Anomalous subsurface VLF electric field changes related to India-Nepal border earthquake (M=5.3) of 4 April 2011 and their lithosphere – atmosphere coupling observed at Mathura

Raj Pal Singh¹ and Birbal Singh²
1. GLA Institute of Technology and Management, Mathura, India
2. Faculty of Engineering and Technology, RBS College, Bichpuri Agra, India

Abstract. Subsurface VLF electric field changes have been monitored at Chaumuhan, Mathura (Geographic Lat. 27.5°N, Geographic Long. 77.68°E), India at the frequency of 3.012 kHz employing borehole and vertical antennas since 24 March 2011. Initial data for the period of 15 days are analysed statistically and it has been found that anomalous enhancements occurred in the VLF amplitudes observed by both the antennas. These anomalous enhancements are examined in the light of magnetic storms, local lightning, and earthquakes and are positively correlated with the devastating India-Nepal border earthquake (M=5.3) occurred on 4 April 2011. The precursory period for borehole data ranges between 3-7 days while for vertical antenna data it is 3 days. The generation and propagation mechanism of ELF/VLF emissions in the crustal region have also been discussed.

Key words: VLF electric field changes, borehole antenna, earthquake

1. Introduction
Several workers have observed electromagnetic emissions before and/or after the occurrence of earthquakes during the last three decades in a wide band of frequencies ranging from direct current (DC) to high frequencies (HF) both on earth surface and in the ionosphere (Gokhberg et al., 1982; Parrot and Mogilevsky, 1989; Fujinawa and Takahashi, 1990; Fraser-Smith et al., 1990, Molchanov et al., 1992, 1993; Hayakawa et al., 1996). Association of these emissions with seismic activities has also been confirmed from the laboratory experiments involving rock fracturing with quartz bearing rocks (Nitsan, 1977; Cress et al., 1987; Yamada et al., 1989). Parrot (1995) and Hayakawa (1999) have reviewed the work done in this field thoroughly. A detailed account of the recent work in this direction is given in Hayakawa and Fujinawa (1994), Hayakawa (1999), Hayakawa and Molchanov (2002), Singh (2008), Molchanov and Hayakawa (2008), Hayakawa (2009, 2012) and references therein.

Among various ground-based techniques employed for monitoring precursory seismogenic emissions, the subsurface measurements of electric and magnetic field emissions at frequencies between ULF (0.01 Hz to 10 Hz) to VLF (3 kHz – 30 kHz) have attracted greater attention recently (Fujinawa and Takahashi, 1994; Hata and Yabashi, 1994; Quin et al., 1994). Using this technique a very important result was obtained by Fujinawa and Takahashi (1995) in which they have found an increased number of VLF pulses prior to the occurrence of Kurile earthquake in 1994. A very convincing ULF precursor to Taiwan earthquakes of 21 September 1999 has been found by Ohta et al., (2001), one week before the main shock. Employing the same technique, measurement of subsurface and simultaneous subsurface and terrestrial measurements of the VLF electric...
field measurements started first at Agra in India from February 1998 and since then several important results have been obtained (Singh et al., 1999, 2000, 2001). Motivated from the work of these workers and the precursory nature of seismogenic emissions, we at Mathura have also started to monitor the vertical component of subsurface VLF electric field emissions associated with seismic activities. We have started our measurements by employing borehole and vertical antennas at the frequency 3.012 kHz since 24 March 2011 and the results of analysis of the VLF data for a brief span of 15 days in relation to the India-Nepal border earthquake (M = 5.3) of 4 April 2011 are presented in this paper.

2. Experimental Setup

The experimental setup employed for monitoring the vertical component of VLF electric field emissions at the frequency of 3.012 kHz is shown in Fig.1.

Fig.1: Experimental setup for monitoring vertical component of VLF electric field emissions.

It is similar to that used at Agra (Singh et al., 1999, 2000, 2001, 2003) except for some minor modifications. We have used two types of antennas: a borehole and a vertical antenna. The borehole antenna is a naked copper wire 120 meter in length and 4 mm diameter which is placed in a water tight PVC pipe of 1.25 cm diameter with its lower end tightly fitted with an insulating cork at the bottom. This is placed in another PVC pipe of 1.9 cm diameter which is open at both ends and is used to reduce the upthrust (buoyancy) on the pipe containing the antenna. Another electrode is placed 3 m down the earth to provide the earth terminal. The borehole antenna is connected to an IC (TL081) based amplifier (gain 26 dB), band-pass filter (bandwidth = 550 Hz, peak frequency 3.012 kHz) and then with a notch filter (notch frequency 50 Hz) and the output is
recorded on a PC using the A/D converter and MATLAB software. For monitoring the atmospheric effect of seismogenic emissions a terrestrial antenna is installed at the double storey building of central library of the Institute which is just adjacent to our observatory. This terrestrial antenna is similar to the borehole antenna but of height 18 meter. It is connected with the similar arrangement as that of borehole antenna and signals induced on both the antennas are recorded on the same PC at the frequency 3.012 kHz. The frequency of filter is chosen to be 3.012 kHz as a trade off between the unwanted noise at the lower frequencies caused by power line radiations and their harmonics, and atmospherics etc and increasing attenuation with frequency. Observations are taken round the clock at Chaumuhan, a rural area, about 17 km north-east of Mathura city where local electric and electromagnetic noises are very low.

3. Sources of earthquake, $\Sigma Kp$ and local lightning data

In Fig.2 we show a map of India and Nepal at the border location of which an earthquake (M=5.7, Geographic Lat.29.70°N, Geographic Long.80.75°E, depth 26 km) occurred on 4 April 2011. The epicenter of earthquake is shown by a solid circle and the observing station at Mathura is shown by a star.

![Fig.2: Map of India and around. The solid circle indicates the location of India-Nepal border earthquake (M = 5.3) while a star in the Indian region indicates the location of the observing station at Chaumuhan, Mathura.](image)

It may be noted that except this earthquake, no other earthquake (M > 5.5 with depth < 30 km) occurred in the observation area during the period of study. Details of the earthquakes are obtained from United States Geological Survey through website: http//neic.usgs.gov. In order to examine the effect of magnetic storms and local lightning
on VLF data we consider the magnetic storm data obtained from the Word Data Centre, Kyoto, Japan through website: http://swdcdb.kugi.kyotoe.ac.jp while the local lightning data are obtained from the website: www.wunderground.com.

4. Results and discussion

Monitoring of vertical component of VLF electric field emissions (frequency 3 kHz) inside and above the ground employing a borehole and a vertical antenna was started first in India at Agra in the year 1998 which was based on an analog technique of measurement. Analysis of the data yielded interesting results (Singh et al., 1999, 2000, 2001, 2003, 2004, 2009). However, our analog method is slow and its time resolution is low. Further, it does not provide information on phase characteristics of the signals. In view of this and on account of availability of fast computers and sophisticated signal processing techniques a digital method of recording is adopted at Chaumuhan, Mathura using borehole and vertical antennas simultaneously. Data are recorded at the rate of 1 sample/sec. Bulk of the data recorded on each day is averaged. It is worthwhile to mention here that only nighttime data (2000 – 0500 h LT) of each day are considered in the present analysis for minimizing the effect of local building noises and power line radiations. As mentioned earlier, we have analyzed only 15 days of initial period of observations from 24 March to 7 April 2011 in this paper. This is for two reasons: first, an earthquake of magnitude 5.3 occurred at our border with Nepal only a few days after we started observations and second, there was a possibility of contamination of the data from other earthquakes if longer days of data were considered. For statistical study of the VLF data mean (m) and standard deviation around the mean (m ± σ) approach has been adopted. Such an approach has been adopted by Ida and Hayakawa (2006) also. The mean (m) and standard deviation around the mean (m ± σ) for borehole antenna are shown by solid and dotted horizontal lines in the top panel of Fig.3. Daily variation of the processed borehole data is shown by the solid line in the same panel of Fig.3.

A downward arrow indicates the day of occurrence of earthquake. From a glance at the daily variation in this figure it is clear that signal amplitude is enhanced significantly beyond the σ lines on 28 March and there is also a minor enhancement on 1 April 2011. This result shows some kind of anomalous situation as compared to rest of the data. This anomalous situation will be examined in the light of earthquakes and some other non-seismogenic sources later on.

Seismogenic signals generated in the crustal region may leak to the atmosphere. In order to examine the effect of these emissions in the atmosphere round the clock monitoring of vertical component of VLF electric field emissions at the same frequency of 3.012 kHz is being carried out using a terrestrial antenna since 24 March 2011. Data of the vertical antenna are also logged at the rate 1 sample/sec and are processed with the same technique as in the case of borehole antenna. Results of daily variation of VLF data are shown by the solid line between m + σ and m – σ lines in the top panel of Fig.4. From a close examination of daily variation of the terrestrial VLF data it is clear that there is an anomalous enhancement on 1 April 2011.
Fig. 3: Daily variations of the VLF data recorded in borehole antenna during 24.03.2011 to 5.04.2011 (Shown by solid lines in the top panel). The mean (m) and standard deviation around the mean (m ± σ) for borehole antenna are shown by solid and dotted horizontal lines. Daily variation of ∑Kp is shown at the bottom.

There are four possibilities in which such an anomalous enhancement in the amplitude may occur. These are effects of magnetic storms, local building noises, local lightning and earthquakes. Here we examine the effect of these possible causative sources and try to fix up the one which appears to be relatively more responsible for the observed anomaly. Magnetospheric electric fields (magnetic storms) may perturb the voltage induced on both the borehole and vertical antennas. In order to examine the effect of magnetic storms on VLF data of the borehole and vertical antennas, daily variations of the ∑Kp are shown by histograms in the bottom panels of Figs. 3 and 4. From these figures it is clear that ∑Kp ≤ 29 during the entire period of data under consideration. Hence such anomalous enhancements in VLF data on 28 March and 1 April in borehole antenna and on 1 April in atmospheric antenna may not be due to magnetic storms. During local lightning, a wide band of electromagnetic radiations ranging from ULF to HF are generated which may interact with the antenna systems and may cause amplitude enhancements in VLF data. In order to examine the effect of such local lightning we consider lightning data of Delhi and Jaipur stations which are around 200 km from the observing site and data for them are available through the website: www.wunderground.com. From a close examination of lightning data it has been found that there have been two thunderstorms, one on 30 March 2011 and another on 2 April 2011 at Delhi station while no event took place at Jaipur. Since significant VLF anomalies at Mathura are observed on 28 March in borehole antenna and on 1 April 2011
Fig.4: Daily variations of the VLF data recorded in vertical antenna during 24.03 2011 to 05.04.2011 (shown by solid lines in the top panel). The mean (m) and standard deviation around the mean (m ± σ) for borehole antenna are shown by solid and dotted horizontal lines. Daily variation of \( \Sigma K_p \) is shown at the bottom.

in vertical antenna, there is no relation between the local lightning and observed VLF anomalies as there is mismatch between the days of two activities. Local power line radiations and other building noises may also affect the VLF data recorded. Since we have used a notch filter (notch frequency = 50 Hz) in our experimental setup which eliminates the effect of local power line radiations, the possibility of anomalous enhancement in borehole and vertical antennas due to power line radiations may be ruled out. Further, VLF data are unlikely to be affected by the local building noises because only nighttime data are considered in the present analysis because such noises are insignificant during this time. Now, since anomalous enhancements observed in borehole and vertical antennas are not correlated with magnetic storms, local lightning, local power line radiations and local building noises, it may be attributed to an underground source developed in the preparation zone of India-Nepal border earthquake which led to the generation of electromagnetic waves before the onset of main shock due to increasing stress in the region.

Our result that anomalies in vertical component of VLF electric field emissions occur 7 days before the main shock in the borehole antenna and 3 days before in the terrestrial antenna is consistent with the results of earlier workers. For example, Parrot et al. (1985) have found enhancement in the wave intensity at the frequency between 500 Hz to 3.6 kHz about 1.5 hour before the occurrence of a moderate earthquake (M=4.7) about 100 km away from the Kerguelen station. Uyeda et al. (2000) have reported slow
transient electric potential changes 1-19 days before 5 seismic events (M ≥ 5) in Japan. Singh et al. (2000) have observed an increase in occurrence number of VLF noise bursts 1 hour to 2.3 days before several earthquakes (M ≥ 4.5) in India and around while Singh et al. (2001) have observed abrupt changes in the vertical component of VLF electric field emissions (frequency = 3 kHz) using a borehole antenna 5 days before the Chamoli earthquake of March/April 1999 and their effect continued up to 1 month.

Now the question arises how the VLF electromagnetic radiations are generated in the preparation zone and propagated to such long distances (386 km) and cause enhancements in the vertical component of VLF electric field emissions at the observing station. In order to answer this question it may be mentioned here that four possible mechanisms viz: electro-kinetic effect, tribo-electric effect, micro-fracturing and piezoelectric effect have been proposed for the generation and propagation of seismo-electromagnetic signals (see, e.g., Molchanov and Hayakawa, 2008). In the electro-kinetic effect, fluid flow through the rocks leads to the generation of electric and magnetic fields (Fenoglio et al., 1995) while in tribo-electric effect electromagnetic emissions are generated due to frictional sliding of rocks (Brady and Rowell, 1986). However, both of these mechanisms show only the local influence and the emissions generated through these mechanisms can not propagate to long distances. In the phenomenon of micro-fracturing electromagnetic emissions are generated due to acceleration of charges as a result of crack motion when the rocks are under indentation. But, this mechanism is found suitable for ULF range of emissions (Molchanov and Hayakawa, 1995). In piezoelectricity, charges are generated at the opposite faces of the rock or the crystal when it is under stress. This results in the formation of large number of elementary dipoles in the source region. When the stresses on the rocks vary due to their motion, dipoles start to oscillate and generation of VLF and other electromagnetic radiations result in (Ikeya et al., 1997). The VLF emissions so generated in the source region (depth ≈ 15km) reach the earth surface through windows of low conductivity from where they appear at the observing station through Earth-ionosphere waveguide. Similar mechanism has been proposed by Mognaschi (2002) for the propagation of VLF/ELF seismogenic emissions.

Acknowledgements

The authors are thankful to the Ministry of Earth Sciences, Government of India, New Delhi for providing a Major Research Project. Thanks are also due to United States Geological Survey and World Data Centre, Kyoto, Japan for providing earthquake and $\Sigma K_p$ data. The valuable help extended by our research colleague Mr. Vishal Chauhan in preparing the figures is gratefully acknowledged.

References


Molchanov, O. A., Yu. A. Kopytenko, P. M. Voronov, E. A. Kopytenko, T. G. Matiaishvili, A. C. Fraser-Smith, and A. Bernardi, Results of ULF magnetic field measurement near the epicenter of Spitak ( Ms = 6.9) and Loma Prieta ( Ms = 7.1) earthquake; comparative analysis, Geophys. Res. Lett., 19, 1495-1498, 1992.


(Rceived August 6, 2012; revised September 30, 2012; accepted October 30, 2012)