Initial results of ultra low frequency magnetic field observations at Agra and their relation with seismic activities

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Employing search coil magnetometers (f = 0.01–30 Hz) the ultra low frequency (ULF) magnetic field observations have been started at Agra since 13 September 2002. The analysis of first three months data shows that the amplitudes of the three components (*Bx*, *By* and *Bz*) are low between 0.01 and 0.30 nT normally, which increase to large values between 0.23 and 2.53 nT occasionally. Three cases of largest enhancements in amplitudes are selected and possible causes for the enhancements are examined in terms of magnetospheric ULF emissions (micropulsations) and ULF emissions associated with earthquakes using polarization parameter (*Z*/*X*) and magnetic storm index *Kp* variation. We show that in the three selected cases the amplitude enhancements are associated with moderately large earthquakes that occurred in the neighbouring countries Pakistan and China. In two of the three cases, the precursory enhancements in amplitudes are identified clearly. The statistical analysis of the data using mean and standard deviation around the mean is carried out which supports the results satisfactorily. The propagation mechanism of the emissions between the source locations and observing station at Agra is also discussed.

IN recent years considerable work has been done based on ground and satellite observations to find convincing evidences of electromagnetic precursors to earthquakes[1–7]. In general, it has been found that out of the wide range of frequencies involved from ultra low frequency (ULF) to high frequency (HF) range (0.001 Hz–30 MHz), the ULF band (0.001–10 Hz) is the only one which can produce reliable precursors to large impending earthquakes. Examples of such precursors can be seen from the observations during Spitak earthquake[8,9] of 8 December 1988, Loma Prieta earthquake[10] of 17 October 1989, Guam earthquake[11,12] of 8 August 1993, and Biak earthquake[13] of 17 February 1996.

The preference of ULF band over others is based on two major factors: (i) the skin-depths for ULF waves cover all expected earthquake source depths from 5 to 700 km, depending on wave period and the crust resistivity. For example, taking into account the resistivities normally encountered in the earth in a range from 1 to 10000 ohm-m, and wave periods from 0.1 to 200 s, one can find the depth range from 1 to 700 km which includes all depths of earthquake sources. Due to this reason ULF waves (geomagnetic pulsations, especially Pc 3–4 types) have been successfully used in magneto-telluric methods for remote sensing of the earth's crust conductivity because any structural change in earthquake regions can lead to a change in the crust resistivity which can affect the behaviour of ground observed ULF fields. (ii) The dynamic processes in the earthquake preparation zones can produce a current system in which the slope of the electric signal depends drastically on the rate of stress variation and specifically appears to follow the first derivative of the externally applied stress. This can become local sources for the generation of electromagnetic fields of different frequencies including ULF. The high frequency waves are attenuated so rapidly that they cannot be observed on the earth surface, whereas ULF waves can propagate through the crust and reach the earth surface. Therefore, the probability of earthquake signature manifestations is much higher in the ULF range than in other frequency ranges[14,15].

During the last 13 years six major earthquakes ($6.0 \le M \le 7.6$) have occurred in the Indian region. They include Bihar–Nepal border earthquake of 1988, Uttarkashi earthquake of 1991, Latur earthquake of 1993, Jabalpur earthquake of 1997, Chamoli earthquake of 1999 and Bhuj earthquake of 2001, all of which have caused widespread destruction of property and loss of lives. Unfortunately, the conventional techniques employed for earthquake prediction studies which included spatio-temporal variation by seismicity, micro-earthquakes, teleseismic P-wave travel time delays, radon emission anomalies, variation in geomagnetic and geoelectric fields, resistivity, animal behaviour, etc. have not yielded successful results. Keeping in view the potential applications of seismo-electromagnetic technique which has been employed globally for earthquake prediction studies in recent years[16–18], we have started precursory studies based on this technique at Agra[19–22] since 1998. Recently, we have installed ULF magnetic field sensors at Bichpuri (Agra) centre (27.2°N, 78°E) to study the magnetic field emissions associated with earthquakes. Bichpuri is located 12 km west of Agra city in the rural area where local electric and electromagnetic disturbances are low. In the present paper we describe the initial results of our observations during the first three months between September and November 2002 and their correlation with earthquakes. We show that the ULF intensity was considerably enhanced from the normal values during the three moderate earthquakes ($4.1 \le M \le 4.7$) which occurred in the neighbouring countries of Pakistan and China at distances less than 1000 km from the observing station at Agra. In two of the three cases the precursory enhancements in amplitudes are identified clearly. In the third case, the earthquake occurred in daytime during which there was no observation and hence precursory time could not be known. These results suggest that the extension of the work on this technique may possibly form a potential tool for earthquake prediction in future.

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The experimental setup employed for magnetic field observations is shown in Figure 1. This includes three Lemi-30 sensors which are search coils oriented in three orthogonal directions (*X*, *Y* and *Z*) measuring three components of magnetic fields, viz. *Bx*, *By* and *Bz*. The sensors are of one metre length each and buried one metre underground in orthogonal directions such that the *X*-direction coincides with the N–S direction. Other components of the magnetometer are a Communication unit, GPS antenna, Data acquisition card and the PC. The magnetometer works in the frequency band 0.01–30 Hz and the magnetic noise level between this frequency range varies from ≤ 20 pT $Hz^{-1/2}$ to ≤ 0.04 pT $Hz^{-1/2}$. The data from each sensor are digitized at a sampling frequency of 60 Hz and recorded on a hard disk for 8 h a day (2200 h–0600 h local time). The data of each channel with the data length of 1024 words are analysed using FFT employed in the MATLAB software.

The earthquake data have been taken from the United State Geological Survey (USGS). Only those earthquakes whose magnitudes are ≥ 4.0 and that occurred during the periods when the ULF intensity was found to be enhanced have been considered. Further, all locations in and around India within latitude and longitude ranges 0°–40°N and 60°–100°E respectively are considered.

The effect of magnetic storms on the ULF data is examined in terms of variation in 3-h *Kp* indices. The *Kp* index indicates the level of worldwide magnetic disturbances produced during magnetic storms. It may have a value between 0 and 9 assigned to a certain level of disturbance according to the observed global fluctuations in the magnetic field during a three-hour interval of Universal Time (UT). According to the World Data Centre 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 *Kp* index data were obtained from the Indian Institute of Geomagnetism, Mumbai.

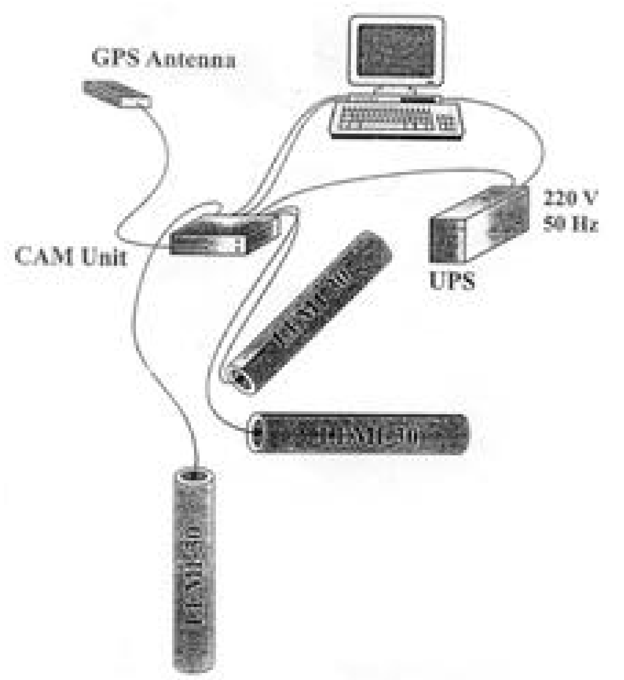

Figure 1. Experimental setup for Ultra Low Frequency observations at Agra. Lemi 30 are the search coil sensors in the orthogonal directions buried 1 m under ground.

We have been conducting regular observations of ULF magnetic field at Bichpuri, Agra station since 13 September 2002. The observations are taken during night-time only (2200 h–0600 h LT) to avoid natural and man-made electric and electromagnetic disturbances. All the three components of the magnetic field (*Bx*, *By*, *Bz*) are recorded in separate files on the hard disk. We have examined the amplitude–time records of the three components for the initial three months (September–November 2002). We find that, normally the background amplitude levels of the three components are low between 0.01 and 0.30 nT. However, on nine days during the later two months of observations between 27 September and 27 November 2002 the amplitudes are found to be enhanced considerably which lie between 0.23 and 2.53 nT. Among these nine cases, there are three cases in which largest enhancements occurred. The days of these enhancements are 3 October, 28 October and 23 November 2002. Figure 2 shows the amplitude–time records of the three components corresponding to these three cases. In rest of the six cases the amplitude data are influenced by the presence of the lower half harmonic of the power line frequency at 25 Hz which modulates the ULF signals and produces pearl type of amplitude variation. Hence these cases are not considered in the present analysis. They are discussed in detail later. The details of the amplitude–time records of the three considered cases are described below. For a comparison with the amplitude levels on the preceding and succeeding days we have shown the data corresponding to one day before to one day after the days on which the largest enhancements occurred.

Figure 2 *a* shows the amplitude data from 2 October to 4 October 2002. Here, the first two panels show the data for the night-time observations and the bottom panel shows the data for the day-time observations because of the power failure during night-time. The amplitudes of the three components on 2 October lie between 0.05 and 0.13 nT but they are enhanced on the next day of 3 October to the values between 0.27 and 0.92 nT. On 4 October the amplitudes return to the values between 0.12 and 0.30 nT. The pearl type amplitude variation between 0000 and 0300 h in the middle panel is due to modulation by half harmonics of the power line frequency at 25 Hz. However, unlike the six dropped cases this case is considered here because the data during the rest of the period are unaffected.

Figure 2 *b* shows the night-time data corresponding to four days from 26 October to 30 October 2002. Here, the amplitudes of the three components on 26 October lie between 0.13 and 0.34 nT but they are enhanced to the values between 0.23 and 0.76 nT around midnight hours on 28 October and continue to be so up to the midnight hours on 30 October 2002. Thereafter the amplitudes are low between 0.03 and 0.07 nT. The purpose of downward arrows at 2256 h in the middle panel will be explained later.

Figure 2 *c* shows the night-time amplitude data corresponding to three days from 22 November to 25 November 2002. Here, the amplitudes of the three components on 22 November lie between 0.05 and 0.19 nT but they are enhanced abnormally to the values between 0.36 and 2.53 nT on 23 November. The amplitudes return to low values between 0.05 and 0.19 nT around 0300 h on 24 November (shown in the middle panel itself). Since the day/night data corresponding to 24 November are not available, we show the amplitude data on 25 November for continuity which are similar to those of the normal values after 0300 h on 24 November 2002 of the middle panel. The purpose of the downward arrows at 0130 h in the middle panel will be explained later.

We have attempted to find a possible cause of the signal amplitude enhancement in the data shown in Figure 2 *a–c*. There are two possibilities, one of which is that the ULF signals of magnetospheric origin (micropulsation) are influencing the data, because such signals (also known as hydromagnetic signals) are usually strong in magnetic fields and they may modulate the background magnetic field signals recorded by us. The other is that the ULF signals generated from earthquake sources lying between the depth range 5 and 250 km (USGS data 2002) modulate the background magnetic field signals and propagate to the ground surface. To further examine the effect of these signals we deduce the polarization ratio Z/X ($\approx Bz/Bx$) from the data at midnight hours for two months of observations from 27 September to 27 November 2002. The polarization ratio Z/X is calculated on the assumption that the signal is propagated in the magnetic meridian which lies in the Z–X plane. The polarization ratio is an important parameter for discriminating the earthquake effect from magnetospheric effect. This ratio is found to be large (≥ 1) due to earthquake effects and small (< 1) due to the magnetospheric effects[9,11,23]. Figure 3 shows the variation of the amplitudes of the three components in the top panel, Z/X in the middle panel, and Kp values in the bottom panel. The definition of the parameter Kp is

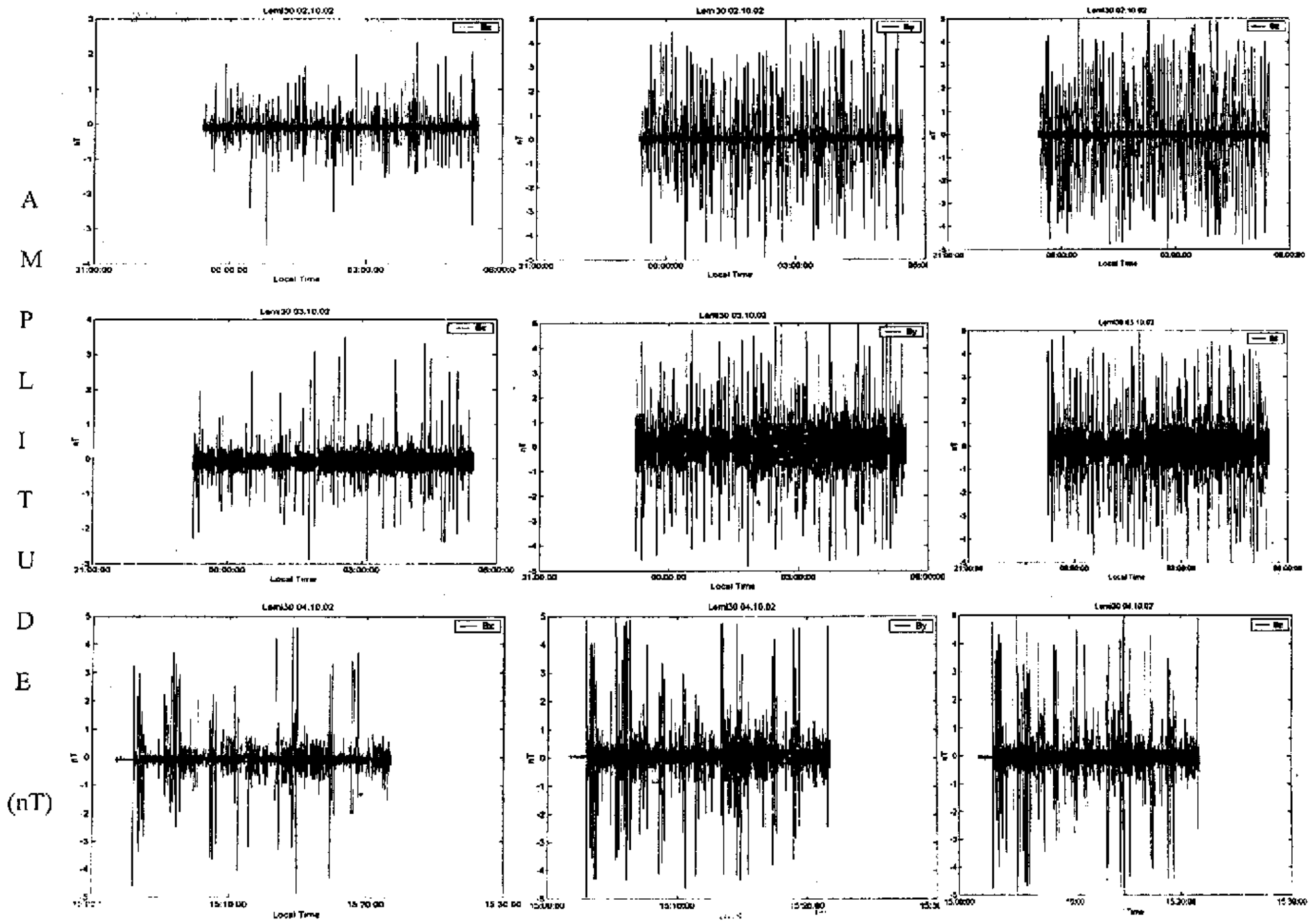

Figure 2 *a*. The amplitude–time record of the three magnetic field components (*Bx*, *By*, *Bz*) on three days between 2 October and 4 October 2002.

already explained earlier. The downward arrows in the top panel show the days of the occurrence of the earthquakes whose magnitudes are also indicated above the arrows. These arrows also indicate the days on which largest enhancements in magnetic field amplitudes are observed. From the *Kp* variation in the bottom panel it is seen that severe magnetic storms ($Kp \geq 6$) occurred on eight days in October and two days in November, i.e. 20 and 21 November. While comparing the amplitude data with *Kp* variation we find that, barring 3 October, there is no coincidence between the days of amplitude enhancements and severe magnetic storms. Hence, the effect of magnetic storms on the amplitude enhancements is ruled out. Thus the only possibility left is that the enhancements are caused due to earthquakes. The variation of polarization parameter Z/X in the middle panel also supports this conclusion because the values of the parameter are ≥ 1 on almost all the days.

From the top panel it is seen that the amplitude enhancements occurred on six more days in addition to those shown by the arrows. These enhancements are also correlated with the occurrence of earthquakes in the region as found from the USGS earthquake data. However, as mentioned earlier these enhancements are influenced by the presence of half harmonics of the power line frequency at 25 Hz. The existence of this signal is verified from the frequency–time spectrograms of the relevant data. The influence of this harmonic has been observed in ULF observations at other places in Japan, Russia and Finland also (M. Hayakawa and A. P. Nickolaenko, pers. commun., University of Electro-Communication, Tokyo, Japan, October 2003). Table 1 presents all the cases of amplitude enhancements and examine their relation with the earthquake parameters, i.e. depth, magnitude and distance from the observing station. The locations of the three earthquakes which occurred near Lahore and Rawalpindi in Pakistan (shown by open circles) and near the Nepal–China border which caused largest amplitude enhancements are shown in Figure 4 by solid circles. Also shown is the location of observing station Agra by open circle.

From Table 1 it is clear that the largest enhancements in the amplitudes in the first three cases are due to locations of the earthquakes being nearer to the observing station within 1000 km. Further, the largest enhancement

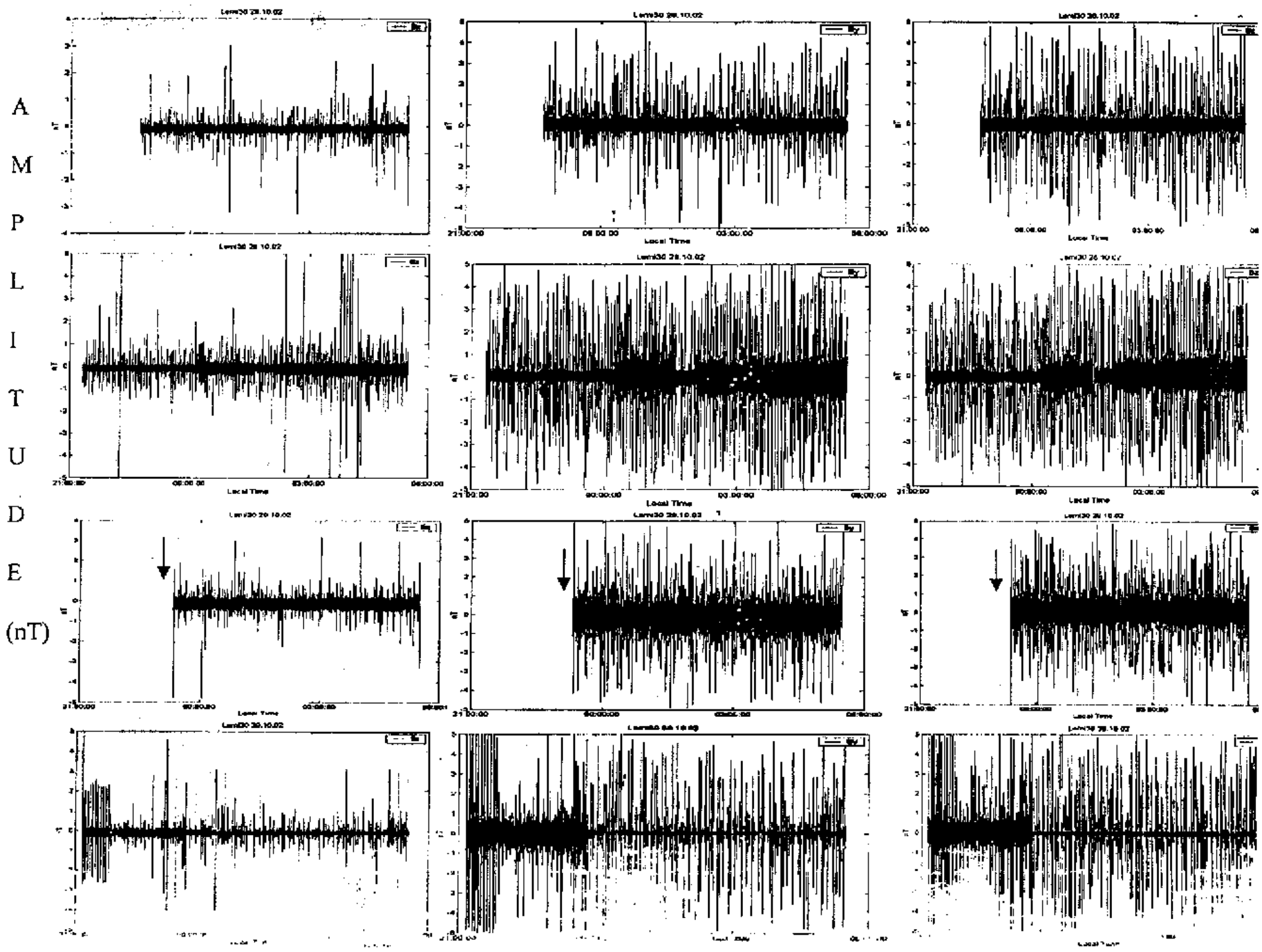

Figure 2 *b*. The same as Figure 2 *a* but for a different case of amplitude enhancement on 28 October 2002.

in the *Z*-components in cases 1 and 3 (0.92 and 2.53 nT) is due to relatively large magnitudes (4.6 and 4.7) as compared to that in case 2. The other cases between 4 and 9 include relatively smaller amplitude enhancements between 0.57 and 0.65 nT. This is because of longer distances between epicentres of earthquakes and observing station except the case 6 in which the distance is 799 km, but in this case the Y-component is enhanced (0.61). However, as mentioned earlier the amplitude enhancements in these cases are influenced by power line radiation and it is difficult to ascertain that the enhancements are solely due to earthquakes. Further, the depths of earthquakes are also important factors in amplitude enhancement in the above cases, but their effect in the present analysis could not be examined because of non-availability of information about them. From the detailed analysis of the data we find that the amplitude variation has regional dependence also. For example, the majority of cases in which there are no amplitude enhancements are found to be unaffected by the earthquakes. In such cases the earthquake occurred in different region. For example during the days of no enhancement between October 13 and 15 two earthquakes of magnitude 4.3 and 4.1 occurred in Andaman–Nicobar Island at distance of 2231 and 3556 km which did not produce any amplitude enhancement in our data.

From the amplitude–time records presented in Figure 2 *a–c*, and dates and times of occurrence of corresponding earthquakes, it is possible to estimate approximately precursory enhancement in the amplitudes of the magnetic field data. In case 1 it is not possible to estimate the precursory time because the earthquake occurred on 3 October 2002 in daytime (0723 UT = 1223 Pakistan time = 1253 Indian time) whereas the ULF magnetic field observations were started at Agra in the night-time. However, in the other two cases it is possible to estimate the precursory times. In case 2 shown in Figure 2 *b* the enhancement is attributed to an earthquake that occurred on 29 October 2002 in China at 1726 UT = 2256 h Indian time. This is shown by downward arrows in panel three. It may be seen from this figure that the enhancement in amplitude started around midnight hours on 28 October and continued till midnight hours on 30 October 2002. Hence, a precursory time of approximately 23 h can easily be seen from this figure. In case 3 shown in Figure 2 *c* the occurrence of earthquake

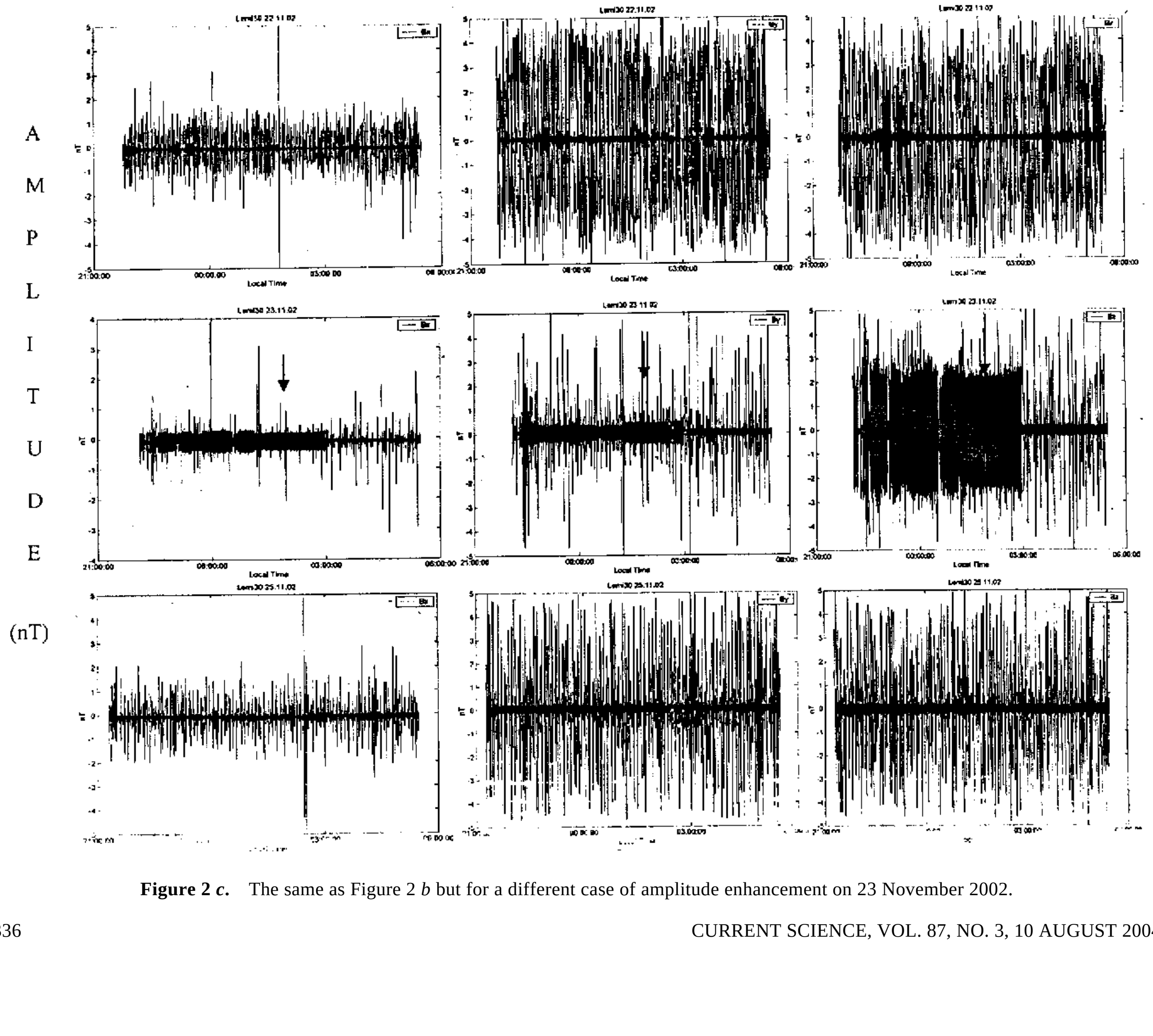

Figure 2 *c*. The same as Figure 2 *b* but for a different case of amplitude enhancement on 23 November 2002.

is shown by downward arrows at 2002 UT = 0102 Pakistan time = 0132 Indian time. The exact precursory time cannot be estimated in this case because observations were not taken during daytime. However, the precursory enhancement can be easily seen from the data because it occurred from the start of the observations at 2200 h Indian time itself.

Figure 5 presents the results of statistical analysis of the data. In fact we have calculated the mean (m) and standard deviation around the mean ($m \pm s$) for the three components from all the data between 13 September and 30 November 2002. These are shown by three horizontal lines in the first three panels of the figure. Also shown are the daily variation of the amplitude of the three components by solid curves and the occurrence of the earthquakes which caused largest enhancement in amplitudes by downward arrows (in the top panel). In the bottom panel the variation of *Kp* indices during the period of observations is repeated to examine its influence on the statistically analysed data. From this figure it is clear that the occurrence of large enhancements in the amplitudes of the three components is significant statistically also. Further, the data are not influenced by the magnetic storms and the largest enhancement in the amplitudes may be correlated with the occurrence of earthquakes.

From Figure 2 *a–c* it is seen that under the influence of earthquakes the amplitudes of the three components are enhanced but the level of the background noise does not change. This is different from the results of earlier workers who have observed a rise in the level of the background noise itself under the influence of earthquakes[24,25]. This is because they have used induction coil magnetometers whereas we have used search coil magnetometers. However, in both the cases the effect of earthquake is well noticed. The question of how the ULF signals can be

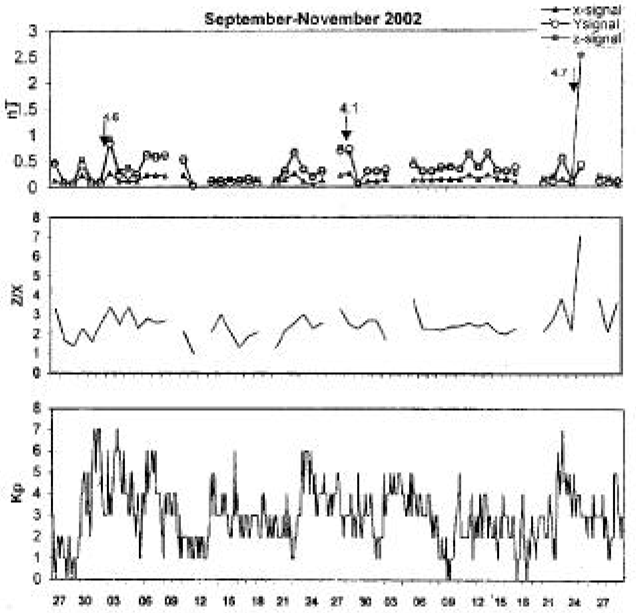

Figure 3. Amplitude variation for the three components from 27 September to 27 November 2002 (top panel), Polarization ratio Z/X (middle panel), and *K*p variation for the same period (bottom panel). The downward arrows indicate the occurrence days of earthquakes which are responsible for largest amplitude enhancements.

Table 1. Amplitude enhancements and earthquake parameters

	Amplitude enhancement		Earthquake details						
Case no.	Date of enhancement	*Z*-component amplitude (nT)	Date of occurrence	Time (UT)	Location latitude & longitude	Depth (km)	Magnitude	Distance from observing station* (km)	Remark
1	03.10.02	0.92	03.10.02	0723	31.69°N 73.70°E	33	4.6	650	–
2	28.10.02	0.76	29.10.02	1726	28.01°N 87.42°E	33	4.1	932	–
3	23.11.02	2.53	23.11.02	2002	33.66°N 71.74E	33	4.7	935	–
4	06.10.02	0.65	06.10.02	1212	39.73°N 74.42°E	33	3.7	1432	Data influenced by harmonic of power line radiation
5	08.10.02	0.61	08.10.02	1711	39.77°N 71.00°E	33	3.7	1540	
6	09.10.02	0.57	09.10.02	1749	34.15°N 80.12°E	33	4.3	799	-do-
7	23.10.02	0.69	23.10.02	1149	11.19°N 92.98°E	33	4.8	2370	-do-
8	10.11.02	0.61	10.11.02	2154	17.21°N 93.76°E	32	5.2	1963	
9	13.11.02	0.61	13.11.02	0344	02.86°N 96.31°E	33	4.4	3334	

*Calculated using a computer program written for great circle path calculations around the world.

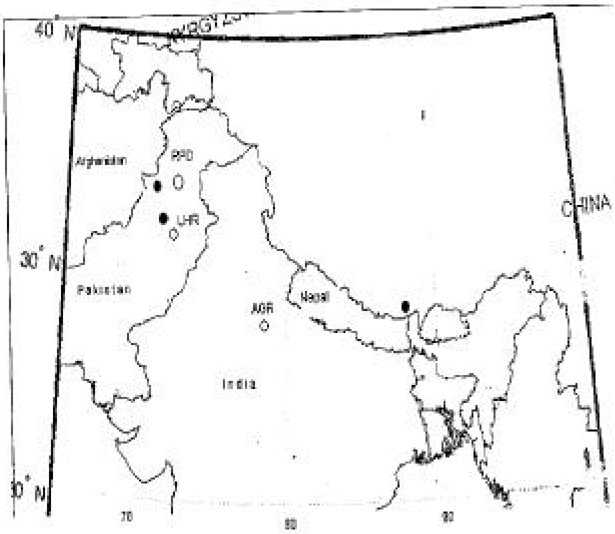

Figure 4. Map showing the locations of earthquakes (solid points) near Lahore (LHR) and Rawalpindi (RPD) in Pakistan (indicated by open circles) and Nepal–China border. The observing station Agra (AGR) is indicated by open circle also.

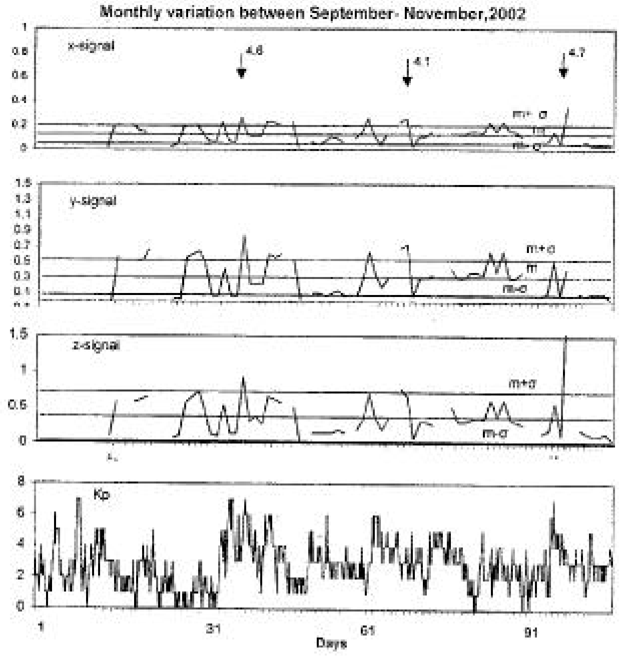

Figure 5. The statistical results showing the amplitude variation of three components across mean (m) and standard deviation around the mean (m ± *s*). The days of occurrence of earthquakes responsible for amplitude enhancement are indicated by downward arrows. The bottom panel shows the *Kp* variation.

generated and propagated to earth surface has been studied in detail by earlier workers. It has been shown that microfracturing in the earth crust is a possible mechanism for generation of ULF electromagnetic emissions observed before and after the earthquakes. The noise generated at the source is dissipated producing ULF emissions on the ground surface with an upper cut-off around 1 Hz due to skin depth attenuation[15,26]. Theoretical calculations have been made to study the penetration characteristics of ULF/ELF electromagnetic emissions from an underground seismic source into the atmosphere, ionosphere and magnetosphere. It has been found that the fields from a magnetic type source can penetrate into the magnetosphere. The expected values of magnetospheric electric and magnetic fields are 1–10 μvolt $m^{-1}Hz^{-1/2}$ and 1–10 pT $Hz^{-1/2}$ respectively and the horizontal scale of their distribution is about 100–200 km[26,27].

The question of how the ULF emissions generated in Pakistan at distances of 635 and 935 km and in China at distance of 932 km can be propagated to our station at Agra may be explained in the light of theoretical calculations by Tsarev and Sasaki[28] who have considered a realistic conductivity model for the middle layer crust and calculated the distance through which a signal of 100 Hz could be propagated. They have found the distance in the range of 100–1000 km. For ULF range of frequency (0.01–30 Hz) this distance could be much larger. Hence, it is possible that the ULF emissions generated at the seismic source in Pakistan and China are propagated to our station at Agra and detected by the magnetometer. This is supported by other evidences of detection of seismogenic ULF emissions at large distances also. For example, Qian *et al.*[29] have reported the observation of ULF signals generated from Jiji earthquake of 21 September 1999 in Taiwan and recorded at many stations at distances of 300–900 km in South East China. Similarly, Ohta *et al.*[25] have reported the observation of ULF/ELF emissions generated from Taiwan earthquake of 21 September, 1999 and recorded at Nakatsugawa station in Japan at a distance of approximately 2000 km.

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ACKNOWLEDGEMENTS. This article was presented in session JSA06 of the XXIII General Assembly of the International Union of Geodesy and Geophysics (IUGG 2003) held at Sopporro, Japan during June 30–July 11 2003. We thank the Seismicity Division of the Department of Science and Technology, New Delhi for financial support in the form of a major research project. We also thank the United State Geological Survey (USGS) for making available the earthquake data. The discussion and help extended by our colleagues Dr Rajpal Singh and Mr Vikram Singh are gratefully acknowledged. B.S. thanks CSIR, New Delhi for support under CSIR Emeritus Scientist Scheme. We are grateful to the referee for going through the manuscript thoroughly and suggesting useful modifications.

Received 3 June 2003; revised accepted 3 March 2004

Utilization of conducting polymer as a sensitizer in solid-state photocells

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Solvent-free, solid-state solar cells were fabricated with mesoporous TiO_2 sensitized by electronically conducting polymer; poly(3-thiophenyleneacetic acid) (P3TAA) and reasonably high photocurrents were observed for the first time in polymer sensitized solid-state photovoltaic devices. When CuI was employed as the hole transporting material together with an ionic liquid 1-ethyl-3-methylimidazolium bis(trifluromethylsulfonyl) amide ($EMImTf_2N$) and $LiTf_2N$ as additives for charge transport promotion, the cell TiO_2/P3TAA/CuI delivered a respectable short circuit photocurrent of ~ 1.2 mA cm^{-2} with an open-circuit voltage of ~ 275 mV under the irradiance of 100 mW cm^{-2} (1.5 Air Mass).

DYE-SENSITIZED mesoporous TiO_2 photoelectrochemical solar cells (DSC) emerged recently as legitimate alterna-

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