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Discussions

Interactive comment on "Monitoring infiltration processes with high-resolution surface-based Ground-Penetrating Radar" *by* P. Klenk et al.

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Brief author's reply to remarks made by anonymous referee #1

We thank the first referee for his/her constructive remarks, which we would like to address right away:

"What is the sampling depth of your direct wave? It comes to my mind as well, whatabout the coupling of the antenna during infiltration? The surrounding media is evolving through time, what do you think about the influence of this evolution on your direct wave?"

The volume of influence of the direct ground wave signal and especially its vertical sen-

sitivity is still a general issue for GPR ground wave methods, which we are well aware of. A number of researchers have already made an attempt to define it for their specific application and have come to partially contradicting results. Early examples include a study by van Overmeeren et al (1997) or the dissertations by Du (1996), Wollny (1999) and Sperl (1999). Galagedara (2005) developed a formula based on FDTD modeling, whereas Grote (2010) relied on experimental field data to discuss this issue quite extensively. In her study, she compared a set of different analytical and empirical dependencies but also concludes that "no single model describes the experimental data well". Hence, to our knowledge, no consensus has been reached on this issue so far. The situation with a localized infiltration is indeed even more difficult because the pronounced heterogeneity will significantly influence the domain propagation of the electromagnetic fields. Our approach with such experiments is thus to (i) accept that information on the measuring volume of a GPR measurement cannot be gained, (ii) obtain precise and temporally highly resolved measurements of the infiltration's development, and (iii) run a high-resolution joint hydraulic and electromagnetic inversion. This paper focuses on (ii).

The second question concerning the antenna coupling, however, can be answered in a straightforward manner. Due to our specific setup (compare figures 2 and 4), the antennas themselves never pass directly over the actual point of infiltration. The reactive nearfield in the immediate vicinity of our transmitters and receivers stays dry. Hence, as can be readily shown by looking at the constant direct wave signals recorded by the four internal channels (T1R1, T2R2, T3R3 and T4R4), the antenna coupling does not change during the infiltration event, in contrast to other studies, such as the setups used, e.g., in Léger et al (2014) or Mangel et al (2012). Note that this is also the reason we do not explicitly show these data in the paper, since the internal channels' direct wave signals are not influenced by the infiltration pulse itself. We will clarify this for the reader in the revised manuscript by adding this information explicitly in the materials and methods section.

*"Let us suppose you have a picking uncertainty of 0.16 ns (2*dt), what is the difference in water content. What I mean by that is, stating 0.001 cc/cc is very very fine determination, so I think you need to speak a bit more about this. I am not asking you to draw a full uncertainty analysis, just at least to give us more information and maybe some warning and precaution about the ultrafine measurement of 0.001 cc/cc."*

For example, assuming porosity $\phi = 0.35$ [-], soil permittivity $\epsilon_{soil} = 5$ [-] and temperature T = 20 °C, a quick calculation shows that a picking error of 0.16 ns would lead to an absolute error in water content of about 0.005. However, such a high picking uncertainty is only true for a single measurement. Due to our high spatial and temporal resolution, we can use the imposed averaging to reduce the impact of such a picking error considerably. For example, for figure 10, we use a spatial averaging of 10 traces (equal to an averaging window of +-0.05 m). As shown in the figure, increasing the horizontal averaging volume to even +-1.3 m only slightly changes the retrieved values. Hence, we can assume these 10 measurements to have sampled the same physical value with uncorrelated picking errors, and the total picking associated error decreases accordingly, leading already to a resulting absolute error in water content of approximately 0.0017. Further averaging of 10 samples in the temporal domain with a moving average filter reduces the impact of a picking error further to 0.0005 except for cases where the observed processes change on a time scale shorter than the averaging filter extent. This becomes relevant right at the start or stop of an infiltration event.
That the true relative precision is indeed on the order of 0.001 already in the spatial domain is also corroborated by figure 11: The fact that we are able to monitor the longterm decrease in water content of about 0.001 per measurement (looking, e.g., at the infiltration around 12.5 m for the measurements between 8 and 29 days after the experiment) in the consistent manner shown in this figure, is a strong indication that the relative precision is of this order.
We will add a corresponding paragraph with these considerations to the manuscript.

"In term of monitoring infiltration, what your dual frequency method can bring (not necessarily on this study)? You are not emphasizing enough on the advantages of your method. I am just wondering if the 200 MHz is the most suited tool to follow near surface infiltration."

We agree, that if the focus of a study was solely on monitoring a near-surface infiltration plume, the resolution of the 200 MHz channels would not be suited best for monitoring the infiltration pulse and we did not imply this in our manuscript. The advantage of the higher center frequency with respect to resolving the infiltration process can also be seen from the timelapse movies provided with this paper. This is the reason why we concentrate on evaluating the 600 MHz data where the infiltration pulse is in the focus. The huge advantage of our method is however, that we can concurrently monitor different aspects of the near-surface dynamics with different frequencies. Moreover, in highly dynamic cases, depending on the specific hydraulic situation at different characteristic times of an experiment, one frequency might be better evaluable than the other. With respect to the capillary fringe monitoring we discuss this, e.g., on page 27, lines 2-9. Finally, if there are other objectives such as calculating averaged water content variations from deeper layer reflections, the lower frequency will have the better signal to noise ratio. We will clarify these aspects in the revised manuscript.

Further answers / clarifications with respect to some of the minor comments

"Abstract line 5: "0.001 [-]". state gravimetric or volumetric [g/g] or [cm3/cm3]"
"Page 30, Conclusion, Line 26: Units for volumetric water content"
We agree that we should have stated more clearly that we are always looking at volumetric water contents. The gravimetric values are actually not measurable with

GPR/TDR. This will be adapted in the revised version of the manuscript. We intend to state that we are looking at volumetric water contents and then keep soil water content to be a dimensionless number.

"Figure 1: Why do you have two different red (dashed and plain) lines for the two infiltration spot ? Does not need to be changed, just wondering if you modified the original figure from Klenk et al. 2015."
The reason for these different line styles was to emphasize that the infiltration events happened at different times. The dashed line is supposed to indicate that this is the spot of the earlier infiltration.

"Page 18, Lines 9 and 12. Accent display problem"
"References: Page 33, Line 14, Line 17: Missing letter with the accent. Page 34, Line 1, Line 15: Same issue."
Unfortunately we cannot reproduce this display problem. As we can display the accents in the pdf downloaded from the websites correctly, we suspect that this might be an issue tied to the software used to display our manuscript.

"Page 19, Line 20: "hydraulic equilibrium". Do you have tensiometers or other devices on site ?"
No, we do not. For a coarse grained medium such as the sands used at the ASSESS site, reaching the true hydraulic equilibrium in the dry regions may take months to years. This is mostly an issue for the potentials, however, since the corresponding water contents are so small that changes are negligible there. For our particular experiment, where the site relaxed for about half a year following the previous experiment under a roof, hydraulic equilibrium with respect to volumetric water content may be assumed.

"Page 20, Line 6: "The sketch in Fig.4". It should be Figure 3, since this is the third you are mentioning.
Will be adapted.

"Figure 4: Is there a layer of wood ? If yes you need to draw it in the sketch, or mention it."
Yes, and thank you for that observation. As can be seen from the picture in Figure 2, there is a thin layer of a 0.9 mm oriented strand board underneath the antennas. The figure will be redrawn for the revised manuscript.

" Page 22, Line 14-24: I think this paragraph should come after. It is too early to speak about additional material, since we haven't seen any material first."
In our understanding, the movies are not merely "additional" material. Due to the nature of our experiments, they are an integral part of this study. Hence the idea is to make the reader aware at this point, that some of the observations that are discussed in the following might be more obvious or more clearly visible from watching the movies.

"Page 23, Line 20-25 and figure 6. "These variations may indicate unresolved signals interfering with the respective direct waves [..] 200 MHz ". I disagree, you took the same time step for the 200 MHz and the 600 MHz ? Then the sampling of you 600 MHz and 200 MHz is not the same, and your picking uncertainty (or variations) is not the same depending on your frequency. On the figure 6, could you display the RMS."
The time sampling on all channels is identical. As stated in L8 on page 21, we always recorded 1024 samples over 80ns. Hence the time sampling is identical (0.0781ns/sample), irrespective of the frequency, leading to identical picking uncertainties. However, the resolution of spatial structures and the differentiability of different signals is a function of the signal's bandwidth, which is higher for the higher center frequency. This is why we assume the differences that we observe for the lower resolution 200 MHz data to be associated with unresolved interferences.

"Page 30, Line 1. Are you planning to conduct lab experiment (hydraulic conductivity test) on soil samples?"
We do not plan laboratory experiments, since we have not been successful in transferring lab-derived parameters to the ASSESS field site due to fundamental issues of scale.

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