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Seasonal variations of impedance in the ionospheric plasma

Iyonosferik plazmadaki empedansın mevsimsel değişimi

***Yazar(lar) (Author(s))**: İbrahim ÜNAL[1], Seçil KARATAY[2], Ali YEŞİL[3], Aybaba HANÇERLİOĞULLARI[4]*

ORCID[1]: 0000-0001-8497-4459

ORCID[2]: 0000-0002-1942-6728

ORCID[3]: 0000-0003-2997-897X

ORCID[4]: 0000-0001-7008-480X

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İyonosferik Plazmadaki Empedansın Mevsimsel Değişimi

Araştırma Makalesi / Research Article

İbrahim ÜNAL[1], Seçil KARATAY[2*], Ali YEŞİL[3], Aybaba HANÇERLİOĞULLARI[4]

[1]Eğitim Fakültesi, Matematik ve Fen Bilimleri Eğitimi Bölümü, İnönü Üniversitesi, Malatya, Türkiye
[2]Mühendislik ve Mimarlık Fakültesi, Elektrik Elektronik Mühendisliği Bölümü, Kastamonu Üniversitesi, Kastamonu, Türkiye
[3]Fen Fakültesi, Fizik Bölümü, Fırat Üniversitesi, Elazığ, Türkiye
[4]Fen Edebiyat Fakültesi, Fizik Bölümü, Kastamonu Üniversitesi, Kastamonu, Türkiye

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ÖZ

İyonosfer, atmosferin 50 km ila 1000 km yükseklikleri arasında yer alan iyonlaşmış bir tabakadır. Bu tabaka, atmosferik iletkenlikte önemli bir rol oynar. İyonosfer büyük miktarda elektrik yüklü parçacıklara sahiptir ve bu nedenle radyo dalgalarının yayılımını etkiler. Bu çalışmada, iyonosferik plazmanın empedansı farklı mevsimler ve farklı jeomanyetik aktivite dönemleri için Yer'in gerçek geometrisi kullanılarak hesaplanmıştır. İyonosferik plazmanın empedansının her doğrultuda genel olarak her mevsim için büyük değerlere sahip olduğu gözlenmiştir. Empedans tensörünün diyagonal bileşenlerinin diğer bileşenlerden daha büyük olduğu bu çalışmada gözlenmiştir. Ayrıca iyonosferik plazmanın, genellikle, her yöne ve mevsimlerde zayıf iletkenliğe sahip olduğu gözlenmiştir. Empedansın, elektron yoğunluğuyla ters olarak değiştiği görülmüştür. Bu nedenle, elektron yoğunluğunda sapmalara neden olan jeomanyetik aktivitenin de empedansı azalttığı gözlenmiştir. İyonosferik plazmanın, çalışmanın yapıldığı coğrafi koordinatlarda reaktif bir karaktere sahip olduğu görülmüştür. İyonosfer, bir dielektrik yapı göstermiştir.

Anahtar Kelimeler: Empedans, elektromanyetik, plazma ugulamaları, iyonosfer, manyetosfer.

Seasonal Variations of Impedance in the Ionospheric Plasma

ABSTRACT

The ionosphere is an ionized layer that extends between 50 km and 1000 km altitudes in the atmosphere. It plays an important role in atmospheric electricity. The ionosphere has the number of electrically charged particles and thus, it affects the propagation of the radio waves. In this study, magnitudes of impedance for different seasons and different geomagnetic activity periods in the ionospheric plasma are calculated using the real geometry of Earth. It is observed that the impedance of the ionospheric plasma in all directions generally has high values for all seasons. The diagonal components of the tensor of the impedance are greater than the other components. It is also observed that the ionospheric plasma, generally, has weak conductivity in all directions and seasons. Impedance varies inversely with electron density. Hence, geomagnetic activity periods which lead to an increase in electron density decreases the impedance. It is observed that the ionospheric plasma has a reactive character in the geographic coordinates where the study was performed. The ionosphere displays a dielectric structure.

Keywords: Impedance, electromagnetics, plasma applications, ionosphere, magnetosphere.

1. INTRODUCTION

The ionosphere is a layer of the Earth's atmosphere extending from 50 to 1000 km and it can significantly affect the propagation of radio waves. The ionosphere may act as an efficient reflector for frequencies below 30 MHz, allowing high frequency (HF) radio communication to distances of many thousands of kilometers. Due to the dependence of radio waves behavior on their frequencies, oscillation frequency of the electron and the refractive index of the ionospheric plasma, the wave can be reflected, refracted or absorbed from the ionosphere.

In recent years, information about the state of the Earth's ionosphere has improved [1-11]. Ionospheric physics is related to plasma physics because the ionosphere is, of course, a weak natural plasma. The ionosphere carries electric currents because winds and electric fields drive ions and electrons. The direction of the drift is at right angles to the geomagnetic field [4, 5]. The electrical conductivity tensor finds application in all areas of ionospheric electrodynamics and at all latitudes. The theory of ionospheric conductivity has been developed by many scientists and is now quite well understood, though refinements are still made from time to time [12, 13]. On the other hand, the most important parameter that determinates the electromagnetic behavior of any medium is the dielectric constant, which determines the refractive index at any frequency, the form of the polarized wave in the medium, the state of wave energy and the propagation of the wave. As known, the dielectric and permeability parameters are related to electric $\left(\varepsilon = \varepsilon_0 \left(1 + \chi\right)\right)$ and magnetic

**Sorumlu Yazar (Corresponding Author)*
e-posta : skaratay@kastamonu.edu.tr

$\left(\mu = \mu_0\left(1+\chi_m\right)\right)$ susceptibilities of the material. Since the velocity $\left(c = 1/\sqrt{\mu\varepsilon}\right)$ and characteristic impedance $\left(\eta = \sqrt{\mu/\varepsilon}\right)$ of an electromagnetic wave travelling in a plasma are dependent on the plasma's properties, the observed refractive index may be used to deduce detailed information about the properties of the ionic plasma. Because of all of these reasons, the impedance of the ionospheric plasma is a measure of its refractive index, reflection, and volume and polarization of the electromagnetic wave. Hence determination of impedance of the ionosphere is very important for figuring out the propagation of an electromagnetic wave in the ionospheric plasma. The most interesting features of the solution of electromagnetic waves for any medium are resonances and cut-offs. Resonances are characterized by the phase velocity going to zero ($v_p=\omega/k\rightarrow 0$) which is equivalent to the refraction index $n=kc/\omega$ going to infinity ($k\rightarrow\infty$). The wave energy is absorbed by ionospheric plasma at resonance points. Cut-offs are defined by the index of refraction or the wave vector going to zero ($k\rightarrow 0$). At these cut-off points, the wavelength goes to infinity and the waves are reflected. Cut-off points can be used for plasma density measurements [3-6, 9-14].

In the literature, the declination angle (D) in the geometry of the Earth's magnetic field is not considered in the calculation of the conductivities [4-15]. This angle was taken into consideration in recent years [9, 16, 17]. It is used for defining the characteristic impedance of the ionospheric plasma and in numerical calculations of the impedance. The declination angle determines the cut-off points of the wave. It also determines the direction and the polarization of the wave, depending on the medium of the ionospheric plasma [17]. We can thus determine whether the ionospheric plasma is active or reactive. The calculated impedance shows which component of the magnetic field is effective in the determination of the propagation coefficient of the electromagnetic wave [18]. In this study, the impedances are calculated using the real geometry of the Earth's magnetic field in the ionospheric plasma. Results are obtained for geomagnetically disturbed and quiet days for different seasons. The analytical calculations and the results are presented in Section 2 and 3, respectively.

2. IMPEDANCE FOR COLD PLASMA

When considering the behavior of a high frequency wave through the ionospheric plasma, taking into account that $\boldsymbol{m_e} \ll \boldsymbol{m_i}$, only the equation of motion for electrons should be considered [6]. Besides, if the thermal motion of particles is neglected and the cold plasma approximation is used, then the equation of motion is defined as follows [7]:

$$m_e \frac{d\boldsymbol{V_e}}{dt} = -e\left(\boldsymbol{E} + \boldsymbol{V_e} \times \boldsymbol{B}\right) - m_e \nu_e \boldsymbol{V_e} \tag{1}$$

Where $\mathrm{m_e}$ is the mass, $\boldsymbol{V_e}$ is the velocity and ν_e $\left(\nu_{ei} + \nu_{en}\right)$ is the collision frequency of the electron. E and B are the electric and the magnetic fields, respectively. Assuming that the velocity and the fields vary as $e^{-i\omega t}$, equation (1) can be written as:

$$\mathrm{i}\omega\boldsymbol{V_e} = \frac{e}{m_e}\left(\boldsymbol{E} + \boldsymbol{V_e} \times \boldsymbol{B}\right) + \nu_e\boldsymbol{V_e} \tag{2}$$

It is assumed that the z-axis of the coordinate system with its origin located on the ground points vertically upward. The x and y-axes represent the geographic eastward and the northward directions in the northern hemisphere. The current density is given by $\boldsymbol{J} = -eN_e\boldsymbol{V_e}$ and the electric field and the electron velocity are $\boldsymbol{E} = \hat{x}E_x + \hat{y}E_y + \hat{z}E_z$ and $\boldsymbol{V} = \hat{x}V_x + \hat{y}V_y + \hat{z}V_z$. The Earth's magnetic field direction is $\boldsymbol{B} = \hat{x}\, B\, CosI\ SinD + \hat{y}\, B\, CosI\ CosD - \hat{z}\, B\, SinI$.

According to Ohm's law $\left([\boldsymbol{J}] = [\sigma]\cdot[\boldsymbol{E}]\right)$, equation (2) is a tensor equation where the conductivity is defined as:

$$\sigma = \begin{bmatrix} \sigma_{xx} & \sigma_{xy} & \sigma_{xz} \\ \sigma_{yx} & \sigma_{yy} & \sigma_{yz} \\ \sigma_{zx} & \sigma_{zy} & \sigma_{zz} \end{bmatrix} \tag{3}$$

The components of the conductivity tensor are given by [9]:

$$\sigma_{xx} = \sigma_1 + (\sigma_0 - \sigma_1)\, Cos^2I\ Sin^2D \tag{4}$$

$$\sigma_{xy} = -\sigma_2\ SinI + (\sigma_0 - \sigma_1)\, Cos^2I\ CosD\ SinD \tag{5}$$

$$\sigma_{xz} = -\sigma_2\ CosI\ CosD - (\sigma_0 - \sigma_1)\ CosI\ SinI\ SinD \tag{6}$$

$$\sigma_{yx} = \sigma_2\ SinI + (\sigma_0 - \sigma_1)\ Cos^2I\ CosD\ SinD \tag{7}$$

$$\sigma_{yy} = \sigma_1 + (\sigma_0 - \sigma_1)\, Cos^2I\ Cos^2D \tag{8}$$

$$\sigma_{yz} = \sigma_2\ CosI\ SinD - (\sigma_0 - \sigma_1)\ CosI\ SinI\ CosD \tag{9}$$

$$\sigma_{zx} = \sigma_2\ CosI\ CosD - (\sigma_0 - \sigma_1)\ CosI\ SinI\ SinD \tag{10}$$

$$\sigma_{zy} = -\sigma_2\ CosI\ SinD - (\sigma_0 - \sigma_1)\ CosI\ SinI\ CosD \tag{11}$$

$$\sigma_{zz} = \sigma_1 + (\sigma_0 - \sigma_1)\, Sin^2I \tag{12}$$

Where, σ_0 is the longitudinal conductivity defined as $\left(\dfrac{e^2\ N_e}{m_e\left(\nu_e - i\omega\right)}\right)$, σ_1 is the Pedersen conductivity defined as $\left(\frac{e^2\ N_e(\nu_e - i\omega)}{m_e\left[\omega_{ce}^2 + (\nu_e - i\omega)^2\right]}\right)$ and σ_2 is the Hall conductivity defined as $\left(\frac{e^2\ N_e\ \omega_{ce}}{m_e\left[\omega_{ce}^2 + (\nu_e - i\omega)^2\right]}\right)$ [8].

In these conductivity equations, N_e is the electron density and ω_{ce} is the gyro frequency defined as $\omega_{ce} = -e\,B/m_e$. Note that σ is a scalar quantity and that it has an imaginary as well as a real part. The real part is usually associated with conductivity: It is the reciprocal of resistivity and thus associated with energy dissipation. The imaginary part is associated with dielectric properties of the medium and is a purely alternating current parameter (inverse of reactance) [19]. A relationship between conductivity with impedance of ionospheric plasma can be defined as follows:

$$Z = \frac{1}{\sigma_R} + i\frac{1}{\sigma_S} = R + iX \quad (13)$$

Where, σ_R is the real part of conductivity, σ_S is the imaginary part of conductivity, R is the resistivity and X is the reactance of the medium. Due to this, all the impedances of the ionospheric plasma must be a function of these conductivities. Thereby, the impedance of ionospheric plasma depends on both the real and imaginary parts of the conductivity. It can be defined as follows:

$$Z = \begin{bmatrix} Z_{xx} & Z_{xy} & Z_{xz} \\ Z_{yx} & Z_{yy} & Z_{yz} \\ Z_{zx} & Z_{zy} & Z_{zz} \end{bmatrix} \quad (14)$$

When

$A = \nu_e^2 + \omega^2$,
$B = \nu_e^2 + \omega^2 + \omega_{ce}^2$,
$C = \nu_e^2 - \omega^2 + \omega_{ce}^2$,
$D = \nu_e^2 + \omega^2 - \omega_{ce}^2$,
$E = \nu_e^2 - 3\omega^2 + \omega_{ce}^2$,
$F = 3\nu_e^2 - \omega^2 + \omega_{ce}^2$

the components of this tensor is obtained depending on the dip and the declination angles as follows:

$$Z_{xx} = \frac{m_e(E^2\nu_e^2 + F^2\omega^2)}{e^2N_e\nu_e(AB + E\omega_{ce}^2Cos^2ISin^2D)} + i\frac{m_e(E^2\nu_e^2+F^2\omega^2)}{e^2N_e\omega(AD+F\omega_{ce}^2Cos^2ISin^2D)} \quad (15)$$

$$Z_{xy} = -\frac{m_e(E^2\nu_e^2+F^2\omega^2)}{e^2N_e\omega_{ce}(ACSinI - E\nu_e\omega_{ce}Cos^2ICosDSinD)} - i\frac{m_e(E^2\nu_e^2+F^2\omega^2)}{e^2N_e\omega\omega_{ce}(2A\nu_eSinI - F\omega_{ce}Cos^2ICosDSinD)} \quad (16)$$

$$Z_{xz} = -\frac{m_e(E^2\nu_e^2+F^2\omega^2)}{e^2N_e\omega_{ce}(ACCosD + E\nu_e\omega_{ce}SinISinD)CosI} - i\frac{m_e(E^2\nu_e^2+F^2\omega^2)}{e^2N_e\omega\omega_{ce}(2A\nu_eCosD + F\omega_{ce}SinISinD)CosI} \quad (17)$$

$$Z_{yx} = \frac{m_e(E^2\nu_e^2+F^2\omega^2)}{e^2N_e\omega_{ce}(ACSinI + E\nu_e\omega_{ce}Cos^2ICosDSinD)} + i\frac{m_e(E^2\nu_e^2+F^2\omega^2)}{e^2N_e\omega\omega_{ce}(2A\nu_eSinI + F\omega_{ce}Cos^2ICosDSinD)} \quad (18)$$

$$Z_{yy} = \frac{m_e(E^2\nu_e^2 + F^2\omega^2)}{e^2N_e\nu_e(AB + \omega_{ce}^2Cos^2ICos^2D)} + i\frac{m_e(E^2\nu_e^2+F^2\omega^2)}{e^2N_e\omega(AD+F\omega_{ce}^2Cos^2ICos^2D)} \quad (19)$$

$$Z_{yz} = \frac{m_e(E^2\nu_e^2 + F^2\omega^2)}{e^2N_e\omega_{ce}(ACSinD - E\nu_e\omega_{ce}SinICosD)CosI} + i\frac{m_e(E^2\nu_e^2+F^2\omega^2)}{e^2N_e\omega\omega_{ce}(2A\nu_eSinD - F\omega_{ce}SinICosD)CosI} \quad (20)$$

$$Z_{zx} = \frac{m_e(E^2\nu_e^2 + F^2\omega^2)}{e^2N_e\omega_{ce}(ACCosD - E\nu_e\omega_{ce}SinISinD)CosI} + i\frac{m_e(E^2\nu_e^2+F^2\omega^2)}{e^2N_e\omega\omega_{ce}(2A\nu_eCosD - F\omega_{ce}SinISinD)CosI} \quad (21)$$

$$Z_{zy} = -\frac{m_e(E^2\nu_e^2+F^2\omega^2)}{e^2N_e\omega_{ce}(ACSinD + E\nu_e\omega_{ce}SinICosD)CosI} - i\frac{m_e(E^2\nu_e^2+F^2\omega^2)}{e^2N_e\omega\omega_{ce}(2A\nu_eSinD + F\omega_{ce}SinICosD)CosI} \quad (22)$$

$$Z_{zz} = \frac{m_e(E^2\nu_e^2 + F^2\omega^2)}{e^2N_e\nu_e(AB + E\omega_{ce}^2Sin^2I)} + i\frac{m_e(E^2\nu_e^2+F^2\omega^2)}{e^2N_e\omega(AD+F\omega_{ce}^2Sin^2I)} \quad (23)$$

In the next section, the numerical analysis and the results are given for two equinoxes and solctices periods.

3. NUMERICAL ANALYSIS AND RESULTS

In this study, the impedances of the ionospheric plasma $\left(Z = R^2 + X^2\right)$ are calculated using Equation (15)-(23) for 38.7° N and 39.2° E, I=55.6º, D=3° and 12.00 LT. Two geomagnetic activity conditions are chosen to define quiet ($0 \leq Kp \leq 2^+$) and disturbed ($Kp > 2^+$) periods for the equinoxes March and September and solstices June and December. The ionospheric parameters used for the calculation are obtained by using the IRI-95 model.

Table 1 gives the pattern that represents the values of the impedance obtained for 16 MHz for geomagnetically quiet and disturbed periods in equinoxes and solstices at h_mF2 where the electron density distribution has maximum values. The diagonal components Z_{xx}, Z_{yy} and Z_{zz} values are greater than the impedance values in Table 1. So these components of the impedance are considered in the numerical analysis.

Figure 1 shows the seasonal variations of impedances Z_{xx}, Z_{yy} and Z_{zz} depending on wave frequency for the quiet periods. The obtained values are magnitudes of the impedance where the real and the imaginary parts of the impedance are taken into account. These values are the mean values obtained for 120 km and 500 km in the ionospheric plasma. All three impedances in Figure 2 increase parabolically with frequency and they have maximas in September and minimas in December.

Similarly Figure 2 shows seasonal variations of impedances Z_{xx}, Z_{yy} and Z_{zz} depending on the wave frequency for the disturbed periods. Details of the calculations are the same as those for periods. Figure 3 shows the variations of the mean magnitudes of the diagonal impedances. It is seen that the graphs are almost similar. The mean impedances for quiet periods are larger during the March equinox and the June solstice. Similarly the mean values for disturbed periods are larger during the September equinox and the December solstice.

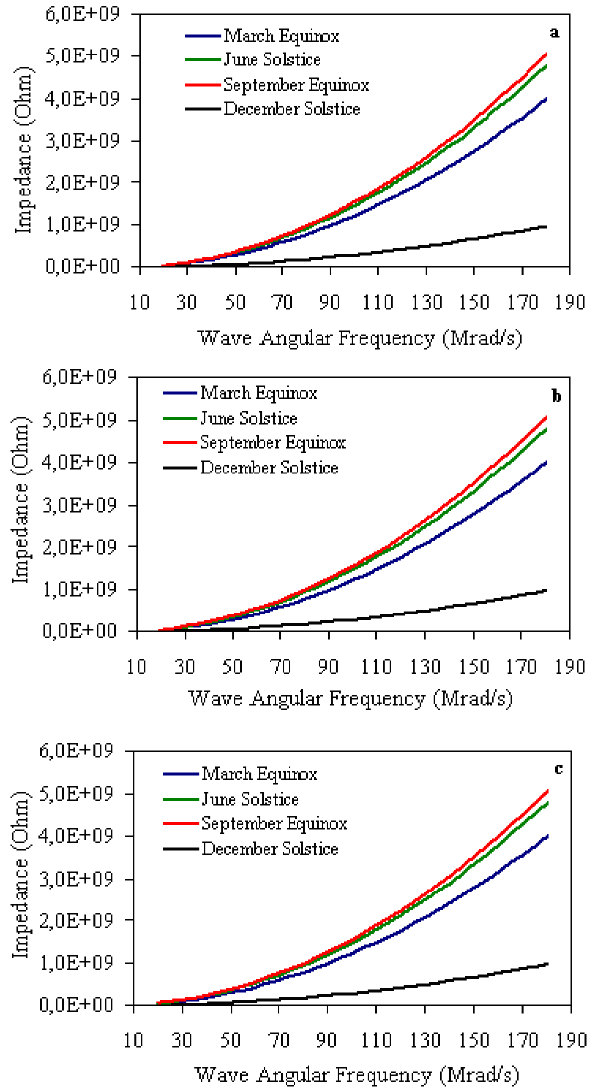

Figure 1. Seasonal variations of the average impedance of the ionospheric plasma depending on the frequency in the quiet periods ($Kp \leq 2^+$) for **a)** Z_{xx} **b)** Z_{yy} **c)** Z_{zz}.

Table 1. Values of the impedance calculated for 100 mrad/s (~16 mhz) in solstices and equinoxes for quiet and disturbed days periods at hmf2.

Impedances (Ohm)	Days							
	$Kp \leq 2^+$				$Kp > 2^+$			
	March Equinox	**June Solstice**	**September Equinox**	**December Solstice**	**March Equinox**	**June Solstice**	**September Equinox**	**December Solstice**
Z_{xx} x10^9	1.21	1.46	1.54	2.94	1.91	7.03	2.09	3.23
Z_{xy} x10^7	6.49	6.1	7.47	2.44	2.25	3.95	9.08	2.58
Z_{xz} x10^7	4.53	4.31	5.21	1.71	1.59	2.76	6.33	1.81
Z_{yx} x10^7	6.57	6.24	7.55	2.48	2.31	4.00	9.17	2.62
Z_{yy} x10^9	1.22	1.46	1.55	0.29	0.19	0.70	2.10	0.32
Z_{yz} x10^6	3.43	3.26	3.94	1.29	1.20	2.09	4.79	1.36
Z_{zx} x10^7	4.51	4.29	5.18	1.69	1.57	2.74	6.30	1.79
Z_{zy} x10^6	3.43	3.26	3.94	1.29	1.20	2.09	4.79	1.36
Z_{zz} x10^9	1.23	1.47	1.55	0.29	0.19	0.78	2.12	0.32

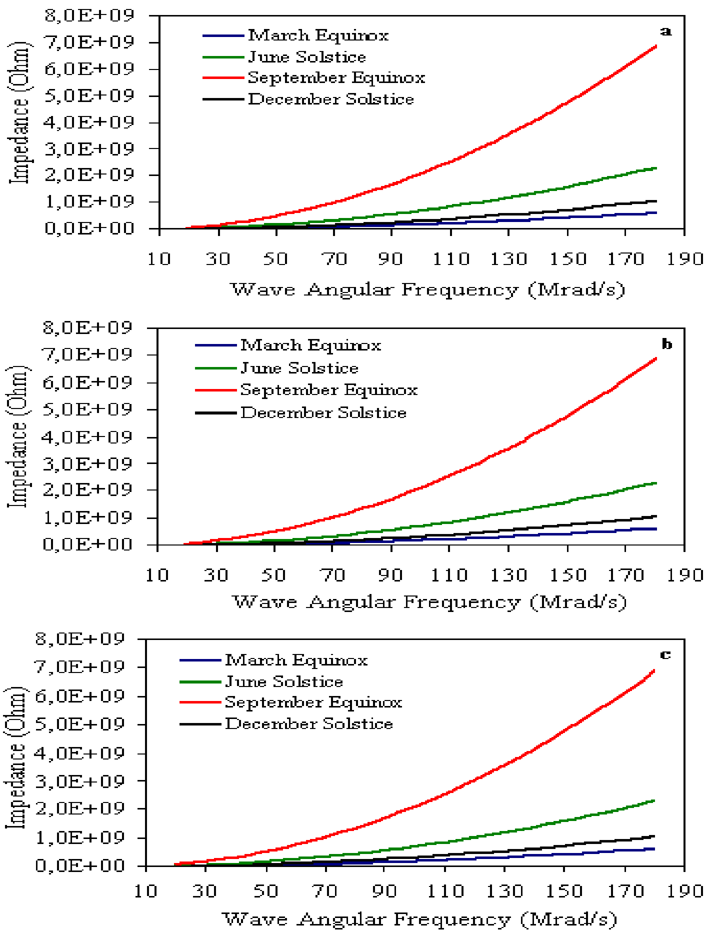

Figure 2. Seasonal variations of the average impedance of the ionospheric plasma depending on the frequency in the disturbed periods ($Kp>2^+$) for **a)** Z_{xx} **b)** Z_{yy} **c)** Z_{zz}..

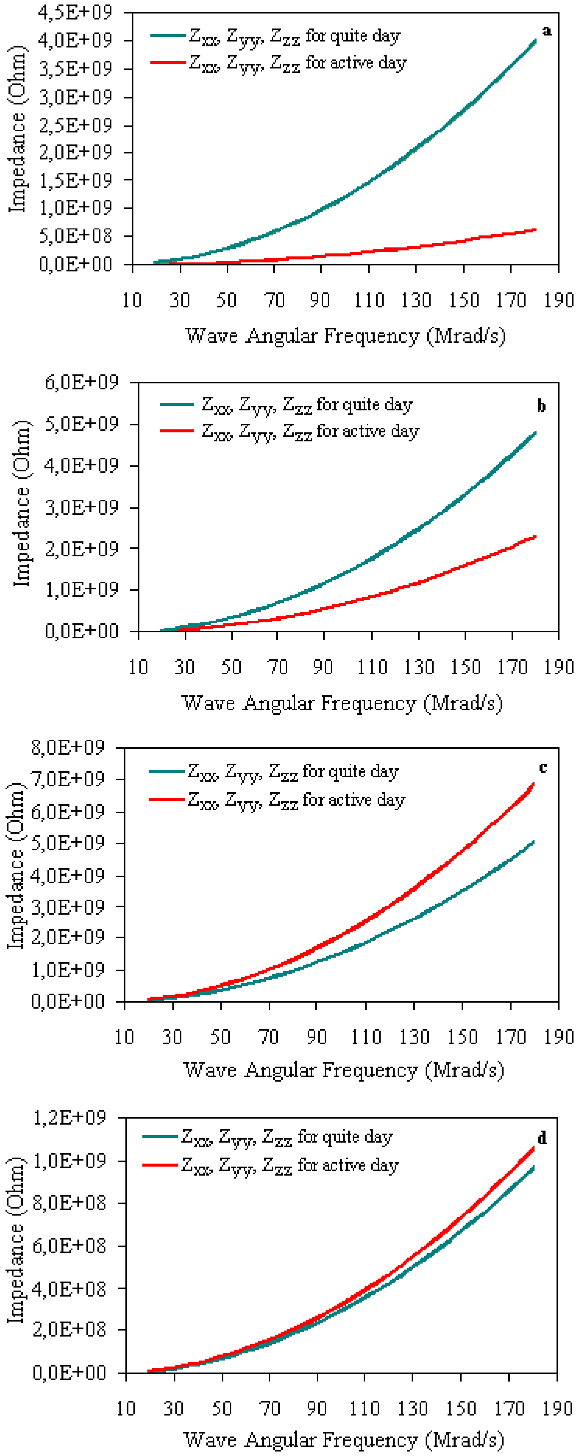

Figure 3. Variations of the average impedance of the ionospheric plasma with the wave angular frequency for quiet and disturbed days: **a)** March equinox, **b)** June solstice, **c)** September equinox, **d)** December solstice.

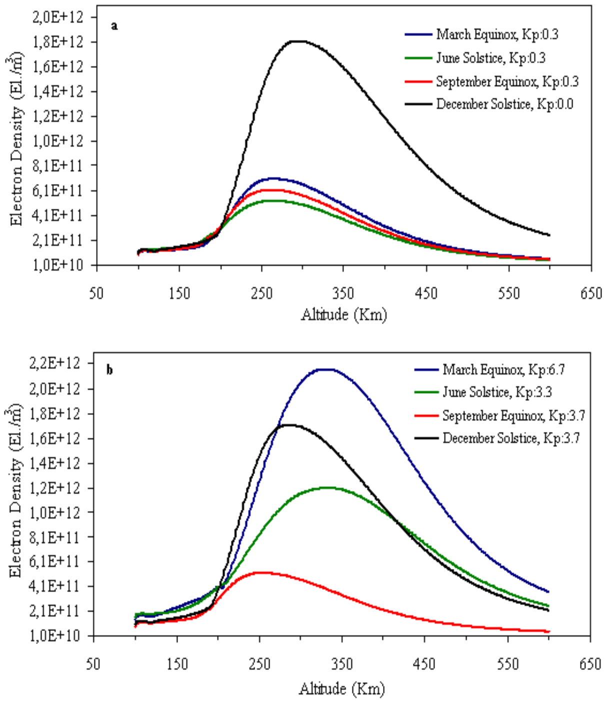

Figure 4. Altitude distribution of electron density in different seasons a) for quite days ($0 \leq Kp \leq 2^+$) **b)** for active days ($Kp > 2^+$).

In this work, the empedance of the ionospheric plasma are computed for December (winter solstice), March (spring equinox), June (summer solstice), September (autumn equinox) months. In the future studies, the analysis will be done over more months and seasons.

4. CONCLUSION

In this study, the mean values of magnitudes of the impedances of the ionospheric plasma are calculated for different seasons and geomagnetic activity periods. It is observed that the diagonal components of the impedance tensor are greater by 102 than the other components. Because the conductivity and dielectric constant exhibited by the medium vary depending on the angular frequency of the wave, the impedance also varies with the angular frequency. Impedance reaches its minimum values when the electron density increases. Similarly, impedance reaches its maxima when electron density is small. Thus impedance decreases as electron density increases in geomagnetically disturbed days periods during the solstices and equinoxes. It is seen that the ionospheric plasma can be characterized as reactive and the ionosphere has a structure capable of behaving as a dielectric in the chosen coordinate. The inductive property of the ionosphere is dominant under related conditions. The radial (z) component of the strength of the magnetic field is more effective for determining the propagation coefficient of the electromagnetic wave since diagonal components of the impedance are larger than the off-diagonals. The increasing of the diagonal components depending on the declination angle can be observed from the analytic expressions.

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