Available online at www.sciencedirect.com

Physics and Chemistry of the Earth 31 (2006) 416–421

www.elsevier.com/locate/pce

Day–night, seismic, and solar flare effect on the propagation of 24 kHz sub-ionospheric VLF transmitter signals

Manoj Kumar [a], Vikram Singh [a], Birbal Singh [b,*], P. Steinbach [b], J. Lichtenberger [b], D. Hamar [b]

[a] *Department of Physics, R.B.S. College, Bichpuri, Agra, India*

[b] *Space Research Group, Department of Geophysics, Eotvos University, Pf32H-1518, Budapest, Hungary*

Accepted 6 February 2006

Abstract

The preliminary results of a collaborative study on the amplitude variation of 24 kHz sub-ionospheric NAA VLF transmitter signals transmitted from Cutler, Maine (Lat. 44.6°N, Long. 67.2°W) and monitored simultaneously at Budapest (Lat. 47.5°N, Long. 19.17°E), Hungary and Agra (Lat. 27.2°N, Long. 78°E), India are presented. The time segments of the propagation paths are so chosen that they lie in the post-midnight hours over Budapest and sunrise hours over Agra. The results show that the amplitude at Budapest decreases after midnight hours by about 3 dB whereas the same at Agra increases by 5 dB during sunrise normally. The anomalous enhancements and reductions in the amplitude variation during the three month period of July–September 2002 along Cutler–Agra great circle path (GCP) are examined in the light of seismic, solar flares, and magnetic storm effects. It is found that the occasional amplitude reductions are caused by earthquakes ($M > 5$) which occurred along the GCP, and the enhancements are caused by solar flares. The magnetic storms do not seem to influence the data except in the case when associated with large solar flares.

Keywords: VLF transmitter signal; Amplitude; Earthquake; Solar flare

1. Introduction

The lower ionosphere undergoes significant localized structural changes as a result of some naturally occurring geophysical phenomena such as precipitation of energetic particles due to wave particle interaction in the upper atmosphere, earthquakes, and solar flares. The lightning-induced particle precipitation, popularly known as Trimpi effect, was detected as early as in 1973 (Helliwell et al., 1973) as short period localized enhancement of ionization in the D region of the ionosphere. The enhancement in ionization has also been found during the periods of earthquakes (Hayakawa and Sato, 1994) and solar flares (Deshpande and Mitra, 1972). An effective technique to study the ionospheric modification caused by these events is to monitor the phase and amplitude of fixed frequency VLF transmitter signals which are propagated to long distances through earth–ionosphere waveguide. Studies have shown that the ionospheric reflection height is reduced by 0.1–1 km during Trimpi effect (Inan et al., 1985), 0.7–2 km during the period of large earthquakes (Hayakawa et al., 1996; Molchanov and Hayakawa, 1998) and 4–11 km during large solar flares (Deshpande and Mitra, 1972; Rodger et al., 1999). This technique has also been found to be very useful in studying the variations in lower ionosphere during changes in solar zenith angle (Thomson, 1993) and red sprites (Hardman et al., 1998). Recently, Clilverd et al. (1999) and Thomson and Clilverd (2000) have studied the sunrise effect and solar cycle changes in daytime VLF attenuation, respectively.

---

[*] Corresponding author. Present address: Department of Electronics and Communication Engineering, Faculty of Engineering and Technology, R.B.S. College, Bichpuri, Agra 283105. Tel.: +91 941237079; fax: +91 562 215 1288.

E-mail address: birbal@sancharnet.in (B. Singh).

1474-7065/$ - see front matter © 2006 Published by Elsevier Ltd.
doi:10.1016/j.pce.2006.02.044

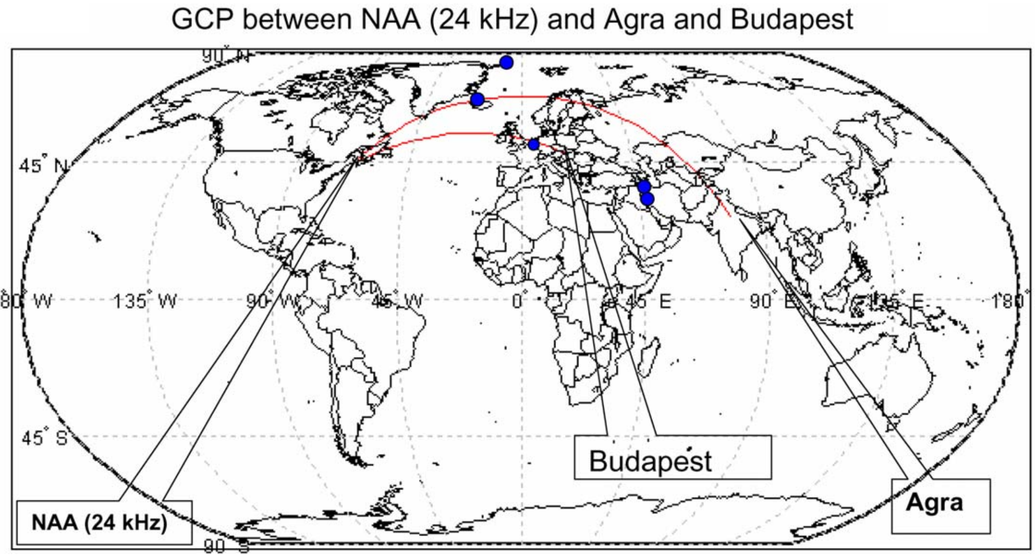

Fig. 1. Great circle path (GCP) between NAA transmitter (Cutler, Maine) and Budapest and Agra. Solid circles indicate the locations of earthquakes which influenced the amplitude of the signal.

The phase and amplitude perturbation of VLF transmitter signals as a result of earthquake-induced structural changes in the lower ionosphere have been studied in rather great detail by a number of research workers (Gokhberg et al., 1989; Gufeld et al., 1994; Hayakawa and Sato, 1994) even though there were negative reports of such perturbations also (Michael, 1996). Hayakawa and Sato (1994) have observed the ionospheric perturbations associated with a number of earthquakes. They have found that the daily mean amplitude of Omega VLF transmitter signal crossed 2δ limit (δ is the standard deviation in amplitude) before the occurrence of these earthquakes. Morgounov et al. (1994) have found anomalous variation of VLF signals associated with large magnitude earthquakes. Recently, a new concept of "Termination times" has been proposed by Hayakawa et al. (1996) to study the seismic effect on lower ionosphere. The termination times are defined as the times of sunrise and sunset when the phase (or amplitude) of received signal exhibits a characteristic minimum. Hayakawa et al. (1996) applied this approach to Hyogo-ken Nanbu earthquake and found abnormal behavior around sunrise and sunset a few days before the occurrence of main shock. Soloviev et al. (2004) have suggested that this technique is effective for shorter propagation paths only.

The VLF research group at Budapest (Lat 47.5°N, Long. 19.17°E), Hungary has been monitoring the phase and amplitude of NAA signals ($f = 24$ kHz) transmitted from Cutler, Maine for almost a decade. Recently, the VLF group at Agra (Lat. 27.2°N, Long. 78.0°E), India has also started monitoring the same frequency since October 2001. On account of geographical locations of the two stations which may lie in night and day hours simultaneously, it is worthwhile to compare the amplitude variation of the NAA signal over the two stations. In the present paper, we report the results of a preliminary collaborative study in which we have compared the amplitudes of the signal monitored simultaneously during post-midnight hours at Budapest and sunrise hours at Agra. We also identify the seismic and solar flare effects on the amplitude of the signal along the Cutler–Agra propagation path where we find that the average amplitude is reduced as a result of moderate earthquakes ($M > 5$) along the propagation path and enhanced substantially as a result of solar flare.

2. Experimental setup

We have employed AbsPAL (Absolute phase and amplitude data logger) receiver to monitor the phase and amplitude of sub-ionospheric VLF signals at three frequencies i.e. 19.8 kHz (NWC, Australia), 21.4 kHz (NPM, Hawaii), and 24 kHz (NAA, Cutler, Maine). The system consists of VLF antenna, amplifier, service unit, DSP card, and necessary software. This system is superior over Omnipal receiver because of the facility of phase locking with GPS which increases the stability and accuracy in phase and amplitude measurement. An Omnipal based measuring network has been set up in Hungary which can log six different transmitter frequencies and monitor the phase and amplitude variation caused by natural events mentioned in the previous section. This system has been set up and operated in collaboration with ELGI geophysical Institute Budapest. The details of Omnipal receiver may be seen in Dowden et al. (1994) and Dowden and Adams (1988). The great circle paths (GCP) between the transmitting and receiving stations are shown in the map of Fig. 1. The GCP lengths are 11280 km and 6311 km for Agra and Budapest, respectively.

3. Results and discussion

We have been carrying out phase and amplitude measurements at the three frequencies mentioned above since 9 October 2001. Initially, as a test case, the observations were taken for limited periods of two and half hours each in the morning, midday, and evening hours i.e. 0530–0800, 1130–0200, and 0430–0700 h Local Time (LT) which correspond to 1200–0300, 0600–0830, and 1100–1330 h Universal Time (UT), respectively (LT = UT + 5.5 h) upto 31 July 2002 and then the observation period was increased to 22 hours from 1400 h to 1200 h LT. Here, we first report the results of a preliminary study on amplitude variations of NAA signals monitored both at Budapest and Agra stations simultaneously where the propagation paths lie in post-midnight and sunrise hours, respectively. Then we study the occasional reductions and enhancements in the average amplitude along the Cutler–Agra path and propose suitable explanations. The studies related to phase measurements at both stations require examination of more data and hence the results related to phase variations will be reported later.

3.1. Day–night effect

For studying the day–night effect on the amplitude variation of NAA signals, we consider the month of November, 2001 at both the stations because Budapest data are available for this month only. The Budapest data correspond to a period of about 9 h each day between 2000 and 0500 h LT (LT = UT + 1 h). On account of geographical locations the sunrise hours at Agra station correspond to after-midnight hours at Budapest station. Therefore, the signal is propagated during post-midnight hours over Budapest and at the same time during sunrise hours at Agra station. This provides an unique opportunity to study the day–night amplitude and phase variations along the propagation path between the source and receiving station.

For the data analysis, we have block averaged the data with block size of 60 (1 min) with sampling rate of 1 sample per second. In Fig. 2, we show an example of the amplitude variation at the two stations using the data of 3 November, 2001. This example is chosen specifically for the reason that it corresponded to a magnetically quiet day ($\sum K_{\mathrm{p}} = 5$). The amplitude variation is shown for a period of 3 hours between 0000 and 0300 h UT, which corresponds to after-midnight and sunrise hours at Budapest and Agra stations, respectively. Here, it may be seen that the amplitude over Budapest falls rapidly from 49 to 46 dB in the post-midnight hours, whereas the same at Agra increases rapidly from 45.5 to 51.5 dB after 0100 h UT. The amplitude reduction at Budapest may be interpreted due to diminishing electron density in the lower ionosphere after midnight hours where the enhancement in amplitude at Agra may be due to increasing electron density during sunrise hours. The amplitude fluctuations in the later case may be interpreted as due to the same effect. We have analysed the amplitude data on other days also which correspond to magnetically quite days and find on the average 3 dB reduction in amplitude at Budapest and 5 dB enhancement at Agra. The amplitude of the signals at Agra is smaller than that of Budapest for the night-time propagation in general. However, the amplitude tends to increase at Agra, as soon as the path lies in the sunrise hours as seen in Fig. 2.

3.2. Seismic and solar flare effect

In Fig. 3 we study the amplitude variations of NAA signals for a longer period of three months between July and September 2002. The study is made along the Cutler–Agra great circle path only because of non-availability of long period data from Budapest station. Since the data correspond to 0000–0300 h LT, the termination time technique is not adopted here for two reasons; firstly because the data do not correspond to sunset and sunrise hours, and secondly because it is good for shorter propagation path (~1000 km), whereas Cutler–Agra great circle path is 11,218 km as mentioned earlier. Here, we analyze the data by taking the block average of 60 samples (1 data point) and running mean of the 3 data points so as to make the

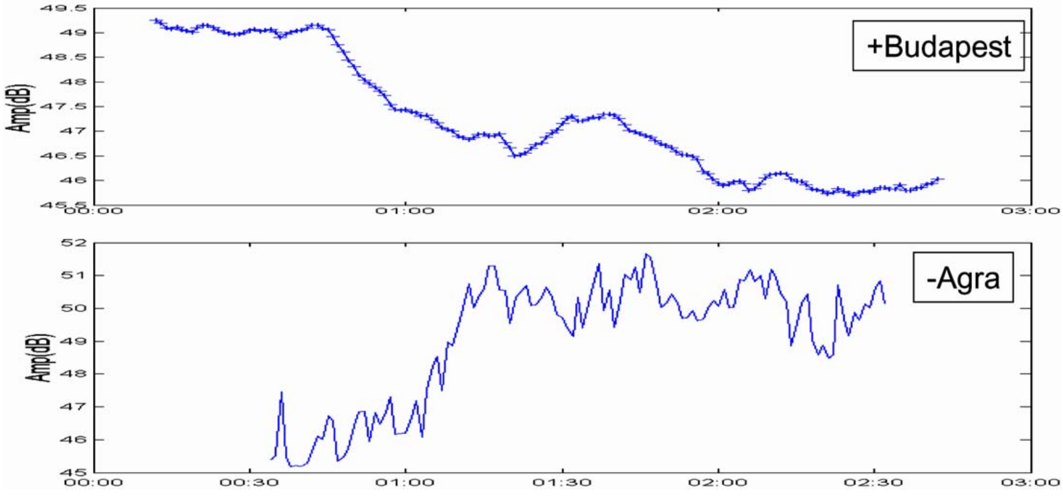

Fig. 2. Amplitude variation over Budapest (top) and Agra (bottom).

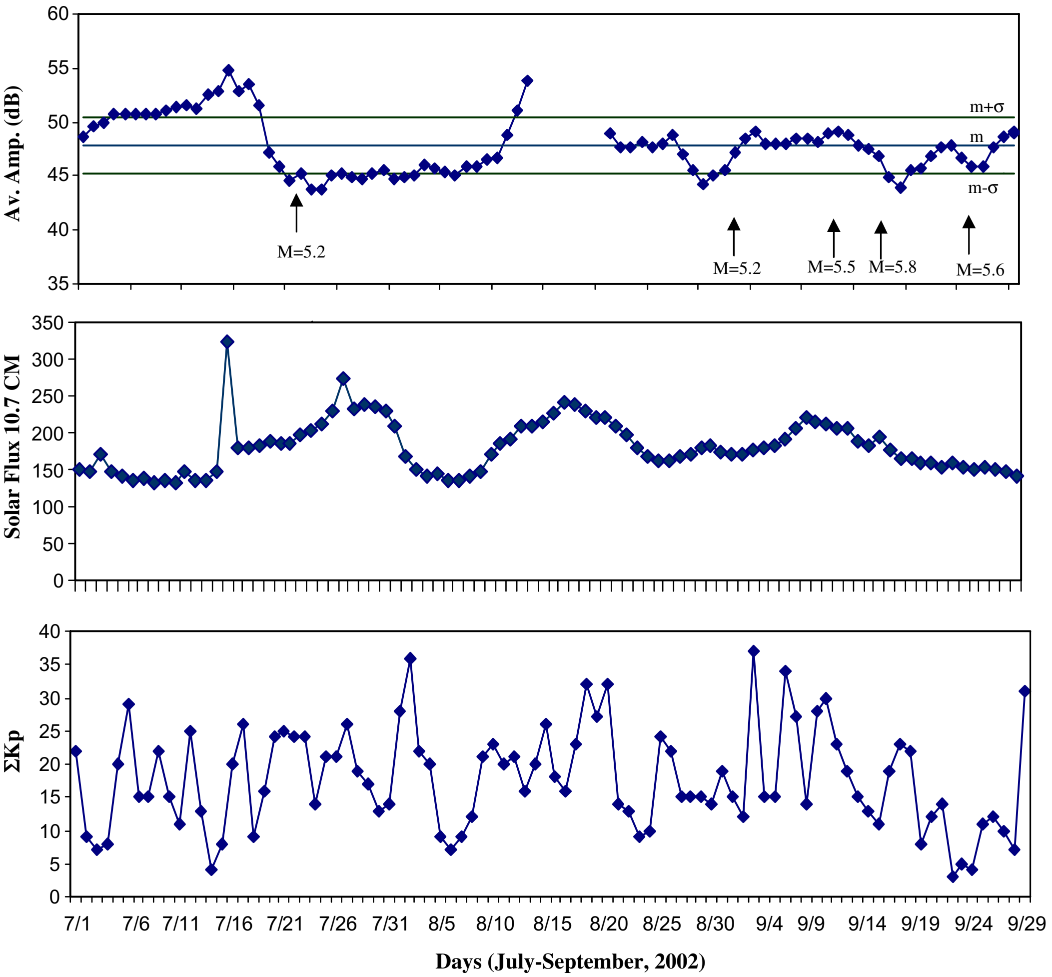

Fig. 3. (Top) Average amplitude variation during July–September, 2002. The three parallel lines indicate the mean (m) and $m \pm \sigma$ (σ is the standard deviation) determined from three months of data. (Middle) The variation of solar 10.7 cm flux during the months of August and September, 2002. (Bottom) $\sum K_p$ variation during the three month period.

data smoothly varying and free from large and abrupt variations caused by sudden ionospheric disturbances. As it may be seen from the top panel of Fig. 3, there are large occasional variations in the amplitude of the signal over the period under consideration. In order to isolate the abnormal changes, we have employed statistical analysis of the data using mean (m) and standard deviation (σ) technique. The three solid parallel lines in this panel correspond to $m + \sigma$, m and $m - \sigma$. We find that the amplitude of the signal is enhanced beyond $m + \sigma$ line on two occasions i.e. on 15 July and 15 August (peak maxima are not known because of non-availability of data) whereas it is reduced below $m - \sigma$ on three occasions i.e. 23 July, 30 August and 18 September. There is another minor reduction on 25 September but the amplitude does not cross the $m - \sigma$ boundary.

In order to find suitable explanations for these occasional enhancements and reductions in the amplitude variation, we study earthquake, solar flares, and magnetic storm (K_p-index) data during the period under consideration. The earthquake data is examined under certain criteria which are large magnitude ($M > 5$), small depth ($D < 20$ km), and distance from GCP not grater than 2500 km. The criteria of the distance is consistent with Morgounov et al. (1994) who have shown that even distant earthquakes from GCP can influence the observations. The earthquake data have been taken from United States Geological Survey (USGS, website; http://neic.usgs.gov) and in Table 1 we present a list of such earthquakes between July and September 2002 which have satisfied the above criteria. These earthquakes have been shown by upward arrows in the panel and also by solid circles in Fig. 1. An interesting result which may be seen here is that these earthquakes occurred within ±2 days of the observed minima in amplitudes except in one case of 11 September where the minima is not observed, though the earthquake occurred at a relatively smaller distance from the other earthquakes. One possible reason for this may be that the earthquake occurred under the sea. The association of earthquakes with observed minima in rest of the cases indicates the possibility that the amplitude reductions are caused by these earthquakes.

Table 1
List of major earthquakes during July–September 2002 and their distances from GCP between Agra and NAA transmitter

Date	Location		Magnitude	Depth (km)	Distance from GCP (km)
	Latitude	Longitude			
22/07/2002	50.89	6.10	5.20	17	2013
02/09/2002	35.70	48.84	5.20	10	2161
11/09/2002	83.14	−6.08	5.50	10	1575
16/09/2002	66.94	−18.46	5.80	10	61.7
25/09/2002	32.00	49.33	5.60	10	2470

In order to explain the large enhancements in amplitude on two occasions, we show the variation of solar 10.7 cm flux in the middle panel of Fig. 3. From this panel it is clearly seen that a strong solar flare occurred between 8 and 26 August coinciding with the large enhancement in the amplitude variation in the top panel. The amplitude enhancement on 15 July may also be explained in terms of transient increase in solar flare occurring on the same day as evident from the solar flare data in the middle panel. The increase in the solar flare activity around 28 July does not seem to influence the amplitude data because of dominant influence of an earthquake occurring prior to that. To study the possibility that the amplitude variation of the signal is not influenced by the magnetic storm, we plot the variation of $\sum K_{\mathrm{p}}$ for the whole period of three months in the bottom panel. Since $\sum K_{\mathrm{p}} > 30$ correspond to magnetic storm, we see from this panel that the magnetic storms occurred on 5 days which are 2 August, 19 August, 21 August, 4 September, and 7 September. The storms of 19 and 21 August correspond very well to the days of solar flares and hence the large enhancement in the amplitude around these days. However, the effect of other storms are not visible on the amplitude data because no significant changes occur in the amplitude variations on these days.

From the above analysis we find that the amplitude reductions on four occasions during the three months of observations are caused by earthquakes of magnitude ($M > 5$) which occurred along the GCP and the anomalous enhancements in the amplitude on two occasion are caused by the solar flares. The amplitude reductions in sub-ionosphere fixed frequency VLF signals under the influence of earthquakes have already been reported by several workers (Hayakawa et al., 1996; Molchanov et al., 1998; Singh et al., 2004). They have interpreted these results in terms of an increase in the density of charged particles assuming an unchanged scale height of the ex-potential altitude conductivity profile. This situation may be brought out either by radon emissions during earthquakes which may create excess of ionization near the boundary of the overhead ionosphere, or due to electric fields associated with internal gravity waves lowering the reflection height by a few kilometers. The enhancement in the density of charged particles in the ionosphere during solar flares and its consequences on sub-ionospheric VLF signals propagation is very well known; hence, this topic is not discussed here.

4. Conclusion

The amplitude of 24 KHz NAA signals propagating along Cutler–Budapest and Cutler–Agra great circle paths are monitored. The time segments are so chosen that the Cutler–Budapest path lies in the night hours and a part of the Cutler–Agra path lies in sunrise hours. It is seen that the amplitude of the signals at Budapest is reduced by 3 dB approximately during post-midnight hours, whereas the same at Agra is increased by 5 dB during sunrise hours. The occasional enhancements and reductions in the amplitude of the signal monitored at Agra station during the period between July and September 2002 are examined in the light of earthquakes occurring along the propagation path, solar flares, and magnetic storms. The results show that the anomalous amplitude reductions are caused by earthquakes ($M > 5$) which occurred within ±2 days of the amplitude minima and the anomalous enhancements are caused by solar flares.

Acknowledgements

The authors are thankful to the Department of Science and Technology, Government of India, New Delhi for providing financial support in the form of a major research project. This work is partially supported by Council of Scientific and Industrial Research (CSIR), New Delhi also under an Emeritus Scientist Scheme for which the two authors (B. Singh and Manoj Kumar) are grateful to CSIR. One of the authors (B. Singh) worked at Eotvos University, Budapest during May/June, 2002 under Indo-Hungarian programme of cooperation in Science and Technology for which he is grateful to DST, New Delhi and Eotvos University, Budapest for providing necessary funds.

References

Clilverd, M.A., Rodger, C.J., Thomson, N.R., 1999. Investigating seismoionospheric effects on a long subionospheric path. J. Geophys. Res. 104, 28171–28179.

Deshpande, S.D., Mitra, A.P., 1972. Ionospheric effects of solar flares IV, electron density profiles deduced from measurements of SCNA's and VLF phase and amplitudes. J. Atmos. Terr. Phys. 34, 255–266.

Dowden, R.L., Adams, C.D.D., 1988. Phase and amplitude perturbations on subionospheric signals explained in terms of echoes from lightning-induced electron precipitation ionization patches. J. Geophys. Res. 93, 11,543.

Dowden, R.L., Adams, C.D.D., Brundell, J., Dowden, P.E., 1994. Rapid onset, rapid decay (RORD), say and amplitude perturbations of VLF subionospheric transmission. J. Atmos. Terr. Phys. 56, 1513–1527.

Gokhberg, M.B., Gufeld, I.L., Rozhnoy, A.A., Marenko, V.F., Yampolsky, V.S., Ponomarev, E.A., 1989. Study of seismic influence on the ionosphere by super long-wave probing of the earth-ionosphere waveguide. Phys. Earth Planet. Inter. 57, 64.

Gufeld, I.L., Gusev, G., Pokhotelov, O., 1994. Is the prediction of earthquake date possible by VLF radio wave monitoring method? In: Hayakawa, M., Fujinawa, Y. (Eds.), Electromagnetic Phenomena

Related to Earthquake Prediction. Terra Sci. Pub. Co., Tokyo, pp. 381–390.

Hardman, S., Rodger, C.J., Dowden, R.L., Brundell, J.B., 1998. Measurements of the VLF scatter pattern of structured plasma of red sprites. IEEE Antennas Propag. Mag. 40, 29–38.

Hayakawa, M., Sato, H., 1994. Ionospheric perturbations associated with earthquakes as detected by subionospheric VLF propagation. In: Hayakawa, M., Fujinawa, Y. (Eds.), Electromagnetic Phenomena Related to Earthquake Prediction. Terra Sci. Pub. Co., Tokyo, pp. 391–398.

Hayakawa, M., Molchanov, O.A., Ondoh, T., Kawai, E., 1996. Anomalies in the subionospheric VLF signals for the 1995 Hyogo-ken Nanbu earthquake. J. Phys. Earth 44, 413–418.

Helliwell, R.A., Katsufrakis, J.P., Trimpi, M.L., 1973. Whistler-induced amplitude perturbation in VLF propagation. J. Geophys. Res. 78, 5515.

Inan, U.S., Carpenter, D.L., Helliwell, R.A., Katsufrakis, J.P., 1985. Sub-Ionospheric VLF/LF phase perturbations produced by lightning-whistler induced particle precipitation. J. Geophys. Res. 90, 7457.

Michael, A.J., 1996. The evaluation of VLF guided waves as possible earthquake precursors. USGS Open-File Report 96–97.

Molchanov, O.A., Hayakawa, M., 1998. Subionospheric VLF signal perturbations possibly related to earthquakes. J. Geophys. Res. 103, 17489–17504.

Molchanov, O.A., Hayakawa, M., Ondoh, T., Kawai, E., 1998. Precursary effects in the subionospheric VLF signals for the Kobe earthquake. Phys. Earth Planet. Inter. 105, 239–248.

Morgounov, V.A., Ondoh, T., Nagai, S., 1994. Anomalous variation of VLF signals associated with strong earthquakes ($M \geqslant 7.0$). In: Hayakawa, M., Fujinawa, Y. (Eds.), Electromagnetic Phenomena Related to Earthquake Prediction. Terra Sci. Pub. Co., Tokyo, pp. 409–428.

Rodger, C.J., Clilverd, M.A., Thomson, N.R., 1999. Modeling of subionospheric VLF signal perturbations associated with earthquakes. Radio Sci. 34, 1177–1185.

Singh, V., Singh, B., Kushwah, V.K., Tomar, M.K., Singh, O.P., 2004. Nighttime amplitude decrease in 19.8 kHz NWC signals observed at Agra possibly caused by moderate seismic activities along the propagation path. J. Atmos. Electr. 24, 1–15.

Soloviev, O.V., Hayakawa, M., Ivanov, V.I., Molchanov, O.A., 2004. Seismo-electromagnetic phenomena in the atmosphere in terms of 3D subionospheric radio wave propagation problem. Phys. Chem. Earth 29, 639–647.

Thomson, N.R., 1993. Experimental daytime VLF ionospheric parameters. J. Atmos. Terr. Phys. 55, 173–184.

Thomson, N.R., Clilverd, M.A., 2000. Solar cycle changes in daytime VLF subionospheric attenuation. J. Atmos. Solar Terr. Phys. 62, 601–608.