We thank the two reviewers who have provided comments on our manuscript while it was available for discussion. We have made most changes suggested by these reviewers or have explained in detail below why we chose not to make specific suggested revisions. The original *review comments* from the discussion are indicated below by RC, whereas each *author response* is indicated by AR. We are grateful to the readers of HESSD for aiding us in improving our contribution to this journal.

Review #1

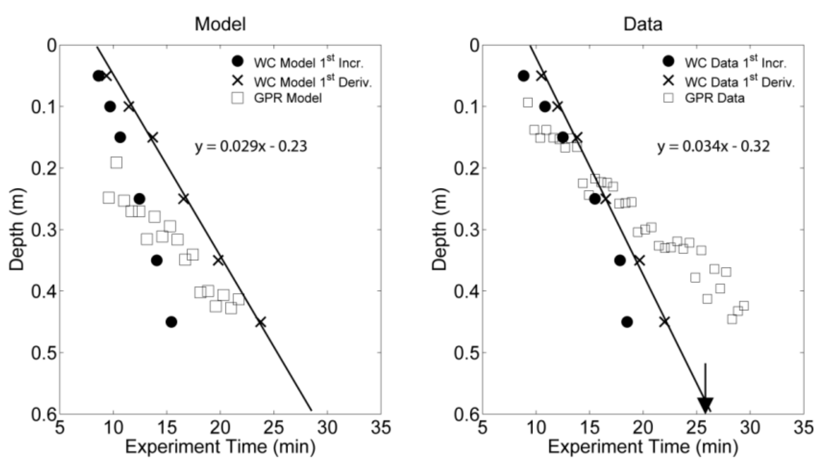
MAJOR COMMENTS

RC *- I have one observation which might be some work but I think it is necessary to make the different sources of measured and modelled data more comparable: The estimated depths to the wetting front shown in Fig. 3 for the WC measurements and the HYDRUS-1D simulations show very large differences. For example, at 16 min the wetting front detected by the water content sensors is at 25 cm depth while the wetting front estimated from the model already reaches a depth of 45 cm. Has the model been calibrated to the measured data? If not, this should be improved.*

AR – We have modified the text and Figure 3 to clarify that it was not our intention for the synthetic data to be directly compared to the experimental data. In our view, the synthetic case provides an evaluation of the transient GPR monitoring methodology for an idealized case where the "true" system was fully known. A comparison that is valid is how well the GPR captures the observed hydrologic behavior for each of the experiments presented (i.e., synthetic and lab independently), but not how the synthetic and lab results compare to each other. This later comparison brings in questions that are far beyond the scope of this manuscript, such as whether measurements made on core-samples (e.g., permeameter and hanging-column measurements) are representative of field-scale flow systems which is a general question in hydrology and not directly relevant to our discussion of GPR given that it is exclusively a field-scale method. In our manuscript, we do comment on the differences between the synthetic case, which explicitly uses a model with uniform one-dimensional flow, versus the lab-experiment, where there is evidence that flow may have been non-uniform and was only approximately one-dimensional in the region of the GPR measurements as the applied infiltration covered the central portion of the tank; the difference in 1D versus 3D flow outside the region of the GPR measurements is probably the biggest reason for the delay between the synthetic and lab data noted by the reviewer. For reasons such as these, fitting the lab data as the reviewer requests will likely produce a set of apparent hydrologic parameters which may not be equivalent to the lab measured parameters due to scale differences and would therefore obfuscate interpretation of our results. We again stress that comparison of core-scale versus field-scale measurements is an interesting problem, but not the topic of this paper.

Based on the reviewers comment, we have also identified and corrected an additional issue with our analysis of the wetting front migration estimated using the GPR data from the tank experiment. Previously, the cross-correlation algorithm used to track the wetting front arrival briefly followed the wrong feature (what we have interpreted as the bottom of sand reflection that has been refracted at the tank surface) for a short time around 15 minutes into the experiment causing the wetting front to appear to "stall" in our results. A programing bug caused the resulting errors to propagate into the later estimates of the wetting front depth. We have fixed this problem and rerun our cross-correlation analysis avoiding the problematic area to produce the results now included in Figure 3 of the paper.

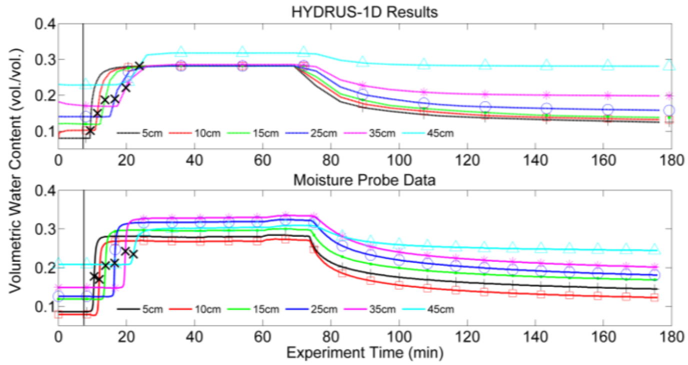
Another issue that this comment by the reviewer has made us consider more closely, however, is how to extract a representative measure of the wetting front from water content measurements for comparison to the GPR results. In our initial manuscript, we simply presented the first change in water content observed by the probes as the "arrival" of the wetting front; these very small initial changes in water content are likely not captured in the radar data. We have therefore recalculated the wetting front arrival as the time when the maximum change in water content occurs (i.e., the first temporal derivative); note that at least for the specific case of our synthetic experiment, we have found that this measure provides a similar result as the time at which the spatial derivative reaches a maximum at each probe location. In our revised version of Figure 3, it is clear that this time can be substantially later than the "first" arrival of the wetting front and, in the case of the synthetic data, the two measures of the wetting front bound the responses evaluated by GPR quite well. For the lab experiment there is good agreement between the wetting front migration as estimated by the probe data and GPR at early times, but poorer agreement at late times. This disagreement may be related to a number of issues ranging from difficulty in picking the wetting front reflection in the GPR data at late times to non-uniformity of the wetting front affecting the probe measurements and GPR response. What part of a wetting front is captured by GPR is not a trivial question and we therefore suggest that a more detailed analysis of this question should be conducted as future work.



Revised Figure 3: Estimated depth to the wetting front based on data from water content probes, GPR, and simulation results. Wetting front arrivals were picked from the water content measurements at each probe depth based on the first increase from initial conditions (closed circles) and the maximum of the first temporal derivative (Xs). The time at which water was observed to discharge from the bottom of the tank is indicated by the arrow.

***RC** - Here, a figure like Fig. 2 comparing the measured and modelled water content dynamics at each sensor depth would be helpful for assessing the performance of the hydraulic model. This* *is also important as the modelled water content profiles are the starting conditions for the subsequent GPR simulations.*

AR – We have revised Figure 2 as requested to show the water contents for both the synthetic and lab experiment. We again stress, however, that direct comparison between the synthetic versus lab data is not our objective. We do not expect a perfect match as the overall flow systems are not identical in the two experiments.



Revised Figure 2: Changes in water content through the experiment observed at six depths in the center of the sand tank for the synthetic (top) and lab (bottom) experiments. The arrival of the wetting front at each depth based on the maximum first temporal derivative of water content is indicated with an "x", whereas the solid black vertical line indicates the start of infiltration.

GENERAL COMMENTS

RC *- The infiltration flux of 0.44 cm min^{-1} applied in the lab experiment to reach the observed high saturation of the sand is extremely high. Field studies conducted under natural atmospheric boundary conditions will have to cope with much smaller infiltration events (usually less than 10 mm per day) and consequently much smaller changes in average water content. Nevertheless, in order to test the method in such kind of lab experiment it is definitely reasonable to cover a large range in water contents.*

AR – We have noted that this flux was selected to create a strong contrast in water content across the wetting front on line 163 of the revised manuscript.

RC *- The discussion could be extended by also discussing the uncertainty in the average water contents calculated from the hydraulic model (see comment above) as well as the interpolated water contents from the sensors since interpolation is not trivial especially with a sharp infiltration front within the profile. In contrast, the GPR measurements have the advantage of really averaging over the complete profile.*

AR – The depth-averaged water content values reported in Figure 6 are calculated using an arithmetic mean through time of water contents at all the probe depths. We have also calculated the average tank water content with a weighted average considering the uneven spacing of the probes and a time-averaged (RMS) water content to better reflect how the radar samples the subsurface. Differences between the averages were on the order of 2-3% for both the probe data and the HYDRUS output (see below). We therefore chose the simplest average, the arithmetic mean, to represent the average water content of the tank from the point measurements.

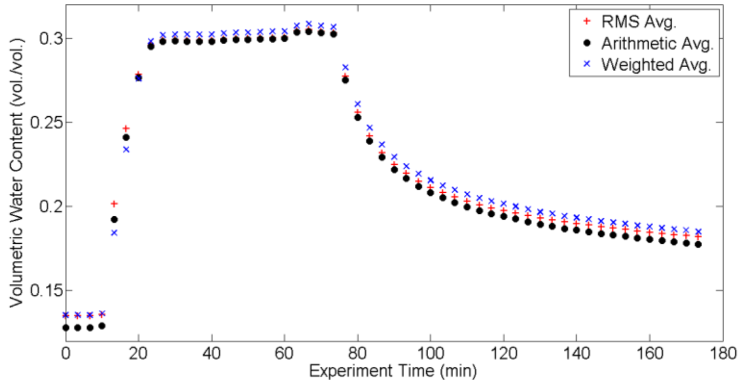


Figure 3: Comparison of methods for estimating the average water content of the tank based on point measurements (HYDRUS results shown).

SPECIFIC COMMENTS

RC *- P 10097, L 12-16: Please add a few references for this statement.*
***AR* - P 10097, :L 12-16 :** References added. (Lunt et al., 2005, Grote et al., 2005, Steelman and Endres, 2010).

RC *- P 10100, L 3-13, Fig. 1: Please add the existence of drains at the lower boundary (Fig. 1) and explain how they are operated during the experiment.*
***AR* - P 10100, L 3-13:** The following change was made to the text: "Drains at the base of the tank were left open at all times to allow for free discharge of effluent."

RC *- P 10102, L 12, 13 and further occurences: I suggest to use "dielectric number" instead of "dielectric constant" as the value depends on temperature etc.*
***AR* - P 10102, L12,13:** "Dieletric constant" is a common term used in the hydrogeophysics literature (e.g., Haarder et al., 2011; Hubbard et al., 1997; Friedman, 1998; Lunt et al., 2005; Topp et al., 1980) and we choose to retain this nomenclature here, despite the fact that it is well known that the value of this parameter varies.

RC *- P 10103, L 9-10, Tab. 1: How were the hydraulic parameters for the HYDRUS-1D simulations chosen? Please explain.*
***AR* - P 10103 L 9-10 Tab.1:** Hydraulic parameters were determined using the hanging column method and constant head permeameter tests. A sentence has been added to both the *Methods* section and to the caption for the table explaining this.

***RC* -** *P 10104, L 12-18, Fig. 3: Figure 3 is rather complicated for the observations described at this place. What about adding a Fig. 2b showing only the WC data right next to the curves presented in Fig. 2 and moving Fig. 3 between Figs. 6 and 7? Please also check the WC data point of the 45 cm sensor in Fig. 3. In Fig. 2 the arrival of the wetting front at 45 cm is > 20 min which indicates a lower velocity also at greater depth.*
***AR* - P 10104 L 12-18:** Figure 3 has been split into 2 figures for clarity (see above). We choose not to move this figure in the text so that the results of the wetting front behavior observed with the probes can be discussed prior to introducing the GPR results. We have also added another plot to Figure 2 showing the data from the HYDRUS model for each observation point (see above). We do not see the inconsistency with the 45cm probe suggested by the reviewer.

RC *- P 10104, L. 13, L. 22 and further occurences: Water content units are inconsistent with y-axis of Fig. 2. I suggest to use [-] or [vol vol^{-1}] throughout the paper.*
***AR* - P 10104 L 13, L 22:** All water content units have been changed to [vol.vol.$^{-1}$].

RC - *P 10107, L. 29: replace "that" by "than"*
***AR* - P 10107 L. 29:** "that" replaced by "than".

RC *- Fig. 2: It is rather difficult to distinguish the lines of the different sensors. Better show a color plot here.*
***AC* -** Figure changed to a color plot.

RC *- Fig. 4: Caption: Please add what (measurement and model) is indicated in the left and right panels of a), b), c).*
***AR* -** Caption has been edited to clarify model vs. data in the figure.

RC *- Fig. 4, 5, 6, caption and various occurences in the text: I would prefer "bottom of sand reflection" instead of "bottom of tank reflection". A bottom of tank reflection could be expected as well but just does not occur in this experiment.*
***AR* - Fig. 4,5,6.** "Bottom of tank reflection" changed to "bottom of sand reflection" in captions and text.

RC *- Fig. 5: Caption: Please add what is indicated by D.*
***AR* -** The caption has been edited to indicate that arrival D is a reflection from the side of the tank.

Review #2

RC *- The average water content values shown in Figure 6 resemble the synthetic data well. However, Figure 3 shows that the estimated depths of the wetting front do not resemble the synthetic data. This Figure should be annotated and discussed in more detail (see also below).*
AR – We have revised Figure 3 as described earlier to indicate an inherent degree of uncertainty in the definition of the wetting front. In our response to reviewer #1, we also discussed that the details of the synthetic and experimental data are not expected to match exactly given the differences between the experiments; i.e., we used the synthetic case as a tool to help us understand and interpret which GPR responses and patterns are feasible to identify in the tank experiment. The fact that the average tank water content matches better between the synthetic and empirical experiments is an indication that average behavior of this system is less sensitive to differences between the experiments than the detailed response at a particular location in space and time, such as the exact position of the wetting front.

RC *- How are the hydraulic properties given in Table 1 obtained?*
AR - The manuscript has been modified to indicate that the hydraulic properties in Table 1 were obtained using hanging column lab tests of the soil and constant head permeameter measurements.

RC *- I suggest to describe in more detail the phenomena taking place when a low-velocity waveguide is present. In my option, the statement on p. 10098 "Whether accurate wave velocities can be estimated from the ground wave during infiltration events has been put into question, however, by van der kruk (2006) who shows shallow, low-velocity waveguides, such as the region behind a wetting front, cause significant dispersion. In contrast, van Overmeeren et al. (1997) : : :" is incomplete. One could mention that conventional ground wave velocity estimation can be used to determine soil water content changes when the medium can be approximated by a homogenous halfspace. As soon as layering is present and multiple reflections and refractions occur, this approach can be less accurate. Especially high contrast low-velocity layers with a thickness comparable to the wavelength result in multiple reflections within the low-velocity waveguide and dispersion can occur due to the interfering multiples (see also Arcone et al. 2003 and Liu et al. 2003). See also a waveguide movie: http://dx.doi.org/10.1190/1.3249780 Similar interfering reflections seem also to be present in the data discussed.*
AR – We agree with the reviewer and have extended our comments within the mansuscript to better describe dispersion caused by waveguides.

RC *- Although it was not recognized as being dispersive, also the paper of van Overmeeren (1997) clearly shows the shingling and corresponding dispersion of the data in Figures 6b, 8b and 9b due to a thin moist top layer. Note also the large antenna separation (up to 20m) which enables the identification of the shingling.*
AR – We have modified the text to note that the characteristic shingling associated with dispersion can be observed in the data from the van Overmeeren paper.

RC*- It is not always easy to identify waveguide dispersion in GPR data. Three key characteristics of dispersive GPR signals are (van der Kruk et al. 2009): 1) Normalizing the data on the maximum amplitude for each trace shows that most energy is contained within the dispersive waves (see also van der Kruk et al. 2010) 2) Shingling elongated reflections are* *present in the data and indicate different phase and group velocities. 3)The phase-velocity spectrum clearly indicates the presence of a frequency-dependent phase velocity (van der Kruk 2006). It is mentioned in the manuscript that "Although the shape of the wavelet is clearly affected at larger offsets, which suggests that dispersion is a factor in the data" (p.10109, line 19-21), "the multiples observed in the modeled wavefield do not appear to create the shingled appearance in the data" (p. 10109, line 14-15)". This is probably due to the waveguide thickness used in the modeling is more than twice the wavelength, which enables the individual identification of the wetting front reflection and its multiple (see Figure 7). I suggest to repeat the modeling and reduce the thickness of the waveguide layer. This will result in an interference of the wetting front reflection and its multiple and the appearance of an elongated wavelet indicating shingling. Another important factor influencing the appearance of the shingling is the offset range. For waveguide trapping taking place, the waves should be reflected with total reflection beyond the critical angle. The minimum offset where a wave guided within the waveguide can be measured is given by x=2*h*tan(theta_c), where theta_c=arcsin(v1/v2). For the case shown in Fig. 7, this offset is approximately 0.98 m, which is at the upper offset range of the data used in the manuscript. I suggest to also look at larger offsets where in most cases this shingling appearance is better visible.*

AR –A preliminary analysis of the data using the approach of van der Kruk et al. (2006) (see below) clearly shows a variation of velocity with frequency early in the experiment. Both the data and the modeled GPR response display wave dispersion at the start of infiltration (8 min) for about 5 minutes, i.e., when the depth to the wetting front is less than the wavelength (~10cm). The second figure below illustrates that the dispersion is indeed related to reflection multiples in the wave guide as discussed by van der Kruk et al. (2006). Because the wave guide phenomena occurs when the thickness of the wetter zone is less than the wavelength, this phenomenon is transient nature and holds promise for characterizing the behavior of the wetting front at early times when it is otherwise difficult to identify. We have modified the text to indicate that further analysis has shown that dispersion is indeed observed in our groundwave data, though we do not go into depth as we feel that a more extensive discussion on this topic is required than is possible in this paper.

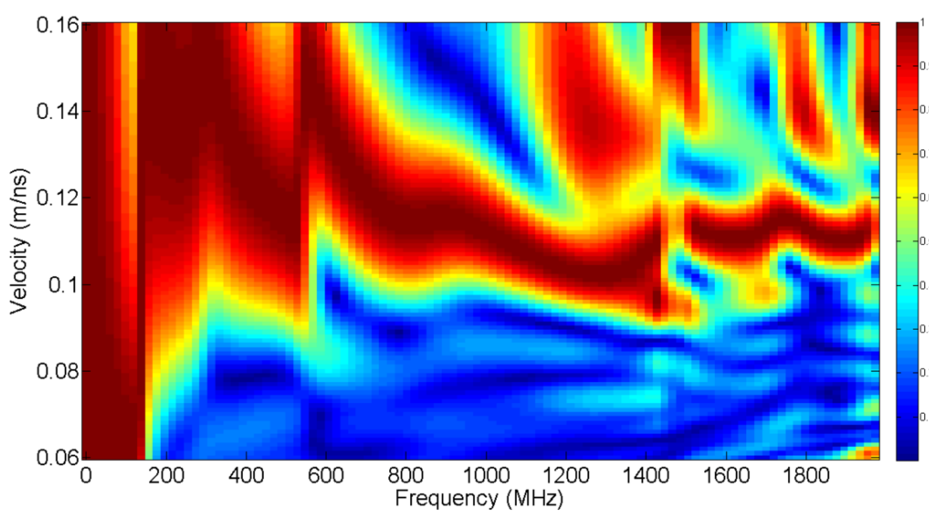


Figure 1: Frequency spectra distribution for radar data at 9 minutes experiment time. Notice the dependence between frequency and velocity between 600-1400MHz. This dependence indicates the presence of a dispersive wave guide, caused by the shallow wetting front.

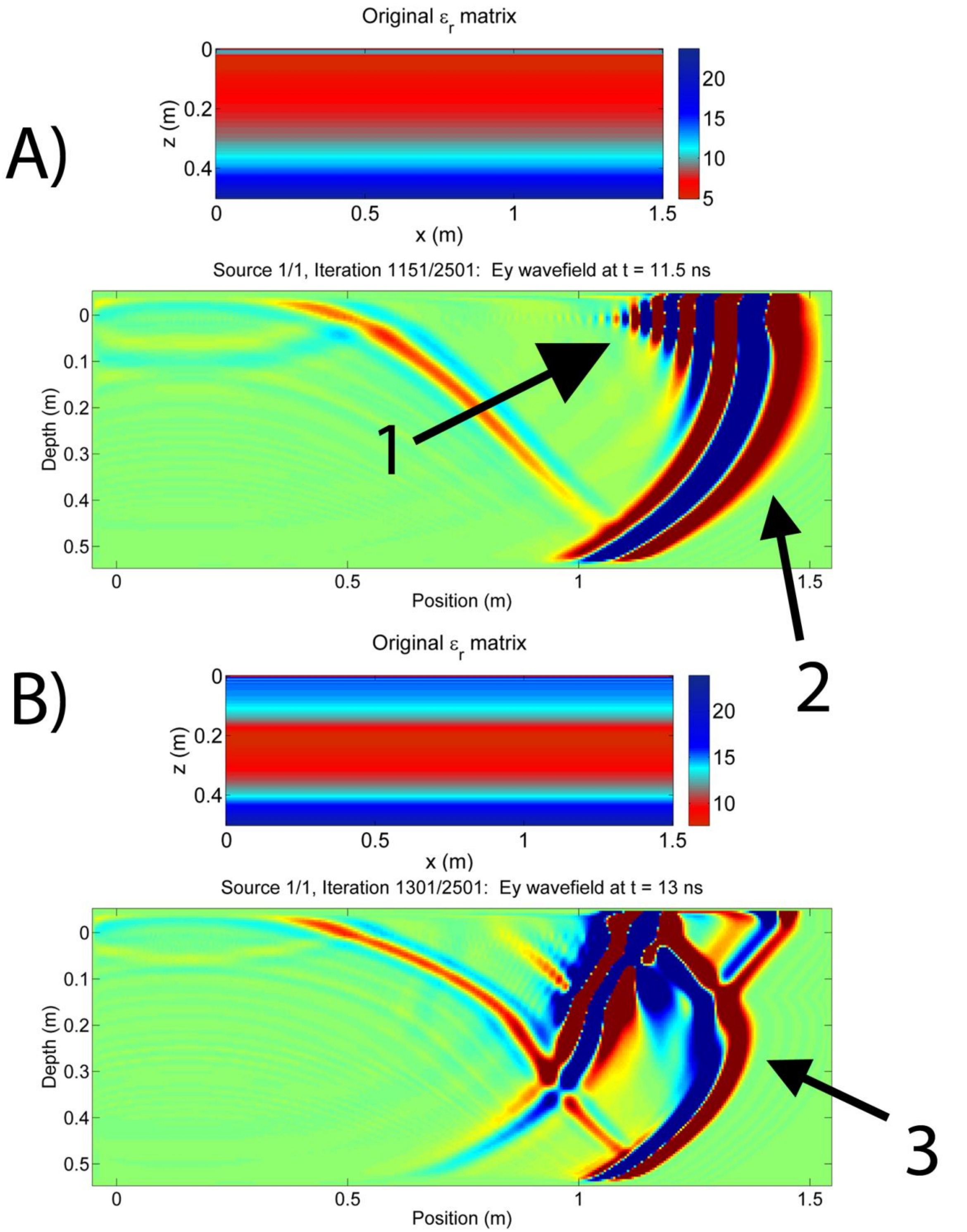


Figure 2: Model animations showing the presence of low-velocity dispersive waveguides for direct waves 2 & 3. A) Just after the start of infiltration (9min) a very shallow wetting front is present (<5cm). This thin, low-velocity layer produces a dispersive waveguide (1) which is illustrated by the resulting simulation image below. B) Further on in time (15min), the wetting front has moved to roughly 20cm, and no longer acts as a dispersive waveguide.

RC *- Although it was recognized that the ground wave contains additional information, it was not used due to the difficult identification. I suggest to include in the outlook some discussion on how to improve the characterization of the processes taking place, such as including the ground wave information using dispersion analysis, or full-waveform inversion.*
AR - We have modified the discussion section and conclusions of the manuscript to indicate that dispersion analysis and full-waveform inversion are promising future avenues for extracting information from the groundwave, particularly when the wetting front is near the ground surface.

RC *- What is the effective center frequency of the measured data? It seems to be lower than 900 MHz.*
AR **-** We are using 900MHz antennas, but frequency (Fourier) analysis of the signal throughout the experiment shows shifts in the center frequency between 500-1200MHz.

RC *- It is mentioned that no processing other than dewow filtering and time zero correction was used. Was a certain gain used to plot the data? If not, mention explicitly.*
AR **-** No processing other than a dewow filter and time zero correction was applied to the data. The plots that are in the paper have not been gained. The following sentence has been appended:

"Note that no processing other than dewow filtering and time zero correction has been performed on these data and plots were made with un-gained data."

RC *- Why were the source and receivers mounted several cm above the sand surface? This distance should be as small as possible to reduce the signal to noise ratio.*
AR **-** The transmitter is located immediately on top of the irrigation grid, which avoids a "dry" spot in the location where the antenna is located. The receiver is mounted on a gantry 4cm above the surface of the sand to allow for motion of this antenna across the tank without disturbing the irrigation grid.

***RC* -** *P. 10096 line 1 change transient into time-lapse*
AR **- P. 10096 L. 1 –** Transient changed to time-lapse.

RC *- p. 10103, line 10: How were the parameters in Table 1 determined?*
AR **- P. 10103 L. 10** – Method of parameter estimation added (see above).

RC *- p. 10103 line 15: what were the cell sizes of the FDTD code?*
AR **- P. 10103 L. 15** – Cells sizes (0.05mx0.025m) added to the GPR modeling methods.

RC *- p. 10103 line 24: use nS/m instead of _S/m,*
AR **- P. 10103 L. 24** – µS/m changed to nS/m.

RC *- p. 10103 line 28: the relative magnetic permeability is probably set to 1, or in other words, the magnetic permeability is set to _0 = 4__10□7*

AR **- P. 10103 L. 28** – The magnetic permeability is set to 1Henry/m and set to 4*Pi* *e-07 within the model code.

RC *- p. 10104 line 18: include after 10-20%a reference to Figure 2 to make the sentence more clear*

AR **- P. 10104 L. 18** – Reference to Figure 2 added.

RC *- p. 10105 line 1: mention if any gain was applied*

AR **- P. 10105 L. 1** – No gain was applied. See above note about Processing.

RC *- p. 10106 lines 10-12: mention this earlier in the text*

AR **- P. 10106 L. 10-12 -** Sentence moved to the middle of the preceding paragraph.

RC *- Figure 2: include arrow which indicates start of infiltration*

AR **- Figure 2:** Arrow added to indicate start of infiltration.

RC *- Figure 3: indicate the wetting front velocity by fitting lines in the figure for experimental and modeled data, and indicate the observed water discharge with an arrow*

AR **- Figure 3:** Best fit lines added to moisture probe and HYDRUS model results. Arrow added to indicate time of water discharge.

RC *- Figure 4: mention explicitly in the caption that measured (left) and modeled data (right) are plotted, or indicate in the figures.*

AR **- Figure 4:** Model vs. data identification added to caption.

RC *- Figure 5: describe what D is, show time window between 5 and 25 ns.*

AR **- Figure 5:** Description of "D" arrival added to caption, time window left as is since the groundwave for all individual figures is coming in before that time.

RC *- Figure 7: focus on the events propagating in the sand box and not from the area surrounding the sand box. Include numbered rays that indicate the air wave, ground wave, wetting front reflection, wetting front multiple, bottom of tank reflection and indicate these events also in the different snap shots. In this way, the rich information content and the complexity of the data becomes more clear. Indicate the experimental time of Figure 7b Does it correspond to the experimental time of 21 Minutes as shown in Figure 4?*

AR **- Figure 7:** Significant arrivals are highlighted using arrows with specific descriptions. Adding more arrows to the wavefield inside of the tank makes the image cluttered.

Figure 7b: Model times added to caption (initial = 0 min) (infiltration = 16 min).

RC *- The reference to van der Kruk et al. 2009 is missing.*

AR **-** Reference to van der Kruk (2009) added.

References

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