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Reply on RC1

Chang-Hwan Park et al.

Author comment on "An inverse dielectric mixing model at 50 MHz that considers soil organic carbon" by Chang-Hwan Park et al., Hydrol. Earth Syst. Sci. Discuss.,
<https://doi.org/10.5194/hess-2021-233-AC1>, 2021

This study developed a general inverse dielectric mixing model that can be applied to retrieve soil moisture from in-situ dielectric data. Considering organic carbon is the novel part of this approach. Overall, I think it is an interesting study. A reliable dielectric mixing model for organic soils is highly needed in order to get accurate soil moisture estimates in the high latitudes from both in-situ sensors or spaceborne microwave sensors. However, there are quite a number of places in the mathematical expressions that should be carefully examined.

The data used for validation also have a very limited range of organic carbon content ($OC < 0.06$ g/g), which are generally not classified as organic soils (rather they are organic-rich mineral soils). If the authors claimed this approach is going to help the soil moisture retrieval in the boreal and Arctic region, more data with a wider range of OC content are needed. Comparison with previous approaches that incorporated SOC (such as Bircher et al. 2016) should be also included and discussed.

Bircher, S., Andreasen, M., Vuollet, J., Vehviläinen, J., Rautiainen, K., Jonard, F., Weihermüller, L., Zakharova, E., Wigneron, J.-P., and Kerr, Y. H.: Soil moisture sensor calibration for organic soil surface layers, Geosci. Instrum. Method. Data Syst., 5, 109–125, <https://doi.org/10.5194/gi-5-109-2016>, 2016.

We thank the reviewer for their thorough assessment and helpful comments. We responded to the two main questions above in the reviewer's specific comments.

Specific comments:

1. Comments on the equations:

(1) Eq (5) and (6): it is confusing whether this applies to 50 MHz, or any frequency ranging from 1.4 GHz to 50 MHz. Also please provide the original references for these two equations.

Thank you for the comment. Our application is targeting for 50 MHz sensor. In order to avoid confusion, we corrected the paragraph (lines 111-112, p.4.) as following. Also, we added the relevant references for Eq.(5) and (6).

“According to Debye Relaxation, the dielectric constant of free water at less than 2GHz frequency has a constant value of approximately 80. However, in the field measurements (Curtis, John O. et al., 1995; Fal et al., 2016; Ishida, 2000; Mironov et al., 2013) it is found that in clay-rich soil, the real part of the dielectric constant increases at lower frequencies, which occurs by the clay-ion-complex interaction (Kelleners et al., 2005). Therefore, in this study for 50 MHz, the clay content and the real part of the dielectric constant at 1.4GHz are empirically considered in the dielectric constant not only for free, but also, for bound water Eqs. (5) and (6).”

Curtis, John O., Charles A. Weiss Jr, Joel B. Everett., 1995. Effect of Soil Composition on Complex Dielectric Properties.

Fal, J., Barylyak, A., Besaha, K., Bobitski, Y.V., Cholewa, M., Zawlik, I., Szmuc, K., Cebulski, J., żyła, G., 2016. Experimental Investigation of Electrical Conductivity and Permittivity of SC-TiO₂-EG Nanofluids. *Nanoscale Res Lett* 11, 375. <https://doi.org/10.1186/s11671-016-1590-7>

Ishida, T., 2000. Dielectric-Relaxation Spectroscopy of Kaolinite, Montmorillonite, Allophane, and Imogolite under Moist Conditions. *Clays and Clay Minerals* 48, 75–84. <https://doi.org/10.1346/CCMN.2000.0480110>

Mironov, V.L., Bobrov, P.P., Fomin, S.V., 2013. Multirelaxation Generalized Refractive Mixing Dielectric Model of Moist Soils. *IEEE Geosci. Remote Sensing Lett.* 10, 603–606. <https://doi.org/10.1109/LGRS.2012.2215574>

Kelleners, T.J., Robinson, D.A., Shouse, P.J., Ayars, J.E., Skaggs, T.H., 2005. Frequency Dependence of the Complex Permittivity and Its Impact on Dielectric Sensor Calibration in Soils. *Soil Sci. Soc. Am. j.* 69, 67–76. <https://doi.org/10.2136/sssaj2005.0067a>

(2) Eq. (8) does not seem correct to me. The correct equation should be: $v_{\text{som}} = 1/((1/\text{SOM}-1)(\text{BD}_{\text{SOM}}/\text{BD}_{\text{soil}})+1)$, where in the original equation, the BD_{soil} and BD_{som} should switch. The authors should also clearly define " BD_{soil} " and " BD_{SOM} ". If " BD_{soil} " is the soil bulk density, it varies greatly based on the SOM concentration, and using a constant value is not proper. Rather, I think here " BD_{soil} " and " BD_{SOM} " should mean the specific density of "mineral" and "organic matter" part of the soil solids. Please double check this.

□ Thank you very much for pointing out this error. The mineral and organic matter should be switched as shown in the corrected Eq.(8). Furthermore, we specified the BD_{SOM} and BD_{MI} are constant based on the Eq.(9) with the assumption of 0 and 56% OC cases (lines 143-145, p.5) which are called as “pure mineral” and “pure organic matter”. We also added the detailed derivation of Eq.(8) in appendix A (lines 390-401, p18).

“The bulk density for organic soils can be computed with pure mineral and organic matter densities (Federer et al., 1993) or be expressed with their total volume and mass of these components (Liu et al., 2013; Jin et al., 2017). By relating these two formulas, we can derive the following volumetric ratio of organic matter (v_{SOM} , $\text{cm}^3 \square \text{cm}^{-3}$) (see appendix A for more details):”

Federer, C., Turcotte, D., Smith, C., 1993. The organic fraction–bulk density relationship and the expression of nutrient content in forest soils. *Can. J. For.*

Res. 23, 1026–1032. <https://doi.org/10.1139/x93-131>

Liu, J., Zhao, S., Jiang, L., Chai, L., Wu, F., 2013. The influence of organic matter on soil dielectric constant at microwave frequencies (0.5–40 GHz), in: 2013 IEEE International Geoscience and Remote Sensing Symposium - IGARSS. Presented at the 2013 IEEE International Geoscience and Remote Sensing Symposium - IGARSS, pp. 13–16. <https://doi.org/10.1109/IGARSS.2013.6721080>

Jin, M., Zheng, X., Jiang, T., Li, X., Li, X.-J., Zhao, K., 2017. Evaluation and Improvement of SMOS and SMAP Soil Moisture Products for Soils with High Organic Matter over a Forested Area in Northeast China. *Remote Sensing* 9, 387. <https://doi.org/10.3390/rs9040387>

(3) Eq. (9): if this equation is used to estimate the soil bulk density for organic soils, it is not applicable to highly organic soils. E.g. when SOM=1 (or OC≈0.58), BD_{SOM}>2 g/cm³. The original reference does not include data with OC > 20%. This is also a common problem in the empirical equations derived for organic soils or organic-rich soils.

The bulk density function is used for the calculation of “pure” organic matter and “pure” mineral particles. As you mentioned for very high OC, the bulk density becomes unrealistically large. Therefore, we replaced it with a more proper and well-known equation to estimate their pure density proposed by Hossain et al., 2015 as follows.

$$BD = 0.071 + 1.322 \cdot \exp(-0.0071 \cdot OC)$$

Which values becomes 1.393 g/cm³ with 0% OC (0g OC per 1kg soil) and 0.097 g/cm³ with 56% OC (560g OC per 1kg soil) converted from 100% SOM with the conversion factor 1.8, respectively.

Hossain, M.F., Chen, W., Zhang, Y., 2015. Bulk density of mineral and organic soils in the Canada’s arctic and sub-arctic. *Information Processing in Agriculture* 2, 183–190. <https://doi.org/10.1016/j.inpa.2015.09.001>

(4) There is no equation (10).

Thank you for the comment. We re-ordered the equation numbers properly.

(5) Eq. (11) & Eq (12): similar as above, the authors should mention under what OC range those equations can be applied to, esp. the estimate of wilting point. For soils with high SOM concentration, Eq. (11) gives a very large estimate, which is even close to the porosity provided by Eq. (12).

In Appendix B, we avoided the issue that the wilting point becomes higher than porosity in high SOM by improving Eq.(11) and (12). In the new parameterization, we could have a porosity that is larger than a wilting point in all SOM and clay ranges. See the attached_image1.png

- Line 185: the authors should provide a brief description how the field estimates of OC was derived.

We added the description about OC sampling as following.

“The field samples of the OC were processed by grinding soil samples, drying soil moisture, and igniting and burning out organic mass at 375 °C. The SOC was determined from the weight difference between before and after igniting the soil samples (Ball, 1964; Wang et al., 2011; Manns and Berg, 2014).”

**Ball, D.F., 1964. Loss-on-Ignition as an Estimate of Organic Matter and Organic Carbon in Non-Calcareous Soils. *Journal of Soil Science* 15, 84–92.
<https://doi.org/10.1111/j.1365-2389.1964.tb00247.x>**

**Wang, Q., Li, Y., Wang, Y., 2011. Optimizing the weight loss-on-ignition methodology to quantify organic and carbonate carbon of sediments from diverse sources. *Environ Monit Assess* 174, 241–257.
<https://doi.org/10.1007/s10661-010-1454-z>**

Manns, H.R., Berg, A.A., 2014. Importance of soil organic carbon on surface soil water content variability among agricultural fields. *Journal of Hydrology, Determination of soil moisture: Measurements and theoretical approaches* 516, 297–303. <https://doi.org/10.1016/j.jhydrol.2013.11.018>

- SoilGrids data: Does the author use SoilGrids 1km or SoilGrids 250m? The authors indicates SoilGrids1km in one place, while it says SoilGrids250m data were used in another place. These two datasets can be quite different in terms of OC estimates. Bedies, SoilGrids1km provide OC estimates at certain depths, while SoilGrids250m provides OC estimates for different soil intervals. Please clarify. Fig.2 (b): please provide colorbar for the OC map.

Thank you for pointing out this error. Because we used SoilGrid1km in our study, we fixed the SoilGrids250m to SoilGrids1km. We added the color bar properly in Fig.2. Please see attached_image2.png

- Comments on the results:

(1) Fig. 5 (a) what are the results derived using the Seyfried model? The red dots?

Yes, the Seyfried model is indicated with the red dots. We corrected the black dots to the red dots in Fig. 5 (a).

(2) Fig.6 & 7: the reduction of the uncertainty in SM estimates is relatively limited. It may be partly due to a narrow range and also a low amount of SOM in the soil samples in the study area. Therefore, it needs additional investigation whether this method applies to highly organic soil (e.g. SOM>30%), prevalent in the boreal and Arctic region, and how it performs if it is applicable.

The direct comparison with Bircher’s study is difficult for this study because of two different conditions; 1) the OC measurements (the OC measurements of Bircher’s study is obtained from soils highly covered with moss, which show very different characteristics from the one obtained from our SMAPVEX12 agricultural soil and 2) the dielectric measurements (Bircher’s study used the theta probe

which the frequency used in is 100MHz).

I would think this method is more general and has a high potential applicable to those conditions. However, the parameterization (including the wilting point, porosity) needs additional improvement.

□ The validation scores after applying new porosity parameterization and the modified wilting point have been improved as shown in Table 3.

It will be also helpful if the authors can compare their results with the previous methods that particularly incorporates organic carbon content. For example, in Bircher et al. 2016, the data do not show substantially dielectric differences in soils with SOM<30%, while this study shows even a small amount of SOM (SOM<~10-11%) can make a significant difference in the relationship between SM and dielectric constant.

□ As the reviewer suggested, the comparison to the study (Bircher et al. 2016) will be very helpful to demonstrate the benefit of our approach for a 50MHz soil moisture sensor. However, as mentioned above response, the current study is not directly applicable due to the difference in the type of organic soil and in the frequency of the soil probe sensor. I agreed with your comments that in the low or medium OC range, the previous study (Bircher) was hard to demonstrate the improvement by OC consideration, and in our study, we made a significant difference as you mentioned in the reviewer's last comment. Therefore, I believe the improvement is meaningful without further experiments. We decided to investigate the possibility of further improvement for higher OC regions in the future study.

Bircher, S., Andreasen, M., Vuollet, J., Vehviläinen, J., Rautiainen, K., Jonard, F., Weihermüller, L., Zakharova, E., Wigneron, J.-P., and Kerr, Y. H.: Soil moisture sensor calibration for organic soil surface layers, *Geosci. Instrum. Method. Data Syst.*, 5, 109–125, <https://doi.org/10.5194/gi-5-109-2016>, 2016.

Please also note the supplement to this comment:

<https://hess.copernicus.org/preprints/hess-2021-233/hess-2021-233-AC1-supplement.zip>