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Numerical modeling of seasonal and diurnal variations of lower ionospheric reflection parameters based on IRI model

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Abstract

Very Low Frequency (VLF) remote sensing technique is used to probe the D-layer modeling for which we use a very conventional model known as Wait′s 2-component ionospheric model. This model is characterized by two ionospheric parameters which are ‘steepness parameter’ (β) and ‘effective reflection height’ (h′). International Reference Ionosphere (IRI 2012) model is an empirical standard model of the ionosphere, based on all available data sources. In this paper, we compute an electron density profile of the ionospheric D-layer by using IRI model under an ionospheric quiet condition for the year 2016 from altitude range 65 km to 85 Km at the VLF reception station IERCOO/ICSP, Sitapur [Lat 22.5° N, Lon 87.48° E]. By numerically best fitting, we compare it with Wait′s empirical formula. Using an auto-generated process we repeat this procedure for several times and computed an authorized data set of Wait′s parameters (β and h′) for four locations viz. Kolkata, Kathmandu, Pune, and Bhuj for the different time of the day and for the entire year. Using linear equation as a best fit to the altitude profile, we try to compute the actual data set of β and h′ for the entire path of the various location of India and its subcontinent for VTX (18.2 kHz) transmitter for summer (July, 2009) and winter (December, 2008) period. By this data set, we showed the seasonal and diurnal variation of these two characteristic parameters behaviors and also using these parameters and Long Wavelength Propagation Capability (LWPC), we generate a spatio-temporal profile of simulated VLF signal amplitude for several baselines.

1 Introduction

The ionosphere is the ionized region of earth’s atmosphere which act as a natural detector and it is composed positive, negative ions and free electrons which affect the propgation of a radio wave signal. Ionosphere is divided into a number of permanent and semi permanent layers and sub-layers depending upon their compositions and physical characteristics. As there are different radiation occurs in the ionosphere which changes electron density profile of these layers[7]. The lowermost layer is D-layer which is highly complicated to analyze in the context of its chemical and physical properties. This Chapman layer consists of electrons, different of types of positive, cluster and hydrated ions and most importantly the negative ions, which are very rare in other higher ionospheric layers (E and F layer). The altitude range of D-layer is 60-90 km and hence impossible to study by direct probing technique by satellite or balloon borne experiments. As D-layer is vey complex so it is necessary to develop a model using VLF technique method.

Numerical modeling of lower D-region ionosphere is rather difficult as the production and recombination processes of electron and ions are comparatively faster than other layers. This dynamic behaviour can be replicated by using proper mechanism which deals with ionospheric chemical processes which in turns gives the information of the production and losses of electrons and ions. In a simplified way, VLF modulation technique is an alternative approach to replicate some ionospheric conditions. In this technique, two major models can be used. Firstly, Wait′s 2-component model [3] of the D-region which deals with the altitude profile of D-layer electron density and conductivity. This model assumes a log-linear profile of these two parameters as function of altitude and it is well capable of estimate their values with an adequate degree of accuracy. The main governing components are called ‘effective reflection height (h')’ and ‘sharpness factor (β)’. The Wait′s exponential formula estimates the electron density profile (N_e) by using them. The second model is the well-known numerical code Long Wavelength Propagation Capability (LWPC) code. This code utilize Wait′s parameters as local ionospheric conditions over the transmitter to receiver path length and replicates the amplitude and phase profile of VLF signal.

There are several works done in earlier where Wait′s model and LWPC were used for replicate the VLF signal perturbation.[4] used this tool to investigate the enhancement of electron density during solar X-ray flares. During the last decade, the ionospheric research team of Indian Centre for Space Physics, Kolkata, achieved an incredible progress in VLF research by development and application of this model. [12] achieved the spatio-temporal dependency of VLF-X-ray correlations by computing α_{eff} for different classes of flares. [9] has developed a realistic ion chemistry model coupled with LWPC to reproduce the true ionospheric conditions.[6] used this model to replicate the VLF modulation and ionospheric electron density profile during solar eclipse. [11] did an unique work by using this Wait′s model and LWPC to examine the spatio-temporal profile of VLF signal as recorded from Antarctica. The solar zenith angle profile which controls the solar flux profile was coupled with this model to emphasize the degree of ionization over long path ($>$ 7500 km) VLF wave propagation characteristics.

In these previous works, before applying the Wait′s model and LWPC to examine the perturbed unpick parameters as well as modulated VLF signal, a quiet condition has to be assumed where a sets of ionospheric reflection parameters were chosen is scientific justifiable method. As LWPC is the only tool which directly generates the VLF amplitude and phase with a direct coupling with ionospheric reflection parameters (h' and β), to have a whole day or whole year estimation of simulated VLF signal characteristics, the full sets of quiet values of (h') and (β) is an absolute need. These sets of quiet ionospheric conditions both diurnally and seasonally can be utilized to replicate the normal VLF signal for any receiving location without knowing the actual signal amplitude. So,this database can used as a important tool for to identify the proper radio receiving location to detect VLF signal.

To achieve our goal, we plan to compute the diurnal and seasonal variation of Wait′s exponential parameters for some kn own paths and verify the model with pre-recorded VLF signal. As, the Wait′s parameters are directly connected with electron density profile (N_e), we use The 'International Reference Ionosphere (IRI-2012) model for computation of (N_e). IRI gives a legitimate distribution of electron and ion density profile globally as function of altitude for ambient solar conditions. The $N_e(h)$ obtained from Wait′s analysis for normal ionospheric conditions more or less agrees with IRI-2012. We adopt a fitting technique with real-time electron density model and Wait′s empirical log-linear profile to use h' and β as fitting parameters to obtain the values of the parameters to be the best fit.

2 Data and Methodology

Our main aim for this work is to compute the true diurnal variation of steepness parameters and effective reflection height for all possible paths of VLF signal. As these Wait′s parameters have a direct connection with the electron density profile, thus we downloaded all the dates of electron density from International Reference Ionospheric model (IRI2012) for some locations for the year 2008, 2009 within the time gap of 6 minute and altitude range from 65 Km to 85 Km, and then we plot the altitude profile of these electron densities under quite condition of the ionosphere. In our entire analysis, we gathered the electron density data from IRI2012 **https : //omniweb.gsfc.nasa.gov/vitmo/iri2012_vitmo.html**.
Now we follow a fitting technique and fit all the electron density profiles and Wait′s empirical log-linear profile to use h′ and β as fitting parameters to calculate the values of h′ and β. For numerical modeling of electron density profile of lower ionosphere, we use Wait′s empirical formula [3] which is characterized by two parameters, steepness parameter (β) and effective reflection height (h′)

$$N_e = N_0 exp(-0.15h')exp[(\beta - 0.15)(h - h')] \qquad (1)$$

where N_0=1.43×10^{13}m^{-3}, N_e=number density of electron in the unit of m^{-3}, h'=Effective reflection height in the unit of Km, β=Steepness parameter(slop of the electron density profile)in the unit of km^{-1}, h= Height (km).
The gradient of altitude profile of electron density is called the steepness parameter (β), or in other words, it can be defined as the logarithmic slope of the variation of electron density with repect to height. The value of steepness parameters varies significantly both diurnally and seasonally rather than being a constant value. We calculate the values of β from the electron density profile .
Effective ionospheric reflection height varies seasonally and diurnally. The diurnal variation of VLF field strength is very sensitive to the variation of reflection height. One has to know this variation accurately in order to reproduce the diurnal variation of VLF signals.
We now calculate β and h′ by converting the equation (1) into linear equation format then compare it with a slandered linear equation. For this, we take log_e both side of the above formula we get,

$$log_e(N_e) = log_e(N_0 exp(-0.15h')exp(\beta - 0.15)(h - h'))$$

$$log_e(N_e) = log_e(N_0) + (\beta - 0.15)h \qquad (2)$$

It looks like a linear equation Now we fit a linear equation, and compute the reflection parameters value corresponding to the best fit.

So by this procedure, we compute electron density from the IRI model and then by the use of Wait′s empirical formula we calculate the values of the ionospheric reflection parameters theoretically. In this paper we divide the VTX-IERCOO into two segments, we compute the values of ionospheric reflection parameters for each segment and create a vast database of β and h′ allowable values for the year of 2008 and 2009. We study the diurnal and seasonal variation of ionospheric reflection parameters for the receiving point which is the location of Ionospheric and Earthquake Research Centre & Optical Observatory (IERCOO) (Lat. 22.5°N, Lon. 87.48°E), Sitapur where all the observation corresponding to VLF signal done by Indian Centre For Space Physics (ICSP). Again we interested in the variations of steepness parameters and effective reflection height from the transmitter to 4 campaign locations for summer and winter seasons, here also we divide the path into two segments, thus we developed the broad database of these reflection parameters for these above mention paths. The summer campaign locations and winter campaign locations are listed below in table. Using this data set of Wait′s parameters we run famous LWPC code and generate VLF amplitude profile. We mainly use rexp subprogram which is based on uniform ionospheric medium condition and compute the spatial variation of VLF signal. This spatial variation gives us magnitude and phase of the signal as a function of distance between the transmitter to receiver from which we generate a temporal variation of the signal over the 4 locations of Indian landmass. We select the time duration for temporal variation one hour before the sunrise time and one hour after the sunset time.

3 Results and Discussion

We give our attention to Figure 1, compare the variation of electron density altitude profiles then it showed that for the same reflection height for the date of 21 January, July, electron density at the local mid-noon 12:00:00 IST is higher than the electron density for after Sunrise time (for summer 06:30:00 IST and for winter 07:30:00 IST). Due to solar radiation, the electron density in summer is greater than the winter

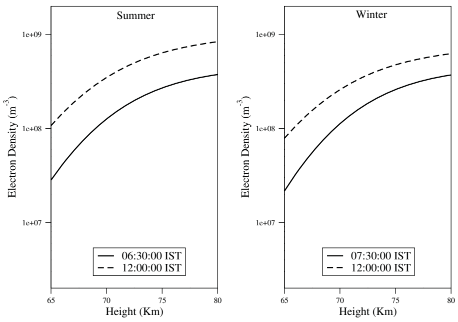

Figure 1. The Altitude profile of electron density variation (per cubic meter) is presented. Along X axis the height is plotted in km and along Y axis electron density is plotted in per cubic meter. (a) The altitude variation of electron density during summer, (b) the same variation for winter. Solid line indicates the value for local mid-noon and dashed line indicate the value just after the Sunrise.

We create a vast database of β and h′ which we compute by the use of an automated algorithm. Now we show the daytime variation of these two ionospheric parameters as a function of hours for the summer, winter in Figure 2 and Figure 3. We select the daytime (in this case we select the time between 05:00:00 IST to 19:00:00 IST) as the D-layer vanishes at nighttime and present only in daytime. We have seen that the estimated values of β and h′ from theoretical model agrees well with the conventional values. The minimum value of β for both seasons is 0.26 km^{-1}, and the maximum value of β in winter is 0.39 km^{-1} and for summer its value is 0.38 km^{-1}. The maximum and minimum values of h′ for summer and winter,ranges between 71 Km-75.6 Km, 72 Km-76.7 Km respectively. Due to the increase and decrease value of electron density the sharp change occurs in the slope just after the sunrise and just before the sunset times. Figure 2 and Figure 3 shows that the value of the sharpness parameter and effective reflection height gains maximum value at sunrise and sunset time and during mid-noon, the values get saturated and gains almost zero value.

Table 1

Place	Latitude and Longitude	Distance (Km)	Sunrise (IST)	Sunset (IST)
Kolkata	22.566°N, 88.400°E	1,963	05:03	18:22
Kathmandu	27.750°N, 85.330°E	2,296	05:06	18:44
Pune	18.560°N, 73.816°E	1,183	06:08	19:13
Bhuj	23.230°N, 69.660°E	1,863	06:17	19:38

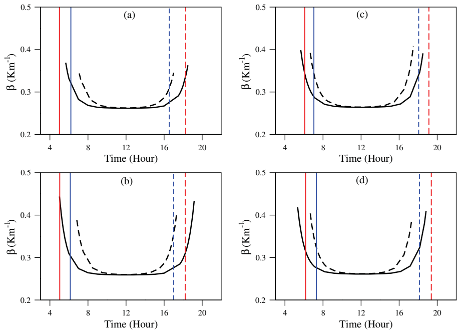

Figure 2. Steepness parameter (β) variation for Summer (solid black line/21–07–2009) and Winter (dashed black line/28–12–2008) for four different receiving locations. Along X-axis time is presented in Hours from 03:00:00 IST to 22:00:00 IST and along Y-axis steepness parameter (/Km) is plotted. The four signal receiving locations are, two East side (a) Kolkata, (b) Kathmandu and two west side (c) Pune and (d) Bhuj are presented.

A lack of symmetry shown in the variation of β and h′ for the summer season, the logic behind this is for the ion/electron production and recombination rate. Production rate is high during sunrise so that electron density is abundant in this region at that time and at sunset time similarly the recombination rate is high and the rate of recombination is different for different species of ions. So that the different values of β and h′ followed electron density values.

The Figure 4 shows that for Kolkata and Kathmandu the nature of VLF signal amplitude profile is W type which is closely similar pattern shown in [5]. This temporal variation carry a scope for simulate sunrise and sunset terminator

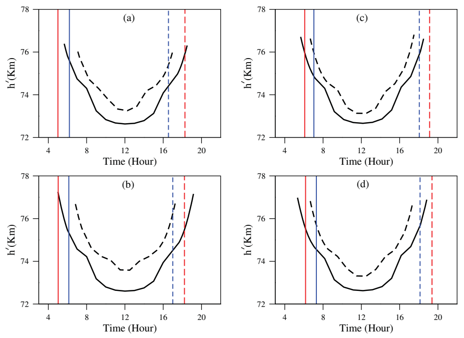

Figure 3. Variation of effective reflection height.

time. So in this paper, our calculation for making the vast database explicitly matches with the accurate ionospheric condition and also verified by VLF signal amplitude for the same receiving point.

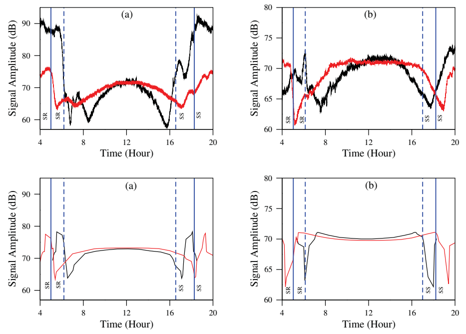

Figure 4. Comparison of observed (upper panel) and simulated (lower panel) amplitude variation for East side receiving locations (a) Kolkata, (b) Kathmandu on Summer (black solid line) and Winter (black dashed line). Along X-axis time is presented in Hour from 04:00:00 IST to 20:00:00 IST and along Y-axis signal amplitude plotted in dB.

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