

Crown's anisotropy of a tree and scattering the signals of navigation satellites frequency band L1

Vladimir Podoprigora^{1,3,*}, Anotoly Sorokin^{2,3}, Daniil Makarov² and Dmitry Kharlamov²

¹Institute of Physics. A.V. Kirensky, SB RAS, Akademgorodok, 50, 660036, Krasnoyarsk, Russia

²Federal Research Center "KSC SB RAS", Akademgorodok, 50, 660036, Krasnoyarsk, Russia

³Siberian Federal University, Avenue Svobodny, 79, 660041, Krasnoyarsk, Russia

Abstract. The model of interaction of signals from navigation satellites with the tree crown is considered. The contribution of the anisotropy of the dielectric constant to the cross section of radio wave scattering due to the orientational ordering of the branches is shown. The calculation of the scattering cross sections for small and large elements is presented. The tensor of orientational ordering of tree branches with division into tiers differing in the size and orientation of elements is introduced. Test measurements of navigation satellite signals passed through the crowns of spruce trees were carried out.

1 Introduction.

The study of the propagation of pulsed signals of navigation satellites (NS) in the forest is aimed at expanding the understanding of the nature of the interaction of polarized coherent electromagnetic waves (EMW) radiation in the frequency range 1-2 GHz with different-scale elements of trees and the stand as a whole. The complexity of using different models of the interaction of electromagnetic waves with the canopy is due to the dependence of the results on a large number of input parameters, including a noticeable dependence of the dielectric constant of wood on moisture and a variety of sizes and shapes of elements of the forest environment. The ratios of the wavelength of NS signals with the sizes of the diverse structural elements of the forest range from much smaller units for leaves and needles, comparable to unity for the diameters of trunks and branches, and many large units for unevenly distributed groups of trees. This leads to many interaction mechanisms and approximations partially presented in reviews [1-3]. The trunk layer has an almost ideal orientational ordering relative to the vertical. The crown layer, formed by branches of different diameters and lengths, leaves and needles, is partially ordered in space, has a biomass density and degree of ordering that varies with height. Therefore, the development of a refractive model of the stand involves taking into account the distribution of bulk density of biomass and the orientational ordering of trunks and branches of crowns.

* Corresponding author: podoprigora46@gmail.com

2 Spatial orderliness the elements of trees stand

The diversity of spatial orientation of tree branches is obvious. There is a noticeable species difference in the orientational ordering of the crowns of individual trees. The crown layer as an ensemble of volumetric structures from tree branches has several tiers with a noticeable ($\approx 10^\circ$) difference in angles between the trunk and branches. Figure 1 shows typical crowns of birch and larch. The description of orientational ordering is presented in sufficient detail in the physics of molecular systems.



Fig. 1. Typical crowns of birch and larch.

In the theory of liquid crystals and polymers, the orientational ordering of molecules is described in the general case by a tensor [4-5]. The elements of the orientational ordering tensor S_{ij} of the tree have the form:

$$S_{ik} = \frac{1}{N-1} \sum^{N-1} \frac{1}{2} (2e_{\alpha}^i e_{\beta}^k - \delta_{ik}), \quad (1)$$

where N is the number of branches, e_{α}^i and e_{β}^k - components of the unit vector along the directions of the α -th and β -th branches, δ_{ik} is the Kronecker symbol.

Three eigenvalues of the tensor S are orientational ordering parameters, and the maximum eigenvalue corresponds to the order parameter S , which is standardly defined in the theory of liquid crystals and polymers as the average value of the second Legendre polynomial in angles θ between the direction vectors of the selected direction (vertical) of the trunks and branches.





In the crowns of different types of trees, the orientational orderings of branches by tiers differ markedly. Table 1 shows the different types of tiers and the corresponding types of tensors of orientational ordering of branches. Tiers are counted from the top of the tree to the soil.

The data on the type of tensor allow us to take into account the contribution of crowns to the vertical dependence of the real part of the anisotropy of the effective dielectric constant of the stand, which has values in the range $0 < \Delta\varepsilon' < \Delta\varepsilon' < (\varepsilon'_l - \varepsilon'_c)$. The indices L and C denote the longitudinal (Long, along the trunk) and transverse (Cross) dielectric constant of wood.

Model calculations of the real part of the effective dielectric constant of crowns are carried out taking into account the volume of wood in crowns and the eigenvalues of the tensor S_{ij} , orientational order parameter. There are experimental data on the dielectric constant of wood with a humidity of 40% at a temperature of 20°C at frequencies of 0.915 and 2.375 GHz [6]. Field measurements of the orientation of the main branches were carried out according to photographs during the year of trees of various species from 20 to 60 years

old from a distance of 30-70 meters. Data were obtained on the orientational structures of birch and larch without foliage and needles, respectively. The orientation parameter of the order of the main branches of the crowns S decreases from the top to the lower border in the following intervals: birch 0.8 - 0, larch from 0.5 to - 0.4. The order parameters of the branches of all types of trees refers to the main branches. The interval S with positive values only has a birch.

Table 1. Types of crown levels and type of tensor S_{ij} .

Type of tier, angle	$\langle s \rangle$	Type of tier, angle	$\langle s \rangle$
I, $\theta = 30^\circ$ 	$\frac{1}{8} \begin{pmatrix} 1 & & \\ & 2 & \\ & & 5 \end{pmatrix}$	II, $\theta = 60^\circ$ 	$\frac{1}{8} \begin{pmatrix} 2 & & \\ & 2 & \\ & & -1 \end{pmatrix}$
I, $\theta = 90^\circ$ 	$\frac{1}{8} \begin{pmatrix} 2 & & \\ & 2 & \\ & & -4 \end{pmatrix}$	IV, $\theta = 120^\circ$ 	$\frac{1}{8} \begin{pmatrix} 2 & & \\ & 2 & \\ & & -1 \end{pmatrix}$

Estimates of the numerical values of $\Delta\varepsilon'$ for the layers of the three upper tiers of the crowns of the test stands of birch and larch are made. Changes in the tiers of the orientation parameter of the order of branches and density of wood are taken into account.

Table 2 presents the calculated values of the dielectric constant anisotropy $\Delta\varepsilon$ of three tiers of birch and larch crowns.

Table 2. Anisotropy of crown stages taking into account the order parameter S .

Tiers of crowns	Birch			Larch		
	$\Delta\varepsilon, S = 1$	S	$\Delta\varepsilon \cdot S$	$\Delta\varepsilon, S = 1$	S	$\Delta\varepsilon \cdot S$
1 tier	0,002	0,6	0,001	0,004	0,4	0,002
2 tiers	0,025	0,3	0,008	0,026	0,2	0,005
3 tiers	0,24	0,1	0,02	0,23	0,1	0,02

3 Attenuation of NS signals in the tree stand

Typical structural characteristics are inherent in any tree of a certain type and age: the shape and size of the crown, the height and diameter of the trunk, the location and orientation of large and small branches, leaves and conifers. In this paper, the tree model is described by a set of canonical elements distributed over different layers (tiers). Tree trunks and branches are modeled by cylinders of finite length, leaves and needles are represented by dielectric ellipsoids. For the radio frequencies of navigation satellites (1.2-1.6 GHz), the elements of the tree are quite transparent, the transmitted and scattered radiation reacts to the anisotropy of the wood and the orientational ordering of trunks and branches [1].

The derivation of expressions for scattering of radio waves by dielectric ellipsoids is based on the generalized Rayleigh-Hans-Debye approximation (RHD), which requires the fulfillment of the constraint:

$$k_0 d |\sqrt{\varepsilon} - 1| \ll 1, \quad (2)$$

where $k_0 = \frac{2\pi}{\lambda}$ - free space wave vector, d - smallest axis of an ellipsoid, ε - the dielectric constant. Expression (2) implies that the diffuser partially transmits the probe wave.

Since the sizes of large tree elements (trunk, branches) in the considered L-frequency range are comparable with the radio wavelength ($\lambda \approx$), scattering cross sections at arbitrary incidence angles were calculated using the diffraction model for infinite and finite cylinders [2,3]. In this model, the only restriction on cylinder size is:

$$h \gg r, k_0 h \gg 1, \quad (3)$$

where h and r – cylinder height and radius, respectively.

It is known [5] that the scattering of electromagnetic waves can be interpreted in terms of low-amplitude fluctuations in the orientations of scattering objects. In this case, the differential scattering cross section σ per unit of scattering volume in a unit of solid angle per unit of change in the angular frequency ω is written as:

$$\frac{d^2\sigma}{d\Omega d\omega} = \pi^2 \lambda^{-4} \int \int_{-\infty}^{+\infty} \langle \delta \varepsilon^2 \rangle \exp[i(\bar{q}\bar{r} - \omega t)] dr dt \quad (4)$$

where $\lambda = \frac{2\pi c}{\omega_0}$ – wave length in vacuum, \bar{q} – wave vector, $\langle \delta \varepsilon^2 \rangle = \langle \delta \varepsilon(0,0) \delta \varepsilon(r, t) \rangle$ – mean square permittivity at a given point at a given time t .

For the wave vector q and frequency ω , the differential scattering cross section per unit volume has the form [5]:

$$\frac{d\sigma}{d\Omega} = \frac{\pi^2}{\lambda^4} \langle \delta \varepsilon^2 \rangle_q = \frac{4\pi^2}{q\lambda^4} (\Delta \varepsilon)^2 \langle S_{ij}^2 \rangle_q \quad (5)$$

where $\delta \varepsilon = \varepsilon_{ij} - \bar{\varepsilon}_i, \bar{\varepsilon}$ – average dielectric constant, $\Delta \varepsilon = \varepsilon_{||} - \varepsilon_{\perp}$ – anisotropy ε between the directions along and across the barrel in the case when the diffusers are parallel to each other, S_{ij} – components of the orientational ordering tensor. Formula (5) is valid if the imaginary part ε is much smaller than the real part.

Tensors $\langle S_{ij} \rangle$ and $\langle S_{ij}^2 \rangle$ can be calculated both for small twigs and needles oriented at certain angles to large branches, and for the main crown-bearing branches and the whole tree, divided into tiers. The tier contains areas of branches with the same angle of inclination θ from the vertical. This angle from tier to tier varies from 20° to 120° . The off-diagonal elements of the tensor are equal to zero due to the axial symmetry of the crown. The off-diagonal components of the tensors $\langle S_{ij}^2 \rangle$ do not generally vanish and can appear in the elements of the scattering tensor during polarization measurements.

Experimental data on the dependence of the elements of the tensor of the complex dielectric constant $\varepsilon = \varepsilon' + i\varepsilon''$ of wood on humidity and temperature for radio frequencies in the range of $20 \cdot 10^{11}$ Hz are presented in the monograph [6]. The difference in the dielectric properties of wood is observed for the orientations of the electric field vector along the fibers (trunk), in the radial and tangential directions. In practical applications, tensor elements corresponding to the longitudinal and transverse directions of the wood are used. Crowns have a vertical length less than the trunks. The share of crown biomass is 0.1-0.2 of the volume of the tree. The diagonal elements of the orientational ordering tensor S_{ij} of branches vary from upper tiers to lower. This circumstance, taking into account the area of interpenetration of the layer of trunks and crowns, makes it possible to make model estimates of the vertical dependence of the effective dielectric constant of the stand as a whole.

4 Radioscopy of crowns.

A coherent pulse signal on the surface of the Earth is practically a plane wave. The NS signal receiver provides registration of the angular coordinates of the wave vector of the signal. The attenuation of the signal in the stand is due to three factors: absorption, scattering

on the elements of the crowns and trunks, the difference in phase delays of the vertical and horizontal components of the electric field.

The direct NS signal recorded by the receiver passing outside the crown is stably reproduced in the absence of multipath. The passage of the probe signal through the crown leads to changes in the amplitude of the signal at the receiver, recording as direct and scattered and reflected signals by the trunks and elements of the crowns. Spatial heterogeneity of the effective dielectric permittivity of the tree stand generates multipath signals at the receiving antenna with a continuous distribution of phase shifts.

In the conditions of neighboring crowns radioscopy, it is possible to select a test option from two trees with close crowns. The radio transmission scheme of two fir trees with developed crowns is shown in Figure 2. The trees are located at a distance between the trunks of 3.4 m. The height of the trees is 24 and 25 m, the diameter of the trunks is 0.32 m. The crowns are conical in shape, with a height of 22 meters. The lower part of the crowns of both trees partially closes.

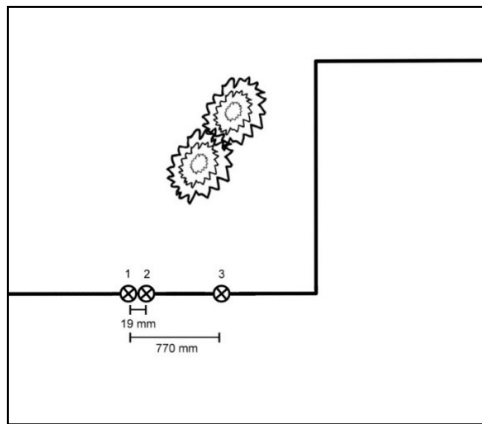


Fig. 2. Scheme of radioscopy of crowns of two fir trees.

The pulsed radiation of NS signals with right circular polarization during passage through the crowns of fir trees is attenuated as a result of scattering and absorption and partially depolarized in the volume occupied by the trees. The depolarization effect is determined by the anisotropy of the effective dielectric constant of the crowns of the trunks. The interference effects of coherent radiation in the forest stand form an EMW of a complex spatio-temporal structure.

Transmitted NS signals were recorded by MRK-32R signal receivers, manufacturer of NPO Radio Communications, and specialized receiver-recorder NSRP-04, manufacturer of Phoenix Engineering Bureau LLC, Krasnoyarsk. A set of antennas was used to receive signals with linear and right circular polarization.

Figure 3 shows the spatio-temporal dependences of the amplitude of NS signals located relative to the antennas in the intervals of azimuth angles α ($-30^\circ - 120^\circ$) and elevation angles φ ($-20^\circ - 60^\circ$). Antennas 1 and 3 received signals of circular polarization right, 2 - linear, oriented vertically. The axes are the amplitudes of the received signal and the number of registration frames. In the array of data recorded by the receiver for each frame, the date, time, and angular coordinates of the NS are indicated. The frame rate is 1 Hz.

The results of scanning crowns in different angles from different angles demonstrate spatial heterogeneities of the effective dielectric constant of the volume occupied by two fir. Further experimental studies and variants of NS signal interaction models suggest polarization measurements, the use of different projections of radioscopy in order to restore

the spatial structure and gradients of the effective dielectric constant of the stand.

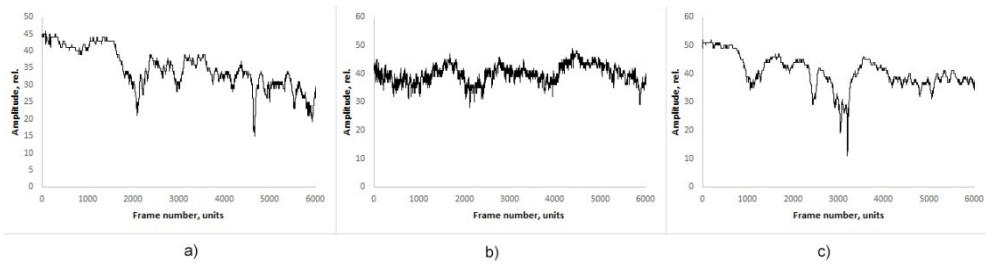


Fig. 3. Dependences of the amplitudes of NS GPS 15 signals attenuated in the crowns of fir trees from antennas: a) – 1, b) – 2, c) – 3.

5 Conclusion

A model of the interaction of signals from navigation satellites with a tree crown is considered. The contribution of the dielectric constant anisotropy to the scattering cross section of radio waves due to the orientational ordering of the branches is shown. The calculation of scattering cross sections for small and large elements is presented. The orientational ordering tensor of tree branches is introduced with the division into tiers differing in the size and orientation of the elements. Implemented the option of using scanning of tree crowns in different directions by signals of navigation satellites. Informative differences of the signal amplitude at the location of the receiving antenna from the paths of the emitting antenna. Variations in the amplitude of the recorded signals are associated with the spatial distribution of the effective dielectric constant of the tree, depending on the volume fractions and humidity of the wood substance of the trunk and crown. The use of radioscopy in a wide range of azimuth and elevation angles of navigation satellites has the prospect of developing radio tomography of the volumetric dielectric structure of a tree crown.

References

1. V.I. Popov, Propagation of radio waves in forests - M.: Hot line - Telecom,.- 392 p. (2015)
2. A.Chukhlantsev, A. Shutko, S. Golovachev. Radio engineering and electronics, 48, 11, 1285 (2003).
3. Ulaby F. T., Tavakoli A., Senior T.B.A. // IEEE Trans 1987. V. GRS-25. P.714-719
4. Blinov L.M., Liquid crystals: structure and properties. M.: Book House <LIBROCOM, 2013. - 480 p.; col. incl.
5. Computer simulation methods for the study of polymers and liquid crystals (responsible editor V.A. Ivanov) Moskva, Izdatelstvo "Mir",. «Librocom». - 696 p. (2009)
6. Torgovnikov G.I. Dielectric Properties of Wood and Wood Based Materials. – Berlin, Springer – Verlag. – 1993. – 194 p.
7. S.N. Novik, A.S. Zavyalov, E.D. Telpukhovskiy, Electrophysical and dissipative characteristics of the properties of the elements of a coniferous stand // Izvestiya Vuzov. Physics. **49**, 7, P.57-67. (2006)