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Application of lightning discharge generated radio atmospherics/tweeks in lower ionospheric plasma diagnostics

A K Maurya[1,4], R Singh[1], B Veenadhari[1], P Pant[2] and A K Singh[3]

[1]Indian Institute of Geomagnetism, New Panvel, Navi Mumbai – 410 218, India.
[2]Aryabhatta Research Institute of Observational Sciences (ARIES), Manora Peak, Nainital – 263129, Uttrakhand, India
[3]Physics Department, Banaras Hindu University, Varanasi – 221005, India.

E-mail: ajeet.iig@gmail.com, akmaurya@iigs.iigm.res.in

Abstract. Lightning discharges during thunderstorm are the significant natural source of electromagnetic waves. They generate electromagnetic pulses, which vary from few Hz to tens of MHz, but the maximum radiated energy is confined in extremely low (ELF: 3-3000Hz) and very low (VLF: 3-30 KHz) frequency band. These pulsed signals with frequency dispersion are known as radio atmospherics or tweeks. These waves propagate through the process of multiple reflections in the earth-ionosphere waveguide over long distances with very low attenuation (2-3 dB/1000km). Since these waves are reflected by lower boundary of ionosphere, these are used extensively for probing the D-region ionosphere. D-region is important to the space weather, as well as the submarine communication and navigational aid. In this perspective the measurement of electron density profiles of the D-region is undoubtedly of great interest to both the development of reliable models and radio wave propagation. Earlier work on the tweeks is mainly focused to the theoretical considerations related to polarization, waveform analysis, and occurrence time and propagation mechanism. In this study we investigate tweeks to determine the equivalent night time electron densities at reflection height of the D-region. Distance traveled by the VLF waves from the causative lightning discharges to the receiving station has also been calculated. Tweeks recorded at a low latitude ground station of Allahabad (Geomag. lat. 16.05^0 N) during the night of 23 March 2007 have been used in the present analysis. Based on the analysis of the fundamental cut-off frequency of tweeks, the estimated equivalent electron density of the D-region has been found to be in the range of ~20 to 25 el/cm³ at ionospheric reflection height of ~80 to 95 km respectively. Propagation distance in Earth-Ionosphere wave guide (EIWG) from causative lightning source to experimental site varies from ~1500 to 8000 km.

1. Introduction

A typical lightning stroke from a thunderstorm radiates energy from few Hz to tens of MHz but there maximum spectral energy is concentrated in the ELF/VLF band. These electromagnetic pulses in the ELF/VLF band from lightning discharges are called as radio atmospherics or 'sferics'. These waves propagate by the process of multiple reflections through the boundaries of the wave-guide formed between the ground and the lower region of the ionosphere.

[4]Corresponding author.

These waves travel very long distances with lower attenuation rate (2-3 db/1000km) [1]. This waveguide mode propagation causes an appreciable dispersion near the cutoff frequency of EIWG around 1.8 kHz [2]. These dispersed sferics are known as 'tweeks'. As these waves show dispersion near cutoff, thereby accurately analyzing first order mode cut-off frequency, we can calculate the equivalent ionospheric electron densities of the D-region at the reflection heights. By accurately measuring the tweek dispersion, the propagation distance in EIWG from causative lightning discharge to the receiving station can be estimated.

In the present study tweeks recorded during the night of 23 March, 2007 at low latitude ground station Allahabad (Geomag. lat. 16.05^0 N) have been analyzed for the estimation of D-region ionospheric parameters like ionospheric reflection height, equivalent electron densities at these reflection height and distance traveled in EIWG. The results obtained shows the usefulness of lightning generated tweek atmospherics in studying lower boundary D-region ionosphere covering large geographical area in the range of ~ 1000-8000 km from the observation site.

The experimental setup for the observation of these waves consists of AWESOME VLF receivers developed by Stanford University, USA. Indian Institute of Geomagnetism, Navi Mumbai is operating three VLF receivers at three sites, namely at Allahabad, Nainital and Varanasi. The VLF receiver consists of two orthogonal crossed loop antennas with 10x10 m base aligned in N-S and E-W magnetic plane. Frequency response by the electronics of the VLF receiver is from 300Hz to 47.5 kHz. The VLF receiver consists of pre-amplifier, which is kept as near as to the receiving antenna for the better amplification of received signals, then it is fed to the line receiver kept in the recording room, connected by a ~300 m long cable. Line receiver is also connected to the GPS for time synchronization. Finally the data are stored in a data recording PC. The data are sampled at 100 kHz with10 microsecond absolute time resolution. The sampled data are analyzed by codes developed in MATLAB.

2. Theoretical background

The refractive index of wave propagation in magnetoactive plasma is expressed by the famous Appleton-Hartree formula [2]:

$$n_r^2 = 1 - \frac{2X(1-X-iZ)}{2(1-iZ)(1-X-iZ) - Y^2\sin^2\alpha \pm \left[Y^4\sin^2\alpha + 4(1-X-iZ)^2 Y^2\cos^2\alpha\right]^{1/2}} \quad (1)$$

where different terms are:

$$X = \left(\frac{\omega_p}{\omega_H}\right)^2 \qquad Y = \frac{\omega_H}{\omega} \qquad Z = \frac{\nu}{\omega}$$

n_r is the refractive index of the medium, α is the angle between the propagation direction of the wave and the external magnetic field vector, υ is the collision frequency of electron with neutrals, ω is the angular frequency of the wave, ω_p is the angular plasma frequency and ω_H is the angular electron gyro-frequency. H is the Earth's magnetic field strength, μ_o is the magnetic permittivity of free space, *e*, and *m* are the electron charge and mass. ω_H and ω_p ($=2\pi f_p$) are given by following expressions:

$$\omega_H = \frac{e\mu_o H}{m} \qquad f_p = \frac{1}{2\pi}\sqrt{\frac{Ne^2}{m\varepsilon_o}} \approx 9.0\sqrt{N}$$

here N is the electron density per cm^3

The upper sign "+" in the denominator of equation (1) corresponds to ordinary waves and the lower sign "-" corresponds to the extraordinary waves in the in the magneto ionic plasma. This ordinary mode corresponds to the right hand circular polarization and an extraordinary wave corresponds to the left hand circular polarization [3].

The polarization feature of tweeks has been found to be nearly left hand circular polarization of tweek tail connected with the vertical component of the geomagnetic field and hence predominance of the extraordinary waves in tweek tails [3-5]. This fact has been used to estimate the ionospheric parameters at the reflection of tweek waves in lower ionosphere.

After using the quasi longitudinal approximation condition in equation (1) Yedemsky et al [4] and Hayakawa et al [3] shows the possibility of full reflection for extraordinary waves at certain altitude where refractive index for extraordinary waves become zero and possibility of propagation for ordinary waves in the lower ionosphere.

The condition for full reflection of extraordinary waves can also be deduced directly from the Appleton-Hartree equation (1) [5], so condition for full reflection is as follows:

$$X=1+Y\sim Y \qquad (2)$$

In order to estimate the electron density at a certain height in the ionosphere we can use the condition in equation (2). Thus the electron density at the tweek reflection height is estimated by using the relation [6]:

$$N=1.66 \times 10^{-2} fc \quad [\mathrm{el/cm^3}] \qquad (3)$$

The earth-ionosphere wave-guide is assumed to be having a plane of two dimensional configurations, with perfectly reflecting walls separated by a distance h. The electromagnetic field in the waveguide can be comprised of a sequence of independent field structures (modes) that propagate with different group velocities. Each mode is defined by its cut-off frequency (f_{cn}). So cut-off frequency for n^{th} mode is given by [2].

$$f_{cn} = \frac{nc}{2h} \qquad (4)$$

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

There are two types of modes associated with each cutoff frequency – the TM (transverse magnetic) and TE (transverse electric) modes, and a single mode which has no cutoff frequency is the TEM (transverse electromagnetic) mode.

The group velocity υ_{gn} for each mode is given by [7]:

$$v_{gn} = c\left(1 - \frac{f_{cn}^2}{f^2}\right)^{1/2} \qquad (5)$$

As the Earth-Ionosphere wave-guide boundary is not perfect conductor, because ionosphere is anisotropic medium, therefore pure TM and TEM modes can not exist as they do in an ideal parallel plate waveguide. However these modes are modified to as quasi-transverse magnetic (QTM) and quasi-transverse electromagnetic (QTEM) modes [8-9]. The QTM mode is similar to the TM mode except that it has a small longitudinal (in the direction of wave propagation) magnetic field component.

The distance'd' propagated in Earth-Ionosphere waveguide is given by [10]:

$$d = dTc \left(1 - \frac{f_{cn}^2}{f^2}\right)^{1/2} \qquad (6)$$

where dT is dispersion time for tweek which can be measured from spectrogram. f_{cn} is cutoff frequency for n^{th} mode and f is frequency of wave.

The reflection height 'h' is obtained by the first order mode cutoff frequency 'f_c 'as follows:

$$h = \frac{c}{2 f_c} \qquad (7)$$

3. Results and Discussion

In the present study ~200 tweeks recorded during the night of 23 March, 2007 at Allahabad have been analyzed to understand the nighttime behavior of lower D-region (<90 km) ionosphere in low latitude region. Dynamic spectrogram of some of the tweeks observed is shown in figure 1. The time duration of the tweek events considered for present study is 12 hours from 06 PM (Indian standard time, IST) in evening to 06 AM (IST) till next morning. During the observations, tweeks were observed up to the 4th harmonic (figure 1a). Higher harmonic tweeks were observed mainly in post midnight period. Kishor et al., [11] have reported tweeks up to 6th harmonic from the site in Fiji islands surrounded by ocean. The difference in harmonics of the tweeks observed at different sites is because of different path conditions in the earth-ionosphere waveguide. At Fiji the major portion of the path is covered by over the sea whereas for Allahabad it is a combination of sea and land. Since the dispersion induced in tweeks depends on the conductivity of the surface over which the wave is guided. For ground the conductivity (~10^{-5} moh/m) is much lower than that of sea water (5.0 moh/m), therefore lower dispersion observed at Allahabad in comparison to the Fiji is attributed to the low conductivity of the ground. Further, tweeks occur mainly during night time as it is difficult to find tweek during the day time due to higher attenuation which depends mainly on the collision frequency of ionospheric constituents [12]. The collision frequency in the day time is ~10^7 Hz when ionosphere is at 60-65km whereas during night it is about 10^5 Hz when ionosphere evolves up to 90 km.

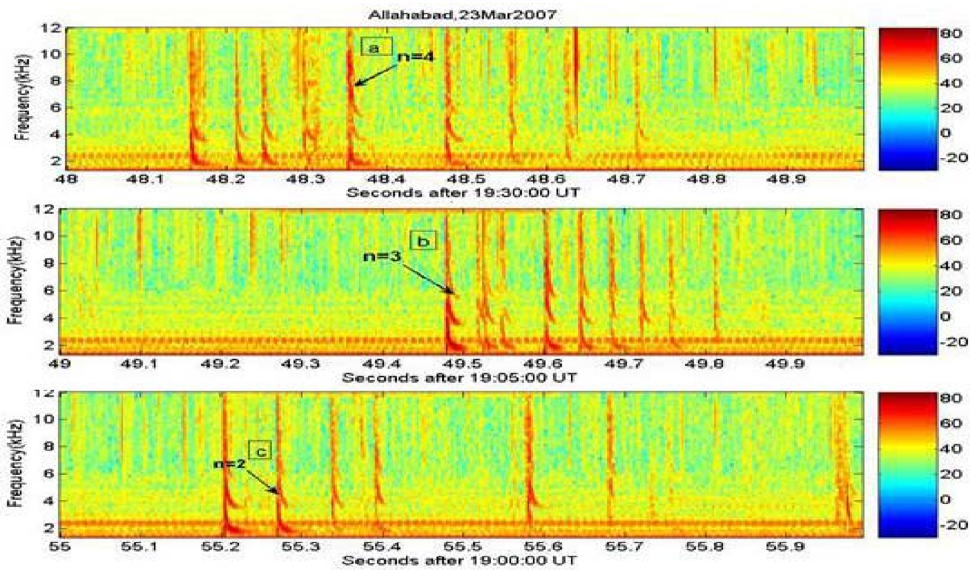

Figure 1. Typical examples of Dynamic spectrograms of tweeks observed on 23 March, 2007.

Dynamic spectrogram of some of the selected tweeks is shown in figure 1. Figure 1a shows examples of tweeks up to 4th harmonic, 1b with 3rd harmonic and 1c with 2nd harmonic. Using equations (3), (4) and (5) ionospheric reflection height of tweeks and electron densities at these heights have been evaluated for different harmonics or modes (n = 1, 2, 3, 4). The distance traveled in Earth ionosphere waveguide from source lightning discharge to the observing site has also been calculated. The calculated parameters are shown in table 1. From the table 1, we see that different modes are reflected from different ionospheric heights, fundamental mode (n=1) is having higher reflection height as compared to higher modes (n = 2, 3, 4). The variation in ionospheric electron density at different altitudes in ionosphere is visible. From the table it is also clear that fundamental mode (n=1) of the electromagnetic wave travels larger distance in comparison to the higher modes.

Table 1. Night time ionospheric reflection height, electron density, and propagation distance parameters as calculated from different modes of tweeks shown in figure 1.

Tweek	Mode (n)	Reflection Height (Km)	Electron Density (el/cc)	Propagation Distance (Km)
a	1	95	22	7439
	2	88	23	6824
	3	85	24	6297
	4	83	25	5956
b	1	94	22	6751
	2	89	23	6131
	3	83	25	5853
c	1	95	22	7690
	2	90	23	7618

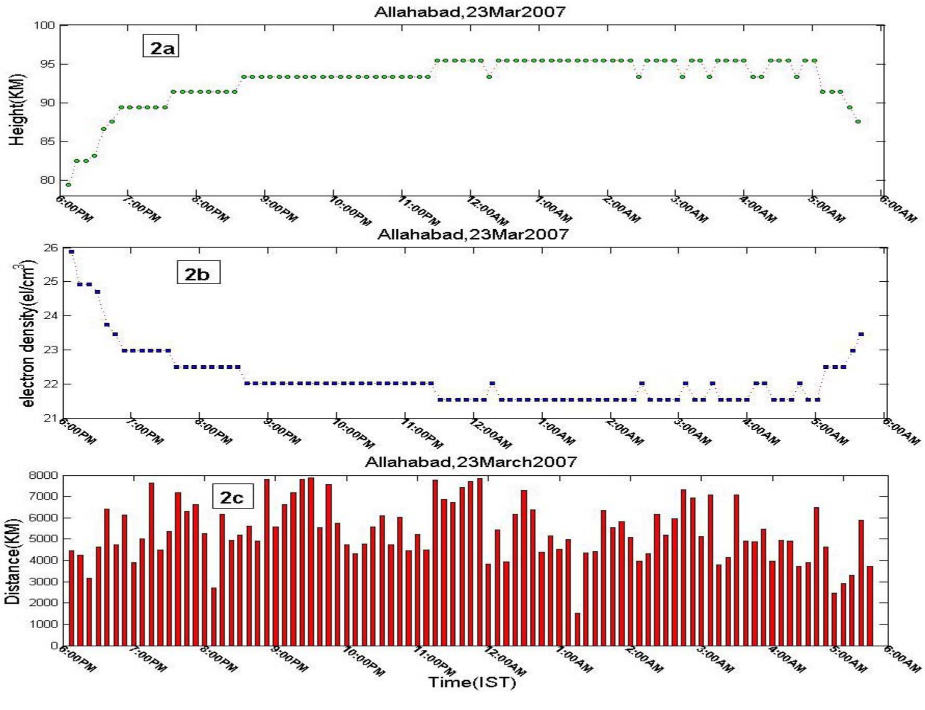

Figure 2. Temporal variation of lower ionosphere in the night of 23 March, 2007

Figure 2 shows the temporal evolution of different parameters of night time lower boundary of ionosphere during 23 March, 2007 from1800 hr (IST) to 0600hr (IST) till next morning. During this period fundamental mode (n=1) of ~200 selected tweeks are analyzed to determine ionospheric reflection height, electron density at these height and distance traveled in EIWG. Figure 2a shows that boundary of the lower ionosphere varies from ~80 to 95 km. After the dusk hours the height of lower ionosphere starts increasing and stabilizes during mid-night, it again starts decreasing during morning hours as the ionization process starts with the sun rise. Figure 2b shows the behavior of electron density variation, it starts decreasing then stabilizes during midnight and again starts increasing during morning hours with sun rise. The electron density variation is found to be in the range of ~ 20-25 el/cm^3, the inferred values are in agreement with results from IRI model [6], MF radar measurements [13] and rocket experiments [14,15]. The obtained features are in consistent with the behavior of ionosphere during perfect quiet geomagnetic conditions. Figure 2c shows distance traveled by tweeks in EIWG from source lightning discharge to the receiving site. The distance traveled is estimated from the dispersion analysis of tweeks using equation (6). Propagation distance was found to vary between ~1500 and 8000 km. The extent of the traveled distance by the lightning discharge generated tweeks shows their usefulness as a diagnostic tool for the D-region ionospheric study of large geographical region.

4. Conclusions

The present study shows how lightning discharge generated tweek radio atmospherics find application in diagnostics of lower D-region of the ionosphere. Some important features about tweek atmospherics are:

- Dispersion is very important feature of tweeks which gives information about ionospheric reflection, electron density at these heights and propagation distance in EIWG.
- Tweeks occurred mostly in night time because of lower attenuation.
- Higher harmonic in tweek travels less distance than lower one.
- Temporal evolution of lower ionosphere during the night of 23 March, 2007 is calculated from the observation of tweeks atmospherics. The Reflection height was found to vary between ~ 80-90 km and electron density variation was in the range of ~ 20-25 el/cm^3.
- The propagation distance of tweeks in EIWG shows the usefulness of tweeks data in studying D-region ionosphere covering large geographical region in the range of ~ 1500 to 8000 km around observation site

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