

## ***Interactive comment on “Dielectric characterization of vegetation at L-band using an open-ended coaxial probe” by Alex Mavrovic et al.***

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Comments from the Referees:

Referee #1:

This paper presents the development and validation of a new open-ended coaxial probe for in situ measurements of the relative permittivity of tree trunks at the microwave L-band. Such measurements are very important to support the decoupling of the integrated signal originating from soil and vegetation. The latter is an essential step in microwave remote sensing applications aiming at soil moisture observations and freeze/thaw detection, since the vegetation contributes to microwave brightness temperature measurements and scatters and attenuates ground surface emissions.

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The here presented measurement technique can help to improve the generally poorly parameterized vegetation canopy radiative transfer models that are used to exploit the satellite data. The paper is well written. The work is conducted carefully, critically reflected and underlined with relevant literature. It is without question of value to the satellite data calibration and validation community. I hope the authors will pursue their work as stated in the conclusions - having a single instrument able to measure the L-band relative permittivity of both soil and vegetation in situ would indeed be very helpful in the scope of better parameterization of microwave radiative transfer models.

I suggest minor revisions of the manuscript to address the points raised in the specific comments detailed below.

Comments:

R1, P3, L12-13: I remember a presentation given by Roger Lang at the MicroRad Symposium in 2016 where I believe he presented microwave permittivity measurements of trees in connection with the SMAP mission. When quickly googeling, I found this reference: Francois, A., Pineiro, Y, and Lang, R. H. (1998). Microwave permittivity measurements of two conifers. IEEE TGRS. But given his talk at the symposium, I assume there might also be more recent publications by this team. You could possibly add a respective reference.

We did not find a reference or abstract for the MicroRad Symposium, but the Francois et a. 1998 reference was added in the Introduction section.

P3, L12-14: To our knowledge, only a small number of measurements of the permittivity of trees at microwave frequencies have been reported (e.g., El-Rayes and Ulaby, 1987; Way et al., 1990; McDonald et al., 2002; Francois et al., 1998).

R1, P4, L5-11: You state “The real part of the permittivity describes the effect of the reorientation of the electric dipole inside the medium that drives wave propagation, and the imaginary part describes the absorption (or loss) by the medium... A high

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value of real permittivity characterizes a medium that strongly resists the application of an external electric field (i.e. permittivity of water  $\sim 90$ ). In contrast, a low real permittivity characterizes a medium that does not strongly resist the application of an external electric field (i.e. permittivity of air  $\sim 1$ ).” I would have said that that the water molecules rotate well with an applied electric field due to their strong dipoles, which for me is the opposite of a resistance...?

It is true that the strong dipoles of water rotate well with an applied electric field, but their reorientation opposed the applied electric field resulting in a weaker global electric field. We replaced the word “resist” by “oppose” to make it clearer.

P4, L9-11: A high value of real permittivity characterizes a medium that strongly opposes the application of an external electric field (i.e.  $\epsilon' \approx 90$ ). In contrast, a low real permittivity characterizes a medium that does not strongly oppose the application of an external electric field (i.e.  $\epsilon' \approx 1$ ).

R1, Figure 2: in the caption you list b) before a). Furthermore, mention SMA connector, N-type connector and RVNA control program in the text (not only in the figure). Also, in the text you state that the gap is filled with PTFE, in the Figure you use the term Teflon – better harmonize.

The letter order was corrected in figure 2 caption. We provided details of the permittivity measurement setup in figure 2 caption. The term “Teflon” was replaced by PTFE in figure 2.

Figure 2: (a) Diagram of the electrical field produced by the open-ended coaxial probe. (b) Open-ended coaxial probe kit for permittivity measurement. The reflectometer manufacturer provides the RVNA control program. To connect the probe to the Planar R54 reflectometer, a SMA/N cable is required.

R1, Section 3 - Methods: Personally, I struggle a bit with this section title. Since the goal of your paper is to “develop and validate a probe” in my opinion sections 2.2 and

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2.3 are also part of the applied methods... Maybe you could rather call section 3 “Tree permittivity measurements with open-ended coaxial probe” and section 3.1 something like “Measurement principle”.

We put all the sections about the development and validation of the probe inside the Methods section. Thereby, subsections “Open-ended coaxial probe measurement principle”, “Open-ended coaxial probe measurement calibration” and “Performance evaluation” are now under the “Methods” section. The “Study sites” subsection is now its own section.

R1, P7, L27-31: Since one of the objectives of the paper is the development of the probe, you could possibly add one figure demonstrating the good reproducibility described in the text.

The objective is to validate the probe for vegetation measurement, and not to validate the development of the probe by itself. Reproducibility of the probe has been demonstrated in Filali et al., (2006). Hence because the fluctuations are small (2%) we decided to remove the sentence on reproducibility.

R1, P8, L7-8: I assume the plumber’s putty used cannot affect the measurement? What does its relative permittivity look like?

We clarified how we made sure the plumber’s putty do not affect the measurement.

P8, L10-13: For continuous measurements, to avoid any oozing or drying issues due to the tree’s biological reaction to the wound, the gap between the probe and the cavity edges were sealed with plumber’s putty. The plumber’s putty does not affect measurements because it is placed around the edge of the probe, away from the open-ended measuring surface of the OECP probe.

R1, P8, L21-23/Table 1: From Table 1 I assume you took the measurements at breast height. Possibly add this to the text. If you have taken measurements at different tree heights, could you see any trend or do you get the same measurement result every-

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where? If you later want to determine the bulk contribution of the trees to the microwave L-band signal observed by space-borne radiometers, then you would certainly need to check this. I see that this does not necessarily fall into the scope of this paper, but I think it would be interesting to the reader if you added some lines on this issue (if ever you have already tried to measure at different tree heights to see if there is a difference).

All measurements presented in this manuscript were taken at breast height, which we specified. A vertical trend is expected along the trunk, but its study is out of the scope of this manuscript.

P8, L25-29: Tree permittivity measurements were taken at three different sites in a total of seven tree species (five conifers and two hardwoods). For each species, several measurements were obtained at several depths per tree. All measurements were taken at breast height ( $\approx 1.3$  m). The vertical variability in permittivity along the trunk was not investigated in this article; a slight increase in permittivity is expected from roots to top of the tree (Franchois et al., 1998). A detailed description of the studied sites and obtained measurements can be found in Table 1.

R1, P9, L3-10: What do you exactly mean by “For this reason, all results shown in this article were taken with samples of thickness greater than 10 mm”? Is this why you give the DBH in Table 1? In Section 3.2 you only mention that you drilled at several depths. In Table 3 you indicate an average permittivity across the whole tree... It would be nice if you could be a bit more precise on the different measurement depths. In that context, it would also be useful to list the respective sapwood thicknesses estimated visually using tree cores extracted with an increment borer. Could you possibly add this information together with the respective drilling depths to Table 1?

We clarified why 10 mm clearance is needed behind the probe/sample interface. The measurement depths are shown in figure 7. In each measured tree, a radial profile was taken. Then the integrated permittivity over the fist 10 mm was calculated. Therefore, it

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is not relevant to give measurements depth for each species and trees. Unfortunately, visual sapwood thickness was only available for few measurements. The average of those visual sapwood thickness is provided in figure 7. However, it is mentioned in figure 7b that the permittivity is the average value over the first cm.

P9, L10-16: The permittivity of a stack of paper sheets stabilized at a thickness of 10 mm (Fig. 4). At that thickness, the effect of paper sheet height is too low to be observed given the probe's precision (see Section 4.2). Since the probed depth depends on the permittivity of the material, it is expected that samples with higher permittivity will have a shallower probed depth. The permittivity of paper is close to the lower end of the range of permittivity expected for vegetation material, thus 10 mm should be seen as the upper limit of the probed depth of the OECF. For this reason, all results shown in this article were taken with samples of thickness greater than 10 mm to ensure there is no measurement disturbance in the probe's effective electrical field.

P10, L24-32: Substantial differences were observed in the frozen permittivity of different tree species (Table 3), ranging from 3.52 to 9.13 for the real part and from 0.36 to 3.23 for the imaginary part. Evaluating thawed tree permittivity is challenging since permittivity changes with depth. However, it should be noted that L-band interaction would be higher with the sapwood because it is the outer layer of the tree and its permittivity is higher than the heartwood. To ensure a representative averaging of the sapwood permittivity, we did not make measurements too close to the interface between sapwood and heartwood to avoid a bias toward lower permittivity. Knowing that the sapwood thickness of the trees used in this study is around 2 cm, the average permittivity reported in Table 3 for different thawed species was estimated by averaging the permittivity through the first centimeter under the bark using a trapezoidal numerical integration over that first centimeter.

R1, Table 3: "average value across the whole tree" - I assume you mean from the bark to the center of the stem as can be seen in Figure 7?

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We clarified the averaging range in table 3 caption

Table 3 caption:  $\epsilon_{1\text{cm}}$  average represents the average value of the trunk permittivity through the first centimeter under the bark, while  $\epsilon_{\text{average}}$  represents the average value across the whole radial profile as seen in Fig. 7. Detailed data are available in supplementary material for thawed trees (Fig. S1 to S5) and frozen trees (Fig. S7).

R1, P9, L32-34: “In the first several millimeters of the trunk, sapwood permittivity is higher due to a high water content, but permittivity decreases quickly to a lower and well-constrained value in the heartwood (Fig. 7).“ I guess the closer you get to the heartwood, the more your penetration depth approaches the max. estimated as 9 mm. Does it mean that close to the border between sapwood and heartwood your measurements - even if still taken in the sapwood - can be influenced by the much drier heartwood, i. e. resulting in a bias towards lower permittivities?

We explained the bias toward lower permittivity and assess that it should not affect our integrated permittivity value for thawed trees because the integration range stays short of the sapwood/heartwood interface.

P9, L10-16: In the first several millimeters of the trunk, sapwood permittivity is higher due to a high water content, but permittivity decreases quickly to a lower and well-constrained value in the heartwood (Fig. 7). It has to be noted that since the probed depth can reach up to 10 mm, there is a bias toward lower permittivity near the interface sapwood/heartwood because the probe is measuring some dryer wood behind the actual sapwood.

P10, L24-32: Substantial differences were observed in the frozen permittivity of different tree species (Table 3), ranging from 3.52 to 9.13 for the real part and from 0.36 to 3.23 for the imaginary part. Evaluating thawed tree permittivity is challenging since permittivity changes with depth. However, it should be noted that L-band interaction would be higher with the sapwood because it is the outer layer of the tree and its permittivity is higher than the heartwood. To ensure a representative averaging of the sap-

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wood permittivity, we did not make measurements too close to the interface between sapwood and heartwood to avoid a bias toward lower permittivity. Knowing that the sapwood thickness of the trees used in this study is around 2 cm, the average permittivity reported in Table 3 for different thawed species was estimated by averaging the permittivity through the first centimeter under the bark using a trapezoidal numerical integration over that first centimeter.

R1, P10, L16-20: “However, it should be noted that L-band penetration depth in thawed trees is limited to 10 mm according to Eq. (1). Therefore, it should not exceed the sapwood depth, which suggests that the sapwood permittivity could be considered as the actual effective permittivity of trees with regards to L-band interactions. Consequently, the average permittivity reported in Table 3 for different thawed species was estimated by averaging the permittivity through the first centimeter under the bark using a trapezoidal numerical integration over that first centimeter. ” ! I had to read this several times to understand what you mean, maybe consider to rephrase to make it clearer. In line with my comments further above (P9, L3-10 and P9, L32-34) I think it would be really helpful to indicate the sapwood depths of all sampled tree types in a table (and not only in Figure 7 for black spruce).

In line with comments (R1, P9, L3-10) and (R1, P9, L32-34), this section was rephrased to clarify the meaning of the thawed tree permittivity average.

P10, L24-32: Substantial differences were observed in the frozen permittivity of different tree species (Table 3), ranging from 3.52 to 9.13 for the real part and from 0.36 to 3.23 for the imaginary part. Evaluating thawed tree permittivity is challenging since permittivity changes with depth. However, it should be noted that L-band interaction would be higher with the sapwood because it is the outer layer of the tree and its permittivity is higher than the heartwood. To ensure a representative averaging of the sapwood permittivity, we did not make measurements too close to the interface between sapwood and heartwood to avoid a bias toward lower permittivity. Knowing that the sapwood thickness of the trees used in this study is around 2 cm, the average permit-

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tivity reported in Table 3 for different thawed species was estimated by averaging the permittivity through the first centimeter under the bark using a trapezoidal numerical integration over that first centimeter.

Figure 8: The color coding of the different soil moisture measurements could be improved. However, I was general wondering, is it actually necessary that you show all these different soil moisture measurements? They all exhibit the same temporal trend, demonstrating the rain evens, and if I understood correctly, that is their purpose here. Thus, one curve would be sufficient. If you keep the vertical probe, then I think you should indicate the sensing depth interval.

We reduced the number of soil moisture curves to two for two soil depths: 5 cm and 10 cm.

Figure 8: (a) Daily cycle of red pine's sapwood L-band permittivity (unitless) at the SIRENE site and (b) soil moisture at 5 and 10 cm (EC-TM probe).

R1, P12, L33-36: "The potential for modifying the dimensions of the probe is limited because probe frequency is geometry dependent. However, it should be possible to reduce the dimensions of the probe for less invasive measurements by increasing the probe frequency." !! I do not understand what you want to say here. The two sentences sound a bit contradictory to me...

We rephrase the first sentence to not sound contradictory with the second one.

P13, L7-11: It is difficult to modify the dimensions of the probe without modifying its frequency limit that is geometry dependent. Nevertheless, it is possible to reduce the dimensions of the probe for less invasive measurements, which will further increase the frequency limit. Moreover, it is possible to produce series of probes operating up to higher frequency limits by reducing the size of their aperture, when the limitation of the probed depth is acceptable.

R1, Figure S7: If I got it right this plot corresponds to the data presented in Table 3? if

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so, you could indicate this in the caption. Why are you not providing the same plot for the 1cm average under thawed conditions?

We had a reference to table 3. We do not have enough data under thawed conditions for a boxplot to be relevant.

Figure S7: Variability of the L-band real ( $\epsilon'_{L}$ ) and imaginary ( $\epsilon''_{L}$ ) relative permittivity (unitless) of the frozen trunk of tree species from OBS, SIRENE and NEIGE-FM sites. The data presented in this boxplot are a detailed version of the data in Table 3. The central red mark of the boxplot indicates the median, the blue box includes the data between the 25th and 75th percentiles, the black whiskers extend the full range of data excluding the outlier data that are represented by a red cross.

R1: Only Figure S5 is referenced in the text ! possibly add respective references to the other supplementary figures as well. That way it is clearer why you provide them.

Figure 4: Real relative permittivity (unitless) in L-band (1-2 GHz averaging) of a stack of paper sheets. The permittivity imaginary part is provided in supplementary material (Fig. S6).

Table 3 caption:  $\epsilon_{1\text{cm}}$  average represents the average value of the trunk permittivity through the first centimeter under the bark, while  $\epsilon_{\text{average}}$  represents the average value across the whole radial profile as seen in Fig. 7. Detailed data are available in supplementary material for thawed trees (Fig. S1 to S5) and frozen trees (Fig. S7).

R1, P5, L4: Define e

We defined e as Euler's number.

P5, L1-3: The range of the electric field defines the thickness of the sampled medium and can be estimated using the penetration depth  $\delta_d$  (Eq. 1) describing the travel distance of an electromagnetic plane wave before being attenuated by a factor  $1/e$  where e is Euler's number.

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R1, P5, L6: f is not part of formula (1)?

f is the frequency and is found in the numerator of the first term of equation 1. A pdf print error made it disappear. We will make sure it appears on the final version.

R1, Formulas 2-4: check that all parameters are defined in the text

We defined explicitly some terms of equation 2.

P5, L25-28: where  $k$  is the wavenumber ( $k=f\sqrt{(\epsilon_r \epsilon_0 \mu_0)}$ ),  $r=\sqrt{(u^2+\tilde{u}^2+2u\tilde{u}\cos\hat{A}_a\varphi)}$  in radians per meter,  $f$  is the frequency in hertz,  $\epsilon_r$  is the media relative permittivity,  $\epsilon_0$  is the vacuum absolute permittivity,  $\mu_0$  is the vacuum absolute permeability,  $(u, u', \varphi)$  are the cylindrical coordinates and  $a$  and  $b$  represent the internal and external radius of the coaxial probe in meters, respectively.

R1, Equation 5: There are two formulas number 5 (P6, L8 and P6, L15)

Equations and equations reference errors due to the two equations numbered 5 were corrected through the whole manuscript.

R1, Table 2: I assume it should read "...in Fig. 5 and 6" (instead of Fig. 7 and 8).

We corrected the figures reference errors.

Table 2: Root-mean-square error (RMSE) between the measured L-band relative permittivity value (real and imaginary parts) and the accepted value in the scientific literature for the data presented in Fig. 5 and 6.

R1, P10, L7: should it read "awakening" instead of awaking?

P10, L15-17: This event was sufficient to melt water inside the trees as the sapwood permittivity measurements of that day reproduced the same behavior as the spring awakening of biological activity in trees.

R1, P11, L11-12: "L-band wavelength is about 20 cm; branches need to have a diam-

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eter at least a significant fraction of the wavelength to influence the signal, which is not the case” ! there seems to be a word missing in this sentence.

We split the sentence in two for better comprehension.

P11, L19-23: The influence of needles and branches on radiometric measurements is considered negligible in L-band because of their size and quantity (Ferrazzoli et al., 2002). The diameter of branches needs to be a significant fraction of the wavelength to influence the signal. In L-band, the wavelength (about 20 cm) is much smaller than the diameter of branches in boreal forests.

Referee #2:

This paper’s objectives are to present a probe to measure the dielectric constant at L-band and to measure the dielectric constants of trees. The topic is very interesting as there are only a few attempts to measure the dielectric constant of trees whereas it is crucial for L-band mission. This paper is well written and the Figures are clear, the authors have made a noticeable effort, which is appreciated.

The paper is recommended for publication with minor changes.

Comments:

R2, Section 2: It is already part of the method which is section 3. The two sections should be combined. One part can present the probe, another the protocol to validate it, and a last one a protocol to collect measurements of the trees.

We combined the two sections. We put all the sections about the development and validation of the probe inside the methods section (see also R1, Section 3 - Methods).

R2, Figure 6 a: do you have any explanations for the change in the behavior of the imaginary part (around 1.3 GHz). The measurements are higher than the model before, and lower after that.

The change in behavior is smaller than the probe’s precision and reproducibility (less

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than 1%). We think that these changes are not statistically significant and that they fall into the probe's precision.

R2, P9, L9-10: "samples of thickness greater than 10 mm" The sentence is not very clear. So is it the minimum distance within a trunk between 2 measurements?

We clarified that a 10 mm clearance is needed behind the probe/sample interface (see also R1, P9, L3-10).

P9, L5-13: The permittivity of a stack of paper sheets stabilized at a thickness of 10 mm (Fig. 4). At that thickness, the effect of paper sheet height is too low to be observed given the probe's precision (see Section 4.2). Since the probed depth depends on the permittivity of the material, it is expected that samples with higher permittivity will have a shallower probed depth. The permittivity of paper is close to the lower end of the range of permittivity expected for vegetation material, thus 10 mm should be seen as the upper limit of the probed depth of the OECP. For this reason, all results shown in this article were taken with samples of thickness greater than 10 mm to ensure there is no measurement disturbance in the probe's effective electrical field.

R2, P5, L6, Equation 1: Under equation 1,  $f$  is presented but is not in the equation. Has it been forgotten?

$f$  is the frequency and is found in the numerator of the first term of equation 1. A pdf print error made it disappear. We will make sure it appears on the final version.

R2, P9, L1-6: The same idea written twice, it can be simplified.

This section was modified and some sentences with repeating ideas were removed.

P9, L9-15: The permittivity of a stack of paper sheets stabilized at a thickness of 10 mm (Fig. 4). At that thickness, the effect of paper sheet height is too low to be observed given the probe's precision (see Section 4.2). Since the probed depth depends on the permittivity of the material, it is expected that samples with higher permittivity will have a shallower probed depth. The permittivity of paper is close to the lower end of the

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range of permittivity expected for vegetation material, thus 10 mm should be seen as the upper limit of the probed depth of the OECP. For this reason, all results shown in this article were taken with samples of thickness greater than 10 mm to ensure there is no measurement disturbance in the probe's effective electrical field.

R2, Equation 5: 2 equation 5

Equations and equations reference errors due to the two equations numbered 5 were corrected through the whole manuscript.

R2, Figure 2: Switch a) and b)

The letter order was corrected in figure 2 caption.

R2, P19, L6-8: Update reference of Pappas et al. 2018

Will be updated as soon as possible.

Referee #3 (the paper is part of Alex Mavrovic master thesis. We thus include reviews from one of the thesis reviewer):

1. Publication p2, Lines 32-33: "Horizontal polarization is more affected. . ." this applies only to oblique angles (other than nadir). Please specify in text. We specify in the text.
2. P2 lines 8-9: not clear why or how microwave models are "poorly parameterized", please elaborate. Add if you are talking specifically about L-band or also other frequencies (regarding some frequencies I would beg to disagree!). We clarify the sentence. We also put the reference of Wigneron et al. (2017), instead of Roy et al. (2016): "Vegetation canopy radiative transfer modeling at L-Band remains a challenge when it comes to quantify the non-negligible scattering and emission effects of vegetation (Wigneron et al. 2017; Kurum et al., 2012)." 3. Publication p3, line 4. As you indicate by the reference, the ice/water fractions vary in the tree as a function of air temperature. This would imply permittivity changes with air temperature. Did you study this possible correlation? Is there enough data collected at sub-zero temperatures to analyze this? At least you could mention here that this correlation is a possible result at the end of the

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paragraph. We mentioned that the ice fraction variations in trunks could lead to change in tree permittivity. “Some of the water in the tree freezes, and the ice fraction in the trunk varies as a function of tree composition and air temperature (Sparks, 2001), and could theoretically lead to a variation of tree permittivity with air temperature.” However, our results show that the permittivity of the tree is very stable and low when the trees are frozen. However, it is true that we see some variation in the permittivity when temperature is around 0°C. We thus add a sentence in the discussion: “However, even if it was shown that the permittivity was very stable when the tree was frozen, there were still some variations when air temperature was around 0°C. Hence, that would be interesting in future work to analyze with continuous measurements how the tree permittivity varies during freeze/thaw transitions.”

4. P4 line 10 and line 11. “i.e.” means “id est” or “that is”. “e.g.” would be more appropriate (“exempli Gratia” or “for example”) Done.

5. P9 line 24: “at L-band”, please correct Done

6. P11 line 12: “.. is not the case for typical trees in the boreal forest zone” or something similar

Changed.

7. P13 Conclusions: you state here the uncertainty of 3.3%, although earlier you admit that a worse precision was obtained with the only solid reference target (PTFE). Would be good to state that again in the conclusions, since I think this is indeed the greatest issue with the type of measurement you use (and your main target is a solid tree).

The value of 3.3% was obtained with the PTFE. It is clarified in the conclusion:

“The OECF device we developed displayed uncertainties of 3.3% with a solid reference target and under 2.5% for liquid standards.”

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<https://doi.org/10.5194/gi-2018-9>, 2018.

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