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Modeling of sub-ionospheric VLF signal perturbations associated with total solar eclipse, 2009 in Indian subcontinent

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Abstract

During the total solar eclipse of 2009, a week-long campaign was conducted in the Indian sub-continent to study the low-latitude D-region ionosphere using the very low frequency (VLF) signal from the Indian Navy transmitter (call sign: VTX3) operating at 18.2 kHz. It was observed that in several places, the signal amplitude is enhanced while in other places the amplitude is reduced. We simulated the observational results using the well known Long Wavelength Propagation Capability (LWPC) code. As a first order approximation, the ionospheric parameters were assumed to vary according to the degree of solar obscuration on the way to the receivers. This automatically brought in non-uniformity of the ionospheric parameters along the propagation paths. We find that an assumption of 4 km increase of lower ionospheric height for places going through totality in the propagation path simulate the observations very well at Kathmandu and Raiganj. We find an increase of the height parameter by $h' = +3.0$ km for the VTX-Malda path and $h' = +1.8$ km for the VTX-Kolkata path. We also present, as an example, the altitude variation of electron number density throughout the eclipse time at Raiganj.

Keywords: Solar eclipse; D-region ionosphere; VLF waves; Electron density; Modeling VLF signals

1. Introduction

It is well known that a solar eclipse produces disturbances in the ionosphere and provides us with a unique opportunity to verify our theoretical understanding about how the ionosphere reacts to impinging radiation, or, for that matter, withdrawal of it. The present paper is concerned with the modeling of the signatures of the total solar eclipse (TSE) which took place on the 22nd of July 2009 in India. During this time, the Indian Centre for Space Physics (ICSP) conducted a campaign in which data from more than a dozen places in India and Nepal were collected before, during, and after the eclipse. The campaign was even more exciting because of the fact that the nearest transmitter, namely, the Indian navy station VTX (Lat: 8.387 N, Long: 77.753 E) transmitting at 18.2 kHz is located near the southern tip of India almost on the magnetic equatorial plane. This allows the paths in all the bearings within India to be roughly of uniform geophysical condition and no disturbances due to equatorial crossing is expected. Second, the magnetic meridian passing through VTX vertically splits the Indian sub-continent into roughly two halves. In the eastern half, the signal is attenuated in the day time, and in the western half, it is just the opposite (Chakrabarti et al., 2010, 2011, 2012). Thus spreading around receivers in the sub-continent allowed us to study the signals under varied wave propagation conditions in a short path (< 3000 km).

There are several papers in the literature which reported the effects of the solar eclipse over both short and long paths using VLF waves. The first report on the effect of the eclipse was reported exactly half a century ago (Bracewell, 1952). Subsequently, several workers have presented the results of amplitude and phase variations, typically from a single

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observations (Sengupta et al., 1980; Lynn, 1981; Buckmaster and Hansen, 1986; Mendes da Costa et al., 1995). However, very few papers discussed the modeling of VLF signals perturbations associated with a solar eclipse. Clilverd et al. (2001) presented results of the total solar eclipse in Europe on August 11, 1999. They had five receiving sets which observed several stations each and thus had altogether 17 different paths. While their path lengths varied from 90 km to 14,510 km, majority were < 2000 km. The major conclusion of Clilverd et al. (2001) was that, for shorter propagation paths (< 2000 km), the amplitude change was positive, i.e., the signal was enhanced. For path lengths > 10,000 km, the amplitude change was negative. These authors also gave an explanation of the nature of the signals using Long Wavelength Propagation Capability (LWPC) waveguide code (Ferguson, 1998). They found an 8 km rise in h' parameter during eclipse conditions over short paths, while over the medium-length paths, the estimation was a rise of 5 km in h' parameter. A similar result was reported by Fleury et al. (2000), who found an increase of about 5 km in the h' parameter at mid-eclipse. The path lengths were within 1000 km and they used a constant $\beta = 0.5$ parameter throughout the eclipse time while changing h' linearly from daytime to night-time values. They also assumed the disturbance of height to be uniform along the whole radio path.

In this paper, we interpret the signals observed during the 2009 total solar eclipse at several places by modeling the propagation of the VLF waves in the earth-ionosphere waveguide. For this purpose, we selected four propagation paths having quite different bearings. For the simulation purpose, we assume that the ionospheric parameters vary according to the degree of solar obscuration along the propagation path. This naturally brought in a non-uniformity in the ionospheric parameters for different receiver locations.

2. Observed effects of solar eclipse

We use ICSP made VLF antenna/receiver systems to monitor VLF signals. Each set consists of a loop type rectangular antenna and Gyrator II type receiver. The system was controlled by PC with a sound card for real time data acquisition.

In Fig. 1, we show the path of totality during July 22nd, 2009 eclipse. While ICSP obtained data at twelve places (Chakrabarti et al., 2011, 2012), we chose in this paper four representative propagation paths of varying character and noise-free signals for the modeling purpose. The VTX-Kolkata propagation path (1946 km) is very much below the belt of totality, while the VTX-Malda (2151 km) path nearly touches the southern boundary of totality. The

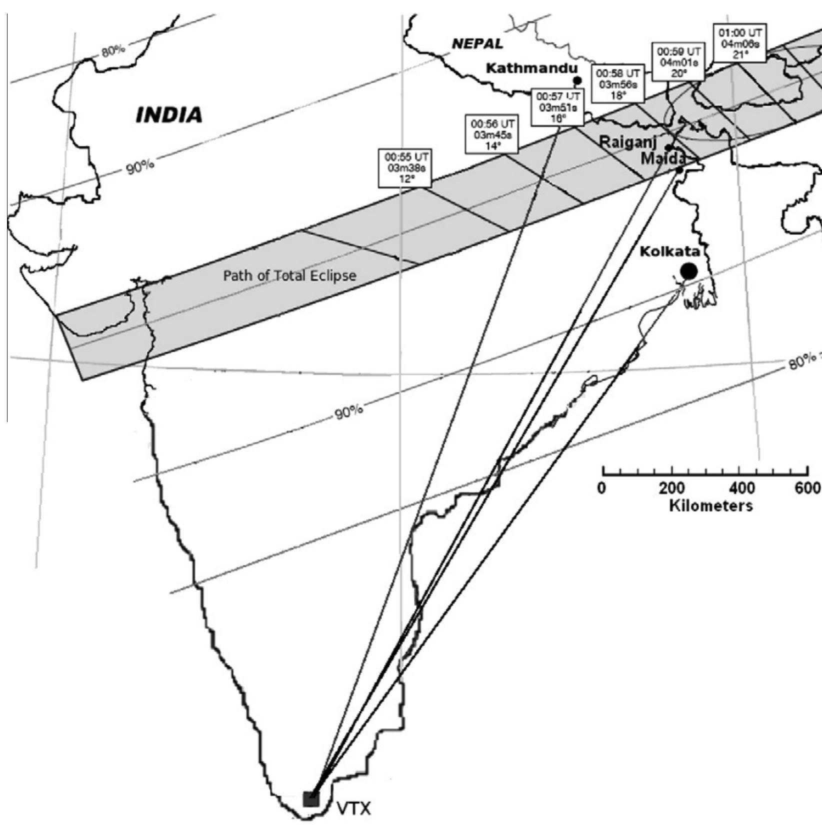

Fig. 1. The propagation paths from the VTX transmitter to four receiving sites showing the path of totality as shaded area over the Indian subcontinent during the total solar eclipse on 22nd July, 2009. The Figure is modified from that provided by Espenak & Anderson in NASA 2009 eclipse bulletin by including our propagation paths.

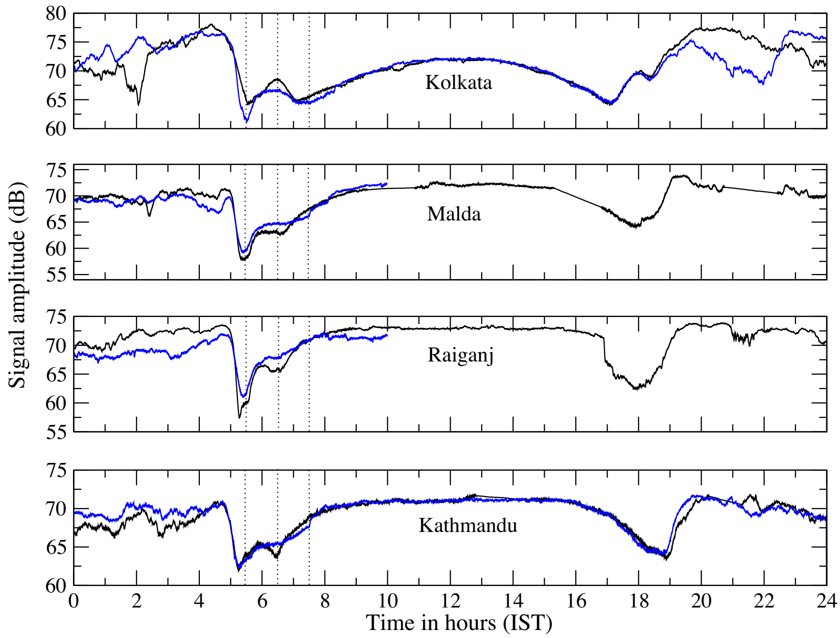

Fig. 2. The diurnal variation of 18.2 kHz VLF signal amplitude for (from top panel to bottom panel) Kolkata, Malda, Raiganj and Kathmandu. Blue curves are the average diurnal variation for normal day and black curves represent the variation on solar eclipse day. Vertical dotted lines represent the times of the first contact of eclipse, the phase of maximum eclipse and the last contact at the receiving places respectively.

VTX-Raiganj (2207 km) path entered the totality belt while the VTX-Kathmandu propagation path (2296 km) actually crossed the path of totality.

In Fig. 2, we present the diurnal variation of 18.2 kHz VLF signal amplitude for places under study in the normal and eclipse days. From top panel to the bottom panel, we present the data for Kolakta, Malda, Raiganj and Kathmandu, respectively. The blue curves are the average diurnal variations for a normal day which are obtained by averaging the data of two days before and two days after the eclipse. The black curves represent the variation on the solar eclipse day. Vertical dotted lines represent the

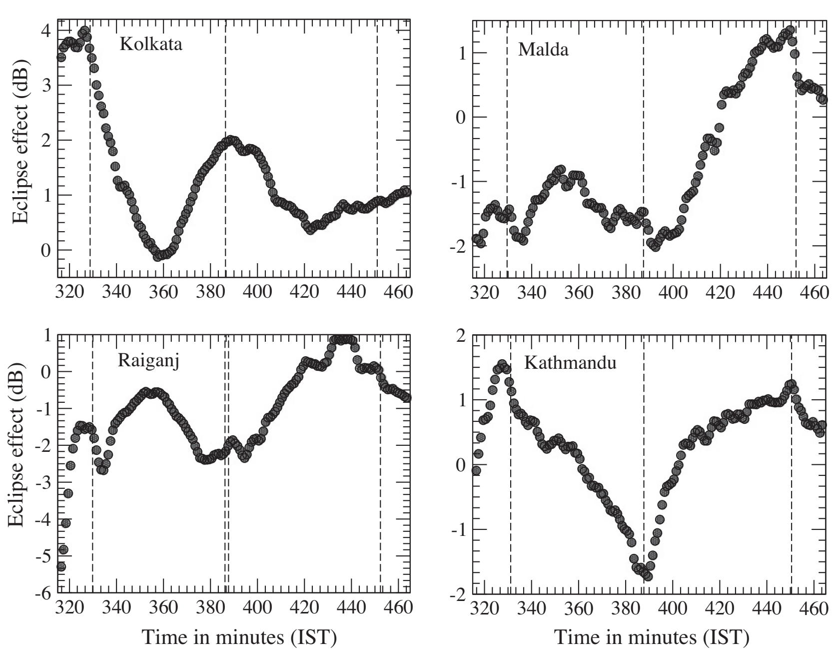

Fig. 3. The variation of the differential amplitude of the VTX signal at four receiving stations during the eclipse time. This variations of amplitude are obtained by subtracting an average unperturbed data from the eclipsed data on 22nd July, 2009. The time is in Indian Standard Time (IST = UT + 5:30). The time of first contact, eclipse maximum (or, second and third contacts, when available), and the last contact are indicated by vertical dashed lines at each receiver.

Table 1
Solar eclipse parameters at different receiving stations.

Place & geog. lat, long	Bearing & dist. (km)	Coverage %	Sunrise	1st (IST) E(°)	Mid (IST) E(°)	2nd (IST) E(°)
Kolkata 22°34′N, 88°24′E	34°37′1946	Partial 89.9	05:04	05:28:46 05	06:26:20 17	07:30:54 32
Malda 25°N, 88°09′E	29°35′2151	Partial 99.6	05:00	05:29:34 05	06:27:24 18	07:32:04 32
Raiganj 25°36′N, 88°08′E	28°36′2207	Total 100	04:59	05:29:52.3 5.6	06:27:43.1 18.1	07:32:22 32.4
Kathmandu 27°45′N, 88°23′E	19°20′2296	Partial 96.3	05:21	05:31:10 04	06:27:43 16	07:30:30 30

times of the first contact of eclipse, maximum phase of the eclipse and last contact at the receiving sites respectively. For Malda and Raiganj stations, the normal day data beyond 10:00 h (IST) are not available due to local power failure. Note that there are no ionospheric disturbances in the signal on the eclipse day due to geomagnetic activities. Indeed, the Kp index for 22nd July, 2009 was 3 between 5:30 IST (0 UT) and 8:30 IST (3 UT). The Dst index was 5, 4 and −5 for 6:30 IST (1 UT), 7:30 IST (2 UT) and 8:30 IST (3 UT) respectively. So the eclipse period was geomagnetically quiet and the observed deviation of the signal amplitude can be safely assumed to be due to the effects of eclipse alone.

In Fig. 3, we show the differential amplitude variations of the VTX signal (18.2 kHz) for the above four propagation paths during eclipse time only. Along the *X*-axis, the time given is in Indian Standard Time (IST = UT + 5:30). These variations of amplitude are obtained by subtracting an unperturbed data (which is obtained by averaging the data of two days before and after the eclipse day) from the eclipsed data on the 22nd July, 2009. In the top left panel, we show the result of VTX-Kolkata path. The eclipse was partial and the maximum obscuration of the solar disk was ~90%. Here, the change in amplitude is positive. The signal is amplified by +2 dB close to the maximum of the eclipse. The top right panel, the bottom-left and bottom-right panels are for VTX-Kathmandu, VTX-Raiganj and VTX-Malda respectively. The signal amplitude was reduced by about 2 dB in all these places.

Table 1 shows the parameters of and at the receiving stations which concern our study. We show the locations with geographic latitude and longitude, bearing angle, distance between the transmitter and the receiver, the percentage of eclipse coverage, the time of the first contact, the time at which the maximum eclipse took place, the last contact and the elevation (E) of the Sun (with respect to the local horizon) in degrees at these times.

3. Modeling procedure

We use the Long Wavelength Propagation Capability (LWPC) code to calculate the amplitudes at receiving sites corresponding to normal and partially eclipsed-ionosphere conditions. LWPC code is a very versatile code and it uses the waveguide mode theory. One has to provide the suitable boundary conditions for the lower and upper waveguides. The lower waveguide parameters i.e., permittivity (ϵ) and conductivity (σ) of the earth have been automatically selected by the code itself. These parameters are constants corresponding to normal and eclipses conditions. The upper waveguide i.e., ionospheric parameters are specified by the electron density $N_e(h)$ and the electron-neutral collision frequency $v_e(h)$ profiles. We use Wait's exponential ionosphere (Wait and Spies, 1964) for the electron density profile with gradient parameter β and reference height h' as given by the equation,

$$N_e(h, h', \beta) = 1.43 \times 10^7 exp(0.15h') exp[(\beta - 0.15)(h - h')],$$

in cm^3. The electron-neutral collision frequency (S^{-1}) is given by the equation,

$$v_e(h) = 1.816 \times 10^{11} exp(-0.15h).$$

These profiles are quite standard and generally agree with directly observed normal D-region ionospheric profiles (Sechrist, 1974; Cummer et al., 1998).

To choose the unperturbed ionospheric profiles for the propagation paths under study, we run the LWPC code at 05:30 AM, 06:30 AM and 07:30 AM (all times in IST = UT + 5:30) respectively and find the amplitudes at each receiver location. Then we look at the average amplitudes observed at that receiver during those times. We take the values $\beta = 0.3\ \mathrm{km}^{-1}$ and $h' = 74.0$ km as appropriate for the VTX-Kathmandu, VTX-Raiganj and VTX-Malda propagation paths as unperturbed ionosphere (Zigman et al., 2007). The parameter set $\beta = 0.3\ \mathrm{km}^{-1}$ and $h' = 74.0$ km does not fit the VTX-Kolkata result very well. For VTX-Kolkata path, matching LWPC data with average observational amplitude of 65.45 dB with respect to 1 μ Vm^{-1} at 6:30 AM (IST) requires $\beta = 0.35\ \mathrm{km}^{-1}$ and $h' = 76.0$ km. These parameters were obtained by assuming a uniform electron density profile throughout the path. We stick to these parameters for an unperturbed ionosphere along VTX-Kolkata path.

To model the partially eclipsed D-region ionosphere we need to calculate the degree of solar obscuration as a function of time along each path. For this, we developed a numerical code to obtain the solar obscuration function $S(t)$ at a particular point along a path using the formalism of Mollmann and Vollmer (2006). The input parameters (i.e., time of starting and ending of eclipse, magnitude of eclipse) for the model are taken from the website of solar eclipse calculator (http://www.chris.obyrne.com/Eclipses/calculator.html) for the solar eclipse of July, 2009. Then we divided each propagation path into several (~ 15) segments along the transmitter to receiver great circle path

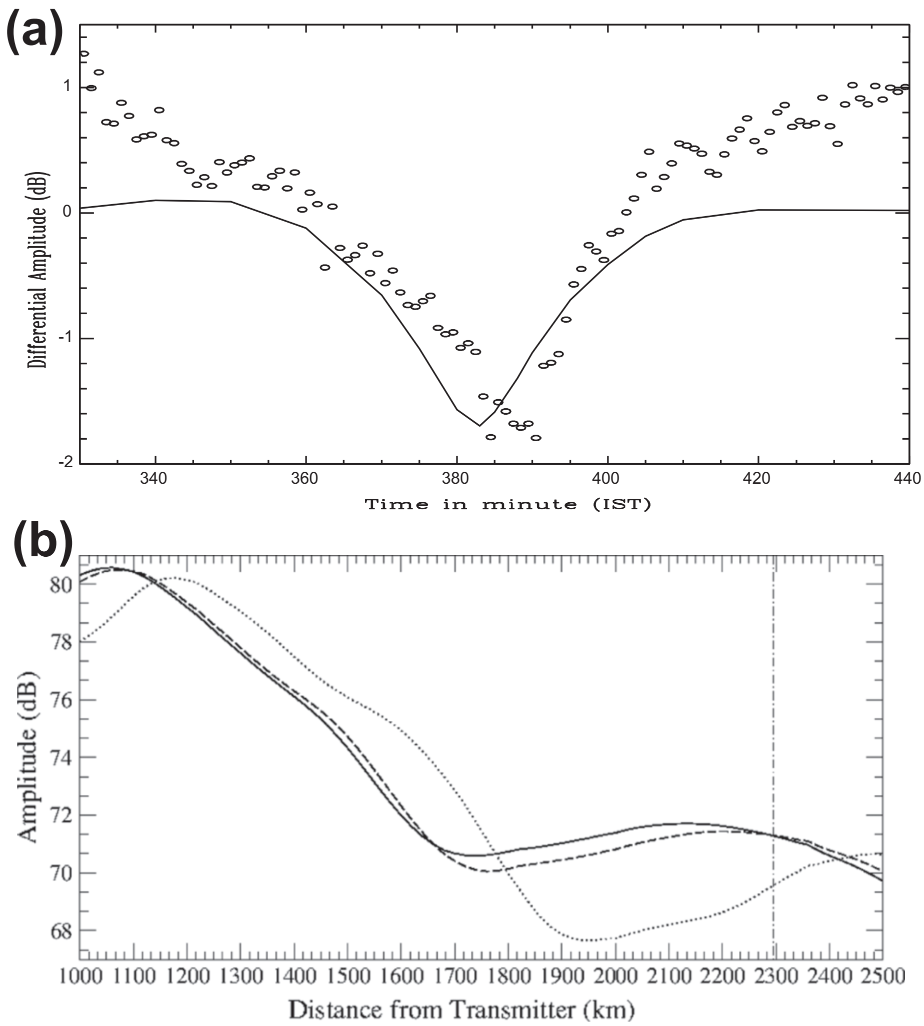

Fig. 4. (a) The model amplitude variation (solid curve) is compared with corresponding observed changes (circle) at Kathmandu. Maximum eclipse effects occur when h' has increased by +4.0 km and β has increased by +0.04 km^{-1} at $t = 383$ min (IST). (b) The variation of the model amplitude with distance from the transmitter for unperturbed conditions (solid line), maximum eclipse conditions (dotted curve) and at $t = 420$ min (dashed curve). The location of the receiver is indicated by a vertical line.

and calculated the degree of solar obscuration as a function of time.

As a first order approximation, we assumed that the ionospheric parameters β and h' vary linearly with obscuration function from the unperturbed one, though the ionospheric response to solar eclipse are generally non-linear phenomena (Lynn, 1981; Patel et al., 1986). Thus the parameters vary with time and distance from the transmitter. Therefore, if the maximum deviations for β and h' are given at any time, the perturbed parameters will be obtained by summing the unperturbed values of the the parameters with the product of the deviation and solar obscuration function.

4. Results

In Fig. 4(a), we show the amplitude variation (solid curve) obtained by the model fit and compare it with the corresponding observed changes (circle) of VTX signal as received at Kathmandu. The maximum eclipse effect occurs when h' is increased by +4.0 km and β is increased by +0.04 km^{-1} at $t = 383.0$ min (IST) while the observed maximum eclipse effect occurs at around $t = 389.5$ min. The variation of the model amplitude with distance from the transmitter (in km) for unperturbed (no eclipse) condition (solid line), maximum eclipse condition (dotted curve) and at $t = 420.0$ min (dashed curve) are shown in Fig. 4(b). The location of the receiver is indicated by a vertical line.

Fig. 5(a) and (b) show similar plots for the VTX-Raiganj propagation path. Here also the maximum eclipse effects occur when h' has increased by +4.0 km and β has increased by +0.04 km^{-1} at $t = 383.0$ min and the observed maximum eclipse effect occurs at around $t = 377.5$ min.

In Fig. 6(a) and (b), we show similar plots for the VTX-Kolkata propagation path. The maximum eclipse effects occur when h' has increased by +1.8 km and β has increased by+0.02 km^{-1} at $t = 390.0$ min at Kolkata.

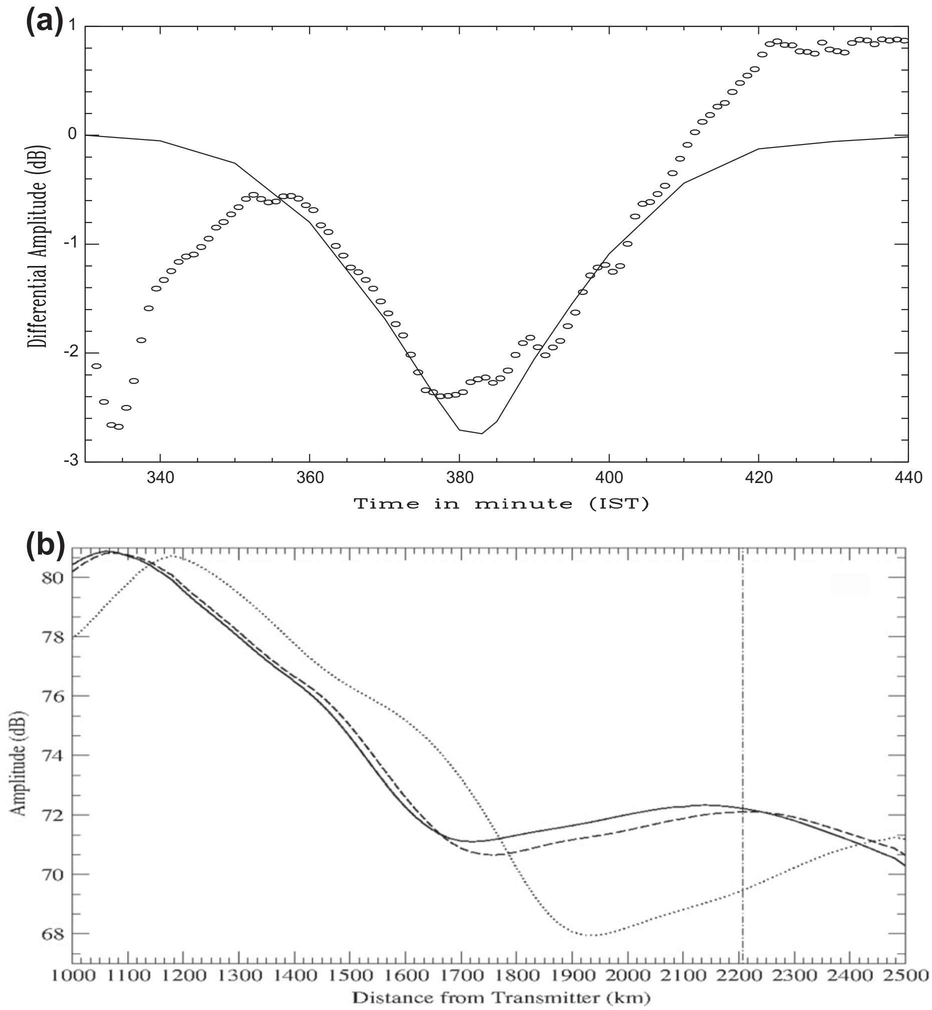

Fig. 5. A plot similar to Fig. 4 for the VTX-Raiganj propagation path. Maximum eclipse effects occur when h' has increased by +4.0 km and β has increased by $+0.04\ \mathrm{km}^{-1}$ at $t = 383$ (IST) minute at the region with the totality of eclipse.

Fig. 7(a) and (b) correspond to the VTX-Malda propagation path where h' has increased by +3.0 km and β has increased by $+0.02\ km^{-1}$ due to the maximum eclipse at $t = 385.0$ min at Malda.

These results for the VTX signal are quite reasonable. In particular, we find that the path which crosses the whole eclipse belt (i.e., that of VTX-Kathmandu) required the highest shift in height, while the path which is farthest from totality (VTX-Kolkata) required the least height variation. Our derived results are also comparable to what Guha et al., 2010 found, where an increase of height parameter about +3.5 km and an increase of gradient parameter about $+0.03\ km^{-1}$ have been reported for a given station.

During totality, a near-nighttime condition is expected to prevail in the lower ionosphere and thus the number density of electrons should be reduced as the D-region nearly disappears. To show this, we consider the data at Raiganj which witnessed totality (see, Table 1). In Fig. 8, we show how the distribution of the electron density (cm^{-3}) with altitude changes with time during the eclipse at Raiganj. The electron density at Raiganj is calculated using the so called Wait's formula (Wait and Spies, 1964) using the calculated variation of β and h' parameters with time. We note that in lower heights the near neutrality is achieved during the mid eclipse. At a height of ~ 90 km, of course, there are still some electrons. The effects of the eclipse at even higher height where the Wait's formula is no longer applicable would be of great interest and would be dealt with elsewhere.

5. Discussions

In this paper, we have modeled the effects of the solar eclipse of July 22nd, 2009 on the VLF signals. We chose four propagation paths in the Indian subcontinent which represent four different situations, starting from a completely partial eclipse (VTX-Kolkata), to marginally touching totality (VTX-Malda), totality (VTX-Raiganj) and crossing the path of totality (VTX-Kathmandu). We notice that there is no direct correspondence between the degree of obscuration and the deviation of the signal. For instance, except the Kolkata data, all other signals were

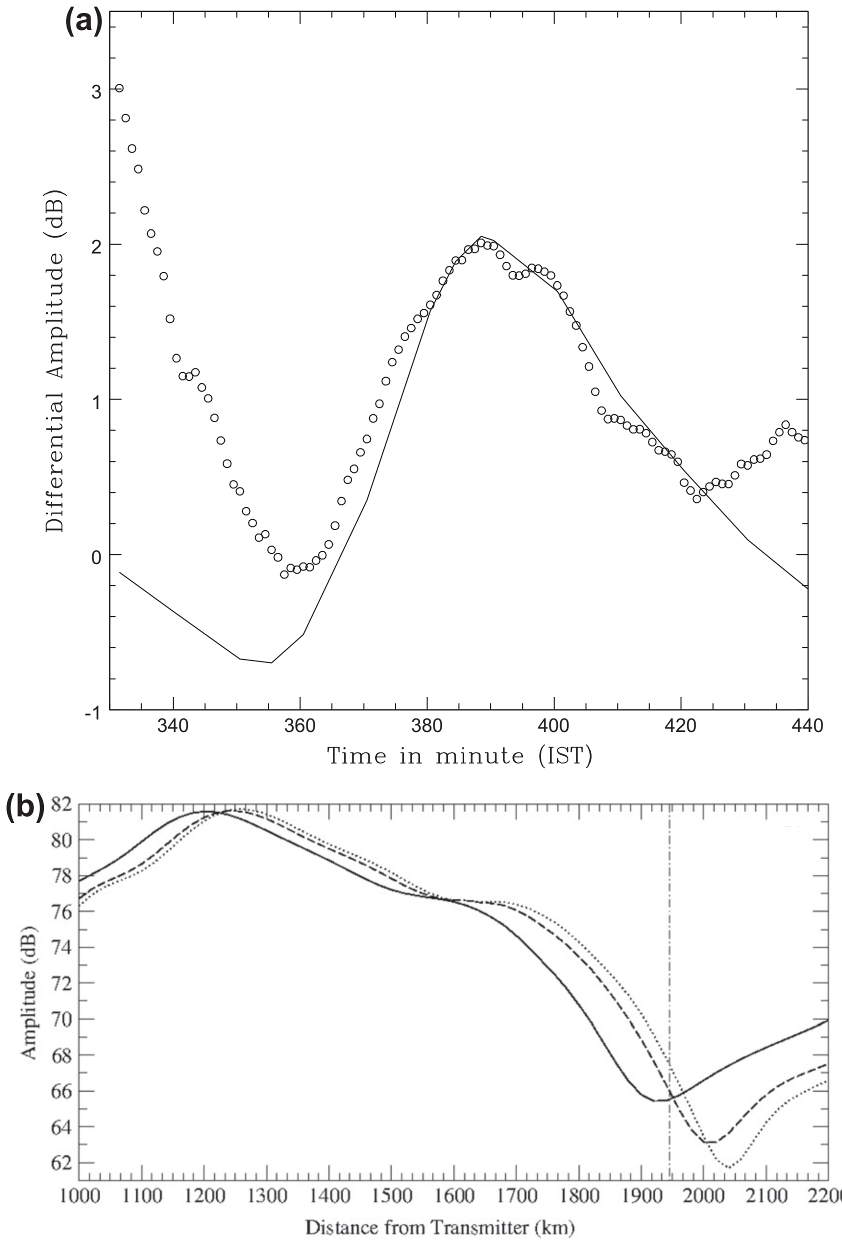

Fig. 6. (a) A plot similar to Fig. 4 for the VTX-Kolkata propagation path. Maximum eclipse effects occur when h' has increased by +1.8 km and β has increased by $+0.02\ \mathrm{km}^{-1}$ at $t = 390$ (IST) minute at Kolkata. (b) The variation of the model amplitude with distance from the transmitter for unperturbed conditions (solid line), maximum eclipse conditions (dotted curve) and at $t = 420$ min (dashed curve) (7:00 AM IST). The location of the receiver is indicated by a vertical line.

actually attenuated during the eclipse maximum. It would mean, in the language of the Wave-hop theory, that whether or not the interference between the sky wave and the ground wave would be constructive or destructive would depend on the path length of each wave and not by the local value of ionization.

In the Introduction we briefly presented the results of Clilverd et al. (2001). They found a positive deviation of amplitude for shorter paths (< 2000 km) and a negative deviation of amplitude for longer paths ($> 10,000$ km). While we indeed found a positive deviation for a 'marginally shorter' path (1946 km), the negative deviation started appearing even if the distance is 'marginally' above 2000 km (see, Table 1). In our case, for instance, any path which has experienced the totality gives a negative deviation, perhaps due to the significant change in the path length (phase) at the totality belt. What appears to be relevant here is the cumulative effects of the ionospheric disturbances due to solar eclipse.

Our model is based on the waveguide mode theory assuming a linear variation of ionospheric parameters with the degree of solar obscuration. Our result generally agrees with what is observed and this gives us the confidence that the outcome is totally due to the propagation effect. There appears to be still some discrepancies between our result and that of the observation, especially close to the sunrise

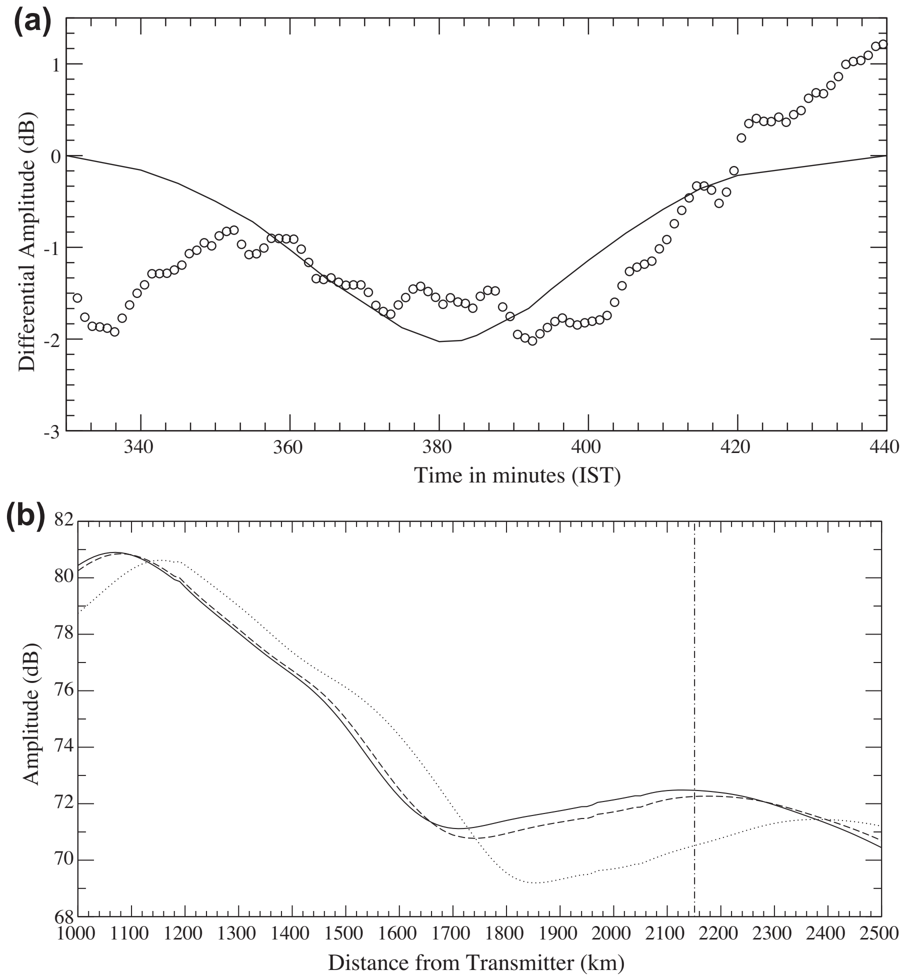

Fig. 7. A plot similar to Fig. 4 for VTX-Malda propagation path. Here the maximum eclipse effects occur when h' has increased by $+3.0$ km and β has increased by $+0.02\ \mathrm{km}^{-1}$ at $t = 385.0$ min at Malda.

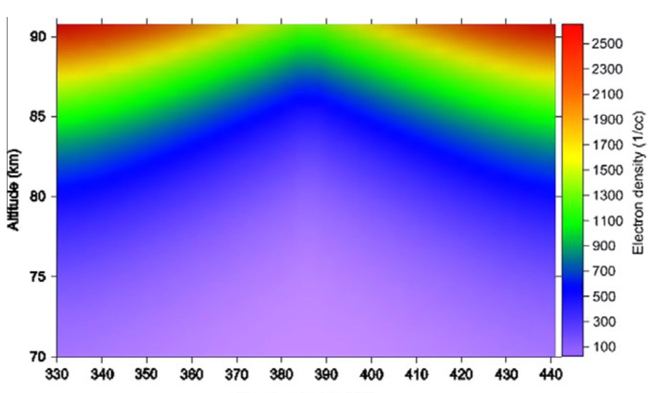

Fig. 8. Altitude variation of electron number density (cm^{-3}) obtained from Wait's formula during eclipse time at Raiganj. Note that at lower height, the number density is ~ 0 due to the near night condition when the D-layer completely disappeared. The ionization of the D-region at lower altitudes recover at a faster rate than the ionization at higher altitudes.

region. This means that our crucial assumption that the variation of ionospheric parameters with the solar obscuration is linear at all points of the propagation path may not be quite accurate. Furthermore, the data close to the sunrise time is contaminated by increasing attenuation due to lowering of the lower ionosphere. A complete agreement could perhaps be reached when the sunrise effects are also included. This is beyond the scope of the present paper.

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References

Bracewell, R.N. Theory of formation of an ionospheric layer below E layer based on eclipse and solar flare effects at 16 kc/sec. J. Atmos. Terr. Phys. 2, 226–235, 1952.

Buckmaster, H.A., Hansen, C.H. 26 February 1979 total solar eclipse induced LF (60 kHz) phase retardation. J. Atmos. Terr. Phys. 48, 393–397, 1986.

Chakrabarti, S.K., Sasmal, S., Pal, S., Mondal, S.K. Results of VLF campaigns in summer, winter and during solar eclipse in indian subcontinent and beyond. AIP Conf. Proc., 1286. AIP, New York, 2010.

Chakrabarti, S.K., Pal, S., Sasmal, S., et al. VLF Observational Results od Total Eclipse of 22nd July, 2009 by ICSP Team. IEEE Con. Publication, 2011.

Chakrabarti, S.K., Mondal, S.K., Sasmal, S., et al., VLF signals in summer and winter in the Indian sub-continent using multi-station campaigns, IJP, 2012, in press.

Clilverd, M.A., Rodger, C.J., Thomson, N.R., et al. Total solar eclipse effects on VLF signals: observations and modeling. Radio Sci. 36 (4), 773, 2001.

Cummer, S.A., Inan, U.S., Bell, T.F. Ionospheric D region remote sensing using VLF radio atmospherics. Radio Sci., 33 1781–1792, 1998.

Ferguson, J.A. Computer programs for assessment of long-wavelength radio communications, version 2.0. Technical document 3030, Space and Naval Warfare Systems Center, San Diego, 1998.

Fleury, R., Lassudrie-Duchesne, P. VLF-LF Propagation Measurements During the 11 August 1999 Solar Eclipse. IEEE Con. Publication, 2000.

Guha, A., De, B.K., Roy, R., Choudhury, A. Response of the equatorial lower ionosphere to the total solar eclipse of 22 July 2009 during sunrise transition period studied using VLF signal. J. Geophys. Res. 115, A11302, 2010.

Lynn, K.J.W. The total solar eclipse of 23 October 1976, observed at VLF. J. Atmos. terr. Phys. 43, 1309–1316, 1981.

Mendes da Costa, A., Rizzo Piazza, L., Paes Leme, N.M. Lower Ionosphere effect observed during the 30 June 1992 total solar eclipse. J. Atmos. Terr. Phys. 57, 13–17, 1995.

Mollmann, K.P., Vollmer, M. Measurements and predictions of the illuminance during a solar eclipse. Eur. J. Phys. 27, 1299, 2006.

Patel, D.B., Kotadia, K.M., Lele, P.D., Jani, K.G. Absorption of radio waves during a solar eclipse. Earth Planet Sci. 95, 193–200, 1986.

Sechrist Jr., C.F. Comparisons of techniques for measurement of D-region electron densities. Radio Sci. 9, 137–149, 1974.

Sengupta, A., Goel, G.K., Mathur, B.S. Effect of the 16 February 1980 solar eclipse on VLF propagation. JATP 42, 907, 1980.

Wait, J.R., Spies, K.P. Characteristics of the Earth-Ionosphere waveguide for VLF radio waves. NBS Tech Note, U.S. 300, 1964.

Zigman, V., Grubor, D., Sulic, D. D-region electron density evaluated from VLF amplitude time delay during X-ray solar flares. JASTP, 775–792, 2007.