Attenuation of ULF-VLF seismo-electromagnetic signals and their propagation to long distances

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Using a two-layer crust model between the source region and earth surface, the attenuation of seismo-electromagnetic signals is calculated. Results show that attenuation of Ultra Low Frequency (ULF) signals is very low and they can penetrate the crustal region to enter the atmosphere and ionosphere over the epicentral area of the earthquakes. However, the attenuation increases steeply in the crust for the ELF and VLF ranges of signals. These results are utilized to discuss the propagation mechanism of VLF signals (\( f = 3 \, \text{kHz} \)), which are recorded at Agra by employing a borehole antenna during the periods of Chamoli earthquakes in India and large magnitude earthquakes in Afghanistan. It is suggested that these VLF signals propagate upward and find windows of very low conductivity in the skin layer through which they get transmitted to the atmosphere. They then propagate to the observing station at Agra through earth-ionosphere waveguide.

Keywords: ULF signal, VLF signal, ELF signal, Seismo-electromagnetic signal, Signal propagation
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1 Introduction

Although a number of electromagnetic phenomena occurring predominantly in frequency ranges of ultra low frequency (ULF, \( f = 0.01-30 \, \text{Hz} \)), extremely low frequency (ELF, \( f = 30-3000 \, \text{Hz} \)), and very low frequency (VLF, \( f = 3-30 \, \text{kHz} \)) before, during, and after the earthquakes have been reported on the basis of ground and satellite based observations\(^1-6\), a clear correlation between the two is still being searched, because of poor understanding of the generation and propagation mechanism of the emissions. In view of this, global scientific efforts are in progress by considering different types of hypothetical models. For example, Ribnikov et al.\(^7\) have used numerical model calculations to suggest that the quasi-static electric field generation in earth’s crust, or on the ground, may be transferred to the ionosphere for a favourable profile of electrical conductivity. Ondoh\(^8\) has estimated the attenuation of electromagnetic waves generated during volcanic activity in wet soil, dry crust, and magma and found that low frequency electromagnetic signals can not penetrate through magma and moist soil from volcanoes interior to ground because of strong attenuation.

In order to explain electromagnetic radiations observed on earth’s surface prior to earthquakes and to avoid the difficulty of their propagation from conductive layers due to skin effect, Sumimoto\(^9\) has proposed that elastic deformations such as seismic waves first come up from seismic source region and then get converted to electromagnetic waves near the earth’s surface. A new mechanism of lithosphere-ionosphere coupling via internal gravity waves which are generated in seismo-active regions by non-stationary thermal anomalies of the atmosphere has been suggested by Gokhberg et al.\(^10\). Molchanov et al.\(^11\) have employed full wave calculations to study the penetration of ULF waves through the earth’s crust, atmosphere, and ionosphere. Tian and Hata\(^12\) have estimated electric and magnetic field components, both due to a single dipole at different depths and a dipole system in epicentral region for explaining their observational results. They have found that only signals of frequencies less than 223 Hz can directly penetrate through the deep crust and there was almost no effect on \( E_x \) and \( E_y \) components for a dipole just near the earth surface, except in the small range of observational distance. Assuming flat and semispherical layers over the epicentre of preparing earthquake, Bliokh\(^13\) has estimated variation of electric fields and currents in lower ionosphere produced by conductivity growth due to additional ionization of air near the earth owing to radioactive emanations. Tsarev and Sasaki\(^14\) have computed transmission efficiency of ELF waves as-
suming earth’s crust as a waveguide and found that the signals can appear at earth’s surface through “windows” in skin layer produced by some geological formations with low conductivity.

In some recent publications15-18 which are based on monitoring of sub-surface vertical electric field emissions at Very Low Frequency (VLF) 3 kHz at Agra using a borehole antenna, we have shown that the observed emissions are associated with not only Indian earthquakes such as that of Chamoli which occurred on 29 March 1999, but also with some distant earthquakes that occurred in Afghanistan in 1998. Since the propagation of such signals to long distances through normal crust is very difficult due to high resistivity and skin effect, it was suggested that the signals propagated to Agra through main boundary fault (MBF) existing between Afghanistan and north-east India along the southern boundary of Himalaya, which acted as waveguide and transverse conductive channels across it near Delhi and Agra. However, the conductivity in a seismic fault is much higher than the surrounding rock19 and long distance seismic faults filled with air to work as waveguide, are unlikely to exist (J L Roeder and M Hayakawa, personal communication, 2003). Then the question arises that how such signals propagated to long distances and observed at Agra?

In the present paper, we calculate attenuation of seismo-electromagnetic signals in the frequency range between Ultra Low Frequency and Very Low Frequency (0.01-104 Hz) in experimentally determined conductivity profiles and then discuss the propagation of VLF signals at Agra station.

2 Selection of conductivity profiles

Magneto-telluric observations have been carried out by Arora and Singh20 to determine the depth resistivity profile in earth’s crust around and over the Trans-Himalayan conductor. According to the model developed by them the conductivity of the upper crust varies in the range 10-2-10-1 S/m. Tsarev and Sasaki14 have used geophysical model of Keller21 and suggested a three-layer model of the earth’s crust, in which the upper layer (thickness between a few metre and few kilometres) has the same conductivity as that found by Arora and Singh20, the middle layer (thickness about 55 km) has much lower conductivity of 10-6-10-3 S/m, and the lower layer including Moho and upper mantle has the large conductivity similar to upper layer. In Fig.1 we show the conductivity models developed by the above two groups. The model of Arora and Singh20 (top) is in fact the resistivity profile but it can be converted into conductivity profile easily. The model of Tsarev and Sasaki14 (bottom) is an idealized version of that resulting from most geophysical models. Here, a indicates the upper layer which may include the oceanic water (conductivity ~ 4.5 mho/m or 4.5 S/m) and continental crust of the conductivities mentioned above, b indicates the middle layer which may be 7.5 km thick for oceanic crust and 35 km thick for continental crust, and c indicates the lower layer, which includes the Moho and upper mantle. Since the foci of most of the devastating earthquakes lie in the shallow depths of middle layer, the conductivity around such foci will vary in the range 10-6-10-4 S/m. It is for this region that Molchanov et al.14 have considered the conductivity of 10-4 S/m in their full wave calculations for the heights in the middle layer.
3 Expressions used for the calculations

The strength of the electric field of an electromagnetic signal is attenuated in traversing a distance $r$ in a conducting media as per equation 22

$$E = E_0 e^{-\alpha r}$$

... (1)

where $\alpha$ (attenuation constant) = $(\omega \mu \sigma/2)^{1/3}$

... (2)

Here, $\omega$ is the angular frequency, $\mu$, the permeability of the medium, and $\sigma$, the conductivity of the medium. From Eq. (1) the attenuation in dB/km may be given by

Attenuation (dB/km) = 8684$\alpha$ = 8684$(\omega \mu \sigma/2)^{1/3}$

... (3)

Ondoh$^8$ used a similar expression for attenuation calculation of ELF/VLF signals in dry crust, wet soil, and magma in volcanic region.

4 Results and discussion

Before we proceed to calculate the attenuation of seismo-electromagnetic signals in the earth’s crust and discuss their long distance propagation mechanism, we would present some of the wave forms of the signals which were recorded at Agra at the frequency of 3 kHz in a 120 m borehole during Afghanistan seismic swarm of 4-27 February, 1998 and Chamoli swarm of 29 March-18 April, 1999. In Fig. 2(a), we show the waveforms of signals recorded during Afghanistan earthquakes on three different occasions. These signals are mostly of short periods between 5 min and 20 min and include square wave

Fig. 2(a) - Waveforms of vertical component of electric field emissions recorded at Agra, Uttar Pradesh, India in a borehole on three different occasions during seismic swarm of 4-27 February, 1998 in Afghanistan
Fig.-2(b) Waveform of vertical electric field emissions recorded in borehole one day before the main shock of earthquakes in Chamoli, India. [There is no such signal in terrestrial antenna above the ground surface.]

pulses of varying amplitudes and durations and pulsating waves of rising amplitudes. During Chamoli earthquakes, a terrestrial antenna of 20 m height above the ground was operated, also in conjunction with the borehole antenna. In Fig.2(b), we show the waveform of the signal recorded on 28 March, 1999, one day before the occurrence of the main shock in Chamoli. It can be seen in the figure that there was no signal of this type recorded by the terrestrial antenna. In our recent report23 we have shown that the borehole data during the period of March to September, 1999 are positively correlated with the number of earthquakes (M > 4.5) that occurred in each month in India and around and satisfied the Null hypothesis.

In order to measure the level of signal strength at the borehole antenna we have conducted the observations of natural dc potential with respect to ground using a digital multimeter model Philips DM-341 from September, 1999 to January, 2000. We found that the geopotential increased from 10 mV in September to 25 mV in January. Around February and March the potential is expected not to be much different from that in January. It means the signal strength must be larger than 200 µV/m at the antenna during Afghanistan and Chamoli earthquakes. Since the signals at the antenna are assumed to have propagated in earth-ionosphere waveguide from the epicentral regions of the two earthquakes during which there were not much attenuation, similar field strength may be expected on the earth’s surface over the epicentral area of the two earthquakes also.

The signals observed at Agra are mostly in the form of signal bursts of varying amplitude and duration [see Fig. 2(a) and (b)]. Since the observations are taken in rural area and the antenna is installed in a borehole, the contamination of the data from various spurious sources such as spherices, power line radiations, building noises, and radio transmissions are reduced considerably. It has been found that during seismic activity days, the borehole data are dominated by the emissions from seismic sources, whereas during non-seismic days the data are dominated from emissions from other sources23.

Now, we proceed to calculate the attenuation suffered by the seismo-electromagnetic signals at the frequency of 3 kHz. We consider a two-layer model of the earth’s crust, in which the signal is propagated from the source region in the middle layer to the top of the earth’s crust through upper layer. As per Arora and Singh20 model the conductivity of the upper layer is in the range $10^{-2} - 10^3$ S/m, with the lower basement conductivity around $10^{-2}$ S/m. Again, as per Tsarev and Sasakij14 model the conductivity of middle layer is in the range $10^6 - 10^{10}$ S/m. Here, for the sake of the convenience in calculations we consider two flat values of conductivities, $10^{-2}$ S/m for the upper layer and $10^{-4}$ S/m for the middle layer, and calculate attenuation of the signals for all the emissions between ULF
and VLF using Eq. (3). The results of calculations are presented in Figs 3(a) and 3(b). Since the attenuation suffered by ULF signals between 0.01 Hz and 1 Hz is less than 2 dB/km in the upper crust model and insignificant in the middle layer model, they are not shown in these figures.

From Figs 3(a) and 3(b) it may be seen that the attenuation for ULF range of signals between 1 and 10 Hz is small, but increases steeply for ELF and VLF signals. Further, the attenuation in the upper crust model is much higher than the middle layer model. At very low frequency of 3 kHz the attenuation in the middle layer model is 13 dB/km but increases to 94.6 dB/km in the upper layer model. From these results it may be concluded that the ULF signals may be propagated to the atmosphere without much attenuation in the crustal region, but the signals of higher frequencies (ELF and VLF) may be propagated to the top of the middle layer only and not to the atmosphere, because of heavy attenuation in the upper crust.

In view of the above results, the question arises that how the VLF signals generated from the source regions are propagated to long distances and observed at Agra, India. One possibility is that since most of the earthquakes occur in seismic faults, the VLF signals so generated are propagated to long distances through the faults themselves. The model of electromagnetic signal propagation through seismic faults acting as waveguides is similar to earth-ionosphere waveguide first developed by Yoshino and Tomizawa\(^24\) and supported by Kingsley\(^25\). Since there exists a long distance fault known as Main Boundary Fault (MBF) at the southern base of the Himalayan belt extending between Afghanistan to north-east India and the earthquakes in Afghanistan and Chamoli occurred in this fault, it appeared to be a good explanation for the long distance propagation of VLF signals generated from Afghanistan and Chamoli earthquakes to Agra, in India. However, this explanation fails to be accepted in view of the fact that the conductivity in a fault is higher than that in the surrounding rocks. Further, a fault filled with air is unlikely and the conductivity in water filled fault will be even much higher. It is for this reason that Park et al.\(^19\) have considered 1000 ohm-m resistivity for the surrounding rock and 10 ohm-m for a 500 m wide by 20 km deep fault, to explain the propagation of low frequency signals.

The other possibility is that since the foci of most of the devastating earthquakes lie in the middle layer, which is characterised by low conductivity, the VLF signals generated from the source region are propagated to long distances through the middle layer itself, which acts as a waveguide. This model was suggested by Tsarev and Sasaki\(^14\) for ULF-ELF propagation to long distances. They suggested that such signals could be observed on the earth surface through "windows" of low conductivity in the upper layer, which are formed as a result of some special geological formations. Employing this model and conductivity of the middle layer as mentioned above, they have made estimates of propagation distances for ULF and ELF signals. They have shown that the ULF signals may be propagated from 100 to 1000 km and ELF signals from 10 to 100 km in this model. From this result it may be understood clearly that for a VLF signal of 3 kHz the propagation distance will be further reduced and would be less than 100 km.
Since the distance between Chamoli and Agra is about 400 km and that between Rustaq region of Afghanistan where large earthquakes have occurred and Agra is more than 1000 km, the VLF signals generated from these earthquakes cannot be propagated to such long distances through the middle layer crust. Thus, the only possibility that seems to be likely is that the signals are propagated upward from their respective source regions and emerged at the earth's surface near the epicenter of the earthquakes to be propagated to the observing station in the ionosphere wave guide mode propagation. A schematic diagram of the propagation mechanism of the signal is shown in Fig. 4. This mechanism is similar to that suggested by Hayakawa et al.\textsuperscript{26} Here, we make an attempt to estimate the total losses suffered by the signals at the frequency of 3 kHz between the source region and the observing station. It is worthwhile to recall here the work of Sumimoto\textsuperscript{9} who has made a rough estimate of the liberated energy during an earthquake of magnitude (M = 6.0) near the hypocenter of the earthquakes. He has assumed 0.1% of the strain energy being liberated for $10^7$-$10^8$ s before the main shock and found the liberated energy $\sim 6 \times 10^7$-$8$ W. However, this energy was calculated to explain the seismo-electric signals (SES) recorded by the VAN group, which corresponds to transient changes of the electro-telluric fields (nearly dc). What would be the radiated energy at VLF in the earth's crust is not known, but an estimate can be made from the work of Tomizawa et al.\textsuperscript{27}, who have conducted experimental explosion underground and measured amplitudes of the signals at various frequencies. It is seen that the amplitude at the frequency of 2.5 kHz is about 80 dB below those of SES range of frequencies.

In the present calculation, we consider this result and calculate the liberated energy at 3 kHz to be 80 dB below $10^7$ W, which comes out to be $10^7$ W. Since the main shock of the Chamoli earthquake occurred at the depth of 15 km, the radiated signal would suffer an attenuation of 195 dB to emerge at the earth's surface, if we assume that there is a window in the skin layer of the same conductivity as in the middle layer crust on the lines of Tsrev and Sasaki.\textsuperscript{14} By invoking this loss, the energy near the epicenter on the earth's surface is found to be $1.75 \times 10^7$ W, which is associated with an electric field of 8.1 mV/m. In order to calculate the attenuation suffered by the signal in the ionosphere waveguide mode propagation between the epicenter and observing station, we consider the work of Gupta and Tantry\textsuperscript{28} who have employed various day and nighttime models for the lower ionosphere and computed attenuation and phase velocity for ELF/VLF signals. From the results presented in their Figs 8 and 9 we scale down the attenuation suffered by the signal of frequency 3 kHz and find it to be about 20 dB/1000 km for daytime and 6 dB/1000 km for nighttime. Since Chamoli is located as a distance of 400 km from Agra, we consider 10 and 3 dB losses for daytime and nighttime propagations in the earth-ionosphere waveguide mode between the epicenter and observing station. Then the electric fields on the ground surface over the borehole antenna during day and nighttimes are found to be 2.7 mV/m and 5.7 mV/m, respectively. Since the borehole antenna is 120 m in the skin layer, the signal would be attenuated by about 10 dB more and hence the estimated signal strength to be recorded will be about 850 $\mu$V/m for daytime and 1.8 mV/m for nighttime. These are higher than 200 $\mu$V/m found by us experimentally and mentioned above in para 2 of this section, but not unreasonable.

The question that the calculated electric fields are recorded by the borehole antenna and not observed above the earth's surface may be answered in the light of the results of recent experiment, which we have conducted by operating a terrestrial antenna (height = 20 m) simultaneously with the borehole antenna.\textsuperscript{23} It is normally seen that on account of excessive VLF noises such as those due to spheres, local lightning activities, transmissions from radio station, and building noises, etc., the signal recorded by the terrestrial antenna is masked, whereas in the borehole such
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