Nighttime amplitude decrease in 19.8 kHz NWC signals observed at Agra possibly caused by moderate seismic activities along the propagation path

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Abstract The preliminary results of day to day variation in the amplitude of the 19.8 kHz VLF signals transmitted from NWC, Australia (lat. 21°49'S, long. 114°9'50''E), monitored at Bichpuri, Agra (lat. 27°12' N, long. 78° E), India since 1 August, 2002 are presented. The nighttime amplitude data between 2200 and 0400 h LT for nine months period between August, 2002 and April, 2003 have been analyzed. The results show decreases in the amplitudes from normal nighttime daily averages on six days during the whole period under consideration. Possible causes for the decreases are examined in the light of magnetic storms and seismic activities. It is seen that the decreases are associated with moderate seismic activities which occurred between the two stations along the VLF propagation path. On two days the decreases occurred earlier than the earthquakes while on other days they occurred either on the same day or after the earthquakes. The possible mechanism involved in the amplitude decrease is discussed in the light of electromagnetic phenomena in the earth's crust and their possible effect on the structure of the lower ionosphere.

Key words: Earthquakes, VLF amplitude, Subionospheric propagation

1. Introduction

The very low frequency (VLF) electromagnetic waves generated either from natural sources such as lightning discharges or from man-made sources such as fixed frequency ground transmitters propagate largely to long distances in the Earth- ionosphere waveguide. In case of fixed frequency ground transmitter signals, significant variations in received amplitude and phase are caused by changes in the structure of the lower ionosphere. The short-period structural changes in the characteristics of the lower ionosphere may be brought out by changes in solar zenith angle, solar flares, lightning- induced electron precipitation, and red sprites . Phase and amplitude perturbations have also been reported in association with large magnitude

earthquakes (Gokhberg et al., 1989, Gufeld et al., 1994, Hayakawa and Sato, 1994). Recently, Hayakawa et al. (1996a,b) have adopted for the first time a new approach to examine the seismo- active effects on subionospheric VLF transmitter signals. They, in fact, introduced the concept of “termination times” which are defined as the times of sunrise and sunset when the phase (or amplitude) of the received signal exhibit a characteristic minimum. They applied this new approach to the propagation of Omega (10.3 kHz) signals radiated from Tsushima and observed at Inubo ground stations about 1000 km apart in Japan which was influenced by a severe earthquake of magnitude $M=7.2$ that occurred at Hyogo-ken Nanbu (popularly known as 17 January, 1995 Kobe earthquake) about 70 km from the VLF great circle path. It was found that the termination times (hereafter TT) showed an anomalous time shift (late for evening TT and early for morning TT) 2 – 3 days before the occurrence of the earthquake. They interpreted the result in terms of lowering of the ionospheric reflection height by about 0.7 km possibly caused by either radon emissions or the concentration of gravity waves during the earthquake process. Since then, the termination times are usually taken as a physical quantity which may provide useful information on long term atmospheric changes in case of rather short VLF path.

The VLF data corresponding to Kobe earthquake was processed in greater detail using the TT method by Molchanov et al. (1998) who have shown that the results obtained by Hayakawa et al.(1996a,b) are statistically significant also and the reflection height could be decreased by about 2 km. Molchanov and Hayakawa (1998) have examined the seismo-ionospheric effect on VLF propagation in case of 10 other great earthquakes ($M>6$) in order to provide a sound footing to this technique. They have plotted the TT differences in phase and amplitude during the ± 45 days span around the earthquakes and found transient oscillations with periodicity in the range of 5-10 days, which started a few weeks before a large earthquake and decayed a few weeks after (Molchanov et al., 1998, Molchanov and Hayakawa, 1998). It is mainly related to crustal earthquakes. It is suggested that the transient oscillations in TT differences could be due to intensification of planetary atmospheric waves with period about 10 days. This suggestion was made in the light of reports that these waves could penetrate the lower ionosphere and have characteristic periods in the range of 2,5,10 or 16 days (Pancheva et al., 1991, Yi and Chen, 1993)

The results of Japanese group based on TT method of analysis mentioned above were criticized by Rodger et al. (1999) and Clilverd et al. (1999) on the ground that in a realistic propagation model the observed changes in TT would require the ionospheric height to be lowered much more by 4 – 11 km which can be brought out only under solar flare conditions. Further, in the propagation model employed by them they have found that in the anomalous cases, the time of the sunrise minimum (morning time TT) does not change significantly, but rather, becomes insufficiently deep to be detected, and the time of the next nearest minimum is logged so that any successful earthquake prediction based on TT method cannot be distinguished from that of chance. However, their arguments have been questioned by Soloviev et al. (2003) on the ground that they employed a very crude model and examined TT changes

on a long (12 Mm) propagation path. It is suggested that the perturbed area by earthquake precursor in the ionosphere is very small as compared with the scale of this path length, and hence it is impossible to expect its appreciable influence on the signal phase and/or amplitude on a long VLF path.

In this paper, we present the preliminary results of the analysis of nighttime amplitude data of 19.8 kHz NWC signals transmitted from a fixed frequency VLF transmitter in Australia (lat. $21^{\circ}49'S$, long. $114^{\circ}9'50''E$) and received at Bichpuri, Agra (lat. $27^{\circ}12'N$, long. $78^{\circ}E$) in India for the period of nine months between August, 2002 and April, 2003 and show that the average nighttime amplitude is decreased occasionally under the influence of even moderate earthquakes along the VLF propagation path.

2. Experimental setup

We have employed AbsPAL (Absolute Phase and Amplitude Logger) receiver obtained from LF*EM Research Ltd, New Zealand (R.L. Dowden, Personal Communication, 2001) to monitor the amplitude and phase of 19.8 kHz VLF signals transmitted from NWC, Australia. The equipment includes GPS antenna, VLF amplifier, service unit, DSP card, and necessary software. We use 1-min average amplitude data in our study. The locations of the transmitter, receiver, and great circle path (propagation path=6735 km) are shown in Fig.1. The regular monitoring of phase and amplitude variation of the aforesaid signal has been started since 1 August, 2002 at Bichpuri, a rural area located at about 12 km west of Agra city where local electric and electromagnetic disturbances are low.

3. Results and discussion

We have analyzed the nighttime amplitude data (2200h – 0400h LT, LT = UT + 5.50 h) for the period of nine months between August, 2002 and April, 2003. The purpose for choosing night time data will be explained later. We have averaged the nighttime data corresponding to above period using MATLAB software and examined the variation in day to day data cautiously. We have found that on six occasions over the whole period of analysis the amplitudes showed decreases in the range of 1 – 10 dB from their average daily variations. These identified days of decreased amplitudes are 27 August, 17 September, 10 December in the year 2002, and 22 January, 16 February, and 5 April in the year 2003. The variation of nighttime amplitudes on these specific days (raw data) are shown in six panels of Fig.2 which are named case 1 to case 6 depending upon the order of their occurrence. The start and end times of observations in UT are mentioned on the top of each panel. The ordinate in each panel shows amplitude in dB and abscissa shows the number of data length for which time may be calculated using the start and end times. For example the time between any two ticks at the abscissa of the top panel is calculated to be about 169 min.

In Figs. 3a, b we show the variation of nighttime daily averages of the amplitudes from 3 days before to 3 days after the decreases for the six cases mentioned above. The non-availability of data on some days is indicated by dashed lines. In cases 2 and 3 the data have been considered

Fig.1 The map showing the locations of fixed frequency VLF transmitter at NWC, Australia and observing station, Agra, India. The open circles indicate the epicenters of earthquakes that occurred near the propagation path

Table 1. The details of the earthquakes considered in this study

Date	Time	Location	Magnitude	Depth (Km)
26.08.02	145513.94	Lat. -6.75, Long. 105.71	5.8	62
18.09.02	120136.31	Lat. 13.11, Long. 93.17	5.5	33
10.12.02	024446.68	Lat. 5.25, Long. 94.46	4.6	67
23.01.03	035840.23	Lat. 7.59, Long. 93.72	4.2	19
16.02.03	222749.86	Lat. -5.73, Long. 102.02	4.4	17
03.04.03	234824.43	Lat. 20.67, Long. 103.22	4.6	10

Fig.2 The un-averaged amplitude records corresponding to six days of lowest nighttime amplitudes observed during the 9- months observation period . The start and end times in UT are mentioned on the top of each record. The ordinate is in dB and abscissa is in number of data length which can be converted in time using the start and end times(see text for details)

Fig.3a Variation of average nighttime amplitude from 3 days before to 3 days after the day of amplitude decrease. The dashed lines indicate the non-availability of data. The corresponding ΣKp variation is also shown. Downward arrows indicate the days of occurrence of moderate earthquakes near the propagation path

Fig.3b The same as Fig.3a but for three other months

five days before the decreases to reduce the gaps in the data. Unfortunately this could not be done in case 1 because of non-availability of such data. Also shown in these figures are the variation of ΣKp along with the amplitude variations for each case so as to examine the possible effect of magnetic storms on the amplitude variation. The downward arrows in each panel of the amplitude variation show the days of occurrence of earthquakes close to the VLF propagation path. The magnitudes of the earthquakes are indicated near the arrows also. In the followings, we discuss the various possibilities under which the amplitude decreases could occur.

From a glance at Figs.3a and 3b it may be seen that the amplitude variations show decreases on some days which range between 1 and 10 dB. The days over which the data are shown in these figures are magnetically quiet as the ΣKp does not exceed 30 in any case. Hence, the possibility of the decreases in the amplitudes as a result of solar flare is ruled out. The amplitude decreases due to energetic particle precipitation (Energy > 1 MeV) is not possible also because Agra corresponds to $L=1.1$ which lies below the bottom of the Van Allen inner radiation belt ($L=1.2$) where electron losses are dominated by atmospheric scattering resulting in the small life time and density of the energetic electrons (Imhof and Smith, 1966, Imhof et al., 1973). Further, out of the six cases cited in the figures the first two cases correspond to the months of rainy season in northern India where Agra is located, whereas the next four cases correspond to the months in which lightning activities exit in the conjugate area in the opposite hemisphere which lies in the Indian ocean. This raises a possibility that the electric fields generated from the lightning activities may penetrate through the ionospheric region and the E-layer is pulled down under $E \times B$ drift which may reduce the amplitude of the VLF signal. However, this possibility is ruled out also due to the fact that large electric fields ($\sim 10^5$ V/m) generated during lightning near the ground are attenuated so much in the atmosphere that they are about 1 mV/m only in the lower ionosphere. The top of the Agra field line at the equator is at the height of 635 km above the F-region peak. The electric field of such a small magnitude may possibly affect the F-region locally but not the E region ionosphere.

Then, the only possibility left is that the amplitudes are decreased under the influence of seismic activities that occurred along the propagation path. The most probable earthquakes are already indicated in the figures. The details of these earthquakes are presented in Table 1 and their locations are shown by open circles in the map of Fig. 1 also. These earthquakes are considered because of their locations close to the propagation path, shallow depth of occurrence, and magnitude greater than 4. It may be mentioned here that in addition to these moderate earthquakes, a large magnitude shallow depth earthquake ($M=6.7$, 21 km) did occur close to the propagation path on 13 September, 2002 corresponding to which reduction in the amplitude was noticed. However, we are not able to show this case here because data corresponding to 3 days before and 3 days after are not available. In order to substantiate our result that the decreases are caused by these earthquakes, we have carried out statistical analysis of the data the results of which is presented in Fig. 4. In fact, we have determined the mean (m) and standard deviation (σ) for the data corresponding to three groups of months divided over

the whole period of nine months of observations. These three groups of months are (August, September, October), (November, December, January), and (February, March, April). The months are divided in three groups due to the reason that there is a large seasonal variation in the amplitude of the VLF signal. This may be verified from Figs.3a and 3b. It can be seen that while the range of amplitudes varies between 40 and 55 dB in the three months of Fig.3a, the same varies between 58 and 65 dB in the three months of Fig.3b. Therefore the statistical analysis is done for the three groups of months separately. The mean and standard deviation are shown by three horizontal lines corresponding to m and $m \pm \sigma$ in each panel. We have also shown the variation of ΣKp during the three groups of months separately below each panel corresponding to the amplitude variation. The amplitude data is shown by curves in each panel. The breakages in the data curves indicate non-availability of the data. The same earthquakes of Table 1 are shown here again by downward arrows. Fig.4 shows decrease in the amplitudes below the $m - \sigma$ line in almost all cases except in two which are the fourth case of 22 January and fifth case of 16 February, 2003. The case of 22 January is special in the sense that the decrease does occur in this case but above the $m + \sigma$ line. This is due to the reason that the range of amplitude in this month is the highest of all (64 –65 dB) whereas the range of amplitudes in the two months included in this group (November and December) is the lowest of all (40 –55 dB) and hence most part of the curves showing amplitude variations in January are above the standard deviation line. In the other case of 16 February the decrease itself is just 1 dB and hence it lies within the standard domain. The two cases of 41th day in the top panel and 54th day of the bottom panel in which the amplitudes are much above the $m + \sigma$ line (in the latter case below $m - \sigma$ line also) are possibly due to storm effect because the ΣKp is between 35 and 40 a few days before the enhancement in amplitudes. Hence, our findings that the occasional decreases in the amplitude of the signal are due to moderate earthquakes are supported by the results in this figure in general.

The result in Fig. 4 may be questioned on the ground that there are so many data gaps in the first two panels so that the period good for analysis is only February – April 2003 during which the VLF anomaly associated with the last earthquake does appear to be convincing. In order to answer this we may mention here that the results presented in the top two panels correspond to the period of initial observations at Agra when the continuity of the observations was hampered due to several reasons which included power failures, system failures, and unfixed schedule of observations etc. However, whatever data are available the preliminary results do reflect the association of VLF anomalies with moderate earthquakes.

From Figs.3a and 3b it is further seen that the amplitude decrease is maximum between 5 – 10 dB in the months of April to December and minimum of 1-2 dB in the months of January and February. Further, out of six cases found, the decreases occurred one day before the occurrence of the earthquakes in two cases and in rest of the cases they occurred either on the same days of earthquakes or after the earthquakes. Although, there is apparently no correlation existing between the magnitude and depth of earthquakes, magnitude of amplitude decreases and number of days of amplitudes decreases in the existing data, the results show that shallow

Fig. 4. The figure shows statistical analysis of the data for three groups of months mentioned on the top of each panel. The 3- horizontal lines show the mean and standard deviations and the solid curves between them is the variation of averaged amplitude data. Breakages in the curves show non-availability of the data. The ΣKp variation is shown for each group of months in separate panels.

earthquakes occurring close to the propagation path may probably influence the propagation characteristics of the signals profoundly.

Using a long wave propagation capability code (LWPC), Clilverd et al. (1999) have modeled the nighttime propagation conditions along a 24 kHz NAA signal path between the transmitter location at Cutler, Maine and observation site at Faraday, Antarctica. They have found a gradual decrease in the amplitude with distance. They have also found regions where the amplitude is significantly reduced. They have explained these amplitude reductions in terms of interference in different propagation modes. However, the amplitude reductions in our case may not be attributed to interference between different modes because we have found such anomalous cases only on six occasions over a period of nine months instead of observing them on a regular basis.

Our results that the amplitude decreases in 19.8 kHz signal propagation are associated with moderate earthquakes occurring along the propagation path may be questioned on the grounds that the data is very limited and much more examples are required than the events presented here to support the conclusion on statistical basis. Further, the analysis deals with the propagation loss in the night where there may be a few propagation modes which may lead to unstable intensity. To avoid this situation one is required to study the daytime data instead of nighttime data. In order to answer the first we may mention that the data considered here correspond to nine months of observation only and the results are preliminary. However, our future report will be based on much longer data set and rigorous statistical analysis in which the results are expected to be even more convincing. To answer the second question we may mention here that the nighttime data have been considered following the work of Gokhberg et al. (1989) who have shown that the amplitudes of Omega transmitter signals (10-13 kHz) were influenced by moderate earthquakes ($M > 4$) in 250 out of 350 cases. These earthquakes occurred at epicenters as far as 700 km away from the great circle path and the disturbances could occur 1-5 days before the earthquakes. The 90% of these cases corresponded to nighttime propagation. The nighttime is chosen also to avoid the sudden ionospheric disturbances produced by solar X-rays. It is true that the daytime propagation analysis may yield better results and hence we have planned to make such studies in future.

Although it is difficult at the moment to suggest the most plausible mechanism involved in the amplitude decrease of the VLF signals observed by us, two possibilities have been suggested by earlier workers while explaining the amplitude and phase decreases observed by TT method (Hayakawa et al., 1996a,b, Molchanov et al., 1998, Molchanov and Hayakawa, 1998). The first possibility is that the radon gas emanated from the seismic regions propagated upward and created inhomogeneity in the electron density at the base of the ionosphere in the form of localized enhancement. The observation of intensified radioactive gas emanations before the earthquakes have already been reported by many workers (King, 1989, Yamauchi, 1992). This possibility is supported by the observation of a clear change in the characteristics of VLF transmitter signals during accidents at large nuclear stations (Martynenko et al., 1996). The other possibility could be the generation of long period gravity waves during the

earthquake process and their intensification at the base of the ionosphere. This possibility has been discussed by Molchanov and Hayakawa (1998) in great detail in order to explain the 5 – 10 days periodicity observed in the TT difference characteristics. They have found that such TT characteristics may appear only when resonant atmospheric oscillations with periods in the range of 5 – 10 days exist before the earthquakes. Later Molchanov et al. (2001) have suggested the higher frequency atmospheric gravity wave as the carrier (with planetary wave as a modulating signal (in amplitude modulation)).

In addition to the above, there is another possibility in which the ionosphere perturbation is caused by seismic activities. This is related to the electric fields generated from the seismic source which may penetrate the lower ionosphere and bring down the layer by a few kilometer so that the phase and amplitude of the subionospheric VLF signals are influenced. Detailed descriptions of several of the mechanisms by which electromagnetic emission can be produced by the earthquakes are available in the literature. However, two main mechanisms are invoked. The first concerns the direct wave production from sources undergoing piezoelectric or turboelectric effect of rock pressure, electrokinetic or magnetokinetic effect due to the diffusion of water through rock pores, and fracture of rock near the focal point (Nitsan, 1977, Warwick et al., 1982, Ogawa et al., 1985, Cress et al., 1987), whereas the second is related to a redistribution of the electric charges in the Earth's atmospheric system which produces electric charges (Gokhberg et al., 1984, Schloessien, 1985). The electric fields generated from seismic sources have been observed in the ionosphere and magnetosphere (Parrot and Mogilevsky, 1989) and their penetration to such heights has been supported theoretically also (Molchanov et al., 1995).

The question of whether the subionospheric perturbation on VLF propagation is due to additional ionization created in the lower ionosphere or due to lowering of the layer by a few kilometer is not yet fully answered, and intensive research work is needed to study this problem .

4. Conclusion

The amplitude variations in 19.8 kHz VLF signals transmitted from NWC, Australia have been monitored at Agra, India since 01 August, 2002 and nine months data up to April, 2003 have been analyzed. The results show that the amplitudes are decreased occasionally from their average nighttime variations. The causes for the decreases are examined in the light of magnetic storms and seismic activities and it is found that the decreases are associated mostly with moderate earthquakes that occurred along the VLF propagation path. Out of the six cases found over the whole data period, the decreases occurred in two cases one day before the occurrence of earthquakes, and in rest of the cases they occurred either on the same day or after the occurrence of earthquakes. Maximum amplitude decrease between 5 – 10 dB occurred in summer time and minimum of 1 – 2 dB in winter time. Apparently no correlation is found between the magnitude and depth of earthquakes and amplitude decrease and days of their occurrence from the existing limited data, but over all results show that moderate and shallow

depth earthquakes occurring close to the propagation path may be responsible to such an amplitude decrease. Further, the results support the findings of Gokhberg *et al.* (1989) and emphasize the need of extensive work in this area. The cause of amplitude decrease is not very clear but the possible mechanisms are discussed in terms of electromagnetic phenomena occurring in the Earth's crust and their effect on lower ionosphere, radon emanations from seismic regions creating inhomogeneity at the base of the ionosphere, and long period gravity waves generated during earthquakes.

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