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On the Propagation of VLF Electric Field Emissions Associated with Earthquakes in the Middle Layer of the Earth Crust

Sharma, S.[1] and Singh, R. P.[2*]

1. Research Scholar, Department of Physics, Institute of Applied Sciences & Humanities, GLA University, Mathura, India

2. Professor, Department of Physics, Institute of Applied Sciences & Humanities, GLA University, Mathura, India

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Abstract

An ensemble of elementary radiators is generated on the basement rock because of the applied stresses in the preparation zone of the earthquakes in the earth crust. Considering such an 'ensemble' as the source of electromagnetic signals, the strength of the electric field is estimated at different distances and frequencies laying in range (3 – 27 kHz) at three different conductivities of the crustal layers (10^{-8}, 10^{-9}, 10^{-10} S/m). The results of the computation are presented in this paper. Moreover, propagation distances for the seismogenic VLF emissions have also been calculated in the frequency band (3 – 27 kHz) at the conductivities laying in the range (10^{-8} - 10^{-10} S/m) within the limit of detectability of measuring instruments (10^{-7} V/m). It is observed that these distances increase with the decrease of conductivity of the middle layer of crust. Furthermore, theoretical results of computations are verified from the experimental observations of the seismic event that occurred at the distance of 698 km from the observing station at Chaumuhan Mathura (Geographic lat. 27.49^0N, long. 77.67^0E). In addition to this, the generation and propagation mechanisms of seismo-electromagnetic radiations have also been discussed briefly.

Keywords: Attenuation, Earthquake, Earth crust, Radiating dipole, VLF waves.

1. Introduction

Several electromagnetic phenomena occurring predominantly in the frequency band ranging from the ultra-low frequency (ULF) (0.01 Hz – 10 Hz) to very low frequency (VLF) (3 kHz – 30 kHz) based on observations taken on the ground and in the atmosphere/ionosphere before and/or after the seismic events have been investigated (Fujinawa et al., 1992; Fujinawa and Takahashi, 1994; Parrot and Mogilevsky, 1989; Parrot, 1994; Hayakawa and Sato et al.,1994; Uyeda et al., 2000; Kushwah et al., 2007; Rozhnoi et al., 2009; Hattori et al., 2013). However, a confirmatory relation between the source and observed events still lacks on account of poor understanding of the generation and propagation mechanism of such radiations. Thus, scientific efforts are in progress globally to solve their problems by taking various kinds of theoretical models into account. For example, Yoshino and Tomizawa (1988) have presented a model wherein a fault is considered as the waveguide for these emissions. Gokhberg *et al*. (1989) have discussed the penetration of the electric field through the earth's surface into the ionosphere considering the source in the earth's crust. Based on the model presented for investigating the connection between earthquake preparation processes and crustal electromagnetic emissions, they have suggested that these emissions are produced by cracking of crustal layers. Ribnikov et al. (1990) carried out numerical model calculations, concluding that the quasi-static seismic electric field generated in the earth crust can traverse to the ionosphere for a suitable electrical conductivity profile. Attenuation calculations for the electromagnetic waves emanated during the volcanic activity were carried out by Ondoh (1992) in wet soil, dry crust and magma; and it was found that low frequency waves cannot reach the surface of the earth from the interior of the volcanoes through the magma and wet soil. In Molchanov and Hayakawa (1995) penetration characteristics of ULF electromagnetic emissions through the earth crust, the atmosphere and the ionosphere are discussed. Tian and Hata (1996) have estimated components of the electric and magnetic field assuming both a single dipole and a system of dipoles at various depths in the epicentral region and concluded that only

*Corresponding author: rp.singh@gla.ac.in

the extremely low frequency (ELF) waves with the frequency less than 223 Hz may penetrate from the deep crust to the surface of the earth. Huang and Ikey (1998) have studied propagation characteristics of seismogenic emissions simulating earth crust, ionosphere, and underground conductive layer by granite slab and aluminum plates, and it was suggested that VLF waves can propagate over a long distance. Bliokh (1999) computed the variation of electric field and current in the lower ionosphere produced by conductivity growth owing to the additional ionization of the air near the earth due to radioactive emanations. Using the method of image charge, Dong et al. (2005) have estimated the subaerial electric field radiated by a unit electric current source in the ground and studied the attenuation and radiation directivity of the electric field from an electric current source. It is concluded that the electromagnetic field on earth surface is found to attenuate more acutely with depth of the source than with the frequency. Based on the ground-penetrating radar (GPR) studies of earth crust Jol (2009) found that the attenuation of electromagnetic waves inside the earth crust increases with its conductivity and permeability while it decreases with permittivity of medium. Bashkuev et al. (2013) have examined the heterogeneity in electrical resistivity of geoelectric sections laying in seismo-active regions of Bailkal Rift zone using the radio wave sounding technique and have assessed their impact on the propagation of electromagnetic radiation in a wide band (2 kHz to 1MHz) from the radio measurement data and modeling. A theoretical model for the generation of electromagnetic radiations was developed by Wang et al. (2015) based on the piezoelectric effect. In addition to this, they studied the variation of intensity of the electric field with distances in the resistivity range 500 Ωm - 8000 Ωm and it was found that the intensity of the field reduces with distance. In order to explain the presence of electromagnetic emissions observed in the preparation zone of the impending earthquake, Kachakhidze et al. (2015) have proposed a model for self-generation of electromagnetic oscillations. This model gives the physical analysis of nonlinear effect of earthquakes and also explains the generation mechanism of VLF electromagnetic radiations before the onset of an earthquake. The ionospheric effect on the wave fields originated from the finite length dipole (150 km) current source co-located at the hypocenter (depth, 19 km) of the Wenchuan earthquake (M = 8.0) in the frequency band (0.01 Hz - 10 Hz) was studied by Li et al. (2016) considering two layers (earth - air) and three layers (earth – air – ionosphere) physical models. Their results of computation show that all the electric fields are independent of ionospheric effects at short distances (e.g. 300 km for 1 Hz), which reduce with an increase of the frequency. The decay of the electric field becomes slow beyond this range on account of constructive interference of the wave fields. Recent work done in this field can be found in monographs written by Singh (2008), Hayakawa (2012, 2016), Pulinets and Ouzounov (2018).

In the present paper, attenuation calculations for the strength of the electric field at different distances laying in the range (100 km-6500 km) in the conductivity range (10^{-8} - 10^{-10} S/m) have been carried out considering an ensemble of elementary radiators in the middle layer of the earth crust, and the results of the computation are presented. Furthermore, the generation and propagation mechanisms of seismogenic emissions are also discussed.

2. Theoretical Consideration

In this section, first, a justification for considering the various physical parameters such as conductivity of crust, focal depth of seismic events, and permittivity of the crustal region in different ranges are given. This is followed by the development of a theoretical formulation for computing the strength of the electric field originated from the elementary radiators existing in the focal region of impending earthquake laying in the middle layer of the crust.

Earth crust comprises three layers namely, upper, middle and lower layers with the average thicknesses around 15 km, 10 km and 15 km, respectively (Artemieva, 2002). In the uppermost layer of the crust, significant water content exists in rocks and hence conduction is the electrolytic type and conductivity is relatively large, laying in the range 0.1-1 S/m (Tsarev and Sasaki, 1999).

The temperature in the earth rises with depth, with an average rate of about 20^0C/km. Thus, the thermal gradient of the middle layer lies between 200^0C – 1000^0C (Fridleifsson et al., 2008), which is moderate and possibly could not trigger thermal conduction much. However at these temperatures, water gets evaporated and hence electrolytic type conduction is stopped. These water vapors enter the rocks through micro-cracks or faults (Miachkin et al., 1975) generated at the depths of about 10 - 30 km wherein foci of the most devastating earthquakes exist (Molchanov et al., 1995) leading to dry them. As a result of this, the electrical conductivity of the rocks, laying in this layer, suddenly drops significantly and reaches 10^{-8}- 10^{-10} S/m (Tsarev and Sasaki, 1999). Lockner et al. (1983) have also proposed such small conductivities during the faulting process in granite rocks, possibly due to the production of excessive heat in frictional sliding of rocks. A similar order of conductivity has been found for the rock samples of the middle layer of the crust experimentally by Keller (1989). This indicates that conductivity of the middle layer of the earth crust may be of that order and the same can be used for computing the strength of the electric field at various distances from the source point safely. On account of such small conductivities in the middle layer, it may safely be considered as insulators where the attenuation of seismogenic waves is significantly less and hence may serve as a waveguide for the propagation of these radiations (Tsarev and Sasaki, 1999). The temperature of the lowermost layer exceeds 1000^0C, possibly due to the excitation of thermal conduction at these temperatures and hence results in a significant enhancement in the electronic conductivity of rocks and becomes equal to that of conductivity of the upper layer of the crust. Further, as pointed out earlier, the foci of most of the devastating earthquakes lie in the range 10-30 km. It seems reasonable to consider the radiation source at an average depth of about 20 km from the earth's surface (Chu et al., 2009).

Stresses build up over time in the focal region of impending earthquakes. When these stresses on basement rocks reach close to the breaking point, the phenomenon of micro fracturing comes into play (Hadjicontis et al., 2004). In this situation, charges of opposite polarity are produced on the fresh surfaces of cracks due to the surface or contact electrification or both (Molchanov and Hayakawa, 1995; Takeuchi and Nagahama, 2001). The cracks during their opening behave like a radiating dipole due to the variation of their length and charge on them (Ogawa et al., 1985; Guo and Liu, 1995; Takeuchi and Nagahama, 2004) and hence emit electromagnetic radiations. Assume an ensemble of these "elementary radiators" randomly oriented and distributed in space and time in the earthquake preparation zone existing in the middle layer of continental crust. The strength of the electric field from the source (a group of randomly oriented radiators) to a field point depends upon the geometry of propagation, damping due to the propagation through dissipative medium and attenuation due to the imperfect conductivity of the waveguide boundaries (Tsarev and Sasaki, 1999). Thus the average electric field at field point due to such a radiating system at a distance 'd' can be enunciated as follows (Tsarev and Sasaki, 1999):

$$< E^2 > = |E_0|^2 < W^2 > \tag{1}$$

where, $|E_0|$ corresponds to the magnitude of the electric field due to a single electric dipole of moment p_0 at a distance, 'd' in an infinite free space and is expressed as (Wait, 1962):

$$|E_0|^2 = {\mu_0}^2 {p_0}^2 \omega^4 / 16\pi^2 d^2 \tag{2}$$

Also $< W^2 >$ stands for the attenuation function of the waveguide and is given by the relation (Wait, 1962; Jackson, 1975)

$$< W^2 > = (d\lambda/2h^2)\exp\{-(\alpha + \beta/h)d\} \tag{3}$$

Here, h, λ, α and β are the depth of the system of radiators available in the focal region, the wavelength of the electromagnetic radiations generated from the "elementary radiators", attenuation and phase constants, respectively. The value of α and β depends upon certain factors, which are represented as (Wait, 1962; Jackson, 1975):

$$\alpha = \omega(2\mu_m \varepsilon_m)^{1/2}\left[\{1 + (\sigma/\varepsilon_m\omega)^2\}^{1/2} - 1\right]^{1/2} \tag{4}$$

$$\beta = (\sigma_m\omega/2\sigma_{b1})^{1/2} + (\sigma_m\omega/2\sigma_{b2})^{1/2} \tag{5}$$

where, ε_m and μ_m are the relative permittivity and permeability of the medium of the middle layer of the crust, while $\sigma_m, \sigma_{b1}, \sigma_{b2}$ and ω are the conductivities of the middle, upper, lower layers of the crust, and angular frequency of the waves emitted from radiators, respectively.
But, $\sigma_m/\varepsilon_m\omega \gg 1$, for the conductivity of the middle layer of crust (10^{-8} - 10^{-10} S/m). Thus, Equation (4) reduces to

$$\alpha = \omega(2\mu_m \varepsilon_m)^{1/2}(\sigma_m/\varepsilon_m\omega)^{1/2} = (2\mu_m \sigma_m\omega)^{1/2} \quad (6)$$

Substituting the value of $|E_0|^2$ and $< W^2 >$ from Equations (2) and (3) in Equation (1), we get:

$$< E^2 > = (\mu_0{}^2 p_0{}^2\omega^4/16\pi^2 d^2) \times [(d\lambda/2h^2)\exp\{-(\alpha + \beta/h)d\}] \quad (7)$$

An ensemble of n randomly oriented dipoles (each of dipole moment p_0) is equivalent to a single dipole of momentum P and if there is no interaction among them (Ikeya et al., 1997), then

$$P = n^{1/2}p_0 \quad (8)$$

Considering the elastic deformation at the level of 10^{-8}, the size (radius, ρ) of the preparation zone was estimated by Dobrovolsky et al. (1979) using the relation $\rho = 10^{0.43M}$ km. For an earthquake with magnitude M = 8.0, the preparation zone radius is 2.75×10^3 km, containing 4.35×10^{28} dipoles with a length of 10^{-3} m (Tzanis and Vallianatos, 2002). Thus, an effective electric field due to a system of randomly oriented dipoles can be written as:

$$[< E^2 >]_{net} = n(\mu_0{}^2 p_0{}^2\omega^4/16\pi^2 d^2) \times [(d\lambda/2h^2)\exp\{-(\alpha + \beta/h)d\}]$$

Or

$$E_{RMS} = \{[< E^2 >]_{net}\}^{1/2} = n^{1/2}\left(\mu_0 p_0\omega^2/4\pi d^{1/2}\right) \times \left[(\lambda/2h^2)^{1/2}\exp\{-(\alpha + \beta/h)d/2\}\right] \quad (9)$$

But, $\lambda = c/f(\varepsilon_r)^{1/2}$ and $\omega = 2\pi f$, where c, f and ε_r are the speed of light in free space, frequency of the wave and the relative permittivity of the middle layer of crust, respectively.
Substituting these values in Equation (9), we have:

$$E_{RMS} = \left[\{ncf^3/2d(\varepsilon_r)^{1/2}\}^{1/2} \times (\mu_0 p_0\pi/h)\right]\exp\{-(\alpha + \beta/h)d/2\} \quad (10)$$

Substituting the value of β and α from Equation (5) and (6) in Equation (10), we have:

$$E_{RMS} = \left[(ncf^3/2d)^{1/2} \times \{\mu_0 p_0\pi/(\varepsilon_r)^{1/4}h\}\right] \exp\left[-\{(\pi f\sigma_m\mu_0)^{1/2}d\} - (d/2h)\{(\pi f\sigma_m)^{1/2}\left((\sigma_{b1})^{-1/2} + (\sigma_{b2})^{-1/2}\right)\}\right] \quad (11)$$

The ranges of various parameters considered for the estimation of the electric field at field point are : $\sigma_{b1} = \sigma_{b2} = 0.1$ Mho/m (for the continental crust), $\varepsilon_r = 10$ (Tsarev and Sasaki, 1999), $\varepsilon_0 = 8.85\times10^{-12}$ F/m, $\mu_m = \mu_0 = 4\pi\times10^{-7}$ H/m, $\sigma_m = 10^{-8} - 10^{-10}$ S/m (Tsarev and Sasaki, 1999), $n = 4.35\times10^{28}$, $p_0 = 10^{-14}$ coulomb $\times$ meter (Ogawa et al., 1985), $d = 10^2 - 6.5\times10^3$ km, and $f = 3.0 - 27$ kHz, $h = 20$ km.

3. Results and Discussion

In this section, results of the computation obtained from the theoretical formulation developed for estimating the strength of the electric field produced by elementary radiators existing in the preparation zone of an impending earthquake which lie in the middle layer of the crust are discussed. This is followed by the validity of the results from experimental observations and some outcome in support of the work done.
As discussed earlier, when stresses reach close to the breaking point phenomenon of micro-fracturing comes into play leading to the generation of radiating dipoles (Ogawa et al., 1985). Considering an ensemble of such radiators oriented randomly and distributed in space and time in the preparation zone laying in the middle layer of the earth crust at a depth of 20 km from earth's surface strength of the electric field is computed. The results of computation for it at various distances laying between $10^2 - 6.5\times10^3$ km at three different conductivities 10^{-8}, 10^{-9} and 10^{-10} S/m in a wide range of frequencies laying between 3-27 kHz using Equation (11) are presented in Figure 1 and Figure 2. In Figure 1, we show the electric field's variation with distance (at different frequencies) in three separate panels corresponding to the conductivities under

consideration. However, its variation with frequency (at different distances) in three different panels at the conductivities 10^{-8}, 10^{-9} and 10^{-10} S/m are shown in Figure 2. The logarithmic scale has been used for plotting these figures.

From a close examination of the top panel of Figure 1, we find that all frequencies are attenuated (electric field decreases) as the distance increases, the attenuation being low for lower frequencies and high for higher frequencies. For example, attenuation is lowest for the signals of 3 kHz, whereas it is maximum at 27 kHz in the frequency band considered. The conditions for propagation to long distances with low attenuation improve as the conductivity decreases. As it may be seen from the bottom panel that the strength of signals of 3 kHz at a distance of 1000 km is around 1.3×10^{-3} V/m, whereas it is 10^{-9} V/m at this distance in the top panel and the same is true for the signals of other frequencies as well. A possible cause for low attenuation at reduced conductivity is that scattering and absorption of seismically induced radiations are less based on the insignificant number of free electrons in the rocks. Moreover, the cause for high attenuation at higher frequencies is when these radiations propagate through the rocks interacting strongly with the free electrons of rocks especially, and led them to vibrate with their frequency and lose their energy at a higher rate.

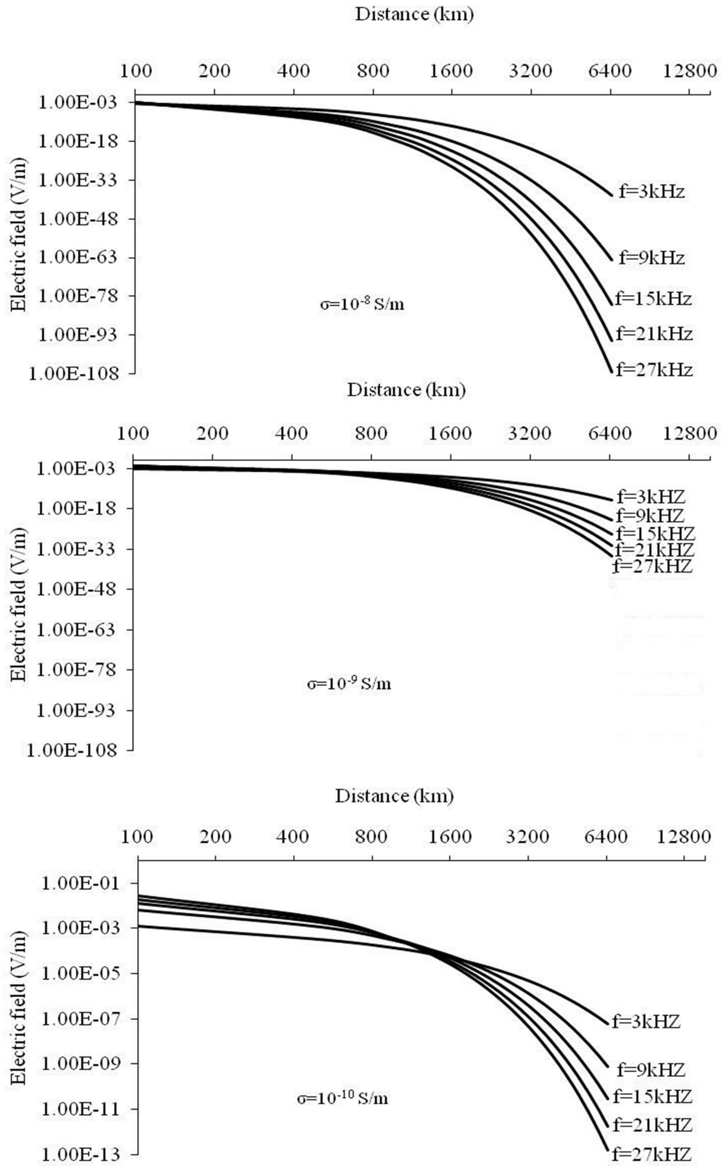

Figure 1. Variation of the electric field with distance (shown by solid curves) at different frequencies laying in the VLF band (3-27 kHz). Top, middle and bottom panels corresponding to the conductivities 10^{-8}, 10^{-9}, and 10^{-10} S/m.

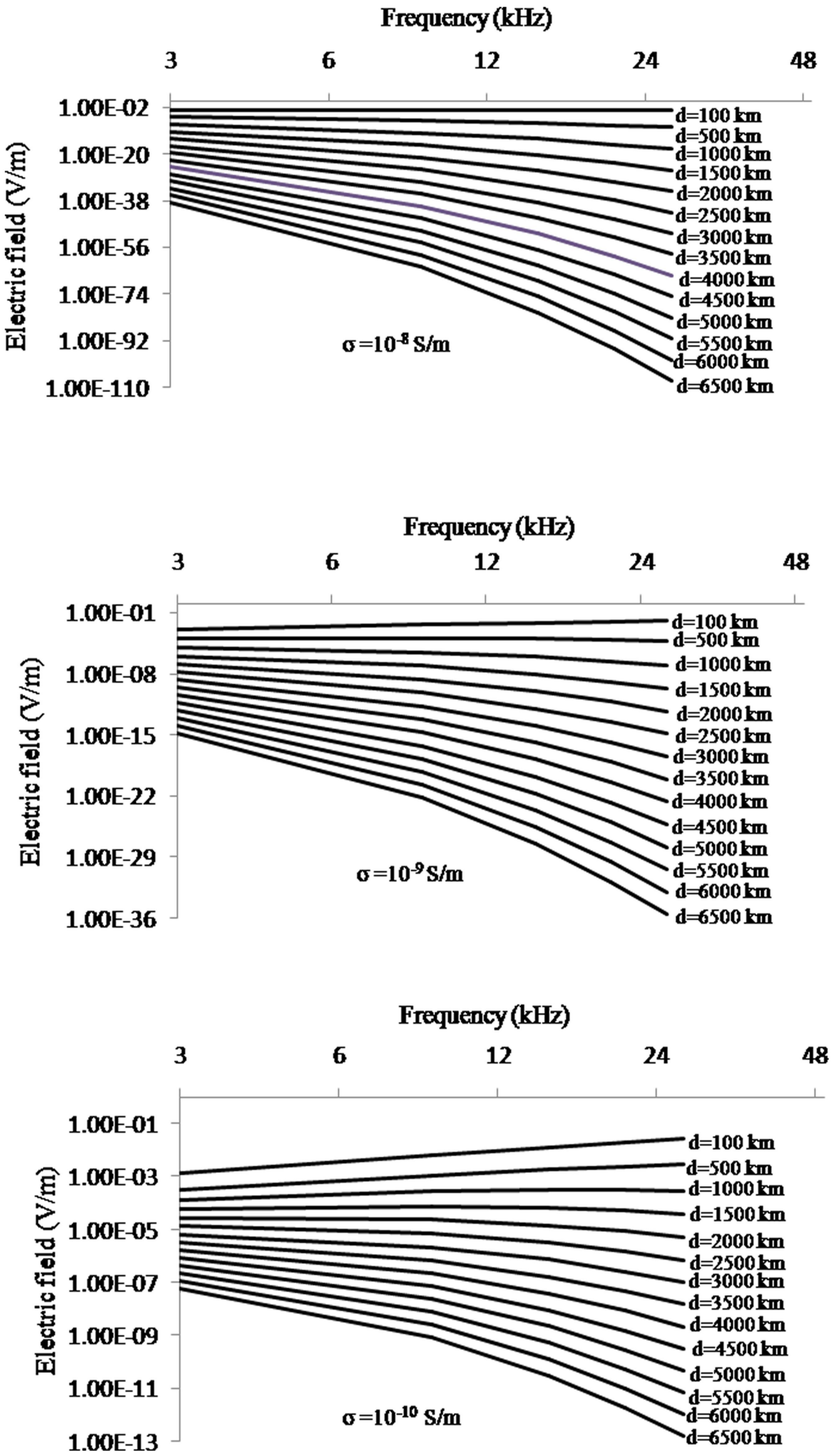

Figure 2. Variation of the electric field with frequency (shown by the solid curves) at different distances between 10^2 – 6.5×10^3 km. Top, middle and bottom panels correspond to conductivities 10^{-8}, 10^{-9}, and 10^{-10} S/m.

In Figure 2, we show the variation of the electric field with frequency in the frequency band (3-27 kHz) at different distances laying in the range ($100\text{-}6.5\times10^3$ km) at three different possible conductivities (i.e., 10^{-8}, 10^{-9}, 10^{-10} S/m) of the middle layer of the crust. It is clear that the electric field attenuates nonlinearly as frequency increases at all distances except those laying between 500-1000 km, where a reverse effect to this is observed because the gain factor of the waveguide dominates over the attenuating term. At lower distances, attenuation increases slowly with increasing frequency in the lower frequency band. It increases rapidly with frequency in the higher frequency band at a higher range of distances. Further, it is also pertinent from three different panels that electromagnetic waves' attenuation increases with conductivity at distances greater than 1000 km.

For the proper organization of earthquake prediction studies in the VLF band, a network of observatories is required for recording the precursory phenomena occurring in this band with a central computing facility for processing all the data. For this purpose, the density of the station network will remain a question that may be resolved by computing the propagation distances for VLF signals in the frequency band (3-27 kHz) at three different conductivities (i.e., 10^{-8}, 10^{-9}, 10^{-10} S/m) in the middle layer of the crust. Keeping this in view, we have computed the propagation distances for the VLF signals at three different conductivities of the earth's crust in light of the limit of detectability of measuring instruments (~10^{-7} V/m) for the electric field as suggested by Garambois and Dietrich (2002). Our theoretical model (discussed already in section 2) is taken into account for this purpose. The results of the computation are shown in Figure 3. From the graphs shown in Figure 3, it is clear that propagation distances decrease with an increase of frequency at all the conductivities rapidly initially in the frequency range 3-9 kHz and later on, the rate of their reduction slowed down at higher frequencies laying between 15-27 kHz. Propagation distances are higher at lower conductivities and lesser at higher conductivities since scattering and absorption of electromagnetic signals reduce with increasing conductivity, as discussed earlier. Some notable effects of change in conductivity on the propagation distances are as follows:

1) VLF signals (3-27 kHz) can propagate to distances laying in the ranges 331- 695 km, 997-2659 km and 3006-6075 km at the conductivities 10^{-8}, 10^{-9}, and 10^{-10} S/m, respectively.

2) The maximum and minimum ranges of propagation of distances for all VLF signals are 695-6075 km and 331-997 km, respectively, within the conductivity range of the middle layer (10^{-8}- 10^{-10} S/m)

3) None of the VLF signals (3-27 kHz) can propagate beyond 6075 km, even in case of reduced conductivities.

To validate the results obtained from the theoretical model presented in the paper, we have computed the strength of the electric field at the conductivity of 10^{-10} S/m in case of the Nepal earthquake occurred on April 25, 2015 at a distance of 698 km from the observing stations as reported in Sharma et al., (2020) by using Equation (11). The details of this event are shown in Table 1.

Table 1. Details of earthquake taken from Sharma et al. (2020), location of the observing stations and the distances of the epicenters from these stations.

Reference	Date of occurrence of earthquake	Magnitude of earthquake	Location of earthquake		Depth (km)	Location of observing station		The distance of epicenter from observing station (km)
			Lat. (^{0}N)	Long. (^{0}E)		Lat. (^{0}N)	Long. (^{0}E)	
Sharma et al. (2020)	25/04/2015	7.8	28.23	84.73	8.22	27.49	77.67	698

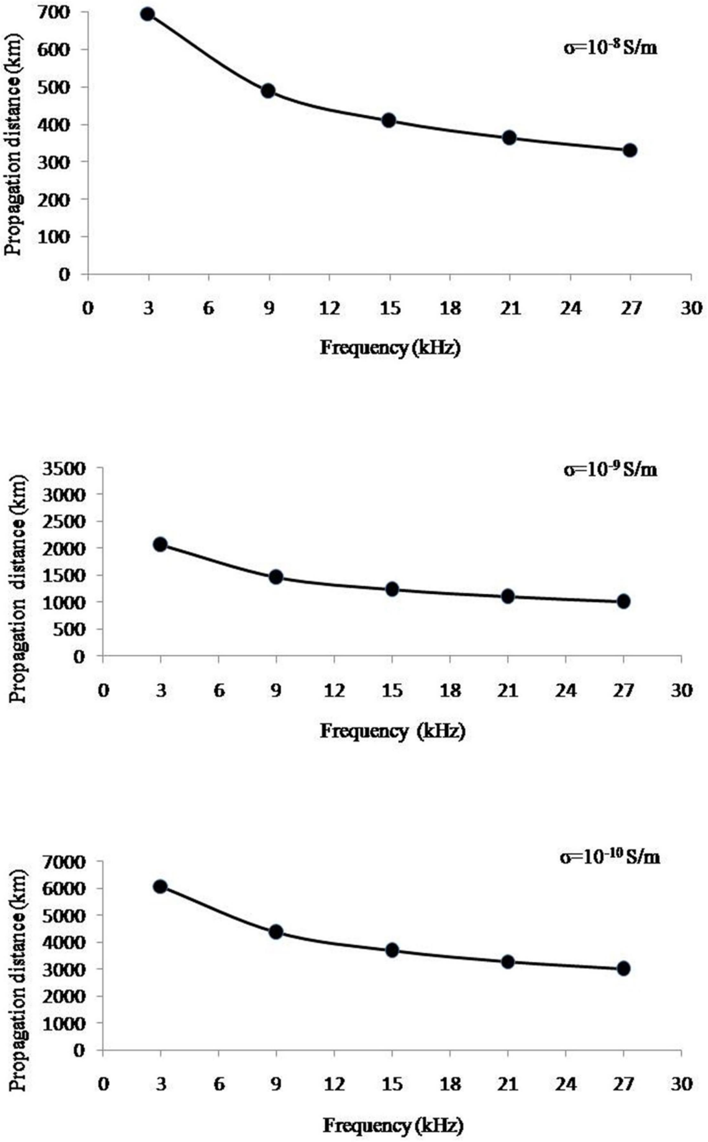

Figure 3. Variation of the propagation distance for signals of various frequencies under consideration at three different conductivities of the middle layer of the crust.

Because of the above facts, first, we furnish the example of real data recorded in the borehole antenna corresponding to the major Nepal earthquake of April 25, 2015 as reported in Sharma et al. (2020). The borehole antenna is a naked copper wire (length 120 m, diameter 4 mm) placed in a watertight PVC pipe vertically inside the ground. It measures the vertical component of subsurface VLF electric field emissions associated with an earthquake at the frequency of 3.012 kHz. The VLF data recorded in the borehole is analyzed using the m±2 σ criterion (where m stands for monthly mean and σ is the standard deviation). Other workers also adopt this criterion (Hattori et al., 2013; Zhou et al., 2017). An anomalous enhancement on 11 April is seen in VLF data 14 days before the onset of the mainshock of this earthquake. This enhancement is not associated with other spurious noises like a magnetic storm, lightning, etc., whose details can be found in Sharma et al. (2020). Abnormal enhancement of 39.97 mV above m+2σ is seen on April 11, 2015 in the top panel of Figure 4. This anomalous voltage enhancement in the borehole antenna caused an electric field of 3.3×10^{-4} V/m in it, which is very close to the electric field's theoretical value ($\sim 3.63\times10^{-4}$ V/m) at the frequency of 3.012 kHz. This confirms that theoretical computations are in good agreement with the experimental ones.

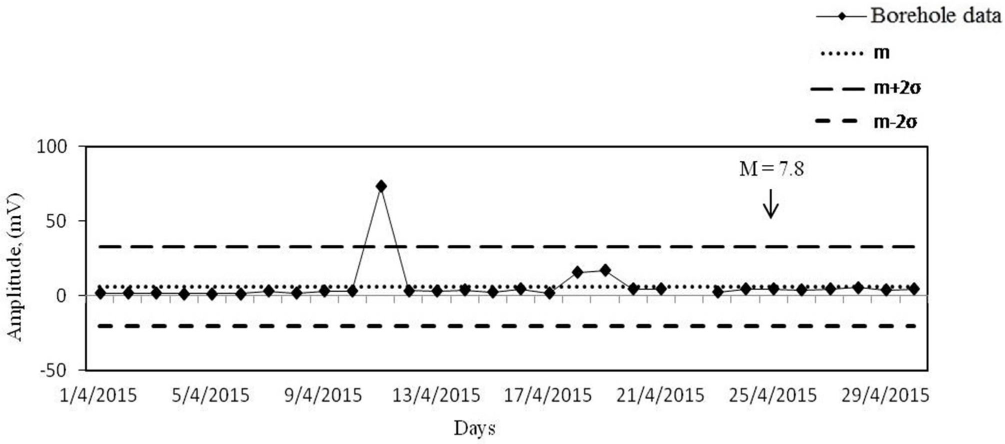

Figure 4. Diurnal variations of vertical component of subsurface VLF electric field emissions (shown by the solid curve) for April 2015. Horizontal dotted line indicates monthly mean while dashed lines show the standard deviation around the mean. Downward arrow shows the date and magnitude of the earthquake.

It is worthwhile to mention here that the strength of the VLF electric field largely decreases in the skin layer of crust owing to its high conductivity (~ 10^{-1}-10^{-2} S/m) and hence VLF signals cannot propagate longer distances in this uppermost layer of the crust. This raises the question that how seismogenic VLF emissions propagating in the midlayer of crust reach the observing station. For answering this question, we may refer to the work of Tsarev and Sasaki (1999) wherein it is suggested that while propagating in the middle layer these signals find some windows of low conductivity (10^{-8}-10^{-10} S/m) in skin layer of crust from where they leak to the earth surface without much attenuation and reach the observing station through the earth-ionosphere waveguide.

Our results that attenuation of electric field increases with the increase of conductivity and frequency and hence propagation distance reduces as conductivity increases are consistent with earlier workers also. For example, attenuation calculation was carried out by Singh et al. (2004) at the two different conductivities 10^{-2} S/m and 10^{-4} S/m of the ground in the ULF-VLF bands (f = 1Hz -10^{4} Hz) and found that the electric field attenuates slowly in ULF band while steeply in VLF band, and it ranges 2 - 172 dB/km at the conductivity 10^{-2} S/m and 0.2 – 24 dB/km at 10^{-4} S/m in the said frequency band. From their theoretical studies, Wang et al. (2015) have shown that propagation distances for seismo-electromagnetic radiations decrease with the increase of frequency and resistivity of rocks. They suggested that discontinuities of geological bodies are responsible for the attenuation of electromagnetic waves. Korpisalo (2016) estimated the attenuation of electromagnetic waves in conductivity range 10^{-5}-10^{-2} S/m at frequencies laying in the frequency band (312.5 kHz- 2500 kHz) at different values of relative permeability (μ_r = 1, 3, 5) and relative permittivity (ε_r = 5, 10, 15) and found that the attenuation of electromagnetic radiations increases with the increase of both frequency and conductivity, and it varies from 10^{-2} dB to 10^{2} dB/m under the said ranges of conductivity and frequency. Almost similar results have been reported in Tsarev and Sasaki (1999), Zhang and Li (2007), Basukev et al. (2013).

Our theoretical results concerning the propagation of seismogenic VLF signals to long distances are also supported well by the experimental results of earlier workers. For example, Singh et al. (1999) observed anomalous subsurface VLF electric field changes at a distance greater than 1000 km in the Afghanistan earthquake (M = 6.9) 1-2 days before its occurrence employing borehole antenna. Utilizing this setup, Singh et al. (2000) also observed an increase in occurrence number of noise bursts for the 14 major earthquakes $4.5 < M \leq 6.5$ that occurred in India and around at distances ranging between 901-2220 km. They explained their results considering the underground propagation of these VLF emissions through a fault. Fujinawa and Takahashi (1998) observed anomalous enhancements in the number of VLF pulses before the Hokkaido – Toho – Oki Japan earthquake (M = 8.1) at a distance of greater than 1000 km from the epicentral region. Singh et al. (2009) reported anomalous amplitude enhancement at distances between 95 and 479 km for the moderate regional earthquakes (M = 4.5-5.1) from the statistical analysis of VLF data obtained from the borehole antenna. Occasional amplitude enhancement in VLF data was found by Singh and Singh (2013) at Mathura observing station for the Nepal earthquake (M = 5.3) of April 4, 2011, the epicenter of which was at a distance about 388 km from the observatory.

4. Conclusion

Assuming an ensemble of elementary radiators oriented and distributed randomly in space and time in the earth's crust generated due to increased stresses close to the breaking point, the strength of the electric field at various distances (100-6500 km) and different conductivities (10^{-8}-10^{-10} S/m) are computed in VLF range (3-27 kHz). The results of the computation show that the attenuation of the wave field increases with the increase of both the conductivity as well as the frequency in general. The VLF signals can propagate up to the distances laying in the ranges 331-695 km, 997-2659 km, 3006-6075 km at the conductivities 10^{-8}, 10^{-9}, and 10^{-10} S/m, respectively within the limit of detectability of measuring instruments. The maximum range of propagation distances is 695-6075 km. In contrast, the minimum range of propagation distances is 331-997 km within the conductivity range (10^{-8}-10^{-10} S/m) of the earth's crust. The results of the computation obtained theoretically are validated from the experimental observations for the electric field as recorded in borehole antenna in case of Nepal earthquake of April 25, 2015. The generation and propagation mechanisms of seismogenic emissions have also been discussed briefly.

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