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Comparison of the calculated absorption and the measured field strength of HF waves reflected from the ionosphere

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Summary. — The absorption (L) of the wave in the ionosphere has been calculated. The 5.47 MHz wave is transmitted from Erciş, Turkey (39.03°N, 43.37 °E) and received at Elazığ, Turkey (38.70°N, 39.20°E). The field strength of this wave is measured by *ITU-Compliant HF Field Strength Monitoring Terminal*, and the absorption L in the ionosphere has been calculated. It is observed that the field strength of the wave is least around noon time and it increases at night times at all seasons. The diurnal and seasonal variations of the calculated absorption L shows that the maximum absorption in the wave occurs around noon time. The behaviour of the diurnal and seasonal variations of the field strength of the wave can be explained with the diurnal and seasonal variations of the calculated absorption L in the ionosphere. Equation (22) in this paper can be used to obtain the imaginary part (β) of the refractive index of the ionospheric plasma, and it can be applied to the HF radio waves propagations in the ionosphere for absorption L.

PACS `94.20.Bb` – Wave propagation.
PACS `94.20.dj` – F region.
PACS `94.20.Vv` – Ionospheric disturbances, irregularities, and storms.

1. – Introduction

High-frequency (HF) radio waves have been and still are one of the basic vehicles for long-distance transmission of information. Hence, the F2-layer is fundamental importance for propagation over long distance. When the radio waves are propagated through the ionospheric plasma, they are absorbed because of the free-electron making collisions. The absorption of the wave is studied by many authors and several approximations were done [1-7]. In recent years the information about the state of the Earth's ionosphere

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Fig. 1. – The geographical map of Erciş-Elazığ link.

was improved. Hence, most of the used approximations for ionospheric calculations are unrealistic. To see the effects of the ionosphere on the wave propagation, more detailed theoretical investigation of the refractive index of the ionosphere [8-10], and the absorption of the electromagnetic waves in the ionosphere are needed. If the collision in the ionosphere is considered, the refractive index (n) of the ionospheric plasma is complex such as $n = \alpha + i\beta$, and then plane electromagnetic waves can be written as

$$E = E_0 e^{-\kappa S} \cdot e^{i\,\omega(\frac{\alpha}{c}S-t)} = E_0' e^{i\,\omega(\frac{\alpha}{c}S-t)}, \tag{1}$$

where $\kappa = \frac{\omega}{c}\beta$ is the absorption coefficient. The absorption of the wave can be measured in terms of the reflection coefficient ρ of the ionosphere. The ratio of the amplitude of a wave is reflected in the ionosphere to the amplitude of a wave would have been received in the absence of attenuation. That is

$$\ln \rho = -\int \kappa \mathrm{d}s. \tag{2}$$

Absorption in the ionosphere L is (in dB)

$$L = 8.68 \int \kappa \mathrm{d}s \tag{3}$$

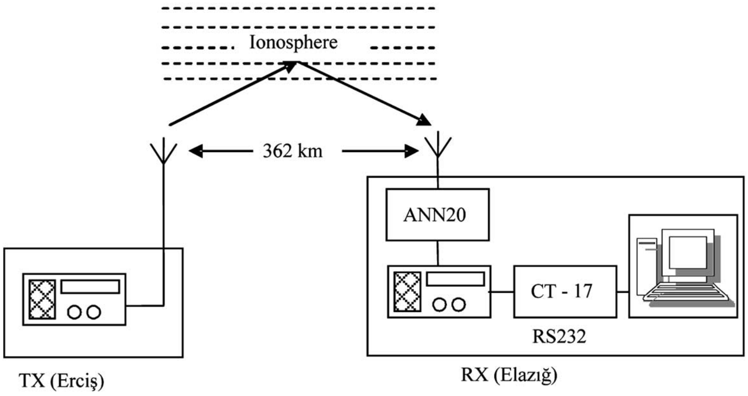

Fig. 2. – Experiment for field strength measurement (RX: ITU-Compliant HF field strength monitoring terminal, TX: Marconi 100 Watt HF SSB).

[11]. In this paper, the absorption L in the ionosphere of the 5.47 MHz wave has been calculated for the path in fig. 1, to explain the variations of the field strength of 5.47 MHz wave which has been measured by *ITU-Compliant HF Field Strength Monitoring Terminal* in fig. 2. For this purpose, the 5.47 MHz wave which is transmitted from Erçiş, Turkey (39.03°N, 43.37 °E) and reflected at oblique incidence from F2-region is received at Elazığ, Turkey (38.70°N, 39.20°E). The horizontal distance between transmitter and receiver is 362 km (fig. 1).

2. – Conductivity tensor

At high frequency, the effects of ions can be neglected. We assumed that the z-axis of the coordinate system with its origin located on the ground is vertical upwards. The x-axis and y-axis are geographic eastward and northward in the northern hemisphere, respectively. $\mathbf{a}_x$, $\mathbf{a}_y$ and $\mathbf{a}_z$ are unit vectors along the x-axis, y-axis and z-axis,

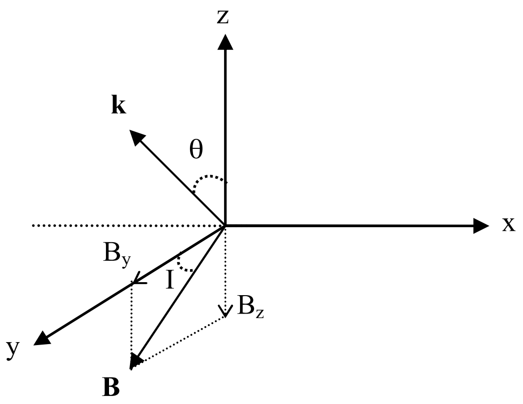

Fig. 3. – The geometry of Earth's magnetic field ($\mathbf{B}$) and the wave propagation vector ($\mathbf{k}$).

respectively. Since the declination angle (d) of the geomagnetic field over Turkey is $\approx 3°$E, and then it is neglected. Hence, the geomagnetic field over Turkey becomes

$$\mathbf{B} = B_y \mathbf{a}_y + B_z \mathbf{a}_z, \tag{4}$$

where $B_y = B\cos I$ and $B_z = -B\sin I$ in which I is the dip angle of the geomagnetic field, as shown in fig. 3. By using this geometry and the results of [8], the conductivity tensor can be written as

$$\sigma = \begin{bmatrix} \sigma_{xx} & \sigma_{xy} & \sigma_{xz} \\ \sigma_{yx} & \sigma_{yy} & \sigma_{yz} \\ \sigma_{zx} & \sigma_{zy} & \sigma_{zz} \end{bmatrix}, \tag{5}$$

where

$$\begin{aligned} &\sigma_{xx} = \sigma_1, \quad \sigma_{xy} = -\sigma_2 \sin I, \quad \sigma_{xz} = -\sigma_2 \cos I, \\ &\sigma_{yx} = \sigma_2 \sin I, \quad \sigma_{yy} = \sigma_1 \sin^2 I + \sigma_0 \cos^2 I, \quad \sigma_{yz} = -\big(\sigma_0 - \sigma_1\big) \cos I \sin I \\ &\sigma_{zx} = \sigma_2 \cos I, \quad \sigma_{zy} = -\big(\sigma_0 - \sigma_1\big) \cos I \sin I, \quad \sigma_{zz} = \sigma_0 \sin^2 I + \sigma_1 \cos^2 I \end{aligned} \tag{6}$$

in which σ_0, σ_1 and σ_2 are longitudinal, Pedersen and Hall conductivities, respectively.

3. – Wave equation

It is assumed that the fields vary as $e^{i(k\cdot r-\omega t)}$. From Maxwell's equations, the following wave equation can be obtained:

$$n^2\mathbf{E} - \mathbf{n}(\mathbf{n}\cdot\mathbf{E}) = \left[I + \frac{i}{\varepsilon_0 \omega}\sigma\right]\cdot\mathbf{E}, \tag{7}$$

in which I is the unit matrix and σ is the conductivity tensor of the ionospheric plasma in eq. (5). Since the wave is propagated in the xz-plane, then the propagation vector of the wave becomes $\mathbf{k} = k_x\mathbf{a}_x + k_z\mathbf{a}_z$ where $k_x = -k\sin\theta$ and $k_z = k\cos\theta$. By using the geometry in fig. 3, eq. (7) can be written as

$$\begin{bmatrix} M_{xx} & M_{xy} & M_{xz} \\ M_{yx} & M_{yy} & M_{yz} \\ M_{zx} & M_{zy} & M_{zz} \end{bmatrix}\cdot\mathbf{E} = 0, \tag{8}$$

where

$$\begin{aligned} &M_{xx} = n^2\cos^2\theta - S, \qquad M_{xy} = -iD\sin I, \qquad M_{xz} = n^2\sin\theta\cos\theta - iD\cos I, \\ &M_{yx} = iD\sin I \qquad M_{yy} = n^2 - S\sin^2 I - P\cos^2 I, \qquad M_{yz} = (P-S)\cos I\sin I, \\ &M_{zx} = n^2\sin\theta\cos\theta + iD\cos I, \quad M_{zy} = (P-S)\cos I\sin I, \\ &M_{zz} = n^2\sin^2\theta - P\sin^2 I - S\cos^2 I \end{aligned} \tag{9}$$

in which

$$(10)\qquad X=\frac{\omega_p^2}{\omega^2}\,,\quad Y=\frac{\omega_{ce}}{\omega}\,,\quad Z=\frac{\nu}{\omega}\,,\quad P=1-\frac{X}{1+iZ}\,,\quad R=1-\frac{X}{1-Y+iZ}\,,$$
$$L=1-\frac{X}{1+Y+iZ}\,,\quad S=\frac{1}{2}(R+L)\quad\text{and}\quad D=\frac{1}{2}(R-L).$$

From the determinant of the matrix M (eq. (8)),

$$(11)\qquad An^4-Bn^2+C=0.$$

The refractive index of the ionospheric plasma is obtained as follows:

$$(12)\qquad n_{12}^2=\frac{B}{2A}\mp\frac{Q^{1/2}}{2A},\qquad Q=B^2-4AC,$$

where

$$(13)\qquad A=P\sin^2 I\cos^2\theta+S\cos^2 I\cos^2\theta+S\sin^2\theta,$$
$$(14)\qquad B=PS\left(1+\sin^2 I\cos^2\theta\right)+RL\left(\cos^2 I+\sin^2 I\sin^2\theta\right),$$
$$(15)\qquad C=PRL.$$

4. – Imaginary part (β) of refractive index

Refractive index (+ sign) in eq. (12) is

$$(16)\qquad n^2=\frac{B}{2A}+\frac{Q^{1/2}}{2A}=M+iN=(\alpha+i\beta)^2.$$

For HF waves, Z^2 becomes $Z^2\ll 1$. Therefore, the expression of $(1+Z^2)^{-1}$ in the refractive indices can be approximate to $(1-Z^2)$ by using the binomial expansion [10]. The higher terms than Z are neglected. By using this approximation, eqs. (10) and

(13)-(15) become as follows:

$$P = P_0 + iXZ, \qquad R = R_0 + i\frac{XZ}{\left(1 - Y^2\right)}, \qquad L = L_0 + i\frac{XZ}{\left(1 + Y^2\right)} \quad \text{and} \tag{17}$$

$$S = S_0 + iXZ\frac{1 + Y^2}{\left(1 - Y^2\right)^2},$$

$$A = \left(1 - Y^2\right)^2 A_0 + iXZ \left\{ \begin{matrix} \left(1 - Y^2\right)^2 \sin^2 I \cos^2\theta + (1+Y)^2 \sin^2\theta \\ +(1+Y)^2 \cos^2\theta \cos^2 I \end{matrix} \right\} \tag{18}$$

$$= A_r + iA_s,$$

$$B = \left(1 - Y^2\right)^2 B_0 + iXZ \left\{ \begin{matrix} \left[\left(1 - Y^2\right)^2 S_0 + \left(1 + Y\right)^2 P_0\right] \left(1 + \cos^2\theta \sin^2 I\right) \\ + \left[(1 - Y)^2 R_0 + (1+Y)^2 L_0\right] \left(1 - \cos^2\theta \sin^2 I\right) \end{matrix} \right\} \tag{19}$$

$$= B_r + iB_s,$$

$$C = \left(1 - Y^2\right)^2 C_0 + iXZ \left[(1 - Y)^2 P_0 R_0 + (1+Y)^2 P_0 L_0 + \left(1 - Y^2\right)^2 R_0 L_0\right] \tag{20}$$

$$= C_r + iC_s$$

where, A_0, B_0, C_0, P_0, R_0, L_0 and S_0 correspond to the collisionless condition. The refractive index n^2 in eq. (16) becomes as follows:

$$n^2 = \frac{B_r + Q^{1/2}}{2A_r} + iXZ\frac{B_s A_r - A_s\left(Q^{1/2} + B_r\right)}{2A_r^2} = M_1 + iN_1 = (\alpha + i\beta)^2. \tag{21}$$

From this equation, the imaginary part (β) of the refractive index n can be obtained as follows:

$$\beta \approx \frac{ZX}{2\left(1 - Y^2\right)^2 A_0} \frac{\left[A_0 B_s - B_0 A_s - A_s\left(B_0^2 - 4A_0 C_0\right)^{1/2}\right]}{\left[A_0 B_0 + A_0\left(B_0^2 - 4A_0 C_0\right)^{1/2}\right]^{1/2}}. \tag{22}$$

This equation makes it possible to calculate the radio wave absorption in the ionosphere.

5. – Field strength measurements and calculations of the absorption L of HF waves

1) *Measurements:* The 5.47 MHz wave is transmitted from Erciş, Turkey (39.03°N, 43.37 °E) and it is received at Elazığ, Turkey (38.7 °N, 39.2°E). The horizontal distance between transmitter and receiver is 362 km (fig. 1). Transmitter is Marconi 100 Watt HF SSB military wireless. The field strength of the wave is measured by *ITU-Compliant HF Field Strength Monitoring Terminal* which is constructed by *HW Communications LTD, Lancaster-England.* Field strength monitoring terminal is set up at Physics Department of Fırat Univesity at Elazığ, Turkey, as shown in fig. 2. The field strength measurements of the 5.47 MHz wave are carried out for the days: 21 June 2003, 21 September 2003, 21 December 2003 and 21 March 2004.

TABLE I. – *The angle* (θ) *between propagation vector* ($\mathbf{k}$) *and* z*-axis at Erciş to receive the 5.47 MHz wave at Elazığ.*

LT	March	June	September	December
	θ	θ	θ	θ
1	29.00	31.90	29.90	–
2	28.10	30.75	29.00	–
3	27.00	30.45	27.80	–
4	25.90	31.40	27.43	–
5	27.10	35.00	31.30	–
6	32.90	38.20	38.35	30.90
7	38.60	39.00	44.75	34.58
8	42.99	38.40	46.30	39.90
9	44.43	36.10	45.40	42.08
10	45.24	34.03	45.10	41.60
11	42.93	34.00	42.50	38.32
12	41.14	35.10	39.06	35.02
13	40.00	35.30	36.30	34.70
14	38.34	34.60	36.75	35.30
15	38.95	35.60	36.00	36.75
16	37.20	36.86	38.50	38.70
17	40.00	37.00	41.00	39.55
18	40.30	38.50	40.30	37.85
19	37.45	38.40	37.60	34.60
20	34.45	35.45	35.00	30.00
21	32.13	34.25	32.85	–
22	30.73	33.80	32.00	–
23	30.00	33.80	30.90	–
24	29.47	33.00	30.10	–

2) *Calculations:* When the radio waves are propagated through the ionospheric plasma, they are absorbed because of the free-electron making collisions. The used plasma parameters in this study for calculation absorption loss L (in dB) have been obtained by using *International Reference Ionosphere* (IRI) for the days: 21 June 2003, 21 September 2003, 21 December 2003 and 21 March 2004. The 5.47 MHz wave is transmitted from Erciş, and received at Elazığ. Ray tracing procedure has been applied to 5.47 MHz wave propagation at oblique incidence. To receive at Elazığ, the angles θ between $\mathbf{k}$ and z-axis at Erciş are calculated, and diurnal and seasonal variations of the angles θ are given in table I. The 5.47 MHz wave travelling with angle θ in table I upwards from Erciş, the refractive index will become zero at some level at which the wave will be reflected. This height (h) is called reflection height. The reflection heights of the 5.47 MHz wave are calculated for March, June, September and December. During the calculation of the reflection heights, the refractive index is taken as 1 up to 120 km, and after 120 km, the refractive index of the ionosphere and the refractive angle of the wave are calculated for 10 km height interval. The diurnal and seasonal of variations of the reflection heights (h) are given in fig. 4. The reflection heights are lower during the day time than the night time values.

The radio wave absorption loss L for oblique propagation in a horizontally stratified ionosphere was calculated by using β (eq. (22)) in eq. (3), and then by numerical in-

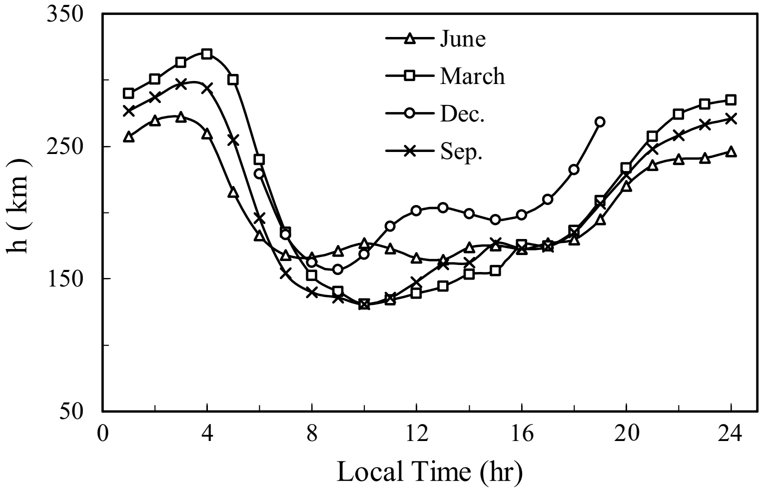

Fig. 4. – Diurnal and seasonal variations of the reflection heights (h) of 5.47 MHz wave which is transmitted from Erciş and received at Elazığ.

tegrating eq. (3) with 1 km height interval from the base of the ionosphere at Erciş to the reflection height, and then from the reflection height to the base of the ionosphere at Elazığ. The results of the measured field strengths and calculated absorption L in the ionosphere for 5.47 MHz wave are given in figs. 5-8. It is shown that the loss in the ionosphere is high during the day time and least during the night time. The measured field strength of the wave decreases during day time hours while it increases during night time hours. The comparisons between the calculated absorption L of the wave in the

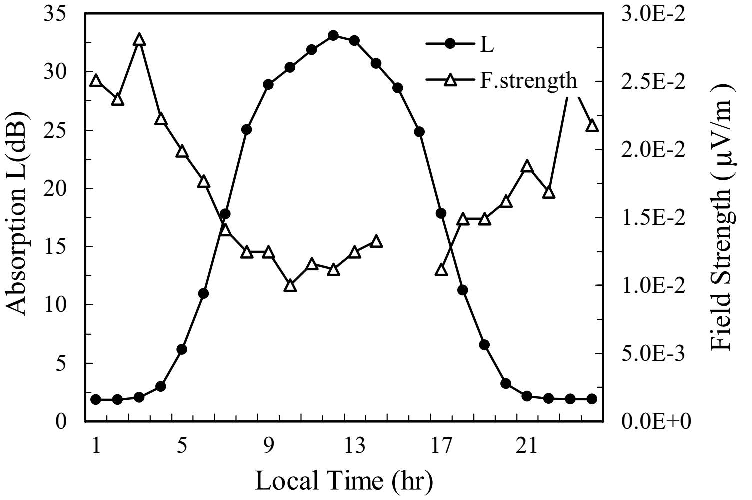

Fig. 5. – The calculated loss (L) and measured field strength of 5.47 MHz wave which is transmitted from Erciş and received at Elazığ for June 21, 2003.

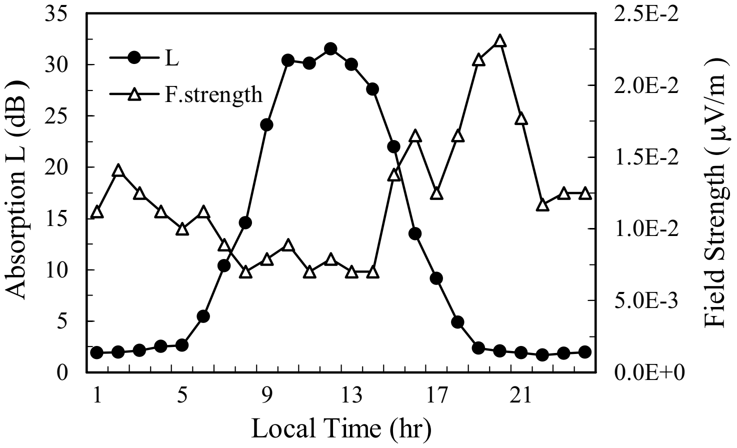

Fig. 6. – The calculated loss (L) and measured field strength of 5.47 MHz wave which is transmitted from Erciş and received at Elazığ for September 21, 2003.

ionosphere and measured field strengths (figs. 5-8) show that the agreement between the computed absorption L and the measured field strength is good at all seasons.

Since the imaginary part (β) of the refractive index is known, it is possible to calculate E_0' along the ray path. The values of E_0' in eq. (1) have been calculated for the path, and the results are given in fig. 9. As shown in figure, E_0' decreases during day time hours while it increases during night time hours at all seasons as the measured field strength. It is shown that theoretical calculations confirm the results of the field strength experiment. Hence, the behaviour of the diurnal and seasonal variations of the field strength of the wave can be explained with the diurnal and seasonal variations of the calculated absorption L in the ionosphere. Hence, the method presented in this paper to obtain the absorption L (eq. (3)) can be applied to the radio waves propagations in the ionosphere.

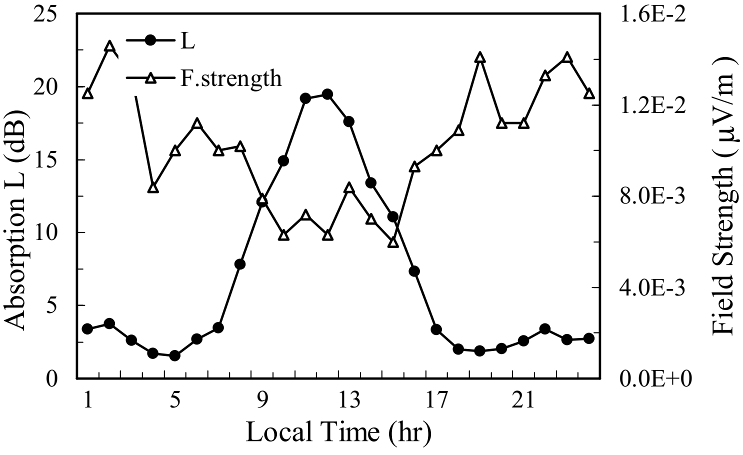

Fig. 7. – The calculated loss (L) and measured field strength of 5.47 wave which is transmitted from Erciş and received at Elazığ for December 21, 2003.

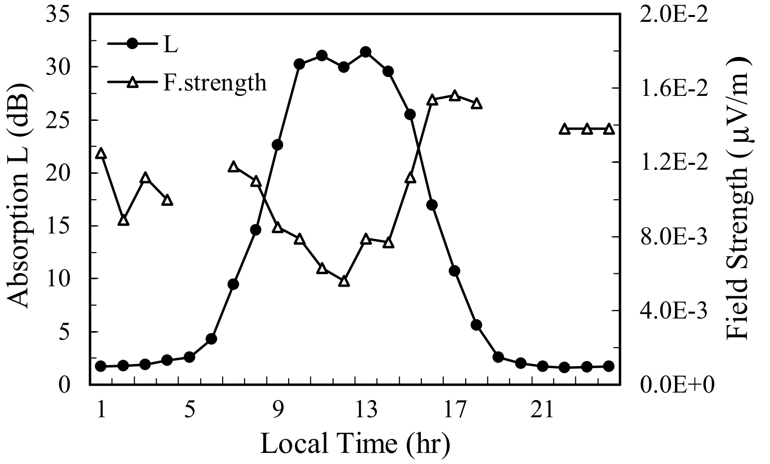

Fig. 8. – The calculated loss (L) and measured field strength of 5.47 MHz wave which is transmitted from Erciş and received at Elazığ for March 21, 2004.

6. – Conclusions

The 5.47 MHz wave which is transmitted from Erciş, Turkey (39.03°N, 43.37 °E) and it is received at Elazığ, Turkey (38.70°N, 39.20°E). The field strength of this wave is measured by *ITU-Compliant HF Field Strength Monitoring Terminal.* The field strength of the wave is decreases around noon time and it increases at night time for all seasons. The behaviour of the diurnal and seasonal variations of the field strength of the wave can be explained with the diurnal and seasonal variations of the calculated absorption L in the ionosphere. It can be concluded that eq. (22) in this paper which is the imaginary part (β) of the refractive index of the ionospheric plasma can be used for absorption L of the HF radio waves propagations in the ionosphere.

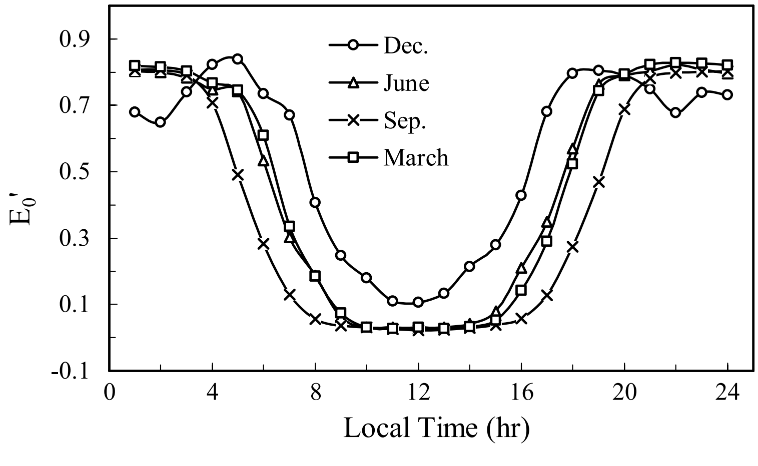

Fig. 9. – Diurnal and seasonal variations of E_0' ($= E_0 e^{-\frac{\omega}{c}\beta S}$ where $E_0 = 1$) in eq. (1), for 5.47 MHz wave.

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