Indian J Phys
DOI 10.1007/s12648-015-0727-3

ORIGINAL PAPER

Remote sensing of D-region ionosphere using multimode tweeks

A K Singh[1]*, U P Verma[1], R Singh[1] and J Lichtenberger[2]

[1]Department of Physics, University of Lucknow, Lucknow 226007, India

[2]Space Research Group, Department of Geophysics and Space Sciences, Eötvös University, Budapest, Hungary

Received: 23 March 2015 / Accepted: 14 May 2015

Abstract: Lightning discharges radiate electromagnetic waves in a wide frequency range, with maximum energy in extremely low frequency/very low frequency band. A part of the radiated extremely low frequency/very low frequency wave energy is trapped in the Earth–ionosphere waveguide and travels thousands of kilometers in different modes with lower attenuation. Amplitude, frequency and phase of these waves are used to study the less explored D-region ionosphere at lower latitudes. Extremely low frequency/very low frequency observations are recorded continuously by automatic whistler detector setup installed at low-latitude Indian station Lucknow (Geom. lat. 17.6°N; long. 154.5°E). In total, 149 cases of tweeks having modes ranging from 3 to 6 have been recorded by automatic whistler detector during December 2010 and analyzed. Result shows that the propagation distance in the Earth–ionosphere waveguide lies between 1.1 and 9.4 Mm. The electron density in the lower D-region varies between 25 and 150 cm^{-3}. The upper boundary of the waveguide varies between 80 and 95 km. The reported results are in good agreement with the earlier measurements at different latitudes and longitudes.

Keywords: Lightning; Earth–ionosphere waveguide; Tweeks/sferics; Electron density; Reflection height; Propagation distance

PACS Nos.: 94.20.Bb; 94.20.D-

1. Introduction

Return stroke current of lightning discharges during active thunderstorm generates electromagnetic wave in vast frequency range from a few hertz to several megahertz with the peak spectral density below 15 kHz [1]. Radiated energy disperses in all directions, and a part of this energy in the extremely low frequency/very low frequency (ELF/VLF) band having frequency range 30 Hz–30 kHz is trapped in the Earth–ionosphere waveguide (EIWG) and propagates at long distances with little attenuation through the process of multiple reflections [2]. At ELF/VLF frequencies, both the Earth and the lower ionosphere act as good conductors and enclosed atmosphere as a good dielectric, so that ELF/VLF waves propagate without dispersion and are recorded as tweeks (sounds like 'tweet' when heard with loudspeaker). The diffused nature of lower D-region ionosphere (about 70–90 km) forming the upper boundary of EIWG causes dispersion at lower frequencies and small attenuation (2–3 dB/1000 km), particularly at night [3]. The tweek waveforms are better resolved and suffer less attenuation at night (typically <0.5 dB Mm^{-1} as compared to 5 dB Mm^{-1} during daytime) due to sharper D-region electron density profiles [4]. Dispersion analysis of tweeks yields information about the state of the D-region ionosphere along the path of propagation [5–10].

The tweeks method for investigation of lower ionosphere has been widely used [5, 11–17]. Ionospheric parameters such as reflection height of tweeks, equivalent electron densities at reflection height, propagation distance and geographic locations of the source discharge have been estimated successfully using tweeks as a diagnostic tool [9, 18–23]. But earlier studies relied on only the first and the second harmonics of tweeks. Very little attention has been devoted experimentally to the use of multimode tweeks [16, 22] that represent the higher-order modes of the EIWG, along with some numerical studies [23, 24]. In comparison with previously used system, we have more precise instruments and better recording facility nowadays.

---

*Corresponding author, E-mail: aksphys@gmail.com

Earlier VLF recording system had sampling rate of 48 kHz and could digitize 2.5 s long signal with 8-bit resolution. Therefore, the dynamic range of a spectrogram generated by the earlier system has been ~40 dB, while the present VLF recording system can sample and store the full raw analogue VLF signal up to 200 kHz with 16-bit resolution continuously, and thus, the dynamic range of a spectrogram is ~90 dB.

In the present study, tweeks with higher harmonics (mode 3–6) have been recorded during December 2010 at the low-latitude Indian station Lucknow and have been analyzed to estimate the nighttime D-region electron density, the tweek reflection heights and the electron density profile of the nighttime lower ionosphere.

2. Theoretical formulation and data analysis

VLF waves have been widely used to study the upper atmosphere [25] and have obvious role in space weather and related phenomena [26–28]. Match filtering and parameter estimation (MFPE) techniques have successfully been used for calculation of various ionospheric medium parameters [29, 30]. VLF waves propagate in the EIWG through multiple reflections. The electromagnetic fields in the waveguide with perfectly conducting walls may be considered to be composed of a sequence of independent field structures (modes) that propagate with different group velocities [31]. Each mode is defined by its cutoff frequency, which for the nth mode is given by

$$f_{cn} = \frac{nc}{2h} \tag{1}$$

where c is the velocity of light in the free space, h is the tweek reflection height and n is the mode number.

The refractive index of wave propagation in magneto-active plasma is expressed by famous Appleton–Hartree formula [31]:

$$n_r^2 = 1 - \frac{2X(1-X-iZ)}{2(1-iZ)(1-X-iZ) - Y^2\mathrm{Sin}^2\alpha \pm \left[Y^4\mathrm{Sin}^4\alpha + 4(1-X-iZ)^2 Y^2\mathrm{Cos}^2\alpha\right]^{\frac{1}{2}}} \tag{2}$$

where X, Y and Z are dimensionless magneto-ionic parameters, defined as $X = \left(\frac{\omega_p}{\omega_H}\right)^2$, $Y = \left(\frac{\omega_H}{\omega}\right)$ and $Z = \frac{\upsilon}{\omega}$, respectively, n_r is the refractive index of medium, α is the angle between the propagation direction of wave and the external magnetic field vector, υ is collision frequency of an electron with neutrals, ω is the angular frequency of the wave, ω_p is angular plasma frequency and ω_H is angular electron gyrofrequency. The upper sign "+" in the denominator of Eq. (2) corresponds to ordinary waves, and the lower sign "−" corresponds to the extraordinary waves in the magneto-ionic plasma. Again, the ordinary mode corresponds to the right-hand circular polarization, and the extraordinary wave corresponds to the left-hand circular polarization [5]. If H is the Earth's magnetic field strength, μ_0 is the permeability in a vacuum, e and m are the electron charge and mass, ω_p $(= 2\pi f_p)$ and ω_H are obtained by the following expressions:

$$f_p = \frac{1}{2\pi}\sqrt{\frac{n_e e^2}{m \in_0}} \approx 9.0\sqrt{n_e} \tag{3}$$

$$\omega_H = \frac{e\mu_0 H}{m} \tag{4}$$

here n_e is electron density per cm^3.

The polarization features of tweeks have been found to be nearly left-hand circular polarization of tweek tail connected with the vertical component of the geomagnetic field and hence predominance of the extraordinary waves in tweek tails [5, 20, 32]. As defined above, the value of X (when $n_r^2 \sim 0$) has been obtained by the following equation that shows wave cutoff without regard to propagation direction:

$$X = 1 \tag{5}$$

$$X = 1 \pm Y \tag{6}$$

Equations (5) and (6) represent ordinary and extraordinary mode waves. The extraordinary mode waves correspond to $X = 1 + Y$ when $Y > 1(\omega_H > \omega)$, and $X = 1 - Y$ when $Y < 1(\omega_H < \omega)$; hence, only $X = 1 + Y$ is used for ELF/VLF waves.

Thus, the electron density n_e at tweek reflection height is derived from $X = 1 + Y$ as follows:

$$n_e = 1.241 \times 10^{-8} f_p(f_c + f_H)\,\mathrm{cm}^{-3} \tag{7}$$

f_p $(=\omega_p/2\pi)$ corresponds to the cutoff frequency of the tweek for the first-order mode and is replaced by the cutoff frequency (f_c) in the following equation. When the first-order mode cutoff frequency of tweek is less than the electron gyrofrequency, then $f_H \gg f_p$ is satisfied and Eq. (7) replaced as follows [8]:

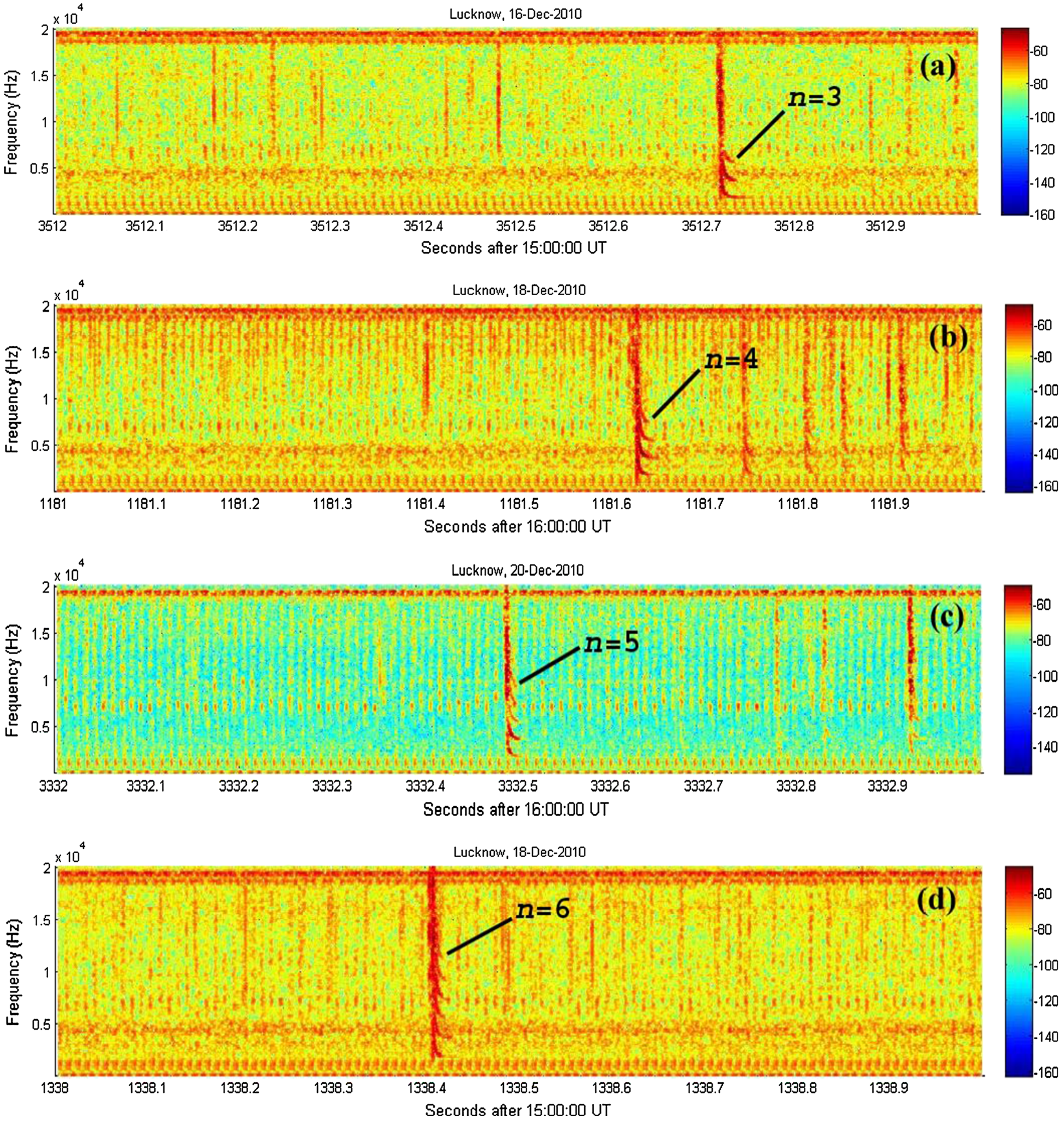

Fig. 1 Spectrograms of multimode tweeks (**a**) for $n = 3$, (**b**) for $n = 4$, (**c**) for $n = 5$ and (**d**) for $n = 6$ observed at low-latitude Indian station Lucknow (Geomag. Lat. 17.6°N; Geomag. Long. 154.5°E)

$$n_e = 1.241 \times 10^{-8} f_c f_H \,\text{cm}^{-3} \tag{8}$$

Since we receive tweek atmospherics from lightning discharges occurred mainly in low-latitude and equatorial regions, we have adopted $f_H = 1.1 \pm 0.2$ MHz according to the International Geomagnetic Reference Field (IGRF) model. Now, the above equation can be modified for the latitudes and altitude range of our interest as:

$$n_e = 1.39 \times 10^{-2} f_{cn} \,\text{cm}^{-3} \tag{9}$$

where f_{cn} is the cutoff frequency of nth mode.

For propagation distance (>2 Mm), the spherical model of the EIWG is considered where curvature of the Earth is taken into consideration for calculating group velocity and propagation distance. The group velocity V_{gn} in the homogeneous spherical EIWG is given by [10] as

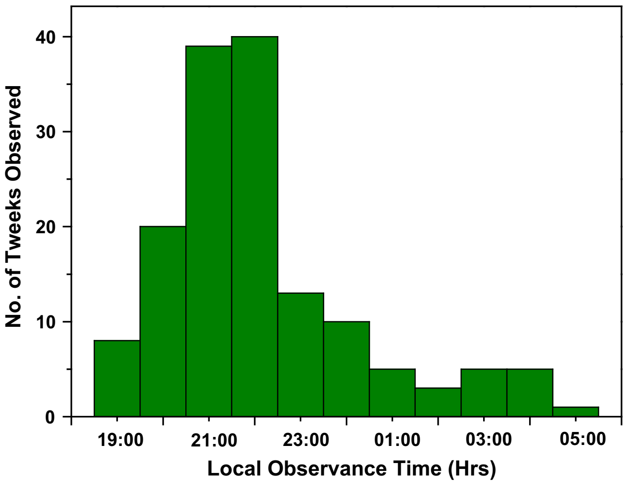

Fig. 2 Histogram shows the variation in number of tweeks observed with local occurrence time

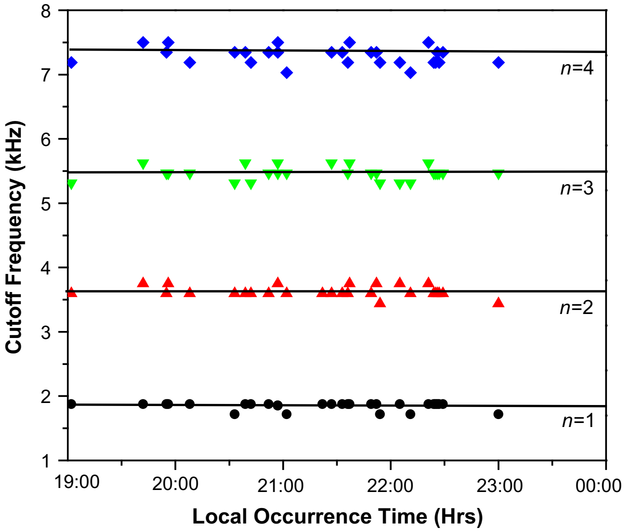

Fig. 3 Variation in cutoff frequency with their occurrence time during December 2010 for various modes of tweeks

$$V_{gn} = \frac{c\left[\left(1 - (f_{cn}/f)^2\right)\right]^{\frac{1}{2}}}{(1 - c/2Rf_{cn})} \tag{10}$$

where R is the radius of the Earth and f_{cn} is the cutoff frequency of nth mode. By calculating difference in propagation time, $\delta t = t_1 - t_2$ of two frequencies f_1 and f_2 close to f_{cn} from tweek spectrograms, the group velocity and hence the propagation distance of tweek atmospherics in the spherical waveguide were calculated from the formula

$$d = \delta t\left(\frac{V_{gf1} \times V_{gf2}}{V_{gf1} - V_{gf2}}\right) \tag{11}$$

where V_{gf1} and V_{gf2} are the group velocities of waves centered at frequencies f_1 and f_1, respectively.

3. Experimental details

VLF data were recorded continuously using automatic whistler detector (AWD) setup installed at Lucknow (Geomag. lat. 17.6°N; long. 154.5°E), India. The AWD system consisted of (1) antenna, (2) preamplifier and (3) AWD software run on a personal computer with a Linux Kernel. A crossed magnetic loop antenna (with area $\sim$ 100 m^2) oriented geomagnetic north–south and east–west was used so that the receiver picked up magnetic field parallel to ground from any direction. Impedance matched preamplifier was placed at the bottom of the antenna for maximum power transfer as well as signal amplification. The VLF data stream was sampled at a rate of 44.1 kHz using a 16-bit soundcard in a standard personal computer. Time measurement in the computer was synchronized with the pulse per second (PPS) signal of a global positioning system (GPS) receiver. The PPS timing accuracy was better than 1 μs, which had been smaller than the data sampling period ($\sim$22 μs) [33]. The operational system could independently sample from the data streams provided from the both NS and EW loops. Detailed observations showed the presence of high man-made noise levels in the EW loop data, as a result we only triggered the NS loop.

We had observed 149 higher harmonic tweeks of 3–6 modes during the month of December 2010 during night hours. Data files had been analyzed with the help of MATLAB code which produced dynamic spectrogram (frequency vs. time) of 1 s duration showing the signature of VLF waves (tweeks). Individual tweek spectrogram had been analyzed separately to obtain the cutoff frequency (f_c) of various modes. The arrival times (t_1 and t_2) of sferics of frequencies (f_1 and f_2) could be read from spectrograms as well to determine propagation distance (d) of the tweeks. The details of AWD software and the MATLAB program for AWD analysis could be obtained from [33, 34].

4. Results and discussion

The dynamic spectrograms of four multimode tweeks observed on (a) Dec 16, 2010, at 20:30:3512 h LT, (b) Dec 18, 2010, at 21:30:1181 h LT, (c) Dec 20, 2010, at 21:30:3332 h LT and (d) Dec 18, 2010, at 20:30:1338 h LT are shown in Fig. 1(a)–1(d) respectively as an example. Number of modes is mentioned on the respective

Table 1 Nighttime ionospheric reflection height, electron density and propagation distance as calculated from different modes of tweeks shown in Fig. 1(a)–1(d) as a special case

Spectrogram	Date	Time	Mode (*n*)	Electron density (el/cm^3)	Ionospheric reflection height (km)	Total propagation distance (km)
a	Dec 16, 2010	20:30:3512 h LT	1	26.06	80	8045
			2	49.95	83	5911
			3	76.01	84	3178
b	Dec 18, 2010	21:30:1181 h LT	1	26.06	80	5379
			2	49.95	83	4324
			3	76.01	85	3248
			4	102.08	86	2077
c	Dec 20, 2010	21:30:3332 h LT	1	26.06	80	3683
			2	49.95	82	2288
			3	76.01	83	2222
			4	99.91	83	1784
			5	127.74	85	1745
d	Dec 18, 2010	20:30:1338 h LT	1	26.06	80	5586
			2	49.95	81	4302
			3	76.01	82	3456
			4	102.08	82	2536
			5	128.14	83	1985
			6	149.84	83	1492

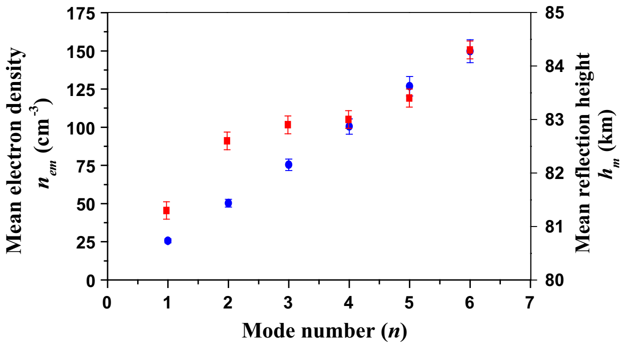

Fig. 4 Variation in mean electron density (*blue dots*) and mean reflection heights (*red squares*) with mode number of observed tweeks. (Color figure online)

spectrograms. The occurrence of tweeks has been grouped into two categories—premidnight (18:00–00:00LT) and postmidnight (00:00–06:00LT). About 88.6 % (132 in number) tweeks occurred in the premidnight, while 11.4 % (17 in number) were observed in the postmidnight sector. This may be because of the diurnal distribution of lightning flashes (source of tweek generation) rate in Asia that shows a peak in afternoon (during 2–4 pm). As time passes, the rate of flash distribution decreases; so, naturally observation of tweeks occurrence rate will decrease in postmidnight as compared to premidnight. Figure 2 depicts the histogram for variation in number of tweeks observed with local time. Further, as the harmonic number increases, the occurrence of higher modes decreases in both of the considered time sectors. The occurrence rate of tweeks with third mode is about four times that of tweeks with fourth mode. As the mode number further increases, occurrence rate sharply decreases.

Figure 3 shows the variation in cutoff frequencies of tweeks for different modes with local times for events that occurred in the premidnight sector. The first, second, third and fourth modes vary between 1.72 and 1.88, 3.44 and 3.75, 5.31 and 5.63, 7.03 and 7.50 kHz, respectively. Measurements of the cutoff frequency and arrival times of frequency components have been made with an accuracy of ±26 Hz and 1 ms, respectively. Cutoff frequencies of different modes do not show any trend in the variation with local nighttime (from 1900 to 2300 h), which means negligible temporal variation in electron density. Careful analysis of spectrum has revealed that dispersed portion of tweeks is reduced as harmonic number is increased. This might be due to higher attenuation at higher frequencies near the cutoff frequencies, which are supposed to be reflected from higher altitudes having relatively larger electron densities.

The theory of tweek propagation through the EIWG is based on the assumption that both the Earth's surface and the lower ionosphere act as good conductor of electricity at low frequencies. However, the conductivity of the ionosphere increases exponentially with height. Here, we have assumed that the conductivity of ionosphere does not vary with latitude and longitude along the paths of propagation of tweeks. The normal reflection height of the VLF waves in the ionosphere varies with frequency, lower frequencies usually reflected from lower heights due to relatively lower electron densities [23]. Table 1 lists the computed value of reflection heights for tweeks and their higher modes showed in Fig. 1 as an example. Usually higher modes of the same tweeks are found to be reflected from higher heights in the nighttime D-region which are consistent with the earlier results [19, 21]. Reflection of different modes of the same tweeks from different heights indicates that the upper boundary (D-region ionosphere) of the waveguide was not sharp (perfectly conducting), rather than conductivity changed with height.

Reflection height and corresponding electron density have been evaluated from the analysis of 149 tweeks having mode numbers between 3 and 6. Computed reflection height and electron density vary from 80 to 95 km and 25 and 150 cm^{-3}, respectively, during the present observations. Reflection height and electron density for the tweeks showed in Fig. 1 are given in Table 1. Propagation distance has been computed using Eq. (11) which varied from 1.1 to 9.4 Mm. The variation in mean electron densities (blue dots) and mean reflection heights (red squares) (including error bar) with mode number of observed tweeks is shown in Fig. 4. The mean electron densities (n_{em}) in the present study vary from 25.63 to 149.84 cm^{-3}, while the mean reflection heights (h_{m}) vary from 81.36 to 84.30 km. The mean electron densities and the mean reflection heights have been computed with accuracy of ± 1.76 cm^{-3} and ± 1.65 km, respectively, for various harmonics. The increase in h_{m} with increase in mode number indicates that the higher-order harmonics of same tweeks penetrates deeper into the lower ionosphere while traveling to the receiver by multiple reflections. This supports our consideration that the ionosphere is not sharply bounded at a fixed height for all harmonics but can be considered as sharply bounded progressively at higher altitudes for increasing order of harmonics of tweeks. The presented results are consistent with those estimated by others [9, 22, 23]. Multi-station observations have their own importance, and they can contribute significantly in making profiles of facts obtained from each individual station.

5. Conclusion

Lightning-generated tweeks/sferics recorded by the AWD setup at low-latitude Indian station Lucknow have been analyzed. Tweeks occur during the local nighttimes between 18:00 and 06:00 h with larger occurrence rate in premidnight period. Tweeks up to sixth harmonics have been observed. The occurrence rate of tweeks with higher harmonics decreases as the harmonic number increases. The electron density estimated using the first-order mode cutoff frequency varies from 25 to 150 cm^{-3}. The reflection height h of nighttime D-region ionosphere varies in the range 80–95 km. The propagation distance varies in the range 1.1–9.4 Mm. Most of the tweeks (~ 90 %) cover propagation distances from 1000 to 4500 km in the EIWG.

Acknowledgments AKS is thankful to Indian Space Research Organization (ISRO) for providing financial support for the present work under CAWSES India phase II program.

References

[1] H Volland, M Schmolders, G W Prölss and J Schäfer *J. Atmos. Terr. Phys.* **49** 33 (1987)

[2] R Barr, D L Jones and C J Rodger *J. Atmos. Solar Terr. Phys.* **62** 1689 (2000)

[3] M Yamashita *J. Atmos. Terr. Phys.* **40** 151 (1978)

[4] F Simões, R Pfaff, J J Berthelier and J Klenzing *Space Sci. Rev.* **168** 551 (2012)

[5] M Hayakawa, K Ohta and K Baba *J. Geophys. Res.* **99** 10733 (1994)

[6] S A Cummer, U S Inan and T F Bell *Radio Sci.* **33** 1781 (1998)

[7] R P Singh, A K Singh and D K Singh *J. Atmos. Solar Terr. Phys.* **60** 495 (1998)

[8] O E Ferencz et al., *Ann. Geophys.* **25** 1103 (2007)

[9] H Ohya, M Nishino, Y Murayama, K Igarashi and A Saito *J. Atmos. Solar Terr. Phys.* **68** 697 (2006)

[10] H Ohya, K Shiokawa and Y Miyoshi *Earth Planets Space* **60** 837 (2008)

[11] J Ohtsu *J. Proc. Res. Inst. Atmos.* **7** 58 (1960)

[12] S Yano, T Ogawa and H Hagino *Res. Lett. Atmos. Electr.* **9** 31 (1989)

[13] S Yano, T Ogawa and H Hagino *Dispersion characteristics and waveform analysis of tweek atmospherics* Environment and Space Electromagnetism H Kikuchi (eds.) (Tokyo: Springer-Verlag) p 227 (1991)

[14] M Hayakawa, K Ohta, S Shimakura and K Baba *J. Atmos. Solar Terr. Phys.* **57** 467 (1995).

[15] A I Sukhorukov *Ann. Geophys.* **14** 33 (1996)

[16] A K Singh and R P Singh *Earth Moon Planets* **73** 277 (1996)

[17] O E Ferencz *Hi-radastechnika "Communications"* **6** 2 (2004)

[18] C D Reeve and M J Rycroft *J. Atmos. Terr. Phys.* **34** 667 (1972)

[19] R N Singh, R P Singh, U P Singh and A K Singh *Indian J. Rad. Spa. Phys.* **21** 377 (1992)

[20] A V Shvets *J. Atmos. Solar Terr. Phys.* **60** 461 (1998)

[21] H Ohya, M Nishino, Y Murayama and K Igarashi *Earth Planets Space* **55** 627 (2003)

[22] A K Maurya et al., *J. Geophys. Res.* **117** A11308 (2012)

[23] A V Shvets, T M Serdiuk, Y V Gorishnyaya, Y Hobara and M Hayakawa *J. Atmos. Solar Terr. Phys.* **108** 1 (2014)

[24] S A Cummer and U S Inan *Radio. Sci.* **35** 1437 (2000)

[25] A K Singh, D Siingh and R P Singh *Planet. Space Sci.* **59** 810 (2011)

[26] A K Singh and R P Singh *Indian J. Phys.* **77B** 611 (2003)

[27] A K Singh, D Singh and R P Singh *Surv. Geophys.* **31** 581 (2010)

[28] A K Singh, A Tonk and R Singh *Indian J. Phys.* **88** 1127 (2014)

[29] R P Singh, D K Singh, A K Singh, D Hamar and J Lichtenberger *J. Atmos. Solar Terr. Phys.* **61** 1081 (1999)

[30] R P Singh, R P Patel, A K Singh, D Hamar and J Lichtenberger *Pramana J. Phys.* **55** 685 (2000)

[31] K G Budden *Radio waves in the Ionosphere*. (U.K.: Cambridge University Press) (1961)

[32] D Yedemsky, B S Ryabov, A Shchokotov and V S Yarotsky *Adv. Space Res.* **12** 25 (1992)

[33] J Lichtenberger, Cs Ferencz, L Bodnar, D Hamar and P Steinbach *J. Geophys. Res.* **113** A12201 (2008)

[34] J Lichtenberger et al., *J. Geophys. Res.* **115** A12214 (2010)