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Influence of vegetable cover on propagation of electromagnetic waves with wavelength longer than 100 m

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[1] The influence of vegetable cover on propagation of electromagnetic waves in the Earth-ionosphere wave channel is studied in the scope of the model of a homogeneous isotropic "forest layer" with effective value of the dielectric permeability $\varepsilon_f = 1.2$ and electric conductivity $\sigma_f(t°\mathrm{C})$ depending on the environmental temperature according to the results obtained in this paper. It is shown that the character of the electromagnetic field behavior in the presence of large forests is of a well-pronounced seasonal character additionally complicated by the diurnal variations of the field depending on the environmental temperature variations. *INDEX TERMS:* 6964 Radio Science: Radio wave propagation; 6999 Radio Science: General or miscellaneous; 0498 Biogeosciences: General or miscellaneous; *KEYWORDS:* Electromagnetic wave propagation; Model of "forest-layer"; Influence of the temperature.

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Introduction

[2] Coniferous, deciduous and tropical forests cover more than 40% of the land on the Earth. About 70% of the steppe regions are covered by serials, fruit gardens, and cotton, coffee and tea plantations. Therefore development of models making it possible to estimate qualitatively and forecast quantitatively electromagnetic field parameters in the Earth–ionosphere waveguide at the presence of the vegetation cover is a quite important problem.

Discussion

[3] We consider the influence of the vegetation cover within a model of homogeneous isotropic "forest layer" with effective values of the electrical conductivity and dielectric permeability. In the case when the wavelength λ of the electromagnetic wave is much longer than the tree height h ($\lambda \gg h$), the influence of the latter on electromagnetic wave propagation may be neglected [*Reinolds*, 1953] in the model of vertical electrical antenna with a capacitive load. In this model the soil and tree branches form plates of a condenser, whereas the tree trunk is equivalent to a resistance put between the plates. In this case, at the impact on the tree of the vertical component of the monochromatic field E_{n1} (the dependence on time is accepted in the form $e^{-i\omega t}$), in the equivalent circuit of the tree with the effective height h_g, trunk resistance R_g, and capacity C_g under the condition $kh_g \ll 1$ a current I (distributed almost homogeneously) appears:

$$I = E_{n1}\frac{h_g}{Z_g} \qquad Z_g = R_g + \frac{i}{\omega C_g} \tag{1}$$

where Z_g is the effective complex resistance of the tree, $k = \omega/c$, ω is the circular frequency, and c is the speed of light in the vacuum.

[4] As a result of theoretical and experimental studies, *Egorov* [1990] showed that the predicted values of R_g and C_g may be calculated with the accuracy of 10% using the formulae

$$R_g = \frac{1}{\sigma_g(t°\mathrm{C})}\frac{h_g}{S_{\mathrm{tr}}} \qquad C_g = \frac{\varepsilon_0 S_{\mathrm{top}}}{h_{\mathrm{top}}} \qquad h_g = 0.8h \tag{2}$$

where $\sigma_g(t°\mathrm{C})$ is the specific electrical conductivity of the wood of the tree trunk depending on the temperature of the surrounding medium, S_{tr} is the average area of the tree trunk, S_{top} is the area of the lower part of its top, and h_{top} is the height of the lower part of the top from the surface.

[5] If one neglects the finite conductivity of the soil and takes the tree into account in the model of the vertical elec-

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trical antenna with the capacity load, then, taking into account (1), the reemitted by the tree vertical component of the electrical field on the ideally conducting plane is determined as

$$E_{n2} = \frac{i\omega\mu_0}{2\pi}\frac{E_{n1}h_g^2}{Z_g}\frac{e^{ikR}}{R}(1+\frac{i}{kR}-\frac{1}{k^2R^2}) \quad (3)$$

where $R=\sqrt{\rho_g^2+h_g^2}$, and ρ_g is the distance from the tree to the observation point.

[6] We consider the case when trees are distributed with some density ν on the ideally conducting plane. Then the total field at the observation point consists of the initial field E_{n1} that would have existed in the absence of the trees and the total field of the trees reemitting:

$$E_n = E_{n1} + \frac{i\omega\mu_0}{2\pi}\frac{h_g^2}{Z_g}\int\limits_{-\infty}^{+\infty}\int\limits_{-\infty}^{+\infty} E_n(x,y)\nu(x,y)\frac{e^{ikR}}{R}\times$$

$$(1+\frac{i}{kR}-\frac{1}{k^2R^2})dxdy \quad (4)$$

Feinberg [1999] showed that the field on the plane-underlying surface with finite values of electrical properties of the lower semispace may be presented in the form

$$E_n \approx E_{n1} + \frac{i\omega\delta}{2\pi}\int\limits_{-\infty}^{+\infty}\int\limits_{-\infty}^{+\infty} E_n(x,y)\frac{e^{ik\rho}}{\rho}dxdy \quad (5)$$

where E_{n1} is the field over the ideally conducting Earth surface, and δ is the reduced surface impedance of the underlying surface.

[7] In the case of neglecting by the influence of static (R^{-3}) and induction (R^{-2}) terms of the field reemitted by the trees (that is, taking into account only the wave (R^{-1}) terms of this field) we obtain, comparing (5) and (4)

$$\delta = \sqrt{\frac{\mu_0}{\varepsilon_0}\frac{h_g^2\nu}{Z_g}} \quad (6)$$

We estimate the ratio of the total field reemitted by all trees and due only to the wave terms of the field to the quasi-static field reemitted by one tree located in the close vicinity of the observation point ($\rho_g^2 \ll h_g^2$).

[8] The normal component of the electrical field in the case when the emitter and the observation point are located on an impedance plane has the form [*Feinberg*, 1999]

$$E_n = \frac{i\omega\mu_0}{2\pi}I_a h_a\frac{e^{ikr}}{r}W(sr) = E_{n1}W(sr) \quad (7)$$

where I_a and h_a are the current in the base of the emitting antenna and its virtual height, respectively, r is the distance from the emission source to the measurement point, $W(sr)$ is the attenuation function, $s = ik\delta^2/2$, and δ is the surface impedance (6).

[9] Equalizing the right-hand sides of formulae (7) and (5), we obtain the following expression for the total field reemitted by the trees due only to the wave terms of the reemitted field (R^{-1}):

$$\sum E_{n2}(R^{-1}) = E_{n1}[W(sr)-1] \quad (8)$$

The normal component of the electrical field reemitted by one tree in the direct vicinity of it may be found in the quasi-static approximation (R^{-3}) from formula (3) under condition $\rho_g^2 \ll h_g^2$, i.e., $kR = kh_g \ll 1$

$$E_{n2}(R^{-3}) = \frac{1}{i\omega\varepsilon_0}\frac{E_{n1}}{2\pi h_g Z_g} \quad (9)$$

Taking into account the designation

$$\varepsilon'_f = \frac{E_{n1}}{E_{n1}+E_{n2}(R^{-3})}$$

we obtain from formulae (8) and (9) the sought for ratio of the total field reemitted by all trees due only to the wave terms of the field to the quasi-static field reemitted by one tree

$$\Delta E_n = \frac{\sum E_{n2}(R^{-1})}{E_{n2}(R^{-3})} = \frac{i\varepsilon'_f}{\varepsilon'_f-1}[W(sr)-1]$$

Here

$$|\Delta E_n| = \left|\frac{\varepsilon'_f}{\varepsilon'_f-1}\right| \qquad |sr| \gg 1$$

$$|\Delta E_n| = \left|\sqrt{\pi sr}\frac{\varepsilon'_f}{\varepsilon'_f-1}\right| \qquad |sr| \ll 1$$

To estimate $|\Delta E_n|$ we use the results of experiments [*Egorov,* 1990]. It follows from the latter that at a frequency of 250 kHz the value $|\varepsilon'_f/(\varepsilon'_f-1)| = 2.3$ at $\rho_g \le h_g/4$. Therefore, even in the most unfavorable case $|sr| \gg 1$, the secondary field reemitted by a tree located at a distance equal to or smaller than $h_g/4$ (i.e., in the direct vicinity of the observation point) is comparable by the modulus to the total secondary field reemitted by all trees due to only the wave terms.

[10] In the quasi-static vicinity of the observation point within a large forest, there are (depending on the wavelength) hundreds (MW), thousands (LW), and even tens of thousands (ELW) of trees. So it is evident that to estimate the secondary field reemitted by the trees, one has in the first turn to take into account the influence of the trees located in the quasi-static zone.

[11] According to the aforesaid we formulate the problem on determination of the vegetation cover on propagation of electromagnetic waves in the following way: on the ideally conducting plane similar trees with the virtual height h_g and effective complex resistance Z_g are distributed homogeneously. One needs to determine in the quasi-static approximation the total field reemitted by the trees. In this case, using formula (3), the total quasi-static field reemitted by the trees may be written in the form

$$\sum E_{n2}(R^{-3}) = \frac{\sum_{j=1}^{\infty} E_{n1}(R_j)(1+\rho_{gj}^2/h_g^2)^{-3/2}}{i\omega\varepsilon_0 2\pi h_g Z_g} \quad (10)$$

where $E_{n1}(R_j)$ is the normal component of the falling electrical field from all the trees in the point of location of the jth tree, R_j is the distance from the emitter to the jth tree, and ρ_{gj} is the distance from the jth tree to the observation point.

[12] It follows from (3) that for all $k\rho_{gj} \geq 1$, i.e., for all the trees outside the radius $\rho_{gj} \geq (\lambda/2\pi)$, the input of the quasi-static terms of reemission by the modulus is less than or equal to the input of the wave terms of the reemission. In the previous considerations we have already neglected the input of the wave terms of the field reemitted by the trees. Therefore we may also neglect the influence of the quasi-static terms of the reemitted field due to the trees located outside the $\lambda/2\pi$ radius. Taking into account the aforesaid, formula (10) may be transformed into the form of a finite sum

$$\sum E_{n2} = \frac{E_{n1}}{i\omega\varepsilon_0 2\pi h_g Z_g} \sum_{j=1}^{m} (1 + \rho_{gj}^2/h_g^2)^{-3/2} \qquad (11)$$

where m is the number of trees located inside the circle with a radius of $\lambda/2\pi$. Formula (11) takes into account that the falling field E_{n1} within the $\lambda/2\pi$ circle stays almost constant.

[13] The total field reemitted by the trees (11) in principle may depend on the location of the observation point within the large forest. We estimate the total reemitted field in two extreme cases, that is, when the observation point is located or directly near a particular tree, or in the middle between four trees.

[14] Estimating the reemitted field in the direct vicinity of a tree, one should take into account the influence of this tree determined by formula (11) in the case of fulfilling the condition $\rho_g/h_g \to 0$ $(m = 1)$. In this case, 8 the nearest trees are located at sides and angles of a rectangle with the side length of $2d$ (d is the distance between trees), that is, on the average located at a distance equal to the semisum of radiuses of the circles inscribed into the rectangle and described around it. The following 16 trees are located at sides and in angles of a rectangle with the side length of $4d$, etc.

$$\sum E_{n2} = \frac{E_{n1}}{i\omega\varepsilon_0 2\pi h_g Z_g} [1 + P_1] \qquad (12)$$

$$P_1 = \sum_{n=1}^{N} \frac{8n}{[1 + ((1+\sqrt{2})n\alpha/2)^2]^{3/2}}$$

$$\alpha = \frac{d}{h_g} \qquad N = \frac{\lambda}{d}\frac{1+\sqrt{2}}{\pi}$$

In the $m\alpha \gg 1$ case,

$$P_1 = \sum_{n=1}^{m} \frac{8n}{[1 + ((1+\sqrt{2})n\alpha/2)^2]^{3/2}} +$$

$$(\frac{4}{1+\sqrt{2}}\frac{1}{\alpha})^3 \sum_{n=m+1}^{N} \frac{1}{n^2}$$

Table 1. Calculation of the Values of A_1+Q_1 and A_2+Q_2 as a Function of the α Parameter Characterizing the Thickness of Large Forests[a]

	α		
	1.0	0.5	0.25
$A_1 + Q_1$	5.7	22.3	89.0
$A_2 + Q_2$	5.9	22.4	90.0

[a] Here, $\alpha = 1$, $\alpha = 0.5$, and $\alpha = 0.25$ correspond to thin, moderate, and thick forests.

That is, series (12) is converging rapidly as a series for the Riemann ξ function $\xi(2)$. Taking into account that

$$\xi(2) = \sum_{n=1}^{\infty} n^{-2} = \frac{\pi}{6}$$

we obtain

$$\sum E_{n2} = \frac{E_{n1}}{i\omega\varepsilon_0 2\pi h_g Z_g} [A_1 + Q_1] \qquad (13)$$

where

$$A_1 = 1 + \sum_{n=1}^{m} \frac{8n}{[1 + ((1+\sqrt{2})n\alpha/2)^2]^{3/2}}$$

and

$$Q_1 \leq (\frac{1}{1+\sqrt{2}}\frac{1}{\alpha})^3 \left[\frac{\pi}{6} - \sum_{n=1}^{m} \frac{1}{n^2}\right]$$

Q_1 characterizing the estimate of an error of the series (13) calculation.

[15] On the analogy to the previous example, the total field of reemission in the point equidistant from the nearest four trees has the form

$$\sum E_{n2} = \frac{E_{n1}}{i\omega\varepsilon_0 2\pi h_g Z_g} [A_2 + Q_2] \qquad (14)$$

$$A_2 = \sum_{n=1}^{m} \frac{4(2n-1)}{[1 + ((1+\sqrt{2})(2n-1)\alpha/4)^2]^{3/2}}$$

$$Q_2 \leq (\frac{8}{1+\sqrt{2}}\frac{1}{\alpha})^3 \left[\frac{\pi^2}{8} - \sum_{n=1}^{m} \frac{1}{(2n-1)^2}\right]$$

where Q_2 characterizes the estimate of calculation of series (14).

[16] Table 1 shows the results of calculation of the values of A_1+Q_1 and A_2+Q_2 as a function of the α parameter characterizing the thickness of large forests: $\alpha = 1$, $\alpha = 0.5$, and $\alpha = 0.25$ correspond to thin, moderate, and thick forests. It follows from the table that the total reemitted field under the given thickness of the forest almost does not depend on the

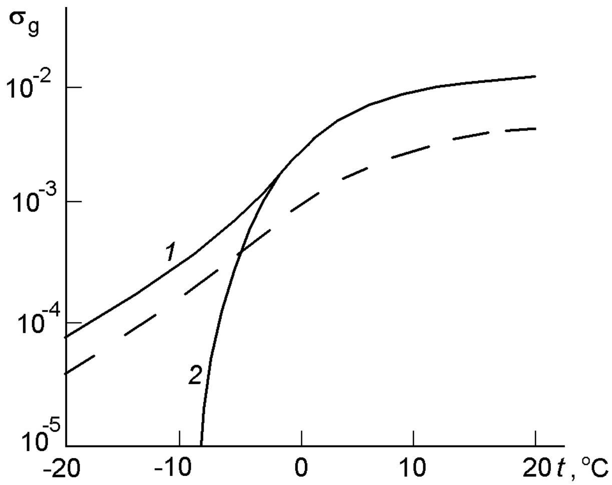

Figure 1. Variations in the specific electric conductivity of tree trunks $\sigma_g(t°\mathrm{C})$ at direct current as a function of the environmental temperature for deciduous (solid curve 1) and coniferous (solid curve 2) tree species typical of central Europe [*Kashprovsky and Kuzubov*, 1971] and for coniferous species (dashed curve) typical of the southern part of western Siberia [*Zakharenko*, 1991].

location of the observation point between the trees, that is, it is a constant value in the quasi-static vicinity $\rho_g \leq \lambda/2\pi$ relative to the observation point. Taking this into account, it follows from (11) that the ratio of the normal component of the falling electrical field E_{n1} to the normal component of the total electrical field within the large forest $E_{n1} + \sum E_{n2}$ is a constant value which according to the boundary conditions for the normal components of the electric field at the boundary between similar media characterizes the relative complex dielectric permeability of the large forest ε'_f in the model of a homogeneous isotropic "forest layer"

$$\varepsilon'_f = \frac{E_{n1}}{E_{n1} + \Sigma E_{n2}} = \varepsilon_f + i\frac{\sigma_f}{\omega\varepsilon_0} \tag{15}$$

It follows from Table 1 that to calculate the total reemitted field within the large forest, one can use the approximate formula correct for any thickness of the forest within the interval:

$$\sum E_{n2} = \frac{E_{n1}}{i\omega\varepsilon_0 h_g Z_g \alpha^2}$$

The formula makes it possible to calculate the total reemitted field with an error less than 5% by the modulus. Taking into account formula (2) we have

$$h_g Z_g \alpha^2 = \frac{1}{\sigma_g(t°\mathrm{C})}\frac{d^2}{S_{\mathrm{tr}}} + i\frac{d^2 h_{\mathrm{top}}}{\omega\varepsilon_0 S_{\mathrm{top}} h_g} \tag{16}$$

[17] In a large forest, the height of the top of all trees h_{top} is much larger than that of a single staying tree and tends to the value of h_g , i.e., $h_{\mathrm{top}} \leq h_g$. At the same time, the treetop in the forest almost covers the entire area d^2 covered by this tree, i.e., $d^2 \geq S_{\mathrm{top}}$. So one can take that the parameter $d^2 h_{\mathrm{top}}/S_{\mathrm{top}} h_g = 1$. Substituting expression (16) into formula (15), we finally obtain

$$\varepsilon'_f = 1 + i\frac{\sigma_f(t°\mathrm{C})}{\omega\varepsilon_0} = 1 + i\frac{\sigma_g(t°\mathrm{C})}{\omega\varepsilon_0}\frac{S_{\mathrm{tr}}}{d^2} \tag{17}$$

Similar consideration may be performed concerning the total reemitted field of the tangential components of the magnetic field of the trees. Because of the circular symmetry of the problem, the tangential components of the magnetic field of the trees are mutually compensated and the total reemitted magnetic field within the large forest is absent.

[18] Thus in the case $\lambda \gg h$, the influence of large forests on propagation of electromagnetic waves (independently of the height of the forest and its thickness) may be taken into account in the model of homogeneous isotropic "forest layer" with the effective dielectric and magnetic permeability equal to the dielectric and magnetic permeability in vacuum, respectively. The effective electric conductivity is determined by the formula

$$\sigma_f(t°\mathrm{C}) = \sigma_g(t°\mathrm{C})\frac{S_{\mathrm{tr}}}{d^2} \tag{18}$$

The dimensionless parameter S_{tr}/d^2 characterizing the ratio of the area covered by the tree trunks to the entire area of the large forest may be determined using topographic maps of the scale 1 : 100,000 and larger, where the mean diameters of tree trunks and distances between them are indicated.

[19] Figure 1 shows the values of the specific electric conductivity of trunks of deciduous (solid curve 1) and coniferous (solid curve 2) species of trees under direct current as a function of the temperature (for central Europe) according to *Kashprovsky and Kuzubov* [1971]. The values of $\sigma_g(t°\mathrm{C})$ for deciduous and coniferous trees coincide with each other in the temperature interval from +20°C to −5°C and vary from 1.1×10^{-2} to 10^{-3} S m^{-1}. For other temperatures the curves diverge strongly. Figure 1 shows also the values of $\sigma_g(t°\mathrm{C})$ for the coniferous species of trees for the southern part of western Siberia (dashed curve) [*Zakharenko*, 1991].

[20] One can see from Figure 1 that the specific electric conductivity of trunks $\sigma_g(t°\mathrm{C})$ of deciduous species of trees in central Europe almost repeats the specific electric conductivity of trunks of coniferous species of trees in the southern part of western Siberia within the entire range of the environmental temperatures from −20°C to +20°C with the a standard deviation by a factor of 2.7.

[21] In principle, one can use the above presented values of $\sigma_g(t°\mathrm{C})$ at direct current in the hypothesis of the absence of frequency dispersion. However, still stay unclear both the representativeness of the $\sigma_g(t°\mathrm{C})$ values at particular trees for different large forests covering 40% of the Earth's land and the reliability of the hypothesis of frequency dispersion absence.

[22] To solve the above indicated problems, we developed a method of measurements of effective electric properties of a "forest layer" directly at the frequencies of the emitted electromagnetic field.

[23] It is known that at falling of a plain vertically polarized wave within a "forest layer" having the effective complex dielectric permeability ε'_f and located on the Earth's

surface with the relative complex dielectric permeability ε'_g, the following relation is true:

$$\frac{H_{\tau f}}{E_{nf}} = \varepsilon'_f \frac{H_{\tau a}}{E_{na}} \qquad (19)$$

where $H_{\tau a}$ is the tangential component of the falling magnetic field at the air-forest boundary in the air, E_{na} is the normal component of the falling electric field at the air-forest boundary in the air, $H_{\tau f}$ is the tangential component of the magnetic field within the "forest layer" at any height $h \leq z \leq 0$, and E_{nf} is the normal component of the falling electric field within the "forest layer" at any height $h \leq z \leq 0$. Formula (19) is correct for any falling angles of a plain vertically polarized wave.

[24] The electromagnetic field from the vertical electrical antenna may be presented as a superposition of plain waves, so one can state that formula (19) is correct for the fields of radio stations at such distances from the source that one can neglect induction-statistical terms of emission and direct penetration of electromagnetic waves through the "forest layer" and underlying Earth's surface, that is, by all mechanisms of underground propagation in the soil and within the large forest.

[25] As a result, we obtain that to determine ε'_f, it is enough to measure the admittances of the electromagnetic field from radio stations within the "forest layer" and in the air over the forest. Because of technical difficulties of measuring admittance over the forest, in the first approximation one can determine ε'_f using measurements of the admittance at some distance from the forest in the field and in the forest along the front of the electromagnetic wave from the radio station at distances $r \leq \lambda$, where λ is the wavelength of the emitted wave.

[26] We determined admittance using a two-channel selective microvoltmeter, which makes it possible to measure the ratio of amplitudes and phase shift of two signals in the MW range channels. A rotating magnetic antenna was connected to one of the channel for tuning to the maximum of the magnetic field. A vertical electric antenna was connected to the other channel. The measurements were conducted in three stages. First, the measuring device was installed in a field at a distance larger than $10\,h_g$ from the forest edge and the measurements of the value of $\gamma_a = (h_m/h_{el})(H_{\tau a}/E_{na})$ were carried out. Then the measuring device was installed in the forest at a distance larger than $10\ h_g$ from the forest edge and the value of $\gamma_f = (h_m/h_{e1})(H_{\tau f}/E_{nf})$ was measured. After than the device was returned to the field at the same point in order to be sure that the amplitude-phase characteristics of the device channels did not change during the experiment. The ratio of γ_f to γ_a makes it possible to exclude unknown values of the virtual heights of the electric h_{el} and magnetic h_m antennae, i.e., to determine the soaked for value of the effective complex dielectric permeability of the "forest layer" ε'_f.

[27] On the basis of numerous measurements of admittances at frequencies of 250 kHz and 550 kHz in the summer, fall, and winter conditions in the neighborhood of St. Petersburg in coniferous (pine) and deciduous (birch) forests, we found that the effective dielectric permeability of the "forest layer" $\varepsilon_f = 1.20 \pm 0.05$ independently of the tree species and

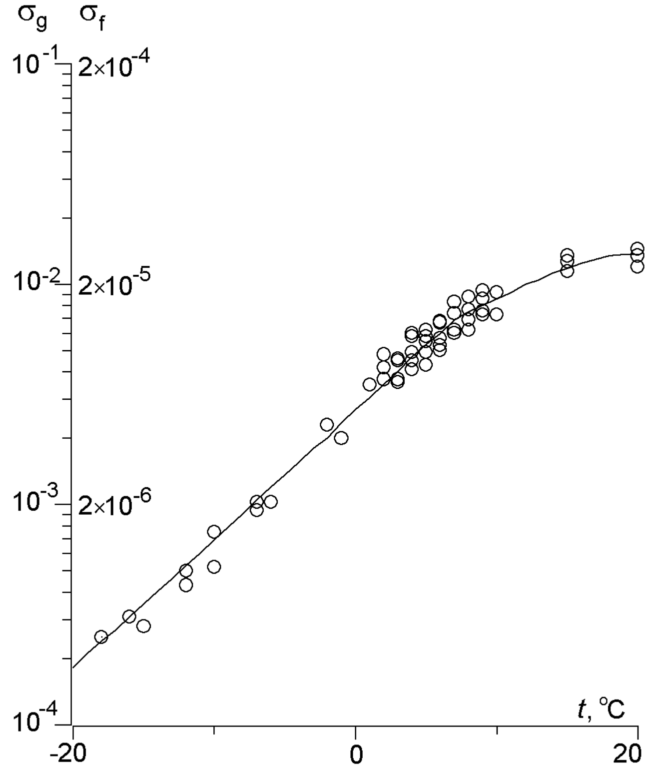

Figure 2. Effective electric conductivity of large forests $\sigma_f(t°\text{C})$ in the model of homogeneous isotropic "forest layer" at middle waves versus the environmental temperature [*Egorov*, 2003].

the temperature of the environment within the entire range from $-20°$C to $+20°$C. The effective electric conductivity of the "forest layer" $\sigma_f(t°\text{C})$ also does not depend on the tree species and varies from 2.5×10^{-5} S m^{-1} (+20°C) to 1.8×10^{-7} S m^{-1} (−20°C). The character of the $\sigma_f(t°\text{C})$ behavior as a function of the air temperature is shown in Figure 2 [*Egorov*, 2003].

[28] Thus we succeeded in obtaining the effective values of the complex dielectric permeability of the "forest layer" as a function of the environmental temperature directly at the electromagnetic field frequencies without any knowledge on the specific electric conductivity of tree trunks $\sigma_g(t°\text{C})$ and on the values of the dimensionless parameter S_{tr}/d^2. It should be noted that the values of the effective dielectric permeability of the "forest layer" are obtained for rather local areas of large forests with the length of a few tens of meters from the forest edge.

[29] In order to estimate the representativeness of the obtained data for vast large forests in the Leningrad Region, we conducted measurements of the modulus $|W|$ and additional phase φ_{add} of the attenuation function at a frequency of 350 kHz along a forest path 100 km long. The results of the measurements are shown in the bottom line of Table 2 [*Egorov*, 2000].

[30] The propagation path may be characterized as a two-layer structure. The large forest with a height of 15 m and effective electric properties ($\varepsilon_f = 1.2$, $\sigma_f = 2.5 \times 10^{-5}$ S m^{-1}

Table 2. Calculated Values of the Modulus and Phase of the Surface Impedance of the Two-Layer Structure and Predicted Values of the Attenuation Function as Well as Results of Measurements of the Modulus $|W|$ and Additional Phase of $\varphi_{\rm add}$ the Attenuation Function at a Frequency of 350 kHz Along a Forest Path 100 km Long

	Summer (+15°C)				Winter (−5°C)			
	$\lvert\delta\rvert$	$\arg\delta$	$\lvert W\rvert$	$\varphi_{\rm add}$	$\lvert\delta\rvert$	$\arg\delta$	$\lvert W\rvert$	$\varphi_{\rm add}$
Calculations	0.11	−52	0.26	2.54	0.076	−46	0.44	1.90
Experiment			0.28	2.41			0.41	1.95

in summer (+15°C) and $\varepsilon_f = 1.2$, $\sigma_f = 2.5 \times 10^{-6}$ S m^{-1} in winter (−5°C), Figure 2) is located on the Earth's surface which within the skin effect is presented by well-studied soils and quaternary sediments and is characterized by the values $\varepsilon_g = 20$, $\sigma_g = 2.5 \times 10^{-2}$ S m^{-1}. The top line of Table 2 shows the calculated values of the modulus and phase of the surface impedance of the two-layer structure and predicted values of the attenuation function.

[31] It follows from Table 2 that the predicted and experimentally measured values of $|W|$ differ by 10% and values of $\varphi_{\rm add}$ differ by 0.1 rad, both values being within the accuracy limits of the model and experiment.

[32] Points in Figure 3 show the experimental values of the attenuation function $|W|$ as a function of the environmental temperature for the frequency of 272 kHz along the path about 200 km long [*Korzhinskaya et al.*, 1991].

[33] The propagation path may be presented in the form of a two-layer structure: the large forest with a height of 15 m with the effective electric properties determined by Figure 2 is located on the Earth's surface which within the skin effect layer is characterized by the values $\varepsilon_g = 20$, $\sigma_g = 1.4 \times 10^{-2}$ S m^{-1}. The predicted values of the modulus of the attenuation function $|W|$ for the above indicated two-layer structure are shown in Figure 3 by the solid curve.

[34] A good agreement of the experiment and theory within the entire range of environmental temperature variations from −20°C to +20°C makes it possible to state that local measurements of the effective electric properties of the "forest layer" conducted in the neighborhood of St. Petersburg are representative for large forest with different area and composition located within the Freznel zones (important for electromagnetic wave propagation) both in the northwest part of the European part of Russia and in the southern part of western Siberia.

[35] In conclusion, we consider one more feature of electromagnetic wave propagation along forest paths. At electromagnetic wave propagation along forest paths we, evidently, have the case, when the modulus of the effective complex dielectric permeability of the "forest layer" is much less than the modulus of the dielectric permeability of the Earth's underlying surface ($|\varepsilon_f'| \ll |\varepsilon_g'|$). Therefore large forests may be physically presented as a thin badly conducting layer located on the well-conducting base. This leads to a decrease of the argument of the impedance of the two-layer path as compared to the impedance of the base, i.e., to a shift into strongly inductive region ($\arg\delta_l < -\pi/4$). *Makarov et al.* [1991] showed that, as a result, the modulus of the attenuation function at some distances from the emitter becomes higher than unity. That means that because of the influence of the Zennek surface wave, the field over forest paths at some distances will be higher by the modulus than the field over an infinite conducting plane.

[36] Figure 4 shows results of the calculations of δ_l for various heights of forest as a function of the frequency for summer conditions. It follows from Figure 4 that for all

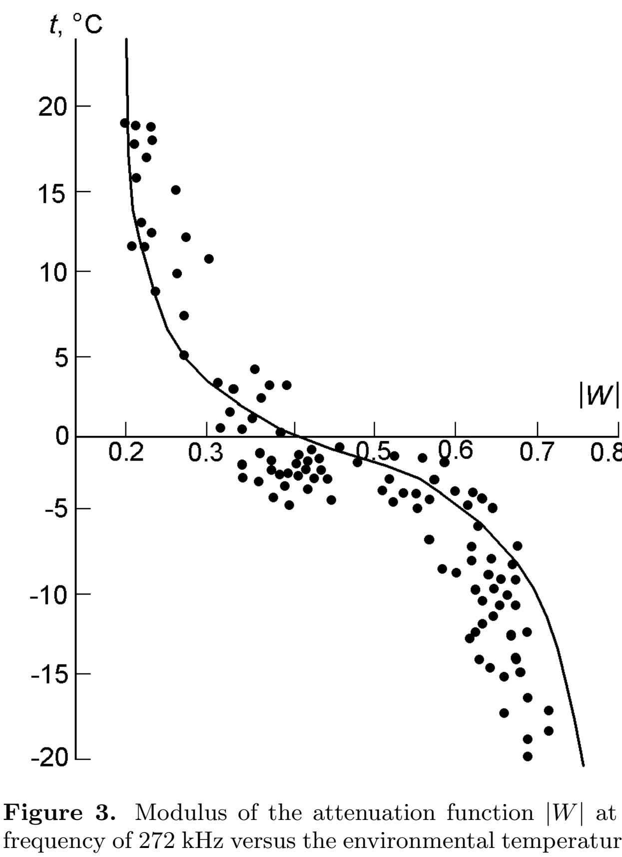

Figure 3. Modulus of the attenuation function $|W|$ at a frequency of 272 kHz versus the environmental temperature: experimental data [*Korzhinskaya et al.*, 1991] (solid circles) and theoretical calculations [*Egorov*, 2000] (solid curve). A good agreement is seen between the developed theory and the experiment.

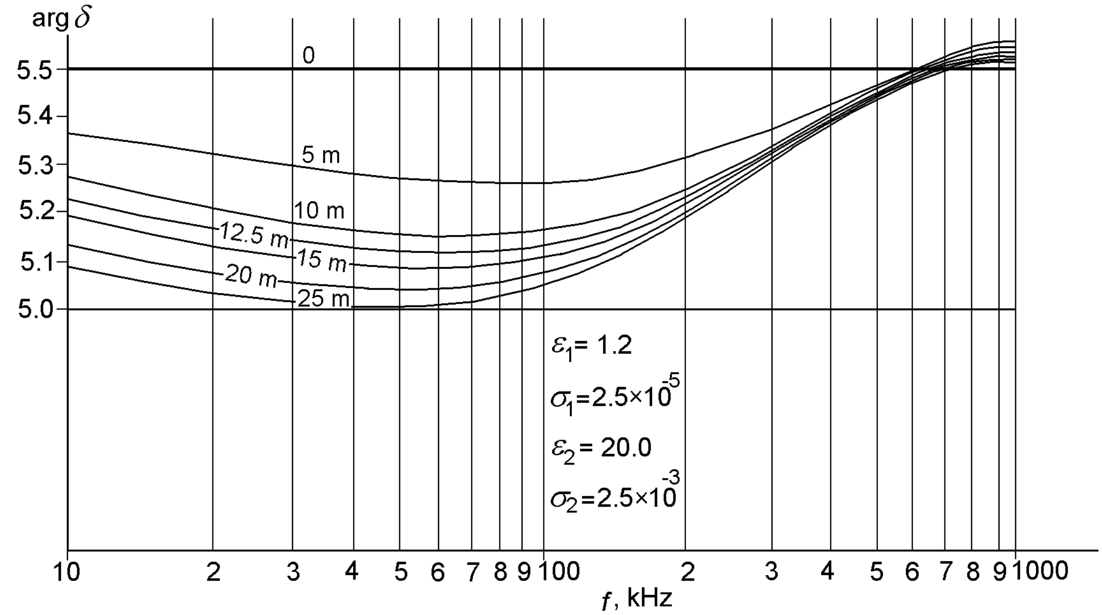

Figure 4. Argument of the surface impedance arg δ (radians) versus the electromagnetic field frequency for the two-layer structure typical of large forests in the northwest part of the European part of Russia; indices by the curves show the forest height.

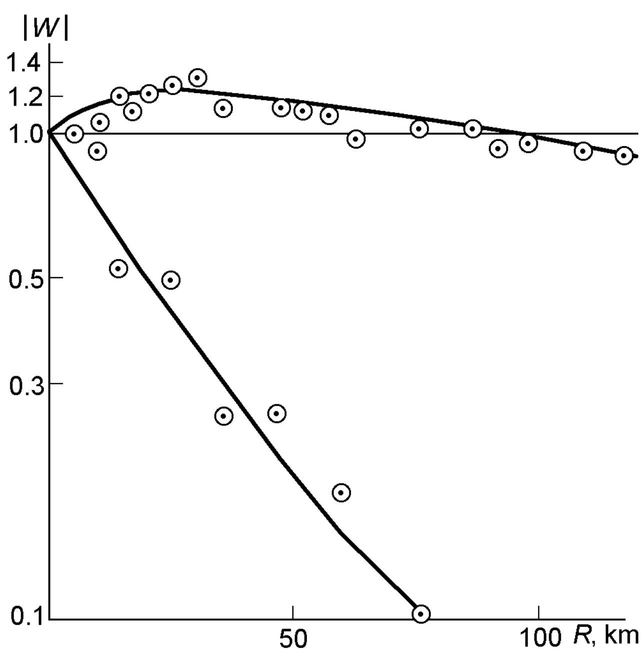

Figure 5. Modulus of the attenuation function $|W|$ versus the distance to the observation point along a forest path: experimental data (circles) and calculations (solid curves) [*Egorov*, 2002]. The experimental data and theoretical calculations (top curve) at a frequency of 236 kHz confirm the influence of the Zennek surface wave $|W| > 1$ at distances up to 100 km. At a frequency of 800 kHz (bottom curve), because of the shift of the surface impedance into the weak induction region, the effect of the Zennek surface wave disappears.

frequencies $f < 600$ kHz, arg $\delta_l < -\pi/4$ (a strongly inductive surface), whereas in the frequency range 600–1000 kHz, arg $\delta_l > -\pi/4$ (a weakly inductive surface).

[37] Figure 5 shows the results of calculations of the attenuation function modulus $|W|$ for the large forests with a height of 12.5 m (solid curves) and of experimental measurements of $|W|$ (circles) at the same path in summer at the air temperature of $+15°$C [*Egorov*, 2002]. It follows from Figure 5 that (in a complete agreement with the developed theory) at the frequency $f = 236$ kHz, because of the influence of the Zennek surface wave, the attenuation function modulus $|W| > 1$ at distances up to 100 km from the emitter, whereas at $f = 800$ kHz, because of the shift of the argument of the surface impedance arg δ_l into weakly inductive region, the effect disappears.

Conclusion

[38] 1. The influence of the vegetable cover on propagation of electromagnetic waves in the Earth–ionosphere wave channel may be taken into account in the model of a homogeneous isotropic “forest layer” with the effective value of the dielectric permeability $\varepsilon_f = 1.2$ and electric conductivity $\sigma_f(t°\text{C})$ depending on the environmental temperature according to the curve shown in Figure 2.

[39] 2. The character of the electromagnetic field behavior at the presence of large forests is of a well-pronounced seasonal character additionally complicated by the diurnal variations of the field depending on the environmental temperature variations.

[40] 3. The modulus of the attenuation function of forest paths at some distances from the emitter is higher than unity because of the influence of the Zennek surface wave.

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