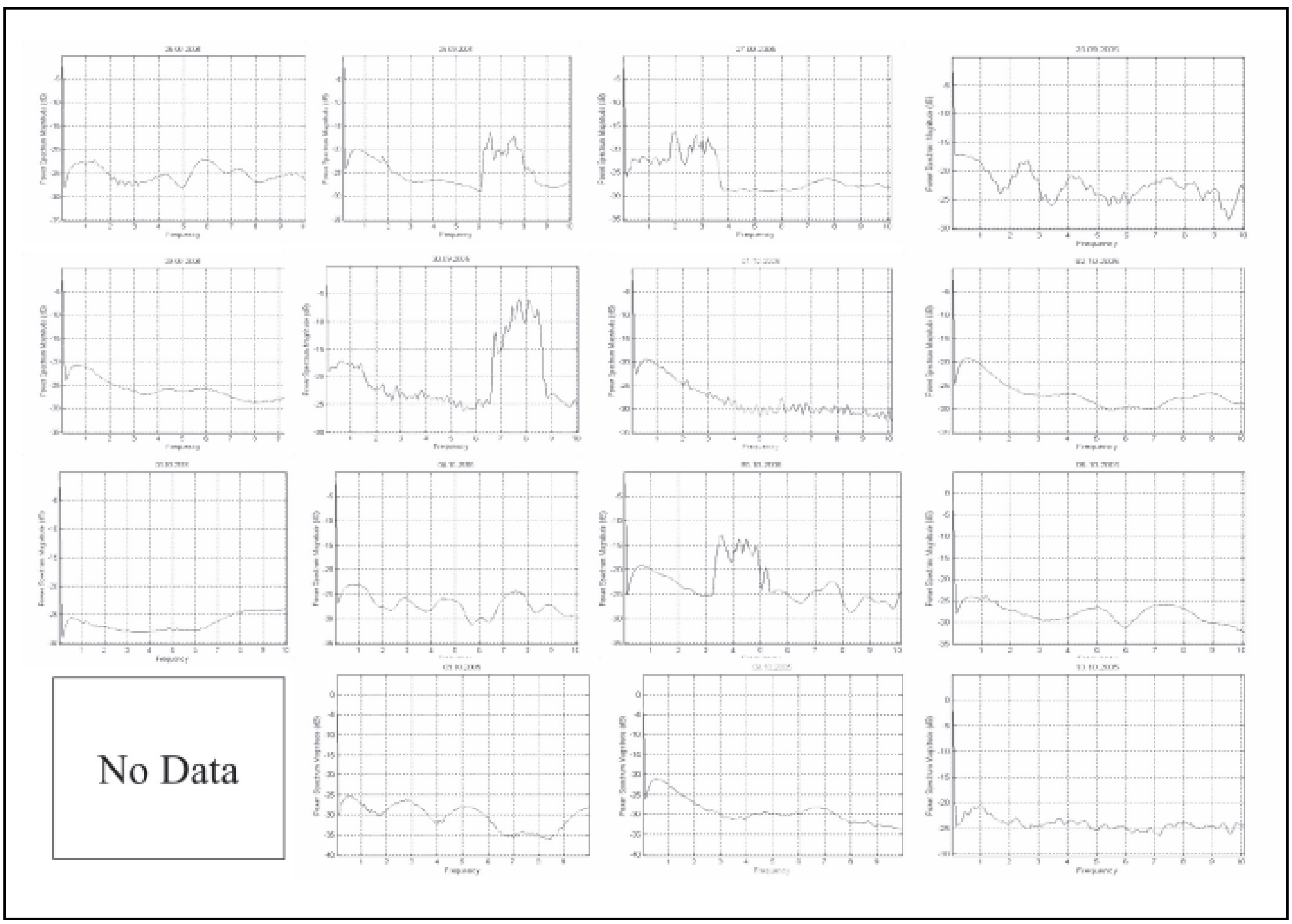

Figure 6. Power spectra of Bz component from 25 September, 2005 to 10 October, 2005.

long. 94.36^{0}E, UT= 220913) on the same day. Since this earthquakes occurred more towards the southeast direction, the effect of the emitted radiation was observed more in the X component.

In Fig. 5 we show the Frequency- time spectrograms of the raw data presented in Fig.3. Here, we find intense emissions appearing on 26, 27 and 30 September and 05 and 06 October 2005 between 6 and 8 Hz whereas no such emissions appear on other days. The emissions also appear around 2 Hz in some of the spectrograms. Although there are amplitude enhancements on 29 September and 03 October 2005 also, their intensities do not appear in frequency time spectrograms because the relevant frequencies are much higher than 10Hz (around 20-23 Hz). Since in majority of cases the frequencies are between 6 and 8 Hz. The frequency scale has been chosen up to 10 Hz only. The data on 4 October do not contain any signal. The non-stationary behaviour in the occurrence of emissions on the spectrogram may be explained in the light of generation mechanism (microfracturing) as stated before. The non-occurrence of emissions between 6-8 Hz on other days except 29 September and 03 October, 2005 is due to non-emission from the generation region. These results confirm the existence of ULF emissions before the earthquake. This is also confirmed by the power spectrum analysis of the same data presented in Fig.6.

A useful technique to discriminate the ULF signals of earthquake origin from those of micropulsations of magnetospheric origin is to study the variation of polarization parameter (Z/X)(Hayakawa et al., 1996). It is well known that $Z/X \geq 1$ identifies the signals related to earthquake source whereas $Z/X < 1$ indicates that the signals are of magnetospheric origin. In Fig.7 we show the variation of Z/X for a period of 30 days as considered for the data presented in Fig.3 in the upper panel. In this calculation the Z and X values are averages of the amplitudes of the signals between 6-8 Hz for all the data. The $\sum$Kp variation is repeated in the bottom panel in the same figure. Here we find that the polarization parameter increases to greater than 1 on 26 September, 30 September and 05 October 2005 indicating that the signals came from below and they are not influenced by magnetic storms. The peaks in the polarization parameters after 15 October are due to after shocks (>M=5.0) in the same location.

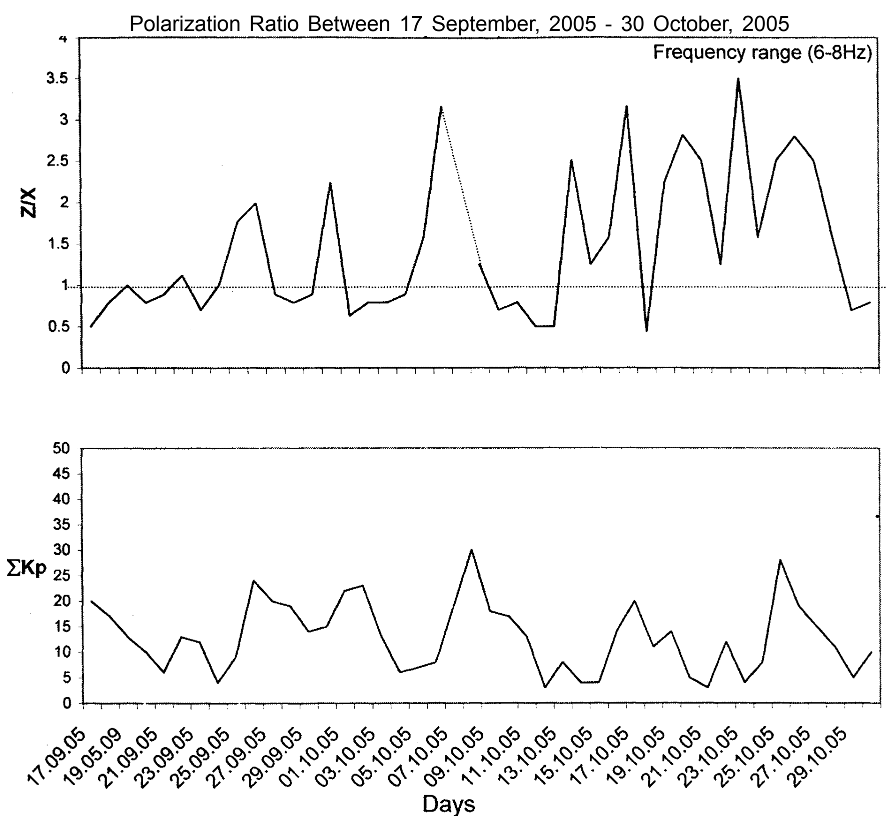

Figure 7. The top panel shows the polarization ratio Z/X from 17 September, 2005 to 30 October, 2005 and the bottom panel shows the magnetic storm ($\sum$Kp) for the same period.

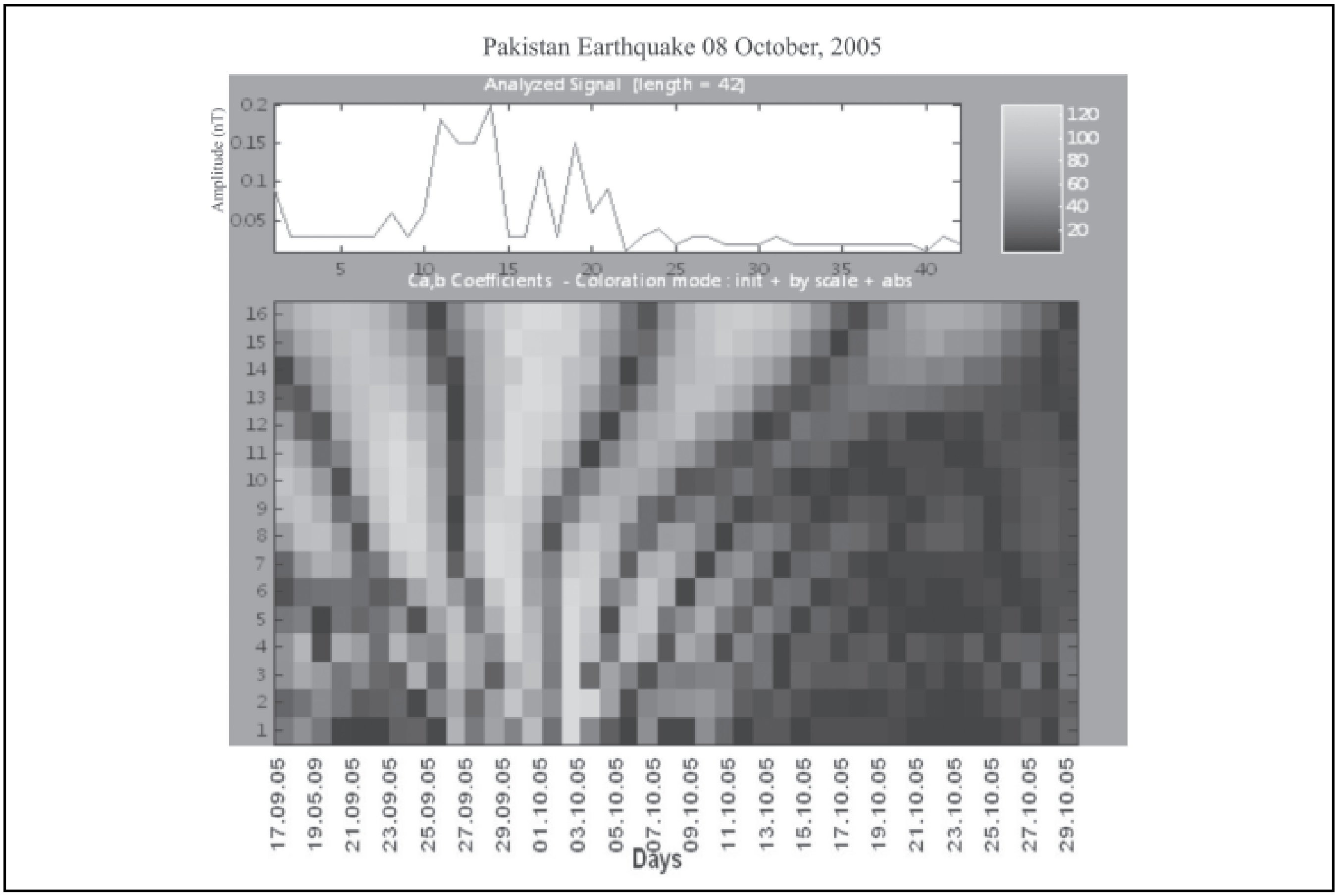

Figure 8. The top panel shows the Bz component amplitude for the same period and the lower panel shows the wavelet analysis.

In the last Fig.8 we carry out a wavelet analysis of the data for the same period presented in Fig.3. Here the top panel shows the Bz component amplitude for the same period and the lower panel shows the results of the wavelet analysis. The reddish part of the analysis shows the enhanced intensity on the above-mentioned days as per intensity scale shown on the right corner. A reddish zone represents the most intense days of the anomalies, which correspond to precursors of Pakistan earthquake of 08 October 2005.

From Table 1, it may be seen that the distance between the epicenter of Pakistan earthquake and the observing station at Agra is 908 Km, which is larger than distances in other cases. This raises the question that how the ULF signals are propagated to such large distances. This question may be answered in the light of the results of calculations done by Tsarev & Sasaki(1999) and Singh et al., (2004). They have shown that in realistic conductivity profiles the attenuation suffered by ULF range of signals is very low and they can propagate to more than 1000 Km through the middle layer crust which acts like a waveguide. Kushwah et al., (2005) have also discussed this problem at length and came to similar conclusion. Large distance propagation of ULF emissions has also been reported by Qian et al., (2002) and Ohta et al., (2004).

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