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Morphological features of tweeks and nighttime *D* region ionosphere at tweek reflection height from the observations in the low-latitude Indian sector

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[1] A total of 19,308 tweeks recorded during April 2007 to March 2008, at Allahabad, a low-latitude station in the Indian sector, has been used to study seasonal occurrence which shows maximum tweek occurrence of about 63% during summer season and about 19% and 18% occurrences during equinox and winter seasons. Maximum occurrence of tweeks during summer season is consistent with the larger number of lightnings detected by World Wide Lightning Location Network in the Indian and Asia Oceania regions during summer as compared to that during equinox and winter. Seasonally, tweek (ionospheric) reflection height in the premidnight (18:00-00:00 LT) during winter is less as compared to that during equinox and summer. Annual (seasonal average) variation of the mean ionospheric reflection height shows a gradual increase in the reflection height from about 19:30 to 04:30 LT. The annual average of postmidnight (00:00–06:00 LT) reflection height is about 5 km higher as compared to that in the premidnight. Our initial results on the variability in the ionospheric reflection height under pure nighttime propagation (21:00–03:00 LT) on magnetically quiet days show a day-to-day variability of up to 8 km. Theoretically calculated attenuation of the Earth-ionosphere waveguide for first six tweek modes in the early and late night periods (21:00–00:00 LT; 00:00–03:00 LT) is less compared to that in the dusk (18:00–21:00 LT) period. The higher attenuation in the dusk period and most of the tweeks in the dawn period traveling partially under daytime conditions explain the lower occurrence of tweeks in these periods.

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1. Introduction

[2] The return strokes of lightning discharges are powerful natural transmitters of the electromagnetic energy over a wide electromagnetic spectrum extending from a few hertz to few tens of megahertz [*Weidman and Krider*, 1986; *Burke and Jones*, 1992], with maximum spectral energy in the extremely low frequency (ELF, 3–3000 Hz) and the very low frequency (VLF, 3–30 kHz) bands [*Uman*, 1987, p. 118]. Lightning generated atmospherics with the ELF-VLF frequency components propagate by multiple reflections in the atmospheric waveguide formed by the Earth and the lower boundary of ionosphere called Earth-Ionosphere Waveguide (EIWG). Lightning-generated sferics, particularly in the night, travel large distances due to low attenuation rate (2–3 dB/1000 km) [*Taylor*, 1960; *Yamashita*, 1978; *Davies*, 1990, p. 389] offered by the EIWG and hence are observed around the world. On propagating large distances in the EIWG, sferics undergo appreciable dispersion near the cutoff frequencies of different modes [*Budden*, 1961]. Such dispersed sferics are known as "tweeks" as they sound like "tweet" when heard with loudspeaker. The fact that tweeks are reflected from lower ionosphere makes them a useful probing tool to investigate the nighttime *D* region ionosphere. *D* region ionosphere typically exists from 60 to 100 km at the low latitudes depending upon the solar zenith angle, solar flux, season and latitude [*Friedrich and Rapp*, 2009].

[3] General features of tweeks have been studied by several researchers [*Outsu*, 1960; *Yano et al.*, 1989; *Kumar et al.*, 1994; *Hayakawa et al.*, 1994, 1995; *Ferencz*,

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2004; *Ferencz et al.*, 2007; *Kumar et al.*, 2008; *Ohya et al.*, 2011]. *Outsu* [1960] studied dispersion characteristics of tweeks considering lower ionosphere as sharply bounded reflecting layer and the Earth as a perfectly conducting medium. The reflection of higher harmonics of tweeks from higher *D* region heights estimated by *Kumar et al.* [2008] suggested that the EIWG deviates from perfect conductor conditions even at the ELF-VLF frequencies. Earth's magnetic field makes ionosphere as an anisotropic medium. *Lynn and Crouchley* [1967] have shown that tweeks coming from east direction are four times more in number than those coming from west direction. *Snyder and Pappert* [1969] determined phase velocity, attenuation factor, polarization, mixing ratio, and excitation factor in the frequency range of 10–30 kHz both for eastward and westward propagations at the midlatitude. *Yamashita* [1978] investigated the propagation mechanism of tweeks near the mode cutoff frequency by calculating attenuation coefficient and excitation factor in the EIWG for the quasi transverse magnetic (QTM) and the quasi transverse electric (QTE) modes. *Prasad* [1981] studied the effect of land and sea parameters on the propagation of tweeks. *Yedemsky et al.* [1992] and *Hayakawa et al.* [1995] have shown that the main polarization of tweek tail is left handed circular polarization which is connected with the vertical component of the geomagnetic field. *Ferencz et al.* [2007] based on the "Spiky Whistlers" (SpW) observed onboard DEMETER satellite suggested that tweeks can leak out off the EIWG even after thousands of kilometers of subionospheric propagation. *Ohya et al.* [2008] have developed an automatic procedure for estimation of the cutoff frequency of tweeks which is used to determine the ionospheric reflection height of tweeks.

[4] Tweeks are novel tools to probe nighttime *D* region ionosphere which otherwise is inaccessible by other ionospheric sounding techniques. *D* region is too high for balloons and too low for satellite measurements. Radio sounding (e.g., ionosondes and incoherent radars) does not work particularly at night since electron densities in this region are low to reflect high-frequency radio waves. Although *D* region measurements by rockets are precise, rocket flights have limited spatial coverage and are expensive. Similarly, MF radar also has limited coverage of ionospheric region (vertically over head). Because of the fact that tweeks are reflected from the *D* region of ionosphere, they have been utilized by several researchers to estimate ionospheric reflection height, equivalent electron density at the reflection height, propagation distance and geographic location of source lightning discharge [*Reeve and Rycroft*, 1972; *Singh et al.*, 1992; *Kumar et al.*, 1994; *Singh and Singh*, 1996; *Shvets and Hayakawa*, 1998; *Ohya et al.*, 2003, 2006, 2008; *Kumar et al.*, 2009; *Maurya et al.*, 2010; *Singh et al.*, 2010, 2011]. Using the field component analysis of multimode tweeks, *Shvets and Hayakawa* [1998] estimated an increase in the electron density from 28 to 224 el/cm^3 at 2 km interval at the ionospheric height of 88 km. *Ohya et al.* [2003] estimated equivalent nighttime electron densities at the reflection heights in the *D* region ionosphere from first mode cutoff frequency of tweeks observed at a low-latitude to midlatitude station in Japan. They estimated equivalent electron densities of 20–28 el/cm^3 at the ionospheric reflection height of 80–85 km. From the analysis of tweeks recorded during September 2003 to July 2004 at Suva (18.1°S, 178.4°E), Fiji, in the South Pacific region, *Kumar et al.* [2008] found that the mean nighttime ionospheric reflection height increases from 18:00 to 23:00 LT, decreases to a minimum at around 01:00 LT and then gradually increases up to 05:00 LT.

[5] There have been some earlier studies in the Indian sector [*Singh et al.*, 1992; *Kumar et al.*, 1994; *Singh and Singh*, 1996] with tweeks to study the lower ionosphere but using a very smaller number of tweeks and from a couple of months of observations only. With the new Stanford University designed ELF-VLF receiving system setup in India we present results obtained from the extensive analysis of tweeks recorded over the 1 year period from April 2007 to March 2008 at a low-latitude station, Allahabad. Further, the electromagnetically quiet location of the Allahabad station provided us with an opportunity to observe tweeks with higher harmonics and estimate cutoff frequency more accurately. A total of 19,308 tweeks recorded during the 1 year period has been used to study the seasonal variation in the occurrence of tweeks. Diurnal and seasonal variations in the tweek ionospheric reflection height have been studied for the first time in detail from tweek observations at this low latitude in the Indian sector. Initial results on day-to-day variability of tweek ionospheric reflection heights on geomagnetically quiet conditions have been presented and discussed. The nighttime tweek occurrence in the four different periods (dusk, 18:00–21:00 LT; early night, 21:00–00:00 LT; late night, 00:00–03:00 LT; dawn, 03:00–06:00 LT) has been explained in relation to the attenuation factor during these four periods of the nighttime and tweek propagations paths.

2. Experimental Setup

[6] The broadband ELF-VLF data were recorded with the Stanford University developed AWESOME VLF receiver [*Cohen et al.*, 2010; *Singh et al.*, 2010] installed at a quiet location near Allahabad (geographic latitude 29.36°N, longitude 79.46°E; geomagnetic latitude 16.05°N, longitude 153.70°E), India. The system consists of two orthogonal crossed loop antennas with 10 × 10 m base with five turns, giving an effective area of 250 m^2 aligned in the north-south (N-S) and the east-west (E-W) magnetic planes, dual preamplifier fixed near the antenna and the ELF-VLF line receiver connected with outputs of the preamplifier through a 300 m long cable and with data logging PC. The frequency response of the ELF-VLF line receiver is flat in the frequency range of 300 Hz to 47.5 kHz. The line receiver utilizes GPS for time synchronization with an accuracy of 100 ns. The data are recorded at 100 kHz, 16-bit sampling, and 10 μs time resolution in the synoptic format (1 min at every 15 min) and analyzed using a MATLAB code which produces dynamic spectrograms of selected durations.

3. Results and Discussion

3.1. Characteristic Features and Occurrence Pattern of Tweeks

[7] Figures 1a, 1b, 1c, and 1d present the spectrograms showing typical multimode tweeks recorded at Allahabad on 12 April 2007 between 19:00 and 23:00 UT, with a maximum up to sixth harmonic (mode) tweek. Local time (LT) = UT + 5.5 h. A total of 19,308 clearly visible tweeks with

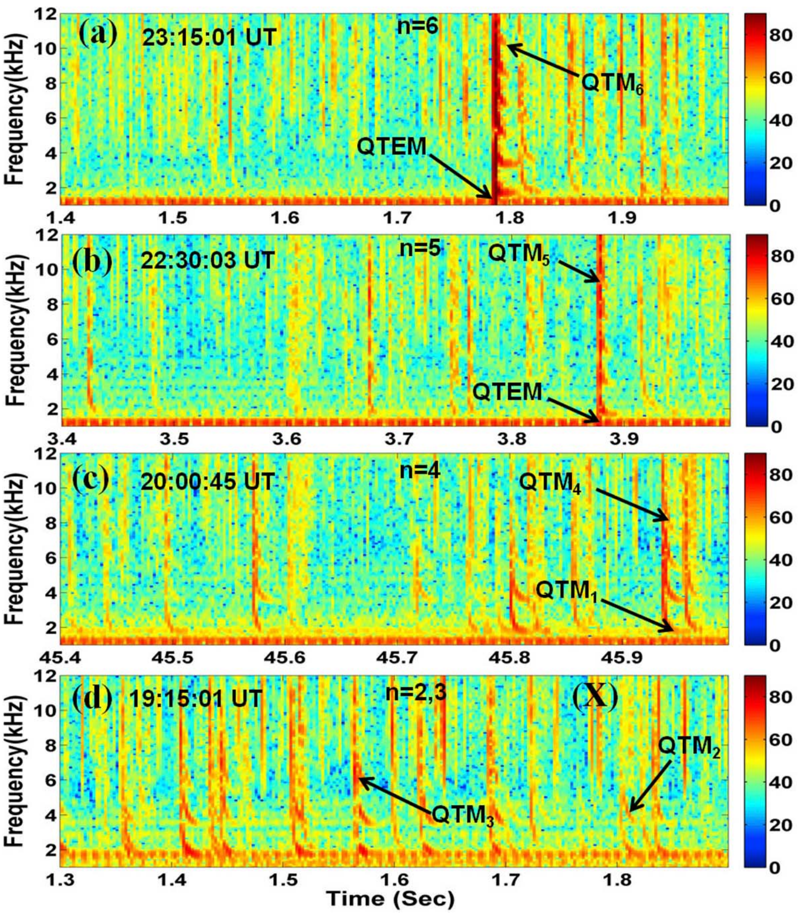

Figure 1. Spectrogram showing multimode tweeks observed on 12 April 2007 between 19:00 and 23:00 UT (00:30–00:4:30 LT) at Allahabad. X indicates tweek with n = 1 and 2.

intensity levels ≥60 dB was observed in the nighttime during one year of observations from April 2007 to March 2008. There were no tweeks detected in the daytime recording due to strong attenuation offered by daytime EIWG. The duration of tweeks section (dispersed section) is found to be in the range of 10–50 ms. *Kumar et al.* [2008] have reported dispersion duration of 15–60 ms for tweeks observed in the South Pacific region. *Reznikov et al.* [1993] found tweek duration in the range of 40–50 ms, which may reach up to 100 ms. The larger duration of dispersed section of tweeks shows the higher distance traveled by tweeks upon reaching the receiving station which depends on conditions along the propagation path and strength of sferics generated by lightnings. Tweeks may consist of different modes as labeled in the spectrograms in Figure 1. The propagation of waves in the EIWG can be understood in terms of quasi-transverse electric (QTE$_n$) and quasi-transverse magnetic (QTM$_n$) modes [*Budden*, 1961], with first mode (n = 1) cutoff frequency (f_{c1}) around 1.8 kHz. Each mode propagates at and above its cutoff frequency except one with no cutoff frequency and has the frequency components below the first mode cutoff frequency. This mode of propagation is called quasi-transverse electromagnetic (QTEM) mode. The attenuation of QTEM mode waves increases exponentially with increase in the frequency, and most of the QTEM frequency components are strongly attenuated above ~1.0 kHz [*Sukhorukov and Stubbe*, 1997]. For frequencies less than 15 kHz the lower-order QTM and QTE modes approximate pure TM and TE modes [*Wood*, 2005]. We therefore treat modes in the EIWG as pure modes and consider TM mode of propagation. The cutoff frequency of first harmonic (f_{c1}) and two other nearby frequencies (f_1 and f_2) with corresponding arrival times (t_1 and t_2) have been utilized to determine the tweek reflection height and the propagation distance from source lightning discharge.

[8] To study the variation in the occurrence pattern of tweeks, the local nighttime is divided into four periods: dusk (18:00–21:00 LT), early night (21:00–00:00 LT), late night (00:00–03:00 LT), and dawn (03:00–6:00 LT). The occurrence of tweeks during three seasons (summer, May, June, July, August; winter, November, December, January, February; and equinox, March, April, September, October) has been presented in Tables 1–3. We have counted the number of tweeks such that first harmonic tweek means tweek has only first mode, second harmonic tweek has first and second modes, third harmonic tweek has first, second and third modes, and so on. The first harmonic is common to all tweeks. A total of 19,308 tweeks observed during three seasons (summer (12,192), winter (3457) and equinox (3659)) has been analyzed in this study. It can be noted from Tables 1–3 that tweek occurrence is maximum during summer season (63%) which is about double of combined

Table 1. Occurrence of Tweeks During Summer Season (May, June, July, August)

Periods of Night	Number of Tweeks	Occurrence (%)	Number of Tweeks (With Harmonics n = 1–6)					
			First	Second	Third	Fourth	Fifth	Sixth
Dusk (18:00–21:00 LT)	2,077	17.03	1,095	978	4	0	0	0
Early night (21:00–00:00 LT)	3,835	31.45	796	3,006	27	4	1	1
Late night (00:00–03:00 LT)	4,389	35.99	647	3,638	96	2	5	1
Dawn (03:00–06:00 LT)	1,891	15.51	366	1,443	73	6	3	0
Total	12,192	100	23.81	74.35	1.64	0.10	0.07	0.02

occurrences during winter (18%) and equinox (19%) seasons. Tweek occurrence is lower in the early night period during summer and equinox (Tables 1 and 3) as compared to that during winter season (Table 2). Thus, overall occurrence of tweeks at Allahabad increases as the night advances with the maximum occurrence in the late night period which decreases to minimum in the dawn period. As given in Table 4, about 71% of tweeks observed during three seasons were associated with first and second modes (n = 1–2), followed by tweeks with only n = 1 (~25%) and tweeks with n = 1–3 (~3.5%). Tweeks having higher modes (n = 4–6) occurred rarely throughout the year with no fifth and sixth mode tweeks (having n = 1–6) observed during the winter season. The occurrence of tweeks with modes higher than n = 3 is too low to study the seasonal variation in the occurrence of tweeks with modes ($n \geq 3$). Although it is the lightning activity which primarily determines the occurrence of tweeks at any station, conditions at lower ionospheric height during different seasons may also have some contribution toward the occurrence of tweeks and their higher modes. The most frequent occurrence of tweeks with lower (n = 1–2) modes is due to low attenuation offered by the EIWG to the frequency components of lower modes [*Wait*, 1957], as also shown in section 3.4 (Figure 7) for different periods of the nighttime for n = 1–6. The attenuation is higher for higher-order modes which explains the higher occurrence of tweeks with lower modes; also, the attenuation in the early and late night periods (21:00–00:00 LT; 00:00–03:00 LT) is less as compared to that in the dusk (18:00–21:00 LT) period and nearly same as in the dawn (03:00–06:00 LT) period. The higher attenuation in the dusk period and most of the tweeks in the dawn period traveling partially under daytime conditions (offering larger attenuation) explains the lower occurrence of tweeks in these periods compared to early and late night periods. Tweeks are observable until 05:00, 5:30, and 5:50 LT in summer, equinox, and winter seasons, showing the effect of attenuation due to increase in the ionosphere ionization and hence decrease in the height of EIWG with the sunrise. To study the dependence of seasonal occurrence of tweeks at the station Allahabad on lightning activity around the station, World-Wide Lightning Location Network (WWLLN) detected nighttime (LT) lightning locations for one month from each season have been plotted in Figure 2. WWLLN detects the global lightning with return stroke currents of more than ~50 kA with spatial and temporal accuracy of roughly 10–20 km and 10 μs, respectively. Global detection efficiency of WWLLN is about 4%, although much higher detection efficiency for high peak current lightning [*Rodger et al.*, 2006] is expected. Figure 2 represents the geographical locations of nighttime (18:00–06:00 LT of Allahabad) lightning strikes detected by WWLLN during July, January and October months of summer, winter and equinox seasons. About 93% of the tweeks have been found to propagate the distance in the range of ~2000–8000 km from there source lightning discharge in the EIWG to Allahabad station as presented in section 3.3. The circles of radii 2000, 4000, 6000, and 8000 km are drawn around Allahabad station to indicate the lightning activity in different areas surrounding the station. The WWLLN lightning locations within 6000 km and 6000–8000 km circles around Allahabad station have been represented by green and pink markers in Figure 2. Blue markers in Figure 2 show lightning locations above 8000 km distance to the station where from tweeks arrive rarely. From lightning locations shown in Figure 2 and the seasonal variation of tweeks occurrence, it can be said that high occurrence (63%) of tweeks during summer is consistent with higher lightning strikes detected by WWLLN during summer as compared to that during winter and equinox seasons in the Indian and surrounding region mainly in the Asia Oceania region. The nocturnal variation of tweek occurrence and lightning strikes during one hour intervals of the nighttime for 12 selected days from summer, winter and equinox is shown in Figure 3. Due to low detection efficiency of WWLLN the correlation between lightings and tweek occurrence has not been studied; rather in Figure 3 we have tried to look at the trend (relative occurrence) of tweek

Table 2. Occurrence of Tweeks During Winter Season (November, December, January, February)

Periods of Night	Number of Tweeks	Occurrence (%)	Number of Tweeks (With Harmonics n = 1–6)					
			First	Second	Third	Fourth	Fifth	Sixth
Dusk (18:00–21:00LT)	943	27.28	480	460	3	0	0	0
Early night (21:00–00:00 LT)	1184	34.25	407	767	9	1	0	0
Late night (00:00–03:00 LT)	1069	30.92	288	764	17	0	0	0
Dawn (03:00–06:00 LT)	261	7.55	96	162	3	0	0	0
Total	3457	100	36.76	62.27	0.92	0.03	0	0

Table 3. Occurrence of Tweeks During Equinox Season (March, April, September, October)

Periods of Night	Number of Tweeks	Occurrence (%)	Number of Tweeks (With Harmonics n = 1–6)					
			First	Second	Third	Fourth	Fifth	Sixth
Dusk (18:00–21:00LT)	991	27.08	324	602	42	18	5	0
Early night (21:00–00:00 LT)	1125	30.75	135	769	165	49	6	1
Late night (00:00–03:00 LT)	1144	31.27	106	842	182	14	0	0
Dawn (03:00–06:00 LT)	399	10.90	130	220	49	0	0	0
Total	3659	100	18.99	66.50	11.97	2.21	0.30	0.03

occurrence and WWLLN detected lightnings within 8000 km circle around the Allahabad station. The tweek occurrence is higher in the nighttime (21:00–03:00 LT) as compared to dusk and dawn periods during all three seasons. It is found that in the early night (21:00–00:00 LT) period and in the late night period until 01:00 LT during summer the occurrence (relative) of tweeks varies with the lightnings. During winter and equinox seasons, tweek occurrence is less as compared to WWLLN lightnings which is because most of the lightning activity is away from the station during these seasons. During summer season both occurrence of tweeks and lightning activity around the station are high. Because of the fact that WWLLN has low detection efficiency and detects only strong lightnings, and since occurrence of tweeks depends upon the several factors such as strength of sferics associated with lightings, lightning occurrences and the attenuation offered by the waveguide, a good consistency between occurrence of lightings and tweek is not expected. However, the overall trend of tweek occurrence in the early and late night period during three seasons seems to be consistent up to some extent with WWLLN detected lighting. In the dawn (03:00–06:00 LT) period and up to some extent in the dusk (18:00–21:00 LT) period, tweek occurrence does not increase with increase in lightning activity. This is because in these periods, tweeks are also likely to come from the daylight path which is most likely to happen in the dawn period as compared to the dusk period as most of lightings are located in the Asia Oceania region. In fact, the daytime (morning) propagation for tweeks coming from the Asia Oceania region may start between 01:00 and 02:00 LT, which is most likely the reason for the decrease in the occurrence of tweeks from about 02:00 LT with the increase in the lightnings (Figure 3). Since tweek propagation in the daylight suffers heavy attenuation as compared to nighttime propagation [*Kumar et al.*, 2008], many of the tweeks originating from the Asia Oceania region in the dawn period would have died out during the propagation.

3.2. Tweek Ionospheric Reflection Height

[9] The cutoff frequency (f_{cn}) of different harmonics of tweeks has been measured with an accuracy of 26 Hz, and arrival times of frequency components have been measured with an accuracy of 1 ms from the spectrograms which correspond to error of ±1.2 km for first harmonic tweek in the reflection height and ±500 km in the propagation distance. The reflection height (h) of the nth harmonic has been calculated using the expression $h = nc/2f_{cn}$ [*Yamashita*, 1978], where c is the velocity of light in free space. The h for the tweeks in Figures 1a–1d as shown in Table 5 varies from ~88 to 96 km. Here we have calculated the reflection height individually for each mode (n = 1–6) of each tweek. In general, higher modes ($n > 1$) of the same tweeks are found to be reflected from higher heights in the nighttime D region, which is consistent with the earlier findings of *Shvets and Hayakawa* [1998] and *Kumar et al.* [2008]. The reflection of higher modes of the same tweek from higher heights also indicates that the upper boundary of the EIWG is not sharp (perfect conductor), rather conductivity/ionization increases with the height. Table 5 shows that tweeks having higher modes are reflected from higher heights; for example, tweek in Figure 1c is reflected at 91.7 km which is about 2 km more compared to tweek in Figure 1d. For calculating tweek reflection height, we have selected in total 910 clearly visible tweeks with intensity >60 dB, with 180 during winter, 190 during equinox, and 540 during summer season. This selection provided us with 3–4 tweeks during winter and equinox seasons and 10–12 tweeks during summer months in the every 15 min interval from 18:00 to 06:00 LT. The annual (seasonal average) and seasonal (winter, summer, equinox) variations of the mean nighttime ionosphere reflection height (h_m) determined from the mean cutoff frequency of first harmonic of tweeks are shown in Figures 4a–4d. The bars indicate the standard deviation in the reflection height. The annual variation of h_m (Figure 4a) shows gradual rise in the range 80–95 km from dusk to dawn. The linear fit analysis between the h_m and time shows sharper gradual rise in h_m with time in the premidnight (18:00–00:00 LT) (y(km) = 1.25x(hours) + 83.69) as compared to that in the postmidnight (y(km) = 0.52x(hours) + 90.68). The h_m is higher in the postmidnight (00:000–6:00 LT) period as compared to that in the premidnight (18:00–00:00 LT) period during three seasons. The h_m in the premidnight during winter season (~78–90 km) is less as compared to that during summer (~84–91 km) and equinox (~80–91 km) seasons, whereas there is almost no difference in the h_m in the postmidnight during these three seasons. The value of h_m in the dusk and dawn periods as seen in Figure 4 is less as compared to rest of the nighttime which is due to comparatively smaller solar zenith angle during dusk and dawn periods and some of the tweeks would have arrived from daylight side of tweek propagation

Table 4. Seasonal Occurrence of Tweek With Different Mode Numbers (n)

Seasons	First	Second	Third	Fourth	Fifth	Sixth	Total	Percent
Summer	2,904	9,065	200	12	9	2	12,192	63.14
Winter	1,271	2,153	32	1	0	0	3,457	17.91
Equinoxes	695	2433	438	81	11	1	3,659	18.95
Percentage (%)	25.22	70.70	3.47	0.49	0.10	0.02		

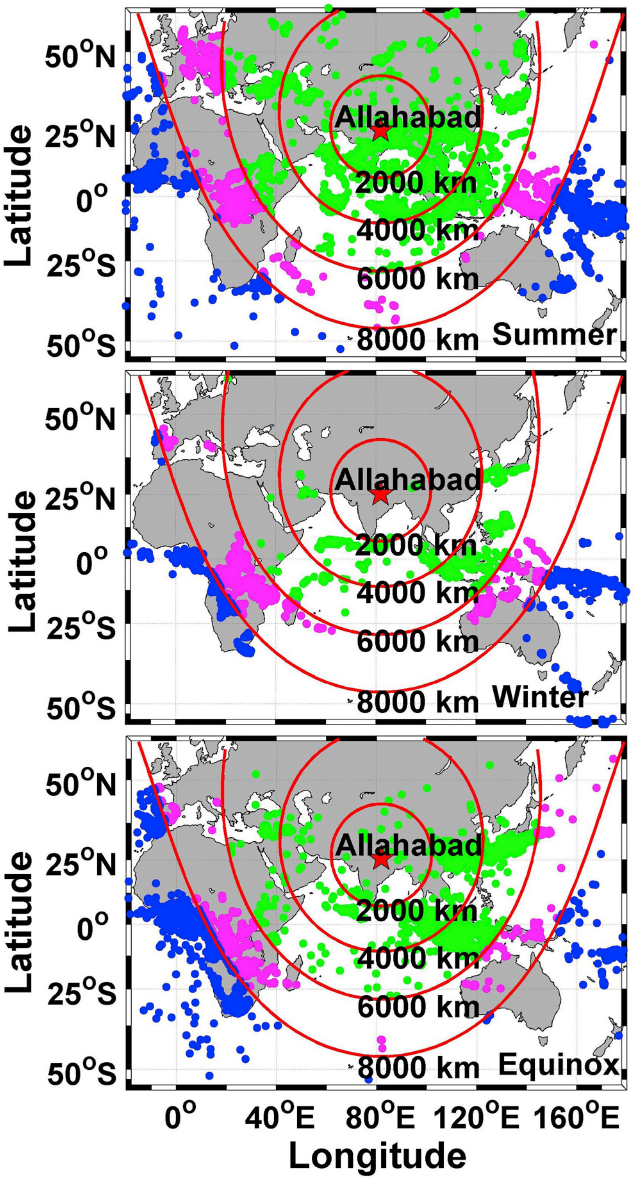

Figure 2. The lightning locations detected by WWLLN during July, January, and October months of summer, winter, and equinox seasons during April 2007 to March 2008 in the nighttime period 18:00–06:00 LT. Green and pink markers indicate lightning locations within 6000 km and 6000–8000 km surrounding Allahabad, and blue dots indicate lightning in rest of area.

paths (lower day time height of EIWG) in the dusk and dawn periods. The daylight side propagation paths are most likely to happen in the dawn period as compared to dusk period as most of the lightings sources are located in the Asia Oceania region. *Thomson* [1993] from the subionospheric VLF observations presented an expression showing the variation of VLF reference height with the solar zenith angle from morning to evening. *Danilov* [1975] studied the ionization-recombination cycle of the D region. The chemistry, ionization, and recombination cycle of the D region are complicated. However, the gradual increase in the reflection height with the nighttime can be attributed to the decrease in electron density at reflection heights mainly due to electron loss processes (recombination and attachment) over the nighttime ionization. Scattered Lyman α is an important source of nighttime D region ionization at the low latitudes and midlatitudes [*Strobel et al.*, 1974]. The geocoronal Lyman α and Lyman β and galactic cosmic rays are other sources of the nighttime D region ionization at the low latitudes. The Lyman α and Lyman β emissions photoionize NO and O_2, respectively. Possible partial explanation of lower h_m in the premidnight during winter season as compared to summer and equinox seasons can be due to lower electron density during daytime in the winter giving rise to slower electron loss processes in the premidnight period of winter. Using a small number of tweeks, *Kumar et al.* [1994] estimated h to vary in the range of 83–89 km from tweek observations taken at a low-latitude station Bhopal (geomagnetic latitude 23.1°N), India. Using the field component analysis of multimode tweeks, *Shvets and Hayakawa* [1998] estimated an increase in the electron density from 28 to 224 el/cm^3 on the 2 km interval at the ionospheric height of 88 km. *Burton and Boardman* [1933] were first to report the nocturnal variation in the reflection height at a midlatitude location (44.0°N, 21.2°W). They found increase in the reflection from 61 km at sunset to 88.5 km at around 21:00 LT and then decrease to 61 km about 15 min before the sunrise. From the analysis of whole set of tweek data recorded on board Academician Vernadsky, *Shvets* [2004] and *Shvets and Gorishnya* [2011] found the ionospheric heights to be in the range of 85–95 km with mean value of about 89 km. *Shvets* [2004] presented the gradual increase in the nighttime tweek reflection height with the increase in the solar zenith angle from about 105° to 150°. *Kumar et al.* [2008] from the observations at Suva (18.2°N, 178.3°E), in the South Pacific region, during September 2003 to July 2004 found the mean reflection heights to vary from 83 to 92 km. The ionospheric reflection height estimated here during April 2007 to March 2008 are consistent within 1–3 km of those estimated by other researchers [*Kumar et al.*, 1994, 2008; *Shvets and Hayakawa*, 1998; *Shvets*, 2004; *Shvets and Gorishnya*, 2011] which in part could be due to varying solar activity levels during these different times of observations. Recently, *Ohya et al.* [2011] studied the long-term (1976–2010) variation in tweek reflection height at Kagoshima, Japan. They found a gradual increase in the mean reflection height from about 94.5 to 97 km (Figure 5) from evening to morning with significant standard deviation. The average nighttime reflection height of about 89.5 km estimated in the present study at a low latitude in the Indian sector is lower by about 6 km than that at midlatitude station Kagoshima (~95.9 km), Japan, reported by *Ohya et al.* [2011].

[10] The maximum and minimum values of the ionospheric reflection height estimated from cutoff frequency of first mode (n = 1) for tweeks with different modes n = 1–6 presented in Table 6 show variations in the maximum reflection heights from ~93 to 95 km and in the minimum reflection height from ~79 to 93 km. Table 6 shows that higher-mode (n > 1) tweeks are reflected from higher heights and show comparatively less variability in the reflection height. With reference to fundamental mode (n = 1), the reflection heights of different harmonics of tweeks in Table 6 are consistent with reflection heights for tweeks in Table 5,

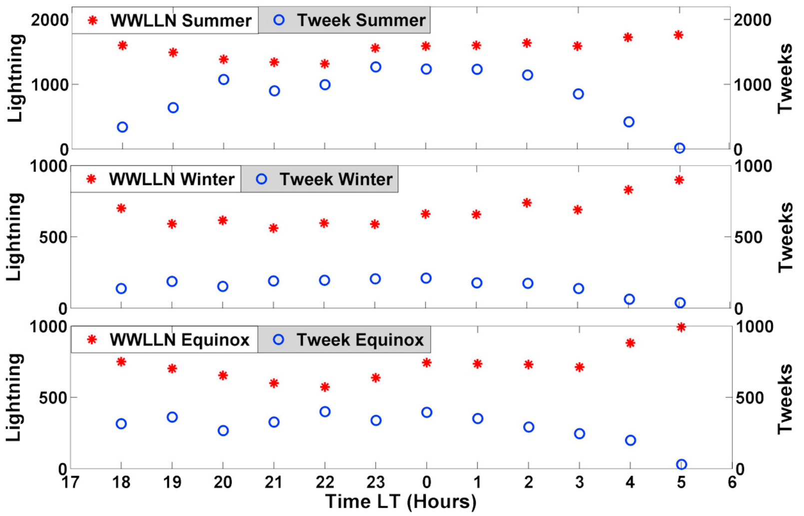

Figure 3. Nighttime hourly occurrence of tweeks on 12 selected days from July 2007, October 2007 and January 2008 and WWLLN lightnings within 8000 km of Allahabad.

which also indicates that tweeks with higher modes are reflected from higher heights. In order to present pure nighttime *D* region variability, we have shown the variation of reflection height in the period 3 h after sunset and 3 h before sunrise, that is, 21:00–03:00 LT (15:30–22:30 UT) on 5 international quiet days from 3 months (1 month from each season). Since reflection height may be affected by geomagnetically disturbed conditions, reflection height analysis on five international disturbed days has not been included in Figure 5. *Ohya et al.* [2006] have shown the changes in the tweek reflection height under the great magnetic storm of October 2000. There were no intense geomagnetic storms during this period of present study. As shown in Figure 5, the maximum reflection height variability in the period 21:00–03:00 LT was around 8 km, and the maximum variation in any 1 h period was around 1.5 km. Thus, the mean reflection height in the period 21:00–03:00 LT given in Figure 5 even under geomagnetically quiet conditions shows large temporal and day-to-day variability of several kilometers in tweek reflection height (nighttime *D* region) in the low-latitude region. The day-to-day variability in the VLF reflection heights at the low latitudes can mainly occur due to direct energy coupling between lightning discharges and lower ionosphere causing short-term

Table 5. The Mode Number, Cutoff Frequencies, Mean Fundamental Frequency (f_{cn}/n), Ionospheric Reflection Height h, and Propagation Distance D for Tweeks Shown in Figure 1

Mode (n)	Cutoff Frequency (kHz)	Mean Frequency (kHz)	Reflection Height (km)	Propagation Distance (km)
		Tweek a in Figure 1		
1	1.5893	1.5893	94.38	2942.58
2	3.1384	1.5692	95.59	
3	4.8210	1.6070	93.34	
4	6.3168	1.5792	95.00	
5	7.8926	1.5785	95.02	
6	9.4658	1.5781	95.05	
		Tweek b in Figure 1		
1	1.6159	1.6159	92.82	3233.14
2	3.2185	1.6092	93.21	
3	4.7943	1.5981	93.86	
4	6.4503	1.6125	93.01	
5	8.0496	1.6095	93.17	
		Tweek c in Figure 1		
1	1.6364	1.6364	91.66	4482.27
2	3.2686	1.6343	91.78	
3	4.8879	1.6293	92.06	
4	6.5119	1.6280	92.14	
		Tweek d in Figure 1		
1	1.6693	1.6693	89.85	5172.60
2	3.3253	1.6627	90.21	
3	4.9271	1.6424	91.33	
		Tweek X in Figure 1		
1	1.6960	1.6960	88.44	5497.17
2	3.3253	1.6627	90.21	

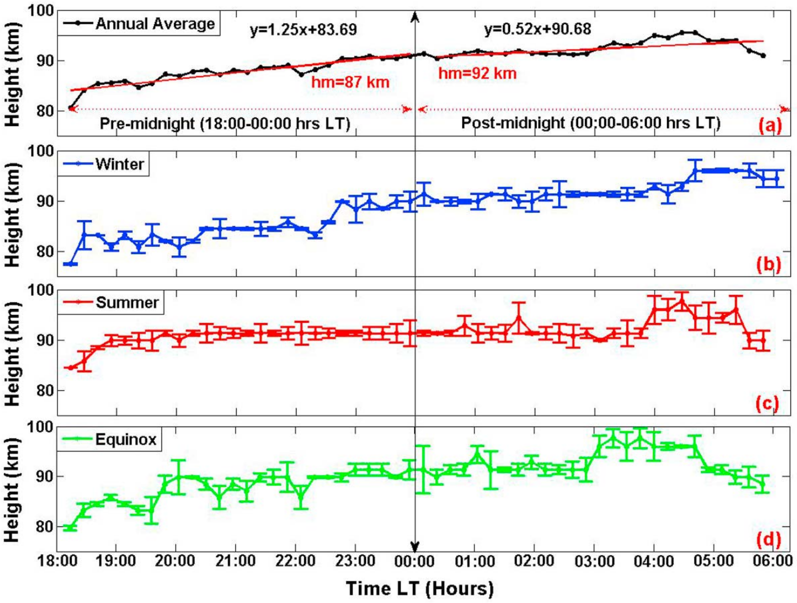

Figure 4. Seasonal variations of mean reflection height during April 2007 to March 2008. The vertical bars in the mean reflection height are standard deviation.

(10–200 s) changes in the electron density or conductivity at the VLF reflection heights [*Inan et al.*, 1988; *Rodger*, 2003]. The heating of lower ionosphere by strong quasi-electrostatic (QE) field generated by strong lightnings causes the conductivity enhancements [e. g. *Pasko et al.*, 1995; *Inan et al.* 1996, 2010] and the electromagnetic pulses (EMPs) from cloud-to-ground and/or successive in-cloud lightning discharges associated with cloud-to-ground discharges can produce appreciable electron density changes which could be electron density enhancements/reductions at the VLF reflection heights [*Inan et al.*, 1993; *Rodger et al.*, 2001; *Marshall et al.*, 2008]. However, there could be other drivers of *D* region reflection height variability at the low latitudes. The day-to-day variability of nighttime reflection height at low latitudes is an area of further experimental and theoretical research. The coming period of higher solar activity would further provide us with an opportunity to study the reflection height and its variability during both the levels of solar activity.

3.3. Tweek Propagation Distance

[11] For distance (>2000 km), 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 in the homogeneous spherical EIWG is given [*Ohya et al.*, 2008] as

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

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

$$D = \delta t\left(\frac{V_{gf_1}\times V_{gf_2}}{V_{gf_1}-V_{gf_2}}\right),$$

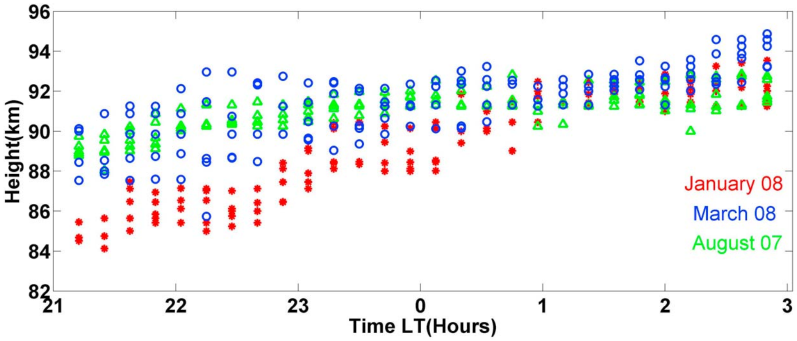

Figure 5. The day-to-day variability of reflection height on five magnetically quiet days of January 2008, March 2008, and August 2007.

Table 6. Ionospheric Reflection Height Range (Maximum to Minimum) for 910 Selected Tweeks Estimated Using Only First Mode (n = 1) for Different Harmonic Tweeks

Modes (n) (Tweeks[a])	Tweek Reflection Range (km)	
	Maximum	Minimum
1 (228)	93.42	79.47
2 (485)	95.49	86.08
3 (163)	94.13	88.56
4 (29)	94.57	91.43
5 (3)	94.86	92.41
6 (2)	94.38	93.15

[a]Number in parentheses shows the total number of modes of tweeks analyzed.

where V_{gf_1} and V_{gf_2} are the group velocities of waves centered at frequencies f_1 and f_2, respectively. The propagation distance calculated under spherical model of the EIWG is about 1.4% higher than that with the flat model of EIWG as used by *Kumar et al.* [2008]. The values of D calculated from the first harmonic (n = 1) of tweeks shown in Figures 1a–1d are given in Table 5 which shows that these tweeks propagated 3000–5000 km before arriving the receiving site. The propagation distance D is comparatively higher for tweeks with lower modes than those with higher modes, e.g., tweek (Figure 1d, marked by X) with n = 1 and 2 mode traveled distance of 5497 km, whereas tweek in Figure 1a with n = 1–6 traveled 2942 km within the accuracy of 500 km. The range of propagation distances (maximum to minimum) and average propagation distances calculated for 910 selected tweeks are given in Table 7. Here we have calculated distance by utilizing fundamental mode (n = 1) for all 910 tweeks. From over all analysis, distance traveled by tweeks is estimated to vary 1500–12,000 km. The average D traveled (Table 7) by tweeks also shows that D is higher for tweeks with lower harmonics than those with higher harmonics. Since higher-order modes reflect at the higher height (i.e., higher conductivity) of 1–2 km than first mode, they are supposed to propagate longer distances, which is not the case here. This is due to higher attenuation offered by EIWG for higher modes (section 3.4, Figure 7) which restricts the higher harmonic tweeks from propagating larger distances. Figure 6 shows percentage of total tweeks (910) that propagated different ranges of distances. From Figure 6 it can be seen that about 23% of tweeks propagated 6000–8000 km, 50% of tweeks from 4000 to 6000 km, 21% of tweeks from 2000 to 4000 km, with a small percentage of tweeks propagating lower (<2000 km) and higher (>8000 km) distances. From earlier measurements of tweeks in India, propagation distances were estimated to be in the range of 900–2500 km [*Kumar et al.*, 1994; *Singh and Singh*, 1996]. This difference can be due to the fact that earlier studies were based on few selected tweeks, and the observation sites were not at very quiet locations. The locally designed receiver was used which was less sensitive and inefficient compared to the new VLF line receiver system used in this study. The propagation distances of tweeks estimated at Allahabad and WWLLN detected lightning locations (Figure 2) within 6000 km and 6000–8000 km areas indicate that about 71% of tweeks were associated with lightnings in the Asia Oceania region, which is one of the three regions of major lightning activity in the world [*Christian et al.*, 2003]. The tweeks arriving from 6000 to 8000 km could propagate a significant portion of their paths in the daytime EIWG particularly those arriving from east and west directions to the Allahabad. With reference to Allahabad station, the EIWG propagation path for tweeks associated with lightning strikes in the Asia Oceania region consists of about 30% ground and 70% sea path. The ELF-VLF propagation over the sea surface undergoes less attenuation as compared to that over the ground [*Kumar et al.*, 2008] which supports the frequent occurrence of tweeks at Allahabad associated with the distant lightnings in the Asia Oceania region. An important observation from Figure 6 is that only a few (0.71%) of the tweeks propagated less than 2000 km. One of the reasons could be that except during the summer season there is very little lightning activity during equinox and winter seasons within 2000 km surrounding the station (Allahabad). During summer most of lightning activity is within 1000–1500 km of the receiving station, and the frequency component of sferics radiated by these nearby lightnings after traveling a small distance may arrive almost simultaneously at the receiving site; hence, tweek waveforms become too short for dynamic spectral analysis applied to recognize and analyze them as the duration of dispersion depends on the propagation distance.

Table 7. Propagation Distance Range (Maximum to Minimum) and Average Propagation Distance Estimated Using Only First Mode (n = 1) for 910 Selected Tweeks With Different Harmonics

Modes (n) (Tweeks[a])	Propagation Range (km)		Average Distance (km)
	Maximum	Minimum	
1 (228)	9495	1932	5130
2 (485)	11,504	2409	6231
3 (163)	9071	2726	4221
4 (29)	8104	3312	3954
5 (3)	5091	2907	3654
6 (2)	3481	2840	3125

[a]Number in parentheses shows the total number of modes of tweeks analyzed.

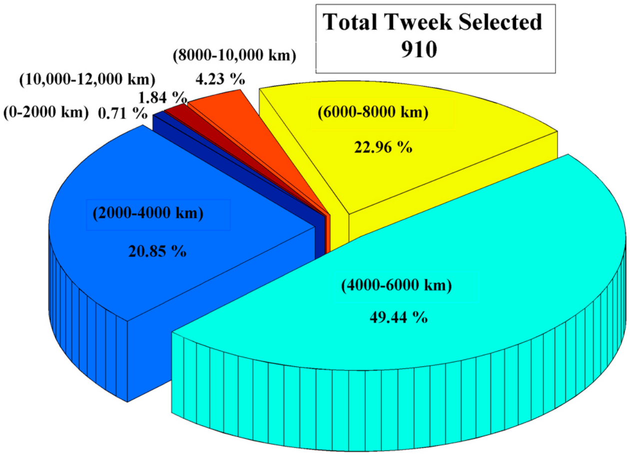

Figure 6. Percentage occurrence of tweeks with propagation distances in different ranges with reference to Allahabad observation site.

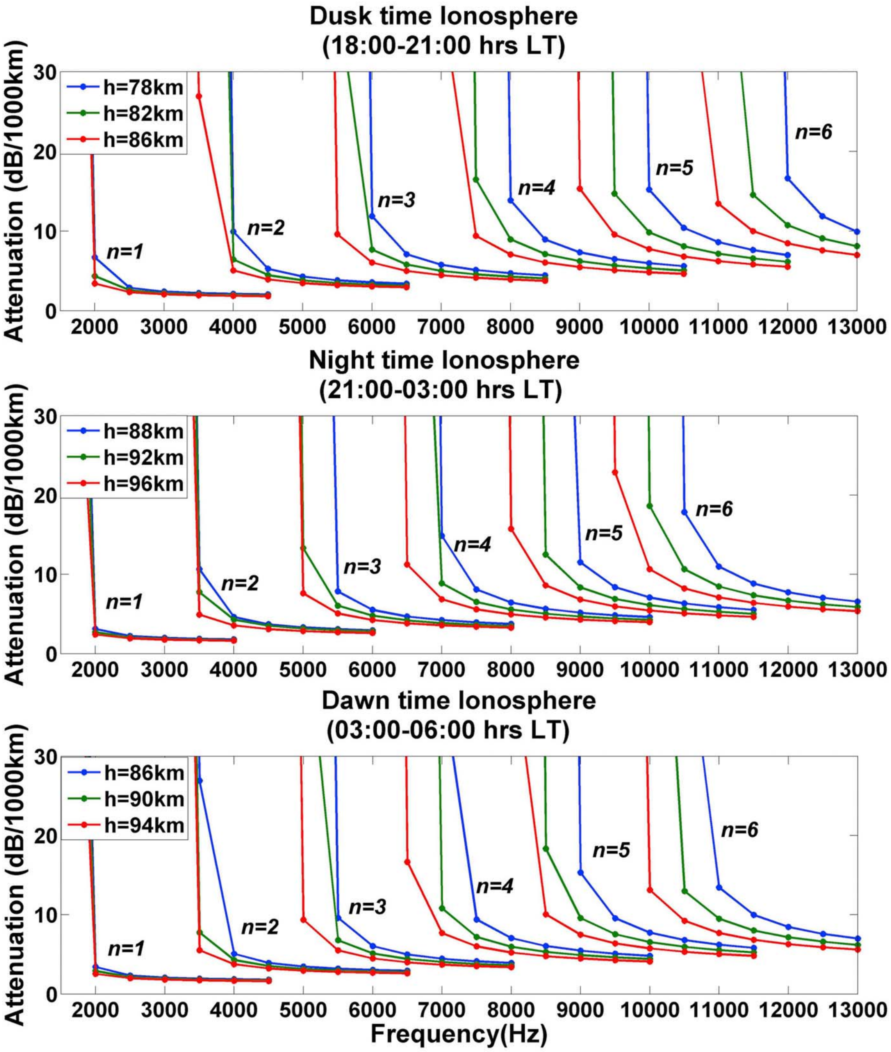

Figure 7. Attenuation factor for different times of local night for modes $n = 1$ to 6 for different periods of the nighttime.

3.4. Attenuation of Tweeks Propagating in the Earth-Ionosphere Waveguide

[12] To explain the occurrence of tweeks in the nighttime and their propagation distances, the attenuation rate [*Wait*, 1957; *Singh and Singh*, 1996], defined as in dB per 1000 km of path length has been theoretically calculated for $n = 1$–6, where k is wave number. Im S_n is imaginary part of complex function S_n which is the "sine" of the complex angle between the wave vector and the normal at the points of incidences in the EIWG and is defined as

$$S_n = \sqrt{1 - \left(\frac{n\pi}{kh}\right)^2 - i\frac{2\Delta}{kh}},$$

where n is mode number and h is height of waveguide. The value of Δ is governed by the electrical conductivities of Earth's surface and the lower ionosphere. The function S_n is dependent on the mode number, wave frequency, reflection height, and conductivity of reflection boundaries [*Wait*, 1957; *Kumar et al.*, 2008]. In the case of perfect conducting boundaries of the EIWG, α_n vanishes for all the modes, and tweeks with higher modes should occur at all the times. In real fact, tweeks presented here and those presented in earlier observations [e.g., *Singh and Singh*, 1996; *Ohya et al.*, 2003; *Cummer et al.*, 1998; *Kumar et al.*, 2008] were observed only in the nighttime due to low attenuation offered by the nighttime EIWG. To calculate the attenuation factor, we consider ionospheric relative permittivity $\varepsilon_{ri} = 0.5$, ground relative permittivity $\varepsilon_{gi} = 20$, sea relative permittivity $\varepsilon_{si} = 81$, ground conductivity $\sigma_g = 10^{-4}$ mho/m, sea conductivity $\sigma_s = 5$ mho/m, ionospheric nighttime conductivity $\sigma_{in} = 3.284 \times 10^{-4}$ mho/m, and ionospheric daytime conductivity $\sigma_{id} = 7.65 \times 10^{-6}$ mho/m [*Westerlund*, 1974; *Prasad*, 1981; *Singh and Singh*, 1996]. Tweek propagation distances and lightning activity in the Asia Oceania region indicate that a good portion of propagation path of tweeks lies over the sea. The nighttime reflection height in the present study is found to vary from 78 to 96 km. The dusk time ionospheric reflection height varies 78–86 km, nighttime reflection height varies 88–96 km, and dawn time height varies 86–94 km. Therefore, attenuation factor (α_n) for different periods of the night (dusk, early night, late night, dawn) has been calculated for above the EIWG heights. The early and late night periods have been taken together because in this time period (21:00–03:00 LT) the attenuation is almost same. The attenuation factor (α_n) calculated for modes 1 to 6 is shown in Figure 7. The α_n increases with the decrease in the frequency with maximum near the cutoff frequency of different modes. The α_n also increases with the increase in the mode number of tweeks. The α_n for n = 1–6 modes in the early and late night periods is less, particularly as compared to that in the dusk period consistent with the higher occurrence of tweeks in the nighttime as compared to that in the dusk period (Tables 1–3). The α_n during the dawn period for the height of the waveguide taken here is not significantly less than that during the nighttime (Figure 7, bottom). Since most of the tweeks in the dawn period originating from lightnings in the Asia Oceanic region travel under daytime and suffer more attenuation. Therefore, the occurrence of tweeks in the dawn period is also less (Tables 1–3) and decreases despite the increase in the WWLLN detected lightings (Figure 3).

4. Summary

[13] Atmospherics (sferics) excited by lightning discharges in the ELF-VLF range form tweeks on propagating large distances in the EIWG in the nighttime with clear dispersion in the lower-frequency components. Morphological features of tweeks observed at low-latitude ground station, Allahabad, India, during the 1 year period from April 2007 to March 2008 and the *D* region reflection heights estimated from tweeks have been presented. A total of 19,308 tweeks was observed in the local nighttime (18:00–6:00 LT). Tweek duration (dispersed section) decreases with the increase in the mode number. The frequency components corresponding to n = 1 are present in all the tweeks. Tweek with modes n = 1 and 2 have been found to occur most frequently with overall occurrence of about 70%, followed by tweeks only with first mode (25%). Tweeks with higher modes n = 3–6 have very less occurrence due to larger attenuation for frequency components of higher modes of tweeks. Seasonal variation of tweek occurrence shows maximum occurrence during summer (63%) and almost same occurrence during equinox and winter seasons (~18–19%). This is consistent with the more lightning activity detected by WWLLN during summer in the Indian and surrounding regions mainly in the Asia Oceania region. The average seasonal (annual) tweek ionospheric reflection height rises gradually from about 80 to 95 km due to increase in the solar zenith angle and electron loss processes in the nighttime. The mean reflection height in the postmidnight is higher by about 5 km as compared to that in premidnight. The tweek reflection height is lower in the premidnight period as compared to that in the postmidnight period during summer, winter, and equinox seasons. The reflection height in the premidnight during winter is lower by 1–3 km as compared to that in the premidnight during summer and equinox. The reflections height estimated in the present study are consistent within 1–3 km of those reported in previous studies. Our initial results on day-to-day variability of reflection height under the pure nighttime (21:00–03:00 LT) propagation on magnetically quiet days selected from three months (5 days from one month of three seasons) show overall day-to-day variability of up to 8 km and maximum variability in any one 1 h period of about 1.5 km. Most likely reasons of day-to-day variability in tweek reflection height at the low latitude seems the direct lightning discharge energy coupling with lower ionosphere producing short-term *D* region electron density perturbations. However, day-to-day variability of nighttime *D* region at the low latitudes is an interesting area of further experimental and theoretical research. Most (~95%) of tweeks propagated distance in the range of 2000–8000 km upon reaching the receiving station. The propagation distance for the tweeks with higher modes is lower as compared to the propagation distance of tweeks with lower modes. The propagation distances and lightnings detected by WWLLN indicate that causative lightnings of the most tweeks observed at this site were located in the Asia Oceania region. The occurrence of tweeks with different harmonics and in the different periods of night is also consistent with higher attenuation offered by the EIWG for higher modes, variation in the attenuation factor for different periods of the night, and the path conditions (day or night) during propagation of tweeks.

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