

IONOSPHERIC ABSORPTION OF HF RADIO WAVE IN VERTICAL PROPAGATION*

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Abstract – In this study, absorption of high frequency radio waves in the ionospheric plasma have been investigated. The wave equation was obtained in terms of ionospheric parameters. The numerical values of the absorption have been calculated for 4 MHz, 4.5 MHz and 5 MHz waves. The necessary parameters for calculation have been obtained using an International Reference Ionosphere (IRI) Model. The altitudinal, diurnal, seasonal and the variations of absorption with frequency have been examined. The calculations show that the highest absorption occurs in the D-region. The absorption is higher in summer than in other seasons and is maximum at daylight. In addition, absorption decreases with the increase of frequency.

Keywords – Ionosphere, HF wave, absorption

1. INTRODUCTION

Ionosphere is very important for radio communication. 3-30 MHz frequencies are called high frequencies (HF) and these frequencies are the biggest frequencies that are reflected from the ionosphere. The most useful way to perform systematic measurements in the ionosphere is to use HF waves. The theory of HF radio waves in the ionospheric plasma started with the formulations of the Appleton-Lassen dispersion relation in the late 1920s and became more important in the second half of the 20th century [1]. The use of HF radio spectrum continues to grow for both civil and military purposes, despite the widespread introduction of satellite-based communication systems. In particular, the HF band is very important when the communication system is destroyed by an unusual event, such as a major earthquake. For this reason, it is important to investigate and understand the HF propagation characteristic in the ionosphere.

Radio waves show different behaviors depending on their frequencies, oscillation frequency of the electron and the refractive index of the ionospheric plasma. Due to these behaviors the wave reflects, refracts or is absorbed by the ionosphere. Radio waves in the ionosphere are subject to some attenuation because the motions of the electrons and ions are damped through collisions with other particles [2-7].

The purpose of this study is to investigate the absorption of the HF electromagnetic wave, which propagates vertical in the ionosphere as a function of height and ionospheric parameters. The refractive index of the ionosphere will be obtained by solving the conductivity equation and dispersion relation. The variations in the absorption will be investigated from the imaginary part of the refractive index.

2. ABSORPTION OF THE RADIO WAVES IN THE IONOSPHERIC PLASMA

A radio wave is given by,

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$$\mathbf{E} = \mathbf{E}_0 e^{i(\mp \mathbf{k} \cdot \mathbf{r} - \omega t)} \quad (1)$$

where ω is the angular frequency and \mathbf{k} wave vector and can be written as follows:

$$\mathbf{k} = \frac{\omega}{c} \mathbf{n} \quad (2)$$

Where \mathbf{n} is the refractive index and c is the speed of light in the free space. The refractive index of the ionospheric plasma is given by [2],

$$n = \mu + i\chi \quad (3)$$

μ is the real part of the refractive index and affects the phase velocity. χ is the complex part and determines the attenuation of the wave [8]. Using Eq. (2) and Eq. (3), Eq. (1) is obtained as,

$$\mathbf{E} = \mathbf{E}_0 e^{i\left(\mp \frac{\omega}{c} \mu r - \omega t\right)} e^{-\frac{\omega}{c} \chi r} \quad (4)$$

The $\frac{\omega}{c} \chi$ term is called the κ absorption coefficient and this expression shows that the radio wave is attenuated by the term of $e^{-\frac{\omega}{c} \chi r}$ and moves by the velocity of $\frac{c}{\mu}$. For the calculation of the absorption, the refractive index of the ionospheric plasma must be known.

2.1. Refractive index for ionospheric plasma

At high frequency, the effect of ions can be neglected [9]. If we take the ambient magnetic field \mathbf{B} in the vertical direction, the conductivity tensor can be obtained as follows [10],

$$\sigma = \begin{bmatrix} \sigma_1 & \sigma_2 & 0 \\ -\sigma_2 & \sigma_1 & 0 \\ 0 & 0 & \sigma_0 \end{bmatrix} \quad (5)$$

in which longitudinal (σ_0), Pedersen (σ_1) and Hall (σ_2) conductivities are, $\sigma_0 = \frac{\varepsilon_0 \omega_{pe}^2}{(v_e - i\omega)}$,

$\sigma_1 = \frac{\varepsilon_0 \omega_{pe}^2 (v_e - i\omega)}{[\omega_{ce}^2 + (v_e - i\omega)^2]}$ and $\sigma_2 = \frac{\varepsilon_0 \omega_{pe}^2 \omega_{ce}}{[\omega_{ce}^2 + (v_e - i\omega)^2]}$ respectively. ε_0 is the dielectric coefficient of the free

space, $\omega_{ce} \left(= -\frac{eB_0}{m_e} \right)$ is electron gyro-frequency, and $\omega_{pe}^2 \left(= \frac{e^2 N_e}{m_e \varepsilon_0} \right)$ is the plasma oscillation frequency

where e is electron charge, m_e is electron mass and N_e is electron density.

$v_e = v_{ei} + v_{en}$ in which $v_{ei} = N_e \left[59 + 4.18 \log \left(\frac{T_e^3}{N_e} \right) \right] \times 10^{-6} T_e^{-3/2}$ and $v_{en} = 5.4 \times 10^{-16} N_n T_e^{1/2}$ are

the electron-ion and the electron-neutral collision frequencies, respectively [11].

If we solve the Maxwell curl Equations

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t} \quad (6)$$

$$\nabla \times \mathbf{B} = \mu_0 \mathbf{J} + \mu_0 \epsilon_0 \frac{\partial \mathbf{E}}{\partial t} \tag{7}$$

by using the current density $[\mathbf{J}] = [\sigma] \cdot [\mathbf{E}]$, the following Equation can be obtained.

$$\mathbf{n}^2 \mathbf{E} - \mathbf{n}(\mathbf{n} \cdot \mathbf{E}) = \left[\mathbf{I} + \frac{i\sigma}{\epsilon_0 \omega} \right] \cdot \mathbf{E} \tag{8}$$

in which I is unit matrix and σ is given in Eq. (5). From Eq. (8) we can obtain,

$$\begin{bmatrix} M_{xx} & M_{xy} & M_{xz} \\ M_{yx} & M_{yy} & M_{yz} \\ M_{zx} & M_{zy} & M_{zz} \end{bmatrix} \cdot \begin{bmatrix} E_x \\ E_y \\ E_z \end{bmatrix} = 0 \tag{9}$$

Where

$$M_{xx} = M_{yy} = n^2 - 1 - \frac{i\sigma_1}{\epsilon_0 \omega}, \quad M_{xy} = -M_{yx} = -\frac{i\sigma_2}{\epsilon_0 \omega}, \quad M_{zz} = -1 - \frac{i\sigma_0}{\epsilon_0 \omega}, \tag{10}$$

$$M_{xz} = M_{yz} = M_{zx} = M_{zy} = 0$$

Det(M)=0 is the basic dispersion relation. The refractive index \mathbf{n} can be obtained in terms of plasma parameters. From this determinant, the following Equation can be obtained.

$$\left(-1 - \frac{i\sigma_0}{\epsilon_0 \omega} \right) \left(n^2 - 1 - \frac{i\sigma_1}{\epsilon_0 \omega} - \frac{\sigma_2}{\epsilon_0 \omega} \right) \left(n^2 - 1 - \frac{i\sigma_1}{\epsilon_0 \omega} + \frac{\sigma_2}{\epsilon_0 \omega} \right) = 0 \tag{11}$$

Eq. (11) gives the following two roots of n^2 .

$$n_1^2 = A + iB \tag{12}$$

$$n_2^2 = C + iD \tag{13}$$

Where

$$A = 1 + \frac{\omega_{pe}^2}{\omega} \left[\frac{(\omega - \omega_{ce})(\omega_{ce}^2 + v_e^2 - \omega^2) - 2\omega v_e^2}{(\omega_{ce}^2 + v_e^2 - \omega^2)^2 + 4\omega^2 v_e^2} \right], \quad B = \frac{\omega_{pe}^2}{\omega} \left[\frac{2\omega v_e(\omega - \omega_{ce}) + v_e(\omega_{ce}^2 + v_e^2 - \omega^2)}{(\omega_{ce}^2 + v_e^2 - \omega^2)^2 + 4\omega^2 v_e^2} \right]$$

$$C = 1 + \frac{\omega_{pe}^2}{\omega} \left[\frac{(\omega + \omega_{ce})(\omega_{ce}^2 + v_e^2 - \omega^2) - 2\omega v_e^2}{(\omega_{ce}^2 + v_e^2 - \omega^2)^2 + 4\omega^2 v_e^2} \right], \quad D = \frac{\omega_{pe}^2}{\omega} \left[\frac{2\omega v_e(\omega + \omega_{ce}) + v_e(\omega_{ce}^2 + v_e^2 - \omega^2)}{(\omega_{ce}^2 + v_e^2 - \omega^2)^2 + 4\omega^2 v_e^2} \right]$$

One of them is the left-hand polarized wave (Eq. (12)) and the other is the right-hand polarized wave (Eq. (13)).

2.2. Wave absorbing expression

The Eq. (12) and Eq. (13) show that the refractive index $n^2 = (\mu + i\chi)^2 = A+iB$ becomes complex if electron collisions are allowed. Then, the imaginary part (χ) of n is,

$$\chi_{1,2} = \left[\frac{\pm (A^2 + B^2)^{1/2} - A}{2} \right]^{1/2} \quad (14)$$

If we use this expression of χ in Eq. (4), the wave Equation for the vertical propagation is obtained as follows,

$$\mathbf{E} = \mathbf{E}_0 e^{i \left(\mp \frac{\omega}{c} \mu z - \omega t \right)} e^{-\frac{\omega}{c} \left[\frac{\pm (A^2 + B^2)^{1/2} - A}{2} \right]^{1/2} z} \quad (15)$$

3. NUMERICAL ANALYSIS AND DISCUSSION

According to the Eq. (15) total absorption for the vertical propagation can be defined as:

$$\text{Total Absorption} = \int_{z_0}^{z_{\text{refl.}}} e^{-\frac{\omega}{c} \left[\frac{\pm (A^2 + B^2)^{1/2} - A}{2} \right]^{1/2} z} dz + \int_{z_{\text{refl.}}}^{z_0} e^{-\frac{\omega}{c} \left[\frac{\pm (A^2 + B^2)^{1/2} - A}{2} \right]^{1/2} z} dz \quad (16)$$

in which z_0 (80 km) is taken for the beginning of the ionosphere, and $z_{\text{refl.}}$ ($n=0$) is the reflection height (Fig. 1).

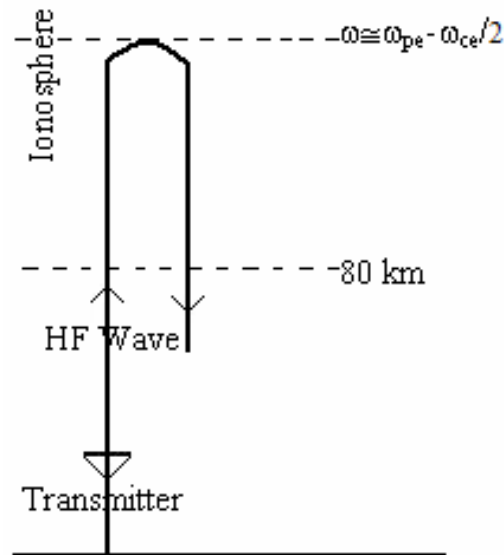


Fig. 1. Schematic illustration of the vertical HF radio waves propagating through ionospheric plasma

The calculations of this Equation have been done for + sign at geographic coordinates of ($38^{\circ} 41'$ E ve $39^{\circ} 14'$ N). In addition, the calculations have been done for quite-solar activity days (the sunspot number is about 10). The amplitude of the wave is taken as 1 V/m at z_0 . Calculations have been done for every 1 km from z_0 to $z_{\text{refl.}}$. We assumed that the wave reflected at height where $\omega \cong \omega_{pe} - \frac{\omega_{ce}}{2}$. The used ionospheric plasma parameters have been calculated by using International Reference Ionosphere (IRI) with the International Radio Consultative Committee (CCIR) Model. The calculations have been done for 21 June, 23 September and 21 December.

The variations of the amplitude with height for 5 MHz is shown in Fig. 2. As is seen from the Figure, the maximum absorption occurs in the ionospheric D and E-region. In the F1 ve F2 region wave absorption is smaller than the D and E-region. This is an accepted result, as the neutral density is bigger than the electron density at low altitudes during daytime (Table 1). So, the total absorption becomes maximum as electron collision frequency increases [12-14].

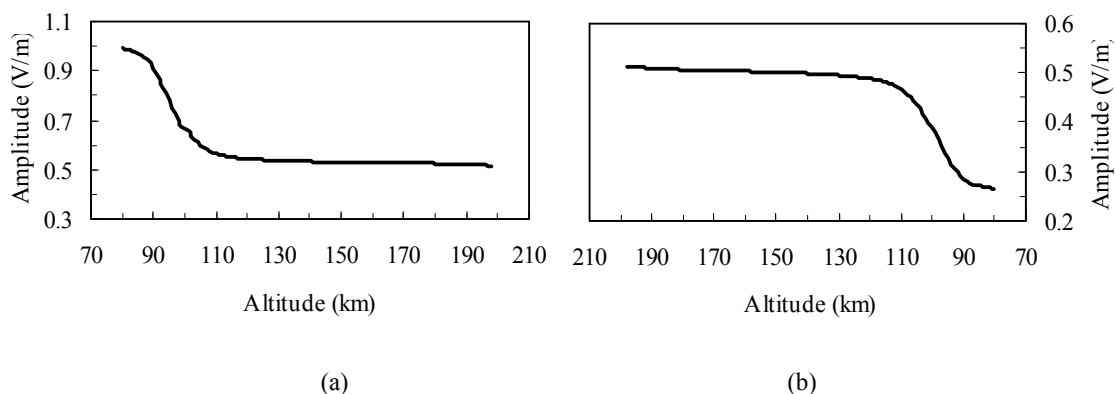


Fig. 2. The variation of the amplitude attenuation with height for 5 MHz. (21 December at 12.00 LT, a: Up to reflection point, b: Then the reflection)

Table 1. The variations of the neutral and electron densities, electron collision frequency and absorption coefficient with height (21 December at 12.00 LT)

h (km)	N_n (par./m ³)	N_e (el./m ³)	ν_e (s ⁻¹)	κ (m ⁻¹)
80	5.18E+20	3.80E+08	5.19E+06	6.66E-06
85	1.77E+20	7.66E+08	1.77E+06	4.66E-06
90	7.15E+19	8.13E+09	7.16E+05	2.02E-05
95	2.88E+19	3.49E+10	2.88E+05	3.62E-05
100	1.16E+19	6.57E+10	1.19E+05	3.25E-05
105	4.78E+18	9.48E+10	4.85E+04	1.83E-05
110	2.12E+18	9.83E+10	2.19E+04	8.59E-06
115	1.02E+18	9.28E+10	1.09E+04	4.01E-06
120	5.46E+17	8.88E+10	6.10E+03	2.13E-06
125	3.19E+17	9.66E+10	4.05E+03	1.56E-06
130	2.03E+17	1.00E+11	2.86E+03	1.16E-06
135	1.37E+17	1.03E+11	2.13E+03	8.89E-07
140	9.81E+16	1.06E+11	1.66E+03	7.16E-07
145	7.31E+16	1.09E+11	1.34E+03	5.98E-07
150	5.62E+16	1.13E+11	1.10E+03	5.15E-07
155	4.44E+16	1.17E+11	9.34E+02	4.56E-07
160	3.58E+16	1.23E+11	8.05E+02	4.16E-07
165	2.93E+16	1.30E+11	7.07E+02	3.95E-07
170	2.44E+16	1.57E+11	6.54E+02	4.65E-07
175	2.05E+16	1.99E+11	6.28E+02	6.31E-07
180	1.74E+16	2.44E+11	6.09E+02	8.57E-07
185	1.49E+16	2.87E+11	5.91E+02	1.18E-06
190	1.28E+16	3.27E+11	5.73E+02	1.71E-06
195	1.11E+16	3.62E+11	5.53E+02	2.96E-06
200	9.69E+15	3.91E+11	5.30E+02	---

The diurnal and seasonal variations of the amplitude for three different frequencies (4 MHz, 4.5 MHz, 5 MHz) are given in Fig. 3. Sometimes these frequencies pass through the ionosphere. As seen in the Figures, the 5 MHz wave does not reflect at night because the critical frequency at h_mF2 (f_0F2) is

approximately 5 MHz. The total absorption has been decreasing with the frequency increase, much greater in summer than winter. Similar results have been obtained by Singer et al. [15]. The diurnal variation of total absorption is related to the variation of the electron density which is given in Fig. 4. As is seen, for 21 December, electron density is less than 21 June and 23 September. However, the wave amplitude at 21 December is higher than the other seasons. So, when the electron density is at maximum, the total absorption has been increasing. Increments in the absorption during the daytime is also related to the increase of the electron temperature [16]. However, according to the IRI Model, the seasonal electron temperature variations are very small, so the seasonal variations of absorption mainly depend on the electron density variations.

These results are able to guide users for experimental studies, especially ionosphere propping technology such as ionosonda HF frequency.

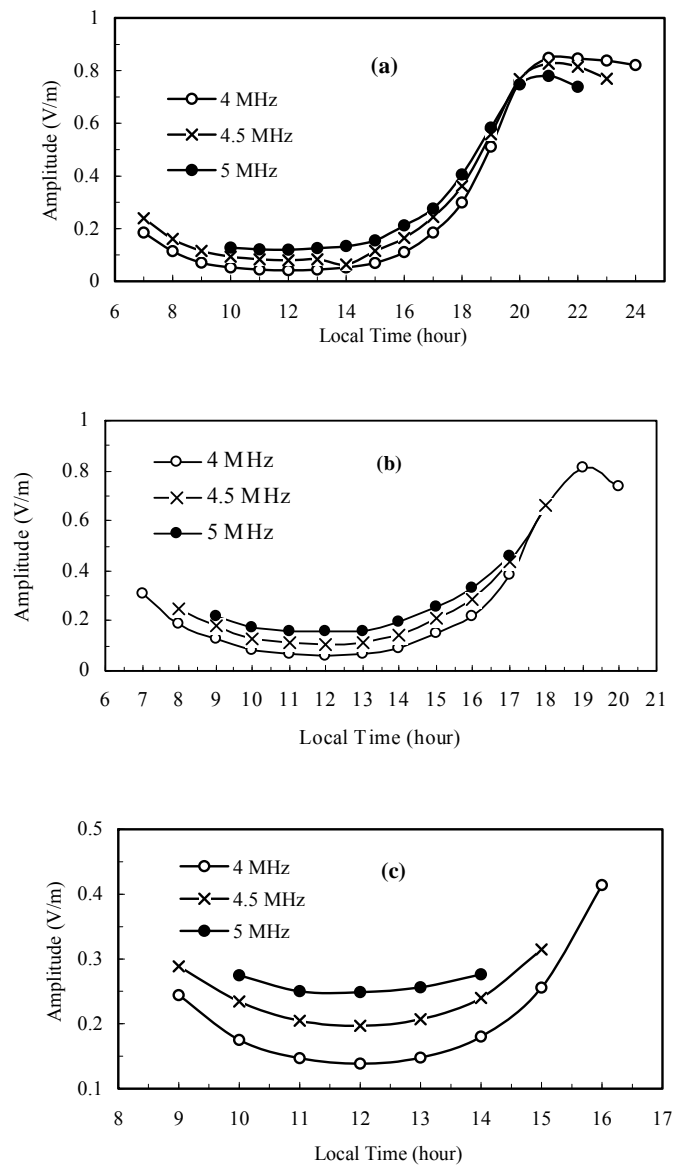


Fig. 3. The diurnal variations of the total absorption during the wave path (a: 21 June, b: 23 September, c: 21 December)

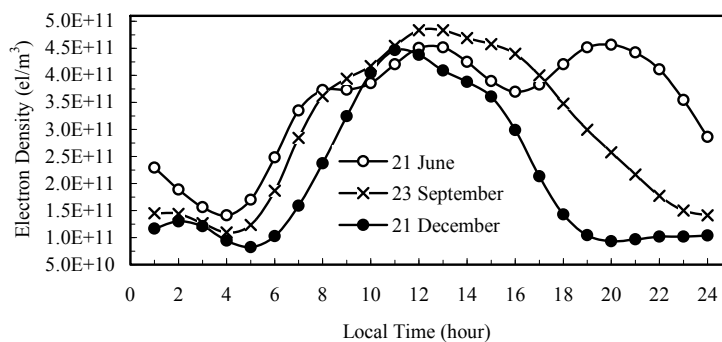


Fig. 4. The diurnal and seasonal variations of the electron density at h_mF2

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