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PECULIARITIES OF DIELECTRIC AND EMISSIVITY CHARACTERISTICS OF TUNDRA VEGETATION IN THE MICROWAVE RANGE AT TEMPERATURE AND MOISTURE VARIATIONS

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The influence of temperature variations from –10 to +20 °C and of the volumetric wetness on the dielectric and emissivity behavior of reindeer lichen (moss), leafy moss, sphagnum, and peat in the microwave range has been investigated. The dependence of the dielectric and emissivity behavior of vegetation on temperature and volumetric wetness has been determined. The temperature dependencies of refractive indices of living and dead vegetation have been demonstrated to differ.

Tundra, vegetation, dielectric characteristics, microwave range

INTRODUCTION

Degradation of the vegetation cover of the planet related to deforestation, changes in the species composition of the plant communities, disappearance of certain plant species, and the anthropogenic impact is one of the major problems of our time. This problem is especially relevant for the northern countries of Europe and for the other Arctic territories, where the tundra occupies an essential part [*Evans, 1997; Kashulina et al., 1997*].

The major causes of the degradation of the tundra vegetation are as follows: industrial activities related to intensification of oil and gas production in the Arctic regions and alienation and anthropogenic contamination of the territories [*Buchkina et al., 1998; Forbes and Jefferies, 1999; Oostdam et al., 2005; Kozak et al., 2013*]; excessive grazing of domesticated reindeer [*Rickbeil et al., 2015*]; impact of cities as heat producing centers [*Virtanen et al., 2002*]; possible influence of climate changes, including melting of ice and permafrost [*Tutubalina and Rees, 2001; Raynolds et al., 2008*].

Reduction of the pasture routes due to alienation of lands for the gas production territories with simultaneous increment of the reindeer population in 1990–2000 brought about negative effects related to degradation of the tundra vegetation as a result of excessive grazing (primarily, reduction of the mass of reindeer lichen (moss) as the main fodder of reindeer) [*Murashko and Dallmann, 2011; Kolosov and Kalashnikov, 2013; Perevalova, 2015*], significant change in the structure of plant communities, reduction of biomass, especially in lichen tundras, and activation of erosion processes [*Golovatin et al., 2008*].

The vegetation cover of the tundra as one of the components of an ecosystem is closely connected with the other components: relief, soil, and geocryological conditions. The temperatures of permafrost soils and vegetation exert essential influence on biodiversity. The anthropogenic impact on the environment resulting from intensification in the gas producing sector contributes to the temperature increase. The increase in the thickness of the moss and lichen cover leads to reduction of the seasonal thawing depth and to decrease in the soil temperature [*Moskalenko, 2009*].

The behavior of tundra ecosystems is investigated by the methods of computer simulation [*Kryazhimsky et al., 2011*], based on satellite data and the taxonomic system of morphological landscape units used [*Peyl, 2011*]. To assess the degree of degradation of the soil and vegetation cover of the tundra, interrelations were studied between the productivity of vegetation and the agrochemical and physical properties of land [*Vasilyevskaya et al., 2006; Grigoryev et al., 2011*]. In accordance with remote survey data of the Arctic territories, it was shown that plant growth in the territories exposed to anthropogenic impact depends on the ways and extent of impact and on the features of the biotope and of the native (bedrock) phytocenoses [*Rusanova, 2000; Telyatnikov and Pristyazhnyuk, 2006; Moskovchenko, 2013; Machulina, 2014*].

Due to the necessity of controlling the anthropogenic load on the plant communities of the tundra, the task of developing operative methods of remote diagnostics of vegetation on large areas at the present time consists in investigating of the spectral characteristics of vegetation in the optic and infrared ranges. Correlation between the spectral brightness coefficients and biometric and agrometeorological characteristics of vegetation was elucidated [*Blokhin and Nezamov, 2010*]. It was shown that components of the geo landscape, relief, loose cover of Quaternary deposits, soils, and vegetation have different influence on the spectral characteristics of satellite images [*Dobretsov et al., 2005*].

To evaluate the content of water in the vegetation, it was proposed to use the vegetation and water indices determined by the data of hyperspectral remote sensing [*Sagalovich et al., 2004*]. A method of determining the parameters of the soil and vegetation cover according to multispectral aerial survey data was developed [*Dmitriev and Kozoderov, 2009*]. Satellite survey and GIS data were applied to evaluation of transformations of natural landscapes of the Tazovsky Peninsula [*Kornienko, 2011; Kornienko et al., 2013*] and of the islands of the Arctic Ocean [*Ammosova et al., 2011*]. A complex technology of mapping and monitoring of the heterogeneous vegetation cover was developed [*Zolnikov et al., 2010*]. Based on multitemporal analysis of satellite survey data in the visible light range and in the heat range, processes were investigated, characterizing successions of leafy moss and lichen vegetation [*Kornienko et al., 2005*].

Combined complex processing of radar and multispectral optical images improves the possibilities of remote classification of the land covers and of qualitative assessment of the biophysical parameters of the forest vegetation [*Bondur, 2007; Bondur and Chimitdorzhiev, 2008; Bondur et al., 2012*]. The study of the dependence of dielectric characteristics of forest vegetation on temperature allowed detection of the first-order phase transition, corresponding to transformation of water into ice, as well as of the second-order phase transition, accompanied by transformation of the water structure [*Bordonskiy, 2013*].

Development of contact and remote methods of operative diagnostics of the condition of the tundra vegetation cover is based on the study of the peculiar characteristics of propagation and interaction of electromagnetic waves with vegetation or with particular parts of plants, like leaves, stalks and stems, and determining the dependences of dielectric and emissivity characteristics on the type of vegetation, temperature, moisture content and the phase content of moisture [*Zhilinskaya, 2006*].

The microwave emission of the geological substrate covered by the vegetation cover depends on the physical characteristics of the vegetation (the thickness and the biomass of the vegetation cover, its moisture content and temperature) on the type of the geological substrate (water, unfrozen or frozen soil) and on its physical properties (for water temperature and salinity, for soil – temperature, moisture content, salinity, and freezing depth).

Combined use of model representations and remote microwave sensing data allows specialists to assess attenuation of electromagnetic waves in the vegetation cover for different soil and plant formations [*Krapivin et al., 2006*].

To ensure simultaneous assessment of the characteristics of soil and vegetation, combined data are used relating to the optical depth of vegetation, albedo, and dielectric permittivity of soil. Synchronous optical and microwave-radiometric measurements of the radiation characteristics of the geological substrate allowed evaluation of the optical depth of the vegetation cover depending on the moisture content of the above-ground layer of the vegetation and assessment of the soil moisture content. The algorithm of evaluating the optical depth of the vegetation cover and of the soil moisture content is based on the use of the emissivity characteristics for two polarizations, the albedo of the vegetation cover and the dielectric parameters of moist soil [*Konings et al., 2016*].

Based on the solution of a radiation transfer equation, a technique was developed for determining the moisture content of soil and the optical depth of the vegetation cover by brightness temperatures measured in two wavelength ranges for vertical and horizontal polarizations [*Sagalovich et al., 2005*].

At present, evaluation of the global changes in the soil water content is carried out based on the data from the SMOS satellite. The MIRAS interferometer-radiometer installed in the satellite ensures production of images which correspond to the intensity of the land surface radiation at the frequency 1.41 GHz, calibrated in the brightness temperature units. At this frequency, the microwave emission of the geological substrate depends on the optical depth and biomass of vegetation, on the moisture content in the soil. and the degree of roughness of the soil surface. The impact of the vegetation was assessed by using the dependences of brightness temperatures of soil on the moisture content for different polarizations and at different angles of the survey [*Parrens et al., 2016*].

In this study, the results of survey at the frequency of 1.41 GHz are shown of the dielectric and emissivity characteristics of reindeer lichen, leafy mosses, sphagnum, and peat, with varying volumetric wetness and air temperature.

THE METHODOLOGY OF THE EXPERIMENT

The main characteristics of microwave emission of the geological substrate are the brightness temperature (T_B) and the emissivity factor (χ), inter-related by the known relation:

$$T_B = \chi T,$$

where $T = 273.15 + t$ [°C] – the temperature of the geological substrate expressed in Kelvin degrees. To describe the dielectric characteristics, the complex refraction index $N = \sqrt{\varepsilon} = n + i\kappa$ and complex dielectric permittivity (CDP) $\varepsilon = \varepsilon' + i\varepsilon''$ are used, inter-related by the formulae

$$\varepsilon' = n^2 - \kappa^2,\ \varepsilon'' = 2n\kappa,$$

where n, κ are the refraction and absorption indices; ε', ε'' – the real and imaginary terms of CDP [*Sharkov,* *2014*]. Dependence of χ on n and κ is determined by the formula [*Komarov et al., 1997*]

$$\chi = \frac{4n}{(n+1)^2 + \kappa^2}. \quad (1)$$

The dielectric characteristics of the tundra vegetation were measured using a laboratory setup of a bridge type and a phase difference meter FK2-18. We measured attenuation and shift of an electromagnetic wave which passed through the plant sample under study, put into a measurement container.

The lay-out of the setup is shown in Fig. 1. The setup included: G – a high-frequency signal generator G4-78 (1.16–1.78 GHz); a coordinated power divider (CPD); VLL – a variable length line; A1, A2, A3 – attenuators (coordinated coaxial attenuators); M – the measurement unit of the phasemeter; A – the reference channel; B – the measurement channel with container C for the sample, made as a coaxial waveguide.

The measurement process consisted in the following. A signal from the generator was applied to the CPD divided equally between the reference channel A and the measurement channel B. If there was no sample in the container, the values of the phase difference and the phasemeter ranges were set as equal to zero. Then the sample was put into the container, and the values of the phase difference and of signal attenuation were recorded from the indicator of the FK2-18 phase difference meter. The setup had the following specifications: the range of single-valued phase measurements ±180; the range of attenuation measurement from 0 to 60 dB; the attenuation measurement error 0.5 dB; the phase measurement error 2°. Description of the sources of possible errors was provided in [*Komarov et al., 1997*].

The samples of reindeer lichen, leafy mosses, sphagnum, and peat collected in the tundra of the Yamal Peninsula were the object of the study.

To ensure qualitative description of the moisture contained in the samples, the volumetric wetness was used, expressed in volume fractions and determined from the relation

$$W = (\rho/\rho_w) M_w / M,$$

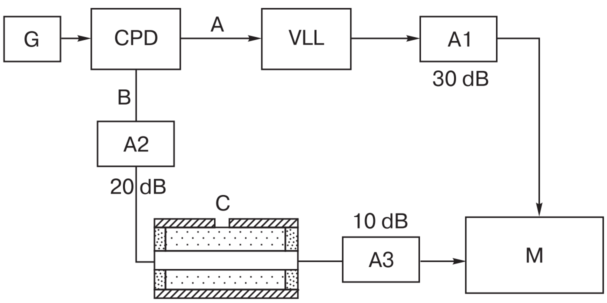


Fig. 1. A lay-out of a bridge-type setup based on a phasemeter (see the description in the text).

where ρ, ρ_w are the density values of the moist sample and water; M is the mass of the moist vegetation ($M = M_d + M_w$); M_d, M_w are the mass values of dry vegetation and of water, measured on an analytical balance with the accuracy up to 0.001 g. In the course of the experiment, W was changed by drying the sample exposed to air at room temperature.

The samples in which all the living plants cells died as a result of drying were further used to study the dielectric characteristics of dead vegetation. For this purpose, they were re-moistened with distilled water, then excessive water was removed, and moistened samples were kept under air-proof film for several hours, to ensure uniform distribution of water in the plant sample.

The experimental studies of the dependences of dielectric characteristics of vegetation on the water content were conducted at temperature (25 ± 1) °C. The temperature dependences were examined in the temperature range from −10 to +25 °C.

The experimental data on changes in the dielectric characteristics at temperature and volumetric wetness variations were approximated by continuous dependences using the Origin 6.1 computer program.

RESULTS AND DISCUSSION

The influence of volumetric wetness on dielectric characteristics of plants

The dielectric and emissivity characteristics of the tundra vegetation are affected by the water contained in the plants, the phase content and the dielectric characteristics of which may differ for different plant species and for different elements of vegetation (roots, leaves, stalk). When plants die and humus and peat are formed, the phase content of water changes and, hence, the dielectric characteristics of vegetation change, too.

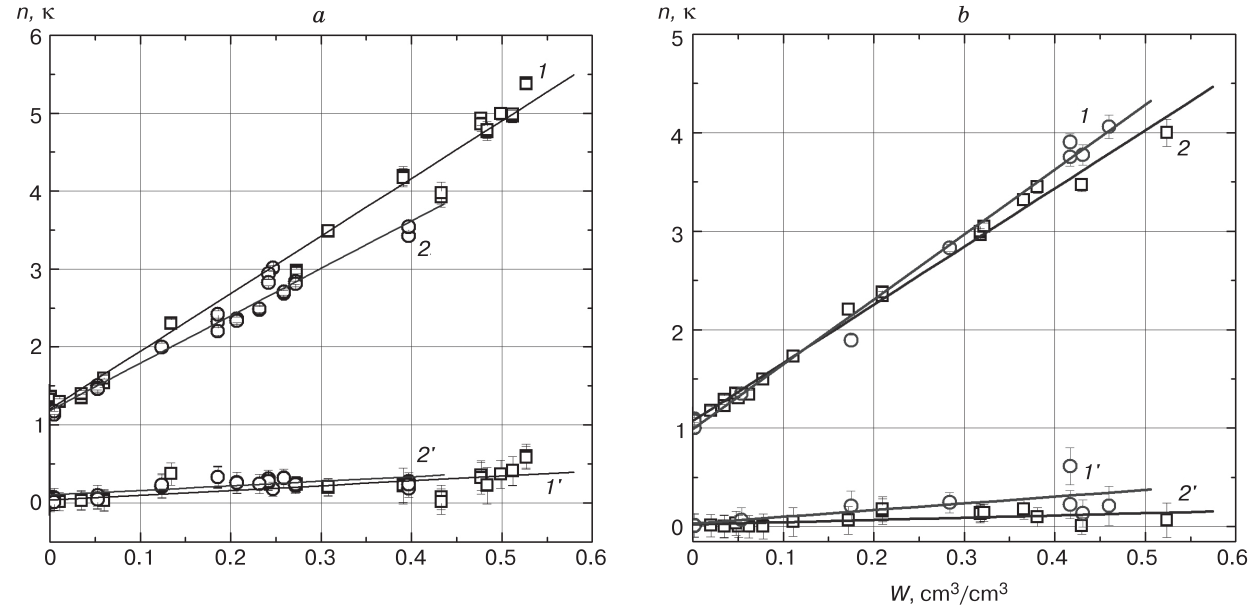
Figure 2 demonstrates the empirical dependences $n(W)$ and $\kappa(W)$ on volumetric wetness for reindeer lichen (*a*), sphagnum (peat moss) and peat (*b*), moss and root systems with fragments of dead vegetation (*c*), approximated with Origin 6.1 program by straight lines

$$n = A_0 + A_1 W; \quad (2)$$

$$\kappa = B_0 + B_1 W, \quad (3)$$

where A_0, A_1, B_0, B_1 are the numerical coefficients shown in Table 1.

It follows from comparison of the experimental data that the dielectric characteristics of dried plants of different species differ insignificantly within the error limits. The main differences are observed as the moisture content in the plants rises. This may be related to the differences in the dielectric characteristics of water in different plant species, changes in the phase content of water in plants as they die, and differences in the dielectric characteristics of water of different phase content present in living and dead plants.



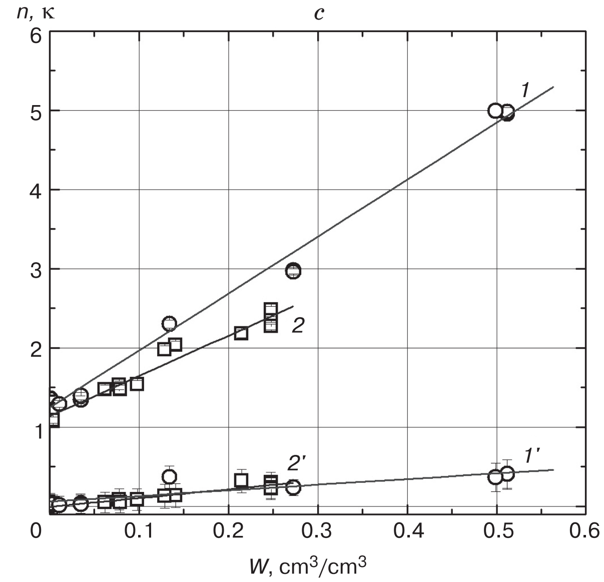


Fig. 2. Dependences of the refraction index *n* (*1*, *2*) and of the absorption index κ (*1*′, *2*′) on volumetric wetness *W*:

a – live reindeer lichen (*1*, *1*′), dead reindeer lichen (*2*, *2*′); *b* – sphagnum (*1*, *1*′), peat (*2*, *2*′); *c* – moss (*1*, *1*′), roots and fragments of dead plants (*2*, *2*′).

Table 1. **Numerical values of indices A_0, A_1, B_1, B_2 in fractions (2), (3)**

Plant type	A_0	A_1	σ_n	B_0	B_1	σ_κ
Reindeer lichen (live)	1.20 ± 0.06	7.4 ± 0.17	0.185	0.04 ± 0.03	0.6 ± 0.11	0.125
Reindeer lichen (dead)	1.18 ± 0.05	6.1 ± 0.20	0.121	0.10 ± 0.03	0.6 ± 0.13	0.080
Sphagnum	0.99 ± 0.06	6.6 ± 0.21	0.118	0.03 ± 0.067	0.7 ± 0.24	0.136
Peat	1.07 ± 0.03	5.9 ± 0.13	0.086	0.02 ± 0.02	0.23 ± 0.09	0.056
Leafy moss	1.14 ± 0.07	5.1 ± 0.41	0.110	0.001 ± 0.2	1.1 ± 0.145	0.040
Root system	1.25 ± 0.05	7.2 ± 0.19	0.140	0.06 ± 0.03	0.7 ± 0.13	0.096

Note. σ_n, σ_κ – mean square errors of determining *n* and κ.

Using the equations (2), (3) and formula (1), we calculated emissivity factors χ for different values of *W*. Dependences χ(*W*) for live (χ_l) and dead (χ_p) reindeer lichen, approximated by straight lines, look as follows:

$$\chi_l = (0.98 \pm 0.006) - (0.846 \pm 0.018)\,W, \quad \sigma = 0.0195; \tag{4}$$

$$\chi_p = (0.99 \pm 0.007) - (0.82 \pm 0.031)\,W, \quad \sigma = 0.0179, \tag{5}$$

where σ stands for mean square errors.

Having transformed equations (4), (5), we obtain formulae for remote determination of the volumetric wetness in live and dead reindeer lichen:

$$W = (1.18 \pm 0.037) - (1.18 \pm 0.044)\,\chi_l,\ \sigma = 0.021;$$

$$W = (1.13 \pm 0.018) - (1.14 \pm 0.023)\,\chi_p,\ \sigma = 0.022.$$

The influence of the air temperature on the dielectric characteristics of vegetation

The tundra vegetation is exposed to negative air temperatures for a large part of the year. In this period, water outside the plants and not bound with their surface by sorptive power becomes frozen and turns into ice. At the same time, water contained in the plants may remain unfrozen in different amounts at very low temperatures (up to −75 °C) [*Bordonskiy et al., 2008; Bordonskiy, 2013*].

Shown is Fig. 3 are the plots of dependences $n(t)$ and $\kappa(t)$ for reindeer lichen, sphagnum, and peat, approximated with sigmoid functions, which look as follows:

$$n = n_2 + (n_1 - n_2)\left(1 + \exp\left[\frac{t - t_0}{dt}\right]\right)^{-1}; \qquad (6)$$

$$\kappa = \kappa_2 + (\kappa_1 - \kappa_2)\left(1 + \exp\left[\frac{t - t_0}{dt}\right]\right)^{-1}, \qquad (7)$$

where n_1, n_2, κ_1, κ_2 are the initial and finite values of the indices of refraction and absorption, respectively; t_0 – the mean temperature; dt – the width of the phase transition.

The numerical values of formulae (6), (7) for different types of live and dead vegetation are shown in Table 2.

Shown in Fig. 3, *a* are the dependences of the indices of refraction (curves *1*, *2*) and absorption (curves *1′*, *2′*) for live and dead reindeer lichen in the air temperature range from −12 to +20 °C. For measurements, the same sample of reindeer lichen was used, which had the volumetric wetness $W = 0.4$ before drying, repeatedly wetted to $W = 0.15$ after drying.

It can be seen that within the entire range of the measured air temperatures, not only quantitative but also qualitative changes are observed in the dependences $n(t)$ and $\kappa(t)$, consisting in different widths of phase transitions. For dead reindeer lichen, the values of n and κ change abruptly as the air temperature rises, while for a live plant, the phase transition is smooth, which may be due to freezing of bound water within a certain range of air temperatures below 0 °C.

In the range of positive air temperatures, the values n and κ of dead reindeer lichen far exceed n and κ of live reindeer lichen. As the volumetric wetness of live reindeer lichen is much higher than the volumetric wetness of dead reindeer lichen, such behavior of the dielectric characteristics may be attributed to the difference between the phase content of water in live and dead reindeer lichen, in particular, to the larger fraction of bound water and to the lesser fraction of gravity water contained in live reindeer lichen, compared to the dead reindeer lichen. In the reindeer lichen, which is a symbiotic association of fungi and microalgae, the internal structure of the microalgae becomes destroyed. As a result of this, water contained in the microalgae or in their cellular membrane and referred to the category of bound water for its

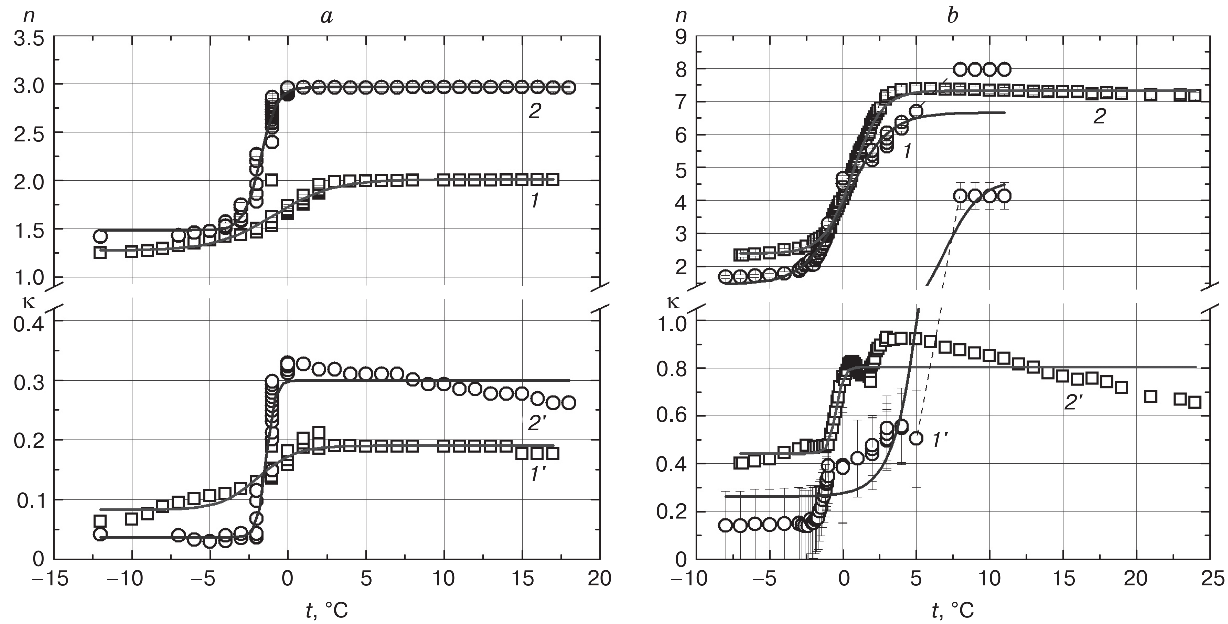


Fig. 3. Dependences of the refraction index n (*1*, *2*) and of the absorption index κ (*1′*, *2′*) on temperature t:
a – live reindeer lichen (*1*, *1′*), dead reindeer lichen (*2*, *2′*); *b* – sphagnum (*1*, *1′*), peat (*2*, *2′*).

Table 2. **Numerical values in formulae (6), (7)**

Sample	n_1	n_2	t_0	dt	σ_n
Reindeer lichen (live)	1.27 ± 0.02	2.01 ± 0.016	−0.87 ± 0.23	1.88 ± 0.22	1.88
Reindeer lichen (dead)	1.49 ± 0.017	2.97 ± 0.009	−1.77 ± 0.03	0.52 ± 0.02	3.85
Sphagnum	1.46 ± 0.028	6.66 ± 0.05	0.21 ± 0.05	1.41 ± 0.03	2.7
Peat	2.39 ± 0.02	7.33 ± 0.02	0.67 ± 0.018	0.98 ± 0.016	1.0
Sample	κ_1	κ_2	t_0	dt	σ_κ
Reindeer lichen (live)	0.08 ± 0.005	0.19 ± 0.003	−1.92 ± 0.29	1.20 ± 0.24	0.001
Reindeer lichen (dead)	0.037 ± 0.007	0.30 ± 0.006	−1.4 ± 0.07	0.28 ± 0.04	0.007
Sphagnum	0.26 ± 0.24	4.63 ± 0.4	6.9 ± 0.53	1.21 ± 0.03	0.82
Peat	0.44 ± 0.04	0.81 ± 0.03	−0.48 ± 0.2	0.26 ± 0.2	0.06

Note. n_1, n_2 – initial and finite values of the refraction index; κ_1, κ_2 – initial and finite values of the absorption index; t_0 – mean temperature; dt – phase transition width; σ_n, σ_κ – mean square errors of the refraction and absorption indices.

phase content becomes gravity water, the values of n and κ of which are much higher than the values of n and κ of bound water.

Essential differences in the dielectric characteristics are observed for sphagnum and for peat. It can be seen from Fig. 3, *b* that for sphagnum in the dependence $\kappa(t)$ (curve *1′*), there are two air temperature ranges (−2...−1 and 5...8 °C), in which abrupt change in the behavior of the dielectric characteristics of sphagnum takes place. This may be related to the peculiar internal structure of sphagnum, in particular, to the presence of empty cavities, in which water may be accumulated in the amount exceeding the mass of the plant many times.

In the range of air temperatures from −8 to −2 °C, part of the water is in the form of ice outside the plant. As this ice melts, gravity water is formed with high values of n and κ, accounting for the dramatic increase of κ. The increase of κ in the range of air temperatures from −2 to +5 °C may be caused by gradual melting of the ice formed in the void sphagnum cells and surrounded by the cell membrane. Ice melting in these cells is slower compared to that of ice outside the plant. In the range of air temperatures from +5 to +12 °C, the dielectric characteristics of sphagnum are close to the dielectric characteristics of fresh water.

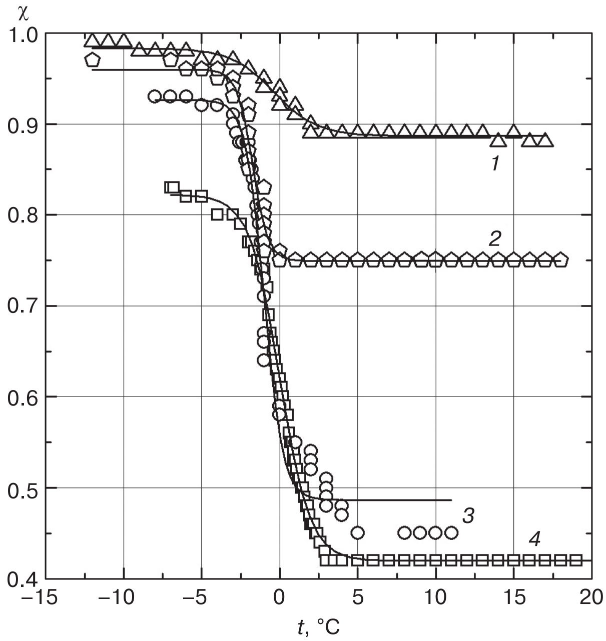


Fig. 4. Dependences of emissivity factors of live (*1*) and dead reindeer lichen (*2*), sphagnum (*3*) and peat (*4*) on temperature.

Using the experimental data and formula (1), the emissivity factors were calculated for reindeer lichen, sphagnum, and peat. Dependences of the emissivity factors on air temperature in the range of −12...

Table 3. **Numerical values part of equation (8)**

Sample	χ_1	χ_2	t_0	dt	σ
Reindeer lichen (live)	0.98 ± 0.002	0.89 ± 0.001	−0.35 ± 0.13	1.39 ± 0.12	0.0003
Reindeer lichen (dead)	0.96 ± 0.004	0.75 ± 0.003	−1.74 ± 0.05	0.49 ± 0.04	0.0002
Sphagnum	0.93 ± 0.011	0.49 ± 0.008	−0.98 ± 0.06	0.60 ± 0.07	0.0008
Peat	0.82 ± 0.003	0.42 ± 0.002	0.005 ± 0.03	0.97 ± 0.02	0.0005

Note. χ_1, χ_2 – initial and finite values of the emissivity factor; t_0 – mean temperature; dt – phase transition width; σ – mean square error.

+20 °C shown in Fig. 4 were approximated with a sigmoid function, which looked as follows:

$$\chi = \frac{\chi_1 - \chi_2}{1 + \exp\left[\dfrac{t - t_0}{dt}\right]} + \chi_2, \qquad (8)$$

where χ_1, χ_2 are the initial and the finite values of the emissivity factor; t_0 is the mean temperature; dt is the width of the phase transition.

The numerical values constituting formula (8) for different types of vegetation are shown in Table 3.

In the expression obtained (8), the values t_0, dt, χ_1, χ_2 relate to the emissivity characteristics of different plant species and may be measured under laboratory conditions. The values of χ and t may be found by a contact method or by the data of remote sensing in the microwave and infrared ranges.

CONCLUSIONS

As a result of the experiments conducted, linear dependences of the indices of refraction and absorption on the volumetric wetness have been established for reindeer lichen, sphagnum, peat, leafy moss, and roots and fragments of dead plants.

For reindeer lichen, sphagnum, and peat, dependences of the indices of refraction and absorption on temperature in the temperature range from –10 to +20 °C were approximated with a sigmoid function. The greatest changes were observed in the range of intense water–ice phase transitions.

The indices of refraction and absorption of live and dead vegetation have been found to differ, which may be related to the differences in the phase content of water in live and dead plant cells.

The dielectric and emissivity parameters of vegetation may act as indicators of degradation of the tundra vegetation. The dependences found may be used for modeling the emissivity characteristics of the tundra vegetation to evaluate the contribution of the vegetation cover to the total microwave emission from the geological substrate.

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