ESTIMATION OF VOLUME FRACTION AND GRAVIMETRIC MOISTURE OF WINTER WHEAT BASED ON MICROWAVE ATTENUATION: A FIELD SCALE STUDY

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ABSTRACT

A considerable amount of water can be stored in vegetation, especially in regions experiencing large quantities of precipitation (mid-latitudes). In this context, an accurate estimate of the actual water status of the vegetation could lead to an improved understanding of the effect of plant water on the water budget. In this study, we developed and validated a novel approach to retrieve the vegetation volume fraction (δ) (i.e., volume percentage of solid plant material of a canopy in air) and the gravimetric vegetation water content (m_g) (i.e., amount of water per wet biomass) for winter wheat. The estimation was based on the attenuation of L-band microwave measurements through vegetation (vegetation optical depth, (τ)-parameter). Ground-based L-band microwave measurements over an entire growing cycle together with in situ measured vegetation characteristics have been used for this purpose. Retrieved δ- and m_g-values revealed to be comparable to literature and in situ measurements (i.e., δ was within the range between 0 and 0.01 and the retrieved m_g had a mean value of 0.58 (0.55 (in situ) and 0.54 (literature))). Finally, we also tested the sensitivity of the δ- and m_g-retrievals to their input-values to investigate their possible mutual dependencies. The analysis showed that already small changes in the input-m_g or -δ result in relatively large changes in the retrieved δ or m_g.

***Index Terms*—** gravimetric vegetation water content, vegetation volume fraction, vegetation optical depth, winter wheat, SMOS, SMAP, L-band

1. INTRODUCTION

In the context of climate change, drastically affecting weather conditions, it is key to closely monitor the vegetation conditions of agricultural fields to secure yield. In this regard, L-band (i.e., 1.4 GHz) passive microwave satellites such as SMOS and SMAP are a promising option to remotely acquire information on vegetation properties (e.g., vegetation moisture) at the global scale with a high temporal and moderate (in terms of kilometers) spatial resolution. Different vegetation water content products can be defined. The vegetation water content (VWC), which is the amount of water per unit area [kg m^{-2}] and the gravimetric vegetation water content (m_g), which is the amount of water per wet biomass [kg kg^{-1}]. The retrieval of VWC has been frequently investigated at the global scale mainly using optical sensors (e.g., [1]). However, VWC is more linked to the biomass (and chlorophyll content) of a plant as it is the amount of water per area and does not reflect directly the available water per plant biomass. The m_g is expected to be more closely related to the actual water status of the vegetation and is well-suited to indicate the plant available water.

Furthermore, a proper characterization of the canopy volume and its structure is a pre-requisite information to estimate the plant properties of a canopy, but such information is generally unknown and therefore fixed as a constant in actual retrieval algorithms (e.g., using the τ-ω model for soil moisture estimation [2]). The vegetation volume fraction (δ) can be used to characterize the canopy filling and is defined as the volume percentage of solid plant material of a canopy in air. In addition, as the thermal emission of vegetation at L-band is sensitive to δ, it is a key driver for water absorption within the canopy and thus may lead to more accurate estimates of the attenuation of microwave emissions by the vegetation layer [3, 4].

The objective of this study is to develop, apply and validate an attenuation-based approach (i.e., based on the attenuation of L-band microwaves through vegetation) to retrieve either δ or m_g of winter wheat in a high-resolution field scale study with tower-based L-band microwave observations and in situ measurements acquired over an entire growing cycle.

2. MATERIALS AND METHODS

Passive microwave measurements over a winter wheat (*Triticum aestivum L.*) field were carried out using the ELBARA-II radiometer during summer 2017 at the Selhausen field laboratory (Germany) [2]. The experiment was conducted for a period of about 4 months from tillering of the winter wheat on April 10th (DOY 100) to the late senescence stage on August 14th (DOY 226). The microwave measurements were performed twice a week over a metal-gridded plot (i.e., soil covered by a metal-grid reflector to block the soil surface emission, but with vegetation growing through the grid) for different incidence angles (40 to 60° in increments of 5°) during the morning (from 8 to 12 a.m.). In addition, weekly in situ measurements of vegetation properties were performed, specifically: leaf area index (LAI), total of above ground biomass (TOB), vegetation water content (VWC), growing stages (BBCH), and vegetation height (d). In the current study, we only used the polarization (p) dependent vegetation optical depth VOD (τ)-parameter, which was retrieved from the 40° incidence angle brightness temperature measurements using the τ-ω model [2]. Finally to be able to compare our estimated m_g with a reference data set, the in situ measured VWC was converted to m_g and will be called in situ measured m_g in the following. A reference data set for the retrieved δ-values was not available.

Our approach (which was firstly tested in a different configuration at the global scale using SMAP data [5]) is based on the attenuation expression of Schmugge and Jackson [4] who found that for a wavelength (λ) [m] at frequencies between 0.2 and 20 GHz the nadir VOD (τ) can be related to the imaginary part of the complex dielectric constant of the canopy (ε_{can}) by:

$$\tau = 4\pi\left(\frac{d}{\lambda}\right)\cdot\ Im\left[\sqrt{\varepsilon_{can}}\right], \qquad (1)$$

where the square root of ε_{can} is applied, since it is directly related to the refractive index of the canopy, and the imaginary part (Im) (also called loss factor) refers to the loss of the electromagnetic energy when the waves propagate through the vegetation layer with thickness d [m]. Thus, τ describes the surface emission attenuation when it passes through the vegetation canopy. For the description of ε_{can}, different two-phase dielectric mixing models can be used, as proposed by de Loor [6]. Thus, the vegetation layer can be described as a two-phase mixture with air as the host material, with a permittivity equal to one, and the vegetation as inclusions with a specific shape (i.e., spheres (s), needles (n), discs (di)), orientation (i.e., random (r) or vertical (v)), complex vegetation dielectric constant (ε_{veg}), and volume fraction (δ). For the winter wheat field, the vertical needles mixing model is expected to be most representative. It should perform best to retrieve δ and m_g, as the winter wheat canopy is mainly vertically oriented (distinct stalk component) and therefore anisotropic attenuation effects might be significant. The equations used to calculate ε_{can} for the different types of inclusion can be found in Ulaby et al. [7].

Figure 1 shows the retrieval scheme of δ (a) and m_g (b) in a conceptual way. For the estimation of δ, in situ measured d and ε_{can} (which is retrieved from ε_{veg} converted from in situ measured m_g using the model of [8]) are the input variables for the τ-model of [4]. In contrast, for the estimation of m_g, in situ measured d and a constant value of δ (a range of constant δ between 0 and 0.01 was tested) are the input variables. For both retrievals, the modeled τ-values are then compared with the radiometer-derived τ by minimizing the objective function (Φ) defined as the cumulative squared error between the modelled and measured τ. The δ-value was chosen (based on a model selection) for the τ-model during the δ-retrieval and the value of ε_{can} (which was calculated from the modelled ε_{veg}) was chosen for the τ-model during the m_g-retrieval, which led to the smallest value in the Φ. Concerning the radiometer-derived τ-parameter, τ_p at horizontal (p = H) or vertical (p = V) polarization was tested for the δ- and also the m_g-retrieval. But finally only τ_V was used for the δ- and m_g-retrieval as τ_H did not lead to a realistic estimation of δ (i.e., significantly deviating temporal evolution and underestimation of δ in comparison to the δ-values which were estimated based on τ_V) and m_g (i.e., significantly deviating temporal evolution and underestimation of m_g in comparison to in situ measured m_g). The fact that τ_V performed better for the m_g-retrieval, could be due to the strong vertical structure of the wheat canopy which is better sensed with V- than with H-polarization.

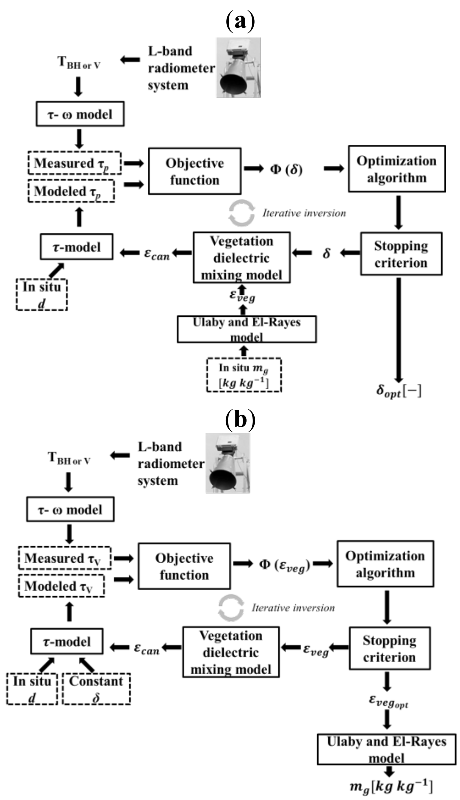

Figure 1: Conceptual schemes of the attenuation-based approach to retrieve the vegetation volume fraction (δ) (a) or the gravimetric vegetation water content (m_g) (b).

3. RESULTS

3.1. Vegetation volume fraction retrieval

Figure 2 shows the results of the δ-retrieval using the radiometer-derived τ_V as an input in the attenuation-based approach for different vegetation dielectric mixing models. Random needles (δ_{rn}) revealed the lowest temporal variation and the lowest values of δ, while spheres (δ_s) resulted in the highest variation over time and highest values of δ. Vertical needles (δ_{vn}) and random discs (δ_{rdi}) lied in between with a mean of 0.007 (*vn*) and 0.005 (*rdi*) and a STD of 0.005. The low values of δ_{rn} could be explained by the fact that assuming the shape of random needles for the vegetation inclusions underestimates the volume of the wheat, as most of the stalks are strongly vertically oriented.

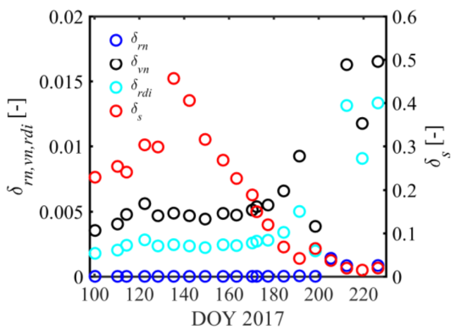

Figure 2: Retrieved δ-values for different dielectric mixing models (i.e., random needles (*rn*), vertical needles (*vn*), random discs (*rdi*), and spheres (*s*)) using the radiometer-derived τ_V as an input in the developed attenuation-based approach. The left y-axis explains the values of the *rn*-, *vn*-, and *rdi*-models and the right y-axis the values of the *s*-model.

The reason for the high values of δ_s, which are much larger than the expected value range for δ (0 - 0.01) [4], is probably due to the fact that δ is affected by the neglected anisotropic interaction of the wheat vegetation with the microwaves, as assuming spherical inclusions is only valid for isotropic vegetation layers. This kind of compensation by δ, but in a vice versa form (as the vegetation is more isotropic during the senescence), might be also present after DOY 180 for δ_{vn} and δ_{rdi}, where δ increases significantly to values around 0.01 and higher as the isotropic interaction of the wheat vegetation with the microwaves is neglected. This seems to indicate the need of changing the dielectric mixing model of the canopy along the phenological stages to avoid such compensating effects on δ.

3.2. Gravimetric vegetation water content retrieval

Figure 3 depicts the results of the m_g-retrieval using the developed attenuation-based approach with different vegetation dielectric mixing models (i.e., *vn* and *rdi*) in comparison to the in situ measured m_g (*ref*). Only the radiometer-derived τ_V was used as an input. Additionally, Table 1 shows the results of the linear regression between in situ measured and radiometer-retrieved m_g for both dielectric mixing models (*vn* and *rdi*). The agreement between the in situ-measured and radiometer-retrieved m_g is significant with a R^2 of 0.89 for both mixing models and RMSE-values of 0.1 and 0.12, respectively. The retrieved m_g shows a mean and STD of 0.58 and 0.20 for *vn* and of 0.55 and 0.18 for *rdi*. The mean and STD of the in situ-measured m_g are 0.55 and 0.26, respectively. The smallest bias can be found for the *rdi* mixing model with a value of 0.009.

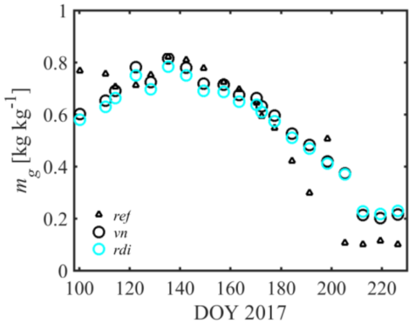

Figure 3: m_g-retrievals for different dielectric mixing models (i.e., vertical needles (*vn*) and random discs (*rdi*)) using τ_V as an input in the developed attenuation-based approach. These values are compared to the in situ-measured m_g (*ref*).

The radiometer-retrieved m_g are comparable to m_g-values found for crops on global scale, where a mean and STD of 0.54 and 0.18 is found [5]. However, the radiometer-retrieved *mg* using the *vn* and *rdi* models is still underestimated in comparison to the in situ-measured m_g between DOY 100 and 120 and overestimated after DOY 180. This is probably due to the fact that we assume a constant δ over the whole growing season as there was not enough information to retrieve two parameters, δ and m_g, at the same time (i.e., not enough degrees of information (DoI)), knowing that the volume of the vegetation is actually changing along phenological phases.

Table 1. Results of the linear regression between the radiometer-retrieved and in-situ measured m_g. Bias, root mean square error (RMSE), and squared Pearson correlation coefficient (R^2) are included.

Var 1	Var 2	slope	intercept	bias	RMSE	R^2
retrieved $m_{g\,(vn)}$	in situ m_g	0.70	0.19	0.03	0.10	0.89
retrieved $m_{g\,(rdi)}$	in situ m_g	0.64	0.20	0.009	0.12	0.89

Concerning the slopes and intercepts of the linear regression lines, the *vn* dielectric mixing model shows the closest fit to the ideal correlation line (1:1 line) with values of 0.70 and 0.19, respectively.

3.3. Sensitivity analyses of retrievals regarding input variables

Here, on one hand the sensitivity of the δ-retrieval by varying the time-variable m_g input as well as on the other hand the sensitivity of the m_g-retrieval by varying the constant δ input is investigated. Figure 4 depicts the results of the δ-retrieval along the growing season using the *vn* dielectric mixing model by adding a bias of ± 5 or 10 % to the in situ measured m_g. Biased inputs of m_g lead to a offset, but the temporal evolution of δ is not directly affected compared to the unbiased δ (δ_{ref}). This indicates that, when the vegetation dries out (having lower m_g) the δ increases and when the vegetation takes up water (towards higher m_g) the δ decreases.

Concerning the sensitivity of the m_g-retrieval to changes on δ, different dielectric mixing models were tested. Results (not shown) revealed that when using, e.g., the *vn* model, a high δ (0.01) leads to an underestimation of m_g and if δ is low (0.004) m_g is overestimated. A δ of 0.0049 leads to the smallest value in the Φ between the modelled and measured τ_V and to the closest fit between the retrieved and in situ measured m_g. In general it can be stated, that already small changes in the m_g- or δ-inputs (i.e., 0.1 for m_g and < 0.01 for δ) could lead to significant changes of the retrieved parameters.

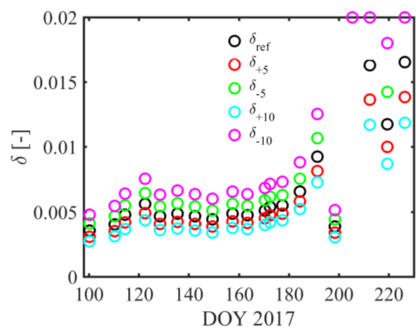

Figure 4: Sensitivity study on the δ-retrieval using the vertical needles (*vn*) dielectric mixing model and varying the m_g-input by ± 5 ($\delta_{+\text{ or }-5}$) or 10 % ($\delta_{+\text{ or }-10}$) in comparison to δ-retrieval where the unbiased, time-variable, in situ measured m_g was used as input (δ_{ref}).

4. CONCLUSIONS AND FINAL REMARKS

In this study, an attenuation-based approach (i.e., based on the attenuation of microwave radiation through vegetation) was developed and applied to retrieve volume fraction δ and gravimetric moisture m_g of wheat vegetation at the field scale over an entire growing season. The retrieved δ indicates that assuming only one static and isotropic (spherical) shape for the vegetation inclusions in the dielectric mixing model of the canopy may lead to an under- or overestimation of the vegetation volume (by not accounting for the anisotropic vegetation structure of wheat stalks). Furthermore, also the temporal evolution of δ could be affected (cf. Figure 2). To avoid such effects, one solution could be to vary the vegetation dielectric mixing model with changing phenological stages instead of assuming a static dielectric mixing model over the whole growing period.

The retrieved m_g-values show a good agreement with the in situ measured m_g ($R^2 > 0.8$), where the *vn* dielectric mixing model performed best for the stalk-dominated wheat vegetation (see Table 1). But the assumption of a constant δ, while knowing that the volume of the vegetation is changing along phenological development, leads to an underestimation of m_g at the beginning of the growth phase and an overestimation of m_g in the senescence phase, respectively.

For mitigation of such effects on the radiometer-retrieved m_g due to erroneous assumptions on δ, it could be retrieved on a daily basis or be adapted for dominant phenological stages. But yet, the assumption of a constant δ seems to be valid for at least the main growth stages of winter wheat (between DOY 120 and 180). In addition, the retrieval of the two parameters, m_g and δ, is not possible at the same time due to limited degrees of information (DoI) (i.e., having more variables to retrieve than observations available as an input). Therefore, we can only assume a constant δ [9] along growing period or use auxiliary information to estimate it, like from the radar vegetation index (RVI) [5].

Concerning the influence of the dielectric mixing model on the m_g-retrieval, it was shown that it is appropriate to describe the vegetation over the whole growing season by the inclusion type which represents the dominant vegetation structure, i.e., vertical wheat stalks in our case, which corresponds to the vertical needles (*vn*) model. The sensitivity analyses showed that already small changes in the m_g- or δ-inputs (i.e., 0.1 for m_g and < 0.01 for δ) could lead to significant changes of the retrieved parameters.

It's worth noting that all findings presented here are only valid for winter wheat vegetation. Future research should apply the proposed attenuation-based approach to other crop types and over longer observation periods.

5. ACKNOWLEDGEMENT

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