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Hydrology and Earth System Sciences Discussions

Interactive comment on "Multi-offset ground-penetrating radar imaging of a lab-scale infiltration test" *by* A. R. Mangel et al.

Anonymous Referee #2

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The manuscript describes a novel laboratory study where time-lapse multi-offset ground penetrating radar measurements are used to monitor infiltration in a sand box. The experiment clearly shows the rich information content and complexity of the GPR data. A conventional normal moveout analysis is used to determine an average velocity from the bottom of tank reflections and to obtain an average soil water content. Numerical 1D modeling was performed and comparison of the average volumetric water content with the measurements showed discrepancies on the order of 3-5 %. The manuscript is well written and appropriately describes the potential and also the difficulties occurring in the data analysis. These results show the capability of modern multi-offset multi-channel GPR devices to monitor dynamic soil hydrologic processes.

Below some comments that need to be addressed:

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). How are the hydraulic properties given in Table 1 obtained?

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.

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.

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.

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.

Minor comments:

What is the effective center frequency of the measured data? It seems to be lower than 900 MHz.

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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.

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.

Other suggestions: P. 10096 line 1 change transient into time-lapse p. 10103, line 10: How were the parameters in Table 1 determined? p. 10103 line 15: what were the cell sizes of the FDTD code? p. 10103 line 24: use nS/m instead of μS/m, p. 10103 line 28: the relative magnetic permeability is probably set to 1, or in other words, the magnetic permeability is set to $\mu 0 = 4\pi \times 10{-}7$ p. 10104 line 18: include after 10-20% a reference to Figure 2 to make the sentence more clear. p. 10105 line 1: mention if any gain was applied p. 10106 lines 10-12: mention this earlier in the text

I suggest to improve the figures by annotating the information content in more detail:

Figure 2: include arrow which indicates start of infiltration 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 Figure 4: mention explicitly in the caption that measured (left) and modeled data (right) are plotted, or indicate in the figures. Figure 5: describe what D is, show time window between 5 and 25 ns. 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?

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

I also suggest to include the following references:

Arcone, S. A., P. R. Peapples, and L. Liu, 2003, Propagation of a ground-penetrating

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radar (GPR) pulse in a thin-surface waveguide: Geophysics, 68, 1922–1933.

Liu, L., and S. A. Arcone, 2003, Numerical simulation of the waveguide effect of the near-surface thin layer on radar wave propagation: Journal of Environmenal and Engineering Geoscience, 8, 133–141.

van der Kruk, J., Jacob, R.W., Vereecken, H, 2010. Properties of precipitation-induced multilayer surface waveguides derived from inversion of dispersive TE and TM GPR data, Geophysics, 75, WA263-273

van der Kruk, Vereecken, H. and Jacob, R.W. Identifying dispersive GPR signals and inverting for surface waveguide properties, The Leading Edge 28, 936–940, 2009.

Interactive comment on Hydrol. Earth Syst. Sci. Discuss., 8, 10095, 2011.