Sudden amplitude and phase changes in subionospheric VLF transmitter signals observed at Agra, India

Vikram Singh*, Shikha Agrawal, and Birbal Singh

Department of Electronics and Communication Engineering, Faculty of Engineering and Technology, R. B. S. College, Bichpuri, Agra, India

* Present address: Department of Physics, K. P. College of Engineering and Technology, Agra

Abstract. The amplitude and phase of VLF transmitter signals NWC (19.8 kHz), NPM (21.4 kHz), and NAA (24 kHz) have been monitored at Agra (geomag. lat. 17.10° N, $L=1.15$), India using AbsPAL receiver for a period of three years between 01 September, 2002 and 30 August, 2005. Seven cases of abrupt amplitude and phase changes have been identified which varied between 3 and 7 dB and 40° and 80° respectively. The onset duration varied around 5 sec. The observed characteristics have been examined in the light of lightning induced electron precipitation (LEP), solar flares, and lightning, and finally attributed to early/slow perturbation caused by distant sprites and lightning along the propagation paths.

Key words: VLF perturbation, early/slow events, sprites

1. Introduction

The very low frequency (VLF) ground based transmitter signals propagate to long distances through earth- ionosphere space after reflections from the ground and lower boundary of the ionosphere. If frequency and reflection distance are fixed, the observed signal parameters (phase and amplitude) are mainly related to position of reflection height and profile of the electron density in the D- layer of the ionosphere. Any short-time structural change in the electron density near the reflection height, brought out by natural sources such as lightning induced precipitation of energetic particles, lightning induced heating, solar flares, and earthquakes etc, can bring out significant variation in phase and amplitude of the signal which, in turn, can help study the phenomena involved. This is known as VLF method and has been very popular in recent times (Hayakawa et al., 1996; Molchanov et al., 1998; Rodger and Dowden, 1998). Although there is bulk of literature on experimental and theoretical research employing VLF technique available, some notable among them may be cited as follows;

The first indirect evidence of lightning induced energetic particle precipitation, popularly known as trimpi phenomena or classic trimpi, was derived from amplitude and phase perturbation in VLF transmitter signals propagating in the earth- ionosphere waveguide (Helliwell et al., 1973; Lohrey and Kaiser, 1979). Such changes consist of fast (~ 1 sec) amplitude increases or decreases of 1-3 dB followed by a ~ 30 sec recovery. Extensive research on this phenomenon has been done later by Inan et al. (1985) and Inan and Carpenter (1987), and references therein.

VLF propagation has been used to study the solar flare induced D- region perturbations of the lower ionosphere also. The extra ionization generated by X-rays lowers the effective reflection height of the D- region ionosphere and enhances the phase

at the receiver in proportion to the intensity of the X-ray flux. The changes in amplitude are much more enhanced (8-9dB), which is found to increase with logarithmic X-ray flux and then saturate for long propagation paths (Mitra, 1974; Pant *et al.*, 1983; McRae and Thomson, 2004; Todoroki *et al.*, 2007).

Gokhberg *et al.* (1989) reported first abnormal precursor influence of earthquakes on the subionospheric VLF propagation. This phenomenon has been studied in great detail by Hayakawa *et al.* (1996) in relation to Kobe earthquake of 17 January, 1995. He employed the termination time (TT) technique (sunrise and sunset minima in amplitude and/or phase of the VLF signal) and showed that days are elongated by about half an hour due to lowering of the reflection height by 1-2 km a few days prior to the occurrence of the impending earthquake. Similar work has been done by other workers also (Molchanov *et al.*, 1998; Molchanov and Hayakawa, 1998). Rodger *et al.* (1999) and Clilverd *et al.* (1999) have found that TT method did not yield expected results for long propagation paths.

Recent observations of Transient Luminous Events (Red Sprites, Blue Jets, Elves) in the mesosphere at various places throughout the world have generated great interest in the electromagnetic coupling of the lightning in troposphere with that in the mesosphere and the lower ionosphere. Detailed reviews on these events have been presented by Strangeways (1996), Rodger (1999) and Mika (2007). Out of these events, red sprites have been observed most commonly and studied thoroughly. The effects of sprites appear on the VLF signals in early (<50 msec) and fast (<20 msec) growth/decay of amplitude and on phase and termed as early/fast events in contrast to classic trimpis caused by lightning induced precipitations. There are evidences showing that in contrast to classic and early/fast trimpis a sizeable group of sprite-related early events do not display a 'fast' onset duration. Instead, they show duration of 1-2 seconds or more. These are leveled as early/slow events (Mika, 2007).

The monitoring of phase and amplitude of VLF transmitter signals has been carried out at Agra (geomag.lat. 17.10°N , $L=1.15$), India during the period from 01 September, 2002 to 30 August, 2005 with the basic objectives of studying some of the phenomena mentioned in introduction in the low latitude ionosphere. In this paper, we present the results of analysis of data and show that seven cases of early/slow events have been recorded at this station. We discuss their characteristics and examine the mechanism of VLF perturbation in the light of different causative sources.

2. Experimental Setup

We have employed Absolute Phase and Amplitude logger (AbsPAL) obtained from LF*EM Research Ltd, Dunedin, New Zealand which is similar to that used by Dowden and Adams (1988). We monitor the phase and amplitude of three different signals of frequencies 19.8 kHz (NWC, Australia), 21.4 kHz (NPM, Hawaii), and 24 kHz (NAA, Cutler). The great circle paths (GCP) of these signals are shown in Fig.1. The equipments include electric antenna, VLF amplifier, a service unit, DSP card, and necessary software. The sampling rate is 1 sample/sec. The observations have been carried out at Bichpuri, a rural area about 12 km west of Agra city where local electric and electromagnetic disturbances are low. The observations have been taken round the clock except two hours break between 1200 h and 1400 h LT.

Fig.1: Great circle paths (GCPs) of the VLF signals of frequencies 19.8 kHz (NWC, Australia), 21.4 kHz (NPM, Hawaii), and 24 kHz (NAN, Cutler).

3. Results and discussion

Keeping in view the potential application of VLF method in studying the ionospheric perturbation related to natural phenomena, we started the phase and amplitude monitoring of three VLF signals described in the previous section from 01 September, 2002 and continued till 30 August, 2005. A detailed analysis of the data yielded seven cases of sudden phase and amplitude changes which appeared to have been caused by localized ionospheric perturbations. The details of these events are presented in Table 1 which shows the date and time of their occurrence, frequency of the transmitter signals, and whether the sudden changes occurred in phase (P), amplitude (A) or in both of them (PA). In Fig.2, we show three minutes of data for three of the four cases in which both phase and amplitude perturbations were observed. These cases occurred on 7 October, 2002, 2 December, 2004 and 15 January, 2005. The date, time, and frequency for each case are mentioned on the top of the amplitude panel. One of the three cases occurring on 7 October, 2002 was recorded during daytime, whereas rests of the cases were recorded during nighttime. As seen from the figure, the changes in amplitudes and phases of the signals occurred between 3 and 7 dB and between 40° and 80° respectively. The onset duration is large ~ 5 sec. The data corresponding to 15 January, 2005 show three times amplitude and phase perturbations as compared to other two cases.

Table-1: Occurrence details of the observed events.

Date	Time, UT	Signal frequencies, kHz	Perturbation in phase (P), amplitude (A) or both (PA)
7 Oct. 2002	15.58	24	PA
27 Sept. 2004	14.07	24	A
3 Oct. 2004	03.48	21.4	PA
6 Oct. 2004	13.37	24	A
11 Oct. 2004	22.58	19.8	A
2 Dec. 2004	22.04	21.4	PA
15 Jan. 2005	23.13	19.8	PA

The VLF perturbations shown in Fig.2 can not be explained in the light of lightning induced electron precipitations (LEP) in the lower D region of the ionosphere for the reason that (i) the onset duration and recovery times are much higher than that caused by LEP, (ii) the phenomena of wave-particle interaction and precipitation is unlikely to occur in the low latitude ionosphere below $L=1.4$ (Voss and Smith, 1980: this applies especially to the data presented in Fig.2c which correspond to NWC signal ($f=19.8$ kHz) whose entire propagation path lies in the low and equatorial region) and (iii) the trimp phenomena due to LEP are known to occur during nighttime (Helliwell et al., 1973) whereas one of the three cases presented in Fig.2a occurred during daytime.

In order to examine the effect of solar flare on the VLF data presented in Fig.2, we look for X-ray flux intensities on the days of the events from the website: www.swpc.noaa.gov/. We find that, while no data are available for the events on 07 October, 2002, the flux intensities are of lower classes (B1.9 and C1.6, where $B < 1.0 \times 10^{-6}$ W/m² and $1.0 \times 10^{-6} < C < 1.0 \times 10^{-5}$) on 02 December, 2004 and 15 January, 2005 respectively. Thus the VLF perturbations shown in Fig.2 are unlikely to be caused by solar flares. This inference is also justified in the light of the work of Todoroki et al. (2007) who have found increasing amplitude of the VLF signal with increasing X-ray flux intensities. In our case, the amplitudes increase between 3 and 7 dB whereas X-ray flux intensities are low.

To examine the effect of earthquakes on the data in Fig.2, we first ascertain if there occurred earthquakes anywhere along the GCP on the days of the events or a few days after the events. We look for earthquakes of magnitude $M > 5.0$ from the website: <http://neic.usgs.gov>. We find that there were no cases of earthquake within ± 5 days for the first two events of 07 October, 2002 and 02 December, 2004. There did occur two earthquakes of magnitudes $M > 5$ on 18 and 19 January, 2005 at locations (35.53°N , 67.95°E) and (41.92°N , 79.17°E), but they are unlikely to influence the third event of 15

January, 2005 because the GCP of this signal was far away from the earthquake epicenters. Hence, the possibility that the VLF perturbation of Fig.2 could be caused by earthquakes is ruled out.

Fig.2: Examples of amplitude and phase perturbations in VLF signals. The date, time and frequency of the signal are mentioned on the top of the amplitude panel of each signal.

Now we examine, finally, the observed events in the light of lightning and thunderstorms activities. Recent observations on hill tops, in high altitude sounding rockets, and in aircrafts have yielded a new class of optical emission known as 'sprites' which are generated over intense thunderstorms in the altitude range between 40 and 85 km. The effect of sprites on subionospheric VLF propagation has been reviewed excellently by Strangeways (1996), Rodger et al. (1999) and Mika (2007). It has been shown that the onset (< 50 msec) and fast growth or decay (< 20 msec) of the amplitude of VLF signal, termed as early/fast perturbations, are very common in observations. Mika (2007) has presented some examples of a new class of VLF perturbations in which the

amplitude growth is slow (>1 sec) and hence it is called as early/slow perturbation. On comparing the characteristics of our data with those of the early/slow perturbation, we find that the events in Fig.2 belong to the category of early/slow events. In order to ascertain that events of Table 1 are caused by lightning around the GCP of the VLF signals under consideration, we make a study similar to that carried out by Otsuyama *et al.* (2004) and Hayakawa *et al.* (2004), in which they have made a statistical study of sub-ionospheric VLF perturbations associated with winter lightning around Japan. Since all the cases of VLF events found by us (refer Table 1) occurred between the months September and January, they belong to winter season in India, hence their study in the light of the results of Otsuyama *et al.* (2004) will be appropriate in the present study also. Some of the significant results of Otsuyama *et al.* (2004) are (i) there is no significant results of VLF trimpis occurrence rate on the local time, (ii) there is no significant difference in the rate of lightning with trimpis between + and - CG discharges, and (iii) trimpis are more easily triggered on the sea of Japan side than Pacific area.

To find the association of VLF events recorded by us with lightning activities, we first look for lightning data in and around India near the propagation paths of VLF signals from the website: www.wunderground.com. We find some specific locations on which there were significant lightning occurred in India and in South-East region. These locations are Delhi, Jaipur, Varanasi, Lucknow, Patna in India, and Indonesia, Malaysia, Singapore in South-East region. These locations are shown in the map of Fig.3 by solid squares.

Fig.3: Locations of lightning events in India and other South-East Asian countries of Indonesia, Malaysia, and Singapore on the days of VLF events.

Since the lightning activities in the Indian region occurred within a range of 200-600 km from Agra they are likely to influence the VLF perturbations observed in the NPM and NAA signals, whereas those which occurred outside India in South-East region may influence predominantly the NWC signal because the GCP of the signal passed over this region.

We show in Fig.4 the lightning activities in the Indian region for the months in which VLF events were recorded at Agra, and in Fig.5 the lightning activities in the same months occurred outside India. We consider three cases of lightning if occurred on the same day on three different locations. In this way, the figures show number of lightning cases on the Y-axis and the days of lightning on the X-axis. The downward arrows show the days of VLF trimpis occurred in different months as shown in Table 1. As seen from Fig.4, four of the events are correlated very well with the enhanced lightning in the Indian region. Since there was no lightning activity in the months of December, 2004 and January, 2005, the respective panels are shown blank in the figure. As seen from Fig.5 the lightning activity in the South-East Asian regions of Indonesia, Malaysia, Singapore occurred on almost every day in the respective months, but they caused VLF trimpis on three days only which are 6 October, 2004, 2 December, 2004, 15 January, 2005. Since we have no data to determine which kind of lightning (+ or - CG) occurred on these days in India and outside region, it is difficult to say whether VLF events are caused by + CG or - CG. Further, the times of lightning activities are not known, hence one to one correlation in time is difficult to confirm.

Fig.4: Lightning activities recorded in the Indian region for different months.

Fig.5: Lightning activities recorded outside the Indian region for the same months as in Fig.4.

In order to support the occurrence of VLF events in association of lightning activities, one is required to present the data of optical observations and/or electromagnetic ELF/VLF observations. Since optical observations related to lightning activities have not been carried out in India during the period in which VLF events were recorded at our station, it is not possible to support above result with the data of optical observations. Though, the facilities for observing spherics and whistlers are available at our Agra station itself, the experiments were not operated during the period of VLF event reported in Table 1, hence such data are not available also.

A mechanism behind the early/slow events needs to explain why soon after a sprite, the VLF perturbation undergoes, for about 1 to 2 seconds or more, a gradual growth to a maximum amplitude instead of an abrupt jump to the same amplitude level as in early/fast events. This suggests a process of gradual ionization build-up at altitude above ~ 70 km, initiated by a sprite breakdown. Such a possibility seems to be compatible with the observation showing the onset of early/slow events to be accomplished by a burst of lightning activity, comprised of a few discrete cloud to ground (CG) and clusters of intra-cloud (IC) discharges. It is interesting that the VLF perturbation attains its maximum when CG and IC activities cease, which suggests the possibility that induced quasi-electrostatic (QE) and electromagnetic pulses (EMP) fields provide the energy for the electron density to accumulate gradually in the upper D-region (Mika, 2007).

4. Conclusion

We have found seven cases of VLF trimpis occurred in the VLF transmitter signal NWC (19.8 kHz), NPM (21.4 kHz), NAA (24 kHz) monitored with the help of AbsPAL receiver for a period of three years between the months of 01 September, 2002 and 30 August, 2005. The data show abrupt amplitude and phase changes between 3 and 7 dB and 40° and 80° respectively with large onset duration of about 5 Sec. These results are examined in the light of energetic particle precipitation, solar flares, earthquakes and lightning and finally identified as early/slow perturbations caused by lightning activities around the observing station in India and in the other South-East Asian regions of Indonesia, Malaysia, and Singapore. The results of early/slow type of occurrence is interpreted in terms of gradual ionization build up in the lower ionosphere due to CG and IC lightning.

Acknowledgment. The authors are thankful to the Department of Science and Technology, Government of India, New Delhi for providing financial assistance in the form of a major research project. The authors are also thankful to Mr. Vishal Chauhan, Senior Research Fellow (SRF) of our research group for help in data processing and useful discussions.

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(Received August 31, 2009; revised January 14, 2010;
accepted January 18, 2010)