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APPLIED RADIO PHYSICS: SPACE, ATMOSPHERE AND EARTH SURFACE RESEARCH

Radio Physical and Structural Parameters of Forests as an Object of Remote Sensing

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ABSTRACT: The object of investigation is the permittivity of a leaf of deciduous trees, the dependence between the forest's outgoing eigen signal and its projective covering, the temperature inhomogeneities of the forest elements, radio wave diffraction and their repeated re-reflections in the tree crowns.

INTRODUCTION

The development of the radio physical remote sensing techniques is stimulated by the ever growing need in the data acquisition to be applied for solving a wide range of problems of the nature conservation and the environmental monitoring, being both of theoretical and practical importance.

The radio physical characteristics of the surface objects like water, soil, crop, etc. are studied quite comprehensively by a number of authors, as well as the laws according to which these objects generate the eigen and secondary radiation in various ranges. Though, the knowledge on the mechanisms of radio location signal generation by forest is still lacking.

This paper considers some of the principal specific features of wood vegetation as an object of a remote sensing in the 3-cm wave range.

PERMITTIVITY OF LEAVES

The key parameter relevant for the forest radiating capacity and reflectivity in the radio range are the dielectric characteristics of its phytoelements, namely of the leaves - for the deciduous forest.

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The dielectric characteristics of leaves have been calculated by using the model suggested in [1]. The initial data for calculations have been obtained experimentally from the quantitative evaluations of the volume moisture content of leaves. The weight moisture content in the leaves of English Oak and Silver Birch has been determined by the gravimetric method (weighing – drying – weighing) using the torsion balance. The leaf volume has been measured by the substitution method, i.e., hundred of leaves have been put in a measuring vessel with oil. The leaf square has been calculated by photogrammetry.

A non-inductive reactance bridge has been used to measure the low-frequency leaf conduction at the frequency of 100 kHz.

By using the model suggested in [1], the orientational component of the complex dielectric permittivity has been calculated in the considered frequency range, which has been summed with the permittivity losses. The application of the model [1] in the leaf analysis had some peculiarity. The object is considered as a three-component system, where the total volume of two its components, i.e., water and air, remains constant. The square ratio of these components is determined by microscopy, the volume ratio is obtained from multiplying the result by the leaf thickness that, in its turn, is a quotient of dividing the leaf volume by its square.

The numerical results have been compared with those of direct measurement of the leaf complex permittivity by using the near-field probes [2] at various frequencies. The coincidence between the numerical and experimental results in most of the cases proves that the direct measuring of dielectric characteristics of leaves is expedient for the dedicated research only. For the remote sensing problems, the above-mentioned measurements of the volume-moisture characteristics of leaves and their low-frequency permittivity suffice for the further calculation of the complex dielectric permittivity (the discrepancy between the measured and the numerical values at $p > 0.95$ never exceeded the experimental error). The measurement and calculation involved bulk samplings of 300 leaves as a minimum. The average values of the dielectric parameters of the English oak and silver birch leaves at the temperature of 25° C are listed in Table 1.

Table 1: Average values of the dielectric parameters of leaves

Breed	λ, cm	ε'	ε"
English Oak	3	13.45	3.65
	10	19.35	4.50
Silver Birch	3	13.85	5.75
	10	19.90	5.55

The values of both the permittivity and dielectric losses of the birch leaves in all cases are reliably higher ($p > 0.98$) than those of the oak. At various wave lengths, the parameter values of one and the same leaves, except for the ε" value of the birch, are as a rule reliably different ($p > 0.98$ for ε' and $p > 0.95$ for ε" of the oak leaves).

Obviously, the permittivity in the range in question increases as the wave length grows, since the permittivity of water increases, too. There are two factors influencing the total dielectric losses: the decrease of the orientational polarizability at longer waves and the increase of the permittivity losses due to the lowering frequency. The differently directed variation of this parameter by a growing wave length in leaves of different breeds is explained by the exceeding total moisture content, as well as the relative free water content in the birch leaves, as compared to the oak leaves.

The obtained results also prove the importance of the air content in a leaf, as one of the factors relevant for the level of its dielectric parameters. A considerable contribution of the volume content of the air bubbles in leaves to the final result allows one to formulate a problem of the forest state remote recognition in the radio range under various conditions, for example, the over-dried forest that means an increased fire hazard can be detected by the pronounced changes in the complex permittivity.

According to our observations, in the state the forest was during the experiments, i.e., a favorable temperature and humidity conditions, the volume content of the air bubbles in the birch leaves was higher than that in the oak leaves (2.2 and 1.5 volume percent, respectively).

The probability density of the dielectric leaf characteristics distribution at $t = 25^0$ C is shown in Fig. 1. The Figure refers to the range of $\varepsilon \pm 3\sigma$, where σ is the root-mean-square deviation. As seen, for both values, $\sigma \le 0.33$.

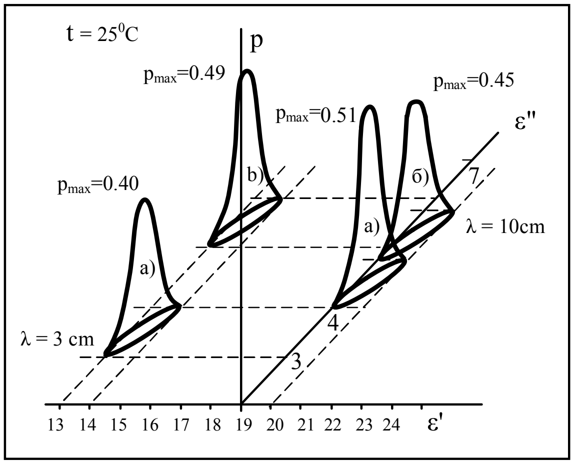

FIGURE 1. Probability density of the dielectric characteristics distribution of leaves: a) English Oak; b) Silver Birch.

The dielectric characteristics of leaves change depending on the temperature, due to the variability of ε' and ε" of the water contained in leaves.

RADIO THERMAL CONTRASTS OF THE TERRESTRIAL COVERS

In the Kharkiv region (~50˚ northern latitude), the brightness temperature of various kinds of terrestrial covers has been measured by using a chopper radiometer ($\lambda = 3$ cm) situated on a tower. A horn antenna having the directional pattern width of $\Delta\varphi = 20^\circ$ has been employed. The radiometer sensitivity at the time constant $\tau = 1$ s was $\delta T_B = 0.1$ K, the receiving band width was $\Delta\nu = 200$ MHz. The calibration has been made with the reference of two sources with the known brightness temperature. The measurement has been performed at the cloud amount of 10 during more than 3 days, calm, midday. Thus we were able to eliminate the influence of the direct solar heating of the forest elements on the measurement results. The viewing angle in all the cases was ~ 50°, i.e., the state of the minimum transparency (see below) of the forest. In this way we can reach the condition when the outgoing eigen radiation of the forest was formed mainly by the leaves.

Due to the properly chosen weather conditions during the experiments the viewing azimuth did not affect the measurement results.

The observation objects were: mixed ash and maple fresh grove (young growth, about 30 year old), plough-land (alumina, the linear dimension of concrements up to 10cm), cultivated soil with corn shoots (projective cover does not exceed 1.5 %, the linear dimension of the soil concrements up to 3 cm) and the spring wheat in the middle of the bushing stage (the projective cover is ≤20%, the linear dimension of the soil concrements up to 3 cm). The moisture content in the soil at all three fields was practically similar and reached about 10 weight percent. The permittivity of the soil, leaves, the above-ground corn shoots and the wheat leaves is listed in Table 2.

Table 2: Dielectric characteristics of the observation object elements

Element of the observation object	293.2, K		291.6, K	
	ε'	ε"	ε'	ε"
Ploughed field	4.129	0.352	4.125	0.350
Soil under corn shoots	4.129	0.352	4.125	0.350
Soil under wheat	4.129	0.352	4.125	0.350
Wheat leaves	15.222	5.032	15.2078	4.895
Corn shoots	18.327	5.678	18.175	5.547
Oak leaves, 290.4 K	13.280	3.530	-	-

In line with the main measurements, we also kept the records of the air temperature at the soil surface, at the height of 0.5 m and 2 m, and at the height of the maximum biomass: in the wheat crops at 10 cm, in forest at 15 m. The relative air humidity was measured at the height of 2 m.

The measurements ran in two series with the 2 hour interval. In both cases the air temperature in forest at the height of 2 m was 290.4 K, the relative air humidity was 93%. The temperature deviations over the whole forest volume did not exceed 0.2°. The effective air temperature, i.e., the weighted one over the vertical profile of forest, was 290.36 K. The brightness temperature (T_B, K) of the grove under the considered conditions was 290.3 K. The radiation coefficients æ, obtained from comparison between the brightness temperature and the air temperature and the effective forest temperature are essentially identical, 0.9996 and 0.9998, respectively.

The temperature vertical profile of agricultural objects under such conditions does not vary much; the effective temperature of the object (T, K) was characterized by the average weighted temperatures at the soil surface and at the heights of 10 and 50 cm. The measurement results are presented in Table 3.

Table 3: Characteristics of various types of terrestrial covers

Cover type	T, K	T_B, K	æ
Grove	290.4	290.3	0.9996
Tillage	293.2	276.3	0.9424
Tillage with shoots	293.2	278.4	0.9495
Tillage under crops	293.2	288.9	0.9853
Tillage	291.6	274.7	0.9420
Tillage with shoots	291.6	276.9	0.9496
Tillage under crops	291.6	287.3	0.9852

The brightness temperature of the forest differed a lot from that for the other cover types, while the radio thermal contrasts were provided both by the difference in the thermodynamic temperature of the objects and their structure.

Obviously, the magnitude of the radiation coefficient æ of all observed covers is substantially lower than that of the forest.

An interesting point is the radio thermal contrasts that are inherent in the objects showing similar dielectric characteristics but different roughness. Thus, the difference in the æ values of a tillage and a tillage with shoots should be explained, due to the identical dielectric characteristics of soil and negligible projective cover, solely by the difference in the geometry of the radiating objects. The considerable radio thermal contrasts occurring due to a big amount of phytomass (tillage with shoots – tillage with crops) with the dielectric characteristics differing substantially from those of soil, that acts as a shield for the latter, offers a clear illustration of the role played by the phytoelements of the soil projective cover in forming the eigen radiation of the terrestrial covers.

INFLUENCE OF THE FOREST PROJECTIVE COVER ON FORMATION OF THEIR OUTGOING EIGEN SIGNAL

The projective cover of the soil surface of the forest breeds is determined by two factors: the crown projection and their transparency. The both factors, on one hand, are characteristics of the breed, i.e., its type, age, state, etc., on the other hand they depend on the viewing angle. The square of the horizontal crown projections is determined by a direct mapping. The measurements of the crown thickness and its vertical profile allow one to calculate the projective cover at various viewing angles.

The inclination angles and the azimuth directivity of leaves have been studied. The measurements have been performed from an “ATP-17” tower crane cradle by means of a primitive arrangement described below. A metal rod is soldered to a plexiglass plate normally to its plane, with a protractor and a plummet attached to the first. I.e., when the plate overlays the most part of a leaf, the rod is situated normally to the latter. The inclination angle and the normal azimuth are registered. Figure 2 shows a typical distribution of the inclination angles of English Oak leaves. As seen, the distribution by the azimuth is actually uniform, while the distribution by the inclination angles has a well-pronounced mode, corresponding, according to our observations in various regions, to the maximum sun rise angle for this very latitude.

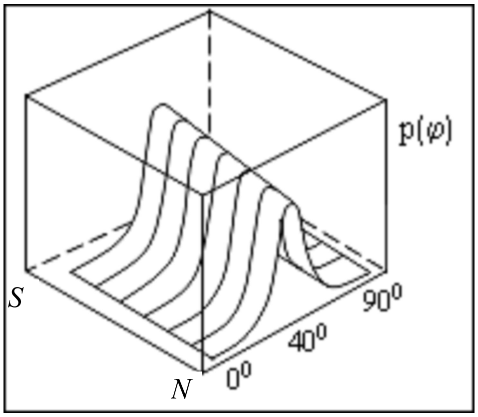

FIGURE 2. Probability density of the leaf inclination and orientation distribution.

Inside the crown, however, the leaf inclinations are distributed practically uniformly.

A special photogrammetry technique has been developed to explore the crown transparency. The crown transparency, either taking into account the perspective distortions in the modeling of the forest infrastructure or not (for the remote terrestrial sensing in the optical range), is evaluated by a simple calculation of the percentage of phytoelement-free squares v.v. covered ones. This characteristics were examined at various viewing angles. The minimum transparency was registered at the viewing angle corresponding to the maximum sun rise over horizon at the latitude the forest belongs to.

For any non-thinned-out forest there is a viewing angle interval, where the projective cover is close to 100%. This is the ± 5÷7 degree interval near the maximum sun rise above horizon, corresponding to the local latitude.

The radio-brightness temperature has been measured in the young birch forest (about 20 year old) and a middle-aged one (about 50 year old), and the middle-aged pine forest (about 70 year old). The measurements were performed in zenith, with the crown transparency in the antenna spot in zenith being 10.0, 11.5 and 12.0%, respectively, the cloud amount of 10, calm. The temperature vertical profile in the crowns practically coincided with the air temperature. The comparison between the measurement data and the weighted temperature over the crown vertical profile above the antenna is presented in Table 4. As seen, the data on æ strongly correlate with the crown transparency *s*.

Table 4: Characteristics of various forests (young (y.) and middle-aged (m.-a.))

Forest	T, K	T_B, K	æ	*s*,%
Birch m.-a.	288.2	274.8	0.9535	10.0
Birch (y.)	288.4	246.7	0.8554	11.5
Pine (m.-a.)	288.2	243.4	0.8445	12.0

When 447.3 leaves per square meter have been removed from the whole antenna spot square in a crown of a middle-aged birch, its transparency increased by about 1 percent, and the brightness temperature decreased by 2 K.

The change of the tilt angle up to about 40º (transparency is < 1%) led to the change of æ of a middle-aged birch to 0.9874.

EFFECT OF DIFFRCATION AND MULTIPLE RE-REFLECTION ON THE FOREST OUTGOING SIGNAL FORMATION

While examining the effect of the projective cover and the transparency of crowns on the level of the forest's eigen radiation, one should take into account that every element of the tree crown is a shield whose linear dimension is comparable with the wavelength, in the case under consideration it is $\lambda = 3$ cm, and whose dielectric characteristics differ a lot from the environment. It is clear that the signal radiated by every single element is diffracted and repeatedly re-reflected. As a result, the total eigen radiation generated by the forest is formed not by the whole its mass, but only by a fraction of crowns.

The object of our experiment was a young, 20 year old, birch (*s* = 11.5%) with the crown mass of 6 m. The measurements were performed from beneath the crown, in zenith, at the air temperature and its relative humidity of 288.4 K and 93%, respectively. The weighted temperature over the vertical crown profile was 288.36 K. The brightness temperature of the whole crown was 251.2 K (æ = 0.87). In series, about the I, II, III and so on layers of the crown, parallel to the antenna aperture plane, a metal screen has been installed that overlaid the whole aperture. The radiation coefficient curve is shown in Fig. 3. The presence of a metal screen in the crown did not effect significantly on the results of the crown's T_B measurement, starting from 4.9 m of its mass. Thus, the crown mass of a young birch, taking an effective part in forming of its eigen radiation at $\lambda = 3$ cm, is about 5 m.

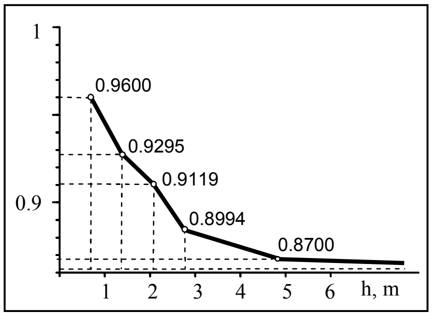

FIGURE 3. Effect of a metal screen situated in the birch crown on its radiation capacity.

INFLUENCE OF THE TEMPERATURE INHOMOGENEITIES IN FOREST ON THEIR RADIATION CAPACITY

The brightness temperature of forest strongly depends on the diversity of the thermodynamic temperature of its components, i.e., the difference in the illumination and, as a result, temperature of opposite sides of the crown, the forest as a whole, glades, etc. Under similar temperature conditions, it varies depending on the presence or lack of the solar illumination as well as its previous history, and on the precipitation [3].

It is a common knowledge that the radiation coefficient of a dense forest in the radio range is close to unity, i.e., within the experimental error, $T_T = T_B$. Still the question - the thermodynamic temperature of what should be compared with the brightness temperature of forest – remains open. Traditionally, it is compared with the air temperature at the height of 2 m, further on this factor will be shortly called the air temperature.

Our long experience demonstrates that the air temperature characterizes the temperature of the total forest volume and its components accurate to the measurement error in the rare cases, corresponding to the following conditions: calm, cloud amount of 10, the same weather conditions three days before the observation, the time interval of ± 3 hours about midday. As we could see, under such conditions the brightness temperature of forest is actually the same with the air temperature in forest at the height of 2 m.

Under other conditions, the temperature profile in the air space of forest is very unstable and depends on many factors, for example the composition of breeds, soil type, presence of young growth, type of undergrowth and grass cover type, weather, day or night, air temperature and its previous history.

There is usually a big difference between the air temperature and that of the forest elements. Thus, e.g. in the dense foliage forests, where by the full leafage the brightness temperature is formed mainly by the leaves, by a bright solar illumination, on one hand, the outer sides of leaves, that are responsible for the signal level, facing the sun become overheated, and, on the other hand, they are cooled down because of an intense water evaporation from their surface. The balance between these two processes is a multifactorial phenomenon, and forecasting of the final result in the general case seems highly improbable.

An essential part in forming the thermal signal of the foliage forest belongs to the temperature difference of leaves depending on their exposure, since the temperature at the shady and sun-lit sides of the crown in a sunny day can differ by 10 and more degrees. This leads to a temperature diversity, whose autocorrelation radius is equal to the distance between trees. The difference has the hysteresis nature, i.e., it depends on the preceding illumination conditions and heating of forest. As for the absolute values, this temperature can be told roughly by the temperature on an open soil area, and the shady-side leaf temperature - by the temperature at the height of 2 m minus 0.5 degree.

The radio-brightness temperature of the same mixed ash and maple fresh grove has been measured by the air temperature of 297.5 K at the height of 2 m, zero cloudiness, calm, the relative air humidity of 55%, and the effective temperature of 298.56 K. A mirror antenna of ∅1.5 m has been applied, having the same viewing angles, but two different azimuths, either from the sunny side and the opposite one. The average brightness temperature of the grove was 301.7 K and 298.3 K, respectively. In other words, by comparing with the forest’s effective temperature, the obtained radiation coefficient was 0.9991 from the shady side. In the rest of the correlations, the brightness temperature always exceeded the thermodynamic air temperature.

Due to the high-directivity of the antenna, during the panoramic surveys in the direction “back from the sun” we were able to obtain fluctuations of T_B, conditioned by the lane structure of the forest under consideration.

CONCLUSIONS

Obviously, the forest as an object of the remote sensing in the radio range is likely the most intricate sort of terrestrial covers to explore and model.

Many factors like roughness of phytoelements and their relative position in the crown, screening capacity of various kinds of forest, etc., remained beyond the consideration in this paper, though being important components of the simulation problem of the forest radio-physical characteristics.

The most of the presented data are not as much results as a basis for stating problems worth a dedicated circumstantial investigation to yield comprehensive materials allowing to solve the urgent problems of the forestry and rational nature management by means of the remote sensing in the radio range.

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