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Variation of D-region ionisation and its effects on VLF radiowave propagation

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The renewed interest in the study of the VLF propagation anomalies due to perturbations in the D-region electron densities under various solar/stellar and geophysical phenomena requires the availability of suitable simulation model as well as a baseline D-region electron density model for the region of interest. A Full Wave Model (FWM) for computing VLF propagation anomalies has been developed and tested by comparing results from a similar model for a given VLF path. The simulation has also been carried out under different conditions of D-region electron density profiles and the anomalies in VLF amplitude and phase for a sample propagation path determined to check the sensitivity of the model. Further work with new observations, computations of the D-region electron density profiles using measured solar radiation fluxes and simulation pertaining to different VLF networks will be required before the technique can be effectively used to identify and confirm anomalies pertaining to new applications.

Keywords: VLF propagation, Full Wave Model (FWM), Solar radiation, Ionosphere.

1 Introduction

The D-region is defined as the part of the ionosphere covering the height range of ~60-90 km. Unlike the E and F regions of the ionosphere where the plasma dynamics is controlled by the earth's magnetic and electric fields, the D region plasma is more bound to the denser neutral atmosphere so that up to about 70-80 km the medium can be considered as isotropic. Above D-region, the neutral-charged particle collision frequency decreases rapidly till about 1000 km altitude, above which (i.e., in the domain of the earth's magnetosphere) it becomes negligible and the plasma is subjected to move primarily by the influence of the earth's magnetic field [1]. The D-region ionisation is the result of the interaction of solar EUV, X-ray and energetic charged particle radiations with the atmospheric molecular constituents like oxygen (O_2), nitrogen (N_2) and nitric oxide (NO). Apart from the electron-ion recombination loss process, the equilibrium condition electron density profile in the D-region depends on many other factors including the presence of negative ions, complex ion-chemical reactions of the water vapour/aerosol cluster ions and perturbations due to the vertically propagating planetary and gravity waves from below [2]. Also the impact of energetic events like solar flare, CME (Coronal Mass Ejection), WEP (Whistlers induced Electron Precipitation), TLE (Transient Luminous Events) etc., make the D-region electron density profiles highly variable in time and space. The VLF/LF (3-300 kHz) radio waves (hereinafter referred to as VLF only) propagating through the lower ionosphere is very sensitive to the D-region electron density variations. Monitoring the VLF field anomalies by the ground stations distributed all over the world is being used to detect, study and forecast solar and extra-solar energetic events and terrestrial phenomena like lightning, whistlers, sprites, jets, elves and earthquakes [3,4].

Before the VLF networks can be effectively used as a cost effective tool in the prognosis of solar and geophysical events, it is necessary to critically evaluate various aspects of baseline D-region electron density profiles and the required sensitivity of VLF propagation models to detect anomalies in the D-region ionisation along its path under various conditions. It is known that the reference D-region electron density models are not well established particularly over the low latitude region due to lack of long term observations using rocket borne probes. Also the ground based multi-frequency radio wave absorption technique utilised to bridge the gap of data scarcity has not been very accurate to derive the electron density profiles of the

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D-region. The main purpose of this paper is to provide details of a VLF amplitude and phase simulation model for any given propagation path using the full wave theory of Budden [5]. The test results of running the Full Wave Model (FWM) developed by the authors and their verification are presented for different electron density profiles. In addition, a survey of D-region electron density data over the Indian region is also included which could serve as reference for studying VLF signal anomalies. For the present available D-region electron density data from middle latitude stations are used as inputs for computations of VLF signal variation and to assess its sensitivity using the FWM.

2 Background Theory

When VLF radio wave is launched into space it propagates with the ground and the ionosphere (D & E layers) acting as the two imperfect reflecting layers of the Earth Ionosphere Wave Guide (EIWG). The ionosphere is a complicated dielectric medium with the refractive index less than that of free space and its properties vary with altitude and direction. VLF signal undergoes a combination of absorption, reflection and transmission through the ionosphere depending on the frequency, the angle of incidence and electron concentration in the ionosphere as a function of time. The absorption of radio waves in a dielectric takes place primarily as a consequence of collisions between electrons and heavier atoms/molecules/ions.

In EIWG propagation for a particular frequency, the ionosphere boundary is not at constant height due mainly to the diurnal, seasonal, solar cycle variation of the electron density profile. This causes the phase and amplitudes of these waves to undergo sharp variations particularly during sunrise and sunset periods as D-region disappears during night time.

The ionosphere radio refractive index is a complex number containing the reflective and absorptive terms and depends on the local properties of the medium (i.e., electron and collision frequency height profiles) and wave direction with respect to the earth's magnetic field in a complicated manner. The partial reflections of VLF signals from the ionosphere take place through interaction over a range of heights. Thus the reflected field components of VLF waves are very sensitive to any changes in the electron density profile of the D-region.

The wave propagation can be analysed by two equivalent methods. The ray optics approach treats the propagation as a sum of plane waves each with the wave vector along a straight line from the transmitter to the reflector and then to the receiver. Waves with relatively few reflections and oblique incidence will dominate the received signal. When the width of the waveguide is comparable to the wavelength it is appropriate to use the waveguide modes to analyse the propagation of the signal within the waveguide. There are discrete waveguide modes and the received signal at any point is the vector sum of signals propagating in each one of these modes.

Budden's pioneering work [6] to determine the reflection coefficient matrix of the ionosphere by numerically solving the differential equations for arbitrary variations of electron density and collision frequency with height led to numerous studies on the subject. The formulation accounted for the anisotropy of the ionosphere induced by the earth's magnetic field and was also used to derive the D-region electron density profiles from experimental VLF data [7].

Associated developments led to the possible solution of modal equation for a waveguide with a vertically inhomogeneous, anisotropic ionosphere and a stratified ground of finite conductivity and provide the modal summations along the propagation path over which the ionosphere and ground parameters changed. A computer programme called Long Wave Propagation Capability (LWPC) has been developed by NOSC (Navy Operational Support Centre) [8]. This programme has been extensively used specially in the area of LEP research.

For anisotropic medium, the path of the ray may be traced by following the phase velocity vector using the Snell's Law:

$$\mu \sin \psi = \sin\theta \tag{1}$$

where μ: phase refractive index, ψ: angle the phase velocity makes with the vertical and θ: angle of incidence.

μ decreases with increasing altitude till a level is reached, where ψ = π /2, when it achieves its reflection height. The wave starts its descent after reaching the height of reflection. In the presence of the earth's magnetic field, the incident wave splits into two polarised components and the level of reflection is governed by the group velocity and μ depends on the unknown angle of refraction ψ and the wave function becomes:

$$\exp[ik(ct - \mu(\psi)\ ((\sin\psi)x + (\cos\psi)z))] \rightarrow \exp[ik(ct - (\sin\theta)x - qz)] \tag{2}$$

where q, a function of electron density, collision frequency, wave-frequency, earth's magnetic field, angle of incidence, is called the Booker Quartic parameter which is the only unknown in the above wave function [9].There is a critical electron density for each magneto-ionic component, above which that component will not penetrate for a given wave-frequency and angle of incidence. Combining the wave function and Maxwell's equations we get the quartic equation as follows:

$$F(q) = \alpha q^4 + \beta q^3 + \gamma q^2 + \delta q + \varepsilon = 0 \tag{3}$$

The complex coefficients of the Booker quartic equation depend on the collision frequencies and the form of the constitutive relation between Polarisation P and the electric field intensity E. The quartic equation can be solved using input data of electron density and collision frequency variation with height, the wave frequency, the angle of incidence at the ground and the earth's magnetic field vector. The wave fields for the upgoing/downcoming ordinary/extraordinary waves are proportional at any altitude to:

$$\exp(ik(ct - (\sin\theta)y - \int_0^z q\,dz) \tag{4}$$

The real part of q determines the phase change in the wave and the imaginary part determines the attenuation as the integration proceeds. The reflection coefficients are calculated by comparing the wave fields at the end of the path with those at the start after all the phase change and attenuation which occur over the whole path have altered the wave.

While the wave fields can be accurately computed using the above method of Booker, for frequencies < 100 kHz, it is necessary to invoke the full wave theory of Budden as the refractive indices of the ionosphere change appreciably within one wavelength. Such full wave technique has been used by many groups to simulate the wave characteristics with changes in ionosphere parameters. For detailed formulation and various assumptions we refer the work by Nagano *et al* [10]. The upgoing energy is converted by the ionosphere to downgoing energy over a range of heights. The reflection coefficients, which are ratios of the fields at any desired altitude to the incident fields, are given in matrix form as below:

$$\overline{\overline{R}} = \begin{pmatrix} {}_{II}R_{II} & {}_{II}R_{\perp} \\ {}_{\perp}R_{II} & {}_{\perp}R_{\perp} \end{pmatrix} = \begin{pmatrix} \dfrac{E_{II}^{(R)}}{E_{II}^{(I)}} & \dfrac{E_{\perp}^{(R)}}{E_{II}^{(I)}} \\ \dfrac{E_{II}^{(R)}}{E_{\perp}^{(I)}} & \dfrac{E_{\perp}^{(R)}}{E_{\perp}^{(I)}} \end{pmatrix}$$

where $E_{II}^{(I)}$ & $E_{\perp}^{(I)}$ are the components of the incident electric field parallel and perpendicular to the plane of propagation and $E_{II}^{(R)}$ & $E_{\perp}^{(R)}$ are the corresponding fields for the reflected wave. We consider the basic equations starting with the force equation, i.e., equation of motion of electrons due to passing fields of the plane wave. Combining this with the Maxwell's equations we derive the electric polarisation in terms of the susceptibility matrix from the constitutive relations. The elements of $\overline{\overline{M}}$ are functions of the wave frequency, plasma frequency, collision frequency, gyro frequency and the direction cosines of the wave vector. If the wave normal or the plane of incidence is the x-z plane we consider the wave fields in the parallel and perpendicular to this plane given by the vector/matrix [E_x – E_y Z_0H_x Z_0H_y], where Z_0 is the characteristic impedance of the medium. The derivative of this matrix with height is computed at desired heights using the D/E region electron density and collision frequency profiles available for a particular geophysical condition.

3 Method of Analysis

A full wave model in the line of LWPC has been developed by the authors with an in-built provision of intermediate results and related graphics of various plots so that the final results can be tested at pre-designated points for checking the reliability of the final results. The main steps for developing and running the programme are as follows: (a) all computations are carried out with double precision, (b) as necessary physical constants are given as fixed values in MKS units, (c) input data of a particular VLF propagation path are entered which include; angle of incidence, azimuth east of magnetic north of the x-axis in the plane of propagation (positive x -axis is in the direction of the horizontal component of the wave vector k), the propagation vector of the wave, wave frequency, dip angle, electron density and collision frequency values with height, (d) check the sum of squares of the 3 direction cosines of the earth's magnetic field which should be equal to unity, (e) calculate the initial values of the reflection coefficients using solutions of the Booker quartic equation for a homogeneous sharply bounded ionosphere. This involves complex computations of M and T matrices and the coefficients α, β, γ, δ of the quartic are incorporated to get the four roots using the method of Sheddy [11], (f) compute the initial reflection coefficients and the derivatives of the reflection coefficients with height, (g) compute elements and derivatives of the Admittance matrix (A) for use as starting values, (h)with these initial values and new inputs of electron density and collision frequency profiles, the integration is started by calculating new values of A and its derivatives for the defined step (height interval), (i) the method of the numerical integration is carried out using the Runge Kutta method to reach the lowest height, (j) the resultant values of A matrix elements are then used to compute the final values of the reflection coefficients. By this technique the effect of electron density profile variation on the VLF amplitude and phase can be determined at every stage of integration.

4 Results and Discussion

The results presented in this paper are divided into 3 parts as follows:

(a) Collection of D-region electron density profiles over the Indian region using published data for representative solar quiet and disturbed periods

(b) Comparison of the test results for Booker quartic and Full wave reflection coefficient matrix values using the present model with those available from the model of Viertel and Sechrist [12].

(c) Computations of reflection coefficients for determining the phase variation (i.e., height of reflection) using Booker quartic solutions and amplitude/phase variations using the Budden's full wave technique for different VLF frequencies under different D-region electron density profiles.

Long series of rocket measurements from Thumba (8.5 ^{o}N):

A series of M-100 rockets carrying a version of Langmuir Probe (LP) were launched around 1600 hr. at weekly interval from the Thumba Equatorial Rocket Launching Station (TERLS) located at the geomagnetic equator (8.5^{o} N, 76.9^{o} E) during low sunspot years, 1984-86 and high sunspot years, 1979-80.

Also over a period 1966-78 a number of Indian made rockets carrying LP were launched from Thumba during daytime covering low and high solar activity periods. Figure 1 shows the mean plots of D-region electron density profiles from these data published using 40 and 12 rockets, respectively. For comparison the electron density profile generated using model calculation of the ion production rates (~χ = 0) and the effective recombination coefficients is also shown. The VLF signals are very sensitive to the electron density variations in the height region below 80-85 km. It is seen from the figure that while the model average profile shows small variations in this range, the observed profiles show considerable variations. This needs to be kept in mind before interpreting day time signal variations due to the occurrence of solar or geophysical related events like solar flares, TLE/TRIMPI, Sprites/Elves, transit of stellar X-ray/γ-ray sources, earthquakes etc.

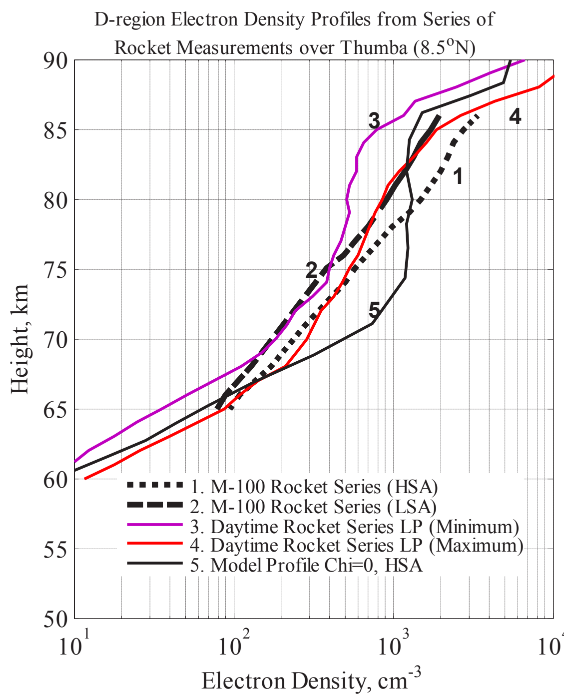


Fig 1. Variation of day time D-region mean electron density profiles measured using series of rocket flights from low latitude station Thumba (8.5° N, 76° E) during high and low solar activity periods as shown by profile numbers 1, 2, 3, & 4 [13] and using model computations for maximum quiet time solar condition and taking χ = 0 as shown by profile number 5 [14]

Sunrise period and solar flare related electron density profiles

Figure 2 shows the enhancement of D-region electron densities due to solar flares and due to layer sunrise when solar zenith angle slowly crosses over to χ = 90° which is the ground sunrise condition. There are different categories of solar X-ray flares depending upon the magnitude of the peak X-ray flux during the event and χ values between 95.4-91.2 indicate different heights in the D-region that are illuminated by the solar radiation. The effect of these modified electron density profiles on the VLF phase and amplitude variations can be determined to serve as bench marks.

In addition to the VLF wave propagation being directly affected by large scale, transient disturbances such as solar flares and polar cap absorption events [16,17], many other such effects include night time enhancement of ionisation e.g., due to transit of major stellar X-ray sources as observed in 164 kHz Tashkent-Ahmedabad [18] & 20 kHz WWVL, Boulder-Wellington [19], transient ionosphere disturbance from strong γ-ray bursts (16 kHz: GBR, England-Palmer Station (PS), Antarctica and 21.4 kHz NPM, Hawaii-PS [20,21] due to whistler induced particle precipitation (LEPs), seismological effects interrupting regular signatures of sunrise/sunset or night time variations of VLF amplitudes/phases (18.2 kHz VTX, Vijayanarayanam-Kolkata) [22]. In order to determine the characteristic perturbations in VLF signals due to the above mentioned solar and geophysical events, the software is first compared with available step by step results from other groups using the full wave technique of Budden. After comparing the programme the bench marks about the magnitude of possible perturbations in VLF signal from the observed or simulated electron density/collision frequency profiles are determined.

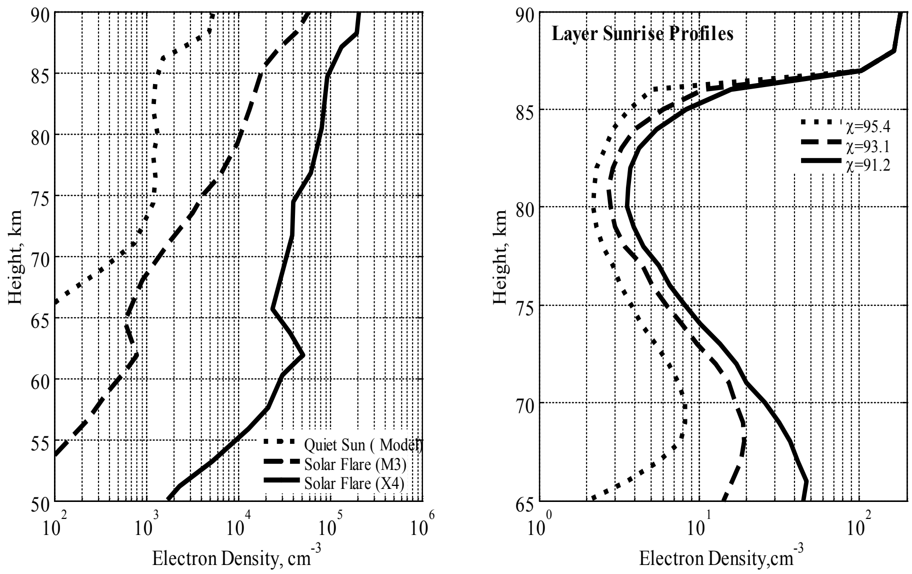


Fig 2. Variation of D-region electron density profiles under (a) quiet solar and solar X-ray flare conditions [14] and (b) conditions of progressive layer sunrise [15]

Test results and comparison of VLF full wave programme:

The first test is conducted by using the VLF propagation path related data as mentioned in Table 1. It provides a comparison of the results of the initial values of the reflection coefficient (R) matrix and Admittance (A) matrix elements. Both the models use the same VLF path and related parameters to compute the initial values. It can be seen that there is an excellent agreement between the results of the two models. The VLF path parameters used in this simulation are same as the 21.4 kHz NSS/NPS transmissions received at Wallops Island, Virginia. Based on the geometry of the propagation path the angle of incidence is taken as 37.8^{o} which is the angle between the incident plane wave (with its wave normal in the x-z plane) and the vertical, the geomagnetic dip taken at 70^{o} and the geomagnetic field induction value at 0.56 gauss with the azimuth angle 152^{o} with respect to the magnetic north. The night time electron density (3.7×10^{10} m^{-3}) and the collision frequency (9.4×10^{4}) values for 94 km are used to compute the initial solutions.

These initial values are computed for a night time condition of lower ionosphere when the VLF waves are reflected from the base of the ionosphere between 85-95 km altitudes. The electron density and collision frequency values are taken at a sufficiently high altitude of ~93-94 km so that from above this height there is no addition to the down coming component of the radio wave. The initial derivatives of the matrix A (not shown in the Table 1) are then integrated down from this initial height to compute the final reflection coefficients at every step of the height interval till the height of ~ 65-70 km. The relative change in the amplitude and phase of the reflection coefficient are used to compute the overall absorption and change of height of reflection of the VLF signals which are easily compared with observations using suitable crossed element loop antennas.

Table 1. comparison of initial values of R and A matrices

(a) Comparison of starting values of Reflection Coefficients (R) matrix

Model	R_{11}Amp	R_{11}Phase	R_{12}Amp	R_{12}Phase	R_{21}Amp	R_{21}Phase	R_{22}Amp	R_{22}Phase
Viertel (ref12)	0.87834	–8.3196	0.13151	38.7545	0.12887	37.5184	0.92199	–5.3095
FWM	0.8669	–8.812	0.14084	37.4169	0.14111	37.4968	0.92904	–4.9806

(b) Comparison of initial values of A (Admittance) matrix

Model	A_{11}Amp	A_{11}Phase	A_{12}Amp	A_{12}Phase	A_{21}Amp	A_{21}Phase	A_{22}Amp	A_{22}Phase
Viertel (ref12)	4.905	–4.8189	4.82998	–4.8949	4.62839	–4.8975	–4.986	4.84364
FWM	4.25584	–3.9405	4.82998	–4.8949	4.84594	–4.8974	–4.986	4.84364

Further test is carried out by computing the reflection coefficients by changing only the angle of incidence (θ) or the frequency (f) in VLF-LF range keeping all other parameters constant. The variations of the amplitude and phase of the R_{11} with θ and f are shown in Fig 3. It can be seen that the amplitude decreases with increase in the angle of incidence up to about 85^{o} beyond which it shows an increase. The phase or the reflection height changes very slowly up to θ value of 70^{o}. The amplitude of R_{11} decreases with frequency and the phase change indicates continuous decrease in reflection level up to about 40 kHz.

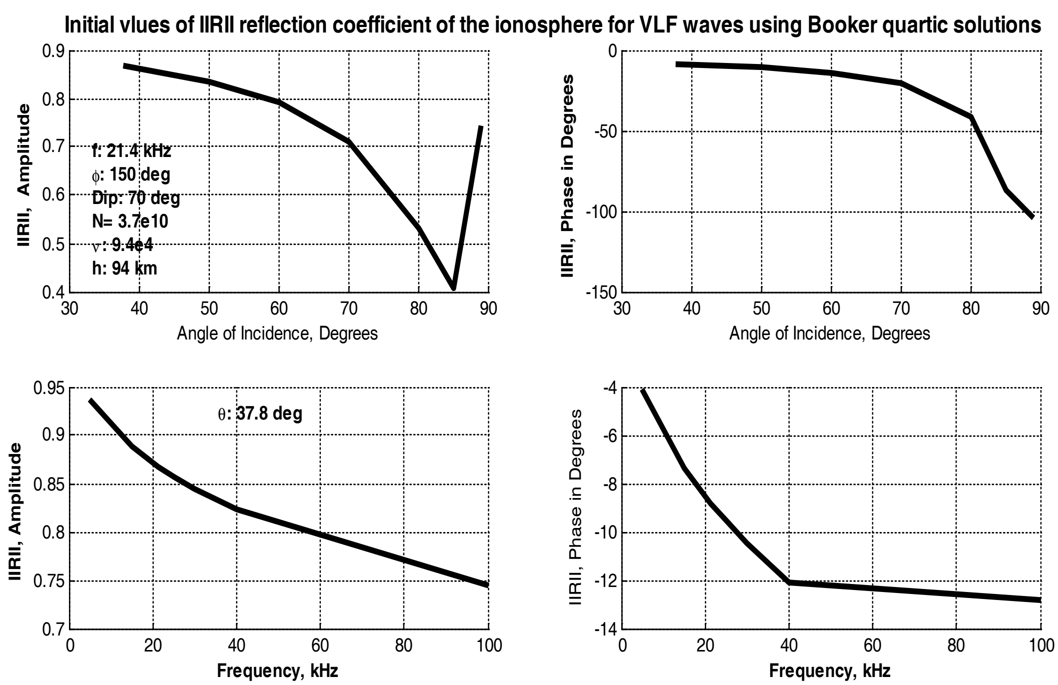


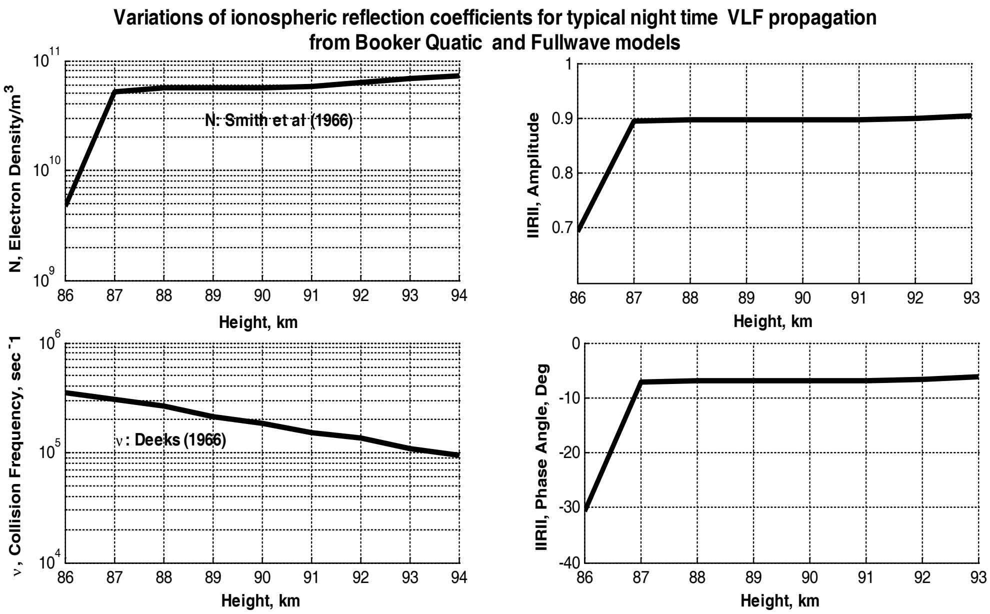
Fig 3. Variation of the parallel reflection coefficient ($_{\|}R_{\|}$) amplitude and phase with the angle of incidence and VLF frequency keeping other input parameters constant

FWM results for different case studies of D-region electron density variations:

The sensitivity of the model to simulate the expected changes in VLF amplitude and phase is tried out keeping the propagation path parameters like frequency, angle of incidence, dip angle etc., constant. The results would help in making an assessment of the possible utility of such technique in other applications particularly like perturbations caused by earthquake related anomalies in the D-region electron density profiles. Figure 4 shows typical night time electron density (N_e) profile and collision frequency (ν) profile in the D/E region ionosphere. The amplitude and phase variation of parallel reflection coefficient (${}_{\|}R_{\|}$) are shown changing the initial height of reflection progressively from 94 to 86 km. It can be seen that up to about 87 km any value (between 93 and 87 km) of the night time N_e and ν can be used as a starting point of integration without affecting the results. Below 87 km the N_e values produce considerable change in the reflection coefficient values causing drops in signal strength and phase height of reflection. The components of the final reflection coefficient matrix values for the whole N_e profile are also given in the figure. According to this the ${}_{\|}R_{\|}$ & ${}_{\perp}R_{\perp}$ have the major contribution to the VLF signal strengths compared to the inverse reflection coefficients, i.e., ${}_{\|}R_{\perp}$ or ${}_{\perp}R_{\|}$. Table 2 shows the matrix elements of the final reflection coefficients using the FWM under different conditions of electron density profiles below the initial level of reflection taken as standard night time value high up in the upper D/E-region. The sign of the effects on the elements of reflection coefficients are different and hence the receiver antennas should be able to pick up the electric field induction both in and perpendicular to the plane of incidence. The anomaly of the VLF signals with respect to the layer sunrise effect shows considerable reduction in the parallel components of the reflection coefficient as against the inverse components which show enhancements. Also after the layer sunrise effect subsequent movement towards ground sunrise does not change the reflection coefficients appreciably for all the four elements. The inverse components of the reflection coefficients are more sensitive to changes in electron density produced in the D-region due to layer sunrise conditions of appropriate solar zenith angle below the horizon. The initial effect of solar flares of enhanced electron density in the D-region on VLF propagation is that of enhanced reflectivity for parallel coefficients and both positive and negative effects on inverse reflection coefficients. While the initial enhanced VLF signals during solar flares is a common phenomenon observed by many stations it would be interesting to know from the theory as how these would vary with the progress of different classes of flares. This would require the availability of the electron density profiles at different stages of these events.

Table 2. Final reflection coefficients using electron density profiles during layer sunrise at different zenith angles

Electron density Profiles	${}_{\|}R_{\|}$		${}_{\|}R_{\perp}$		${}_{\perp}R_{\|}$		${}_{\perp}R_{\perp}$	
	Amplitude	Phase	Amplitude	Phase	Amplitude	Phase	Amplitude	Phase
Typical Night time	0.908797	–5.536	0.102022	46.25	0.134297	1.126	0.886230	–0.3357
Layer Sunrise at χ = 95.4°	0.652020	19.88	0.778071	–27.37	0.778487	–26.30	0.726469	–64.38
Layer Sunrise at χ = 93.1°	0.646048	21.08	0.776529	–26.68	0.776753	–25.62	0.728606	–63.64
Layer Sunrise at χ = 91.2°	0.646052	21.08	0.776506	–26.68	0.776739	–25.62	0.728607	–63.64
Model solar quiet	0.697858	–28.64	0.303840	29.95	0.324616	26.81	0.806099	–14.80
M3 flare	0.872710	–6.781	0.988537	54.86	0.143784	12.44	0.882241	–2.690
X4 flare	1.00000	–0.6382	0.138667	47.46	0.212217	–89.97	0.997410	0.1126



Final values of night-time Reflection Coefficients using FWM

$$\overline{\overline{R}} = \begin{pmatrix} {}_{II}R_{II} & {}_{II}R_{\perp} \\ {}_{\perp}R_{II} & {}_{\perp}R_{\perp} \end{pmatrix} = \begin{matrix} [\ 0.90879497618, & -5.5365111945\ ] \\ [\ 0.10202222125, & 46.254150460\ ] \\ [\ 0.13429796990, & 1.1268297411\ ] \\ [0.88623053574, & -0.33571119640] \end{matrix}$$

Fig 4. Clockwise (a) typical night time electron density profile of D/E region, (b) Height profile of final reflection coefficient (${}_{||}R_{||}$) using FWM, (c) variation of VLF phase of final reflection coefficients using FWM, (d) typical collision frequency profile of D/E region

5 Summary and Conclusion

(a) Recent observational evidence of signal anomalies related to various solar and geophysical phenomena has renewed the interest in the studies of VLF radio propagation through the D/E region ionosphere. The correct interpretation of these effects requires availability of a simulation technique which would provide different benchmarks of signal anomalies under different but known conditions for a given VLF path. Based on these results it would be possible to monitor the observations for linking with any new anomalous situation to improve our capability of identifying future events. One such simulation model called FWM has been developed and the preliminary test results have been presented.

(b) The prerequisite to carry out such simulation requires the D-region electron density profiles under different conditions of day-night, solar activity periods. While the available data is clearly inadequate, as a proxy, these could be computed using the current satellite data on the variation of solar ionising radiation and other parameters like the ion loss coefficients. Comparison of the experimental data and computed values of electron density profiles in the D-region over Indian station presented here show certain differences in the shape of the curve which would need further understanding.

(c) After verifying the performance of the FWM model, it is used to compute the VLF anomalies under conditions of sunrise and solar flare conditions. These results indicate that for the sample VLF propagation path, the parallel and inverse reflection coefficients get affected differently. Hence for operating such VLF networks with a view to determine and identify possible causes of propagation anomalies, observations should be made to receive the signals both parallel and perpendicular to the plane of incidence with a provision to measure both the signal amplitudes and phases.

(d) The FWM results on the sensitivities of the reflection coefficients during the sunrise and solar flare events indicate that the night time observations may be better suited to identify anomalies due to any transient phenomenon which produces enhanced ionisation in the D-region.

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