Boreal Forest Transmissivity in the Microwave Domain Using Ground-Based Measurements

Mickaël Pardé, Kalifa Goïta, Alain Royer, and François Vachon

***Abstract*—This letter proposes an estimation of microwave transmissivity within the Canadian boreal forest. The aim is to correct the forest effect in snow water equivalent estimation from Special Sensor Microwave Imager and Advanced Microwave Scanning Radiometer microwave measurements. The estimation was carried out using ground-based radiometric measurements, at 19 and 37 GHz, and for both polarizations. The results show that the transmissivity is correlated with the stem volume and is independent of the tree species. For high stem volumes (>100 m^3/ha), the transmissivity is found to be 0.4 and 0.3 for 19 and 37 GHz, respectively.**

***Index Terms*—Boreal forest, microwave radiometry, transmissivity.**

I. Introduction

OVER NORTHERN latitudes, snow and ice are important in determining current hydrological conditions and future states through the storage of moisture and the influence of incoming energy fluxes. Their effects on water resources and flooding have considerable socio-economical implications. Like other cryospheric components, snow cover is felt to be a sensitive integrator of basic climate elements. Its variations may potentially be an effective indicator of regional and global change. Therefore, the quantitative determination of snow properties (extent and water equivalent) is a high interest research topic in northern latitude regions. In addition to climate-related issues, water gernerated from snowmelt during the spring period is crucial for agriculture management and hydropower production.

During the past 30 years, spaceborne passive microwave observations have been investigated for the estimation of snow cover extent and water equivalent [1]. For example, empirical approaches using a scattering index calculated from passive microwave brightness temperatures were proposed to estimate snow water equivalent (SWE) over land [2]. Such an approach was successfully developed for the Canadian Prairies and evolved to a near real-time system, processing microwave data and creating snow cover maps for that region [3].

Unlike prairies, forested lands are more complex environments, where SWE estimation is complicated by the attenuation of the ground microwave signal propagating through the canopy and by the vegetation cover contribution to the surface brightness temperature. A number of physically based models have been proposed in the literature to understand the different contributions to the microwave signal [4], [5]. Previous investigations have shown that the Helsinki University of Technology (HUT) snow emission model [4] offers interesting potential for SWE estimation [6].

So far, the attenuation of the snow microwave emission by the forest canopy is not well understood and documented. Limited studies and experiments are available in the literature. In [7], microwave data were acquired using a helicopter system in different frequencies over a boreal forest, and forest transmissivities were determined by comparing forested and nonforested measurements.

A forest transmissivity function that links transmissivities to forest stem volume was then developed and is currently used in the HUT model. Moreover, Mätzler *et al.* [8] realized an experiment over a single beech tree and determined transmissivity using ground-based passive microwave measurements.

This study is a contribution to the unknown area of wintertime forest attenuation of microwave emission from snow-covered terrain. We propose here to estimate the transmissivity in the Canadian boreal forest using ground-based radiometric measurements at 19 and 37 GHz.

II. Description of Data and Experiment

A. Test Site

The experiment site is located in the former Boreal Ecosystem-Atmosphere Study (BOREAS) southern site, north of Prince Albert in Saskatchewan, AB, Canada (latitude 53°25′ to 54°19′N, longitude 104°14′ to 106°19′W). The southern study area is covered mainly by black spruce with scattered birch and jack pine stands. On this site, forest density, age, and height are highly variable within a few square kilometers, due to forest management and harvesting practices. Clear cuts, young, and dense stands of jack pine, black spruce, and aspen were localized for the purpose of the experiment.

B. Ground-Based Radiometric Measurements

The ground-based radiometric measurements were taken using a set of microwave radiometers operating at 19 and 37 GHz in both horizontal (H) and vertical (V) polarizations. The radiometers were mounted on a hauling sled towed by a snow mobile and were looking up through the trees with an incidence angle of 55° at a height of 1.7 m. The radiometer 3-dB beamwidth was 15°, and the radio-frequency bandwidth was 500 MHz at 19 GHz and 4 GHz at 37 GHz. The sensitivity

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TABLE I
TREE TYPE, STEM VOLUME, AND TYPE OF RADIOMETRIC MEASUREMENT FOR EACH TEST SITE FOR THE 2003 CAMPAIGN. MEASUREMENT TYPE: P FOR PUNCTUAL MEASUREMENTS AND T FOR TRANSECT

Latitude (N)	Longitude (W)	Forest type	Stem vol m^3/ha	Type
53° 48' 08.4"	104° 36' 32.4"	Black Spruce 1	71	P
53° 48' 08.7"	104° 36' 51.0"	Black Spruce 2	53	T
53° 48' 07.7"	104° 36' 57.3"	Black Spruce 3	285	P / T
53° 43' 26.1"	104° 35' 40.1"	Black Spruce 4	19	P
53° 54' 56.0"	104° 41' 23.3"	Jack pine 1	159	P
53° 54' 55.0"	104° 41' 16.1"	Jack pine 2	65	P
53° 54' 46.1"	104° 38' 37.0"	Jack pine 3	3	P
53° 54' 47.6"	104° 38' 40.3"	Jack pine 4	3	T
53° 54' 43.6"	104° 38' 31.6"	Jack pine 5	155	P / T
53° 54' 45.1"	104° 38' 34.3"	Jack pine 6	206	P / T
53° 52' 48.2"	104° 37' 19.5"	Jack pine 7	15	P
53° 52' 49.0"	104° 37' 20.3"	Jack pine 8	76	P
53° 52' 32.6"	104° 38' 37.3"	Jack pine 9	20	T
53° 52' 31.7"	104° 38' 17.7"	Jack pine 10	71	T
53° 39' 31.4"	104° 37' 11.0"	Aspen	501	T
53° 39' 31.4"	104° 37' 11.0"	Aspen	506	T
53° 40' 56.5"	104° 36' 06.5"	Aspen	40	T
53° 39' 31.4"	104° 37' 11.0"	Aspen	512	T
53° 39' 31.4"	104° 37' 11.0"	Mixed	79	T
53° 38' 32.6"	104° 36' 13.6"	Mixed	254	T
53° 53' 15.6"	104° 37' 07.5"	Mixed	198	P

was 2 K at 19 and 37 GHz, and the calibration accuracy was evaluate to be approximatively 3 K. The radiometers were operated into two different positions. In the first protocol, the radiometers were used in fixed position. A total of ten sites were measured in these conditions with five measurements per site. In the second protocol, radiometers were moving along selected transects with a sampling rate of one measurement per second. Thirteen transects of different forest types and conditions were considered. This second methodology allows us to estimate the spatial variability of the forest transmissivity. For each site, the physical temperature of the vegetation and snow cover was measured with an infrared radiometer.

C. Forest Measurements

A forest inventory was conducted in each site based on a fixed-area sampling plot method. We considered half circle sampling plots of 10 or 15 m of radius. For each plot, we counted all trees to determine forest density. The diameter at the breast height (DBH at 1.30 m) was also measured for each tree. These inventory data were used to estimate forest stem volume, which seems to be related to forest transmissivities in the microwave domain according to previous studies [7].

Stem taper functions developed by [9] in the study area context were used to estimate forest volume. The values found are reported in Table I. The initial values were corrected to take into account the height of the radiometer.

In general, the different sites are composed by only one species, except for three sites where both black spruce and aspen were present (Table I).

III. TRANSMISSIVITY ESTIMATION

Following a method proposed by Mätzler *et al.* [8], microwave transmissivity of a forest canopy can be estimated from ground-based measurements using a microwave radiometer and a thermal infrared radiometer. The proposed

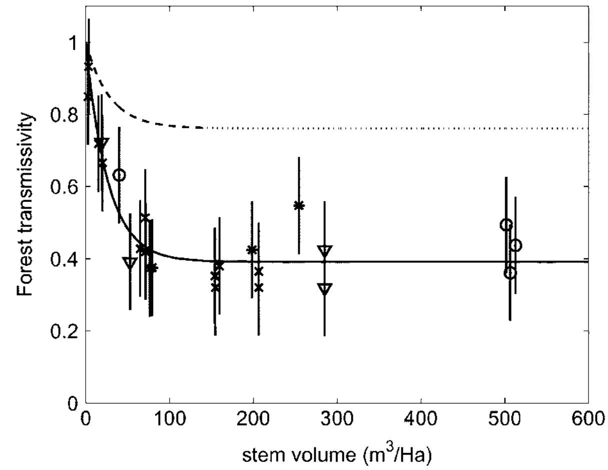

Fig. 1. Estimated values of the vegetation transmittivity compared to the stem volume at 19 GHz. $*$ are the jackpine; ∇ are the black spruce; $\circ$ are the aspen trees; and $\times$ are the mixed areas (Black spruce and aspen). Dashed line corresponds to the Kruopis model over its validity range and for 19 GHz.

methodology consists in measuring the brightness temperature of the sky ($T_{\rm b}^{\rm sky}$) simultaneously with the radiometric measurements through the forest. Comparison between the two brightness temperatures allows the computation of the transmissivity in the forest canopy.

The downwelling microwave radiation through the canopy cover ($T_{\rm b}^{\rm down}$) measured by the radiometers at the ground level can be expressed as

$$T_b^{\rm down} = \tau^{\rm veg} T_b^{\rm sky} + r^{\rm veg} T_b^{\rm surf} + \epsilon^{\rm veg} T^{\rm veg} \qquad (1)$$

were $\tau^{\rm veg}$, $r^{\rm veg}$, and $\epsilon^{\rm veg}$ are, respectively, the vegetation transmissivity, reflectivity, and emissivity. $T_b^{\rm sky}$ is the downwelling sky brightness temperature, $T_b^{\rm surf}$ is the brightness temperature of the snow-covered ground, and $T^{\rm veg}$ the physical vegetation temperature.

Using expressions of the different terms in (1), Mätzler *et al.* [8] show that the expression of $\tau^{\rm veg}$ can be written as follows:

$$\tau^{\rm veg} \approx \frac{T^{\rm veg} - T_b^{\rm down}}{T^{\rm veg} - T_b^{\rm sky}}. \qquad (2)$$

The assumptions are that the vegetation reflectivity is negligible, and the $T_b^{\rm surf}$ is close to $T^{\rm veg}$. As indicated in Section II, $T^{\rm veg}$ values were measured using a thermal infrared radiometer, while $T_b^{\rm down}$ and $T_b^{\rm sky}$ where measured using microwave radiometers.

IV. RESULTS AND DISCUSSION

In Figs. 1 and 2, we present the estimations of the transmittivity of microwave radiations in the canopy with respect to the forest stem volume data for both 19- and 37-GHz frequencies, including both polarizations H and V. In these figures, vertical lines represent the standart deviation due to the spatial variability of the forest density as well as the temporal variations of the radiometric signal during the measurements periods.

The values provided by the ground-based measurements show that, for the 19-GHz frequency, the transmissivity reached a mean minimum value of 0.4 for stem volume above 100 m^3/ha and 0.28 at 37 GHz.

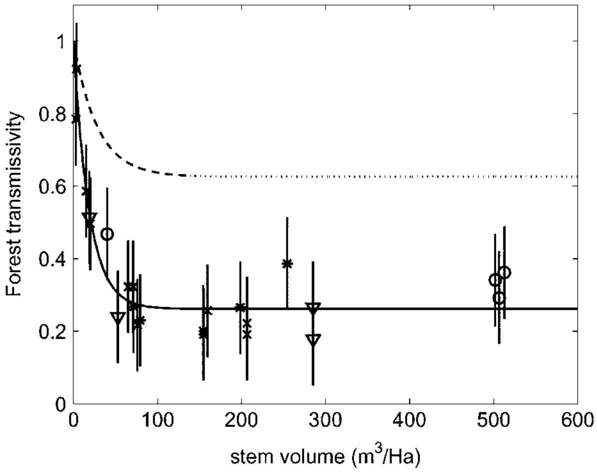

Fig. 2. Same as Fig. 1 but for 37 GHz.

We used these measurements to define a new model describing the vegetation transmissivity variations as a function of stem volume. We adopted the same functional form as in [7]

$$t(f, V) = a + [1 - a]\exp(-bV) \quad (3)$$

where V is the stem volume (cubic meters per hectare), f is the frequency, and a and b are constants fitted by nonlinear regression. In [7], a is a function of frequency (4), and b is equal to 0.035.

$$a(f) = 0.42 + [1 - 0.42]\exp(-0.028f). \quad (4)$$

In this work, new values for a and b were found for each frequency including both polarizations. The estimated transmissivities for both polarizations were similar for each frequency. Values of a and b are 0.3918 and 0.0379, respectively, for the 19-GHz frequency and 0.2615 and 0.0535 for the 37-GHz frequency.

Our results show that a relative constant value could be used for most of the dense Canadian forest. Indeed, for a forest density above 100 m^3/ha, t is equal to 0.4 and 0.3, for 19 and 37 GHz, respectively. For high stem volumes, the intensity of the transmissivity within the boreal forest is significantly greater than the one predicted by the model proposed by the Finish analysis over pine forests. In these figures, we plotted the predicted transmissivity with the model established by Kruopis *et al.* [7] for the Finnish boreal forest. At 19 GHz (Fig. 1), the transmissivity varies from 1 for the bare snow cover, to 0.8 for stem volumes exceeding 100 m^3/ha. At 37 GHz (Fig. 2), the transmissivity varies from 1 to 0.65 for stem volumes exceeding 100 m^3/ha. In [7], estimations of the transmissivity were done at frequencies below 19 GHz, for stem volumes varying from 0–150 m^3/ha. These volumes are lower than the values present in our experiment site (see dashed lines in Fig. 1); therefore, only the decreasing phase of the transmissivity function was used to estimate the model parameters [7]. Moreover, due to the difficulty in estimating the transmissivity for small trees (the elevation of the radiometer introduces a bias), it is hard to compare the transmissivities for this range of stem volumes. Nevertheless, we assume that the variations in the results could come from the difference in forest type and probably from the structure of each target: a radiometer looking at the trees from above and one from below may not see the same tree brightness temperature.

V. CONCLUSION

The objective of this study was to investigate values of the boreal forest transmissivity in the microwave domain. Ground-based radiometric measurements were used to compute the forest transmissivity for the purpose of defining a new relation between forest transmissivity and forest stem volume. We showed that the values for high boreal stem volumes are significantly lower than those found in [7] and that there is no specific relation for each tree type. The difference could be explained by the difference in experimental approach, the range of stem volumes investigated, and the errors resulting from ground-based measurements for trees with low values of stem volume. However, our transmissivity values are in agreement with those measured by Mätzler *et al.* [8]. Two relations were established for the 19- and 37-GHz frequencies, respectively. These relations provide good agreement between estimated and measured transmissivities. These results should improve the snow water equivalent retrieval from microwave spaceborne brightness temperatures using a snow emission model for snow under the Canadian boreal forest.

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REFERENCES

[1] A. Chang, J. Foster, D. Hall, B. Goodison, A. Walker, and J. Metcalfe, "Snow parameters derived from microwave measurements during the BOREAS winter field campaign," *J. Geophys. Res.*, vol. 102, no. D24, pp. 29 663–29 671, 1997.

[2] K. Goïta, A. Walker, and B. Goodison, "Algorithm development for the estimation of snow water equivalent in the boreal forest using passive microwave data," *Int. J. Remote Sens.*, vol. 24, no. 5, pp. 1094–1102, 2003.

[3] B. Goodison and A. Walker, "Canadian development and use of snow cover information from passive microwave satellite data," *Passive Microw. Remote Sens. Land—Atmos. Interact.*, pp. 245–262, 1994.

[4] J. Pulliainen, J. Grandel, and M. Hallikainen, "HUT snow emission model and its applicability to snow water equivalent retrieval," *IEEE Trans. Geosci. Remote Sens.*, vol. 37, no. 3, pp. 1378–1390, May 1999.

[5] A. Wiesmann and C. Mätzler, "Microwave emission model of layered snowpack," *Remote Sens. Environ.*, vol. 70, pp. 307–316, 1999.

[6] V. Roy, K. Goïta, A. Royer, A. Walker, and B. Goodison, "Snow water equivalent retrieval in a Canadian boreal environment from microwave measurements using the HUT snow emission model," *IEEE Trans. Geosci. Remote Sensing*, vol. 42, no. 9, pp. 1850–1859, Sep. 2004, to be published.

[7] N. Kruopis, J. Parks, A. Arslan, H. Alasalmi, J. Koskinen, and M. Hallikainen, "Passive microwave measurements of snow-covered forest areas in emac'95," *IEEE Trans. Geosci. Remote Sensing*, vol. 37, no. 5, pp. 2699–2705, Sep. 1999.

[8] C. Mätzler, "Microwave transimissivity of a forest canopy: Experiments made with a beech," *Remote Sens. Environ.*, vol. 48, pp. 172–180, 1994.

[9] J. Gàl and I. Bella, "New stem taper functions of 12 Saskatchewan timber species," Northwest Region, Can. Forest Service, Tech. Rep. NOR-X-338, 1994.