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Discussions

Interactive comment on "Soil hydraulic material properties and subsurface architecture from time-lapse GPR" *by* Stefan Jaumann and Kurt Roth

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The authors deduce subsurface hydraulic properties by an inversion of time-lapse surface GPR measurements during an imbibition experiment of an artificial test site. The coupled inversion process includes a hydraulic simulation by solving the 1D Richards equation and a simulation of radar wave propagation by 2D finite-differences calculation. Water content distribution and electromagnetic soil properties are coupled by a petrophysical relation (CRIM). During the inversion, the misfit between events, i.e. traveltimes and amplitudes of selected reflections, in experimental and synthetic GPR data is minimised. The authors use an inversion scheme that combines several optimisation steps including global and gradient techniques. The approach is first demonstrated for synthetic data and later for experimental data. The result is a 1D subsurface model and

for both predefined layers the characteristic hydraulic properties of a Brooks-Corey parameterisation of the water retention function is fitted.

The presented work is a relevant contribution towards a non-destructive hydraulic characterisation of the subsurface, which is still an unsolved problem for the unsaturated zone. However, the manuscript has to be overworked as the whole analysis including GPR data processing and inversion is somehow nebulous and difficult to follow. I would also suggest to shorten the text by writing more tersely, avoiding repetitions and possibly moving some parts into an appendix as e.g. GPR data conversion due to Bleistein, details on event detection/association and inversion. Besides this, some major points have to be clarified:

1. Amplitude handling: The formula used for spherical divergence correction for 3D data (P 7 Eq. 10) seems not correct. Correcting with square root of distance is used for 2D data. Also the dimensions of Eq. 10 do not fit. Various formulations of adequate gain functions for 3D (experimental) data is given in Yilmaz: Seismic Data Analysis (2001), e.g. Eq. (1-8a) $g(t) = \frac{v^2(t)t}{v_0^2 t_0}$. The whole amplitude balancing in the manuscript is not clear to me. The radar traces are normalised several times (P8 L1-2) and normalisation is done relative to the maximal absolute amplitude, which is the first reflection. Is the reflector characteristics constant during the entire experiment? What is the advantage of the complicated amplitude adaption due to Bleistein (1986) compared to a simple correction of 2D circular divergence with the square root of the distance? I would suggest to provide a flow chart of amplitude handling for both experimental (3D) and synthetic (2D) radar data. It seems you use different amplitude handling for event detection and the inversion process?

2. Neglecting dielectric losses. I'm wondering if at frequencies of about 400 MHz, the impact of free water relaxation can be neglected and whether the imaginary part of permittivity has to be taken into account. When using complex permittivity

of water according to Kaatze et al. (1989) and the CRIM formula and a DC conductivity of 0.003 S/m this results in: 3 dB/m (2 dB/m from free water relaxation, 1 dB/m from DC conductivity) for 10vol% water content and 5 dB/m (4 dB/m from free water relaxation and 1 dB/m from DC conductivity) for full saturation (40vol% water content). This means that up to 80% of total loss is caused by polarisation effects of free water. Neglecting these effects results in wrong amplitudes of the simulated data and I'm wondering how they can fit to the field data. At the end of the imbibition experiment (water table at -0.6 m) the amplitudes of the lower reflections (1 m saturated material above, i.e. 2 m two-way travel path) should appear to be approximately 8 dB (2.5 times) higher in the synthetic data than in the field data. I suggest to use the true complex permittivity of water at 400 MHz or, if the FDTD code cannot handle complex property values, an effective HF conductivity including both, DC conduction losses and HF polarisation losses.

3. GPR forward calculation: Why is a 2D FDTD code used for a horizontally layered model? A 1D reflectivity method as e.g. used by Bradford et al., (2014) or a 1D FDTD code would be much more efficient. The power of FDTD is certainly that it can be used for complicated 2D/3D subsurface models and thus for inverting 2D/3D data with an according hydraulic simulation. However, in the presented study only 1D data are used and no outlook is given how to adopt the strategy to 2D or 3D problems. From this it is not clear why the expensive 2D FDTD algorithm is used. The source wavelet of the simulation is different to the wavelet of the experimental data. When dealing with gradient interfaces as the capillary transition zone, the wavelet shape may have a big impact on the maximal amplitude of the reflected signal. Why not using the first reflected signal, which is used for normalisation, as source wavelet in the simulation?

4. Inversion. The complex inversion scheme is a nesting of global and gradient methods. It is somewhat nebulous and it's difficult to get an impression of the quality of original data fit. Why do you use different but relatively narrow boundaries (fit ranges) for the inversion parameters of the two layers? By doing this, the inversion result is biased by a-priori information that is usually not known but the actual aim of the investigation. The inversion should work with the same (broader) fit range for both layers. If not, it cannot be adopted to the field. The fit ranges should be used to provide outer boundaries of the deduced material properties in Fig. 9 and Fig. 14. I'm also missing a figure showing experimental GPR data traces and synthetic traces based on the inversion models to prove that the experimental data are well described. This figure should include the resulting synthetic radar traces of the ten best inversion results to get an idea of the fluctuations and an idea of the fitting quality.

5. In the analysis, the reflection of the compaction layer is excluded. If this interface causes a GPR reflection, this must be caused by different water contents on both sides and hence, there must be significant differences in the material hydraulic properties (see P24 L25ff). So why should I ignore an interface that is present in the subsurface and reflects changes in hydraulic properties? Please explain.

6. The title is misleading, I would suggest to delete "…and subsurface architecture…" as this would imply at least a 2D subsurface model. The section headings of 2.2 sound unusual to me. From a geophysical perspective the following headings would give a better description: 2.2.1 Water dynamics, 2.2.2 Hydraulic material characterisation 2.2.3 Time lapse experiment 2.2.4 GPR investigation and electromagnetic material characterisation.

Further comments

- (P2 L27) References are a bit biased by the own workgroup. E.g., when introducing the FDTD method I would expect the basic work of Yee, Taflove…and,e.g., the former ETHZ geophysics group or from the gprMax developers.

- (P6 L23ff) The CRIM formula uses the square root of permittivities (see your original reference: Birchak et al., 1974). There is no need to first define a general formulation with an exponent α, which is not the original CRIM formula, and then fix the exponent $\alpha = 0.5$. Keep it simple and use the square root from the beginning.
- (P6 L9) You should describe that you use the static permittivity of water (which is acceptable for 400 MHz, at least for the real part of permittivity).
- (P7 L14) "...removal of the direct and trailing signal". What is the trailing signal? Is this the interference of ground wave, crosstalk, reflection at the ground surface and the antenna metal shielding? In Fig. 3, a part of this trailing signal is remaining, which is confusing. Why not muting this part?
- (P7 L15) "...we pick the direct signal and subtract it from the radargram" is confusing. Not the signal is subtracted but the travel time.
- (P8 L5) "normalized amplitude (original amplitude)". Rephrase, as the amplitude is either normalized or original.
- (P8 L6) "amplitude is amplified quadratically with travel time" means they are corrected for spherical divergence twice consecutively? Is this just an arbitrary gain function that showed to work well and to correct for spherical and intrinsic attenuation at the specific site? Please explain.
- (P11 L3) Eq. 11: I think the expression has to be divided by M to get the classical χ with $\chi^2 = 1$ if the data are described within the error.
- (P11 L4) How is the standard deviation of the normalised travel times and amplitudes calculated, i.e. what are the input data?
- (P13 L33) "...infinite dipole pointing in x dimension". This should be y dimension (into the plane of projection). Please provide x,y direction in Fig. 6.

- (P13 L34) a Ricker function is the second derivative of a Gauss-fct, not the first derivative
- (P15 L11) Please specify how you calculate the STD of the measured data. Do you really use all amplitudes of the radar trace and all travel times?
- (P18 L26) What is the meaning of amplitude information of a single channel? You are using a single channel GPR system and only one antenna, so this expression is confusing.
- (P24 L30) Couldn't the uncertainty of the groundwater table relative to the ground surface be overcome by simple levelling the ground surface?
- (P26 L20ff) is a partial repetition of (P22 L5ff (the lower line 5)).
- (P26 L26) "...and that (ii) the direct electric conductivity can be assessed with GPR measurements". I cannot understand the context.
- (P27 L13ff) This is again a partial repetition of (P22 L5ff) and (P26 L20ff).
- (P27 L18) Better use "constant offset" (CO) instead of "single-channel" GPR data.
- Fig. 3, caption. Are these synthetic or experimental data?
- Fig. 6: Which E-field component is shown, what is the x and y direction?
- Fig. 12, bottom: y-axis label: standardized residual: Does 10 mean that the residual is 10 times the STD or should it be 10
- Fig. 13: I suggest to split the figure into two individual figures as it might be very confusing to mix the 2D radar section with the time lapse data at one location. The label for the groundwater table reflection is "l" in the upper radar section and "2" in the lower time-lapse data. Actually, it's very hard to distinguish the label "l"

from the label “1” in the upper radar section. Please use the same and distinct labels for the GWT reflection in all figures.

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