

Nighttime *D*-region equivalent electron density determined from tweek sferics observed in the South Pacific Region

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Atmospherics or sferics that originate from lightning discharges on propagating large distances in the Earth-ionosphere waveguide, particularly at the night, form dispersed sferics called tweeks. Tweeks are novel diagnostic tool to monitor the nighttime *D*-region ionosphere. Mean equivalent electron density n_{em} at mean tweek reflection heights h_m and electron density profile have been estimated using the higher harmonic tweeks recorded in the time between 21–03 hrs LT at Suva (18.2°S, 178.3°E), Fiji, during a period March–December 2006. The values of n_{em} vary from 29–170 cm⁻³ in the altitude range of about 3.5 km at h_m of about 83 km. In terms of usually used exponential electron density profile, the ionospheric reference height and the exponential sharpness factor are calculated to be 83.1 km and 0.64 km⁻¹, respectively. The scale height is calculated to be 1.9 km. Equivalent electron density profile of the nighttime lower ionosphere, using tweek method, shows lower values of electron density by about 20–45% than those obtained from the IRI-2001 model.

Key words: Earth-ionosphere waveguide, tweek atmospherics, reflection heights, equivalent electron densities.

1. Introduction

The *D*-region of ionosphere ranges from 60–90 km wherein collisions between charged particles and neutrals dominate. The lower ionosphere, consisting of *D* and *E*-regions, is too high for balloons and too low for the satellite measurements. Radio sounding does not work, particularly at night, since electron densities in this region are low to reflect high frequency radio waves with ionosondes and incoherent radars. Therefore, the lower ionosphere (~60–140 km) remains the least studied region of the Earth's atmosphere (Cummer and Inan, 2000). Impulse-like signals containing bulk of the energy in the Extremely Low Frequency (ELF) and the Very Low Frequency (VLF) bands generated by lightning discharges propagate through the Earth-ionosphere waveguide (EIWG) by multiple reflections and are received as radio atmospherics or sferics at receiver. Dispersed sferics called tweeks due to long distance propagation in the EIWG, particularly at night, when attenuation is less, contain information about the state of the lower ionosphere along the propagation path (Hayakawa *et al.*, 1994; Cummer *et al.*, 1998; Ohya *et al.*, 2006, 2008; Ferencz *et al.*, 2007).

In this work, tweeks with higher harmonics observed during the period March–December 2006 at the low latitude station, Suva (geog. lat. 18.2°S, geog. long. 178.3°E), Fiji, are utilized to estimate the nighttime *D*-region equivalent electron density at the tweek reflections heights and the equivalent electron density profile of the nighttime lower ionosphere. The broadband ELF-VLF data were recorded

using World Wide Lightning Location Network (WWLLN) VLF setup at The University of the South Pacific, Suva, Fiji. There are 28 universities and national institutes all over the world currently participating in WWLLN.

2. Theoretical Background

The electromagnetic field in the waveguide can be decomposed into a sequence of independent field structures (modes) which propagate with different group velocities. Each of the modes (n) is defined by its cutoff frequency f_{cn} which is determined by the height h of the waveguide or the VLF reflection height. We consider a conventional spherical EIWG and suppose the Earth as an ideal perfect conductor. We consider that the lower ionosphere (upper boundary of EIWG) also acts as an ideal perfect conductor but at higher altitudes for higher harmonics of the same tweeks. For a waveguide having perfectly conducting boundaries, the reflection heights of different harmonics is given by (Budden, 1961; Yamashita, 1978):

$$h = \frac{nc}{2f_{cn}}, \quad (1)$$

where c is the velocity of light in free space.

The distribution of charged particles in the ionosphere depends in a complicated way on latitude, solar zenith angle, season, and solar activity etc. In the simplest approach, the exponential increase in the lower-ionospheric electron density n_e expressed in cm⁻³, can be described by *Wait profile*, valid up to about 100 km altitude (Wait and Spies, 1964):

$$n_e(h) = 1.43 \times 10^7 \exp(-0.15h') \times \exp[(\beta - 0.15)(h - h')], \quad \text{cm}^{-3} \quad (2)$$

where h' is the ionospheric reference height in km and β is the parameter measured in km^{-1} that describes the sharpness of the electron density profile.

The propagation of electromagnetic waves in collisional magnetized plasma is formulated by the magnetoionic theory which also applies to the ionosphere (Ratcliffe, 1959). Ionosphere is weakly ionized, inhomogeneous, collisional, and anisotropic plasma. The complex refractive index μ of waves in the ionosphere is given by the famous Appleton-Hartree equation (Budden, 1961):

$$\mu^2 = 1 - \frac{X}{1 - iZ - \left[\frac{Y_T^2}{2(1-X-iZ)} \right] \pm \left[\sqrt{\frac{Y_T^4}{4(1-X-iZ)^2} + Y_L^2} \right]}, \quad (3)$$

where X , Y_T , Y_L and Z are dimensionless magneto-ionic parameters, defined as:

$$X = \left(\frac{\omega_p}{\omega} \right)^2, \quad Y_T = \frac{\omega_H}{\omega} \sin \theta = Y \sin \theta, \\ Y_L = \frac{\omega_H}{\omega} \cos \theta = Y \cos \theta, \quad \text{and} \quad Z = \frac{\nu_e}{\omega},$$

where ω_p , ω_H , and ω are the angular plasma frequency, electron gyrofrequency, and wave frequency, respectively. ν_e is the angular electron-neutral collision frequency and θ is the angle between the propagation direction and the Earth's magnetic field vector. ω_p is given by: $\omega_p = \sqrt{n_e e^2 / \epsilon_0 m_e}$, where n_e is the electron density, e ($= -1.602 \times 10^{-19}$ C) is charge of an electron, ϵ_0 ($= 8.854 \times 10^{-12}$ F/m) is permittivity of free space, and m_e ($= 9.109 \times 10^{-31}$ kg) is the mass of an electron.

The ν_e profile can be very closely approximated by (Wait and Spies, 1964):

$$\nu_e = 1.816 \times 10^{11} \exp(-0.15h), \quad \text{s}^{-1} \quad (4)$$

where h is the altitude measured in km.

VLF waves reflect at the bottom-side of the ionosphere, that is, in the *D*-region. The upper sign “+” in Eq. (3) corresponds to ordinary-mode (O-mode) waves and lower sign “-” corresponds to extraordinary-mode (X-mode) waves. X-mode waves undergo full reflection at the altitude at which μ becomes zero. The O-mode waves are not reflected and penetrate into the ionosphere. The condition of full wave reflection for X-mode wave can be easily obtained using the quasi-longitudinal (QL) approximation (θ small). Under QL approximation, excluding the terms containing $\sin^2 \theta$ and $\sin^4 \theta$ and equating Y_L to Y , Eq. (3) for VLF waves becomes:

$$\mu^2 = 1 - \frac{X}{1 - iZ \pm Y}. \quad (5)$$

At VLF, both ω_H and ν_e in the lower ionosphere at the VLF reflection heights are larger than the tweek wave frequency ($\nu_e > \omega$ and $\omega_H \gg \omega$ i.e. $Y > 1$). The value of X where μ^2 becomes zero is given by following condition:

$$X = 1 - iZ \pm Y. \quad (6)$$

The X-mode waves would correspond to $X = 1 - iZ + Y$ when $Y > 1$ and $X = 1 - iZ - Y$ when $Y < 1$. For

tweek frequencies (ELF/VLF) of our interest, the condition of reflection for X-mode waves would be met only with $X = 1 - iZ + Y$. Therefore, the values of n_e at the reflection heights of tweeks are obtained from $X = 1 - iZ + Y$. Thus the magnitude of X is given as:

$$X = [(1 + Y)^2 + Z^2]^{\frac{1}{2}}. \quad (7)$$

Substituting the values of X , Y and Z , expression for n_e at h of different harmonics of tweeks can be obtained as:

$$n_e = 1.9790 \times 10^{-9} \times f_{cn} \times [2\pi(f_{cn} + f_H)]^2 \\ + (1.816 \times 10^{11} \exp(-0.15 \times h))^2]^{\frac{1}{2}}, \quad \text{cm}^{-3} \quad (8)$$

where f_H is the electron gyro frequency. Second term is the contribution to n_e due to electron-neutral collisional frequency and is very small as compared to the contribution due to first term. In the absence of the last term the expression reduces to that given by Ohya *et al.* (2003).

3. Observational Data

WWLLN system used for ELF-VLF consists of a short (1.5 m) whip antenna, pre-amplifier, and a receiving unit. Whip antenna receives the vertical electric field component E_Z of transverse magnetic (TM) and quasi-transverse electromagnetic (QTEM) mode waves. Global Position System (GPS) is utilized for precise measurements of arrival times of tweeks. The details of the system have been described by Dowden *et al.* (2002). The lightning software installed in WWLLN PC records the broadband data in files of 11 MB per minute. Data were recorded for 5 minutes at every hour in the nighttime during March–December 2006. The files were analyzed using a MATLAB code which produces spectrograms (frequency f vs. time t) of one-second duration. To accurately read the frequency and corresponding arrival times, we have used Getdata Graph Digitizer software. First the spectrograms were loaded into paint software and saved in bitmap format. In the next step, these bitmap files were uploaded in the GetData Graph Digitizer software and calibrated for the frequency and time axes of the spectrograms. The cutoff frequency f_{c1} of first harmonics and two nearby frequencies (f_1 and f_2) together with their corresponding time (t_1 and t_2) displayed by GetData Graph Digitizer software were then obtained. The propagation paths of tweeks observed at Suva are mostly over the sea and we have considered tweeks which propagated about 6000 km, thus the overall attenuation is small especially for the first harmonic frequency components. Therefore, we consider that the energy of waves at f_{c1} does not go below the noise level and f_{c1} is measured quite accurately using the GetData Graph Digitizer which can show the frequency components above the noise level clearly. Whereas, higher harmonics of tweeks while propagating in the EIWG suffer higher attenuation as compared to the first harmonic which is progressively higher for higher harmonic waves and increases sharply as frequencies approach the cutoff frequency (Kumar *et al.*, 2008). Due to this, some of the frequency components of higher harmonics of tweeks near their cutoff frequencies might not be received. The accurate cutoff frequencies of higher harmonics were obtained using

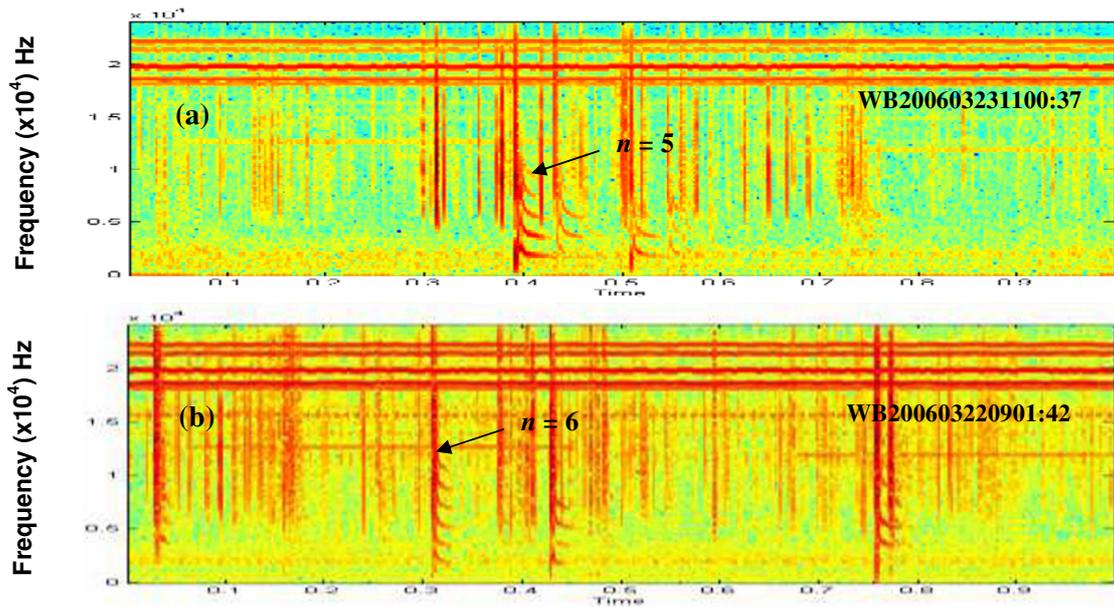


Fig. 1. Typical spectrograms showing tweeks observed on (a) 23 March 2006 at 23:00:37 hrs LT, and (b) 22 March 2006 at 21:01:42 hrs LT.

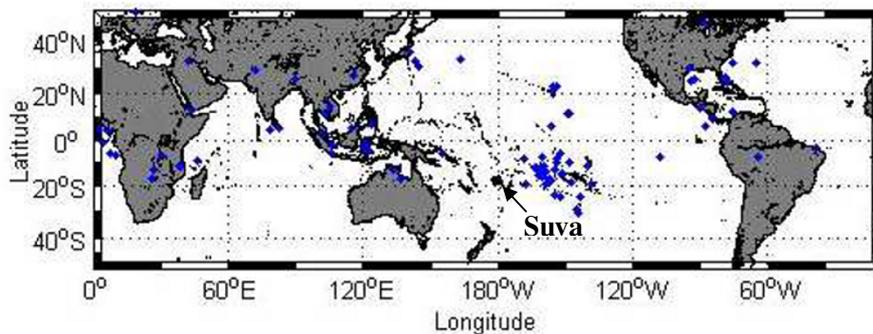


Fig. 2. Lightning locations of tweeks determined from WWLLN data. Blue color square marks indicate location of lightnings associated with tweeks.

the above steps and by fitting (extrapolating) the dispersion up to the time of arrival of the cutoff frequency of the first harmonic of tweeks. The resolution in the frequency and time components is 35 Hz and 1 ms, respectively.

4. Results and Discussion

4.1 General overview of tweeks observed at Suva

First observations of tweeks at this station were made during September 2003–July 2004 for a total of 30 min. at different hours in the night and the day times. Data analysis showed no tweeks in the daytime recordings. General features of tweeks recorded during above period have been published by Kumar *et al.* (2008). A more systematic recording of data was made during March–December 2006 when ELF-VLF data were recorded for 5 minutes at every hour in the nighttime (18–06 hrs LT). A total of 1039 tweeks were selected on the basis of clarity of tweeks seen in the spectrograms. Figure 1(a, b) presents the spectrograms showing typical multimode tweeks observed on (a) 23 March 2006 at 23:00:37 hrs LT and (b) 22 March 2006 at 21:01:42 hrs

LT. The frequency components below the cutoff frequency of first mode (harmonic) correspond to zeroth-order mode (TM_0). To identify the location of lightnings associated with tweeks, WWLLN data were analyzed. The lightning stroke detection within 50 ms earlier to tweeks observation and that best matched the tweek propagation distance (in case of more than one lightning within 50 ms) was taken as the causative lightning of that particular tweek. Under these criteria out of 1039 tweeks, the lightning source locations of only 87 tweeks were found. This is due to the low detection efficiency of WWLLN system. WWLLN detects global lightnings with return stroke currents of more than ~ 50 kA with spatial and temporal accuracy of roughly 10–20 km and 10 μ s, respectively, and has global detection efficiency less than 4% (Rodger *et al.*, 2006), although a much higher detection efficiency for stronger lightnings is expected. Figure 2 shows the locations of lightnings associated with 87 tweeks. The causative lightnings were distributed over a wide range of locations but majority of them ($\sim 60\%$) occurred in the geographic latitude and longitude ranges of

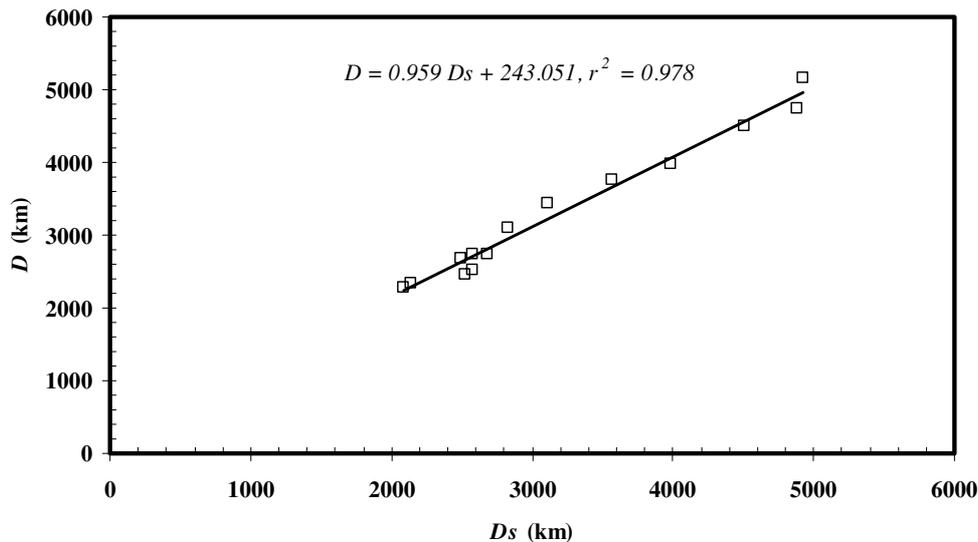


Fig. 3. Correlation of great circle distance (D_s) with propagation distance (D) calculated using Haversine and tweak methods, respectively.

Table 1. Reflection heights h and electron densities n_e at h obtained from tweeks shown in Fig. 1.

Spectrogram	Time (LT hrs)	Mode number (n)	Cut-off frequency f_c (kHz)	Tweak reflection height h (km)	Electron density n_e (el./cm ³)
a	23:00:37. 391	1	1.794	83.6	29.1
		2	3.588	83.6	58.3
		3	5.323	84.5	86.6
		4	7.117	84.3	115.9
		5	8.793	85.3	143.3
b	22:01:42. 308	1	1.814	82.6	29.6
		2	3.518	85.3	57.1
		3	5.263	85.5	85.5
		4	6.997	85.8	113.8
		5	8.792	85.3	143.3
		6	10.447	86.1	170.5

10°S to 30°S and 140°W to 170°W, respectively, which are geographic locations of a group of islands. Out of 1039 tweeks observed in the nighttime (18–06 hrs LT), tweeks observed during 21–03 hrs LT and those propagated distances up to 5000 to as high as 5900 km, were selected, so that the error contribution due to day-time propagation path particularly for tweeks coming from E-W directions and the refraction on the day-night terminator is avoided. Under these criteria we end up with 448 tweeks which are used for analysis in this paper. Tweeks propagation distance (D) in the spherical EIWG 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 $\delta t = |t_1 - t_2|$ 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_{gf_1} and v_{gf_2} are the corresponding group velocities. The distances calculated by this method are within the accuracy of about ± 900 km. To check the validity of tweak method of calculating the propagation distance, the great circle distance (D_s) between the identified locations of lightning and the measurement site were calculated using Haversine formula (online at <http://www.movable-type.co.uk/scripts/LatLong.html>), for

14 best matched lightning locations. Plot of D_s against D is shown in Fig. 3. The squared value of linear correlation coefficient r^2 for the graph is 0.98 indicating a strong correlation between the propagation distances calculated both by Haversine and tweak methods.

4.2 Equivalent electron density at reflections heights

At ELF and VLF, the Earth's surface and the lower ionosphere act as good electrical conductors. For tweeks considered in this paper, most of their propagation is on the sea so that the Earth can be considered as perfect conductor, but it is essential to treat the ionosphere as an anisotropic medium whose conductivity increases exponentially with height. We consider that the ionospheric conductivity does not vary with latitude and longitude along the propagation paths of tweeks. The normal reflection height of the electromagnetic waves in the ionosphere varies with frequency, with lower frequencies usually reflected at lower heights due to lower electron densities (Cummer and Inan, 2000). The fact that ELF and VLF waves are reflected by the D -region and D -region is a significantly better reflector at the night than at the day makes them useful diagnostic tools to estimate the nighttime electron densities n_e at the ionospheric reflection heights h . These (partial) reflections oc-

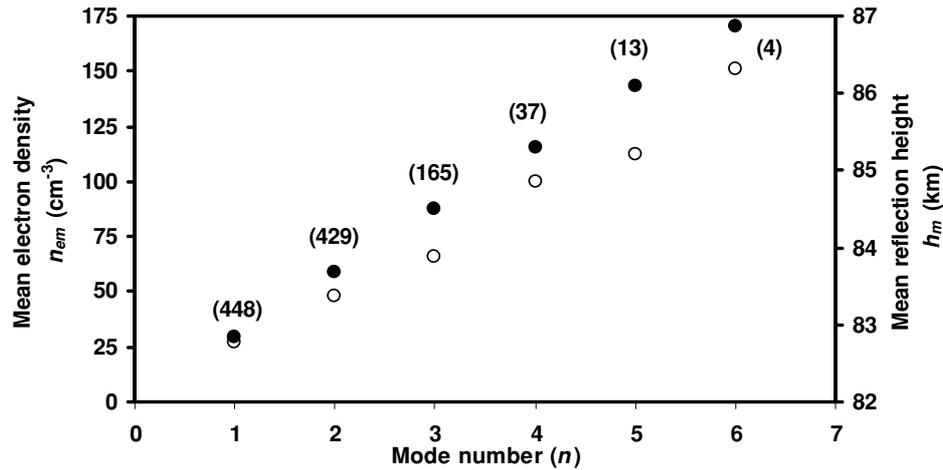


Fig. 4. Mean electron densities n_{em} (left hand scale, solid circles) at mean reflection heights h_m (right hand scale, hollow circles) calculated using cut-off frequency of different modes n for 448 tweeks observed during March–December 2006. The numbers in the parentheses indicate the total number of tweeks utilized.

cur because the electron density in the lower ionosphere increases rapidly and higher harmonics are reflected from the higher altitudes. Using a qualitative analysis of radio wave propagation in infinite, collisionless, anisotropic, weakly ionized ionospheric plasma and by analyzing tweeks up to the 8th harmonics observed during January–April 1991, Shvets and Hayakawa (1998) estimated the numerical value of equivalent n_e at h of tweeks. In this paper, the values of h and n_e have been calculated using Eqs. (1) and (8), respectively, for collisional ionosphere, using the modes $n = 1$ –6 of tweeks shown in Fig. 1, and are presented in Table 1. Calculations have been made using $f_H = 1.3$ MHz for the latitudes and altitude range of our interest. It can be noted from Table 1 that n_e varies from 30–171 cm^{-3} in the altitude range about 3.5 km at the height of about 82.6 km. The calculated value of n_e using the International Reference Ionosphere (IRI-2001) model at a height 82.6 km, on 22 March 2006 at 21:00 hrs LT, the time of observation of tweeks marked in panels (a) and (b) of Fig. 1, is 85 cm^{-3} which is higher compared to the values shown in Table 1.

Under the selection criteria described in Section 4.1, a total of 448 tweeks were selected for the analysis from the broadband data recorded during the period March–December 2006. The mean cutoff frequency f_{cm} of different modes and mean fundamental frequency f_{cm}/n with mode number n were obtained from these tweeks. The f_{cm}/n changes from 1.812 kHz to 1.738 kHz for $n = 1$ –6 which indicates that the cut-off frequencies of higher harmonics ($n > 1$) are not exact multiples of the cut-off frequency of first mode f_{c1} and n , rather are slightly lower than $f_{c1} \times n$. Similar variation of f_{cm}/n for 503 tweeks recorded at this station in the nighttime (18–06 hrs LT) during September 2003–July 2004 was reported by Kumar *et al.* (2008).

The f_{cm}/n and f_{cm} are used to calculate mean reflection height h_m and mean electron densities n_{em} from different harmonics (1–6) using Eqs. (1) and (8), respectively. The n_{em} at h_m for each mode is plotted in Fig. 4. The numbers in the parentheses indicate the total number of tweeks used in the analysis. It is found that the n_e increases from 29.4–

170.0 cm^{-3} over the h_m in the range of 82.8–86.3 km, for $n = 1$ –6. The frequency components from the spectrograms are measured with an accuracy of ± 35 Hz which gives the reflection heights accurate to about ± 1.8 , ± 0.8 , ± 0.6 , ± 0.5 , ± 0.4 , ± 0.3 km for $n = 1$ –6, respectively, and the electron density to about ± 0.7 cm^{-3} for all harmonics. The increase in h_m with increase in n indicates that the higher order harmonics of same tweeks penetrate 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 (perfectly conducting) progressively at higher altitudes for increasing order of harmonics of tweeks. A difference of about 3.5 km in h for $n = 1$ –6 can be established from Fig. 4. Using multimode tweeks up to 8th harmonics and assuming lower ionosphere as collision free, Shvets and Hayakawa (1998) found an increase in n_{em} from 28–224 cm^{-3} in the altitude range of about 2 km at a height of about 81 km. The nighttime h_m reported in this work during a low solar activity period March–December 2006, are higher by 1–2 km than those estimated by Shvets and Hayakawa (1998), indicating a spatial and solar activity dependence of the electron density and hence the reflection heights. The ionospheric VLF reflection height is somewhat lower during solar maximum as compared to solar minimum (McRae and Thomson, 2004). The equivalent electron densities at reflection heights seem to be lower than those reported by Shvets and Hayakawa (1998). Ohya *et al.* (2003) analyzing the first-order mode cutoff frequency of tweek atmospheric received at Moshiri (44.37°N) and Kagoshima (31.48°N) in Japan, and using the same approach as used by Shvets and Hayakawa (1998), estimated equivalent electron density to vary from 20–28 cm^{-3} at reflection heights of 80–85 km. Solar activity dependence of the *D*-region of the ionosphere is still not clear. Some authors found a decrease in electron density of the lower ionosphere with an increase in the solar activity whereas others found increase in the electron density with an increase in the solar activity (Danilov, 1998 and references therein).

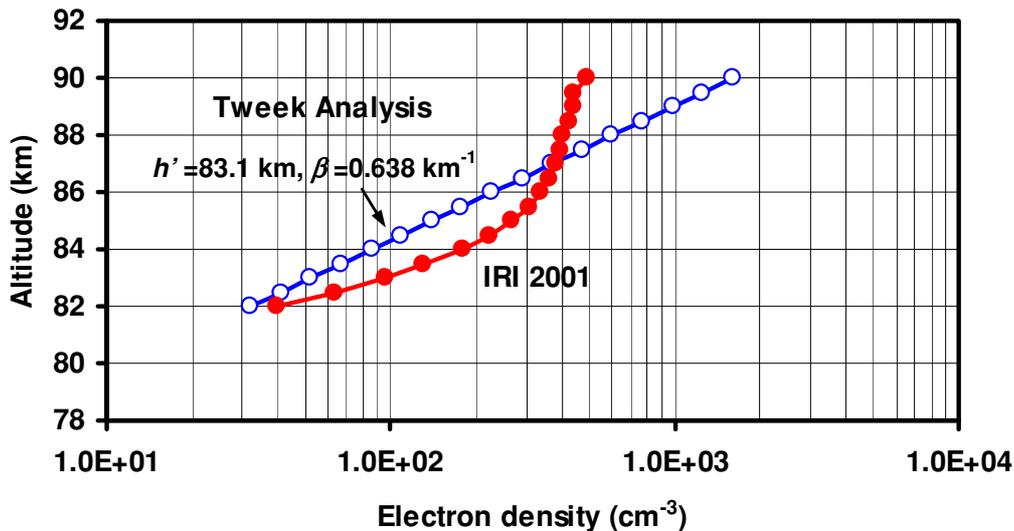


Fig. 5. A comparison of electron density profiles of the lower ionosphere obtained using overall analysis of tweeks (Blue solid line with hollow circles) up to 3rd harmonics and the IRI-2001 model (red solid line with solid circles) at 00:00 hrs LT at location of Suva on 15th day of every month from March–December 2006.

4.3 Equivalent electron density profile and scale height

The lower ionosphere can be characterized as the “Wait ionosphere” defined by a reference height h' in km and an exponential sharpness factor β in km^{-1} as considered by many researchers (e.g. Cummer *et al.*, 1998; Cummer and Inan, 2000; Thomson *et al.*, 2007). Lower ionosphere has been studied employing the VLF technique (Cummer *et al.*, 1998) and ELF technique (Cummer and Inan, 2000). Using Long Wave Propagation Code (LWPC), they simulated for a variety of ionospheres, the VLF and ELF spectra of the signals radiated by lightning discharges and received at 1000–2000 km away from the lightning source. The value of β extracted from the VLF technique by Cummer *et al.* (1998) was 0.49 km^{-1} which was lower by as much as 0.15 km^{-1} than the value of β extracted from ELF technique by Cummer and Inan (2000). ELF (<1.5 kHz) radio atmospherics propagate by QTEM mode of wave propagation which can be influenced by E and F regions of the ionosphere (Cummer and Inan, 2000). Comparing the observed nighttime VLF phase and amplitude of navigational transmitters signals with long wave propagation models, Thomson *et al.* (2007) determined nighttime values of $h' = 85.1 \pm 0.4 \text{ km}$ and $\beta = 0.63 \pm 0.04 \text{ km}^{-1}$ for the mid latitude D -region near solar minimum.

Tweek method utilized here gives path-integrated electron density. Substitution of n_{em} and h_m from Fig. 4 in Eq. (2) for $n = 1, 2, 3$ gives three equations dealing with h' and β corresponding to the each value of n which on solving yield values of h' and β as 83.1 km and 0.638 km^{-1} , respectively. The value of β thus obtained is higher by 0.15 km^{-1} than that obtained by Cummer *et al.* (1998) using the VLF sferics observed during low solar activity month of July 1996 (Sun spot number $R_z \sim 10$) and is consistent with that obtained by Thomson *et al.* (2007). The period March–December 2006 also falls in lower solar activity period ($R_z \sim 15$). Figure 5 shows the nighttime D -region n_e profile (hollow circle) calculated using Eq. (2) for $h' = 83.1 \text{ km}$ and $\beta = 0.638 \text{ km}^{-1}$ for the altitudes ranges of

82–90 km. The n_{em} profile (solid circle) obtained using the IRI-2001 model at 00:00 hrs LT at the location of Suva on 15th day of every month from March–December 2006 is also plotted in Fig. 5. The period March–December 2006 was geomagnetically a quite period and there occurred no geomagnetic storms on 14th or 15th days of the months up to November. However, a Sudden Storm Commencement occurred at 14:14 UT on 14 December that caused an intense geomagnetic storm with a minimum D_{st} index (on line at <http://swdcwww.kugi.kyoto-u.ac.jp>) value of -146 nT at 08:00 UT (20:00 LT) on 15 December. Such storms may increase lower ionospheric electron density and hence decrease the reflection heights (Ohya *et al.*, 2006). Unfortunately our recoding of ELF-VLF data was off during 13–17 December 2006 due to some technical problem with the recording system. Thus n_{em} values obtained using the IRI-2001 model at 00:00 hrs LT on 15th day of every month can be considered as good estimates of nighttime monthly mean values at our location (Suva). The values of n_{em} obtained by tweek analysis are lower by 20–45% at the altitudes 82–86 km with a very good match at about 87 km. The trend of variation of the n_{em} in the lower ionosphere around the altitude 82–86 km is almost the same, indicating that tweek method is useful for estimating the electron density profile of the lower part of the nighttime D -region ionosphere. Tweek method corresponds to a scale height of 1.9 km (Fig. 5) in terms of usually used exponential electron density profile whereas the scale height calculated using the IRI-2001 values of n_{em} is about 1.5 km. The characteristic scale height estimated using the tweeks is consistent with the results (1.6 km) of Hughes *et al.* (1974) but higher in comparison to that estimated (1 km) by Shvets and Hayakawa (1998) from the measurement of night-time ELF-VLF sferics spectra.

5. Summary

The nighttime VLF reflection heights from the cut-off frequency of different harmonics of tweeks atmospherics

at a low latitude station in Fiji were obtained using waveguide mode theory. An expression for electron density at the VLF ionospheric reflection heights is obtained using magnetoionic theory of wave propagation in the ionosphere which is weakly ionized inhomogeneous, anisotropic and collisional plasma. Equivalent electron densities ranged from 29–170 cm⁻³ in the altitude range of about 3.5 km at the height of 82.8 km. The main focus of this work is to obtain the electron density profile of the lower ionosphere using cutoff frequency of first three harmonics which has not been attempted so far using tweek measurements. From the analysis of the first three harmonics of tweeks the values of h' and β are calculated to be 83.1 km and 0.64 km⁻¹, respectively. Equivalent electron density profile of the nighttime lower ionosphere shows lower values than those obtained from the IRI-2001 model, however, the trend of electron density variation in the lower ionosphere in the altitude range of 82–86 km is almost the same. Nighttime *D*-region scale height is estimated to be 1.9 km.

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References

- Budden, K. G., *Radio Waves in the ionosphere*, Cambridge University Press, New York, 1961.
- Cummer, S. A. and U. S. Inan, Ionospheric *E* region remote sensing with ELF radio atmospherics, *Radio Sci.*, **35**, 1437–1444, 2000.
- Cummer, S. A., U. S. Inan, and T. F. Bell, Ionospheric *D* region remote sensing using VLF radio atmospherics, *Radio Sci.*, **33**, 1781–1792, 1998.
- Danilov, A. D., Solar cycle variations of the *D*-region ionosphere, *Ann. Geophys.*, **25**, 1527–1533, 1998.
- Dowden, R. L., J. B. Brundell, and C. J. Rodger, VLF lightning location by time of group arrival (TOGA) at multiple sites, *J. Atmos. Sol.-Terr. Phys.*, **64**, 817–830, 2002.
- Ferencz, O. E., Cs. Ferencz, P. Steinbach, J. Lichtenberger, D. Hamar, M. Parrot, F. Lefeuvre, and J. J. Berthelier, The effects of subionospheric propagation on whistlers recorded by the DEMETER satellite—observation and modeling, *Ann. Geophys.*, **25**, 1103–1112, 2007.
- Hayakawa, M., K. Ohta, and K. Baba, Wave characteristics of tweek atmospherics deduced from the direction-finding measurement and theoretical interpretation, *J. Geophys. Res.*, **99**, 10,733–10,743, 1994.
- Hughes, H. G., R. J. Gallenburger, and R. A. Pappert, Evaluation of nighttime exponential ionospheric models using VLF atmospherics, *Radio Sci.*, **9**, 1109–1116, 1974.
- Kumar, S., A. Kishore, and V. Ramachandran, Higher harmonic tweek sferics observed at low latitude: Estimation of VLF reflection heights and tweeks propagation distance, *Ann. Geophys.*, **25**, 1451–1459, 2008.
- McRae, W. M. and N. R. Thomson, Solar flare induced ionospheric *D*-region enhancements from VLF phase and amplitude observations, *J. Atmos. Sol.-Terr. Phys.*, **66**, 77–87, 2004.
- Ohya, H., M. Nishino, Y. Murayama, and K. Igarashi, Equivalent electron densities at reflection heights of tweek atmospherics in the low-middle latitude *D*-region ionosphere, *Earth Planets Space*, **55**, 627–635, 2003.
- Ohya, H., M. Nishino, Y. Murayama, K. Igarashi, and A. Saito, Using tweek atmospherics to measure the response of the low-middle latitude *D*-region ionosphere to a magnetic storm, *J. Atmos. Sol.-Terr. Phys.*, **68**, 697–709, 2006.
- Ohya, H., K. Shiokawa, and Y. Miyoshi, Development of an automatic procedure to estimate the reflection height of tweek atmospherics, *Earth Planets Space*, **60**, 837–843, 2008.
- Ratcliffe, J. A., *The magneto-ionic theory and its applications to the ionosphere*, Cambridge University Press, Cambridge, 1959.
- Rodger, C. J., S. W. Werner, J. B. Brundell, N. R. Thomson, E. H. Lay, R. H. Holzworth, and R. L. Dowden, Detection efficiency of the VLF World-Wide Lightning Location Network (WWLLN): Initial case study, *Ann. Geophys.*, **24**, 3197–3214, 2006.
- Shvets, A. V. and M. Hayakawa, Polarization effects for tweek propagation, *J. Atmos. Sol.-Terr. Phys.*, **60**, 461–469, 1998.
- Thomson, N. R., M. A. Clilverd, and W. M. McRae, Nighttime *D* region parameters from VLF amplitude and Phase, *J. Geophys. Res.*, **112**, A07304, doi:10.1029/2007JA01227, 2007.
- Wait, J. R. and K. P. Spies, Characteristics of the Earth-ionosphere waveguide for VLF radio waves, *NBS Tech. Not.*, 300 pp., 1964.
- Yamashita, M., Propagation of tweek atmospherics, *J. Atmos. Terr. Phys.*, **40**, 151–156, 1978.

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