Global Journal of Science Frontier Research: A
Physics and Space Science
Volume 18 Issue 10 Version 1.0 Year 2018
Type: Double Blind Peer Reviewed International Research Journal
Publisher: Global Journals
Online ISSN: 2249-4626 & Print ISSN: 0975-5896

Remote Sensing of Mid/Upper Atmosphere using ELF/VLF Waves

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Keywords: *lightning discharges; tweeks; whistlers; ionosphere; magnetosphere; electron density; hybrid mode of propagation; dispersion.*

GJSFR-A Classification: *FOR Code: 291003*

REMOTESENSINGOFMIDUPPERATMOSPHEREUSINGELFVLFWAVES

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Remote Sensing of Mid/Upper Atmosphere using ELF/VLF Waves

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Keywords: lightning discharges; tweeks; whistlers; ionosphere; magnetosphere; electron density; hybrid mode of propagation; dispersion.

I. Introduction

Grounds monitoring of extremely low frequency (ELF) / very low frequency (VLF) waves in satellite age have still its role because of the continuity and suitability in many respects. Ground observations of ELF/VLF waves are carried out with very simple and low-cost equipment and are very successful in the monitoring of mid/upper atmosphere. Till date monitoring of D-region atmosphere is being carried out by ELF/VLF waves because of the limitation of balloon experiments at higher height, and incapability of the satellite accessibility at lower region (Singh et al., 2014; 2016). For in-situ measurements of the lower ionosphere rockets have been used (Friedrich and Torkar, 2001; Nagano and Okada, 2000) but limitation with the rocket technique is that it can be launched only for specific time and might not be able for continuous monitoring. Some other ground-based active experiments like ionosondes and incoherent scatter radars in the HF-VHF range are used for lower atmosphere monitoring but these methods are not so successful in this region because they are unable to receive ionospheric echoes due to low electron densities (< 10^3 el./cm^3) especially in the nighttime (Hargreaves, 1992). MF radar has been utilized (Igarashi et al., 2000) at some locations but this method requires very high costs in comparison to ELF/VLF active radio measurements. Actually, at these frequencies, a major portion of electromagnetic energy radiated during the return strokes of lightning discharges propagates approximately the speed of light in the Earth-Ionosphere Waveguide (EIWG) at large distances by the process of multiple reflections. The return strokes of lightning discharges generate electromagnetic waves in a wide frequency range with peak spectral power at around 5 kHz (Prasad and Singh, 1982).

Earlier workers considered the tweek studies based on propagation characteristics only (Outsu, 1960; Yedemsky et al., 1992; Hayakawa et al., 1995; Sukhorukov and Stubbe, 1997; Kumar et al., 2008). Tweeks were used to study the land and the sea parameters (Prasad, 1981) while the polarization properties that revealed tweek tail is left-handed circular polarization that connect the vertical component of the geomagnetic field with it (Yedemsky et al., 1992; Hayakawa et al., 1995). But in the recent past the main focus of tweek studies have been in D – region investigations (Maurya et al., 2012; Shvets et al., 2014; Singh et al., 2016). Storey (1953) explained the details of whistler spectra regarding the magneto-ionic theory and predicted that the path of whistler propagation was more or less aligned with the Earth's magnetic field and extended between the hemispheres. Various researchers have studied the propagation characteristics of whistlers and have used whistler as potential tool for investigating ionosphere/ magnetosphere (Helliwell, 1965; Carpenter, 1966; Sazhin et al., 1992; Singh, 1995; Singh et al., 1998a,

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1998b, 1999; Carpenter, 2007; Singh, 2008; Lichtenberger, 2009; Singh et al., 2014). The propagation modes of whistlers are classified into ducted mode propagating along field-aligned irregularities of enhanced ionization (Cerisier, 1974; Singh and Singh, 1999) and non-ducted with greater wave normal angles to geomagnetic field lines (Aikyo et al., 1972). Ion cyclotron whistlers, only detectable in space, also provide some information on the ion composition (Gurnett et al., 1965; Singh et al., 1998c; Singh et al., 2003).

In this paper, we have considered both ELF/VLF phenomena (tweeks and whistlers) as remote sensing tool to explore mid/upper atmosphere. At lower latitude the D-region ionosphere extends within 60-100km and that depends on the variation in the solar zenith angle, solar flux, season and latitude as well (Friedrich and Rapp, 2009) while the collisions between charged particles and neutrals dominate and this region remains the least studied region of the ionosphere.

The reflection property of the ELF/VLF waves from the D-region are also used in the study of D-region through the VLF transmitters (Bainbridge and Inan, 2003; Thomson et al., 2007; Thomson and McRae, 2009) but the disadvantage of this technique is limited to only spatial coverage along the propagation path. As the wave velocity is a function of electron density, the dispersion analysis of whistlers are widely being used in obtaining the information about the ambient medium, electron acceleration and precipitation from radiation belts (Summers and Ma, 2000; Horne et al., 2005). Similarly, the non-linear wave-wave interactions with the Alfvén waves are used as a valuable tool in the characteristic study of the structure of the ionized terrestrial environment (Park et al., 1978; Sharma et al., 2010).

In this paper, we have attempted an empirical study of ELF/VLF waves and emphasized that these waves can serve as a diagnostic tool for remote sensing of the mid/upper atmosphere. The paper has been organized in a few sections. Introductory remarks have been provided in section 1. The details of experimental arrangements and the data analysis are presented in section 2 while section 3 has dealt with the discussion of results obtained, and finally, the conclusions are presented in section 4.

II. Experimental Data And Method Of Analysis

The broadband ELF/VLF data analyzed in the present study have been recorded by the Automatic Whistler Detector (AWD) system installed at Physics Department, University of Lucknow, Lucknow (Geomagnetic latitude = 17.6^{0}N, Geomagnetic longitude = 154.5^{0}E, L = 1.10), India. ELF/VLF wave field as a function of time and frequency was continuously monitored and recorded by AWD setup. The detailed description of the AWD system operation and algorithm development can be found in Lichtenberger et al. (2008). This system has been especially devoted to the observation of ELF/VLF waves. The AWD system can record data in the synoptic mode with 1 min at every 15 min interval. Large numbers of tweeks and whistlers are recorded at our station (Lucknow) during the continuous observations. The data have been analyzed using a MATLAB code which produces dynamic spectrograms for the selected duration showing tweeks and whistlers.

Dynamic spectrograms of some higher harmonic tweeks recorded at our station (Lucknow) have been shown in Figure 1. The first order cut-off mode frequency *(fc)* of tweeks have been measured from the spectrograms and which is further used for the calculation of the ionospheric reflection height (h) and the D-region electron density *(n_e)*. For the present study, we have selected tweeks recorded in July 2012 during night hours of local time (LT) [= UT (Universal time) + 5:30 hrs]. Mode numbers of tweeks have been labeled on every spectrogram. Spectrograms shown in figure 1 have also showed a horizontal line near 18.2 kHz frequency which is the VTX transmitter signal operated by India at Katabomman (latitude 8.47^{0}N, longitude 77.40^0 E). We have adopted electron gyrofrequency f_H = 1.1±0.2 MHz according to the International Geomagnetic Reference Field (IGRF) model because the tweeks are observed at lower latitudes. For the calculation of electron density n_e, we have used the expression obtained by Shvets and Hayakawa (1998):

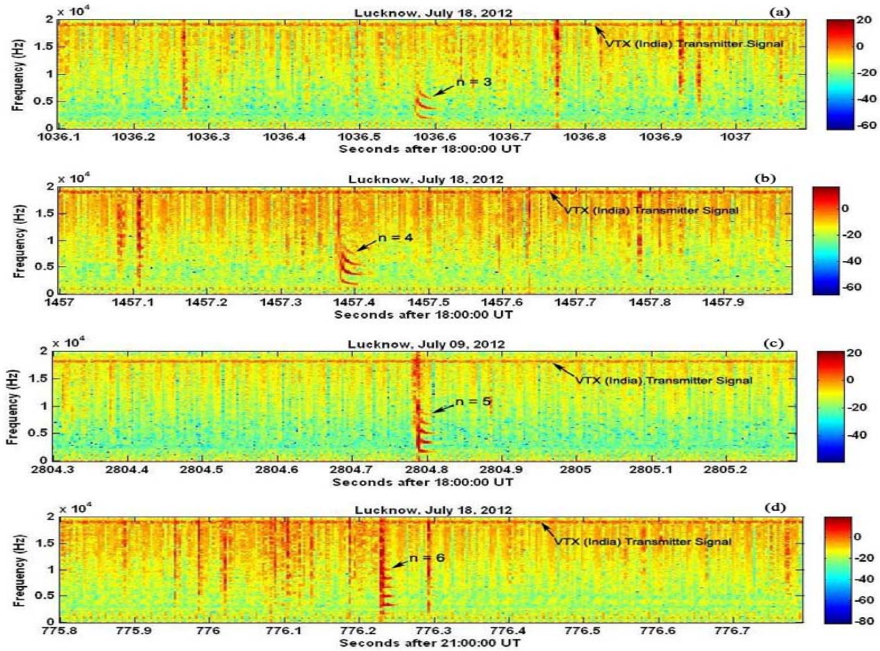

Figure 1: Dynamic spectra of some higher harmonic tweeks recorded in July 2012. The color scale shows the intensity variation of tweeks.

$$n_e = 1.39 \times 10^{-2} f_{cn} \quad \text{cm}^{-3} \tag{1}$$

where f_{cn} is the cut-off frequency of n^{th} mode. Here each mode is defined by its cut-off frequency that for the n^{th} mode is given by

$$f_{cn} = \frac{nc}{2h} \tag{2}$$

where c is the velocity of light in the free space, h is the tweek reflection height and n is the mode number (Budden, 1961).

For magnetospheric studies, we have analyzed the data mainly for whistlers. The whistler occurrence rate at lower latitude stations is low and very sporadic (Singh et al. 1998b, 1999, 2014), but once it starts, the occurrence rate becomes comparable to that of mid-latitude stations (Singh et al. 2014). We have observed whistlers at Lucknow (L = 1.10) on 24/25 March 2015 during 00:20:00 – 01:01:00 hour LT (Local Time) for the first time. We have noticed 16 whistlers of good quality with sharp dynamic spectra observed on March 24/25, 2015 during nighttime. Based on visual inspection of every dynamic spectrogram, we can infer that the intensity of the spectra slightly varied from event to event, but no general pattern has been obtained.

The recorded data files (wav_files) have analyzed with the help of MATLAB programs. The ELF/VLF raw data was translated to the frequency-time spectrogram using Fast Fourier Transform (FFT) codes (awd_wav_browse_win). The occurrence pattern of whistlers seen from the spectrograms at this stage was identified and further run these wav-files in another MATLAB code (ftpairs512) which produces dynamic spectrogram of whistler. Using diffusive equilibrium (DE-1) model in MATLAB program, we have calculated various magnetospheric parameters like the dispersion of whistlers, path of the propagation (L-value), equatorial electron density and total electron content in a flux tube, etc. The analysis of whistlers from a ground-based station has been regarded as inexpensive and efficient tool for upper atmospheric diagnostics (Sazhin et al., 1992; Singh et al., 1998a; Carpenter, 2007).

III. Results and Discussion

The whistler mode waves (natural magnetospheric radio emissions) have been extensively studied for wave diagnostics. Of the multitude of ground observations of ELF/VLF waves in the literature comparatively a few studies present quantitative treatment of remote sensing observations/ measurements. In this paper, we have used tweeks for ionospheric probing and whistlers for magnetospheric probing. A total of 555 visible tweeks have been observed in July 2012 during night hours while not a single tweek has been reported during day hours may be due to strong attenuation in the earth-ionosphere waveguide during the daytime. The local nighttime was divided into two portions: pre-midnight (18:00 – 00:00 LT) and post-midnight (00:00 – 6:00 LT). The number of tweeks has been counted mode wise (harmonic). The overall occurrence of tweeks increased as the night advances, and the maximum has been obtained during the post-midnight period. Although it is the lightning activity that determines the occurrence pattern of tweeks at any observation site but the conditions at lower ionospheric height during different

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seasons may also have some contribution towards the occurrence of tweeks and their higher modes. Figure 2 has depicted the pattern of tweeks considered in the present study and has revealed that tweek occurrence was maximum in post-midnight hours as compared to pre-midnight and further it might be associated with attenuation.

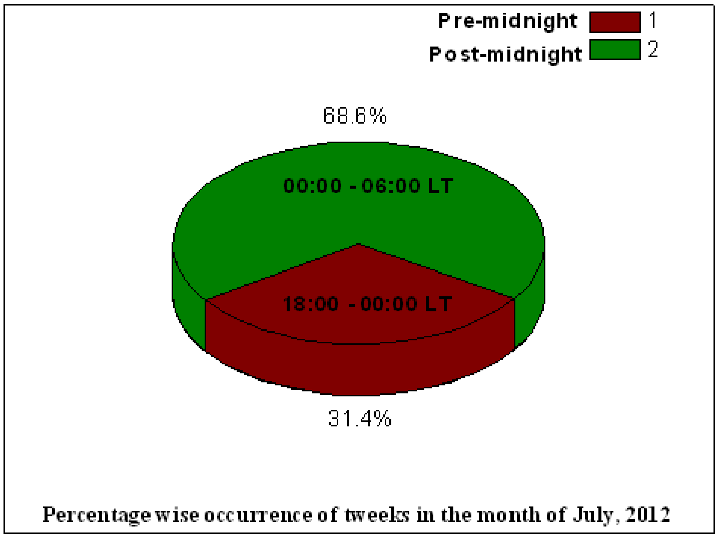

Figure 2: Piechart of percentage wise occurrence of tweek atmospherics during pre/post-midnight time sectors.

The D-region atmosphere is better reflector during the night hours than during the daytime, and this characteristic makes ELF/VLF waves a potential diagnostic tool to estimate the nighttime electron densities (n_e) at ionospheric reflection heights (h). These reflections occur because the electron density in the lower ionosphere increases rapidly and higher harmonics have been reflected from the higher altitudes. Danilov (1975) studied the chemistry and complicated cycle of ionization-recombination of the D-region atmosphere. Scattered Lyman α is well known source of the nighttime D-region ionization at the low/mid-latitudes while geocoronal Lyman α, Lyman β, and galactic cosmic rays are some other sources of the nighttime D-region ionization (Strobel et al., 1974). During our analysis the D-region electron density estimated from cut-off frequencies of the first-order mode ranged from 22.5 - 26.06cm^{-3} for the ionospheric reflection heights of 80.0 - 92.5 km while the electron density estimated for 6th harmonic varied from 22.51 - 132.46cm^{-3} over the ionospheric reflection height of 92.5 - 94.4 km in the altitude range of 1.9 km. The electron density for the second mode was almost double to that obtained from the first mode and so on for higher harmonics of tweeks. Figure 3 has shown the variation profile of nighttime electron density estimated using tweek analysis. The electron density has decreased during evening hours with the sunset, almost stabilized during post-midnight hours and again started increasing during morning hours with the sunrise. The obtained features were inconsistent with the variation of ionosphere during quiet geomagnetic conditions. We have also estimated the mean electron density (nem) with mode numbers that varied from 24.82-136.82cm^{-3} and have showed in Figure 4. We have calculated the mean reflection height which has increased with mode number showing that higher mode of same tweek has penetrated deeper into the D-region atmosphere. The relative amplitude of tweeks (shown in Figure 1) for different harmonics (n = 3 - 6) are calculated, and the variation of the same has been depicted in Figure 5. But we have not found any regular pattern in relative amplitude might be due to the return strokes of pulses suffer from successive reflections from the ionosphere. Table 1 has listed the details of parameters obtained from tweek analysis.

Table 1: Various remote sensing parameters observed from tweek analysis

Spectrogram	Date	Time of occurrence	Mode (n)	Electron Density (el/cm^3) (n_e)	Ionospheric Reflection Height (km) (h)
a	18 July 2012	23:30:1036.1hrs LT	1	23.76	87.7
			2	46.56	89.5
			3	68.38	91.4
b	18 July 2012	23:30:1457hrs LT	1	23.35	89.2
			2	45.73	91.1
			3	67.55	92.5
			4	89.09	93.6
c	09 July 2012	23:30:2804.3hrs LT	1	23.35	89.2
			2	46.28	90.0
			3	68.24	91.6
			4	90.51	92.1
			5	112.03	93.0
d	18 July 2012	02:30:775.8hrs LT	1	22.51	92.5
			2	44.61	93.4
			3	66.72	93.7
			4	88.68	94.0
			5	110.50	94.3
			6	132.46	94.4

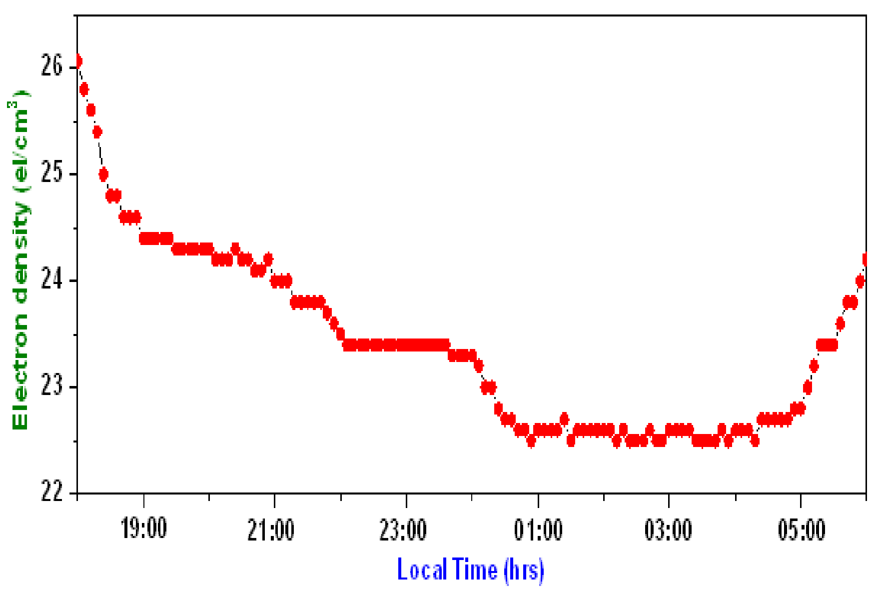

Figure 3: Temporal variation in the nighttime electron density of tweeks considered for the study.

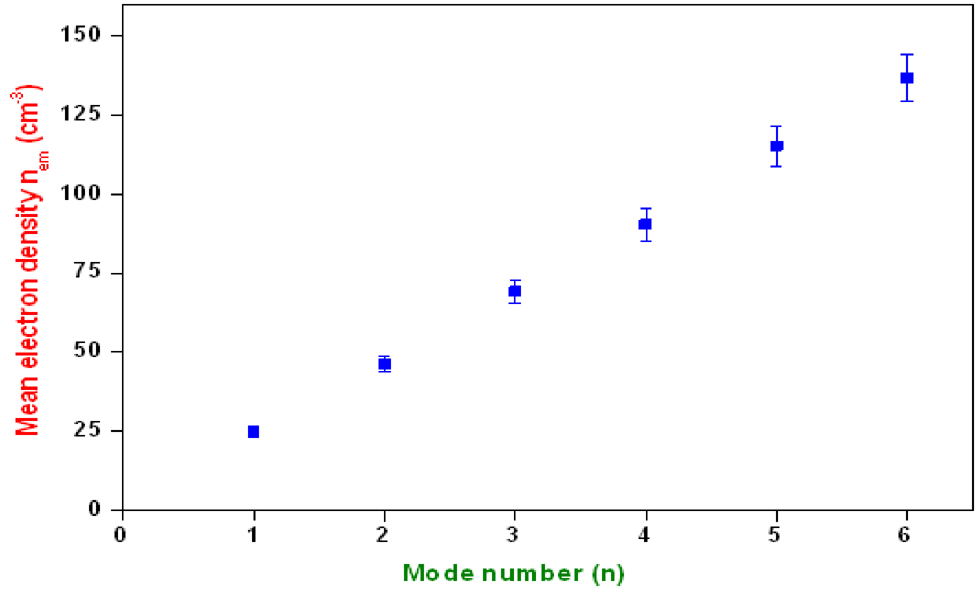

Figure 4: Variation of mean electron density (blue squares with error bar) with mode numbers of observed tweeks.

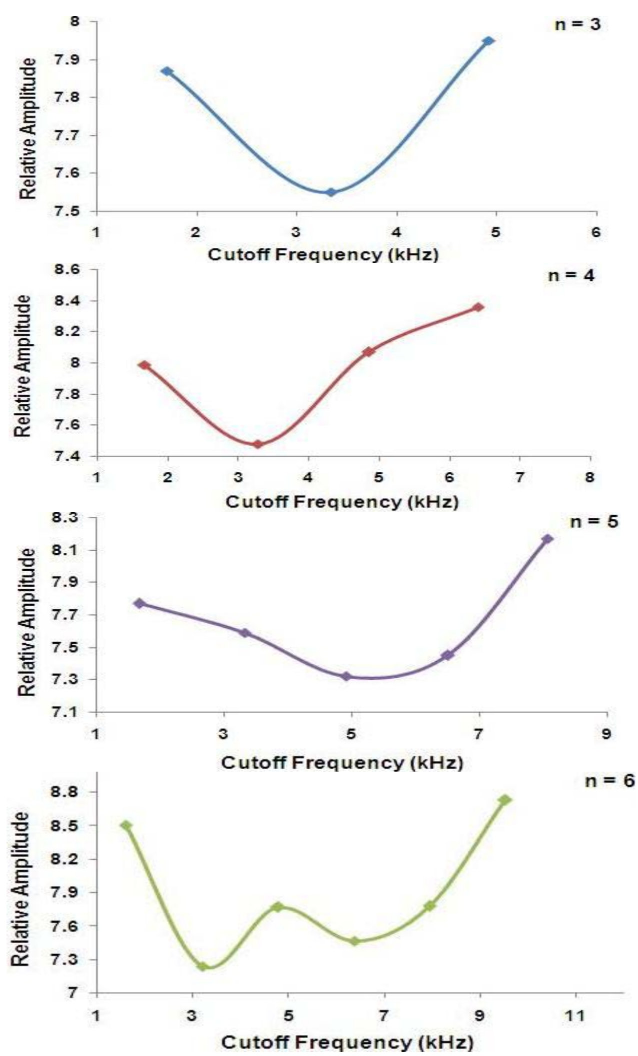

Figure 5: Variation of the relative amplitude of tweeks for different modes (3-6).

The second part of our analysis was devoted to whistler waves. Some good quality whistlers have been recorded on March 24/25, 2015 during the geomagnetically moderate period having maximum Kp index = 4 and Dst index < - 21nT. Figure 6 has represented the geomagnetic conditions during March 23-25, 2015. During the analysis, we found that the lowest frequency component of observed whistlers was well above the cut-off frequency of first-order mode of causative sferic (tweek) shown by its arrival time t_0. The causative sferics of whistlers have located by the intercept t_0 and was obtained by plotting time t versus $f^{-1/2}$ of the whistler frequencies and extrapolating the line to meet the time axis. The method of determination of causative sferic by the time t_0 for the whistlers observed is depicted in Figure 7 while Figure 8 has provided the spectra of some good quality whistlers recorded and analyzed.

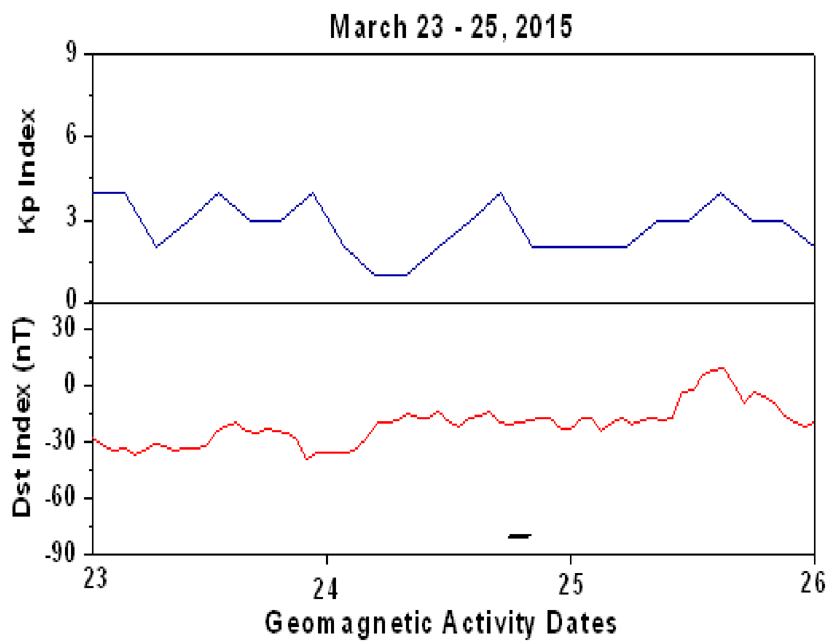

Figure 6: Variation in Dst and Kp indices during 23-25 March 2015 showing the moderate geomagnetic conditions. (Data Source: wdc.kugi.kyoto-u.ac.jp/index.html)

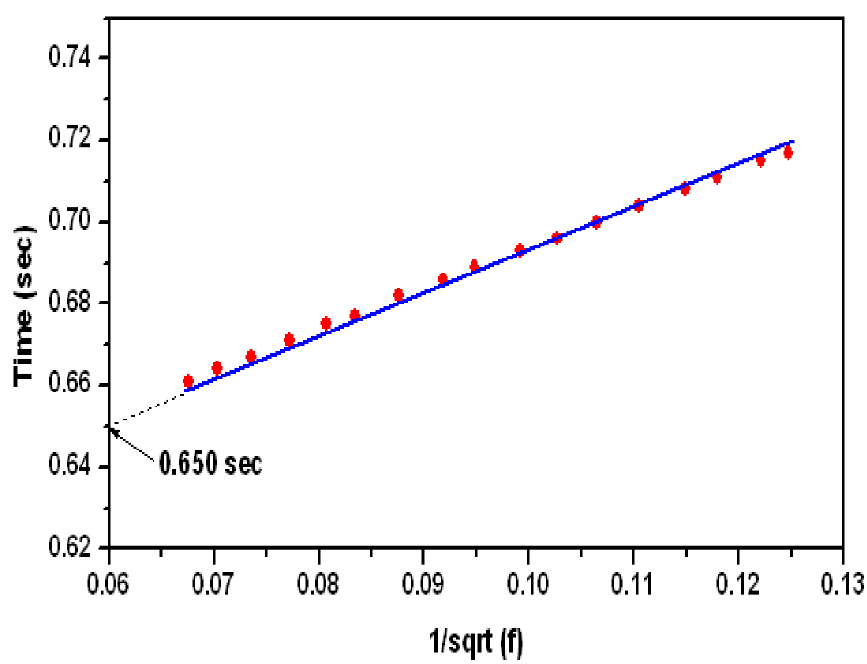

Figure 7: Time t versus f -1/2 plots for knowing the causative sferic locations of whistlers observed.

The products of travel time ($t - t_0$) of whistler frequency components ($f^{-1/2}$) gives dispersion D. Propagation mechanisms of very low latitude whistlers are still unclear. Both ducted and non-ducted theories have been given for the propagation (Singh, 1995; Singh and Singh, 1999). Generally, whistler occurrence activities at lower latitudes are very weak as compared to the mid/high latitudes may be due to location of conjugate points. The conjugate point of Lucknow lies over the Indian Ocean and hence thunderstorm activities are relatively very low as compared to that over the land (Christian et al. 2003). Due to the increased lightning activity in the Indian Ocean during March/April, this season is more pronounced for whistler activities at lower latitudes Indian stations.

Table 2 has listed the various parameters calculated from observed whistlers shown in Figure 8. Dispersion of the observed whistlers has varied from $20.2sec^{1/2}$ to $36.9sec^{1/2}$. The change in dispersion could be either due to change in electron density distribution or due to change in the location of the duct through which whistlers have propagated or it might be due to both reasons. On the other hand, the change in whistler path is interpreted as the drift of the plasma supporting the duct in the equatorial plane. This has been produced by the presence of a large-scale convective electric field in the region. Further, the propagation path of whistlers in the present study varied from L = 1.7 to L = 3.0 (ΔL = 1.3), i.e., whistlers have propagated along higher L values.

Table 2: Various magnetospheric parameters estimated from observed whistlers shown in figure 8

S. No.	Occurrence time (LT)	Dispersion ($s^{1/2}$)	L – value	Electron density (cm^{-3})	Total Electron Content in a flux tube (electrons/cm^2-tube)
1	00:21:16.801	21.1 ± 0.4	1.950 ±0.089	999 ± 188	$4.62 \times 10^{12} \pm 0.05 \times 10^{12}$
2	00:21:16.916	22.6 ± 3.2	2.165 ± 0.429	633 ± 448	$4.64 \times 10^{12} \pm 0.44 \times 10^{12}$
3	00:21:16.949	21.2 ± 0.8	1.954 ± 0.165	998 ± 346	$4.66 \times 10^{12} \pm 0.08 \times 10^{12}$
4	00:22:48.149	21.7 ± 1.0	2.284 ± 0.218	434 ± 169	$4.00 \times 10^{12} \pm 0.08 \times 10^{12}$
5	00:22:48.226	32.4 ± 12	3.050 ± 0.287	210 ± 58	$6.53 \times 10^{12} \pm 4.20 \times 10^{12}$
6	00:26:06.928	20.4 ± 0.3	1.822 ± 0.107	1406 ± 367	$4.77 \times 10^{12} \pm 0.13 \times 10^{12}$
7	00:29:41.659	23.1 ± 1.0	2.225 ± 0.098	565 ± 77	$4.66 \times 10^{12} \pm 0.20 \times 10^{12}$
8	00:31:38.518	21.1 ± 0.3	1.917 ± 0.083	1105 ± 206	$4.74 \times 10^{12} \pm 0.07 \times 10^{12}$
9	00:31:38.555	21.3 ± 1.9	1.863 ± 0.493	1345 ± 546	$5.06 \times 10^{12} \pm 0.50 \times 10^{12}$
10	00:31:38.601	36.9 ± 4.5	2.808 ± 0.039	411 ± 80	$9.11 \times 10^{12} \pm 2.10 \times 10^{12}$
11	00:31:38.610	20.4 ± 0.4	1.860 ± 0.038	1310 ± 266	$5.04 \times 10^{12} \pm 0.05 \times 10^{12}$
12	00:31:38.633	21.0 ± 0.8	1.962 ± 0.157	959 ± 313	$4.55 \times 10^{12} \pm 0.08 \times 10^{12}$
13	00:33:53.175	20.6 ± 0.6	1.796 ± 0.174	1569 ± 663	$4.99 \times 10^{12} \pm 0.19 \times 10^{12}$
14	00:33:53.340	24.1 ± 3.3	2.246 ± 0.163	583 ± 58	$5.01 \times 10^{12} \pm 1.00 \times 10^{12}$
15	00:36:18.285	20.2 ± 0.4	1.786 ± 0.158	1572 ± 631	$4.86 \times 10^{12} \pm 0.23 \times 10^{12}$
16	01:00:51.666	22.0 ± 1.4	1.965 ± 0.268	1044 ± 588	$5.00 \times 10^{12} \pm 0.16 \times 10^{12}$

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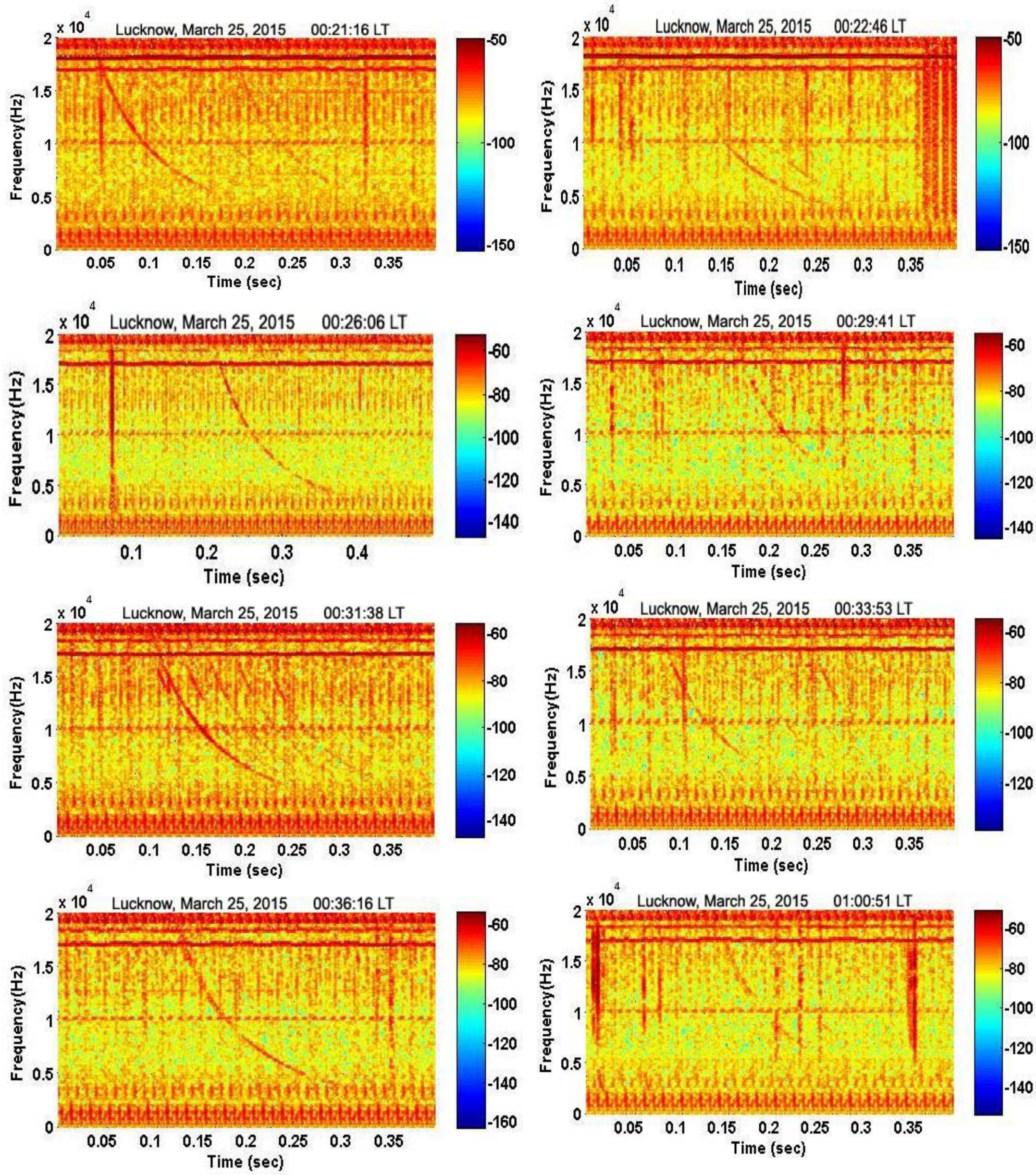

Figure 8: Dynamic spectra of some whistlers recorded at Lucknow (L = 1.10) on 24/25 March 2015.

Dispersion analysis of observed whistlers has indicated about the existence of various ducts in the magnetosphere, and it is evident that different whistlers have propagated along the geomagnetic field lines in different ducts. The lower and higher values of the L-shell for the observed whistlers come out to be 1.7 and 3.0, and equatorial electron density was calculated from 1572 to 210 electrons cm-3. The reported values of these parameters are very much comparable to the values reported by some earlier workers (Tarcsai et al., 1988; Singh, 1995; Singh et al., 1998b). The minimum and maximum value of total electron content for whistlers recorded at Lucknow were obtained as 4.00×10^{12} and 9.11×10^{12} electrons/cm2-tube respectively. The change in total electron content might be due to change in the path of propagation of whistlers.

IV. Conclusions

In this paper, we have used ELF/VLF waves (tweeks and whistlers) as remote sensing tool to explore the mid and upper atmosphere. Tweeks are used in the estimation of nighttime electron density at reflection heights from the cut-off frequencies of different harmonics. The D-region electron densities have been found of the order of 22.5-26.06cm^{-3} over ionospheric reflection height of 80.0-92.5 km. We have shown the variation in relative amplitude of tweeks and have not found any particular trend in its variability. The whistler data recorded on March 24/25, 2015 during night hours were analyzed to study the propagation characteristics and for estimation of some ambient medium parameters like dispersion, L-values (path of propagation), the equatorial electron density and the total electron content in a flux tube. Dispersion of the observed whistlers varied between 20.2 and 36.9 sec$^{1/2}$. We have observed that whistlers recorded at low latitude station (Lucknow) have traveled along higher L-values lying in the range of 1.7 to 3.0 and have propagated in the ducted mode along the geomagnetic field line in the magnetosphere, and waveguide mode after exit from the ionosphere into the Earth-ionosphere waveguide. The electron density in the equatorial region varied between 1572 and 210 electrons/cm^3 as L varied from L = 1.7 to L = 3.0. The minimum and maximum values of total electron content for whistlers were calculated to be 4.00×10^{12} and 9.11×10^{12} electrons/cm^2-tube respectively. High values of dispersion and other parameters have supported the statement of the propagation of whistler waves traveling through higher latitude. Importance of the present results might be in providing a good input to understand the propagational mechanism to ELF/VLF waves, electron density profiling of ionosphere and magnetosphere as well as the ground-based remote sensing of the mid/upper atmosphere.

Acknowledgments

Authors are thankful to the Indian Space Research Organization (ISRO) for providing financial support under CAWSES phase II program.

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