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ATTENUATION OF ELECTROMAGNETIC WAVES BY VEGETATION CANOPIES IN THE 100 – 10000 MHz FREQUENCY BAND

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Abstract – An analytical overview of research involving EM waves attenuation by vegetation canopies in the frequency range 100…10000 MHz is given. Brief descriptions of objects of investigation and typical biometric features are presented. The models of vegetation as a continuous medium and as a collection of scatterers are considered. Dielectric properties of vegetative material are discussed. The relation between electromagnetic and biometric parameters of vegetation is established. Methods of measurements of attenuation are reviewed. Available experimental data of attenuation are analyzed and the directions of future research needs are presented.

I. INTRODUCTION

The impact of different types of vegetation, from grassy to forested types, is one of the main problems to be discussed when conducting remote sensing of the land surface. There are two types of interest arising in this area of remote sensing. The first one consists in revealing the screening effect of vegetative cover on the remote sensing of a land surface itself and developing technologies by taking this effect into consideration when assessing the land surface condition. The second one consists of developing technologies of remote sensing application for assessing the properties of vegetative cover. In both cases the attenuation of EM waves and its relation to biometrical features of vegetation is of a great importance.

Prevalence of mobile radio systems requires studies of spectral characteristics of electromagnetic wave attenuation by vegetative media in wide frequency range. It is necessary to assess the influence of vegetation on the quality of radio communication, especially for radio communication in forested terrains.

The investigations mentioned above were actively conducted over the last three decades by groups of scientists working in different countries and institutions including the Institute of Radioengineering and Electronics, Soviet/Russian Academy of Sciences. This paper intends to summarize and to analyze the known theoretical and experimental results on the attenuation of EM waves by vegetation canopies in the frequency range 100 – 10000 MHz.

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II. THEORETICAL ASPECTS OF EM WAVES PROPAGATION IN VEGETATION CANOPIES.

1. Basic approaches.

1.1. Vegetation canopies as the object of research.

Vegetation canopies are very dynamic and complicated object of investigation. The morphology of plants changes during the vegetation period leading to a change of vegetation canopy characteristic electrodynamic parameters. From the standpoint of remote sensing the following canopy features are most often used for modeling of EM propagation through a vegetation media [1-3]:

a. Type and stage/phase of growth.
b. Shape and size of leaves, stalks, branches, and trunks.
c. Distributions of leaf, stalk, and branch angles.
d. Volumetric moisture content of plant elements m_V.
e. Vegetation volume density p (the relative volume occupied by vegetation in canopy); $p = nV_s$, where V_s is the volume of plant element, n is the number density of elements.

f. Vegetation water content per unit volume $w = pm_v\rho_W$, where ρ_W is the density of water.

g. The number of plants (trunks) per unit area N.
h. Vegetation average height *h*.
i. Vegetation wet biomass *Q* (the weight of vegetation per unit area).
j. Vegetation water content per unit area *W*.
k. Vegetation gravimetric moisture $m = W/Q$.

Some biometric features of agricultural vegetation are collected from different sources and are presented in Table 1. These data can be useful for modeling of attenuation by main crops during the vegetation period. The change of biometric parameters of crops during a growing process can be found in [5-11, 162].

Forests occupy a third of the Earth's land surface (about 50 millions square kilometers) and play a key role in the formation of global circulation of carbon and nitrogen and in the influence upon the energy and water balance of the biosphere. Boreal forests of Europe, Russia, Canada, and USA occupy about 15 millions square kilometers. Tropical forests make up about 53% of the world forest store.

A characteristic feature of forests is the tier structure. The basic components of forest phytocenosis are stand, undergrowth, live soil cover, and dead litter [12, 13].

The stand consists of one or more tiers formed by trees of different height and breed. The main breeds of boreal forests are pine, larch, spruce, silver fir, cedar, birch, aspen, oak, beech, and ash-tree. Forest canopy has a small density of 0.03…0.3 kg/m^3, a big height of 2… 25 m, a small size of elements (branches and leaves), and relatively stable water content (gravimetric moisture). The wet biomass of a forest canopy varies from 0.2 to 1.2 kg/m^2.

Table 1. Biometric features of agricultural vegetation.

Crop [reference]	The number of plants per unit area N, 1/m^2	Vegetation average height *h*, m	Vegetation wet biomass *Q*, kg	Vegetation gravimetric moisture *m*	Vegetation water content per unit area *W*, kg
Winter wheat [4]	400 – 1000	0.6 – 1.12	0.2 – 1.3	0.5 – 0.85	0.25 – 1.1
Winter rye [4]	330 – 700	1.2 – 1.5	0.2 – 0.45	0.5 – 0.84	
Corn [4]	5 – 30	1.2 – 3.2		0.81 – 0.84	
Sugar beat [4]	4 – 8	0.3 – 0.5	1.25 – 3	0.8 – 0.9	1.2 – 2.8
Corn [5]	6 – 7	1.8	7	0.76	5.3
Alfalfa [5]		0.6	2.2	0.82	1.8
Soybean [6]		0.2 – 1.04	0.25 – 2.8	0.78	
Corn [6]-		2.6	5.5		
Winter wheat [7]	900	1.05	Volume fraction: Stalk – 0.00363 Heads – 0.01	Head – 0.45 Stalk – 0.63 Leaf – 0.16	
Soybean [7]	26	0.82	Volume fraction: 0.0282	Leaf – 0.76 Stalk – 0.81	

Corn [8]	Row spacing – 76 cm Average plant spacing – 19.8 cm	2.7	Volume fraction: Stalk – 0.0035 Leaf – 0.00058	Volumetric moisture: Stalk – 0.47 Leaf – 0.65	
Oat [9]	180 – 440	1.35	6	0.7 – 0.86	
Alfalfa [10]		0.17 – 0.73	Data on volumetric water content *w* are presented		0.23 – 1.95
Corn [10]		0.3 – 2.7			0.2 – 10
Milo [10]		0.3 – 1.17			0.66 – 10.9
Wheat [10]		0.96			5.3
Tomato [11]	7 – 10		7 – 15		

The live soil cover is formed with bushes and shrubs, grass, moss, and lichen. Bushes have a height of 0.1…0.5 m and a wet mass of 0.1…0.5 kg/m^2. The grass cover has a height up to 2 m and a wet mass of 0.05…0.5 kg/m^2 with volumetric density of 0.2…1.0 kg/m^3.

In the absence of live cover, a layer of dead needles, leaves, small branches, and bark is formed on the soil surface. This layer has a friable structure and a high speed of drying and moistening. The height of the layer is 0.01…0.07 m, its mass is 0.1…0.6 kg/m^2, and its density is 5…30 kg/m^3.

The density of a forest stand is described by the normal distribution

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where is the distance between the trees, is the average distance between the trees, where is the coefficient of variability of distance [12]. The height of a tree relates to its diameter in accordance with an approximation .

The crown diameter *D*, the crown length *l*, the height of crown widest part h_0, and the height of crown beginning *h*, describes the canopy structure. These values are correlated and are connected to each other by known regression relations [12, 13].

An estimate of wet mass of tree components can be obtained due to a stable correlation between the trunk dimension and mass of leaves and branches [13, 15, and 16]. For example, the mass of leaves of 21 years old fir is given as

where *g* is the trunk cross section at the breast height. Similar relations are known for the mass of branches and trunks.

Tropical forests have some special features [14]. There is no dominated type of tree in this kind of forest. At a site of 1 ha there can be up to 100 different types of trees. They usually occupy 3-4 tiers. The single standing trees with height of 50…70 m form the upper tier; the main tier is formed by trees with not more than 35 m height and with dense canopy. Undergrowth is weak. Tropical forests have the greatest values of biomass up to 40…60 kg/m^2.

Modeling the EM propagation in a forest requires a number of biometric parameters [1, 17-19]. Examples of forest parameters used in well known backscatter models are presented in Tables 2, 3. These parameters are *in-situ* measured and provide information on the biometrical features of some breeds of trees. Some data on biometric parameters of forest stands and their relationships and correlation can be found in [20-23, 83, 85, 86, 114, 150, and 159].

Table 2. Stand parameters for backscatter model simulation [1, 17, and 18]

Species	Aspen	Hemlock
Stems/ha	1100	1100
Height (m)	15	15
Crown diameter (m)	3.0	3.0
Crown length (m)	7.0	7.0
DBH (cm)	20	20
Branches/m^3	10	105
Leaves/m^3	800	196000
Moisture content (% gravimetric)		
- trunks and branches	50	50
- leaves	60	60

Table 3. Stand description and summary of MIMICS backscatter model [1, 19].

Forest type	Red Pine & White Pine	Maple/Beech
Dry biomass (tons/ha)		
Total		
Apr-92	182	203
Jul-92	83	206
Trunk	152	157
Branch	22.4	45
Foliar	8.3	3.3
Leaf Area Index (July)	6.4	3.89
*Stems/ha (upper stratum)	1018	925
*Mean trunk height (m)	15.7	16.1
*Mean trunk diameter (cm)	17.9	17.5
*Mean crown thickness (m)	8.5	7.4
*Crown layer geometry		
Leaves		
Thickness (cm)	0.074	0.1
Length (cm)	12.5	6.4
Mass (g)	0.026	0.37
Density (no/m^3)	3838.5	118.1
Primary branches		
Length (m)	0.73	2
Diameter (cm)	0.99	1.5
Mass/branch (g)	23.4	189.4
Density (no/m^3)	7.49	2.14
Secondary branches		
Length (m)	0.33	1
Diameter (cm)	0.57	0.75
Mass/branch (g)	3.5	23.7

Density (no/m^3)	25	8.6
Canopy moisture (% gravimetric)		
Trunk		
Apr-92	57	46
Jul-92	50	48
Leaves		
Apr-92	65	-
Jul-92	65	57
Branches		
Apr-92	57	46
Jul-92	50	50
*Orientation function		
Secondary branches	0.5sin(θ)	1.23sin(θ-30)^9
Primary branches, uniform	0.5sin(θ)	0.5sin(θ)
Laves, uniform	0.5sin(θ)	0.5sin(θ)
Trunks	1.64cos(θ^8)	1.64cos(θ^8)
**Indicates parameters directly used in model*		

1.2. The role and significance of attenuation by vegetation in remote sensing. What kind of attenuation is under the investigation?

Remote sensing of environment is based on retrieving algorithms that relate the environmental parameters (such as soil moisture, vegetation biomass, forest stem volume, and others) to the remotely sensed radiation characteristics (brightness temperature T_b, backscattering coefficient σ^0, and others). There are three general types of the retrieving algorithms. The first one uses the experimentally obtained regression relations between geophysical and radiation parameters. A disadvantage of this approach is a limited application (often, the regression relation can be used only within the test site or the region it was obtained). The second technique is based on the neural network approach and is being successfully developed for last years [24, 25]. For good results, this approach requires neural network training with statistically representative sampling that is not always possible. The third type of algorithms, which is most widely applied, uses the model approach [20, 26-40]. The models for radiation parameters mentioned above are being developed on the base of some theoretical assumptions about modeled object (vegetated soil, forests, and other) and are being specified and verified at the test sites under the control of geophysical parameters. The retrieving algorithms produce the inversion of radiation parameters into geophysical ones on the base of the developed models. Of course, this approach also has disadvantages. One of them is the influence of model error on the final result. Any modeling implies a simplification and idealization of a real object and, therefore, leads to the difference between the calculated and measured values of radiation parameters and to the error of geophysical parameters retrieving. Nevertheless, the model approach is still applied and developed due to its certain advantages. It makes it possible to understand the role of different object parameters in forming emission or backscattering, to estimate the sensitivity of radiation parameters to the change of geophysical parameters, to find out the possible dynamic range of radiation parameters change due to the change of geophysical parameters, to find and to analyze the spectral dependence of radiation parameters, and, then, to choose optimal frequencies for remote sensing. After this work, the model approach can be added by the first two mentioned algorithms to obtain the best results.

Brightness temperature (or backscattering coefficient) is a measure of *intensity* of radiation emitted (or backscattered) by the Earth's surface. Therefore, the theory of radiation transfer is usually applied to model the emission and backscattering from vegetated terrain. This theory is a phenomenological one. The rigorous validation of its applicability to the case considered is not given (some words about it are said in [3]) and its applicability is grounded by a good agreement of model simulations with experimental results. The radiative transfer equation is not solved in the general case. The numerical solution of the equation [17-19, 41-46] is exact in that it includes all orders of multiple scattering. But this solution is inconvenient for experimentalists because of its complexity. It is also difficult to analyze and to understand the contribution of the different model parameters (see Tables 2 and 3) to the final result. By these reasons, simple analytical expressions for T_b and σ^0 are usually used which are either semi-empirical [40] or are derived from the radiative transfer equation on the basis of some simplifying assumptions (single scattering etc) [2,3]. These expressions are very convenient for calculations and analyses. Their accuracy is evaluated by comparing with a numerical solution of transfer equation [46, 47] and the error for T_b and σ^0 does not exceed 10 K and 2 dB, respectively that are comparable with the error of the model itself.

A zero-order solution of the radiative transfer equation for a vegetation covered soil can be written as a combination of three components [2, 3, 6, 48-50]

$$T_b = T_v(1 - r - q) + \kappa_s T_s q + T_v(1 - r - q)(1 - \kappa_s)q \qquad (1)$$

where T_v is the vegetation temperature, T_s is the soil temperature, r is the reflectivity and q is the transmissivity of a vegetation layer, and κ_s is the emissivity of soil;

(2)

where is the backscatter of soil, is the backscatter of vegetation half-space, and represents the interaction term. More sophisticated models [1, 19, and 40] take into account additional components for σ^0. Transmissivity q is usually approximated by the expression , where is the optical depth of the vegetation layer, is the viewing angle. Transmissivity of the vegetation layer determines the canopy attenuation ( ) and is very important and significant in remote sensing of vegetated terrain due to the following reasons.

Attenuation by vegetation strongly depends on the frequency. At high frequencies (X-band) attenuation is large and the brightness temperature and the backscattering coefficient relate to these values for the vegetation layer only. It allows crop classification by radar [1, 51], crop state monitoring by radar [52] and by microwave radiometry [5, 53, and 54]. At low frequencies (L-band) attenuation is not so big and that enables researchers to estimate soil parameters using linear regressions [55] or simple procedures [11].

Knowledge of spectral dependence of attenuation gives a possibility of multi channel (multi frequency) measurements of radiation parameters with inversion of measured data into, for example, soil moisture and vegetation water content [28, 29, 35-38].

For forest vegetation, the attenuation determines the penetration capability of radar sounding [1] and the possibility of objects detection beneath the forest canopy.

In radio communication the attenuation of *the coherent field* and its spectral dependence is of great interest [56] since it determines the capability of communication links. It follows therefore that investigations of attenuation spectrum of vegetation are of great importance and actuality.

1.3. General approach for EM waves propagation in vegetation.

The investigation of EM wave's propagation, attenuation, emission, and scattering in vegetation canopies meets some difficulties. From a theoretical point of view vegetation canopies are principally random media with inhomogeneities of varying forms and dimensions. In the frequency band of interest the dimensions of leaves and stalks, brunches and trunks are comparable with the wavelength making it extremely difficult to model propagation in such a medium due to the required application of diffraction theory to examine the scattering by a single inhomogeneity. A rigorous theoretical solution of the EM propagation problem for a vegetation layer is very complicated (if possible at all). Due to this reason approximate models have to be used. These models either treat vegetation as a collection of randomly distributed lossy scatterers (discrete approach) or they consider the canopy as a slab with random dielectric permittivity (continuous approach). In order to understand the relation between these two conceptually different approaches and to determine the limits of their validity the problem of EM propagation in vegetation should be considered from the position of random media propagation theory [3]. The electric field in a random medium is given by the integral equation [57]

(3)

is the incident field, is the wave number in free space ( ), is the random dielectric permittivity, and is the free space dyadic Green's function. To obtain the moments of the field the multiple scattering series is derived from (3), and, then, this series is averaged that leads to the Dyson equation for the mean field and the Bethe-Salpeter equation for the covariance. The principal point of the theory is the appropriate choice of the initial field inside the inhomogeneity in the multiple scattering series. The formal approach for the continuous case gives

(4)

It is important to emphasize that the integration in (3) for a truly discrete medium (like vegetation, for example) is to be performed only over those volume elements where , i.e. the elements of the scatterers. Hence, separating the volumes of scatterers expression (3) can be rewritten as

(5)

where the index *i* indicates that this value is related to the *i*-th scatterer; *N* is the total number of scatterers. For the field inside *i*-th scatterer it can be obtained from (5)

(6)

From equations (5) and (6) the multiple scattering series can be written by substituting (6) into (5) and iterating this process

(7)

In (7) is the field inside the isolated scatterer which is given by the scattering operator

(8)

One can see that in the discrete approach due to the separation of particle volumes the multiple scattering series begins with the field inside the isolated inhomogeneity. Of course, this field has to be known but it can be found from the solution of the diffraction problem.

It is interesting to find out [3] when the continuous and the discrete approaches coincide. It is clear from (4), (7), and (8) that this is the case when the scattering operator of an isolated particle may be represented by the Born series (weak scatterers). It is seen from (8) that this is valid under the following conditions. The first is: ; this corresponds to the Rayleigh–Gans scattering by particles and to the theory of small perturbations of continuous media. The second is: where *d* is the characteristic size of the scatterer (for example, leaf thickness); this corresponds to Rayleigh scattering for particles and to the strong fluctuations theory for the continuous case.

If the scatterer is strong the formal Born series obtained from (8) may not converge and the application of the continuous approach to the discrete media makes no sense. From the sufficient condition

(9)

one can estimate the limits of validity of the continuous approach for vegetation. For leaves $d \sim 0.2$ mm (leaf thickness of the most crops and trees), $e \sim 20$ and taking one has $l \sim 8$ cm. This implies that both models may be successfully applied for modeling vegetation up to the C-band. For higher frequencies the use of the discrete approach is more correct.

2. The model of vegetation as a continuous medium.

2.1. EM waves propagation in a random continuous medium.

In the continuous approach the vegetation is described by the effective permittivity tensor . In [7, 8, 31, and 58] authors used formulas for obtained for mixture of dielectrics in the electrostatic approach. In [64] the continuous medium concept is used to find the attenuation by foliage. The wave corrections for were derived in [59-61] on the basis of small perturbation theory. The vector problem which has to take into account the singularity of the Green’s function was considered in [62, 63] using the results of strong fluctuation theory.

In the latter case the dyadic Green’s function is decomposed into a principal value part and a Dirac delta function part [57, 62, and 63]

(10)

where *P.S.* stands for the principal value and *R* is a constant uniaxial matrix. Then new variables are introduced

(11)

where and is a deterministic uniaxial permittivity tensor (quasistatic part of) which is to be chosen such that the contribution of the singularity term of the dyadic Green’s function cancels, and *I* is the unit matrix. The integral equation in the new variables is used to find the mean field by conventional methods [57, 62, and 63]. The tensor is determined from the condition where brackets denote ensemble averaging. In the low frequency limit the effective permittivity is given by

(12)

where is the correlation function of .

The results of strong fluctuation theory stated above were applied to find the effective permittivity of vegetative media in [62, 63]. The success of determining depends on the appropriate choice of matrix *R* that allows canceling completely the singularity of the Green's function. In [62] it was chosen in such a way that the frequency independent terms of would equal to zero. In this case represents only wave corrections to the static part of the effective permittivity. In [63] it was shown that it is expedient to find the matrix *R* considering the electrostatic problem for inhomogeneity of the medium. The inhomogeneities in form of discs and needles were considered. The following expressions for the static part of effective permittivity have been found:

a. Thin chaotic discs

(13)

where is the permittivity of the scatterer and *p* is the fractional volume occupied by discs (vegetation volume density).

b. Thin chaotic needles

(14)

c. Thin vertical needles (here)

(15)

When p << 1 (see Table 1; *p* is less than 0.01) and >> 1 the above expressions reduce to the form that often used by experimentalists

(Chaotic discs); (16)

(Chaotic needles) (17)

(Vertical needles) (18)

It is shown in [3, 63] that the wave corrections to corresponds to the scattering of Rayleigh particles and in the case of small scatterers the continuous and the discrete approaches provide analogous results for attenuation. The advantage of the continuous model is that it provides for dense (*p* ~ 1) media (for example, snow), while the discrete model is applied for sparse media.

2.2. Effective dielectric constant of vegetation.

Expressions (13) – (18) were used by researchers to calculate the effective dielectric constant of vegetation and the values connected with it.

In work by Du and Peake [65], attenuation properties of foliage media in UHF-band were calculated using concept for *p* = 0.001-0.005 and where is the dielectric constant of saline water contained in leaves at the ionic conductivity values of (2…4)·10^{-3} Ohm^{-1} cm^{-1}. Reflection from vegetation canopies at small sliding angles was calculated in [66] using Fresnel formulas and expressions (16), (17). Tensor of dielectric permittivity of foliage media was derived in [67] where the data on conductivity and on volume fraction of vegetation are presented. The effective dielectric constant of foliage was calculated in [68] using data from [67].

Effective dielectric constant was calculated in [7] for wheat and soybean and in [8] for corn. In works [64, 70], the effective dielectric constant of foliage is calculated for spherical inhomogeneities. In papers [71, 69], the effective dielectric constant of vegetation is modeled by the expression

(19)

with (linear model), (refractive model), and (cubic model). The best results are found for the refractive mixing model. In paper [72], formulas (17), (18) were used to calculate the attenuation in forest canopy. Unfortunately, data on the direct measurements of the effective dielectric constant of vegetation were not found. In the works mentioned above was used to calculate the attenuation (or the reflection). Calculated values of attenuation (reflection) were in good agreement with measured ones. It shows a capability of the continuous concept in vegetation modeling.

Data on the effective dielectric constant of vegetation given by researchers are presented in Table 4. One can see that because the vegetation is very a sparse medium the effective dielectric constant is only slightly differs from the unit. It provides the very low (negligible) values of reflection coefficient at the near to nadir angle. Reflection is significant only at small sliding angles. At the same time the reflectivity of a vegetation layer can achieve the values of 0.05…0.15 [2] due to the scattering by the plant elements. In the continuous approach the scattering effects are neglected since the size of scatterers is proposed very small compared with wavelength. This circumstance places a limit (as it was mentioned) on the continuous approach applicability.

Table 4. Effective dielectric constant of vegetation.

Vegetation type	Frequency band	Effective dielectric constant
Wheat stalks [7]	X-band (10.2 GHz)	1.036 + j0.01644 ( ) 1.006 + j0.00042 ( )
Soybean [7]	X-band (10.2 GHz)	1.038 + j.01707
Coniferous forest [68]	L-band (1.4 GHz)	(1.00095…1.0028) + j(0.00019…0.014)
Deciduous forest [68]	L-band (1.4 GHz)	(1.0028…1.19) + j(0.00058…0.038)
Foliage [70]	50 MHz 200 MHz 500 MHz 800 MHz 1300 MHz	1.03 + 0.00073 1.03 + 0.00046 1.03 + 0.00028 1.03 + 0.00021 1.03 + 0.00020

3. The model of vegetation as a collection of scatterers (discrete model).

3.1. EM waves propagation in a random discrete medium.

The discrete model was applied in [8, 17-20, 40-45, 47, 48, 75-91] to find the propagation and scattering characteristics of vegetation canopies. To understand some peculiarities of the discrete approach the main results of the theory of wave propagation through discrete random media should be considered [88-90, 3].

The propagation of the mean field through such a medium may be described by the dispersion equation for the wave number [88]

(20)

where is the Fourier transform of the mass operator of the Dyson equation for the mean field. Based on

Finkelberg's approach [88]

(21)

where is the *s*-point correlation function and T_s is the scattering operator for a system of *s* scatterers located at the points . For independent scatterers and

(22)

where *n* is the number density of scatterers and T_1 is the scattering operator of one isolated scatterer. This is the Foldy-Twersky approach for independent point scatterers. The substitution of in the dispersion equation by signifies neglecting spatial dispersion of the mean field and leads to the radiative transfer equation for the field coherence function. It is valid when

(23)

Under this condition dispersion equation can be approximated as

(24)

In this case (fare-zone approximation) EM parameters of a discrete media are determined by scattering and extinction of electromagnetic wave by a single scatterer. The field scattered by the scatterer in the far-zone is given as [89]

(25)

where is the complex scattering amplitude. The extinction cross section and scattering cross section of the scatterer are found from the expressions

= (26)

(27)

where is a unit vector defining the polarization of incident wave, is the element of solid angle, and Im denotes the imaginary part. The absorption cross section is determined by the Ohmic losses of the field inside the scatterer

(28)

where is the imaginary part of scatterer dielectric permittivity. According to the optic theorem

(29)

Parameters of the transfer theory are the extinction coefficient , the single scattering albedo , and phase function . These values are given by the expressions

, , (30)

and (31)

Practically, considering the discrete model as applied to vegetation canopies, all studies used the radiative transfer theory. The applicability of transfer theory is theoretically proved for the case when the individual scatterers are located in the far zone of each other [90]. In this case the extinction is a linear function of the number density (neglecting correlation between particle positions). It is shown in [3, 73-74] that it is valid for the vegetation canopies with fractional volume density . For dense vegetation the "dense medium radiative transfer theory" [91] or "dense medium phase and amplitude correction theory" [87] can be applied.

3.2. Attenuation and scattering of EM waves by plant elements.

3.2.1. Theoretical models.

Electrodynamic parameters of vegetation media in the discrete model is characterized by the scattering operator (or scattering amplitude, or scattering and extinction cross sections and , respectively) of a single scatterer and, hence, it is important to examine scattering and extinction by different individual plant elements. The sizes of leaves, stalks, branches, and trunks in the frequency band of interest are comparable with the wavelength (resonance region) and, therefore, the scattering and extinction cross sections must be calculated from diffraction models that take into account the shape and size of a plant element as precisely as possible. Since the elements of plants are similar in shape to flat discs, strips (leaves), and cylinders (stalks, branches, and trunks), the diffraction problems for bodies with the above shapes are usually discussed. Known solutions for perfectly conducting infinitely thin disc and strip are not applicable to find the emissivity of vegetation layer because the last is determined by the active losses in a medium (but they may be useful in calculating scattering from vegetation [92]). The solutions of the diffraction problems for dielectric discs and strips are not known. In this case the cross sections and can be found only under some restrictive assumption between the size of an element and the wavelength. The following models were used.

a. Small particles (low-frequency asymptotic case).

A general formulation for the scattered field can be obtained via the Helmholtz integral equation. For a scatterer located at the origin, the Helmholtz integral equation relates the far zone scattered field to the field inside the scatterer through the relation [3, 93-98]

(32)

where is the unit dyad and is the observation direction. For small spheroid

= (33)

where is the polarizability tensor and is the incident wave at a given point.

For a small disc and for the principle directions [97]

(34)

where *d* is the thickness, *a* is the radius, and is the area of the disc.

b. Very large plane particles (high-frequency case).

The absorption and scattering cross sections of such particles can be expressed, neglecting edge effects, in terms of the reflection coefficient and the transmission coefficient of an infinite layer of the same thickness [97, 99]

(35)

For , a condition that is satisfied for leaves up to the X-band, when the wave is normally incident upon the layer [97]

(36)

c. Plane thin particles (resonance case).

This problem is considered in [94, 97, and 100] with the use of generalized Rayleigh-Gans approximation. When the wave vector of the incident wave is normal to the plane of the particle it was found for discs [97, 100]

(37)

where is the Bessel function of the first order. These expressions reduce to the case of small disc with . The results for arbitrary incidence and polarization one can find in [94].

d. Dielectric cylinders.

The relationships for the extinction and scattering cross sections of a cylinder can be found in [8, 94, 97, 100, 101, and 102]. As a rule, the solution of diffraction problem for infinite cylinder first given by Wait [105, 106] for arbitrary incident angle is used. The calculations and experiments have shown that in this case the effect of resonance extinction and scattering are significant [8, 94, and 100].

3.2.2. Experimental data.

Actually, there are rather few papers where experimental data on microwave scattering and absorption by pant elements are presented. Passive (radiometric) and active (radar) methods were used to measure the extinction, scattering, and backscattering cross sections of leaves, stalks, and brunches.

Measurements of the attenuation loss for horizontally polarized and vertically polarized waves transmitted through a fully grown corn canopy, and of the phase difference between the two transmitted waves were conducted in [8] at frequencies of 1.62, 4.75, and 10.2 GHz. The measurements were made at incidence angles of 20°, 40°, 60°, and 90° relative to the normal incidence. Experimental data were compared with computed ones which were based on a model of infinite cylinders (stalks) and randomly oriented discs (leaves). The proposed model was suitable for corn-like canopies.

Measurements of backscattering from leaves were conducted in [92, 94]. In [94] the disc and finite cylinder models based on the generalized Rayleigh-Gans approximation were compared with measurements of backscattering cross sections for an aspen leaf and a birch stick. There was a good agreement between the theory and the measurement except of small incident angles for stick that was explained by possible diffraction from the stick ends (the model considers the inner field equaled to the field inside an infinite cylinder; this was first noted in [100] where the diffraction problem at the end of circular cylinder was discussed and additional extinction due to the diffraction at the end of cylinder was calculated).

Propagation in simulated canopies composed of bare deciduous twigs and leafy coniferous brunches was investigated at 9 GHz [103] and interpreted [104] upon the Foldy-Lax theory for coherent wave propagation through a sparsely discrete random medium. The infinite cylinder scattering function was applied. A good agreement was obtained between the model and attenuation observations.

A radiometric method was proposed in [107] to measure the transmissivity and the reflectivity of leaves at frequencies 21, 35, and 94 GHz. Different kinds of crops and trees leaves were investigated. The model of an infinite flat dielectric sheet (very large plane particle) was in good agreement with the measurement and was used to examine the dielectric behavior of leaves in the frequency band reported.

The radiometric method was also applied to measure the extinction and scattering cross sections of leaves and branches at frequencies of 1, 1.67, and 13.3 GHz [97, 100]. Dependencies of the cross sections on the leaves and brunches dimensions were investigated. The experimental results were compared with theoretical ones obtained for the models introduced above.

Analysis of data of the numbered investigations enables one to make the following conclusions.

The general behavior of EM extinction and scattering by leaves is well described by the thin plane particle model (the generalized Rayleigh-Gans approximation) at frequencies below S-band. This model is successfully applied in known backscatter MIMICS and Santa Barbara models for vegetation [18, 19]. At centimeter wavelengths, the resonance attenuation and scattering (appearing when the leaf dimension is comparable with the wavelength) is significant [3, 97]. In this frequency range further development of models is required to evaluate the extinction and the scattering by leaves. For (*a* is the width of a leaf in the form the of a strip, and *D* is the diameter of a round leaf) the large plane particle model can be applied. The long cylinder model is a satisfactory one for calculating and of stems and branches when their length . For , the small (Rayleigh's) particles model can be used. When , resonance effects of extinction can be significant [97, 100].

4. Dielectric properties of vegetation constituents.

4.1. Theoretical models.

The dielectric constant of vegetation material is a significant point of the theory. This value is governed by water content and salinity of plant elements. Despite its fundamental importance, however, the dielectric behavior of vegetation material is not well understood in the frequency band considered. The dielectric mixture models to relate the dielectric constant of vegetation to the dielectrics of its constituents – the bulk vegetation material and liquid water – changed from quite simplistic forms [60] capable of providing approximate estimates at best to complicated ones such as the dual-dispersion model [108], for example.

The simplest approximation for the dielectric constant was proposed by Peake [75] and was used by many researchers. It reads

(38)

where is the relative complex dielectric constant of water. The relative complex dielectric constant of saline water is given by the Debye relaxation equation [108]

(39)

where and are the static and high-frequency limits of , $= 8.854\times10^{-12}$ F·m^{-1} is the permittivity of free space, *f* is the frequency in hertz, and *s* is the ionic conductivity of the aqueous solution in siemens per meter. Conductivity value is determined by salinity *S* of the solution. The salinity is defined as the total mass of solid salt in grams dissolved in 1 kg of solution and is expressed in parts per thousand (^{o}/oo) on a weight basis. The relation of the model parameters to the temperature and the salinity of the solution can be found, for example, in [113].

In work [109], different dielectric mixing models were examined to fit experimental data on the dielectric constant of wheat and corn leaves and stalks. The propagation (refractive) two-phase model, the random-needle two-phase model, the random-disc two-phase model, the three-component random-needle model (accounting for “depressed” value of due to an action of suction forces [110]), and the four-phase refractive model (where the water was subdivided into a *bound*-water component and a *free*-water component; bound water refers to water molecules that are tightly held to organic compounds by physical forces, and free water refers to water molecules that can move within the material with relative ease) were considered. The free-water component is assigned the dielectric properties of bulk water (the Debye equations) and the bound-water component is assumed to have dielectric properties similar to those of ice. It was noted in [109] that until further work is performed to better determine the roles of free and bound water in heterogeneous materials, it will not be possible to uniquely specify a dielectric mixing model for a vegetation-water mixture.

To determine the dielectric dispersion properties of bound water, measurements were made [108] for sucrose-water solution of known volume ratios. On this basis the Debye-Cole dual-dispersion model was proposed by Ulaby and El-Rayes and was found to give excellent agreement with experimental data for corn leaves and stalks over the entire 0.2…20 GHz frequency range [108].

The three component model has the form

(40)

where and are the dielectric constants of free and bound water, respectively; is the volume fraction of free water, is the volume fraction of the bulk vegetation – bound water mixture. At room temperature (*T* = 22°C) and salinity °/oo is given by [108]

(41)

where *f* is in gigahertz and *s* (the ionic conductivity of the free water solution) is in siemens per meter. One of the unknown properties of the mixture is the water distribution between free and bound fractions. The magnitudes of and *s* and their variations with the gravimetric moisture content were determined in [108] by fitting the model to the measured data of . For green leaves (=0.6…0.7) volume fractions of free water and bound water ([108]) occurred to be approximately equal. In general, it was proposed in [111] that most water is in a bound state when the water content of vegetation is low, and the fraction of free water increases with increasing water content. For example, the amount of free water for green leaves varies from 20% to 40% of total saturated weight, while the amount of bound water varies from 15% to 40%. In young xylem tissue [111], free water represents about 51% of the stem volume and reduces to 1% in wood older than 40 years. The amount of bound water is around 12% - 13% and remains essentially unchanged with age.

One can see that the apportionment of water between bound and free states is a critical point of the model. Relations, which related the volume fractions of free and bound water to the gravimetric moisture content and which were found in [108] for corn, can not be valid for forest vegetation, for example.

Another critical point is that the model makes assumptions about the organic material which may not be appropriate for forest constituents, for instance, for forest litter [112]. In particular, the dual-dispersion model, which is used to model corn leaves, assumes that the water in the organic material is composed of two parts, some of which is free and the rest is molecularly bound to sucrose sugar. While this model is more than adequate for corn leaves, other sugars may predominate in aspen and pine, for example [112]. As a result, bound water can demonstrate other dispersion characteristics.

The dual-dispersion model was used in a number of radar backscatter experiments on forests to derive complex permittivity values. Some researchers use more straightforward approach i.e. direct dielectric measurements on trunks, branches, and needles [114].

A semi-empirical formula for was developed in [115, 116] for broad leaves of different plants. The explicit parameters are the dry-matter fraction, = (dry mass)/(fresh mass), of the leaf and the complex permittivity of saline water . Implicit parameters are temperature, salinity, and frequency as determining . For most plants the salinity was assumed close to 1 °/oo (that is several times less than in [108, 109]). The formula is applicable in the frequency band of 1…100 GHz to fresh leaves; their value is in the range 0.1…0.5 while their density is near 1 g/cm^3. The explicit form for is given by

(42)

The simplicity of the equation and its validity over a large frequency range makes this formula attractive for the electromagnetic modeling of vegetation canopies.

4.2. Experimental data.

An extensive study of dielectric properties of vegetation materials started from works [109, 117]. In work [109], three waveguide transmission systems were used to measure the magnitude and phase of the field transmission coefficient of the sample contained in the sample holder. The sample holder was filled with chopped vegetation material. The relative complex dielectric constant of the sample was determined from measurements of the transmission coefficient and, then, was recalculated into the dielectric constant of vegetation material using the simple propagation (refractive) model. The dielectric data reported in [117] were based on measurements of the amplitude and phase of the reflection coefficient of a coaxial probe terminated in the material under test. To avoid the difficulties with measurements of thin materials a technique was developed that included measurements of the input admittance when the probe is terminated with a thin dielectric slab placed against a background consisting of an electrically thick material with known dielectric constant.

The coaxial probe technique was developed further to design an Applied Microwave Corporation Field Portable Dielectric Probe (PDP) [111, 114, and 118]. Appearance of PDP allowed a set of extensive *in situ* and *in vivo* measurements of the complex permittivity of tree material [119-126, 111, and 114]. Some experimental data can be found also in [116, 127, and 128].

The relationship between xylem tissue dielectric constant, xylem sap flux density, and xylem sap chemical composition as measured in the stems of two Norway spruce was examined in [111] at frequency of 0.5 GHz. It was shown that spatial and temporal variability in the xylem tissue dielectric constant is influenced not only by water content, but by variations in xylem sap chemistry as well. For tree A the real part of changed along the trunk height in the limits of 6…11; the imaginary part of changed along the trunk height in the limits of 1…2. The temporal variations of and did not exceed 2 and 0.5 units, respectively. For tree B the real part of changed along the trunk height in the limits of 7…22; the imaginary part of changed along the trunk height in the limits of 0…4. The temporal variations of and did not exceed 6…14 and 2 units, respectively. The correlation between dielectric properties and water regime and sap chemistry has important implications for microwave remote sensing of forested landscapes.

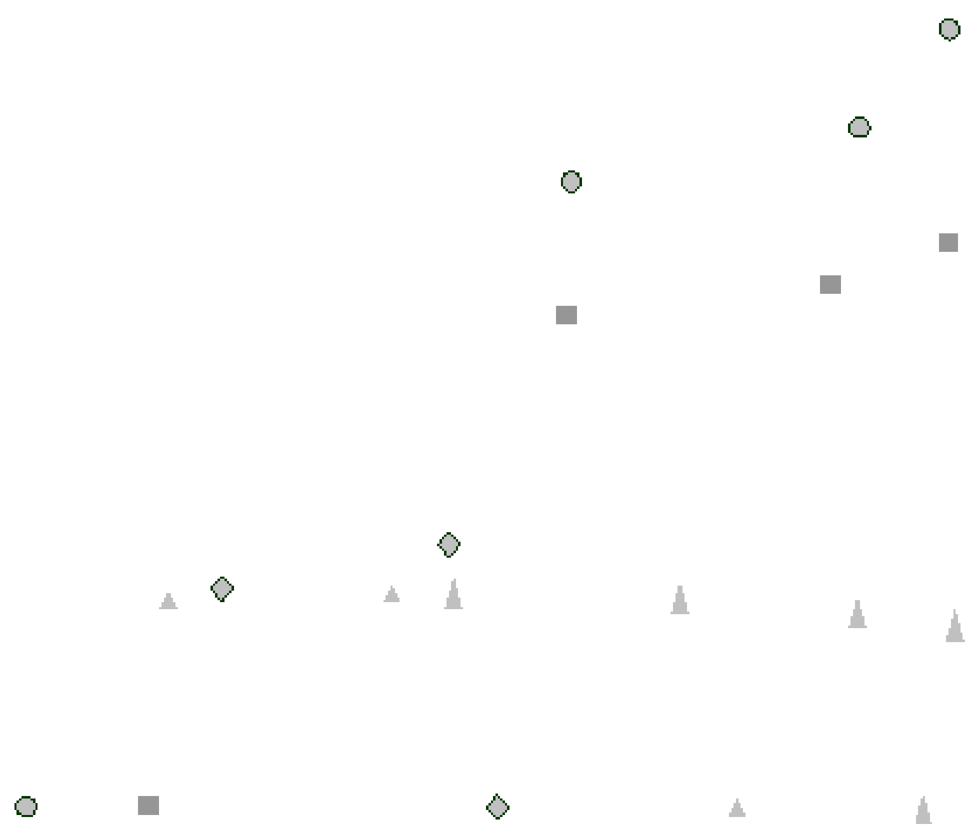

Fig.1. Measured values of the imaginary part of the dielectric constant for different forest and plant constituents. [114]: 1 – new and old needles of the spruce and old needles of the fir; 2 – new needles of the fir;

3 – trunk xylem of the fir (in the longitudinal direction); 4 - trunk xylem of the spruce (in the longitudinal direction); [108]: 5 – corn leaves (m_g = 0.68); [111]: 6 – Norway spruce trunk xylem; [117, 129]: 7 – aspen leaves; [128]: 8 – pine branches; [114]: 9 – branches xylem of the fir (in the longitudinal direction); [129]: 10 – trunk of balsam fir (m_v = 0.17).

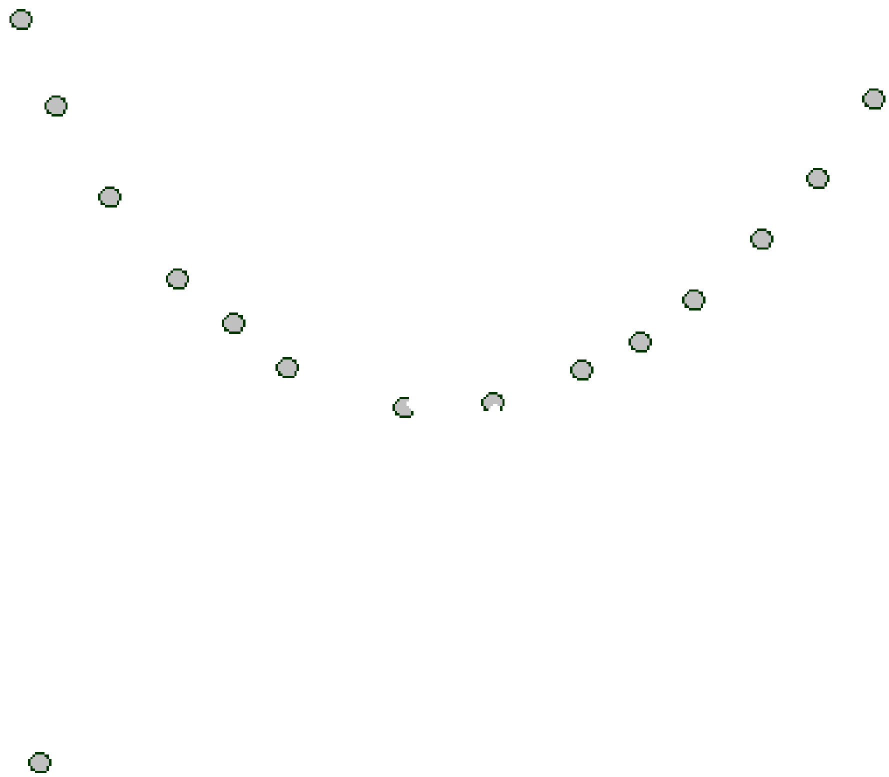

Fig.2. Frequency dependence of the imaginary part of the dielectric constant for free and bound water. 1 – free water (salinity S = 0 º/oo); 2 – free water (salinity S = 2 º/oo); 3 – bound water.

Similar values of spatial variations of the dielectric constant were found in [114]. The measurements were conducted in the frequency range 1 – 10 GHz. The measurement method was based on an open ended coaxial probe reflection technique with a rational function approximation model for the probe tip aperture admittance. With this model, no calibration on reference liquids is required and sufficiently accurate results for the dielectric constant ( ) and loss factor ( ) can be obtained. Results were presented for branches, parts of trunks, and needles from different tree heights. Values obtained with the probe oriented along different stem directions of the trunk confirmed the anisotropic nature of wood. The longitudinal complex permittivity was roughly 1.5 – 3 times higher than the transverse component. Representative average values for trunks, branches, and needles were given.

From the standpoint of attenuation in vegetation it is interesting to consider frequency dependence of . We plot some available data of versus frequency (Fig.1). Fig.2 shows the response of the imaginary part of the free and bound water dielectric constant as a function of frequency [108, 111]. Analysis of the data presented in Fig. 1, 2 shows the following.

In the frequency range 2…10 GHz (S, C, and X band) the loss factor of tree needles and leaves amounts to 8…15. These values are higher than the highest values for corn leaves. It can be explained by the other, than for corn leaves, apportionment between free and bound water states in tree leaves tissue. The values of are in agreement with data of the other researchers. Trunk xylem changes in limits of 7…10; that is less than of needles but higher than that of corn leaves. We have to note that other researchers reported lower values of for trunks. For example [129], at frequency of 5 GHz measured data of amounts to 1.96 – 5.97 for the old aspen, to 1.2 – 6.34 for the spruce, to 0.93 – 6.13 for the old pine, and to 1.02 – 4.56 for the young pine. Low values of branches xylem in contrast to those of trunk xylem, nevertheless, are in agreement with data of for young pine [129].

Frequency dependence of in the range 1…10 GHz are in good agreement with the dependence predicted by dual dispersion model with appropriate composition of volume fractions of free water and bulk vegetation – bound water mixture . For green leaves is large and contribution of free water component is significant that leads to the increase of with the increase of frequency. Accurate choice of model parameters and could be done by fitting experimental data like it was done in [108]. Our estimate shows that the measured values of for leaves and the observed slope of its frequency dependence can be provided by the model with = 0.2…0.3 and ~ 0.5. For example, we plot the frequency dependence of for = 0.3 and = 0.5 (S = 2º/oo). It is shown in Fig.1 by asterisks. One can see that the model can well explain the spectral behavior of . Larger values of produce greater slope of frequency dependence that is in a contradiction with experiment. With low values of m_v (see data for balsam fir in Fig.1), the free water component is practically absent and frequency dependence is similar to that of bound water mixture (Fig. 2).

Maetzler's semi-empirical formula [115, 116] also gives good agreement with experimental data. We plot the calculated data in Fig.1 by black points for = 0.4 and S = 2º/oo. It should be noted that smaller values of would produce greater slope of frequency dependence that disagrees with experiment.

Unfortunately, we couldn't find data on dielectric properties of tree leaves and branches in the frequency range 0.1 – 1 GHz (data for corn leaves are presented in [108, 117]). Probably the open-ended coaxial probe reflection technique meets some difficulties in this frequency domain [114] and should be further developed or another technique should be suggested. There are also very few data for trunks in this band. We think that extensive measurements of in this frequency range with continuous change of frequency (like it was done in [114] in the range 1.9 – 9.1 GHz) would be extremely useful to understand the frequency dependence of attenuation by vegetation and of emission and backscattering from vegetated terrain.

5. EM waves propagation through a vegetation layer. Relation between electromagnetic and biometric vegetation parameters.

To calculate radar return (or emissivity) from vegetation canopies the vector radiative transfer equation is used [96]. It is of the following form: For

(43)

where is a 4×1 column vector denoting the modified Stokes parameters in direction , is the 4×4 phase matrix denoting scattering from direction into direction , and is the extinction matrix which can be expressed in terms of the forward scattering amplitudes (see Section 3.1). For the case of thermal emission the right side of the equation is added by the term where is the absorption matrix and T is the physical temperature of the canopy.

The relation between the components of , particularly, the extinction coefficient γ for given polarization (or the optical depth) and biometric parameters is established by expressions (26) – (30). The extinction cross sections are calculated for simple geometric elements (ellipsoid, cylinder, and disc) (see Section 3.2.1) which are characterized by their dimensions and dielectric constant (see Section 4).

For the simplest case of small chaotic ellipsoids it was obtained [3, 48] using (33) and (34)

(44)

where u = 1 for small needles and u = 2 for small discs (see the nomenclature in Section 1.1). For other cases the semi-empirical equations is used [48, 2]

(45)

where A is the coefficient (form factor) related to the plant structure, f is the frequency. Taking into account that in the microwave band weakly depends on the frequency (see Fig.1) and ~ 10 the simple equation could be obtained for attenuation by crops and foliage in the frequency range 1 – 10 GHz [3, 28, 29, 130]

(46)

where α is the attenuation in dB, U = 2.5…5 depending on the vegetation type, λ is the wavelength in cm (λ [cm] =), W is the vegetation water content in kg per square meter. More complicated equations are given in [74].

The equations given above are very simple and can provide only rough estimates of attenuation by vegetation canopies. Nevertheless, these expressions are rather useful since they help someone to understand what the attenuation in vegetation depends on.

To obtain more accurate estimates of attenuation numerical solution of the transfer equation is used [1, 17 – 19]. The scattering amplitudes of dielectric needles, discs, and cylinders are computed on the base of generalized Rayleigh-Gans approach or other developed approaches for dimensions and dielectric constant of scatterers obtained from *in-situ* measurements (see Table 2 and 3). Computed data of backscattering coefficients are in good agreement with experimental data [1]. Unfortunately, when a numerical solution of transfer equation is used it is rather difficult to separate the influence of the change of model parameters (dimension of scatterers, their number density and moisture content, etc) on the value of attenuation or backscattering coefficient. In other words, it is not clear enough as to what biometric parameters determine the attenuation by a canopy and how strong they influence the attenuation.

Besides, applying the numerical solution, a researcher should remember the following.

i. Vegetation elements are substituted in the model by simple forms like circular discs and circular cylinders of finite length. However, even for these bodies the rigorous solution of the diffraction problem is not known and approximate models are used. The extinction coefficient is calculated as the sum of extinction cross sections of elements occupied a unit volume (30). That does not take into account the effects of mutual screening and correlation of scatterers [3, 74]. As a result, the error of the model can be significant.

ii. Because a vegetation canopy is an inhomogeneous medium, its coherent attenuation should be treated as a random value [8]. Calculating extinction with given dimensions, angular distributions, and number densities of scatterers we should understand that we obtain the mean value of extinction and the sampling values can change in wide limits for the given canopy. For example, variations of attenuation for corn canopy amounts to 50 % and more within the test site [8]. It shows that it is interesting to know the relative level of attenuation at different frequencies rather than absolute values of attenuation.

Theoretical models are extremely important and should play a vital role in the research process since they are indispensable for conducting sensitivity analyses and for pointing the directions of future research. But, in our opinion, because any model is based on certain assumptions, modeling process can only indicate the factors determining, for instance, attenuation by vegetation. Parameters of the model should be found by regression analysis of experimental data. For example, for a part of the frequency band considered the extinction coefficient could be found out in the form [130]

(47)

where *A* is the form factor determining by vegetation type, *b* is the coefficient depending on the vegetation moisture content, *f* is the frequency, and *w* is vegetation water content per unit volume. Other forms of the regression models can be also suggested.

The angular dependences of attenuation by stands described in Table 1 and 2 are presented in [1] for different frequency bands. Attenuation is given as the percent of radar beam power lost (scattered and absorbed) while traveling through the canopy along the direction of propagation to the forest floor. We recalculated these data to the attenuation in decibels. These data for incident angle of 30° are presented in Table 5.

Table 5. Attenuation by the stands from Table 2 and 3.

Stand	Attenuation in dB (H polarization)			
	P – band	L – band	C – band	X – band
Aspen leaf on	2.2	3.5	16	> 16
Hemlock leaf on	0.7	2.4	12.5	>16
Maple/beech	4	11	16	
Red/white pine	1.7	5.5	13	

One can see that the computed attenuation values differ from each other by several times for the stands. Strong frequency dependence of attenuation is present.

Polarization signatures of attenuation arise when an oriented component (stalks, trunks) is present in the vegetation canopy [6-9, 17-19, 29, 38, 58, 73, 74, 79, 83, 97, 100, 103]. The difference in attenuation of vertically and horizontally polarized waves can be large and is used in retrieving algorithms [28, 29, and 38].

Shutko

III. EXPERIMENTAL STUDIES OF EM WAVES ATTENUATION IN VEGETATION CANOPIES.

1. The methods of measurements.

Measurements of attenuation by vegetation were conducted under laboratory conditions, under ground-based field conditions, and from aircrafts.

Laboratory experiments have the advantage that parameters of investigated objects can be changed and controlled. They allow examining the influence of individual parameters on the EM propagation characteristics of the medium.

Ground-based field measurements produced the largest amount of information on propagation properties of vegetation canopies. The natural conditions provide the possibility to obtain data during the whole period of canopy growth and to compare them with ground truth data.

Airborne sensors provide a possibility to gather quickly a large data set for different types of vegetation under various states and conditions.

Methods which were used to measure the attenuation can be divided into active and passive ones. In active methods, the attenuation over the path between transmitting and receiving antennas is measured. Airborne radar studies used corner reflectors and active calibrators placed on the ground at different locations within a canopy. Several typical configurations of active measurements are presented in Fig.3.

Configuration Fig.3 A) was used in [7, 8, 58, and 109] to measure attenuation in different crops such as wheat, corn, soybeans, etc. The transmitters were placed on a truck-mounted platform and the receivers were

Fig.3. Typical configurations of active measurements of attenuation.

Fig.4. Typical configurations of passive measurements of attenuation.

placed underneath the canopy. Measurements were conducted at different frequencies, polarizations, and incidence angles. Besides, measurements of the phase difference between horizontally polarized and vertically polarized simultaneously transmitted waves were presented in [8]. Calibration was provided by cutting and removing the plants to establish a free-space reference signal.

Configuration Fig.3 B) with different height of antennas above the ground is usually used for investigation of electromagnetic waves propagation in forest environment [131, 139-142, 163].

Configuration Fig.3 C) was used in laboratory measurements of attenuation by forest litter [112] and forest fragments [103]. A vector network analyzer measured the power and phase of the signal passing through the cell [112].

Attenuation constant of a layer was determined by comparing measurements of litter with that of the empty cell. In work [103], vegetation samples were placed on a Styrofoam frame, in one row or several rows with different spacing. Measurements were performed with vegetative targets and the transmitted power was recorded. After removing the targets the reference power was then recorded to find the attenuation. Configuration Fig.3 D) is used in airborne and space borne radar studies of attenuation and backscattering [132-138, 155-158, 160, 161, 164]. Attenuation is determined by comparing signals from reflectors placed beneath the canopy and placed on the open ground.

Passive methods use the measurements of thermal emission from the investigated object in the presence of atmosphere and space emission as the background. Typical configurations used in passive (radiometric) measurements of attenuation are shown in Fig.4.

Configuration Fig 4. A) was proposed in [30, 6] for the field measurements of attenuation by corn and soybeans. The zero-order solution of the transfer equation for the emission from vegetated soil was reduced to

(48)

where T_0 is the vegetation and soil physical temperature, R_s is the reflectivity of the soil surface ( ), and T_{sky} is the down welling sky (atmosphere and space) brightness temperature. The simplified equation was used to determine the reflectivity *r* and the transmissivity *q* by measuring the brightness temperature T_b for a) bare soil, b) canopy over soil, c) bare absorbing material with an emissivity close to unit, and d) canopy over the absorbing material. To increase the accuracy of measurements the soil was covered by screens which were wire meshes with an inter wire spacing of 1.6 mm and wire thickness of 0.3 mm. The brightness temperature was measured by a dual-frequency 2.7 and 5.1 GHz), dual-polarization radiometer mounted atop a truck-mounted boom. It was shown that the canopy is highly anisotropic, the emission exhibits a strong dependence on polarization and look direction, and the reflectivity is typically less than 0.1.

The technique described ensures good accuracy but it is very cumbersome. Field measurements of the transmissivity were conducted with microwave radiometers mounted on a truck [5, 11, and 134] and on a car [133]. The transmissivity was estimated by the relation that one can easy obtain from (1)

(49)

where and are the emissivity of vegetated and bare soil, respectively, with the same moisture content (and the reflectivity) within a site.

The technique proposed in [30, 6] for field measurements can be easily performed under the laboratory conditions [100, 77, 145-147] (configuration Fig. 4 B)). The fresh-cut plants were placed on the reflector located in the far zone of the antenna of the radiometer. As the reflector, a “blackbody” and a metal plate were used. The transmissivity of the vegetation layer was estimated from the expression

(50)

where is the brightness temperature contrast between the bare blackbody and the bare metal plate and is the same contrast but when the reflectors are covered by vegetation.

Configuration Fig. 4 C) was used in [74] to measure the transmissivity of a vegetation layer and in [148, 68] for field measurements of the transmissivity of trees. Attenuation values were estimated by comparing measurements of the brightness temperature with vegetation and without vegetation.

Configuration Fig. 4 D) is used for measurements of attenuation with the help of airborne radiometers [48, 150, and 151].

2. The results of measurements and their comparison with calculating data.

Agricultural vegetation.

Data of measurements of attenuation by crops in the microwave band for different polarizations and look directions are presented in papers [2 - 9, 11, 26-32, 34-36, 40, 43, 48, 49, 53, 54, 58, 69, 71, 74, 81, 100, 109, 130, 143-145]. Analysis of the data shows the following [130].

The dependence of attenuation on the vegetation water content can be approximated by a linear function, i. e. expressions (44) – (46) give a satisfactory estimate for this dependence. Nonlinear dependence of the attenuation on the water content was reported in [3, 5, 40, and 74] and can be explained by mutual screening of vegetation elements [3] or by the temporal change of vegetation water status [40, 74].

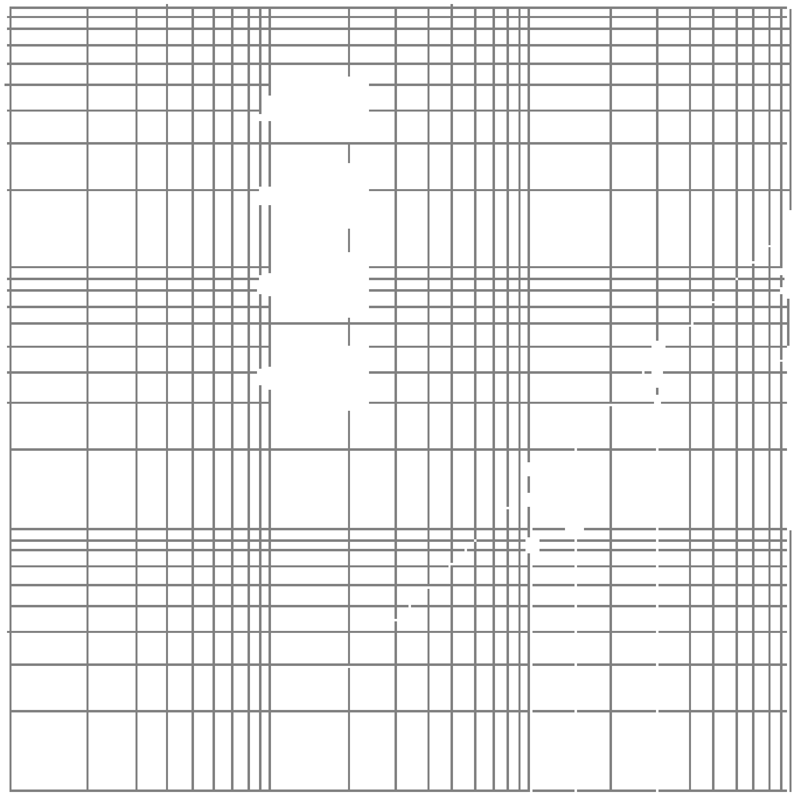

Fig.5. Characteristic values of attenuation by different crops. 1 – corn, sunflower; 2 – pea, alfalfa; 3 – grains (wheat, barley, oat, etc); 4 – soybeans, cotton.

Fig.6. Experimental data on attenuation by different forests. 1, 2, 3, 4 – [64]; 5 – calculated data from [83]; 6 – [151]; 7, 8 – [154]; 9 – [135]; 10 – [134, 152]; 11 – [153].

The generalized frequency dependence of attenuation is presented in Fig. 5 [130]. Data in Fig. 5 relate to the mature state of crops and represent the maximum level of attenuation. In the microwave band, the attenuation by crops is proportional to the frequency in ( ) power ( ) where d = 0…0.2 depending on the crop and vegetation moisture content.

In the microwave band, a rough estimate of attenuation can be obtained from expression (46) . The calculated dependence of attenuation for U = 3 and W = 4 kg/m^2 is presented in Fig.5 by the dashed line. More accurate estimate of attenuation can be obtained from the models taking into account the vegetation structure and dimensions, orientation, and dielectric properties of leaves and stalks (Sections 4 and 5). Numerical calculation of attenuation with use of a computer is required in this case [8].

We could not find experimental data on attenuation by crops in the frequency range 100…1000 MHz. In this band, the salinity of free water contained in vegetation material (or conductivity of plant elements) could be a major factor determining the spectral dependence of attenuation. This factor is not yet sufficiently studied. Measurements and modeling of attenuation in the frequency range 100…1000 MHz and of direct current conductivity of plant elements could be a subject of future research.

Forest vegetation.

Experimental data of the extinction coefficient for different types of forests (rain, coniferous, deciduous) are presented in Fig. 6. We recalculated data on penetration depths found in [1, 83, 134, 135, 151 -153] in the values of attenuation in dB per meter; some data are reported in [64, 154].

Available data of the attenuation by forest canopies are very limited and it is rather difficult to make certain conclusions about the attenuation and its spectral dependence. Nevertheless, the data presented can give someone an idea about observed values of the attenuation and their dependence on the frequency. Analysis of the data shows the following.

There is not a big difference in attenuation values for different types of forests in 100…1000 MHz frequency range. For higher frequencies the values of extinction coefficient at a given frequency reported by different authors differ from each other by several (2…5) times.

The data in Fig. 6 show the general trend of frequency dependence of extinction. In the frequency range 100…1000 MHz this dependence can be approximated by a linear dependence [130]

$$b = 0.8 \qquad (51)$$

where is the attenuation in dB per meter, $c = 8\cdot10^{-4}$ is the regression coefficient, and f is the frequency in MHz. This dependence is shown in Fig. 6 by the dashed line. In the frequency range 1000…10000 MHz a greater slope of frequency dependence is observed.

The values of attenuation (5 in Fig.6) calculated by the model [83] are in agreement with experimental data reported by other researchers. However, the slope of model frequency dependence does not coincide with the general trend of frequency dependence for data presented in Fig.6.

The total extinction in a forest media at frequencies below 1000 MHz is mainly determined by extinction by branches and trunks [1, 64]. The last is not completely studied. A further development of attenuation models requires spectral measurements of attenuation in the wide band and measurements of dielectric constant and conductivity of branches and leaves.

IV. CONCLUSIONS.

An analytical overview conducted in the paper allows us to make the following concluding remarks.

Due to the efforts of many researchers and research groups the basic questions of EM propagation and attenuation in vegetation canopies are clarified. Appropriate models are developed to describe the extinction of EM waves by plant elements and by vegetation volume as a whole. Theoretical and empirical models are available to calculate the dielectric constant of vegetation material in the microwave band. Experimental data of dielectric constant and of attenuation are well fitted by the models.

Nevertheless, several problems remain unsolved that enables one to point the directions of future research areas. In our opinion, these areas could be:

i. Extensive measurements of dielectric permittivity of plant elements in 100…1000 MHz frequency range and of the direct current conductivity of different plant elements;

ii. Extensive measurements of EM attenuation spectra by vegetation canopies under laboratory and field conditions;

iii. Verification of the known models and developing, if it is necessary, new ones to fit spectral data of attenuation.

The designated research areas are planned to be a subject of our further work.

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