Vegetation Effects on Passive Microwave Measurements

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Abstract. The developed laboratory waveguide transmission system for measuring the attenuation of microwaves by vegetation canopies is discussed. Some results obtained for the attenuation effects by fragments of trees in the frequency band 0.8 – 10.0 GHz are presented. The waveguide transmission system and the measuring procedure provide the acquiring of continuous attenuation spectra in a wide frequency band under controlled vegetation parameters. The propagation characteristics of the electromagnetic waves in the ultra-wide band waveguide transmission system are similar to the propagation characteristics in the free space. This makes possible to use the laboratory results in practice.

I. INTRODUCTION

Forests play a vital role in human life since they represent about 90% of the standing biomass and determine the hydrological and biogeochemical cycles of the Earth. Remote sensing techniques, in particular microwave radiometry, have the potential of monitoring and assessing forest canopies. However, the interpretation of the microwave radiometric data requires a series of efforts such as developing an appropriate theoretical model of forest canopies, establishing a relation between electro-dynamic properties of the forest medium and its biometric features, and estimating forest parameters from radiometric data. In this respect, knowledge of the attenuation effects of forest canopies on microwave measurements is extremely important. First of all, the propagation properties of the forest canopy play a key role in modeling the microwave emission behavior of the canopy. Further, attenuation values and their dependence on the frequency, incident angle, polarization, and vegetation biometrical features, lay at the root of remote sensing retrieval algorithms.

Microwave radiometry is based on measurements of the emitted by the Earth surface electromagnetic radiation in the millimeter to decimeters wavelength range. Within this spectral band the microwave radiation is primarily a function of the free water content in the soil being influenced also by soil texture, water salinity and temperature, as well as by the above-ground vegetation biomass.

The measure of the microwave radiation intensity is referred to as brightness temperature (Tb) which is a product of the emissivity (ε) and the thermodynamic temperature (Te) 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. Figure 1 shows the microwave radiation intensity of different surfaces (metal, water, soil) with varying properties.

II. MATERIALS AND METHODS

In this paper a wide-band waveguide transition system has been created and a measuring technique has been developed to obtain continuous attenuation spectra of vegetation fragments in the frequency range 0.8-10.0 GHz is presented. The system consists of a wide-band rectangular waveguide, two horn antennas matched with the waveguide, and a Vector Network Analyzer. The antennas serve as filters of spatial harmonics providing a single-mode propagation regimen in the waveguide and correct interpretation of attenuation measurements.

Attenuation spectra of aspen, birch, maple and other tree types have been obtained from different tree components. Some results of the performed measurements are presented, which show the distinct difference in the magnitude and frequency dependence of the attenuation by different tree types and tree components. Besides, the influence of vegetation parameters such as moisture content has been examined and found to have a significant effect on microwave measurements.
taken into account. Such an affect, for instance, is the attenuation of microwaves by vegetation canopies. In Fig. 2, the spectral dependence of vegetation transparency for land surface microwave radiation is seen. The figure illustrates also the influence of different vegetation types and vegetation elements on microwave attenuation.

The attenuation of the electromagnetic radiation in the microwave spectral domain is an essential phenomenon in land cover monitoring. The knowledge of different attenuation aspects (wavelength, incident angle, polarization, vegetation canopy influence) is extremely important for the accuracy of microwave data in environmental investigations as well as for improving the reliability of radio communications. Figure 3 is an example of vegetation impact on the accuracy of soil moisture estimation from microwave radiometric data. Three cases are presented: bare soil, vegetation cover when no information about the biomass is available, and when the biomass amount is approximately known. It is seen that the error of soil moisture retrieval significantly increases if not accounting for the vegetation canopy and amount.

The multiple dependence of microwaves attenuation by vegetation canopies on such vegetation features as water content, density and other biophysical variables and structural specifics, 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 spectral ranges and continuously changing frequency.

In our paper we present results from laboratory studies of microwaves attenuation by different tree types and tree fragments. Leaves, bare and leafy branches, tree crowns have been measured considering vegetation size and water content. The continuous attenuation spectra of microwaves in the frequency range 0.8 - 10.0 GHz has been examined. The obtained spectral dependences of the attenuation as a function of the wavelength in a wide-wavelength range are quite valuable. The module-diagram of the developed and used in the study wide-band waveguide transition system is shown in Fig. 4. Figure 5 is a photo of the experimental set-up.

The following equipment is used: • 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 band 800-10000 MHz; • Measuring camera in the form of rectangular waveguide section with a cross section of 350×260 mm and a length of 1500 mm.

The horn antenna transforms the TEM wave of the coaxial cable into a \( H_{0w} \)-wave of the rectangular waveguide. Since the divergence angle of the antenna is not large, the excitation level of high-order waves is small. When a \( H_{0w} \)-wave passes through the camera, it is attenuated by the investigated object. The second horn antenna, in turn, transforms the coming wave into a TEM wave of the coaxial cable. Therefore, the antennas serve as filters of spatial harmonics providing a single-mode propagation mode in the waveguide and a correct interpretation of the attenuation measurements. Direct measurements of the electric field distribution in the waveguide confirm the realization of a single-mode propagation regimen. These measurements were performed using a diode probe. The electric properties of the system are described in detail in [1].

When the \( H_{0w} \)-wave of the rectangular waveguide propagates in the waveguide, the transmission coefficient \( T \) of a layer with thickness \( d \) is described by the expression [2]:

\[
T = \frac{(1 - R^2) e^{j\gamma d}}{1 - R^2 e^{2j\gamma d}}
\]

where \( R \) is the field reflection coefficient and \( \gamma \) 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. The equation (1) reduces to:

\[
T \approx e^{j\gamma d}
\]

(2)

The propagation constant of the \( H_{0w} \)-wave is expressed by:

\[
\gamma = \sqrt{k_0^2 \varepsilon - \left( \frac{\pi}{a} \right)^2} = k_0 \sqrt{\varepsilon - 1} \frac{\lambda}{2a} = \gamma_0 \sqrt{1 - \frac{\varepsilon}{\varepsilon_0}}
\]

(3)

where \( \gamma_0 \) is the propagation constant in the free space; \( \varepsilon \) - the dielectric constant in the waveguide; \( a \) - the waveguide width.

Comparing the transmission in the waveguide (2) with the transmission in the free space, it is found that due to the slight difference from (1) of the vegetation effective dielectric permittivity, the measured attenuation values \( B(dB) \) can be re-calculated to the attenuation in the free space \( B_0(dB) \) by the equation:

\[
B_0(dB) \approx \frac{B(dB)}{\sqrt{1 - \left( \frac{\lambda}{2a} \right)^2}}
\]

(4)

The transition coefficient \( T \) is determined by the subtraction of the transition coefficient of the empty waveguide from the transition coefficient of the vegetation-filled waveguide when the data are presented in \( dB \). The attenuation is equal to \( 1/T \).

The measuring error of panoramic measurements is approximately 0.1 dB and does not contribute appreciably to the total error. The error is determined mainly by the following factors. Not-uniform field distribution inside the waveguide results in different contribution of the different components of the sample to the total attenuation. Besides, the field distribution is different at different frequencies. That leads to an error of the relative level of the attenuation at different frequencies. This error can be partially compensated by i) uniform distribution of the sample over the waveguide aperture, and ii) replicates of measurements of the same sample but with different position and orientation of its components, and consequent averaging of the obtained values.

As the system is not completely matched, multiple reflection between the antennas can arise which leads to multiple-path attenuation at frequencies where the SWR is big. This circumstance can cause distortions in the frequency dependence of the attenuation. The error due to this factor was evaluated by controlling the attenuation at frequencies where the SWR was close to 1.0, and comparing these attenuation values with those at neighbor frequencies where the SWR was high. The estimates showed that the total error did not exceed 10-20 %.

### III. RESULTS AND DISCUSSION

The following measuring procedure was applied. Freshly cut branches were put into the waveguide in order to obtain the attenuation spectrum. The branch was then cut to smaller pieces with different thickness (smaller than 5 mm, 5-20 mm, 20-50 mm). Samples with and without leaves were examined. The attenuation spectra of leaf component were estimated by subtracting the attenuation of bare branches from the attenuation of leafy branches. Every branch was numbered, weighted, and marked. After several days, the measurements were repeated with the same samples. The weight of the branches was measured again in order to control the water content. When the branches were completely dried, their initial and current water content was estimated in terms of gravimetric moisture content:

\[
m_w = \frac{w - w_d}{w}
\]

(5)

where \( w_d \) is the dry weight, \( w \) is the wet weight.

These measurements enable the study of the effects of vegetation water content on the attenuation level and on the slope of the frequency dependence. To assess the influence of vegetation biomass on the attenuation, measurements were conducted on samples with different weight. For investigating the influence of vegetation fraction volume on the attenuation, measurements were carried out on the same sample distributed over the full waveguide length of 1500 mm, and, then, condensed over a smaller length. Every measuring cycle started and finished with a control measurement of the attenuation of the empty camera.

The not-uniform field distribution inside the waveguide results in a different contribution of the different parts of the sample in 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, and 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/m² of the water content of the component. It has been shown in [3] that the optical thickness of a vegetation layer \( \tau \) is related to the vegetation water content \( W \) (kg/m²) by the expression:

\[
\tau = bW
\]

where \( b \) is a coefficient characterizing the attenuation which depends on the frequency of the electromagnetic wave, the vegetation type and the gravimetric moisture content.

This model has been tested by numerous researchers and has been found acceptable for interpretation and modeling the microwave radiometric features of vegetated lands [4]. To test and validate this model, we performed measurements of tree components with different weight. It was found that the dependence of the attenuation \( B \) on the vegetation weight \( W \) (water content) was close to linear (Fig. 6).

\[
\text{Fig. 6. Dependence of the attenuation at two wavelengths: a) } 1.0 \text{ GHz; b) } 8.0 \text{ GHz on the water content of pine branches (the gravimetric moisture is 62.7 %)}
\]

Although these results are only preliminary ones, they enable us to draw some important conclusions. First, a strong dependence of the attenuation on the frequency is observed. The slope of the dependence changed with the variance of samples gravimetric moisture and disposition inside the camera. The average slope of the attenuation spectrum for the pine samples was \( b \approx 2.05, 1.69, \) and \( 0.72 \) with gravimetric moisture given in Fig. 7. Second, an approximately linear dependence of the attenuation on the biomass is observed. To verify these relationships more precise and detailed measurements are required. Third, the attenuation values and the spectrum slope are strongly dependent on the vegetation water content (Fig. 7).

The measuring procedure was conducted in three steps. At the first, freshly cut branches forming a sample were used. Their water content corresponded to their natural status in a winter period. At the second and third steps, all measurements were repeated over the same sample but after it had been dried at room temperature and air humidity of about 50 %. The gravimetric moisture of the wet branches was determined (57 %) after their complete drying. At the second step the gravimetric moisture was 41 %, and at the third it was 21 %.

An example of the frequency dependence of the attenuation by pine samples is Fig. 7. The total wet weight of the sample was 2525 g. To derive the slope of the attenuation spectra the frequency dependences are plotted in a logarithmic scale for both axes - attenuation (dB) and frequency (GHz). The obtained linear regressions \( Y = aX^b \) (where \( Y \) is the attenuation, \( X \) is the frequency, and \( b \) is the slope of the frequency dependence) between the attenuation and the gravimetric moisture content are presented in Fig. 7.

\[
\text{Fig. 7. Frequency dependences of the attenuation by pine samples with different gravimetric moisture content: 57%, 41% and 21% (top – down)}
\]

Some more results on the microwave attenuation obtained for aspen and maple samples with varying size, tree components and gravimetric moisture are given in Fig. 8 and Fig.9.

\[
\text{Fig. 8. Spectral dependence of the specific attenuation (Np per kg/m²) by aspen samples: 1 - leafy branches with a diameter up to 5 mm (m_w = 47%); 2 - the same bare branches (m_w = 46%); 3 - thick branches with a diameter 5-20 mm (m_w = 45%); 4 - thick branches with a diameter 20-50 mm (m_w = 45%); 5 - natural crown (m_w = 46%)}
\]
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 electrodynamic models of branches as dielectric cylinders can only give a qualitative explanation of the experimental data [5] 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/m²) by crown fragments of different tree types with gravimetric moisture content from 42 to 52% are shown in Fig. 10.

IV. CONCLUSIONS

The following results could be emphasized and the following concluding remarks could be made:

- The waveguide transmission system was created for measuring attenuation of microwave waves by fragments of vegetation canopies. The system provides a relatively easy acquisition of continuous attenuation spectra under a direct control of vegetation biometric parameters.
- The presented results distinctly show that the attenuation values and spectra slope are strongly dependent on the vegetation type, biomass, water content, and vegetation fraction volume. Deeper investigation of these dependences is a subject of future research.
- The created system will be used to examine the attenuation spectra of different trees branches (bare and leafy with varying size) as well as of different crops components.

Information about the frequency dependence of the microwave attenuation as a function of the wavelength and about the specific attenuation by vegetation types, fragments size and water content, has a practical importance allowing to evaluate the attenuation of microwaves when passing through different vegetation canopies. The solution of the inverse task permits the assessment of vegetation parameters from attenuation data.

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

ACKNOWLEDGMENT

The paper was prepared under the support of the ISTC Project 2059, the NSFB Contracts NZ-1410/04 and “Infrastruktura”, and RAN-BAN collaboration projects “Aerokosm” and “Development of new technologies in aerospace remote sensing of the Earth surface”.

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