Indian J. Phys., Vol. 85, No. 3, pp. 447-470, March, 2011

Studies on the anomalies in the behaviour of transmitted subionospheric VLF electromagnetic signals and the changes in the fourth Schumann resonance mode as signatures of two pending earthquakes

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Received 19 November 2009, accepted 06 September 2010

Abstract : Some anomalies are observed in the subinospheric VLF electromagnetic (EM) signals at 19.8 kHz transmitted from North West Cape, Australia (lat : 21.82° S; long : 114.16° E) and 40 kHz from Fukushima, Japan (lat : 36.18° N, long : 139.85° E), recorded by VLF receivers near Kolkata (lat : 22.56° N, long : 88.5° E) during the occurrence of the two earthquakes at Andaman Island (lat :14.018° N, long : 92.92° E), India and other at South Coast of Honsu (lat : 34.78° N, long : 138.27° E), Japan. The analyses of these seismo-ionospheric VLF EM anomalies at these two frequencies during some days before and after the occurrence of earthquake on August 11, 2009 will be presented here. VLF-LF transient variations of significant magnitude in the form of spikes are observed few days prior to the day of occurrence of the earthquakes that continued several days more, then decaying gradually and finally ceased. Signals are examined to describe their connectivity with earthquakes.

The enhancements of the amplitude and frequency of the fourth mode of Schumann resonance spectra have been detected during the occurrence of the two earthquakes, which will also be reported here.

Keywords : Earthquake, seismo-electromagnetism, ionospheric perturbations, subionospheric propagation.

PACS Nos. : 91.30.P-, 91.30.Dk, 94.20.Vv

1. Introduction

Surrounding the earthquake zones, both precursory and post-seismic variations in the VLF-LF amplitudes of the transmitted signals and in the subionospheric parameters are well-known from ground based as well as satellite-based observations [1–6].

Electric field is generated during the occurrence of any strong earthquake within the upper atmosphere due to seismo-ionospheric coupling phenomena [5,7–10]. The

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intensity of electric field increases when underground gas discharges carry submicron aerosols at the near ground in the earthquake preparation zone due to the drop in air conductivity created by aerosols [11–14]. In the seismically active zones, sismo-EM emissions have been observed in the ULF-ELF-VLF-LF bands prior to the incidence of any large earthquake [15–17]. The anomaly in the propagation of EM waves in these frequency bands is reported by many investigators [18–20]. These emissions are different from lightning induced emissions and technogenic emissions.

The ionospheric perturbations as detected by VLF-LF propagation are now considered to be significant tools for short-term earthquake prediction [21–23]. It is also reported that several days before the occurrence of the earthquake, electron density of plasma in the upper ionosphere over the epicenter also increases extraordinarily [24]. Moreover, there exists the interrelation between the tectonic activity and the anomalous changes of the geophysical, geochemical and geohydrological parameters characterizing the Earth's lithosphere [25]. As a result, the seismo-EM emissions would be expected to cover almost the whole of ULF-ELF-VLF-LF band. In the process, there would be increase of thermal plasma noise along with other types of emissions, *e.g.*, Cerenkov, and Bremsstrahlung. This sort of plasma instability at the surface may be assumed to be simulated in dusty plasma [26]. During earthquakes, spiky type VLF excitation in presence of anomalous electric field has been remarked and assessed [27].

EM anomalies before the destructive earthquake on September 7, 1999 in Athens, Greece (lat : 38.2°N, long : 23.6°E) have been correlated with the fault model characteristics of the associated earthquake. Through the *in situ* laboratory experiments of rupture and seismological arguments related to Kozani Grevena earthquake on May 13, 1995 in Greece (lat : 40.2°N, long : 21.7°E) pre-seismic very low frequency (VLF) EM signals have been investigated [28]. Spiky nature of EM signals at 3 kHz frequency is detected which is alike with the VLF pre-seismic signals of Kozani Grevena earthquake. In the observations of the 1995 Hyogo-Ken Nanbu earthquake, similar records at VLF frequencies have been reported [29,30]. Spiky signatures are also reported in the publications of other investigators [31,32].

The anomalous behavior of Schumann resonance is observed in association with the Chi-Chi (lat : 23.85°N, long : 120.78°E) earthquake in Taiwan [33,34]. Schumann resonance intensity changes associated with a localized decrease in the lower ionosphere height over the earthquake epicenter have been explained by the modified knee model [34]. Similar records from Japan are explained by the impact of a localized decrease in the lower ionospheric conductivity over the epicenter of the earthquake [34].

The effect of earthquakes on VLF has two independent aspects : (i) The perturbations in the ionosphere in terms of change in electron density and lowering of VLF reflection height and (ii) the emission of EM noise from the region of earthquakes. The first one can be studied by analyzing irregularities in the amplitude of VLF-LF signal transmitted from a station and being received at a distant station. The terminator time method is also proposed by several researchers. The terminator time is defined as the time when diurnal amplitude variations exhibit a minimum around sunrise and sunset [9]. These are called morning terminator time (Tm) and evening terminator time (Te). The deviation of terminator time from the monthly average is being suggested as a tool of short time precursor to earthquake. The lowering of ionosphere by a few km is assumed to be the variation of terminator time. The GPS techniques of determining total electron content (TEC) is also proposed as another method to study the earthquake related changes in the ionosphere. The effect of seismic wave on the ionosphere *via* acoustic coupling between the earth's surface and ionosphere based on long wave propagation over a path of 5100 km from Japan to Kolkata has been reported [35]. The process included the consideration of Love wave propagation along the earth's surface and continuous launching of acoustic wave. The second one, *i.e.*, the VLF-LF emission can be studied examining whether the normal diurnal variation of VLF signal is hampered. This is because superposition of VLF-LF EM waves emitted by earthquake can suppress the actual signal. This will require VLF-LF receiver of narrow bandwidth. For this purpose, we have chosen two VLF signals along two different paths.

In this paper, the results of some significant effects in the observations of VLF-LF transmitted signals at frequencies 40 kHz and 19.8 kHz recorded near Kolkata during the earthquakes at Andaman Island, India (M : 7.6, depth : 33.1 km) and South Coast of Honsu, Japan (M : 6.4, depth : 26 km), occurred on August 11, 2009 at 01:25:39 IST and 01:37:08 IST respectively, will be presented. The time gap in the occurrence of these two earthquakes was 11 min. 29 sec. The observed signatures can be considered to be the precursory and the post-seismic effects of these two large earthquakes [36]. The observations have been analysed from two independent points of view. Irregularities in the observed amplitude in the form of transient variations are related to the emission of VLF-LF radio waves from earthquake regions and in relation to the fluctuation in terminator times from the average value related to the variation of ionospheric height.

Schumann resonance (SR) is a global EM resonance phenomenon generated by global lightning discharges within the resonator formed by the Earth and the ionosphere. During the past several decades, a number of papers appeared with the results of various aspects of SR phenomenon [37–49]. The seasonal and day-to-day variability of SR intensities, frequencies and quality-factors have been reported by many authors along with the possible explanations for such changes [50–55]. The changes are interpreted mainly by the influences of the temporal and spatial variations of inhomogeneity and conductivity of the medium along with the variations of location and intensities of the three global thunderstorm generating centers. The changes of ionization in the lower ionosphere with the change of zenith angle of the sun along with the signal propagation path from lightning flashes to the point of observations are also responsible for the process. The inhomogeneities originate from the asymmetry of the day- and night-time ionosphere yielding the two hemispheres with different impedances. This kind of inhomogenity is a regular feature in the global atmosphere.

Balser and Wagner (1960) [56] suggested that variations of SR frequency are related to thunderstorm distribution and may be used as an indicator of distribution of thunderstorm sources. Schumann resonance frequency variations have been established as an indicator of the thunderstorm distribution over the globe [57].

Moreover, the anomalous enhancements of Schumann resonance intensity and frequency of the fourth mode as observed through the recorded data nearby Kolkata during the times of occurrences of these two earthquakes are being reported. The variations may be interpreted in terms of reduction of ionization in the middle atmosphere and the influences of the three lightning and global thunderstorm centers during the earthquakes.

2. Experimental set-up

Round the clock measurements of the VLF-LF transmitted signals at frequencies 40 kHz and 19.8 kHz are regularly recorded near Kolkata over the last several years. For the reception of these signals, a straight horizontal copper wire of 8 SWG with 20 m length is used in the form of an inverted 'L'-type antenna. The antenna is installed at about 10 m above the ground. The antenna is sensitive to the vertical electric field of the EM signal. To record the signal, a Gyrator-II VLF receiver has been fabricated [58]. A block diagram of the recording system is given in Figure 1. The VLF receiver at first

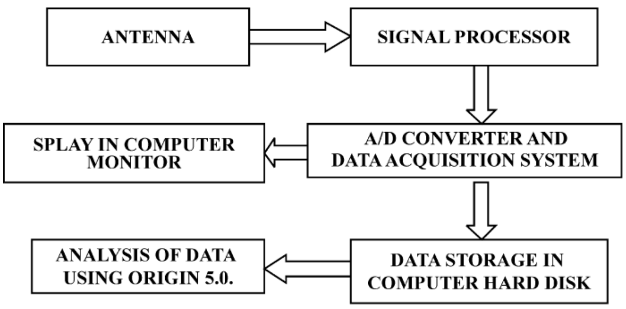

Figure 1. Block diagram of VLF measurement system.

was tuned at 40 kHz and at 19.8 kHz with a quality factor of 250. The overall gain of the amplifier is around 40 dB. The receivers' bandwidths have been made low to attain good sensitivity of receivers toward the interference of EM wave originated from earthquake regions. Of course, the atmospherics will also interfere dominantly with the signal. But the nature of output record during thunderstorm is of a typical known nature as shown later (Figure 11). Other kind of interference that exists during earthquake can be identified. The variation in terminator time is the signature for the variation of ionospheric height whereas the distortion in diurnal behaviour is certainly related to the emission of EM waves. The r.m.s. value of the signals were recorded by computerized data acquisition system through a PCI 1050, 16 channel 12 bit DAS card. These are then processed and being stored in a computer. The r.m.s. values of the filtered data are analyzed regularly using Origin 5.0 software.

For the observations of Schumann resonance spectra, centrally circular square-loop antenna has been erected on the ground at a vast bare land nearby Kolkata. Two such loops have been mounted on wooden structures connected in series and their effective gain is increased beyond 5 dB with this arrangement. One square loop has 1 m side with a total of 75 turns and the other square loop with 90 turns has 1.3 m side. A co-axial cable of length 50 m is used to transfer the signal from antenna to the input of the receiver where it is pre-amplified. A stereo-preamplifier-integrated circuit with LA3161 chip is chosen whose low frequency response starts below 5 Hz and extends to a few kHz. It is superior to others in handling input voltage in the range of few μVs to mVs. The frequency selective stages are designed with active circuit elements. A wide-band amplifier whose output is taken through an active low-pass filter having cut-off frequency nearly 35 Hz further amplifies it. This signal information is then stored in a computer by data acquisition system in which a 40 kHz generator is used to convert analog signal into digital signal. A wide-band very low input voltage sensitive and low frequency sensitive receiver has been designed, which can detect input signals from 100 μV to 500 μV.

3. Observations

3.1. Spiky nature of VLF-LF variations :

The propagation paths of VLF subionospheric transmitted signals at 40 kHz from Fukushima, Japan and 19.8 kHz from North West cape, Australia to the receiving station near Kolkata along with the epicenters of two earthquakes at Andaman Island, India and at South Coast of Honsu, Japan have been illustrated in Figure 2. The distance between 40 kHz transmitter and Kolkata is nearly 5120 km and that between NWC and Kolkata is about 5670 km.

A large number of spiky variations with significant magnitude at frequencies 40 kHz and 19.8 kHz are observed on some adjacent days of the day of occurrences of the dual large earthquakes at Andaman Islands, India and South Coast of Honsu, Japan on August 11, 2009. The spiky variations are transient in nature. So the spikes are being called VLF-LF transients. Figure 3 depicts the VLF transient variations in the form of spikes seven days prior to the day of occurrences (on August 3, 2009), showing the precursory effects of these earthquakes. Figures 4 and 5 represent the transient variations on August 9, 2009 and August 10, 2009, respectively, which are more dense than the records of seven days earlier. The number density of spikes and

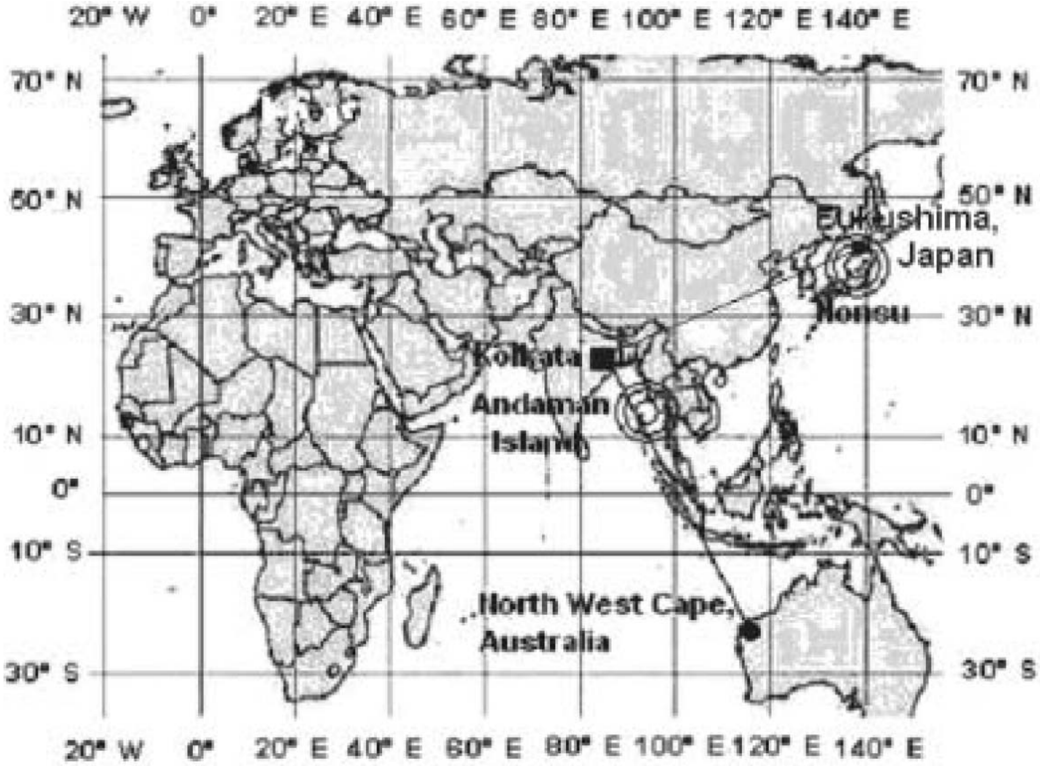

Figure 2. The propagation paths of VLF subionospheric transmitted signals at 40 kHz from Japan and 19.8 kHz from North West cape, Australia to the receiving station near Kolkata along with the epicenters of two earthquakes at Andaman Island, India and at South Coast of Honsu, Japan.

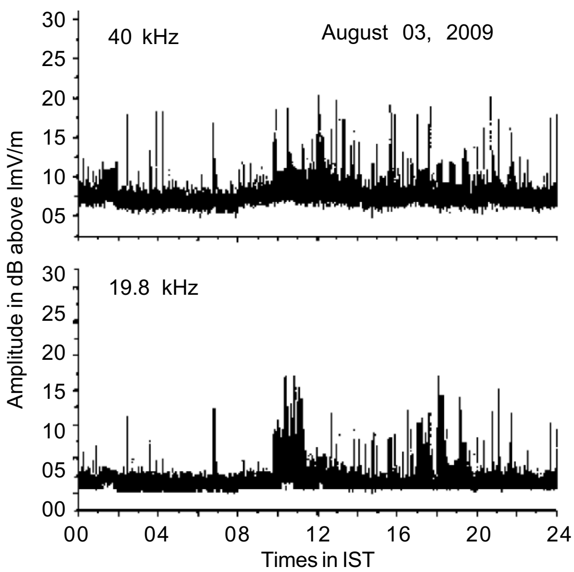

Figure 3. Diurnal variation of VLF transmitted signals observed over Kolkata. Date : August 3, 2009. The records show typical VLF transients beginning around midnight.

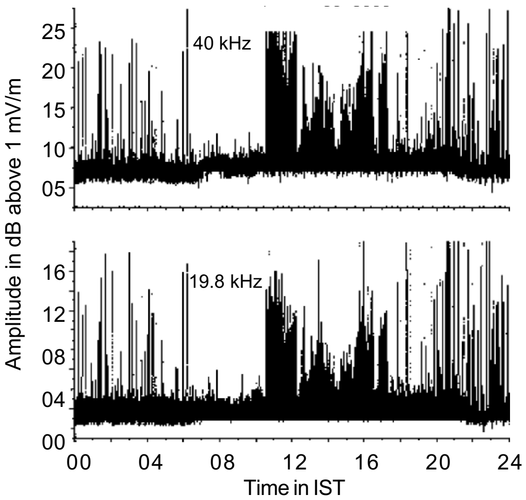

Figure 4. Diurnal variation of amplitude of VLF transmitted signals in dB above 1 mV/m observed over Kolkata. Date : August 9, 2009.

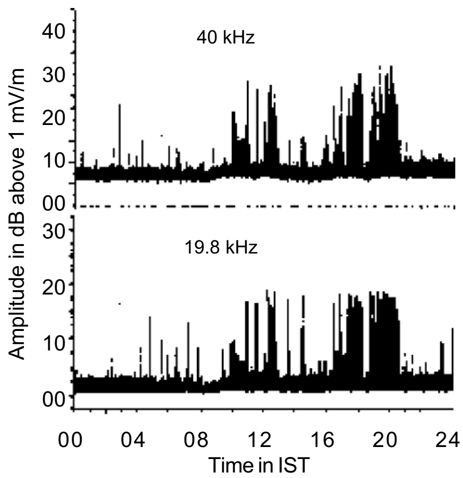

Figure 5. Diurnal variation of amplitude of VLF transmitted signals in dB above 1 mV/m observed over Kolkata. Date : August 10, 2009.

heights of VLF transients have increased gradually and attained maximum on the day of occurrence of the vast dual earthquakes on August 11, 2009. It may be realized that the spiky transients are the precursors and the post-seismic effects of the earthquakes. The transient variations on August 11, 2009, in larger number and greater magnitudes relative to other days are shown in Figure 6. The total number and magnitude of the

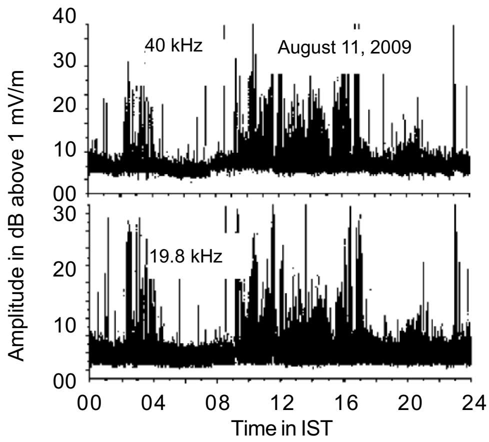

Figure 6. Diurnal variation of amplitude of VLF transmitted signals in dB above 1 mV/m observed over Kolkata. Date : August 11, 2009.

VLF-LF transient variations gradually reduced day by day, and then almost ceased after August 19, 2009. Figures 7–9 indicate such variations of VLF-LF signals at both the frequencies on August 12, 14 and 18, 2009, respectively. These may be considered as the post earthquake effects. It may be realized that the spiky variations are the precursors and the post-seismic effects of the earthquakes. Due to the power failure in the experimental site, some data are missing in the records of VLF transmitted signals (Figures 7 and 8). The effects in 19.8 kHz signal have been found to be higher than 40 kHz signal. This is due to the fact that Andaman earthquake is stronger than Honsu earthquake.

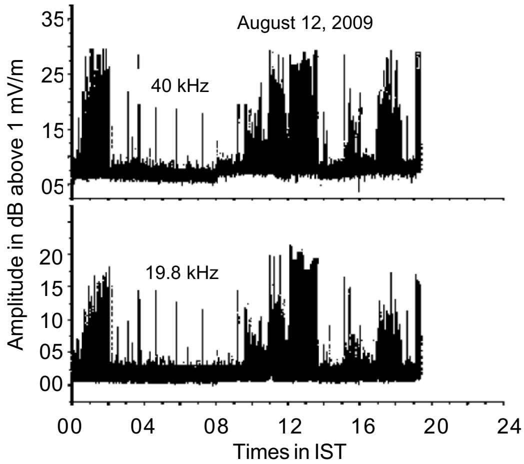

Figure 7. Diurnal variation of amplitude of VLF transmitted signals in dB above 1 mV/m observed over Kolkata. Date : August 12, 2009.

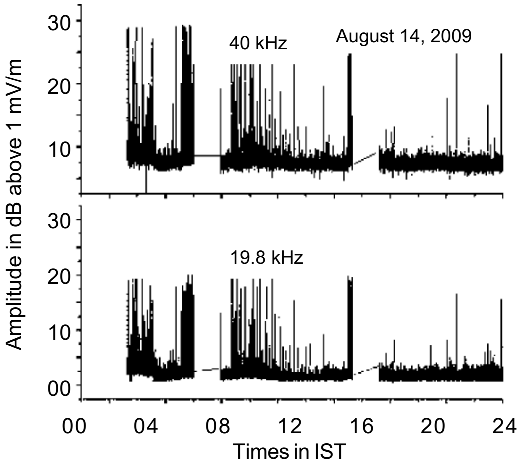

Figure 8. Diurnal variation of amplitude of VLF transmitted signals in dB above 1 mV/m observed over Kolkata. Date : August 14, 2009.

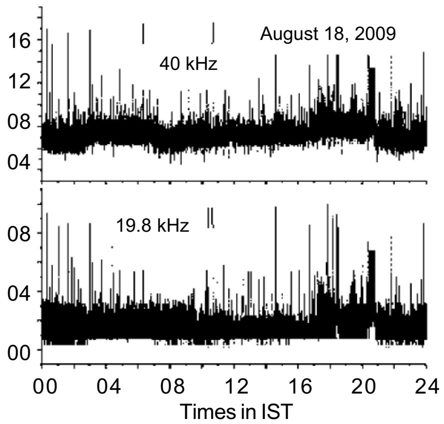

Figure 9. Diurnal variation of amplitude of VLF transmitted signals in dB above 1 mV/m observed over Kolkata. Date : August 18, 2009.

The appearance of the VLF and LF spikes were initially doubtful whether those are the signatures of geophysical phenomena or local noise. Local man-made noise has been almost ruled out as the experimental site is in a remote village area, situated about 25 km away from the city. The concerned building has also been thoroughly checked up to find out whether there is any electrical fault that may produce leakage giving such variations in the VLF-LF transmitted signal records. No such fault is found. The mid-night transients are also recorded which are even devoid of any man-made noise since the locality is a purely rural area, free from any small and large industries. The nature of VLF transients for the earthquake and their characteristics are completely different from other known events, *e.g.*, solar flares, meteor showers, geomagnetic storms, *etc.* Between August 1, 2009 and August 20, 2009, there were no thundershowers, cyclones and heavy rain on the Australia-Kolkata and Japan-Kolkata paths. This is confirmed by weather report from website. In the earthquake related events, the VLF-LF spikes maintain an interval of the order of 2-5 minutes on an average and distinguishable from each other and the base level of the signal appeared to be constant. VLF-LF transients produced by thunderstorms are associated with the variations in the base level of the signal.

In a meteorologically normal day, the raw data of the VLF-LF transmitted signals at frequencies 40 kHz and 19.8 kHz are depicted in Figure 10. For the period from

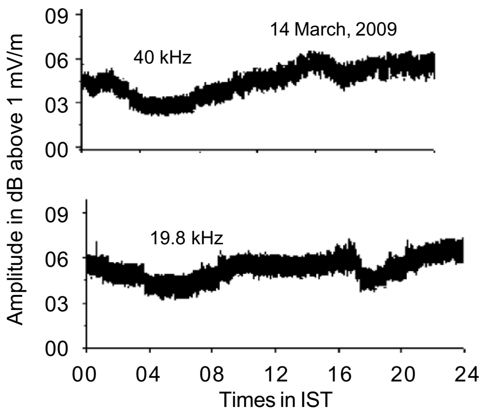

Figure 10. A normal day record of VLF subionospheric transmitted signals at 40 and 19.8 kHz in a meteorologically clear day. The amplitude of VLF transmitted signals are in dB above 1 mV/m.

February 2009 to October 2009, VLF transients are occasionally observed in the records of VLF subionospheric transmitted signals. Figure 11(a) depicts the raw data of VLF transmitted signals at frequencies 40 kHz and 19.8 kHz during the severe cyclone with overhead shower and lightning on May 25, 2009. This Figure shows that the ambient level of raw data lifted upwards to a certain value during cyclone. This type of signal variation is totally different from the recording of transmitted signal during large earthquake.

Regarding Figure 11(a), it is worth mentioning that May 24, 2009 was also disturbed with respect to the atmospheric activity and the output attained saturation due to severe cloud discharge. So the receiver gain was lowered until May 27, 2009. On May 25, signal was too small in strength to be detected. Around 10:30 IST thunderstorm activity started to grow over surrounding areas of the receiving station.

This Figure has been presented here to indicate the fact that interference of VLF radio waves from earthquake is completely different from those due to thunderstorm activity. In Figure 11(b), we show normal diurnal variations on another day (June 20, 2009) of moderate thunderstorm activity with overhead shower. The diurnal pattern is not

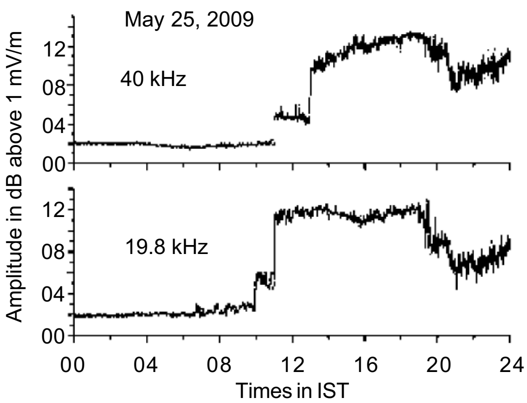

Figure 11(a). A typical record of VLF transmitted signals at 40 and 19.8 kHz during the severe cyclone with overhead shower and lightning on May 25, 2009 over Kolkata. The amplitudes of VLF transmitted signals are in dB above 1 mV/m. The signal amplitude is distorted and diurnal pattern is lost for the whole day.

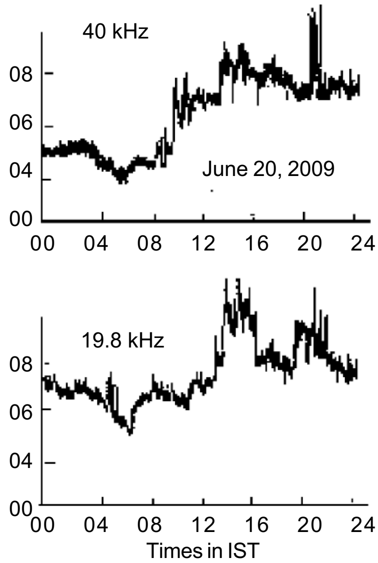

Figure 11(b). A typical record of VLF transmitted signals at 40 and 19.8 kHz during a day of moderate thunder activity with overhead shower on June 20, 2009 over Kolkata. The amplitude of VLF transmitted signals are in dB above 1 mV/m. After mid-day, the diurnal pattern is lost.

disturbed up to mid-day after which the signal is perturbed by thunderstorm activity. So, it is found that in a day of thunder activity, the usual diurnal pattern may or may not be lost depending upon severity of the thunderstorm. Regarding low bandwidth, we say that during earthquakes electro-magnetic emission occurs near the fracture in the earth-crust. These VLF part of EM emission are guided between the earth-ionosphere waveguide with less attenuation upto distance which may be of the order of thousand km. The strength of the electromagnetic radiation emitted from earthquake region may be several dB above the signal level when received in the narrow band mode. We say this is an advantage of using narrow band receiver. With narrow band receiver one can get the diurnal behaviour of the signal lost by the EM emission by earthquake. If the bandwidth of the signal receiver be 300 Hz or above, the interference of EM wave radiated from earthquake zone is hardly to dominate over the signal.

The occurrence numbers of VLF transients/spikes during the days before and after these large dual earthquakes and on the day of earthquakes have been presented by bar graphs in Figure 12. The number is maximum in the day of earthquakes (EQ) and decreases gradually on two sides of the day of earthquakes. The average of hourly

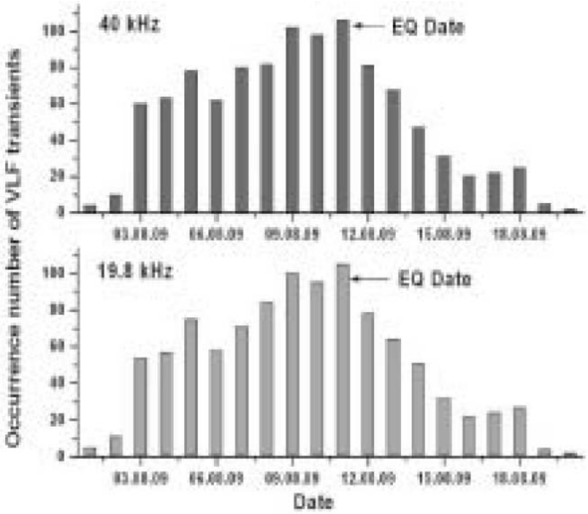

Figure 12. Number of occurrences of VLF transients on the days before and after the day of earthquake.

rate of occurrence of VLF transients at these two frequencies of 40 kHz and 19.8 kHz are shown in Figure 13. This rate is also maximum on the day of earthquakes (EQ) and decreases gradually on two sides of the day of earthquakes. The heights of VLF transients above the ambient level in dB on various days are shown in Figure 14. The height of VLF transients decreases on two sides of the day of occurrence of earthquakes. Both precursory and post-seismic effects are different at these two frequencies. Table 1 shows the statistical analyses of different characteristic parameters of these earthquakes from the recorded data.

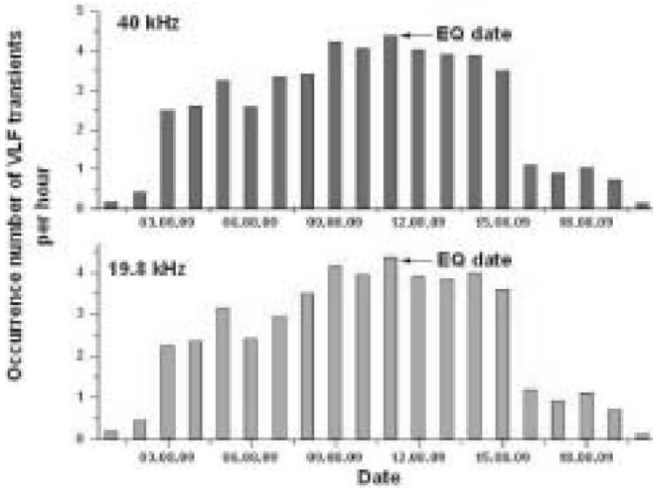

Figure 13. Number density of occurrence of VLF transients per hour on the days before and after the day of earthquake.

We have presented the anomaly in reference to two earthquakes at Andaman Island, India and at South Coast of Honsu, Japan. The VLF emission during earthquake

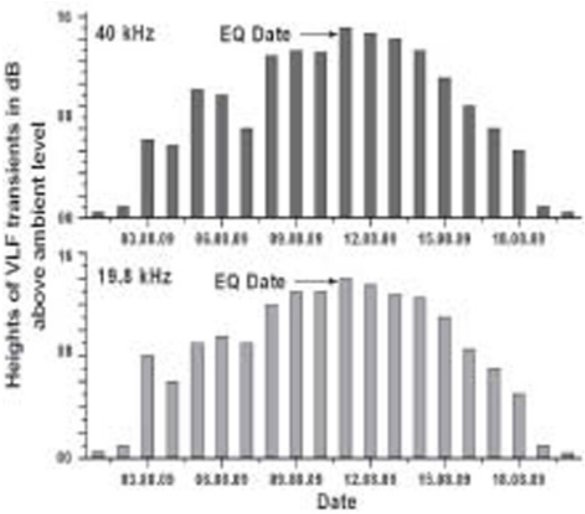

Figure 14. Average of variation of VLF transients heights above the ambient level on the days before and after the day of earthquake. The variations are in dB above the ambient level.

is guided with less attenuation in the Earth-ionosphere waveguide and can travel several thousands of km round the Earth [59]. So the transient variation in signal transmitted between Kolkata and Japan, may be assigned to be due to earthquakes occurring at South Coast of Honsu, Japan on the same day.

3.2 Terminator time fluctuation :

The EM effects associated with earthquake are thought to be responsible for ionospheric perturbation which could be detected by VLF/LF subionospheric transmitted signals. Variations in terminator times of the two different signals at 40 kHz and 19.8 kHz during morning and evening periods about the days of two earthquakes at two different places are measured regularly at Kolkata. The amplitude of signals recorded at Kolkata showed diurnal variations over which other geophysical or solar effect may be superimposed. The diurnal patterns of the signal variations are lost during the day of earthquake, prior to some days of earthquake and some days after the earthquake. In Figure 15(a), we show the diurnal pattern of the amplitudes of two signals as received at Kolkata. These graphs are plotted considering the average of days excluding ±5 days about the day of earthquake. The average terminator time has been defined with respect to the diurnal variation, which is the minimum value of amplitude during sunrise and sunset [9]. The propagation of LF-VLF wave at 40 kHz and 19.8 kHz in the cavity between earth-and lower ionosphere does not fall under the conception of so-called ray theory. The conception of sky-wave and ground wave is meaningless. It is a kind of waveguide mode propagation. Over large distances (about 5120 km between Japan and Kolkata and 5670 km between NWC and Kolkata, respectively), only two modes are dominant. The sunrise minimum and the sunset minimum are the result of interference between the first and the second modes. During sunrise and sunset, due to

Table 1. Statistical analyses of different characteristic parameters of the earthquakes from the recorded data

Date	Freq. (kHz)	Spike ambient level (mV); of spikes (mV) average height	Total no. of spikes	Total no. of spikes per hour	Average height of all spikes above spike ambient level (mV)
01.08.09	40	0.90; 0.95	4	0.17	0.05
	19.8	0.40; 0.45	5	0.21	0.05
02.08.09	40	0.90; 1.00	10	0.42	0.10
	19.8	0.40; 0.50	11	0.46	0.10
03.08.09	40	1.00; 1.70	60	2.50	0.70
	19.8	0.40; 1.20	54	2.25	0.80
04.08.09	40	1.00; 1.65	63	2.62	0.65
	19.8	0.40; 1.00	57	2.37	0.60
05.08.09	40	1.25; 2.40	78	3.25	1.15
	19.8	0.50; 1.40	75	3.13	0.90
06.08.09	40	1.00; 2.10	62	2.58	1.10
	19.8	0.40; 1.35	58	2.42	0.95
07.08.09	40	0.90; 1.70	80	3.33	0.80
	19.8	0.40; 1.30	71	2.96	0.90
08.08.09	40	1.00; 2.45	82	3.42	1.45
	19.8	0.40; 1.60	84	3.50	1.20
09.08.09	40	1.00; 2.50	102	4.25	1.50
	19.8	0.40; 1.70	100	4.17	1.30
10.08.09	40	1.00; 2.48	98	4.08	1.48
	19.8	0.40; 1.70	95	3.96	1.30
11.08.09	40	1.00; 2.70	106	4.42	1.70
	19.8	0.40; 1.80	105	4.37	1.40
12.08.09	40	1.00; 2.65	81	4.05	1.65
	19.8	0.50; 1.85	78	3.90	1.35
13.08.09	40	1.00; 2.60	68	3.92	1.60
	19.8	0.50; 1.78	64	3.84	1.28
14.08.09	40	1.00; 2.50	47	3.90	1.50
	19.8	0.50; 1.75	51	4.00	1.25
15.08.09	40	1.00; 2.25	31	3.50	1.25
	19.8	0.40; 1.50	32	3.62	1.10
16.08.09	40	1.00; 2.00	20	1.10	1.00
	19.8	0.40; 1.25	22	1.20	0.85
17.08.09	40	1.00; 1.80	22	0.90	0.80
	19.8	0.40; 1.10	24	0.93	0.70
18.08.09	40	0.90; 1.50	25	1.05	0.60
	19.8	0.40; 0.90	27	1.12	0.50
19.08.09	40	0.90; 1.00	5	0.75	0.10
	19.8	0.30; 0.40	4	0.73	0.10
20.08.09	40	0.90; 0.95	2	0.14	0.05
	19.8	0.40; 0.44	2	0.14	0.04

discontinuity at the boundary of day and night, the second mode gains energy from the first mode. Two modes are then comparable, a fact called mode conversion [60]. The destructive interference between two modes provides the signal minimum. From the point of view of propagation, the time of the signal minima during sunrise and sunset are called terminator times.

During the days of spiky variations, the superposition of EM radiation emitted prior to the time and after the earthquake destroys the diurnal pattern of signal amplitude. So it is not possible to find out the terminator time from raw data. But removal of abruptly large data points (data values of higher by 6 dB or more above the mean) produce a diurnal pattern of the signal as usual. Figure 15(b) is the sample of

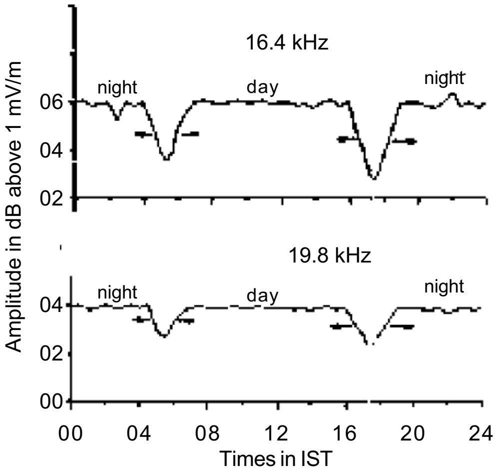

Figure 15(a). The diurnal pattern of the amplitudes of two LF and VLF signals at 40 kHz and 19.8 kHz as received at Kolkata. These graphs have been plotted considering the average of days excluding ±5 days about the day of earthquake. The amplitude of VLF signals are in dB above 1 mV/m.

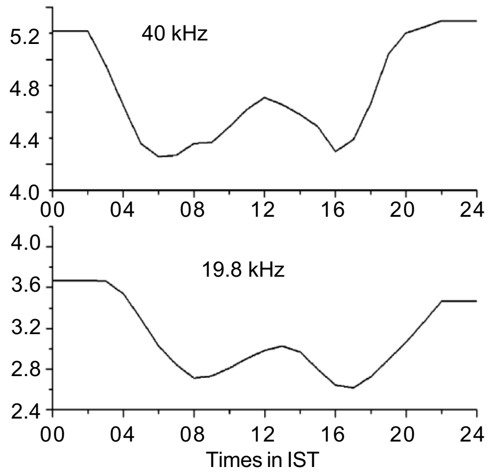

Figure 15(b). The diurnal pattern of the amplitudes of two LF and VLF signals at 40 kHz and 19.8 kHz as received at Kolkata. These graphs have been plotted by removing abruptly large data points which are higher by 6 dB or more above the average on the day of earthquake (11.08.2009). The amplitude of VLF signals are in dB above 1 mV/m.

diurnal pattern recovered for the day of earthquake. In this way, we could have found the terminator times both for morning and evening. The difference of terminator times from their average values are depicted in Figure 16(a) for April, 2009. During this undisturbed month, the difference in terminator time from their mean value shows a gradual variation from negative to positive value. This is true for both signals and for both terminator times, morning and evening terminator time. In Figure 16(b), the variations in terminator times around the day of earthquake have been shown. It is clear that the difference in terminator from their mean value shows oscillatory variations between positive and negative values rather than systematic variation of increased type or decreased type. The deviations from the normal kind of variation in terminator time both in morning and evening values and for both signals at 40 kHz and 19.8 kHz

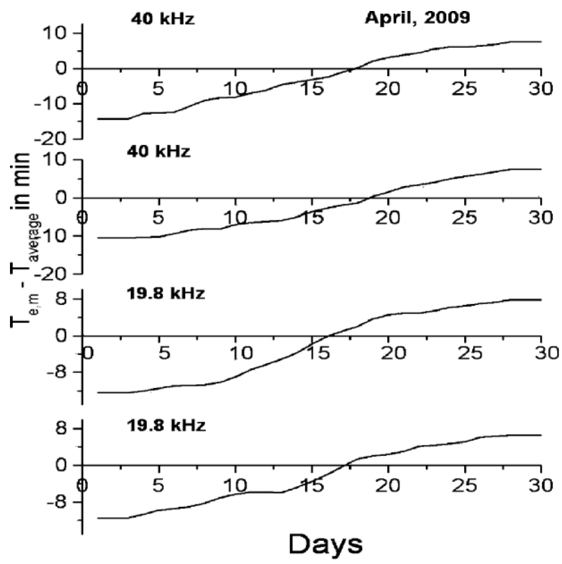

Figure 16(a). Shift in terminator time in the days of April, 2009 about the monthly mean value. Upper two panels are for 40 kHz morning and evening terminator time while lower two panels represent the same parameter for 19.8 kHz.

clearly indicate the influence of perturbation in the ionosphere due to earthquakes. The shift gradually changes while the date of occurrence would approach.

3.3. Anomalies of the 4th mode of Schumann resonance spectra :

Significant enhancement in amplitude of the fourth mode of Schumann resonance spectra and the increase in its peak frequency are obtained during the period of these two earthquakes. Figure 17 depicts the results of analyses of the recorded data of August 11, 2009, the day of occurrence of earthquakes, along with the regular normal day data. Magnitude of Fourier transform results in arbitrary unit have been plotted against frequency. Thin continuous line represents the Schumann resonance spectra within the undisturbed Earth-ionosphere waveguide and the bold line indicates the variation when the disturbance over the earthquake zone sets in. Amplitude as well as peak frequency around the fourth mode of Schumann resonance spectra (26 Hz) are found to increase. Shift in peak frequency about 1.25 Hz is obtained. Amplitude variation of fourth mode Schumann resonance spectra is plotted in Figure 18. Continuous line curve is the plot of signals on the day of occurrence of the earthquakes. Large dashed and short dashed curves, respectively, are for the two days earlier and two days later from the earthquake date. Around the time of main shocks of both the earthquakes, amplitude sustains higher values about 2.4 in arbitrary unit. It is nearly 17% increase from the pre- and post-seismic values.

4. Discussions

The EM emissions that were observed prior, during and preceding of any earthquake

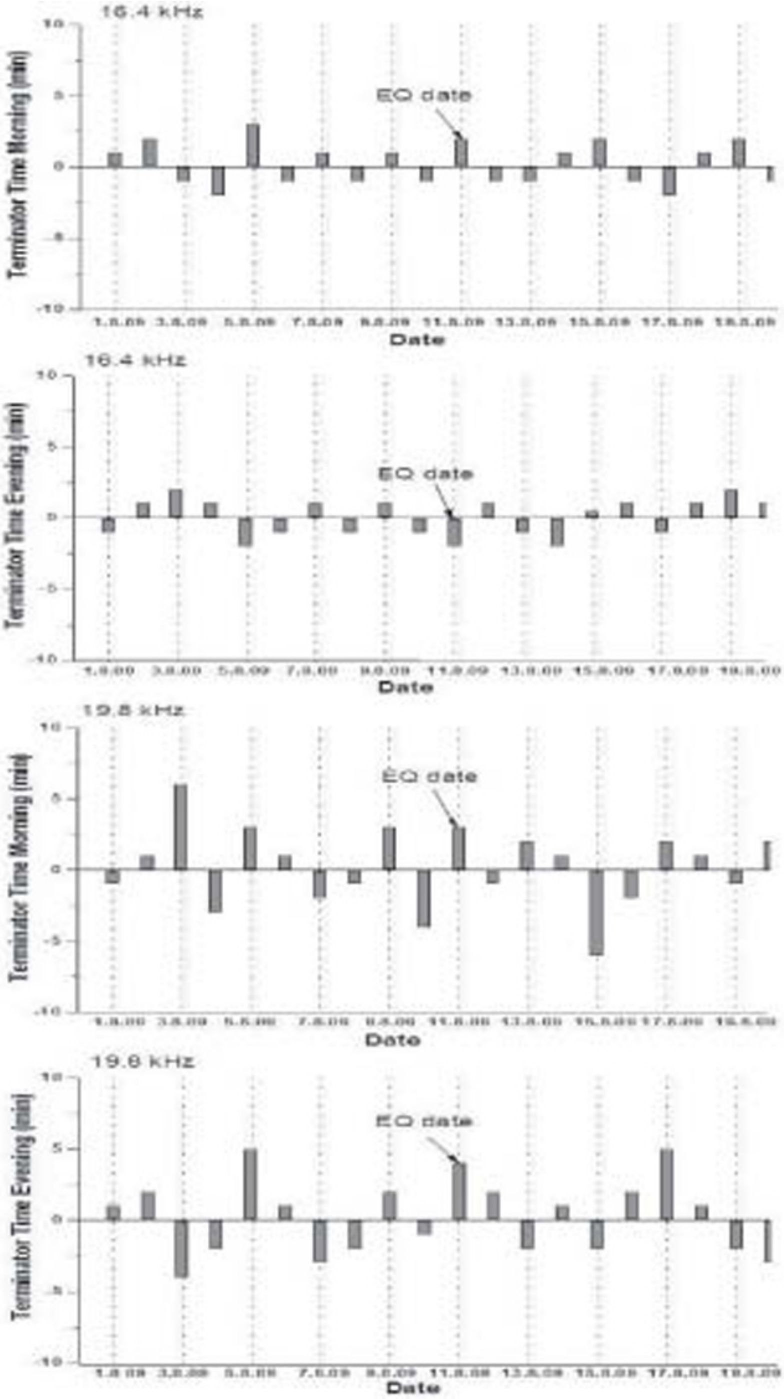

Figure 16(b). Shift in terminator time surrounding the day of occurrence of the two earthquakes, Andaman Island, India and South Coast of Honsu, Japan. The results are presented in terms of their histogram. Upper two panels are for 40 kHz morning and evening terminator time while lower two panels represent the same parameter for 19.8 kHz.

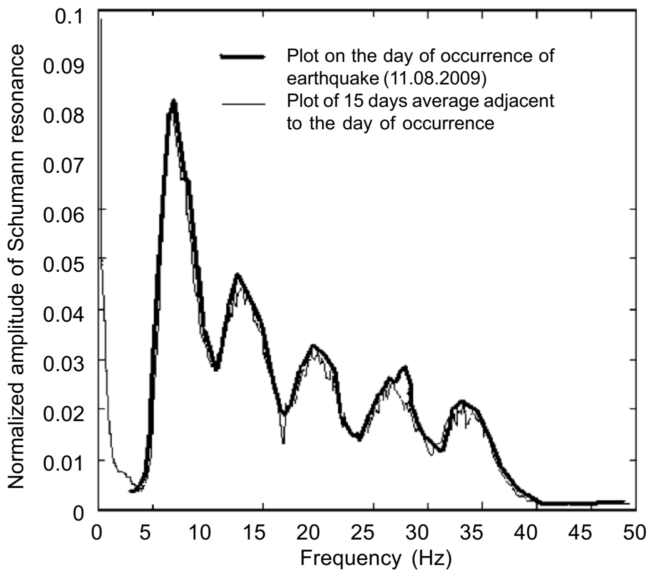

Figure 17. Frequency spectrum of Schumann resonance on the day of occurrence of Andaman Island, India and Honsu, Japan earthquake on August 11, 2009 (bold line curve) along with the 15 days average plot adjacent to the day of occurrence (thin line curve)

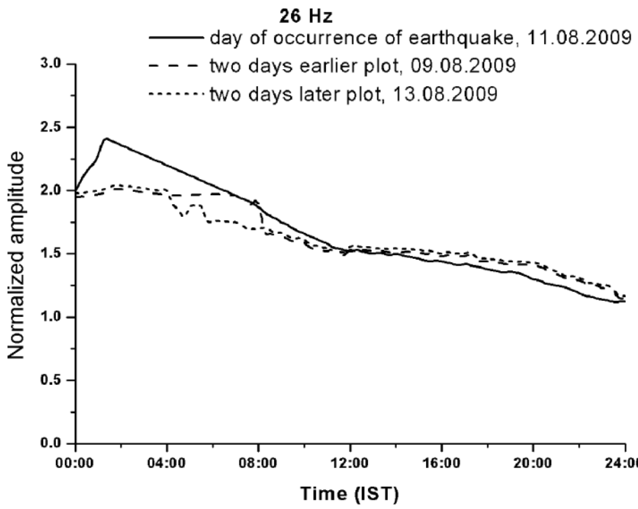

Figure 18. Variation of amplitude of the fourth mode of Schumann resonance spectra on the day of occurrences of the two earthquakes on August 11, 2009 (continuous line curve). Variation of the same parameter two days earlier (large dashed line curve) and two days later (short dashed line curve) from the date of occurrence.

have been reported by many authors over the world. Observational system is installed at Uji station, Kyoto, Japan since 1981. At Kyoto University, continuous observations of EM pulses at 163 kHz of LF band since 1983 and at 1–20 kHz of VLF band since 1987 are being conducted. The results of observations were reported by Oike and Ogawa (1986), Oike and Murakami (1993), Oike and Yamada (1994), Yamada and Oike (1996), and Yamada (1998) [61–65]. A number of amplified pulses with amplitude exceeding a fixed threshold was counted and recorded. Just before and after the 1995 Hyogo-ken Nanbu earthquake, continuous waveform data of VLF EM pulses are recorded. Remarkable increase in the number of LF EM pulses was observed at Uji station several days before of any large earthquake, such as, the 1984 Western Nagano Prefecture earthquake [61]. Oike and Murakami (1993) [62] investigated the correlation between the observed number of pulses during the occurrence of 10 shallow earthquakes which were taken place in land or under shallow sea at a water depth of about 1000 m or less near Japan during the period from 1983 to 1991. The LF pulses were also seen in the case of 1993 Hokkaido-Nansei-Oki earthquake [63].

Prediction of earthquakes has always been an important research. Optimistic progresses in the field of long-term prediction are made with substantial effort over many years by various authors. The short-term earthquake prediction, on a time scale of hours to several days, still a subject of long run research. Many researchers are giving stress to the point that pre-seismic EM phenomena may be a tool for short-term prediction of earthquakes. Much research activities have been conducted on pre-seismic EM signals in various frequency ranges [66]. All these reports almost showed temporal correlations between "seismic" EM signals and the occurrence of earthquakes. In some cases [66–68], signals were from epicentral areas. The relationship between these anomalous EM emission and earthquakes, however, has not been established in a straight forward way. The nature of such signals is still not clear due to involvement of various parameters in the recorded data and insufficient theoretical background. Still there are two basic unsolved problems in general. The first problem is the difference in the features of EM radiation observed by antenna in the field and in the laboratory. Of course, the EM emission associated with rock fracture is a well known phenomenon [69]. The piezoelectric effect and electrokinetic effect are thought to be the mechanisms of EM radiation [70–74]. The laboratory experimental results assert that the largest EM radiation should be observed at the time of an earthquake when the largest stress change occurs. But, experimental results showed that maximum amount of radiation may occur a few days earlier to the day of earthquake. The second one is the attenuation problem. The EM signals which are generated at depth cannot reach the earth's surface ("Skin depth" effect). However, the second problem may be overcome with lower frequency EM waves which have more possibilities to reach the earth's surface due to smaller skin depth. Underground water diffusion in a region associated with deformation of the crust prior to earthquake raises the electrical conductivity in the crust [71]. Thus in order to explain the EM radiation associated with earthquakes and volcanic activities, one has to calculate the attenuation of ELF/VLF waves in dry crust and wet soil.

Now, the electric field of EM waves may be expressed as

$$\boldsymbol{E} = \boldsymbol{E}_0 \exp\left\{ j(\omega t + \boldsymbol{k}\cdot\boldsymbol{r}) \right\}, \tag{1}$$

where ***k*** is the wave vector given by $k^2 = \varepsilon\mu\omega^2 - j\sigma\mu\omega$. ω is the angular wave frequency; ***k***, the wave vector; ***r***, the radial vector from the radiation source; μ, the permeability; ε, the dielectric constant and σ is the electrical conductivity. The complex wave number is given by $k = \alpha + j\beta$, $(\alpha > 0, \beta \geqq 0)$, α represents the propagation constant and β is the attenuation constant. The attenuation constant is derived as

$$\beta = \omega \left\{ \varepsilon\mu \Big/ 2 \left(\sqrt{1 + (\sigma / \varepsilon\omega)^2} \right) - 1 \right\}^{1/2} \tag{2}$$

$= (\sigma\mu\omega/2)^{1/2} = 1/\delta$ for $\sigma/\varepsilon\omega >> 1$, where δ is the skin depth. The dielectric constant is expressed by $\varepsilon = \varepsilon_o\varepsilon_r$. $\varepsilon_o = 1/(36\pi \times 10^9) F/m$ is the dielectric constant or permittivity of free space and ε_r is the relative dielectric constant. The magnetic permeability μ is usually approximated by the permeability of vacuum $\mu_o = 4\pi \times 10^{-7} H/m$, if the material concerned is not ferromagnetic. Relative dielectric constants ε_r of the material concerned are as follows : 1 for gas, 80 for water at 20°C. For water ε_r = 55 at 100°C. The electric conductivities σ of the material concerned are as follows : 10^{-2} mho/m for wet soil and 10^{-5} mho/m for dry crust. The expression of $\beta = 1/\delta$ can be properly used for EM wave attenuation below 100 kHz in wet soil and below 10 kHz in dry crust. For frequencies from 100 Hz to 10 kHz, the attenuation of EM waves in dry crust is less than 4 dB/km, while it is from 17.3 dB/km at 100 Hz and above 100 dB/km at 1 kHz in wet soil. Therefore, if EM radiation is generated in dry crust by rock fractures over a vast region before and after the main shock of a shallow earthquake, anomalous EM waves will be observed even in the VLF band. The present observations are confined at 19.8 kHz and 40 kHz. The poor presence of spikes below 40 kHz may be due to propagational attenuation in the earth-ionosphere waveguide. It is worth mentioning that based on the study of pre-seismic EM signal, Kapiris *et al* (2002) [28] attempted to establish a set of necessary conditions referring to the underlying critical stage of the earthquake generation process. Moreover, Eftaxias *et al* (2002) [75] evaluated EM signals in terms of their relations with earthquakes in comparison with laboratory measurement on rock samples.

The first experiment of radio sounding for earthquake-ionospheric link was done by Russian scientists using VLF propagation over a long path (5000 to 9000 km) [76, 77] using Omega signals. The observed anomaly over two long distant paths were from Renion to Moscow and to Omsk. For short path, they paid attention to the terminator time and found that there is a significant change in terminator time before earthquakes. Hayakawa *et al* (1996) [19] first reported convincing result on the seismo-ionospheric perturbations with VLF sounding for the Kobe earthquake in 1995 (M = 7.3 and depth = 20 km). Some important features of the paper are that the propagation distance (from Tsushima Omega to Inubo observatory) is relatively a short-path (~1000 km) as compared to 5000 ~ 9000 km [76,77]. They found that the fluctuation method was not so effective for the short-propagation path. So, they paid attention to the terminator times (morning and evening) and they found significant shifts in the terminator times before the earthquake. Along their path, morning terminator time (T_m) shifted to early hours, and evening terminator time (T_e) shifted to later hours. The significance of the result is that the daytime felt by subionospheric VLF signals is elongated for a few days around the earthquake and the theoretical estimations [19,78,79] suggest that the lower boundary of the ionosphere gets lowered before the earthquake. Molchanov and Hayakawa (1998) [3] made extensive study based on the 11 events during 13 years with earthquakes of magnitude greater than M = 6.0 and within the 1st Fresnel zone for the same propagation path from the Omega, Tsushima to Inubo. They found it for depth smaller than 30 km. Four earthquakes exhibited the same terminator time anomaly as for the Kobe earthquake. For depth of epicenter in the range between 30 and 100 km, there were two observed events. One event exhibited the same terminator time anomaly.

Earthquakes having depth larger than 100 km did not show any anomaly. This shows a probability of the order of 70~80% of the propagation anomaly, in the form of terminator time anomaly, for larger earthquakes located relatively close to the great-circle path, *e.g.*, 1st Fresnel zone. In Japanese VLF/LF network established within the framework of the Frontier Project, there are seven observing stations : Moshiri (Hokkaido), Chofu (Tokyo), Tateyama (Chiba), Shimizu (Shizuoka), Kasugai (Nagoya), Maizuru (Kyoto) and Kochi. The VLF/LF transmitters were JJY (40 kHz, Fukushima), JJI (22.2 kHz, Ebino, Kyushu), NWC (19.8 kHz, Australia), NPM (21.4 kHz, Hawaii) and NLK (24.8 kHz, America). Each VLF/LF receiver is designed to measure very slow and small changes in amplitude and phase. The magnitude of slow phase and amplitude perturbations claimed for earthquake precursors are much greater than this, so it should be detectable. The distance of the epicenters from the path of propagation in the case of 40 kHz and 19.8 kHz is well supported by the results of Molchanov and Hayakawa (1998) [3], *i.e.*, within the Fresnel's first half period zone. The paths are well within the sensitive zone. Strengths are well above M = 6. The depth of Hansu earthquake is 26 km and that of Andaman earthquake is 33.1 km. The depths are also supported by Molchanov and Hayakawa (1998) [3] to cause ionospheric disturbance. But our observation is an oscillatory variation in terminator time.

Comparison of our result with those of Molchanov and Hayakawa (1998) [3] shows that terminator time anomaly, in our case, is different from their result in the sense that we have seen oscillatory variations in terminator time between some positive and negative values. From the point of view of explanation, it is to be ascertained that around the day of earthquake, the lower surface of the ionosphere undergoes periodic rise and fall in its altitude.

Generally speaking, it is only true in the ray approach for the wave propagation in the earth-ionosphere cavity. This kind of approach becomes meaningless in the case of VLF and LF propagation which follow the waveguide mode propagation. Apart from this, the above is a statement with respect to the variation of terminator time which is a propagational aspect. In our case, the effects of earthquake on terminator time are meager. We are interested to highlight the EM radiation emitted during earthquake. The superposition EM radiation on the signal at the receiving antenna does not involve the idea of Fresnel's half period zone. It is also remarkable to mention that Fifth Fresnel Zone can also be useful and effective as the VLF sensitive zone for the earthquakes with M = 6–7 [14]. Anyway, the ray theory is not suitable for this purpose.

The earliest models of ELF propagation parameters in the earth-ionosphere waveguide were on the supposition that the lower ionosphere conductivity profile is horizontally homogeneous and vary exponentially in the vertical direction. During solar activity there may be two kinds of changes – (i) increase in ionization level at the normal D region reflection heights and ii) the variation of D regions lower edge [79]. According to this model, the variation of first SR is given [79] as

$$\frac{\Delta f_1}{f_1} \approx 0.36\left(\frac{\Delta N}{2N} + \frac{\Delta h}{h}\right).$$

This expression shows that the frequency can change due to both electron density variations in the ionospheric D region and the change of height of the lower boundary of the D region [80]. As the variation of height of D region is supported by terminator time anomaly, the same variation of ionospheric height may be the cause of the variation of the 4th SR mode.

4. Conclusions

The most important EM effect associated with earthquake is the ionospheric perturbations which are justified through subionospheric transmitted VLF/LF signal propagation [7,38]. Some attempts in this paper are made to secure informations about seismo-EM effects through ionospheric perturbations associated with the two earthquakes which occurred at Andaman, India and Honsu, Japan on August 11, 2009 at a gap of 11 min 29 sec, upon the two transmitted signals at 40 kHz and 19.8 kHz, recorded near Kolkata. Earthquakes near the great-circle path from the source to the point of reception can affect the propagation characteristics of VLF transmitted signals. For this, seismo-ionospheric perturbation can be studied by the use of VLF/LF subionospheric transmitted signals.

The correlation of VLF-LF emission with the occurrence of earthquakes cannot be inferred from temporal correlation only. The agreement between the direction of arrival of VLF-LF radio wave and that of the place of earthquake should have to be well checked. In order to remove the influence of lightning, Some researchers [66,81] adopted direction finding method and identification by waveform. Of course, the FFT study of the waveform of EM radiation observed during the earthquake and their comparison with those due to lightning may lead to infer whether an earthquake related

EM actually occurs there. At the same time, a huge database is required to check whether an earthquake can trigger a lightning activity, or, whether there is any kind of relationship between earthquake and lightning.

The present authors are confident that precursor to earthquake can be identified with simultaneous measurement of extra-ordinary VLF-LF emission, ionospheric disorder including TEC measurement and the measurements of SR frequency and amplitude.

Acknowledgments

The authors acknowledge with thanks the financial support from Indian Space Research Organization (ISRO) through S K Mitra Centre for Research in Space Environment, University of Calcutta, Kolkata, India for carrying out the study. They are thankful to the adjudicators for their critical and valuable comments which are carefully introduced in the paper.

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