D-region ionosphere response to the total solar eclipse of 22 July 2009 deduced from ELF-VLF tweek observations in the Indian sector

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[1] Observations of tweeks with higher harmonics ($n > 1$) at low latitude stations Allahabad and Nainital, in the Indian sector, during the total solar eclipse on 22 July 2009, are presented. Allahabad and Nainital stations were in 100% and 85% of the totality paths. Observations suggest that about 30–40% obscuration of solar disc can lead to the tweeks occurrence which otherwise occur only in nighttime. A total of 148 tweeks at Allahabad and 20 tweeks at Nainital were recorded with some of them up to 3rd harmonics. The World Wide Lightning Location Network data indicated that tweeks observed were generated by lightning's located in the partial eclipse area of Asia-Oceania region. The changes in D-region ionospheric VLF reflection height and electron density (~22–23 cm^{-3}) during eclipse have been estimated from the first cut-off frequency of the tweeks. The reflection height increased from ~89 km from the first occurrence of tweek to about 91–92 km at the totality and then decreased to ~87 km at the end of the eclipse, suggesting a change of about 5 km in the reflection height during eclipse. The reflection heights are lower by 2–3 km as compared to normal nighttime tweek reflection heights. The above increase in the reflection height indicate that the partial nighttime condition is created during eclipse, as the main D-region ionizing radiation Lyman α is blocked but solar soft X-ray and EUV radiations originating from the limb solar corona are not totally blocked which produce some of ionization in the D-region.

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1. Introduction

[2] A solar eclipse provides us with an excellent and rare opportunity to monitor the changes in the ionosphere associated with the sudden solar radiation variations during the solar eclipse. There are good number of ionospheric observations during solar eclipses mainly dedicated to E and *F* regions of the ionosphere (above altitude of 100 km) through rocket, radar and ionosonde techniques [*Minnis*, 1952; *Accordo et al.*, 1972; *Farges et al.*, 2001; *Chandra et al.*, 2007; *Le et al.*, 2008a, 2008b; *Patra et al.*, 2009; *Chen et al.*, 2010]. D-region is the lowest part of ionosphere ranging from ~60–75 km in the daytime and ~75–95 km in the nighttime [*Hargreaves*, 1992]. The probing of D-region of ionosphere is difficult as the altitude is too low for satellites and too high for balloon studies. Therefore, it remains the least studied region of the Earth's atmosphere. The Extremely Low Frequency (ELF: 30 Hz–3 kHz) and the Very Low Frequency (VLF: 3–30 kHz) waves generated by lightning discharges propagate by multiple reflections through the waveguide formed by the earth and the lower ionosphere (Earth-ionosphere waveguide) and form the novel tools to study the D-region of the ionosphere.

[3] During a solar eclipse, the decrease in solar flux due to moon's shadow causes sudden change in the D-region physical and chemical processes. During the totality due to blocking of Lyman-α 1215Å (major D-region ionizing radiation) by moon's umbral shadow, the electron density decreases drastically toward the nighttime values [*Smith*, 1972]. Tweeks are formed when lightning generated ELF-VLF atmospherics propagate long distances, particularly in the night, in the Earth-ionosphere waveguide with a low

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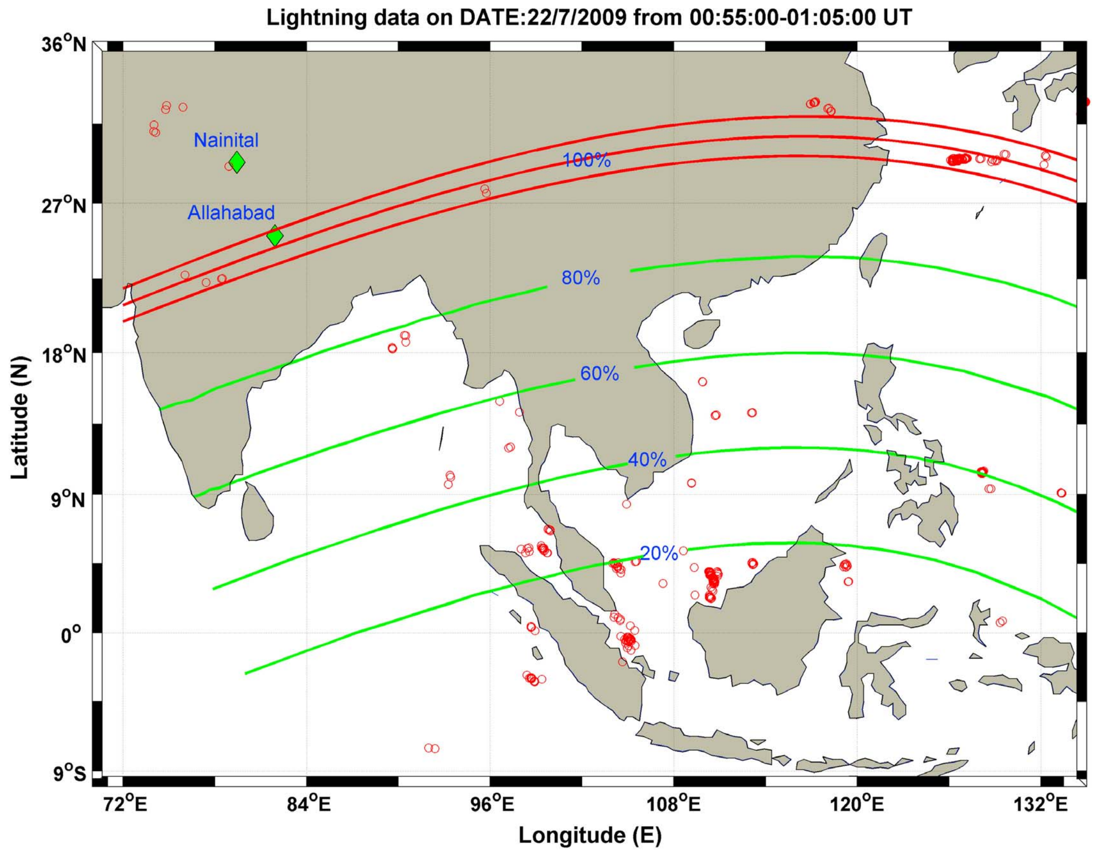

Figure 1. The solar eclipse paths in India and Asia on 22 July, 2009. The locations of VLF receivers at Allahabad and Nainital are represented by green diamonds. The WWLLN detected lighting locations for 10 min (00:55:00-01:05:00 hrs UT) during the total solar eclipse are represented by red circles.

attenuation of 2–3 dB/1000 km [*Yamashita*, 1978; *Davies*, 1990, p. 389]. The received sferic is then slightly dispersed having a sharp low frequency cutoff at around 1.5–2 kHz. *Burton and Boardman* [1933] were first to report observation of 17 tweeks during a total solar eclipse of 31 August 1932 at Conway, New Hampshire and suggested that atmospheric intensity variations indicated an approach to the nighttime condition near the period of totality. During the total solar eclipse of 7 March 1970, in Newfound land, Canada, *Rycroft and Reeve* [1970] observed about 60 tweeks and utilized these tweeks to determine the change in the ionospheric reflection heights during the eclipse. They estimated an increase of about ~7 km above the normal daytime reflection heights. Many workers have successfully used tweeks as novel tool to study the nighttime D-region of ionosphere [*Kumar et al.*, 1994, 2008, 2009; *Hayakawa et al.*, 1994; *Cummer et al.*, 1998; *Ohya et al.*, 2006; *Saini and Gwal*, 2010; *Maurya et al.*, 2010].

[4] Recently, East and South Asian regions witnessed the largest total solar eclipse of this century on 22 July 2009 with totality duration of about 6 min and 39 s. The total solar eclipse of 22 July 2009 is also the longest solar eclipse of this century. It occurred just after sunrise time in India with a magnitude (the ratio of apparent size of moon to the apparent size of sun during eclipse) of 1.026 and width of about 280 km. The detailed information about this eclipse can be found at http://eclipse.gsfc.nasa.gov/SEmono/TSE2009/TSE2009.html. The path of moon's umbral shadow began in India and passed through Nepal, Bangladesh, Bhutan, Myanmar, China and then reached to the Pacific Ocean. A partial eclipse was seen within the much broader path of moon's penumbral shadow including the rest of India and Asia-Oceania. The total solar eclipse of 22 July 2009 was also unique in the sense that it occurred during night-day transition period in India when D-region ionosphere is not totally developed. Indian Institute of Geomagnetism, India, conducted a multistation observation campaign during this solar eclipse. The present study is part of this campaign in which continuous VLF measurements were taken at three low latitude stations: Allahabad (Geog. lat., 25.40°N; Geog. long. 81.93°E; Geomag. lat. 16.05°N), Varanasi (Geog. lat., 25.27°N; Geog. long., 82.98°E; Geomag lat 14.55°N) and Nainital (Geog. lat., 29.35°N; Geog. long. 79.45°E; Geomag. lat. 20.48°N). Allahabad and Varanasi were in 100% of totality and Nainital was in the partial eclipse (85% of totality), respectively. The totality path and partial eclipse conditions in India and in remaining regions of Asia are shown in Figure 1. In the present paper we have analyzed the broadband VLF data recorded at Allahabad and Nainital for tweeks during the solar eclipse of 22 July 2009. Tweeks observed at Allahabad and Nainital have been utilized to estimate the changes in the VLF reflection heights and electron densities

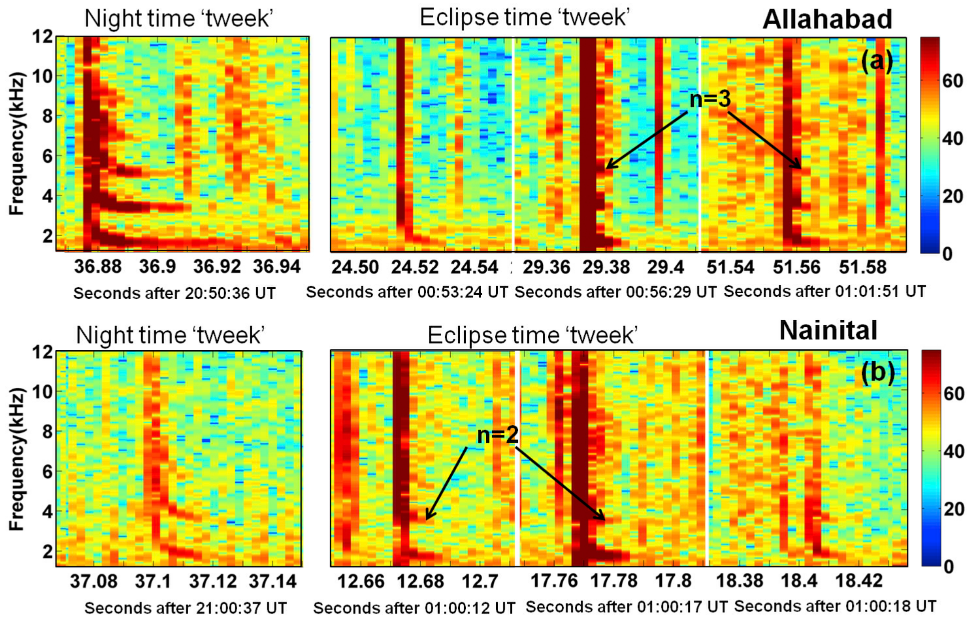

Figure 2. The tweeks examples observed at (a) Allahabad and (b) Nainital stations on 22 July 2009 before, during and after the eclipse totality. The second and third harmonic tweeks are indicated as $n = 2$ and $n = 3$. On the left sides of Figures 2a and 2b, tweeks observed in the nighttime on 22 July 2009 are shown.

in the D-region ionosphere. Data from Varanasi are not used because of the masking of the lower frequency components of tweeks by power line harmonic interference. This study is second after *Reeve and Rycroft* [1972] in which eclipse time tweeks have been utilized to study the morphological changes in *D*-region ionosphere during total solar eclipse.

2. Experimental Setup

[5] The present study is based on the VLF observations made at Allahabad and Nainital during a special campaign for 22 July 2009 total solar eclipse. The recording system consists of a Stanford University built AWESOME VLF receiver [*Cohen et al.*, 2009; *Singh et al.*, 2010] with two crossed loop antennas to receive East-West and North-South horizontal magnetic field components. A pre-amplifier is kept near the antennas for impedance matching to ensure maximum power transfer and pre-amplification of received signal. It is connected with line receiver by a long cable of about 300 m. The line receiver performs anti-aliasing filtering, GPS time synchronization and post processing of the data. The acquired data are sampled by 16-bit analog-to-digital converter at 100 kHz sampling frequency. The lower and upper cut-off frequency of the receiver is between ~300 Hz to 47 kHz. Detailed information about the experimental setup is given by *Singh et al.* [2010]. The Indian VLF stations are part of global AWESOME network of ground based VLF stations, setup under the auspices of the International Heliophysical Year 2007 [*Scherrer et al.*, 2008; *Singh et al.*, 2010]. We have two types of data recording: broadband data (from 300 Hz - 47.5 kHz) and narrowband data (amplitude and phase of VLF transmitter frequencies). Normally, we record broadband data in synoptic mode (one minute at every 15 min interval) but during the special campaign for this solar eclipse, broadband data at Allahabad were recorded in continuous mode and at Nainital in the synoptic mode.

3. Observations

[6] Tweeks atmospherics launched by lightning discharge are signals observed in the nighttime from 18:00 - 5:30 h LT because of low attenuation during the nighttime [*Kumar et al.*, 2008]. LT (IST-Indian Standard Time) = UT + 5.5 h. Figures 2a and 2b show examples of tweeks observed on 22 July 2009 at Allahabad (Figure 2a) and Nainital (Figure 2b) arranged in chronological order, from nighttime to the eclipse totality period and after the totality. The tweeks observed at Allahabad in the nighttime at 20:50 h UT (02:20 h LT) and at 21:00 UT (02:30 h LT) at Nainital are shown in Figure 2 (left). The remaining tweeks shown were observed ±5 min intervals around the eclipse totality at both the stations with the cutoff frequency ~1.8 kHz. At Allahabad, eclipse totality started at 00:55:08.9 h UT and lasted for a duration of about 45.4 s. Nainital station was under partial eclipse with a maximum of 85% at 00:57:18.3 h UT. During the solar eclipse period the tweeks up to 3rd harmonics were observed. There are characteristic differences between the tweeks observed in the nighttime (before eclipse) with those observed during the eclipse period. Nighttime tweeks are brighter, having clarity and more tweek dispersion duration (dispersed section). To study the occurrence of tweeks at Allahabad with the variation in solar eclipse conditions we have counted the total number of tweeks in 5 min intervals of eclipse period starting from 00:00:00–02:00:00 h UT (or 05:30–07:30 h LT). The number of tweeks observed in the intervals of 5 min in the period 00:00:00–02:00:00 h UT along with the number of higher harmonics during the eclipse totality at Allahabad is represented in Figure 3a. A total of

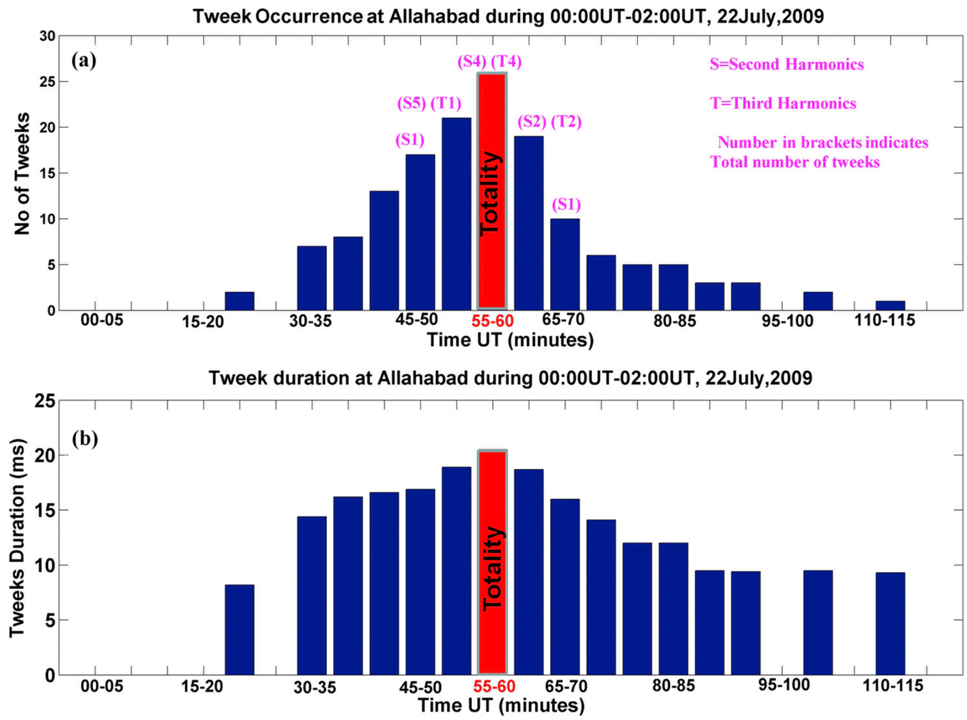

Figure 3. The tweek occurrence between 00:00–02:00 h UT in 5 min intervals at Allahabad. Other than tweek with single harmonic, tweeks with second and third harmonics are denoted by S and T and the numbers in brackets represent the number of tweeks observed in respective intervals. The (a) occurrence of tweeks and (b) duration of their dispersed section during the totality is shown by red bars.

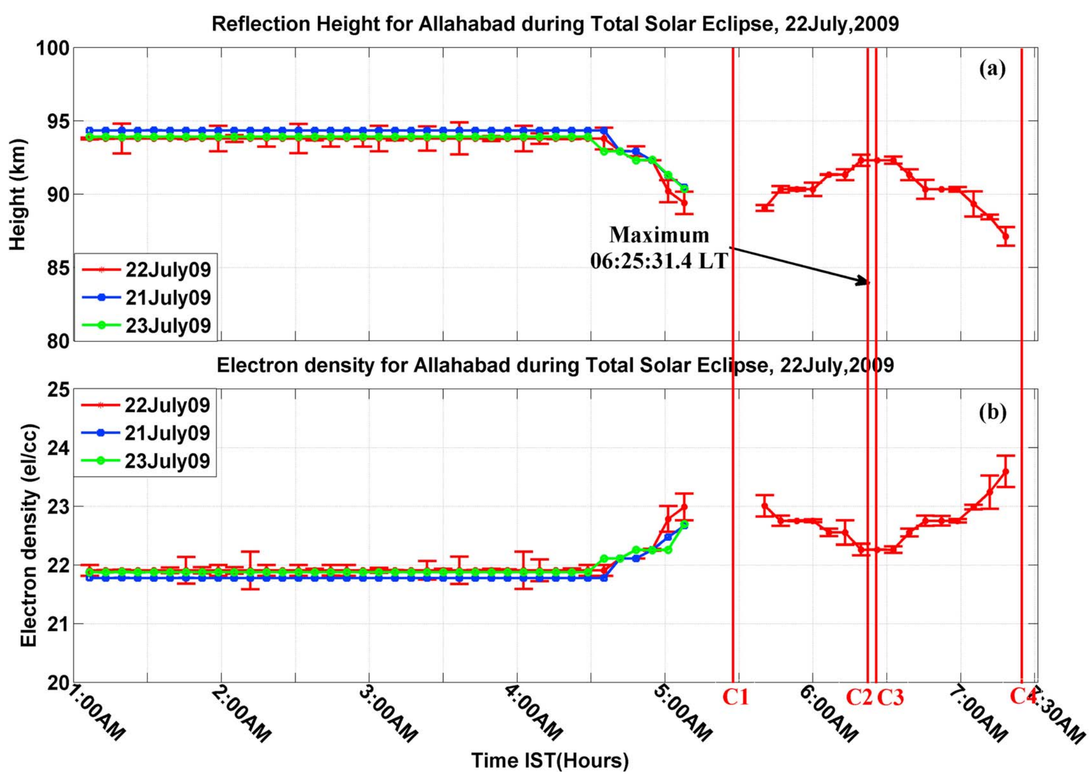

Figure 4. The variation of (a) reflection height and (b) electron density at reflection heights calculated from first harmonic cutoff frequency of tweeks observed at Allahabad on 21–23 July 2009 over 5 min intervals from 01:00–07:30 h LT. The vertical line marked with C1 represents the beginning of the solar eclipse, C2-C3 represents the totality period and C4 represents the end of solar eclipse at Allahabad (Table 1).

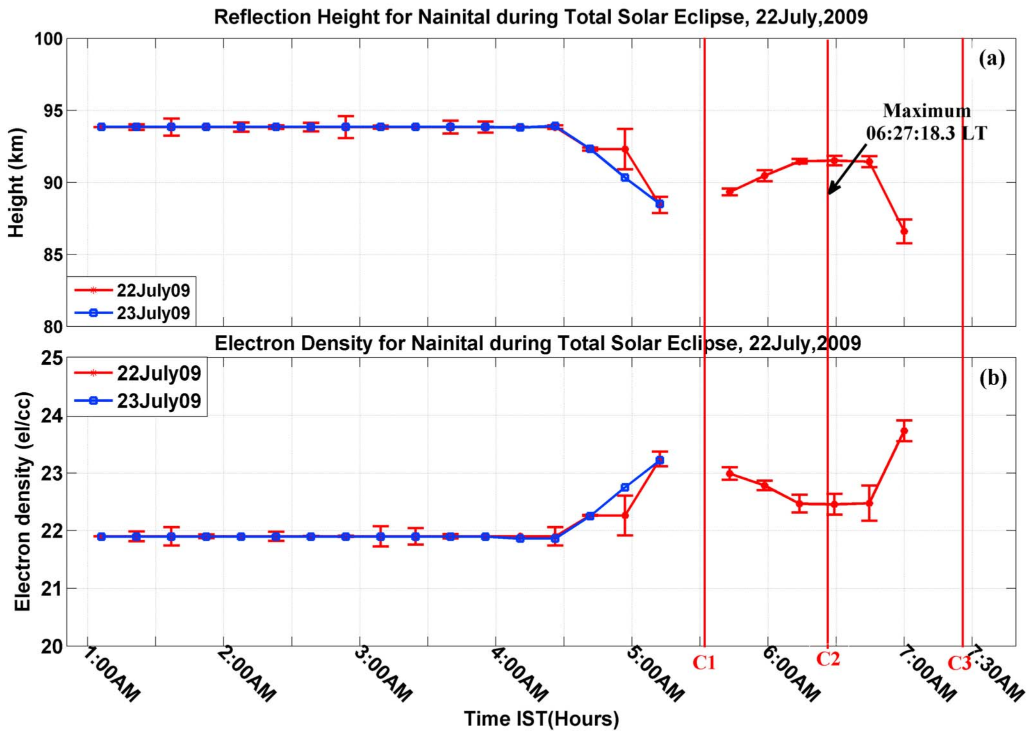

Figure 5. The variation of (a) reflection height and (b) electron density at reflection heights calculated from first harmonic cutoff frequency of tweeks observed at Nainital on 21–23 July 2009 over 15 min intervals from 01:00–07:30 h LT. The vertical lines marked with C1 (beginning), C2 (maximum) and C3 (end) represent the different eclipse conditions at Nainital (Table 2).

148 tweeks, out of which 140 occurred in the 1 h period (from 00:30:00–01:30:00 h UT), were observed in the total eclipse duration of ~00:00:00–02:00:00 h UT. Tweek occurrence was more in the interval of 00:55–01:00 h UT (around total solar eclipse) at Allahabad on 22 July 2009 as compared to other 5 min intervals. Tweeks with higher harmonics ($n > 1$) up to 3rd harmonics were observed only during the totality period and about 10 min before and after the totality. Figure 3b shows the variation in the average tweek duration (dispersed portion) in 5 min intervals during the eclipse period starting from 00:30:00–01:30:00 h UT at Allahabad. The tweek duration is found to vary from 14 ms at the beginning to 21 ms at the totality and 9.5 ms at the end of the eclipse. The duration of tweek, in general, at these two stations is about 30 ms (Figure 2, left). The shorter duration of tweeks during solar eclipse as compared to normal nighttime tweek duration may result from shorter propagation distances of tweeks during the solar eclipse. The characteristics of tweeks (not shown here) recorded at Nanital are same as those observed at Allahabad. The observation of 148 and 20 tweeks at both the stations during two hours around the eclipse totality is important, because this number of tweeks can be easily seen in the regular observations in the nighttime within short period of 1–5 min. Thus making eclipse time tweek observations important to understand the solar eclipse effect on D-region ionosphere.

[7] The cutoff frequency (f_c) of each tweek has been measured with an accuracy of 26 Hz and time by 1 ms from the spectrograms which correspond to errors of ±1.6 km in the reflection height, ±0.35 el/cc in the electron density, and ±500 km in the propagation distance. The reflection height (h) has been calculated using the expression $h = c/2f_c$ [*Yamashita*, 1978], where c is the velocity of light in free space. The electron density (n_e) at the h has been determined using the expression n_e (cm^{-3}) = $1.3651 \times 10^{-2} f_c$ [*Ohya et al.*, 2003]. The results are presented in Figures 4 and 5 for Allahabad and

Table 1. Variation of 22 July 2009 Solar Eclipse Magnitude and Duration at Allahabad[a]

Event	Date	Time (UT)	Altitude (deg)	Azimuth (deg)
Start of partial eclipse (C1)	22/07/09	00:00:17.0	000.4	067.6
Start of total eclipse (C2)	22/07/09	00:55:08.9	012.1	073.1
Maximum eclipse	22/07/09	00:55:31.4	012.2	073.1
End of total eclipse (C3)	22/07/09	00:55:54.3	012.3	073.2
End of partial eclipse (C4)	22/07/09	01:56:46.1	025.6	078.6

[a]Allahabad: Lat = 25.408°N, Long = 81.936°E; Eclipse Magnitude = 1.001; Duration = 45.4 s. Source: http://eclipse.gsfc.nasa.gov/SEgoogle/SEgoogle2001/SE2009Jul22Tgoogle.html.

Table 2. Variation of 22 July 2009 Solar Eclipse Magnitude and Duration at Nainital[a]

Event	Date	Time (UT)	Altitude (deg)	Azimuth (deg)
Start of partial eclipse (C1)	22/07/09	00:03:36.5	0.6	66.9
Maximum eclipse (C2)	22/07/09	00:57:18.3	11.6	73.1
End of partial eclipse (C3)	22/07/09	01:56:19.0	24.1	79.4

[a]Nainital: Lat = 29.359°N, Long = 79.458°E; Eclipse Magnitude = 0.845. Source: http://eclipse.gsfc.nasa.gov/SEgoogle/SEgoogle2001/SE2009Jul22Tgoogle.html.

Nainital, respectively. Figure 4 shows the variation of the h (Figure 4a) and n_e (Figure 4b) at the h estimated from the average f_c of first harmonic of tweeks in 5 min intervals observed at Allahabad in the period 1:00-07-30 h LT on pre-eclipse day (21 July), eclipse day (22 July) and post-eclipse day (23 July). 21 July was the magnetically a quiet day whereas 22 and 23 July were magnetically moderate disturbed days. The eclipse day was accompanied with a moderated magnetic storm whose main phase onset occurred after the passage of the moon's umbral shadow and had a minimum in D_{st} of −78 nT at 07:00 h UT. It is seen from the Figure 4, that the h and n_e on 21–23 July were almost same in the period 01:00–05:15 h LT indicating no effect of this storm on h and n_e. However, moderate magnetic storms of such intensity may have a minimal effect on the D-region ionosphere. The normal feature seen on normal days at the stations is, h starts decreasing and n_e increasing after around ~04:30 h LT due to the increase in the morning time D-region ionization and tweeks are not observed after 05:15 h LT, the reason being increase in ionospheric attenuation with sun rise. On 22 July after sunrise when solar eclipse appeared, a good number of tweeks were observed in the eclipse period, which has been utilized to estimate the h and n_e at h with the variation in solar radiation. The build up time of eclipse, maximum (totality) period and end of eclipse have been marked with C1, C2-C3, and C4, respectively (see Tables 1 and 2 for details). It can be seen from Figure 4a that h increased from 88 km at the beginning of solar eclipse to 92 km at the totality and then decreased to 87 km at the end of eclipse. It is also found that the increase in h coincides well with the maximum totality time (period of C2–C3). The estimated n_e at h is 22–23 cm^{-3}.

[8] Figure 5 presents the variation in the h (Figure 5a) and n_e at h (Figure 5b) from tweeks observed at Nainital in the period 1:00–07:30 h LT for one minute durations at 15 min intervals due to synoptic mode (1 min every 15 min) of the broadband data recording at this station. We have compared h (Figure 5a) and n_e estimations with post-eclipse day (23 July) as the observations on 21 July could not be made due to technical difficulty. Similar to Figure 4, the h (Figure 5a) and n_e were almost same during the period of 01:00–05:30 h LT both on 22 and 23 July. The maximum in

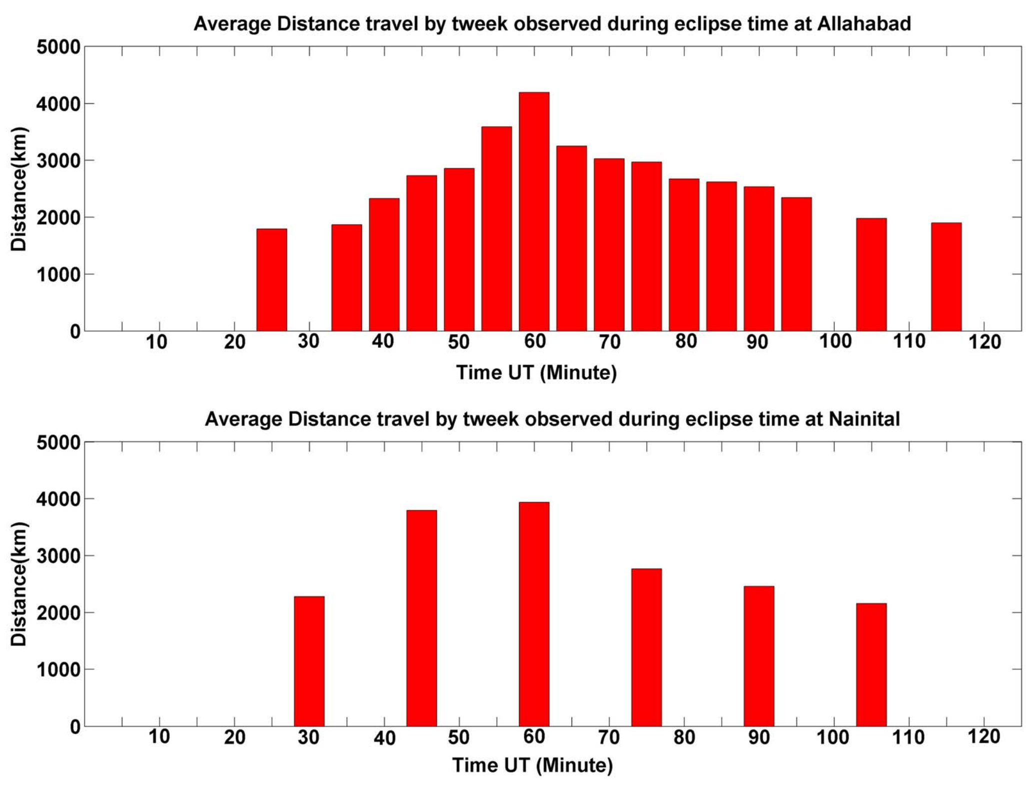

Figure 6. Propagation distance traveled by tweeks observed during total solar eclipse of 22 July 2009 at (top) Allahabad and (bottom) Nainital.

h was 91 km at Nainital during the totality. Less number of tweeks were observed at Nainital as compared to Allahabad, because of Nainital was under partial eclipse (85% of eclipse), however, the maximum of *h* during eclipse period occurred at the same time (marked with C2) at both the stations.

[9] Tweek propagation distance (*D*) in the waveguide having perfectly conducting boundaries were calculated using the method used by *Kumar et al.* [2008], given as $D = \delta t\ (v_{gf_1} \times v_{gf_2})\ |(v_{gf_1} - v_{gf_2})|^{-1}$. where $\delta t = t_2 - t_1$ is the difference in arrival times of two frequencies f_1 and f_2 close to the cutoff frequency of the first harmonic of tweeks and v_{gf1} and v_{gf2} are the corresponding group velocities. The group velocities (V_{gf_1}, V_{gf_2}) are first calculated using $v_{gf} = c(1 - f_{cn}^2/f^2)^{-1/2}$ from the cutoff frequency and frequency f (f_1 or f_2). The group velocities are then used to calculate the propagation distance. The calculated *D* from tweeks observed during eclipse time is found to vary in the range from ~1000–4000 km as shown in Figure 6, indicating that lightning source were located within 4000 km surrounding area of our observation sites. To find the causative lighting sources of the tweeks, we have checked the World Wide Lightning Location Network (WWLLN) lightning data. For more information on WWLLN interested reader is referred to *Rodger et al.* [2006]. WWLLN detected lightning locations for 10 min around the eclipse maximum are plotted in Figure 1 (in red circles). Most of the lightning sources are laid in partial eclipse and totality regions and some of them nearly coincide with tweek occurrence time, so it is reasonable to expect that tweeks received during eclipse time, have the sources in Asia-Oceania region. To find the accurate source locations, direction finding technique needs to be utilized which is not a part of present work.

4. Discussion

[10] The solar eclipse of 22 July 2009 was unique in the sense that it occurred during night-day transition time (dawn hours) during which the daytime lower ionosphere is in developing stage. VLF observations from the two low latitude stations in the Indian region, one in totality and other in partial eclipse, have been used to study the D-region changes during this solar eclipse. There are not many previous studies on the observation of tweeks during solar eclipses except by *Burton and Boardman* [1933] during the solar eclipse of 31 August 1932 at Conway, New Hampshire and by *Rycroft and Reeve* [1970] for the solar eclipse of 07 March 1970. *Reeve and Rycroft* [1972] observed only the first harmonic tweeks and estimated an increase in the ionospheric reflection height of about 7 km over the normal daytime reflection heights. Present study deals with the detailed properties of tweeks such as occurrence, duration of dispersed portion of tweeks, changes in the reflection heights, and the electron density over the reflection heights during the solar eclipse.

[11] Typical tweeks samples given in Figure 2 show distinct differences between tweeks observed during the eclipse time and during the normal nighttime mainly due to different attenuation rates, propagation distances, and conditions both during solar eclipse and the nighttime. Attenuation of waves depends on the conductivity of boundaries of waveguide, wave frequency, ionospheric reflection height, and the mode number [*Singh and Singh*, 1996; *Kumar et al.*, 2008]. In the nighttime attenuation is less hence the propagation is favorable for observation of tweek with higher harmonics. The tweeks up to 6th harmonics have been observed during the normal nighttime conditions with propagation distances longer than of the tweeks observed during this solar eclipse [*Hayakawa et al.*, 1994; *Kumar et al.*, 2008]. During solar eclipse maximum, the peak reflection height was 92 km and 91 km at Allahabad and Nainital, respectively, which is 2–3 km less as compared to reflection heights estimated on pre and post-eclipse days in the nighttime at these stations. The tweeks only up to 3rd harmonics were observed during the solar eclipse of 22 July 2009 at Allahabad and Nainital. The propagation paths for most of the tweeks were in the partial eclipse region which offers more attenuation as compared to the nighttime propagation paths. Due to higher attenuation and less propagation distances during solar eclipse as compared to normal nighttime conditions, the observed tweeks at Allahabad and Nainital stations during this eclipse have less dispersed duration and are not very bright as the nighttime tweeks, and most of them have only first harmonics. Maximum number of tweeks was observed during the totality period when attenuation is less (Figure 3a). Duration of dispersed portion (tweek duration) of tweeks also followed the eclipse conditions at Allahabad as tweeks with higher tweek duration (~20 ms) occurred in the totality interval (55–60 min, Figure 3b). It shows that the tweeks during the totality have propagated longer distances to the receiver as during the totality lower ionosphere (D-region) offers maximum reflection height and minimum attenuation. The tweek duration depends on distance traveled by tweek from source to receiver [*Kumar et al.*, 2008]. The duration of tweeks observed here is less than the average tweek duration of ~30–50 ms in the nighttime [*Ryabov*, 1992; *Kumar et al.*, 2008].

[12] The sunrise times on 22 July 2009 at the ground locations of Allahabad and Nainital were 23:54:00 and 23:56:00 h UT, respectively (source: http://www.usno.navy.mil/USNO/astronomical-applications/data-services/rs-one-day-world). Solar eclipse commenced at 00:00:00 h UT (05:30:00 h LT) and ended at ~01:57:00 h UT (07:27:00 h LT) at both the stations. Regular observations show that during the month of July tweeks are observed in the local nighttime between ~19:00 h LT - 05:30 h LT (13:30 h UT 00:00 h UT). On the eclipse day (22 July), the tweeks were observed up to 05:21:41 h LT (23:51:41 h UT) like the normal days, but tweeks were again observed after a gap of ~30 min. Tweeks started appearing at 05:50:00 h LT (00:20:00 h UT) and ended at 07:22:47 LT (01:52:47 h UT) at Allahabad. At Nainital tweeks were observed in the period 05:45:00–07:15:00 h UT (00:15:47–01: 45:00 h UT). A total number of 148 and 20 tweeks were observed at Allahabad and Nainital, respectively. Thus tweeks occurred for the total duration of 90 min and started appearing after the 20 min of beginning of solar eclipse at Allahabad and after 15 min of beginning of solar eclipse at Nainital. It can be said here that 20 min after first contact of eclipse shadow at Allahabad about 40% of sun's disc was obscured by moon and about 30% at Nainital after 15 min of its first contact. It can be said that about 30–40% obscuration of sun's disc could be good enough to create the propagation conditions in the area of source and receiver for observation of tweeks. After the eclipse totality, tweek were observed up to 10 min before the end of eclipse at Allahabad and 30 min at Nainital. The difference is due to the

stronger nighttime conditions at Allahabad due to total solar eclipse at this station. The relationship between the occurrence rates of tweeks and the increase in the intensity of solar eclipse at both the stations seems to be linear. However, a nonlinear relationship between ionization and solar radiation in the lower ionosphere has also been suggested [*Patel et al.*, 1986; *Guha et al.*, 2010].

[13] The reflection height of about 94 km in the nighttime and about 89 km near the sunrise time and electron density about 20–23 cm^{-3} at reflection heights presented in Figures 4 and 5 are consistent with earlier finding [e.g., *Kumar et al.*, 1994, 2008; *Ohya et al.*, 2003; *Maurya et al.*, 2010]. From the tweeks analysis observed at Newfoundland, Canada for 07 March 1970 solar eclipse, *Reeve and Rycroft* [1972] reported that the reflection height increased from 69 km at the start of the eclipse to 76 km at maximum totality, showing variation in ionospheric reflection height by 7 km. During this eclipse of 22 July 2009, at Allahabad, reflection height varied from 89 km from the first contact to 92 km after the eclipse maximum and then decreased to 87 km at end of eclipse showing a increase of about 5 km change in the tweek reflection height. Further, the maximum difference observed between the normal nighttime reflection and the reflection heights during the solar eclipse is ~2 km for Allahabad and ~3 km for Nainital. It indicates that the electron density in the D-region ionosphere even during eclipse totality is higher than the usual nighttime electron density (Figure 4b). It is due to the partial nighttime conditions (reduction in the ionization) even at totality period. This solar eclipse occurred just after sunrise. The sunrise transition effects on the lower ionosphere continue for a few hours before and after sunrise and hence the tweek reflection heights/electron densities are expected to decrease/increase at and after sunrise. However, under normal conditions, tweeks have not been observed so far at these stations after sunrise due to higher attenuation offered by EIWG to estimate the effect of sunrise on the tweek reflection heights and electron density. The primary ionizing radiation at the D-region altitude is Lyman α which is blocked during the total solar eclipse but some of the solar soft X-ray and EUV radiations originating from the limb solar corona are not obscured during totality and produce some ionization [*Bowling et al.*, 1967; *Davis et al.*, 2000; *Curto et al.*, 2006] contributing to the reflection heights less than the normal nighttime conditions. The gravity waves are also induced by the solar eclipse in the low and middle latitude ionosphere [*Šauli et al.*, 2006; *Zhang et al.*, 2010] which propagate upward and couple with ionosphere. *Zhang et al.* [2010] have reported the gravity waves of about 40 min associated with the 22 July 2009 solar eclipse and oscillations in the sporadic E (Es) and F-layers due the gravity waves at low and middle latitudes in China. The gravity waves associated wavelike oscillation changes were not seen in the D-region VLF reflection heights calculated from tweeks observed during the solar eclipse of 22 July 2009 at Indian stations.

5. Summary and Conclusions

[14] The total solar eclipse of 22 July 2009 provided us a unique opportunity to study the lightning sferics activity and hence the response of low latitude D-region ionosphere to the sudden changes in the solar radiation. The maximum number of tweeks and tweeks with higher harmonics were observed at and around the totality, occurrence of which decreased on both the sides of totality. There are distinct differences between tweeks observed in the nighttime and eclipse time due to comparatively less propagation distances of tweeks during the solar eclipse. The distance traveled by the tweeks observed at low latitude station in Indian sector during eclipse from their source lightning discharge is found to vary in the range from ~1000–4000 km, and WWLLN lightning activity showed lightning to be located in the partial eclipse area of Asia-Oceania region. The VLF ionospheric reflection height for the observed tweeks is estimated to vary from 87 to 89 km to about 91–92 km from the eclipse start to totality and end, showing an increase of 5 km in reflection height during eclipse. The electron density at the tweek reflection height is found to vary in the range ~22–23 cm^{-3}. *Rycroft and Reeve* [1970] for the total eclipse of 7 March, 1970 estimated an increase of about 7 km in the tweek reflection heights. For the 22 July 2009 eclipse an increase of 5 km in the reflection height indicates reduction in D-region ionization and conditions similar to partial nighttime during eclipse, because D-region ionizing radiation Lyman α is blocked during eclipse, but some of the solar soft X-ray and EUV radiations originating from the limb solar corona still arrive into D-region and produce some ionization during eclipse.

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