CALCULATION OF ELECTRIC FIELD STRENGTH IN THE IONOSPHERIC F-REGION

by

Ali YESIL * ***and Kadri KURT***

Department of Physics, Faculty of Sciences, Fırat University, Elazig, Turkey

Original scientific paper
https://doi.org/10.2298/TSCI170630282Y

In this study, we have calculated the electric field strength, E_y, of a plane electromagnetic wave with frequency, ω, propagation along z-axes and the polarized y-axes in 1-D by using Wentzel, Kramers, and Brillouin method for both with and without collision conditions in ionospheric F-region with regard to seasonal and local time. Also, the refractive index of ordinary wave and attenuation factor was computed for collision and collision-free conditions. When the collisions were calculated in the F-region of the ionosphere, it was observed that the electric field strength decreased for all seasons and E_y increased between 275-400 km altitudes encountering approximately hmF2 "the peak of F2" for the accepted conditions.

Key words: *electric field strength, jonospheric plasma, Wentzel, Kramers, and Brillouin method*

Introduction

The ionosphere surrounding the atmosphere of the Earth constitutes 50-1000 km as an upper atmosphere region and has an important effect over the Earths' environment because of strong coupling process with both below and above regions [1-8]. One of most important features of the ionosphere is to reflect electromagnetic waves up to 30 MHz sent from Earth to ionosphere [3, 8, 9]. Especially, the propagation of these radio waves on the HF band makes it necessary to know the features and the characteristics of cold-warm ionospheric plasma. When the radio waves travel in the ionospheric plasma, these waves are reflected, transmit or refracted related to the vibration frequency of ions and electrons in the medium and the refractive index of ionospheric plasma. Thus, when any wave having HF band arrives at the ionosphere, a part of it is absorbed and reflected by ionospheric plasma [9-12].

Propagation of radio waves travelling in the ionosphere is strongly affected by the double-refractive structure of ionosphere depending on its conductivity and refractive index [9, 12-14]. The conductivity of ionosphere was studied by numerous investigators not only for D.C. but also for A.C. and is well understood up to now, though refinements are still made from time to time. On the other hand, one of the most important criteria determining the characteristic of any medium is the dielectric properties of the medium, which at any frequency determines the refractive index, energy and the propagation of wave, the form of wave in medium to be polarized, and the state of wave. Although we seldom encounter uniform unbounded plasmas in practice, studying wave phenomena in such an idealized case reveals that numerous fundamental waves can be excited in a plasma medium. Also, when the characteristic lengths of non-uni-

* Corresponding author, e-mail: ayesil@firat.edu.tr

formities plasma are much longer than wavelengths of concerned waves, wave propagation can be analyzed by Wentzel, Kramers, and Brillouin (WKB) approximation developed for uniform plasmas. If the ionospheric plasma is anisotropic, that is $\mathbf{B} \neq 0$, it can support various kinds of electromagnetic waves [9, 12-15]. Since ionospheric plasma consists of light electrons and heavy ions, the effective frequencies vary from low frequency ion cyclotron frequency to high frequency electron cyclotron frequency. In general, particle dynamics must be incorporated carefully at the analysis of plasma waves for electrons and ions. A remarkable feature of waves in a plasma medium is that they are subject to damping even in the absence of particle collisions such as Landau and cyclotron damping. The wave damping of collision and collision-free conditions plays important roles in plasma heating (and current drive) and it can be effectively used in further raising the temperature of a plasma already having a high-enough temperature so that collisional Joule heating is ineffective [3, 9-15].

To understand the behavior of electromagnetic waves emitted from within the ionospheric plasma and to produce the analytical solutions, it is necessary to know the parameters of the medium such as the refractive index. Problems in plasma physics about the conductivity, dielectric constants and refractive index will be defined according to the media parameters of the ionosphere [4, 8, 16, 17]. These expressions will be examined using Maxwells' equations expressed in the wave dispersion equation, wave propagation depending on the parameters of the environment. By examining the dispersion relation, the types of wave occurred in the media and relaxation mechanisms, polarizations and conflicts caused by ionospheric amplitude attenuation of these waves will be obtained analytically. Thus, the basic information will be understood by resolving the problems of ionospheric plasma in the emitted radio waves [9, 12-15].

The basic aim of this study is to compare the magnitude of electric field strength, E_y, obtained by using WKB method for collisional and collision-free condition in ionospheric F-region for different conditions.

The approximation of WKB in ionospheric plasma for 1-D electric field

According to WKB approximation, it is assumed that a plane electromagnetic wave has become *of frequency ω, propagation along z-axes, and the polarized along y-axes* in any medium. If the refractive index of medium is n and change to z-direction, $n(z)$, the electric field component of plane wave propagating z-direction is given [2, 12, 13]:

$$\boldsymbol{E}_y\left(\boldsymbol{z},\boldsymbol{t}\right) \equiv E_y(z)\exp\left(-i\omega t\right) \tag{1}$$

and magnetic field component:

$$\boldsymbol{B}_x(\boldsymbol{z},\boldsymbol{t}) \equiv B_x(z)\exp(-i\omega t) \tag{2}$$

The $E_y(z)$ and $B_x(z)$ satisfy differential equation. From Maxwell equations, a differential equation for electric field $E_y(z)$ is obtained:

$$\frac{\mathrm{d}^2 E_y}{\mathrm{d}z^2} + k_0^2 n^2 E_y = 0 \tag{3}$$

where $k_0 = \omega/c$ is the wave number in free space, n – the refractive index of medium but the actual wave number is $\mathbf{k} = k_0\mathbf{n}$. According to WKB solutions, when a propagating wave is normally incident on a medium in which the refractive index changes slowly along the direction of the propagation of the wave, then the wave is not reflected at all. If $n(z)$ can be accepted as a *slowly* *varying* function as long as its variation length-scale is far longer than the wave-length, after the approximations included with respect to WKB solution, the electric field is obtained [13-15]:

$$\boldsymbol{E}_y \cong \frac{E_0}{\sqrt{n}} \exp\left(\pm i k_0 \int^z n \mathrm{d}z \right) \tag{4}$$

where E_0 is a constant number determined by initial conditions and it shows polarization direction of wave.

The general refractive index of ionospheric plasma

The refractive index, $\boldsymbol{n}$, determines the behavior of electromagnetic wave in a medium and refractive index of the medium is found by using Maxwell and motion equation. When the progress vector of the wave, **k**, is parallel or anti-parallel to the Earth magnetic field or to the any components of the Earth magnetic field, two cases can be observed for the ionospheric plasma depending on the refractive index of the medium. For example, if the wave propagates in the *z*-direction such as in the vertical ionosondes, the vertical component of the Earth magnetic field effects the propagation of the wave. These waves are ordinary and the extra-ordinary waves depending upon collisions (electron-ion and electron- neutral) in ionospheric plasma [8, 13-14]:

$$\boldsymbol{n}_o^2 = 1 - \frac{X}{1+Z^2} + iZ\frac{X}{1+Z^2} \tag{5}$$

where $X = \omega_p^2/\omega^2$ and $Z = \nu/\omega$ are magneto-ionic parameters. The $\nu_e = \nu_{ei} + \nu_{en}$ and $\omega_p^2 = Ne^2/m\varepsilon_0$ is plasma frequency for electron, N, electron density in ionospheric plasma. If $Z = 0$, eq. (5) is given:

$$\boldsymbol{n}_o^2 = 1 - X \tag{6}$$

If $Z \neq 0$, the refractive index of ionospheric plasma has the complex structure possessing both the real and imaginary part as eq. (5) is given. The refractive index is given:

$$\boldsymbol{n}^2 = (\mu + i\chi)^2 = M + iN \tag{7}$$

where μ is the part propagating wave and χ – the attenuation factor [3, 10, 11, 16]:

$$\mu^2 = \frac{1}{2}\left(\sqrt{M^2+N^2} + M\right) \tag{8}$$

$$\chi^2 = \frac{1}{2}\left(\sqrt{M^2+N^2} - M\right) \tag{9}$$

$$E_y \cong \frac{E_0}{\sqrt{n}} \exp\left(\pm i k_0 \int^z n \mathrm{d}z \right), \quad (\mathrm{Z}=0) \tag{10}$$

$$E_y \cong \frac{E_0}{\sqrt{\mu + i\chi}} \exp\left(\pm i k_0 \int^z (\mu + i\chi) \mathrm{d}z \right), \quad (\mathrm{Z} \neq 0) \tag{11}$$

Numerical analysis and results

In this study, the electric field strength, E_y, the refractive index, $\boldsymbol{n}$, (both collisional and collision-free) and the attenuation factor were calculated at geographic co-ordinates of

(39.13°N; 38.14°E, $f \approx 14$ MHz) by using eqs. (5)-(10) with both local time and altitude for the year 1990 (maximum sunspot number). The ionospheric parameters used for calculation were obtained by using the IRI model.

According to the results of WKB solutions, *independent-time* in eqs. (10) and (11), the electric field strength sharply depends on the refractive index of any medium such as ionospheric plasma, but the refractive index of ionospheric plasma change a lot of parameters such as the collision frequency between particles and Earth magnetic field, and the structure of conductivity. We investigated E_y, refractive index and attenuation factor in figs. 1 and 2. The change with altitude of the refractive index of ordinary wave for both collision-free, $Z \neq 0$, and collision case, $Z = 0$, is given as in fig. 1(a). The magnitudes of the refractive index of ordinary wave with respect to the altitudes are $\boldsymbol{n} < 1$, and they decrease between 275-400 km encountering the peak of F-region and the reflection of wave but for $Z = 0$ it is bigger than other case, $Z \neq 0$, in both seasons. When the collision frequency was calculated, it was found that the refractive index decreased. Besides, the attenuation factor, $Z \neq 0$, related to energy loss of the wave increases between 275-400 km, fig. 1(b), however, in fig. 1(a), the magnitude of it is bigger on March 21st than on September 23rd. The change of E_y with altitude for both $Z = 0$ and $Z \neq 0$ has been given in figs. 1(c) and 1(d). According to this, if $Z = 0$, E_y increases between approximately 275-400 km height unlike $\boldsymbol{n}$, but parallel to the attenuation factor, χ, when $Z \neq 0$, the diagram of E_y with altitude is similar to fig. 1(c) as trend but the magnitudes of E_y in fig. 1(d) are smaller than fig. 1(c). The values of E_y for altitudes below ≈ 250 km are negative. This shows that *of frequency* ω is stop-band below 250 km altitude both on March 21st and on September 23rd.

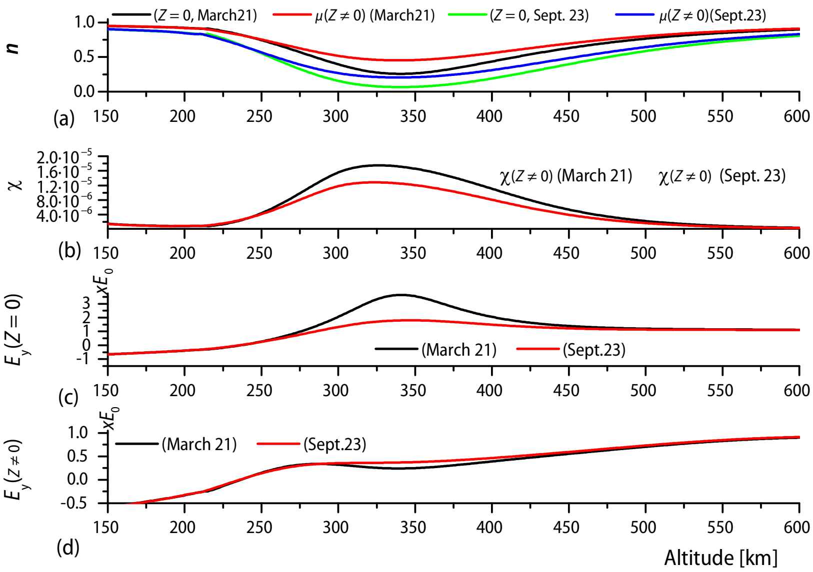

Figure 1. The change of: (a) $\boldsymbol{n}$, (b) χ, (c) E_y ($Z = 0$), and (d) E_y ($Z \neq 0$) with altitude for equinox days (*for color image see journal web site*)

The diagram of E_y, $\boldsymbol{n}$, and χ with local time for the accepted conditions is given in figs. 2(a)-2(d). According to fig. 2(a), the magnitude of the refractive index ($\boldsymbol{n}$, $Z = 0$) and of the real part of refractive index (μ, $Z \neq 0$) change between 0.0 and 0.9 for equinox days. But they decrease between 10.00-17.00 LT (local time) and get a minimum value around 13.00 LT. This

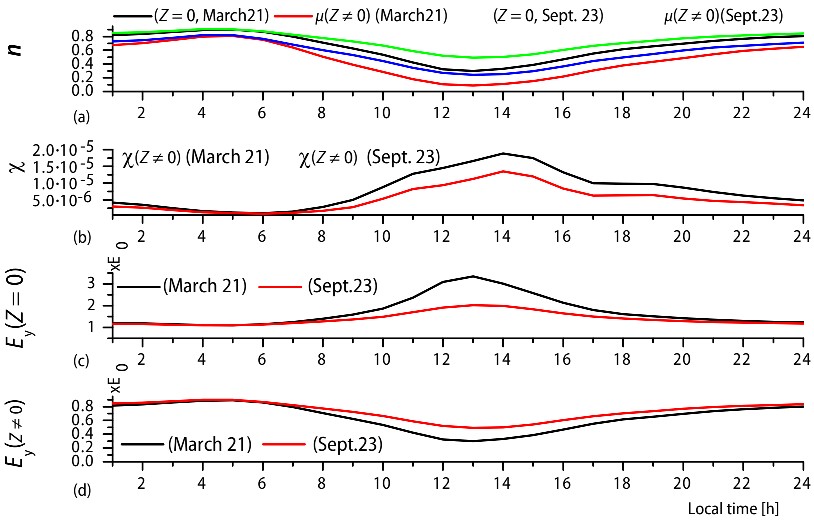

Figure 2. The change of: (a) *n*, (b) χ, (c) E_y (*Z* = 0), and (d) E_y ($Z \neq 0$) with local time for equinox days (*for color image see journal web site*)

clock is one of the hours when the Sun is most effective on the Earth. The attenuation factor, χ, gets a maximum value around the same hours. It has the biggest value around 14.00 LT and is bigger on March 21st than on September 23rd in fig. 2(b). For every two seasons, when $Z = 0$, E_y increases with local time between 10.00-17.00 LT and reaches peak value around 13.00 LT. Besides the magnitude of it is bigger on March 21st than on September 23rd in fig. 2(c). If $Z \neq 0$, the magnitudes of E_y decrease remarkably with local time in fig. 2(d) and reaches minimum value around 13.00 LT unlike fig. 2(c). But the magnitude of E_y is bigger on September 23rd than on March 21st with respect to local time.

Conclusions

The most basic parameters characterized by any of the media such as ionospheric plasma are refractive index, ***n***, conductivity, σ, and dielectric constant, ε. The reflection, refraction and transmission of electromagnetic waves depend on these parameters especially in the ionospheric plasma. The working principle of ionosonde based on reflection of a wave vertical or oblique sent from the Earth to ionosphere. If wave frequency is equal to the frequency of the ionospheric plasma composed of plasma frequency of electrons and ions ($\omega_p = \omega_{pe} + \omega_{pi}$), the wave is reflected otherwise passing into ionosphere. In this context, our basic aim was to investigate how much the collisions frequency changed E_y obtained by WKB solution in ionospheric plasma. Our findings are given as follows.

- The refractive index of ordinary wave for both collision-free ($Z \neq 0$) and collisional conditions ($Z = 0$) has a minimum value between 275-400 km. If ($Z \neq 0$), the magnitudes of ***n*** decrease. Due to this, the reflection height of electromagnetic wave decreases in the ionospheric plasma. Besides, the values of ***n*** are bigger on March 21st than on September 23rd for the accepted conditions. An abnormal case could be explained as anomaly.
- The refractive index of ordinary wave for cases both collision-free ($Z \neq 0$) and collisional conditions ($Z = 0$) with local time decreased between 8.00-18.00 LT. These hours nearly encounter sunrise and sunset but the smallest value of n occurred around 13.00 LT. It can be possible that the phase speed of wave is maximum for the same hour (13.00 LT).

- We could say that altitudes between 250-450, 500 km and hours between 8.00-18.00 LT are critic altitudes and hours. Because the peak height of F-region (maximum electron density) occurs around 250-400 km and the maximum ionization approximately takes part at these hours but the peak of F-region and maximum ionization could change a lot of parameters in ionospheric plasma. The refractive index of ordinary wave was calculated ($Z \neq 0$), and it decreased because of the decreasing phase of the wave.
- The magnitudes of electric field strength are negative below 240 km, and above this altitude, it is positive for both $Z = 0$ and $Z \neq 0$. Actually, this height has a critic importance. So, the heights below 240 km are stop-band, and above this height, there is the pass-band for the used wave, ω. When $Z \neq 0$, the electric field strength decreases remarkably for two seasons and for local time and altitude. It could be interpreted that energy is transferred from wave to ionospheric plasma. If particle collisions can not be calculated, the values of E_y are bigger on March 21st than on September 23rd in contrast to $Z \neq 0$. It could be a result of seasonal anomaly.

References

[1] Sagir, S., *et al.*, The Effect of the Stratospheric QBO on the Neutral Density of the D Region, *Annals of Geophysics*, *58* (2015), 3, A0331
[2] Schunk, R., Nagy, A., *Ionospheres: Physics, Plasma Physics, and Chemistry*, Cambridge University Press, Cambridge, UK, 2009
[3] Aydogdu, M., *et al.*, Comparison of the Calculated Absorption and the Measured Field Strength of HF Waves Reflected from the Ionosphere, *Il Nuovo Cimento*, *30* (2007), 3, pp. 243-253
[4] Yesil, A., *et al.*, Comparison of Maximum Electron Density Predicted by IRI-2001 with that Measured over Chilton Station, *Physical Science (NWSA)*, *3* (2009), July, pp. 92-99
[5] Sagir, S., *et al.*, The Characterization of Diffusion Tensor for Mid-Latitude Ionospheric Plasma, *Annals of Geophysics*, *57* (2014), 2, A0216
[6] Sagir, S., The Change of Diffusion Coefficients of Middle Latitude Ionosphere and Investigation of Relation to F10.7 Solar Flux, *Science and Eng., J. of Fırat Univ., 29* (2017), 1, pp. 211-216
[7] Yesil, A., *et al.*, The Behavior of the Classical Diffusion Tensor for Equatorial Ionospheric Plasma, *Journal of Science*, *13* (2016), Dec., pp. 123-128
[8] Aydogdu, M., Ozcan, O., Effect of Magnetic Declination on Refractive Index and Wave Polarization Coefficients of Electromagnetic Wave in Mid-Latitude Ionosphere, *Indian Journal of Radio & Space Science*, *25* (1996), Oct., pp. 263-70
[9] Swanson, D. G., *Plasma Waves*, Academic Press, New York, USA, 1989
[10] Unal, I., *et al.*, Ionospheric Absorption of HF Radio Wave in Vertical Propagation, *Iranian Journal of Science &Technology, Transaction A*, *31* (2007), 4, pp. 413-419
[11] Ozcan, O., *et al.*, Effect of the Adiabatic Sound Speed on the Electric Conductivities of the Ionospheric Plasma, *Balkan Physics Letters*, *6* (1998), pp. 204-213
[12] Whitten, R. C., Poppoff, I. G., *Fundamentals of Aeronomy*, John Willey and Sons, New York, USA, 1971
[13] Budden, K. G., *The Propagation of Radio Waves*, Cambridge University Press, Cambridge, UK, 1988
[14] Budden, K. G., Stott, G. F., Rays in Magneto-Ionic Theory-II, *Journal of Atmospheric and Solar Terrestrial Physics*, *42* (1980), Sept.-Oct., pp. 791-800
[15] Richard, F., *The Physics of Plasma*, CRC press, New York, 2014, pp. 50-140
[16] Aydogdu, M., *et al.*, The Group Refractive Indices of HF Waves in the Ionosphere and Departure from the Magnitude Without Collisions, *Journal of Atmospheric and Solar-Terrestrial Physics*, *66* (2004), 5, pp. 343-348
[17] Aydogdu, M., Ozcan, O., The Possible Effects of the Magnetic Declination on the Wave Polarization Coefficients at the Cutoff Point, *Progress in Electromagnetic Research, PIER, 30* (2001), pp. 179190

Paper submitted: June 30, 2017
Paper revised: November 10, 2017
Paper accepted: November 17, 2017