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Interactive comment on "Soil dielectric characterization at L-band microwave frequencies during freeze-thaw transitions" *by* Alex Mavrovic et al.

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—-General Comments:—-

This manuscript describes a laboratory experiment in which the relative dielectric permittivity at L-band of a variety of different types of soil are measured during the freeze <-> thaw process with a dedicated microwave open-ended coaxial probe (OECP) and a commercial soil moisture probe: Hydraprobe (HP). The measurements with both

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the OECP and HP show a clear hysteresis effect associated with the freeze and thaw process in the graphs of complex relative dielectric permittivity (epsilon) versus soil temperature. Although there are some differences in the measured epsilon between the OECP and HP the authors argue that soil moisture sensors such as HP, which are relatively cheap, tested and verified, can be used construct validation networks for passive microwave remote sensing. Additionally, the manuscript addresses that current models for soil epsilon don't incorporate the freeze <-> thaw hysteresis effect.

The experiment, its results, and proposed application in building validation networks for soil dielectric permittivity with soil moisture probes, I consider as a valuable contribution to the microwave remote sensing community. The title does not fully reflect the contents of the paper, I think you could add "with a soil moisture probe" in the end. Description of the experimental design should be improved. Also the description and explanation of the observed freeze <-> thaw hysteresis should be more elaborate. Finally, throughout the paper the structure of the sentences can be improved.

—-Specific Comments:—-

[1] Line 188 and Figure 3: "The OECP and HP were fully . . ." Why was the OECP inside the OBS soil sample and not inside the other three soil samples? And if it was buried inside the OBS sample would not this disturb the sample? I suppose the sample structure was better preserved in the configuration of figure 3b.

[2] General remark on the samples and measurement setup. With the OBS sample HP measurements were taken at three positions. As Figure 5 shows the measured responses at these three positions varies. Why were there not also measurements at multiple positions for the OECP with the OBS sample? And why were the other 3 samples not also measured with the HP (and the OECP) at multiple positions? Was this because the OBS sample was expected to be less homogeneous due to the organic content? And why only one sample per soil type was measured? The choices the authors made in this regard should be explained in the text, even if simply for practical

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reasons.

[3] Line 243: The amplification of the hysteresis -effect by the setup, is it possible to explain this in the text with a few sentences? You refer to this hysteresis amplification later on, it would be better if the reader could find an explanation for this effect in this manuscript rather than somewhere else (the reference). You can of course leave the reference.

[4] Lines 252 - 255: I am not sure whether I completely agree with your explanation. You ascribe the difference in measured transition to the different probing volumes of both sensors and that with the HP there is a longer time required for the freezing/thawing front to penetrate the probed volume. The way I see it for both sensors the temperature gradient is from top/bottom (because of your nice trick of placing sand around the sample) so ideally the progression of this freezing/thawing front is the same for both sensors. What is different is the diameter of the sensor's probing volume, see Figure 2. For the OECP this is roughly half the diameter of the HP, which would explain a more abrupt transition. Another difference is the length of the probing volume. For wet conditions the length for the HP is about 15x that of the OECP. The way I see it the HP then performs 15 OECP measurements at 15 different positions. If there is variation in the soil over this length, the HP then shows a kind of average transition over all these 15 volumes. This is the reason I was also wondering why the OECP was not used at multiple positions within one sample (comment [2]). You could maybe test your volume explanation by taking the OECP result and scale it to the HP volume.

[5] Figures 5 - 8: During the thawing process there appears to be maximum epsilon' and epsilon" directly after the main thawing process after which the epsilon' and epsilon" decrease again slightly. This is effect is most pronounced in Figure 7. Do you have an explanation for this effect?

[6] Lines 270 - 272: Based on the Figures 5 - 8 I find the freeze/thaw transitions not similar. Can the differences of the OECP and HP measurements be explained by the

difference in probing volume? Also you mention that the main difference between the OECP and HP measurements are the epsilon values at the end of the cycle, at the "stable plateaus" as you call it. But isn't the hysteresis just as important? Perhaps if a found calibration equation for a given soil is applied to the HP results the freeze/thaw hysteresis is more like that of the OECP?

[7] Lines 283 - 289: What do the authors want to say with this paragraph? Is the point that, should a network of (tried, tested, and cheap) hydraprobes be installed over a large area as surrogate L-band permittivity sensors (lines 274 – 275), one must realize that the volume over which it measures is not exactly what radiometers probe?

[8] Line 300: What hypothesis do the authors refer to?

[9] Figure 11: With the freezing cycle you see both epsilons increase first before they decrease rapidly when all soil freezes. Why don't we see this behaviour during of the freezing fast freeze/thaw experiment? We do see it during the thawing (see comment [5]), are these processes linked?

—-Technical corrections:—-

[10] Line 20: You state that you show in the manuscript that the OECP is a suitable device for measuring epsilon .... The demonstration that OECP can measure the epsilon of any homogeneous material is given in your previous studies Mavrovic2018 and Mavrovic2020, not in this manuscript. In this manuscript you use the OECP to quantify the performance of the HP. I propose to change the sentence to .. the OECP measured the frozen soil epsilon' to be 3.5 to 6.0, the epsilon" to be 0.4 – 1.2 etc.

[11] Line 41, 42: Cite not only papers that use the tau-omega model for microwave scattering of vegetation. Give examples of papers that solve the radiative transfer equations differently, such as the Tor Vergata model (Bracaglia, Ferrazzoli, and Guerriero, RSE, 1995) or the MIMICS model (Ulaby, Sarabandi, et al., 1990 IJRS).

[12] Line 50: Propose to change to: "Permittivity is characterized by a complex number,

where the real part describes the translation and rotation of molecular dipoles, which drive the wave propagation, and the imaginary part describes the energy loss associated with this process." Further I propose to refer to a textbook on electrodynamics, for example: Griffiths D.J., Introduction to Electrodynamics.

[13] Line 63: remove the word passive here.

[14] Line 75: "to collect permittivity estimates", propose to change to "to collect better permittivity estimates." Also "... for the validation of passive microwave instruments". Propose to change to ".. for the validation of microwave radiometric observations". Or something similar, but it's the observations than need to be validated.

[15] Line 86: Add OECP between assess and L-band.

[16] Line 109: The reflectometer generates an electromagnetic wave, not only a propagating electric field.

[17] Line 110: Over what frequency band were the measurements performed?

[18] Line 116: "The penetration depth of the ..." This sentence is too vague for my taste. I propose something like: "The sensing depth of the OECP is the maximum depth at which the medium is polarized due to the incident electric field, and as such contributes to the reflection of the EM wave backwards into the coax."

[19] Line 118: "The magnitude of this effective electric..." the effective electric field has not been defined or explained previously. I assume you refer the resulting electric field in the medium? Which is the sum of the original electric field coming from the coax E0, which polarizes (rotates and or translates) the molecules and the electric field produced by the rotated or displaced molecules themselves Ed. Latter counters E0, which counters Ed, which counters E0 etc. You end up with a resulting electric field E, which is actually lower in magnitude for a higher epsilon.

[20] Line 119: You describe the electric field generated by the reflectometer in terms of power (dBm = 1 mW) which is incorrect. I propose to state simply that the generated

power is 10 dBm.

[21] Line 131: If applicable, note what type of Hydraprobe you used (for example type A or B100 or . . .)

[22] Line 137: ".. it uses the ratio of the incident and reflected waves to numerically solve Maxwell's equations, yielding the impedance and complex permittivity." That the device solves the Maxwell's equations sounds far-fetched to me. One of the papers on found on the Hydraprobe website should provide you with a better (quick) description on how the device works. In my understanding the Hydraprobe indeed works similar to the OECP: The epsilon of the material between the steel tines determines the characteristic impedance (symbol Z0 typically, or its inverse the characteristic admittance Y0) . The reflection of the The steel tines, together with the material (soil) they are in, forms a microwave transmission line with characteristic impedance Z0 (or its inverse Y0). The reflection coefficient, measured by the device, is dependent on this Z0.

[23] Line 140: mention ± 0.01 and ± 0.03 are uncertainties.

[24] Line 185: It confused me whether the samples were collected from the temperature chamber or from the sites. It is the latter I understand? Further, I propose to use distinguishing names. Call the PVC boxes with the collected soil 'samples' as is, but refer to the cardboard boxes, filled with samples and surrounding sand, with a different name. Maybe sample assembly. Indicate these names in Figure 3. This way you can mention for example that the "sample assemblies were placed in the temperature chamber and were subjected to 3 (? mention this as well) freeze/thaw cycles".

[25] Lines 243 – 246. Authors state that trends of OECP and HP are "very similar" and the fully frozen/thawed epsilon values are "also similar". I disagree with this description. Judging from Figures 5 - 8 there are significant differences. These differences and explanations for their causes are discussed further down in the text.

[26] line 251: ".. the freeze/thaw transition measurements are smoother with the HP

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than. . ." Perhaps there is a better alternative for "smoother", perhaps "less abrupt"? Also sentence should be "We also observe that the measured freeze/thaw transitions are less abrupt (?) with the measurements of the HP than with the OECP." Same for line 261.

[27] Lines 325 - 327: The question whether the OECP correctly measures the epsilon in not shown in this manuscript. It is implied by your earlier work, see also comment [10].

[28] Figures 5 – 8: To make comparison easier I propose to let all figures have the same axis limits for epsilon' and epsilon", even if this implies having only one figure per page. Further I would recommend using more contrasting colours for the curves and to plot the graphs in vector format (PDF).

[29] Tables 2 and 3: Besides the absolute uncertainty also indicate the relative uncertainty.

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