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LIGHTNING GENERATED SFERICS: DIAGNOSTICS TOOLS TO STUDY UPPER ATMOSPHERE

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Atmospherics or sferics that originate from lightning discharges on propagating large distances in the Earth-ionosphere waveguide or in the dispersive regions of ionosphere and magnetosphere form dispersed sferics called tweeks and whistlers respectively. Tweeks are novel diagnostic tool to monitor the nighttime D-region ionosphere. In this paper the lightning sferics (tweeks) recorded at a low latitude station, Suva (18.2^{o}S, 178.3^{o}E, geomag. lat. 22.2^{o}S, L = 1.17)) Fiji, in the South Pacific region and Allahabad (geomag. lat. 16.49^0 N, L=1.09) in India, will be presented and shown how they could be used to probe the night time D-region of the ionosphere. The computed D-region electron density is then compared with the electron density profile obtained from International Reference Ionosphere (IRI) 2007 model. Typical records of whistlers observed in Fiji and in India are presented.

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 [1]. 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 sferics at the receiver [2]. At night, sferics propagate with low attenuation in the EIWG, 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.* [3] utilized tweeks to estimate the tweek reflection height h and their 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 [4] estimated an increase in the electron density n_e from 28 – 224 el.cm^{-3} at h = 81-83 km. Ohya *et al.* [5] estimated the equivalent n_e at the h of the night-time lower ionosphere using the first order mode cut-off frequency. From tweek analysis, Ohya *et al*. [6] found a decrease in the h and increase in the n_e of the D-region ionosphere during the main phase of the great magnetic storm of 1 – 12 October 2000.

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" [7]). Tweeks generated by strong lightning can also leak out of the EIWG and excite the "Spiky Whistlers" (SpW) even after several thousand of km of subionospheric propagation. SpW whistlers have been recently observed by the DEMETER satellite [8]. 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. The high frequency components travel faster than the lower frequency components. A breakthrough in the whistler research started after Storey [9] presented a convincing interpretation of whistlers and explained the whistler spectra in terms of the magneto-ionic theory. Storey [9] predicted that the path of whistler propagation was more or less aligned with the Earth's magnetic field and extended between the hemispheres. Following *Storey's* publication many researchers have studied the occurrence and dispersion characteristics of whistlers and physics of whistler propagation, and have utilized whistlers for plasmaspheric investigation [10-14]. Some researchers have reported a good number of whistlers at the low latitudes from their nighttime observations [12-14]. 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 night-time whistlers [13], however, in some cases whistlers propagating in ducted mode have also been observed at the low latitudes [17].

In this work tweeks observed at a low latitude station, Suva (geog. lat.18.2^{o} S, geog. long.178.3^{o} E), Fiji, are utilized to estimate the night-time D-region equivalent electron density at the tweek reflections heights. The tweeks observed at a low station Allahabad (geomag. lat. 16.49^{0} N), in the Indian sector, are also presented. The broadband ELF-VLF data were recorded using the World Wide Lightning Location Network **(**WWLLN**)** VLF setup at The University of the South Pacific, Suva, Fiji and Atmospheric Weather Electromagnetic System for

Observation, Modeling and Education (AWESOME) VLF receiver at Allahabad in India. Typical examples of whistlers recorded in Fiji and India at the low latitudes are presented.

2. Experimental Data

The details of the experimental set-up utilized in Fiji have been described by Dowden *et al*. [16]. The data are recorded in files of 11 MB per minute using the lightning software. ELF-VLF data files are analyzed using a MATLAB code which produces spectrograms of one-second durations. Tweeks sferics are visually identified from spectrograms (see Figure 1) and then analyzed in two steps: first spectrograms are copied and loaded into paint software which are then saved in bitmap format, 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 frequencies f_{cn} of different harmonics of tweeks is then determined with an accuracy of 35 Hz. The AWESOME VLF receiver setup and analysis technique used in India have been discussed in detail by Singh *et al.* [17] and Cohen *et al.* [18].

3. Theoretical considerations

For a waveguide having perfectly conducting boundaries, the modes are defined completely by their cut-off frequencies f_{cn} given by Yamashita [19]:

$$f_{cn} = \frac{n\,c}{2\,h}\,. \tag{1}$$

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 heights of the tweek harmonics is obtained:

$$n_e = 1.241\times 10^{-8}\, f_{cn}\, f_H\ [\mathrm{cm}^{-3}]\,. \tag{2}$$

The f_{cn} is obtained from spectrograms. We take f_H = 1.3 MHz according to International Geomagnetic Reference Field (IGRF) model. Then Eq. (2) reduces to:

$$n_e = 1.613\times 10^{-2}\, f_{cn}\ [\mathrm{cm}^{-3}]\,. \tag{3}$$

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 [20] as:

$$n_e = 1.43 \times 10^7 \exp(-0.15h') \exp[(\beta - 0.15)(h - h')] \ . \qquad (4)$$

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.

3. Results and Discussion

Electron density of the D-region ionosphere is too low for conventional ionosondes and the altitude of D-region is too low for satellite measurements and too high for balloon measurements. Therefore, it remains the least studied region of the Earth's atmosphere. Fact that ELF-VLF waves are reflected by the lower ionosphere can be utilized to study the electron density in the lower ionosphere. Figure 1a,b shows typical examples of tweeks observed at the Suva station on 01 January 2004 and at Allahabad, India, on 23 March 2007. The propagation features of tweeks recorded at Suva, in general, have recently been reported by Kumar *et al.* [21].

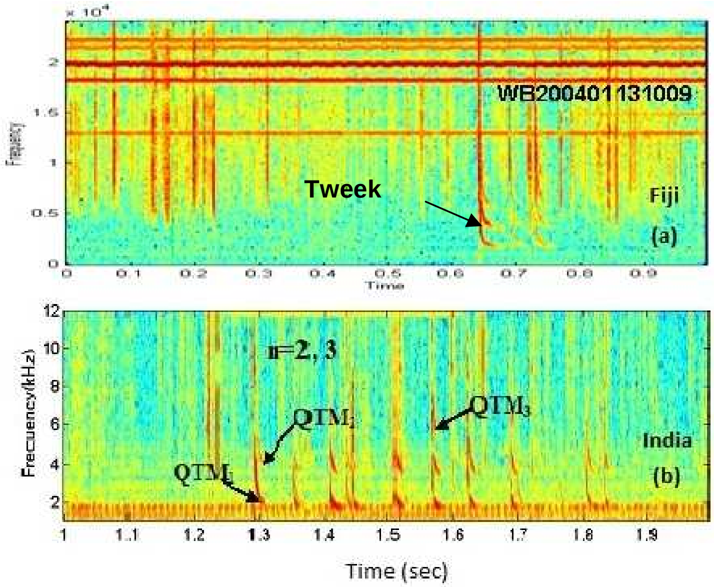

Figure 1. Typical spectrograms showing tweeks observed 13 January 2004 at 1009 UT at Suva, Fiji and on 23 March 2007 at Allahabad, India.

The ionospheric reflection heights h and equivalent electron density n_e from cut-off frequency of modes $n = 1 – 3$, for the tweek observed at Suva as indicated in the Figure (a), have been estimated using Eqs. (1) and (3), respectively. This method estimates the n_e at h of the lower ionosphere over the entire propagation path of the tweek sferics. It is estimated that the n_e varies from 28 – 87 el cm^{-3} over the h in the range 82.7 – 83.8 km. 120 first harmonic tweeks observed at Suva during January-February 2004 were analysed to calculate the average h and n_e and found to be 84.6 km and 29 el cm^{-3} , respectively. From the analysis of the first harmonic tweeks, Ohya *et al.* [5] estimated the n_e to vary from ~ 20 – 28 el./cm^3 which are consistent with our calculations. The lower ionosphere can be characterized as a “Wait ionosphere” defined by a reference height h' in km and the exponential sharpness factor β in km^{-1}. Tweek method utilized here gives path-integrated electron density. Substitution of n_e and h from Figure 1 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 to be 83.4 km and 0.65 km^{-1}, respectively. The value of β thus obtained is higher by 0.16 km^{-1} than that obtained by Cummer *et al.* [22] using the VLF sferics observed during low solar activity month of July 1996 (Sun spot number R_Z = 10) but is consistent with that obtained by Thomson *et al.* [23] and Kumar *et al.* [24]. Figure 2 shows the nighttime D-region n_e profile (hollow circle) calculated using Eq. (4) for h' = 83.4 km and β = 0.65 km^{-1} for the altitudes ranges of 82-90 km. The n_e profile (solid circle) obtained using IRI-2007 model at Suva on 13 January 2004 at 22:09 LT is also plotted in the Figure 2. The n_e values were obtained using the IRI-2007 model. The n_e obtained by tweek analysis are lower in the range of 82-86 km with a very well match at about 87 km.

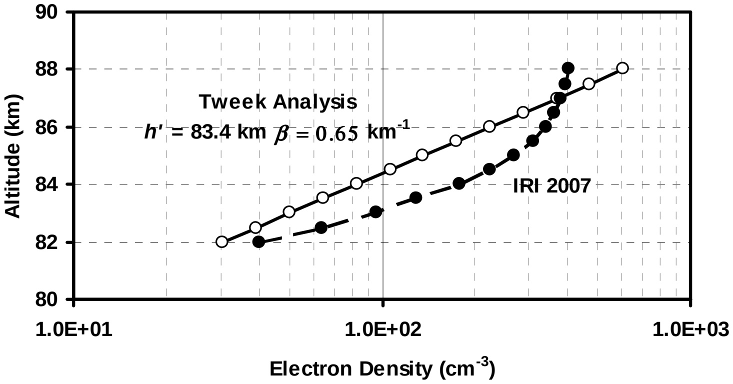

Figure 2. A comparison of electron density profiles of the lower ionosphere obtained using tweek in Figure 1a (solid line with hollow circles) and the IRI-2007 model.

It has been well established that whistlers propagate in ionosphere and magnetosphere to middle and high latitudes mostly in the ducted mode. The propagation mechanisms of low latitude whistlers have been a subject of controversy over the years. However, there is a now a growing consensus about the propagation mechanism of the low latitude whistlers in favor of non-ducted PL mode of propagation in the presence of negative latitudinal electron density gradient in the ionization [13-14]. However, in some cases ducted mode whistlers can be observed at the low latitudes such as that of Suva (geomag. lat., 22.2°S). The whistler observed on 20 September 2006 at 11:03:17 hrs UT as shown in Figure 3, most likely propagated along field-aligned ducts followed by a small propagation in the EIWG to the Suva station or vice versa. The dispersion and *L-shell* parameter for this whistler were estimated 15.5 $s^{-1/2}$ and 1.3, respectively.

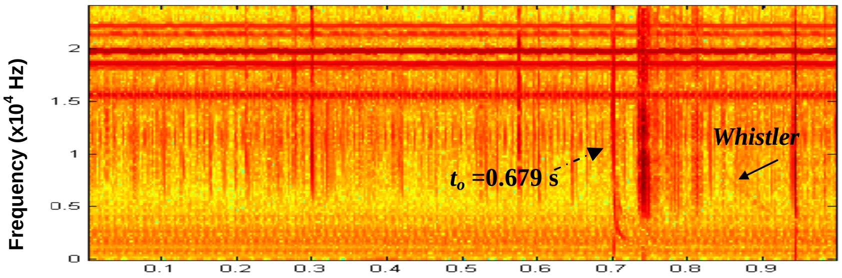

Figure 3**.** Typical spectrogram showing a whistler recorded at Suva, Fiji on 20 September 2006 at 11:03:17 hrs UT.

Around the time of occurrence of whistler in Figure 3 there were no noticeable electron density gradients at 300-1000 km in the conjugate area of Suva checked using the IRI 2007 model. This does not support PL mode of propagation as it requires a negative latitude gradient. This whistler 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 at the low latitudes. 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. However, there is no spread-F data available to verify it. In Figure 4 we present dynamic spectra of one of the whistlers recorded using AWESOME set-up on 17 June, 2008, at 12:30 UT. During the period of one hour several whistlers were observed (not shown here). The lower and the upper cut off frequencies varied between 1.68-3.12 kHz and 5.63-7.86 5.63 kHz, respectively. The dispersion of the whistlers varied between 15.72-18.26 sec$^{1/2}$, respectively [25].

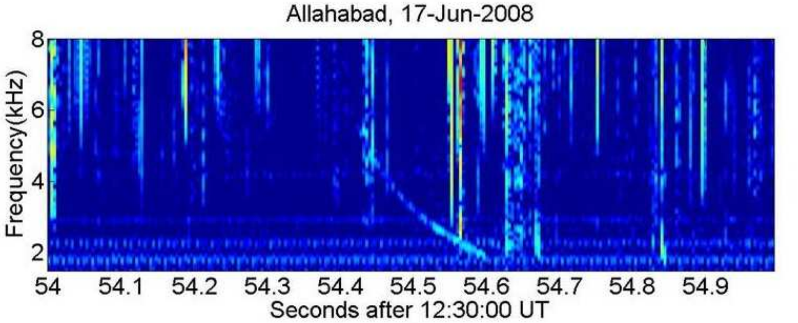

Figure 4. Typical spectrogram showing whistler recorded at Allahabad, India a low latitude Indian station on 17 June, 2008 at 12:30 UT.

The characteristic difference between low and mid-high latitude whistler spectra is (a) the upper cut-off frequency of low latitude whistler is higher than those observed at mid-high latitudes, (b) the nose-frequency (~ 0.4 f_{He}, where f_{He} is the equatorial electron gyrofrequency) for low latitude whistler is ~ 100 kHz or more and hence is not observed due to heavy attenuation (the absorption coefficient is minimum ~ 5 kHz and increases with frequency), and (c) the dispersion is smaller than for mid-high latitude whistlers. Whistlers propagated such can be used to determine the plasmaspheric parameters which will be part of our future studies.

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