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Spectrally-dependent attenuation of microwaves by vegetation canopies

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ABSTRACT: A wide-band waveguide transmission system and measuring technique have been developed to obtain continuous attenuation spectra of microwaves by vegetation in the frequency range 0.8–10.0 GHz. Laboratory experiments have been performed in order to examine the spectral dependence of the attenuation by different trees and tree fragments. Some results are presented showing the distinct difference of the attenuation as a function of the wavelength, vegetation type and moisture content.

1 INTRODUCTION

The attenuation of the microwave electromagnetic radiation by vegetation canopies is an essential factor in land cover radiometric studies. The knowledge of the attenuation effects is extremely important for remote sensing investigations as well as for improving the reliability of radio communications. The multiple dependence of the attenuation on such factors as the wavelength, incident angle, polarization, vegetation moisture, density and structural peculiarities makes the solution of the problem still more difficult.

The available experimental data on microwave attenuation are quite limited and acquired at single wavelengths. Actually, there are almost no data over larger wavelength ranges and continuously changing frequency.

Laboratory experiments could provide data about the spectral dependence of the attenuation by vegetation fragments along with a direct control of the biometric parameters. However, in this case some problems arise. For the correct data interpretation, similar or near to the free space propagation conditions should be provided. At the same time, the influence of surrounding objects (walls, etc.) on the measurements should be minimized. These problems can be avoided by conducting measurements in an anechoic room or using a waveguide camera.

In this paper some results are presented from laboratory measurements of the microwave attenuation by different vegetation types and vegetation fragments (leaves, branches with and without leaves) taking into account vegetation moisture content. Not less valuable are the obtained spectral dependences of the attenuation in a wide wavelength range.

2 BACKGROUND

Passive microwave radiometry is based on measurements of the naturally emitted electromagnetic radiation by ground objects in the mm to dm wavelength range. Inside this band, land cover radiation is primarily a function of the free water content in the soil (which depends on the rainfall rate, artificial watering, shallow groundwater) and is influenced also by other factors, such as soil structure, water salinity and temperature, and above-ground vegetation biomass.

The measure of the microwave radiation intensity is referred to as brightness temperature (T_b) which is a product of the emissivity ($æ$) and the thermodynamic temperature (T_e) within the effectively emitting layer of the object. The emissivity is a function of the dielectric permittivity of the surface. It is negatively correlated with the moisture content.

As example the principle of soil moisture determination by passive microwave radiometry is illustrated in Fig. 1.

Fig. 2 shows the spectral dependence of vegetation transparency for land surface microwave radiation.

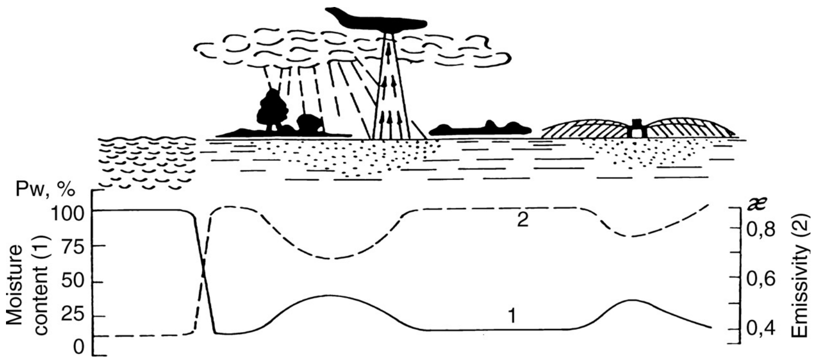

Figure 1. Principle of soil moisture determination by microwave radiometry.

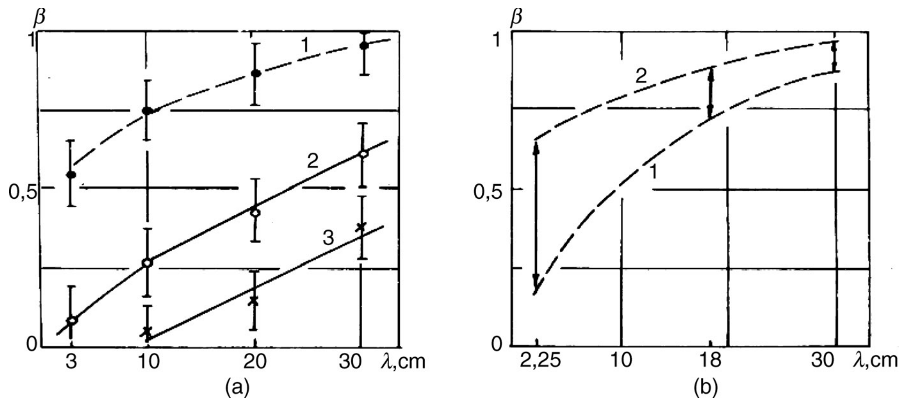

Figure 2. Spectral dependence of vegetation transparency for land surface microwave radiation a) 1- narrow-leaf crops, 2- broad-leaf crops, 3- bushes and trees; b) 1, 2 - majority of agricultural crops.

Figure 3. Photos of the experimental equipment.

3 WAVEGUIDE TRANSMISSION SYSTEM AND MEASURING TECHNIQUE

A wide-band waveguide transmission system is created and a measuring technique is developed to obtain continuous attenuation spectra of vegetation fragments in the frequency range 0.8–10.0 GHz. Photos of the experimental set up are shown in Fig. 3.

The system consists of a wide-band rectangular waveguide, two horn antennas matched with the waveguide, and a Vector Network Analyzer. The block-diagram of the transmission system is presented in Fig. 4. The following equipment is used in the system:

- Vector Network Analyzer;
- two measuring wide-band horn antennas with a coaxial input; the horn aperture is (350 × 260) mm; the antennas operate in the frequency range 0.8–10.0 GHz;
- measuring camera in the form of a rectangular waveguide section with cross section of (350 × 260) mm and length of 1500 mm.

The horn antenna transforms the TEM-wave of the coaxial cable into a H_{10}-wave of the waveguide. Since the antenna divergence angle is not large, the excitation level

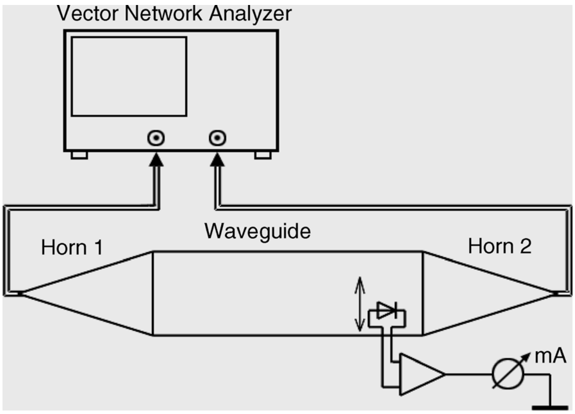

Figure 4. Block-diagram of the transmission system.

of high-order waves is small. When a H_{10}-wave passes through the camera it is attenuated by the object. The second horn antenna, in turn, transforms the coming wave into a TEM-wave of the coaxial cable. In such a way the antennas serve as filters of spatial harmonics providing a single-mode propagation regime in the waveguide and ensuring the correct interpretation of the attenuation measurements. Direct measurements of the electric field distribution in the waveguide confirm the realization of a single-mode propagation regime. They were performed using a diode probe. The electric properties of the system are described in detail in (A.A. Chukhlantsev *et al.*, 2004).

When a H_{10}-wave of the rectangular waveguide propagates in the waveguide the transmission coefficient T of a layer with thickness d is given by the expression (M.T. Hallikainen *et al.*, 1985):

$$T = \left| \frac{(1 - R^2) e^{j\gamma d}}{1 - R^2 e^{2j\gamma d}} \right|^2 \tag{1}$$

where R is the field reflection coefficient and γ is the propagation constant of the dielectric-filled waveguide. Due to the low density of the vegetation samples the vegetation effective dielectric permittivity slightly differs from (1), and the reflection coefficient is small. Equation (1) reduces to:

$$T \approx \left| e^{j\gamma d} \right|^2 \tag{2}$$

The propagation constant of the H_{10}-wave is expressed by

$$\gamma = \sqrt{k_0^2 \varepsilon - \left(\frac{\pi}{a}\right)^2} = k_0 \sqrt{\varepsilon} \sqrt{1 - \frac{1}{\varepsilon}\left(\frac{\lambda}{2a}\right)^2} = \gamma_0 \sqrt{1 - \frac{1}{\varepsilon}\left(\frac{\lambda}{2a}\right)^2} \tag{3}$$

where γ_0 is the propagation constant in the free space, ε is the dielectric constant in the waveguide, a is the waveguide width. Comparing the transmission in the waveguide (2) with the transmission in the free space given by the formula:

$$T_0 \approx \left| e^{j\gamma_0 d} \right|^2 \tag{4}$$

it is found that, due to the slight difference of the vegetation effective dielectric permittivity from (1), the measured attenuation values B(dB) can be recalculated into attenuation in the free space $B_0(\text{dB})$ from the equation

$$B_0(dB) \cong \frac{B(dB)}{\sqrt{1 - \left(\frac{\lambda}{2a}\right)^2}} \tag{5}$$

The transmission coefficient T is estimated by subtraction of the transmission coefficient of the empty waveguide from the transmission coefficient of the vegetation-filled waveguide when the data are presented in dB. The attenuation is related to the transmission coefficient as $B(dB) = -T(dB)$.

4 MEASUREMENT RESULTS

The following measuring procedure was applied. Freshly cut branches were put into the waveguide in order to obtain the attenuation spectrum. The branches were then cut into smaller pieces with different thickness (less than 5 mm, 5–20 mm, 20–50 mm). Samples with and without leaves were examined. The attenuation spectrum by the leaf component was estimated by subtracting bare branches attenuation from the attenuation by leafy branches.

The not-uniform field distribution inside the waveguide results in a different contribution of the different sample parts to the total attenuation. This effect can be partially compensated through: i) uniform distribution of the sample over the waveguide aperture, and ii) repetition (up to ten times) of the measurements with varying position and orientation of the sample components averaging the measurement records. The weight and gravimetric moisture of the samples had been determined before the attenuation was measured. The attenuation values of each sample were recalculated to find the spectral dependences of the specific attenuation of the tree components, i.e., the attenuation per kg/m^2 of the water content of the component.

It was shown in (A.M. Shutko and A.A. Chukhlantsev, 1982) that the optical thickness of a vegetation layer τ is related to the vegetation water content W (kg/m^2) by the expression:

$$\tau = bW \tag{6}$$

where b is a coefficient (characterizing attenuation) which depends on the frequency of the electromagnetic wave, on vegetation type and gravimetric moisture content. This model has been tested by numerous researchers and found to be acceptable for interpretation and modeling microwave radiometric features of vegetated lands (E.G. Njoku *et al*., 2003 and T. Pellarin *et al*., 2003). One of our goals was to study the spectral dependence of the coefficient b.

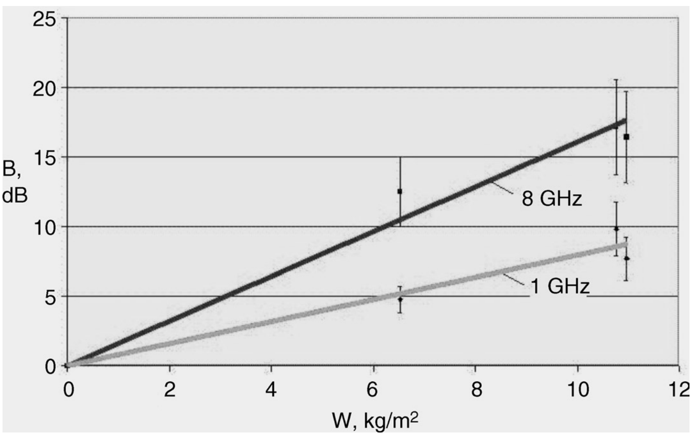

Figure 5. Dependence of the attenuation at two wavelengths on the water content of pine branches (gravimetric moisture 62.7%).

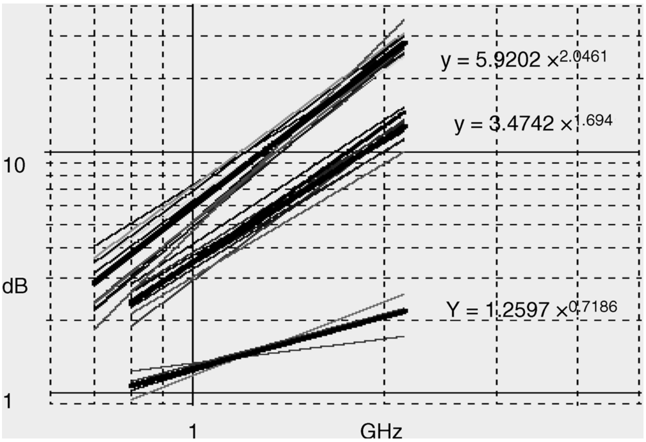

Figure 6. Frequency dependence of the attenuation by pine samples with different gravimetric moisture content: 57%, 41% and 21% (top – down).

$$y = cx^{\beta}(y\text{-attenuation},\ x\text{-frequency}, c\text{-coefficient}, \beta\text{-slope})$$

To test and validate this model, measurements were made of component samples with different weight. It was found that the dependence of the attenuation B on vegetation weight W (water content) was close to linear (Fig. 5).

The frequency dependence of the attenuation by pine samples with different gravimetric moisture content is shown in Fig. 6.

The obtained dependence of the average attenuation slope β on the gravimetric moisture M_g of pine samples is presented in Fig. 7. Some measurement results of aspen samples with gravimetric moisture content 57% are given in Fig. 8. Similar results were obtained for fir, pine and maple tree components.

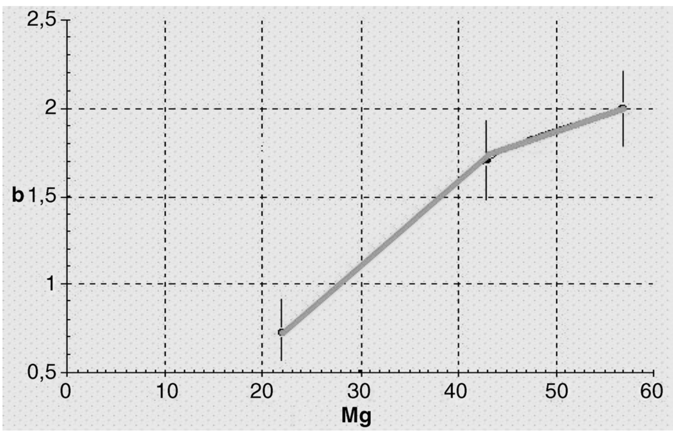

Figure 7. Experimental dependence of the average attenuation slope β on the gravimetric moisture M_g of pine samples.

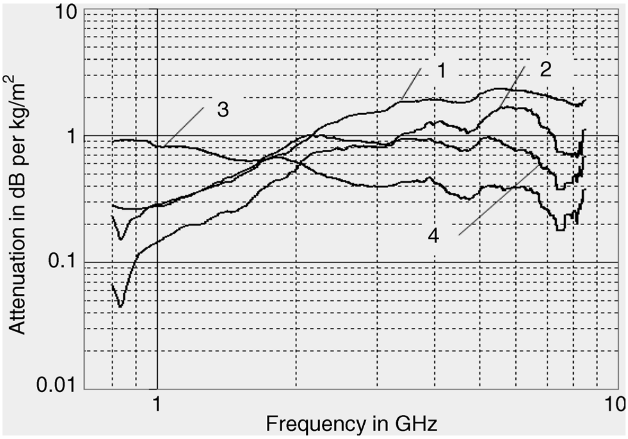

Figure 8. Spectral dependence of the specific attenuation by: (1) leafy branches with a diameter up to 5 mm, (2) the same bare branches, (3) thick branches with a diameter 20–50 mm, (4) branches with a diameter 5–20 mm.

The spectral dependence of the attenuation by leafy and bare branches of different size appeared to be quite different. This can be explained by the resonant character of the attenuation in the microwave band. The available electro dynamic models of branches as dielectric cylinders can only give a qualitative explanation of the experimental data (P. Ferrazzoli and L. Guerriero, 1996) due to the extreme complexity of the investigated object. Attenuation measurements in a wide frequency band, however, can serve as a basis for modeling forest attenuation properties.

The frequency dependences of the attenuation *b* (in Np per kg/m^2) by crown fragments of different tree types with gravimetric moisture content from 42 to 52% are shown in Fig. 9.

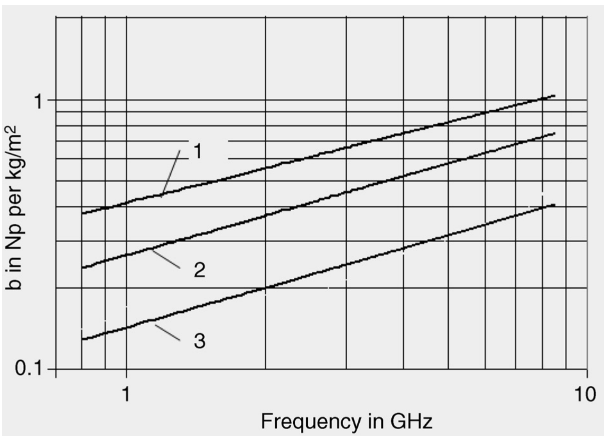

Figure 9. Frequency dependence of the attenuation by crown fragments of different tree types: 1 - maple, 2 - aspen, 3 - pine.

5 CONCLUSIONS

The following work is planned for the future. Forest stands can be considered as consisting of trunks, uniformly distributed primary branches and uniformly distributed secondary branches with leaves. The microwave attenuation by each of the components is estimated on the basis of physical models and experimental data obtained as described above. Regression coefficients are determined by fitting the models to experimental data. The forest attenuation is considered as a sum of the attenuation values of the forest stand components. To reduce the number of biometric parameters the volume of leaves and branches can be related to the volume of trunks per unit area using available correlation links between these parameters.

The presented results of the performed study have practical importance allowing to assess the attenuation of microwaves when passing through different vegetation canopies. The solution of the inverse task permits the evaluation of vegetation parameters from microwave attenuation data.

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