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Upper Atmospheric Remote Sensing Using ELF – VLF Lightning Generated Tweek and Whistler Sferics

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Abstract

Tweek and whistler atmospherics (sferics) recorded at a low latitude station, Suva (18.2°S, 178.3°E, geomag. lat. 22.2°S, L = 1.17) Fiji, in the South Pacific region, during September 2003 – July 2004 and March – December 2006 were analyzed to probe the nighttime D-region ionosphere and plasmasphere. From the first harmonic analysis of the selected 1063 tweeks, the path integrated ionospheric reflection height was estimated mostly between 75 – 97 km with median and standard deviation of 83.6 and 4.1 km, respectively. The path integrated mean electron density was estimated to vary from 24.4 – 31.5 cm^{-3} over the reflection heights. The whistler recorded on 20 September 2006, a magnetically quite day with maximum three hourly K_p value of 2_o, most likely propagated in the ducted mode to this station. The whistler spectrum was used to calculate the equatorial magnetic field and the equatorial electron density at L = 1.3 which are in agreement with low latitude whistler observations.
Keywords: *Tweeks, Whistlers, Lower ionosphere, Plasmasphere*.

1. Introduction

The return strokes of lightning discharges generate enormous amount of energy spread over a wideband in the electromagnetic spectrum with peak power density around 10 kHz . Major part of the radiation in the Extremely Low Frequency (ELF) and the Very Low Frequency (VLF) bands propagates through the Earth-ionosphere waveguide (EIWG) by multiple reflections and is received as sferic at the receiver (Barr *et al.*, 2000). The ELF and VLF propagations in the EIWG occur with low attenuation typically few dB per 1000 km (Cummer *et al*., 1998; Taylor, 1960), which allows the sferics to be observed around the world from a single lightning discharge. Therefore, tweeks are used as a cost effective diagnostic tool for probing the night-time D-region of the ionosphere. Several authors have studied tweeks and used them to study the morphology of the lower ionosphere. Kumar *et al.* (1994) utilized tweeks to estimate the tweek reflection height h and propagation distance to low latitude station in the Indian sector. By analyzing tweeks up to the 8th harmonics observed during January-April 1991, Shvets and Hayakawa (1998) estimated an increase in the electron density n_e in the range 28 to 224 cm^{-3} at h = 81 – 83 km. Ohya *et al.* (2003) estimated the equivalent n_e at the h of the night-time lower ionosphere by using the first order mode cut-off frequency. Tweeks have recently been used to study the D-region reflection height changes during solar eclipses (Ohya *et al*., 2012) and seasonal variation of D-region by Tan *et al.* (2015).

A small portion of lightning radiation can penetrate into the dispersive regions of ionosphere and magnetosphere and travels to the opposite hemisphere where it is received as tones of descending and ascending frequencies called “whistlers” (Helliwell, 1965). The whistler sferics during their propagation through the ionosphere and magnetosphere interact with the ambient plasma in the presence of geomagnetic field and get dispersed. Usually the high frequency components travel faster than the lower frequency components. A breakthrough in the whistler research started after Storey (1953) presented a convincing interpretation of whistlers and explained the whistler spectra in terms of the magneto-ionic theory. Storey (1953) predicted that the path of whistler propagation was more or less aligned with the Earth’s magnetic field and extended between the hemispheres. Many researchers have reported a good number of whistlers at the low latitudes from their nighttime observations (Hayakawa *et al.*, 1973; Hayakawa *et al.*, 1990; Singh *et al.*, 1998; Singh and Hayakawa, 2001; Kumar *et al.*, 2007). However, the propagation characteristics of low latitude whistlers are not properly understood yet and have been the subject of controversy for a long time. There is a growing consensus in favor of the non-ducted pro-longitudinal (PL) mode of propagation for nighttime whistlers (Singh and Hayakawa, 2001); however, in some cases whistlers propagating in ducted mode have also been observed at low latitudes (Hayakawa and Ohtsu, 1973). One such whistler has been observed at our low latitude station.

In this paper, ELF – VLF data recorded during September 2003 – July 2004 and March – December 2006, at low latitude station Suva (geomagnetic lat. 22.2 °S, L = 1.17), Fiji, in the South Pacific region, have been analyzed to detect tweeks and whistlers. Tweeks were analyzed to estimate the nighttime electron density at the tweek reflection heights. A whistler which most likely propagated in the ducted mode was analyzed to determine the plasmaspheric electron density along the *L-shell* of propagation.

2. Experimental Set-Up and Data Analysis

The experimental set-up consists of a short (1.5 m) whip antenna to receive the vertical electric field component E_Z of sferics. A pre-amplifier connected at the bottom of the whip antenna is coupled to the ELF – VLF receiving unit (SU). A Global Position System (GPS) antenna is connected to a GPS receiver also built into the SU. For a more detailed description of the system the reader is encouraged to see the paper by Dowden et al. (2002). The lightning software is programmed to record the received ELF – VLF signals for the desired period of time. The data was recorded for 2 min every hour from 19:00 – 04:00 hrs LT. The data files were analyzed using MATLAB software which produces spectrograms of one-second durations. Tweek sferics are identified from spectrograms (Figure 1) and then analyzed in two steps: firstly spectrograms are converted into image files (bitmap format) using the Microsoft Paint software. The second step involves uploading these bitmap files in the graph digitizer software (GetData Graph Digitizer) and calibrating the frequency and time axes of the spectrogram. The cut-off frequency f_{cn} of different harmonics of tweeks is then determined with an accuracy of 30 Hz.

3. Theoretical Considerations

3.1. Propagation of ELF – VLF Waves in EIWG

For a waveguide having perfectly conducting boundaries, the modes are defined completely by their cut-off frequency f_{cn} given by Yamashita (1978):

$$f_{cn} = nc/2h, \qquad (1)$$

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

The expression for electron density n_e at the reflection height of the tweek harmonics is given as (Ohya *et al.*, 2003):

$$n_e = 1.241\times10^{-8} f_{cn} f_H \left[cm^{-3}\right], \qquad (2)$$

where, f_{cn} is cut-off frequency in Hz of n^{th} harmonics of tweeks obtained from spectrograms. We assume that the tweek sferics received at our station come from lightning discharges occurred mainly at equatorial-low latitudes.

We take f_H = 1.3 MHz according to the International Geomagnetic Reference Field (IGRF) model. Eq. 2 reduces to:

$$n_e = 1.613\times10^{-2} f_{cn} \left[cm^{-3}\right], \qquad (3)$$

3.2. Whistler Propagation at the Low Latitudes

Whistler sferics shows the variation of frequency with time. The *Eckersley's* relationship between travel time τ and the wave frequency is given as:

$$\tau = t - t_o = D/\sqrt{f}\ , \qquad (4)$$

where, D is the dispersion of the whistler, t_o is the time of the causative sferic, and *t is* the time of appearance of different frequency components on the spectrogram. The Eckersley's approximation Eq. (4) is a well-known theoretical model for dispersion of whistlers (Helliwell, 1965). The intercept on the dispersion graph of t vs $f^{-1/2}$ gives the time (t_o) the causative atmospheric of the received whistler. Dowden and Allcock (1971) introduced a function:

$$Q(f) = [D(f)]^{-1}, \qquad (5)$$

which is more convenient for approximating the whistler dispersion. A plot of *Q (f)* against f gives a straight line, and this was approximated (Dowden and Allcock 1971) to be:

$$Q(f) = Q_o\left(1 - \frac{f}{\alpha\, f_n}\right), \qquad (6)$$

where, $\alpha = 3.09 \pm 0.04$, $Q_o = 1/D_o$, D_o is the zero frequency dispersion and f_n is the nose frequency of the whistler. The intercept of Q (f) on f axis gives $f_o = \alpha\, f_n$ from which f_n of whistler can be determined. This technique is particularly useful for whistlers which obey *Eckersleys* law. To remove the slight non-linearity in the *Q (f)* function, Dowden and Allcock (1971) estimated an error Δf_n in the determination of f_n given by the equation:

$$\Delta f_n = 0.12\left(\bar{f} - 0.75 f_n\right), \qquad (7)$$

where, $\bar{f}$ is the whistler mean frequency. The electron gyrofrequency f_{He} is obtained using f_n (Sazhin *et al.*, 1992):

$$f_{He} = f_n/0.4 \qquad (8)$$

The MacIIwain parameter L of the field-aligned duct can be calculated using f_{He} (Sazhin *et al.*, 1992) and is given by:

$$L = 9.56\, f_{He}^{-1/3}, \qquad (9)$$

where, $f_{\rm He}$ is frequency in kHz. The L value gives the radial distance from the center of the Earth (in units of Earth radii) to the minimum B along the line intersecting the magnetic equator. Hence, L = 1 means the point is at the geomagnetic equator on the surface of the Earth. The magnitude of the magnetic field B_o at the Earth's equator is given as:

$$B_o = \frac{f_{He}\, m_e}{e}, \tag{10}$$

Several models have been proposed to determine the electron density in the plasmasphere such as gyro-frequency model (electron density proportional to geomagnetic field) and diffusive equilibrium model (DE-1, DE-2, DE-3, DE-4) (Sazhin *et al.*, 1992 and references therein). Carpenter and Smith (1964) and Angerami (1966) suggested that the electron density distribution N_{eq} along dipolar geomagnetic field line is given by:

$$N_{eq} = K\, R^{-3}, \tag{11}$$

where, K is a constant and R is the geocentric distance in Earth radii. The value of K at low latitudes under f_H » f for the electron density distribution given by Eq. 11 can be obtained using the relationship given as (Singh *et al.*, 1993):

$$D_o = \frac{9LR_o^{1/2}K}{2cf_{He}^{1/2}} \int_0^{\text{Ø}'} \cos\text{Ø}(1+3\sin^2\text{Ø})^{1/4}\, d\text{Ø} \quad , \tag{12}$$

where, Ø' is the geomagnetic latitude of the station at the ionospheric height (~ 500 km for low latitudes), R_o is the Earth's radius and Ø_o is the geomagnetic latitude of the field line at the surface of the Earth.

4. Results and Discussion

4.1. Ionospheric D-region Remote Sensing Using Tweeks

The propagation features of tweeks recorded at Suva during September 2003 – July 2004 have been reported by Kumar *et al*. (2008) wherein only the reflection height from different harmonics was calculated. Kumar *et al*. (2009) presented the analysis of tweeks recorded during March – December 2006 for ionospheric reflection heights h and equivalent electron density n_e from cut-off frequency of modes n = 1 – 6 using Eqs.1 and 3, respectively. Here we use n_e for the tweeks recorded during the September 2003 – July 2004 also and combined with tweek analysis of Kumar *et al.* (2009) and present mainly the day-to-day variability of h and n_e which was not attempted by Kumar *et al.* (2008) and Kumar *et al*. (2009). We have only used the first harmonic of tweeks which are most clear and reliable for the data analysis. The tweeks analyzed were measured during times 19:00 – 04:00 hrs LT.

An example of the tweek with 3rd harmonic is shown in Figure 1. The f_c of first harmonic is 1.742 kHz giving h and n_e of 81.6 km and 28.1 cm^{-3}, respectively. From the overall analysis of the 1063 tweeks recorded at our station, the median f_c is 1.79426 ± 0.039 kHz for the first mode with standard deviation of 82.39 Hz. The maximum and minimum values of f_c are 1.26761 and 2.29166 kHz, respectively. The analysis of the path integrated h using f_c shows that h mostly ranges from about 75 – 97 km with median and standard deviation of 83.6 and 4.1 km, respectively. Similarly, path integrated n_e was estimated that varies from 24.4 – 31.5 cm^{-3} over the reflection heights with median and standard deviation of 28.9 and 1.33 cm^{-3}, respectively. Figure 2a shows n_e calculated from percentage of tweeks out of total 1063 tweeks. In total 61.4% of the tweeks give n_e varying between 28 – 29 cm^{-3}. An analysis for h given in Figure 2b shows that 63.2% of the tweeks were reflected from heights in the range 83 – 85 km which is the most frequent path integrated night-time tweek reflection height at the station.

From the analysis of the first harmonic tweeks, Ohya *et al.* (2003) estimated the n_e to vary from ~ 20 – 28 cm^{-3}. Shvets and Hayakawa (1998) have shown that the cut-off frequency of the first harmonic falls in the range of 1.6 – 2.0 kHz which compares well with the value obtained here. However, the variability in f_c and hence in h and n_e is larger as compared to these authors. Maurya *et al*. (2012) analyzed the tweek data recorded during 2010 at the Indian low latitude stations (Allahabad and Nainital) and showed that D-region electron density varies 21.5 – 24.5 cm^{-3} over the ionospheric reflection height of 85 – 95 km. Tweeks occurred on magnetically quiet days and showed day-to-day variability of up to 8 km under purely nighttime VLF propagation. Our results of h varying from 75 – 97 km show that some of the tweeks originating from the dayside would have propagated to our station in contrast to the observations by Maurya *et al*. (2012). This is likely to happen at our station as most of the tweek propagation path is over sea whereas propagation to Indian low latitude stations is mostly over the land which offers higher attenuation (Kumar *et al.*, 2008). Nighttime D-region ionization is mainly caused by Lyman-α and Lyman-β which ionize NO and O_2. The Galactic Cosmic Rays of which intensity is the highest during solar minimum and the lowest during solar maximum are another important source of ionization of the nighttime D-region below heights of 65 – 70 km, while above these heights, the Lyman-α radiation dominates (Thomson *et al*., 2011). However, the main source of nighttime D-region variability appears to be atmospheric gravity waves (AWGs) of different origins including meteorological origin such as strong thunderstorms that can generate the acoustic and gravity waves (Lay *et al*., 2015). It is known that thunderstorms occur most frequently in the temperate latitudes. AGWs are quasi-periodic oscillations with typical periods from 10^2 s to about a day and propagate upwards and outwards from the troposphere up to altitudes of 500 km, covering the entire ionosphere.

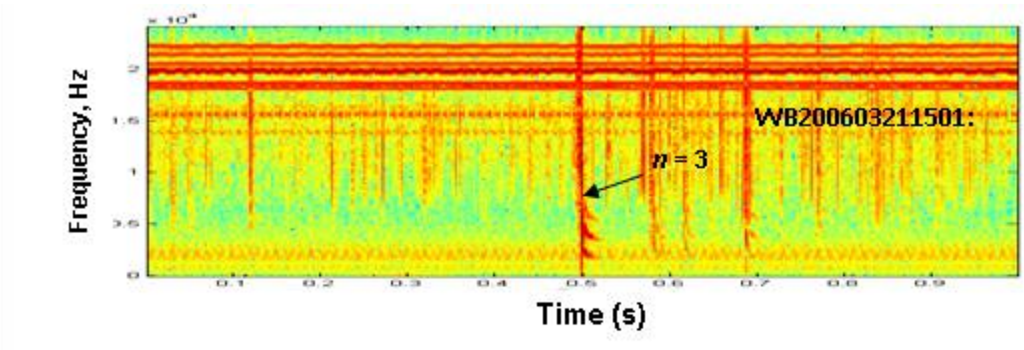

Figure 1. Typical spectrogram showing tweeks observed on 22 at Suva station on 22 March at 03:01:22 hrs LT. WB200603211501 stands for year 2006, month 03, day 21, time 1501 UT.

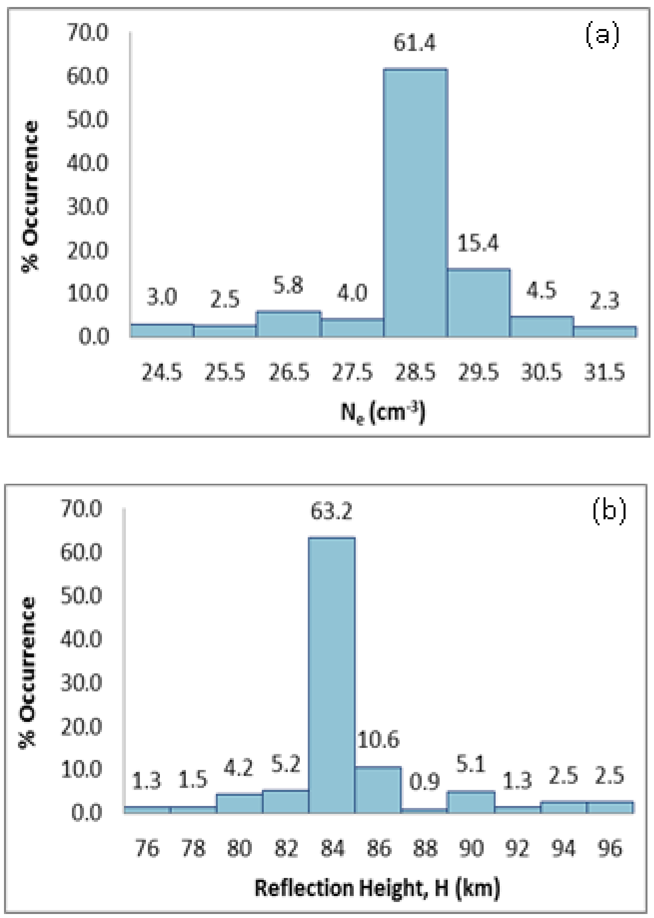

Figure 2. Night-time variation of the D-region observed from low latitude station (Suva, Fiji): (a) Electron density distribution from 1063 tweeks analyzed, (b) Reflection height distribution from these tweeks.

4.2. Plasmaspheric Remote Sensing Using Whistlers

The main interest in whistler research lies in utilizing the whistler data to probe the plasmasphere that consists of cold plasma and surrounds the Earth to an equatorial distance of up to several Earth radii. At mid (30^o – 60^o) and high (> 60^o) latitudes both satellite and ground based whistler data have been extensively exploited to probe the plasmasphere. At low latitudes (< 30^o) whistler data have not been used to determine plasmaspheric parameters, the main reason being that the propagation mechanism of low latitude whistlers cannot be determined from the whistler spectra (Singh and Hayakawa, 2001). This is because the nose frequency of such whistlers is higher than 100 kHz, well above the frequency range of the receiver. The propagation mechanisms of low latitude whistlers have been a subject of controversy over the years. Some researchers have supported non-ducted PL mode of propagation in the presence of negative latitudinal electron density gradient in the ionization (Kumar *et al*., 2007 and references therein; Singh and Hayakawa, 2001). Recently, based on correlation between observed low-latitude whistlers and lightning activity detected by the World-Wide Lightning Location Network near the conjugate point (geography 9.87°S, 83.59°E) of station Allahabad, India, Gokani *et al*. (2015) have shown a possibility of ducted mode of propagation even for such very low latitude whistlers. So in some cases ducted mode whistlers can be observed at the low latitudes such as in this case at Suva (geomag. lat. 22.2^oS).

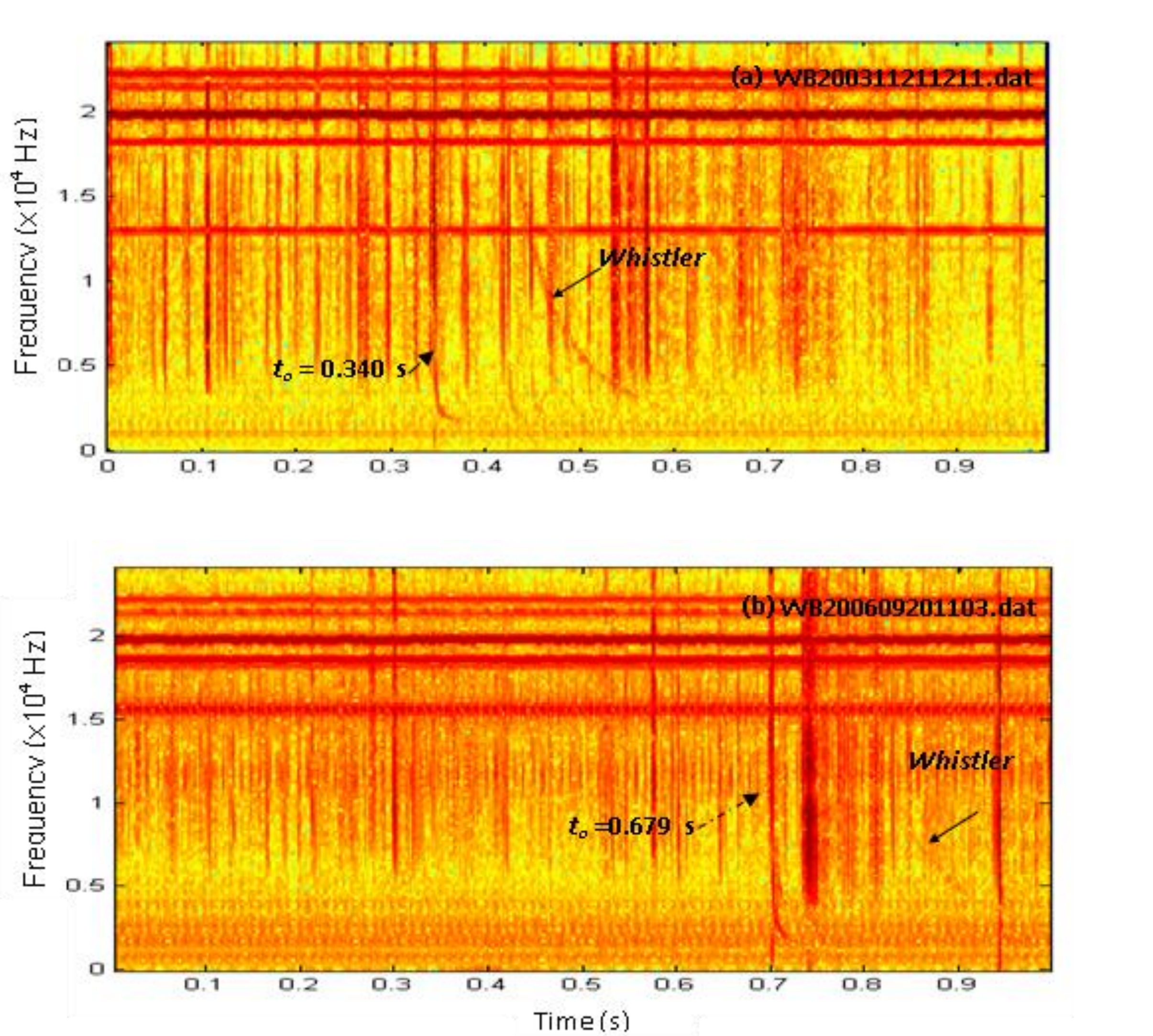

Figure 3. Typical spectrograms with whistlers recorded at Suva on: **(a)** 21 November 2003 at 12:11:22 hrs UT or 22 November 2003 at 00:11:22 hrs LT (Kumar *et al.*, 2007) and **(b)** 20 September 2006 at 11:03:17 hrs UT or 20 September 2006 at 23:03:17 hrs LT.

The diagnosis of plasmasphere using whistler method is based on the estimation of nose frequency f_n and arrival time t_n of f_n of whistlers. The nose frequency is characteristic of a particular class of whistlers called nose whistlers. The nose whistlers exhibit simultaneous rising and falling tones starting at the nose frequency. For most observed whistlers the nose is not visible and the determination of one or both these parameters (t_n and f_n) directly from the spectrogram is not possible. Several authors have suggested extrapolation methods to determine the f_n of ducted whistlers whose nose is not visible (Dowden and Allcock, 1971; Helliwell, 1965; Sazchin *et al.*, 1992). However, nose extension methods assume field-aligned ducted propagation and do not apply to PL mode low latitude whistlers (Singh and Hayakawa, 2001).

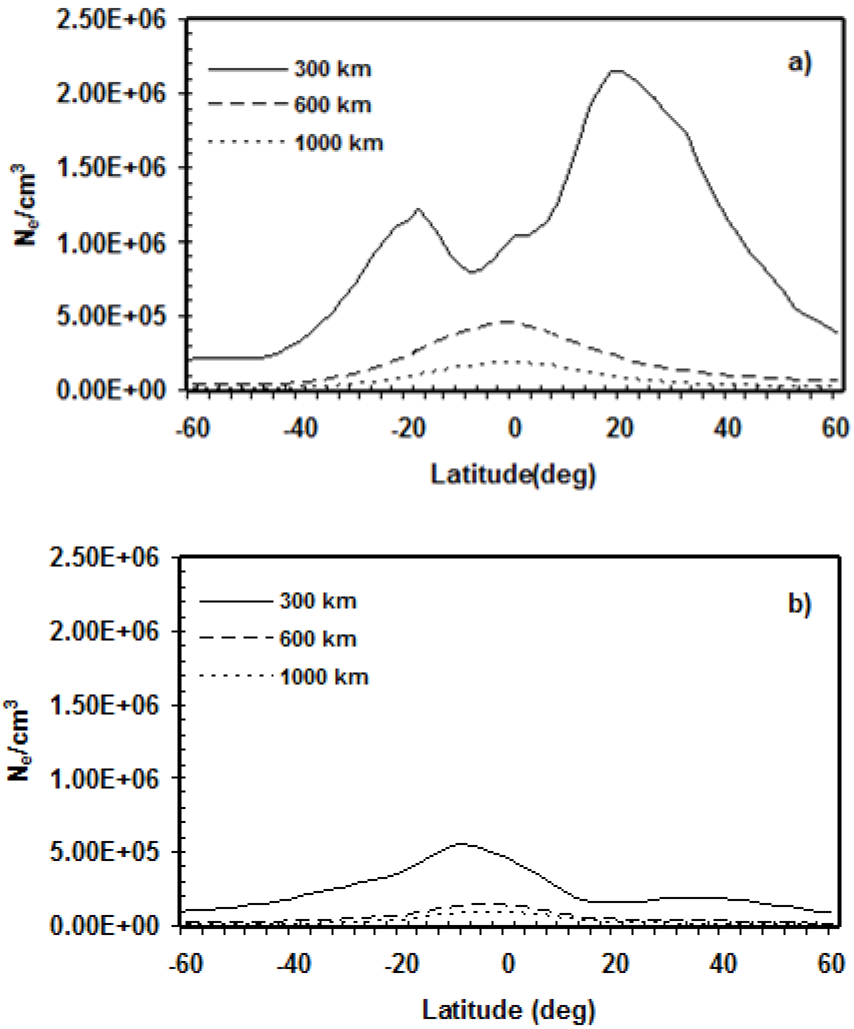

Figure 4. Ionospheric latitudinal electron density (el./cm^3) obtained from International Ionospheric Reference (IRI-2001) 2001 model at the geomagnetic longitude of Suva at 300, 600, and 1000 km: **a)** for geomagnetic storm of 20 – 22 November 2003 at 12:00 hrs UT on 21 November 2003 and **b)** on 20 September 2006 at 11:00 hrs UT.

We look at the possibility of determining the plasmaspheric parameters from the whistlers shown in Figure 3 (a, b) observed on 21 November 2003 at 12:00 hrs UT and on 20 September 2006, respectively with dispersions of 12.7 $s^{-1/2}$ and 15.5 $s^{-1/2}$. To identify the most likely propagation path of both the whistlers, the latitudinal electron density profiles were calculated using the IRI-2001 model and are plotted in Figure 4 (a, b) in the geomagnetic latitude range of - 60^o – + 60^o and at 253^o geomagnetic longitude (geomag. long. of Suva) for 21 November 2003 at 00:00 hrs LT and for 20 September 2006 at 23:00 hrs LT. The heights were chosen as 300 km, 600 km, and 1000 km. From Figure 4a, the horizontal negative ionization gradients at the altitudes of 600 and 1000 km in the latitude range of about - 30^o to + 30^o can be clearly seen. The negative gradients are sharp at 300 km but limited in the latitude range of - 20^o to - 30^o and + 20^o to + 30^o. The reduction in the electron density between 0^o to 10^o appears due to very intense magnetic storm of 20 – 22 November 2003 with minimum *Dst* index of – 422 nT that appears to have reversed normal nighttime downward E×B drift to upwards, lifting the plasma up from magnetic equator and depositing around ± 10^o – 20^o at F-region heights. The data in Figure 4a provides strong supporting evidence in favor of PL propagation of whistler observed on 21 November 2003 at 12:00 hrs UT during magnetic storms. The propagation mechanisms of whistlers to Suva during magnetic storms including that shown in Figure 4a have been reported by Kumar *et al.* (2007). From ray tracing analysis, Bortnik *et al.* (2002) found that the horizontal ionospheric latitudinal electron density gradients can cause whistler wave energy to focus near the geomagnetic equator and can result in a spatially narrow energetic electron precipitation at low *L* shells values (1.40 < *L* < 1.65). Thus the above results indicate PL mode of propagation in the presence of negative horizontal latitudinal gradients in the F-region ionosphere is the most likely mode of propagation for whistler in Figure 3a. The whistler shown in Figure 3b most likely propagated along field-aligned ducts followed by a small propagation in the EIWG to the Suva station or vice versa. Around the time of occurrence of whistler in Figure 4b there were no noticeable electron density gradients at 300 – 1000 km in the conjugate area of Suva. This does not support PL mode of propagation as it requires a negative latitude gradient. The whistler shown in Figure 3b occurred on a magnetically quite day, with a maximum value of three hourly K_p index of 2_o.

During quiet days, spread-F occurs more often in the pre-midnight than in the post-midnight (Kumar and Gwal, 2000) at the low latitudes. Spread-Fs are F-region plasma instabilities that arise during the post-sunset period as a result of the Gravitational Rayleigh Taylor instability coupled with the E × B drift. Generally, the down coming whistler waves emerging from the ionosphere have their wave normal oriented towards the pole. Spread-F irregularity can turn the wave-normal direction of down coming waves almost vertical at the base of the F-region, so that the waves may penetrate the lower ionosphere and reach the ground at low latitudes. The occurrence of the whistler, shown in Figure 3b, on a quiet day, in the pre-midnight time (at 23:03 hrs LT) and with no negative electron density gradients in the ionosphere, indirectly suggests that the whistler wave may have been trapped in the field-aligned columns of ionization and thus propagated in ducted mode towards Suva (22.2 ^{o}S). However, there is possibility that it may have propagated in the mixed mode (ducted and EIWG propagations). The estimation of the plasmaspheric parameters requires various assumptions about the wave propagation and the medium (Singh *et al.,* 1998; Tarcsai *et al.,* 1988). This whistler falls in the third class where the nose frequency is not observed on the spectrogram. Considering a field-aligned ducted propagation, the extension method outlined by Dowden and Allcock (1971) is used to estimate the nose frequency of this whistler.

Table 1. Plasmaspheric parameters estimated from whistler shown in Figure 3b.

Parameters	Estimated values
f_o	531.89 kHz
f_n	172.13 kHz
Δf_n	- 14.70 kHz
$f_n + \Delta f_n$	157.44 kHz
f_{He}	393.59 kHz
L	1.30
B_o	5.373 μT
N_{eq}	1.1×10^4 el./cm^3

For the whistler shown in Figure 3b the values of f_n = 172.13 kHz, D_o = 15.45 s$^{1/2}$ and f_{He} = 393.6 kHz are obtained. To obtain the value of *K* the integral in Eq. 12 was evaluated using Mathematica software and value of *K* was found 8.11×10^9. Assuming ducted propagation of this whistler, the electron density N_{eq} is approximated to be 1.1×10^4 cm^{-3} at *L* = 1.3 using Eqs. 11 and 9**.** Table 1 shows the whistler and its path parameters and the electron density along the whistler path received at the Suva station on 20 September 2006 at 23:03:17 hrs LT (Figure 3b). The electron density of 1.1×10^4 cm^{-3} obtained from the whistler recorded at the low latitude Suva station on a magnetically quite day (K_p = 2_o) is in agreement with the values obtained by Singh *et al.* (1993, 1998). Analyzing a large number of whistlers observed at low latitude stations in India: Varanasi (geomagnetic latitude 16.50^{o}N), Nainital (geomagnetic latitude 19.01^o N) and Gulmarg (geomagnetic latitude 24.43^o N), Singh *et al.* (1993), reported that the electron density varied between 3×10^4 – 8×10^4 cm^{-3}, 4×10^4 – 2×10^5 cm^{-3} and 2×10^4 – 3×10^5 cm^{-3}, respectively. Singh *et al.* (1998) computed the variation of electron density with *L*-value. They showed that the electron density sharply increases as the *L* value decreases from *L* = 1.8 to 1.4. Slightly lower electron density obtained here can be attributed to the variation in the magnetic activity as the whistler at the Suva station was observed on a geomagnetically quiet day whereas the whistlers at the Indian stations were observed on geomagnetically disturbed days. Tarcsai *et al.* (1988) reported electron density of 2×10^4 cm^{-3} at *L* = 1.4 and 5×10^2 cm^{-3} at *L* = 3.2 during geomagnetic storms. At lower *L*-values (*L* ≤

2), there is an increasing tendency to underestimate the electron densities due to a number of approximations in the whistler analysis (Tarcsai *et al.*, 1988). Hence it is noted that the estimation of plasmaspheric parameters using low latitude whistlers as reported here may not be very reliable, but this is an area of further research.

5. Conclusion

The significant findings from the ELF – VLF observations and analysis in this work can be concluded as follows:

- Tweek occurrence at the Suva station was found to be a common phenomenon at night mainly between 20:00 – 04:00 hrs LT. The median cut-off frequency for mode $n = 1$ was estimated to be 1.7942 ± 0.039 kHz. The path integrated h varies between 75 – 97 km with median and standard deviation of 83.6 and 4.1 km, respectively.
- The path integrated n_e was estimated to vary from 24.4 – 31.5 cm^{-3} over the reflection heights in the altitude range of 75 – 97 km with median value of 28.9 cm^{-3}. The variability in h and n_e indicates that the night-time D-region is unstable possibly due to AGWs of meteorological origin.
- Whistler occurrence to Suva station is rare and sporadic and is mostly limited to geomagnetic storms. However, the whistler recorded on the geomagnetically quite day suggests that ducted propagation to this station may be possible.
- Considering ducted mode of propagation for the whistler observed on 20 September 2006, the plasmaspheric parameters were calculated as: corrected nose frequency f_n = 162.093 kHz, electron cyclotron frequency f_{He} = 405.234 kHz, *L-shell value* = 1.3, and equatorial magnetic field B_o = 2.305 μT, and equatorial electron density $N_{eq} = 1.1\times10^4$ cm^{-3} at L = 1.3.

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