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Discussions

Interactive comment on "Improving soil moisture profile prediction from ground-penetrating radar data: a maximum likelihood ensemble filter approach" *by* A. P. Tran et al.

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General Comments: In the manuscript "Improving soil moisture profile prediction from ground-penetrating radar data: a maximum likelihood ensemble filter approach" concern authors' efforts to use sequential assimilation procedure to determine the accuracy of the soil moisture profile prediction using time-lapse ground-penetrating radar (GPR). In general, I found the paper to be well written and the subject of the research

is both timely and important. However, I feel that many of the real world complications associated with a field case have not been addressed in this paper, and a major revision is needed before it is accepted for publication. Three big assumptions were made in this research, which should be addressed:

a. In the proposed synthetic study four models were combined (HYDRUS-1D, two petrophysical relationships and radar model) in a sequential assimilation procedure to improve soil moisture profiles and no error was considered in these four models which is a very big assumption. For instance, flow is not 1-D in nature due to heterogeneity, petrophysical relationships can vary from one place to other, and always there are measurement errors in any geophysical data. Some percentage of error should be included in all four models to get a better picture how much the GPR signal is sensitive to these errors.

Reply: The measurement errors were accounted for in the study by the observation error covariance R in the cost function. In our origin manuscript, we claimed that "As for the measurement error covariance, we assumed that only the elements in the main diagonal (i.e., variances) of the observation error covariance matrix R are different from zero. These elements were calculated corresponding to a constant variance of each element in the soil moisture profile, σ^2=0.013^2." This measurement error accounted for the error of the radar model, petrophysical relationships and GPR measurements. In the revised version, for more realistic application, the observed GPR data were modified by adding the random noises with mean zero and standard deviation of $\sqrt{R}$ to the synthetic GPR data.

In addition, the model error of Hydrus-1D will be considered in the revised version. The model error component ω_t in Equation (8) of the origin manuscript is a Gaussian noise with zero mean and covariance Q, which is assumed to be the same functional form as the forecast error covariance matrix, P_f, but with a smaller value:

$Q = 5\% P_f$

b. The frequency used to generate GPR signal was in the range of 1-3 GHz. In such a high frequency range the subsurface permittivity and electrical conductivity profiles are frequency dependent, whereas in the proposed method frequency independent conductivity and permittivity models were used. Furthermore, no discussion in the paper about the phase center used for the antenna as in such a wide range of frequency the phase center of the antenna is frequency dependent. Please justify why electrical material properties can be considered to be frequency independent, since the Green's function used for wave propagation in 3-D multilayered media is frequency dependent.

Reply: We agree with the reviewer that in real application, consideration of the frequency dependence of the electrical properties can obtain more accurately the soil moisture profile and reduce the observation operator error. This issue was addressed by the recent study of the first author (Tran et al., 2012). However, for this synthetic study, inclusion of the frequency dependence of the electrical properties does not change the assimilation results because the same observation operator is used for both synthetic data generation and data assimilation. To guide for future realistic applications, the following discussion sentences, which present how to include the frequency dependence of the electrical properties, will be added in the revised manuscript.

"The electrical conductivity and dielectric permittivity are frequency-dependent quantities. Inconsideration of this problem is a source of the observation operator error. In order to reduce this error, the frequency dependence of these properties should be taken into account in realistic applications. This problem can be solved by using the conceptual dielectric mixing models (e.g, CRIM model) to relate the effective complex permittivity with the soil moisture, instead of the empirical formulas (Equation (6) and (7)) like in this synthetic study (Tran et al., 2012). The soil in the dielectric mixing models is considered to be a mixture of three components, namely, air, water and soil matrix. The frequency dependence of the soil electrical properties is accounted for via that of water, which varies with frequency by the Debye's equation (Debye, 1929)."

With respect to the antenna phase center, Jadoon et al. (2011) showed that the antenna modeling results were not significantly affected by the position of the phase center because the frequency-dependent transfer function coefficients of the far-field GPR model (Equation (4) in Jadoon et al. ,2011) inherently accounts for it. For that fact, phase center and its dependence on the frequency were not discussed in our study.

c. In real field conditions the initial condition, lower boundary condition and the hydraulic parameters are mostly unknown, especially in terms of spatial soil heterogeneity. In this study the soil hydraulic parameters were fixed and lower boundary condition was assumed to be known, which is a big assumption. The idea in the proposed method is to use GPR as a remote sensing tool to improve the soil moisture profile prediction. How will the GPR signal respond if these assumptions are not considered? All these limitations should be discussed in the paper.

Reply: The objective of our study is to explore that if the wrong initial condition problem can be solved by GPR data assimilation. To do that, we compared the performance of proposed approach with the open-loop prediction (without data assimilation). The obtained results indicate that with the GPR assimilation, the wrong initial condition can be solved much more quickly than the open-loop prediction. The problem unknown hydraulic soil parameters were not considered in this study and it is the topic of our next paper. This problem can be solved by combing the data assimilation algorithm and the state augmentation technique. The idea is to formulate the augmented state vector by adding the model parameters to the state vector and correct this augmented vector instead of the state vector like in this study (please see Zpupanski and Zupanski (2006) for more detailed explanation of this augmentation technique).

As for the lower boundary condition, because the computation domain is fixed to 80 cm, which is far from the water table (in normal condition), it is natural to set the free drainage is the lower boundary condition. Correspondingly, in the 3-D electromagnetic model, we assumed the lower haft space for the soil layers below the computation domain (z>80 cm). Therefore, in our opinion, this is quite practical assumption which is widely used in hydrogeophysics.

Specific Comments:

1. In the first paragraph of the introduction and the first sentence of the abstract main focus is on the root zone soil moisture, whereas in this paper synthetic analysis were performed considering a bare soil. I think root zone can be replaced with shallow unsaturated zone.

Reply: The phase “root zone” was replaced by the “shallow unsaturated zone”

2. Page 1584 L 6: Remove “Recently”. As it’s almost decay that Lambot et al. (2004b) developed this method.

Reply: This was removed.

3. Page 1588 L 3: Please explain in more detail why the distance between the antenna and medium was fixed to 37 cm? No explanation is provided at which distance the antenna phase center was considered as the antenna phase center is frequency dependent.

Reply: The distance between the antenna and medium was fixed to 37 cm to satisfy the far-field assumptions of the far-field antenna model. In the revised version, the sentence will be modified to “The distance between the antenna and medium was 37 cm, for which the far-field assumptions can be satisfied”.

4. Page 1589 Eq 6, 7: Please justify why these specific frequency independent models were used? Why frequency dependent models for permittivity and electrical conductivity are not used?

Reply: For this synthetic study, inclusion of the frequency dependence of the electrical properties does not change the assimilation results because the same petrophysical models were used for both synthetic data generation and data assimilation. As a result, for simplification, we didn’t use the frequency dependence models in this study.

5. Page 1590 Equation 8 9: The superscript “f” and “a” can be in italic format as other

variables are mentioned in italic format. Similar in description on line 17.

Reply: This will be changed in the revise version

6. Page 1590 L 18: In the proposed approach four models (HYDRUS-1D, two petrophysical relationships and radar model) are used in a close loop and the model error vector (ωt) was considered zero, which is a very big assumption. Include some errors in all the four models as the real world is more complex.

Reply: In the Maximum likelihood ensemble filter (MLEF), the measurement errors are accounted for via the error covariance matrix R in the likelihood function. We stated in the origin manuscript that we assumed that only the elements in the main diagonal (i.e. variances) of the observation error covariance matrix R are different from zero. These elements were calculated corresponding to a constant variance of each element in the soil moisture profile, $\sigma^2 = 0.0132^2$. However, there is no noise in the observation data. In the revised version, for more realistic application, the observed GPR data were modified by adding the random error with mean zero and standard deviation of $\sqrt{R}$ to the synthetic GPR data. These was shown in figure 3b,d,f.

The model error of Hydrus-1D will be also considered in the revised version. The model error component ω_t in Equation (8) of the origin manuscript is a Gaussian noise with zero mean and covariance Q, which is assumed to be the same functional form as the forecast error covariance matrix, P_f, but with a smaller value:

$Q = 5\% P_f$

7. Page 1592 L 20: In a synthetic homogenous soil column with a depth of 80 cm was discretized into 32 equidistance elements. To have a good resolution of subsurface the layer thicknesses in the electromagnetic model should be less than one tenth of minimal wavelength. Have you considered this while considering your discretization? The existing 32 equidistance elements (2.5 cm) is a big discretization if we consider maximum frequency of 3 GHz used in this study.

Reply: The soil moisture profile was discredized into 80 equidistance layers, corresponding to 1 cm for the thickness of each layer. When the number of layers increases to more than 80, the synthetic GPR data only negligibly change. As a result, for the revised version, the moisture profile was selected to be discredized into 80 equidistance layers.

8. Page 1594 L 15: Clearly mention that the signal shown in the figure is the amplitude of the frequency-domain. Why phase of the frequency-domain is not shown? Please mention if the phase does not show these variations.

Reply: Given the fact that the antenna height was fixed, the phase of the GPR data in the frequency domain does not change during the simulation time, the phase does not provide any information for the assimilation. Therefore, we used the absolute value of the Green's function as the observation data and we only show the amplitude values. This information wil be added to the revised version as below:

"For the fact that the assimilation procedure works with real number and the phase of the GPR data does not vary, given the fixed antenna height for all measurements, we used the absolute values of the complex GPR data in the frequency domain as the observation data."

9. Page 1594 L 18-19: It is discussed that the frequency range of 1-3 GHz was used whereas the frequency domain plots in the figure 3b, d, f shows the range of 0-350 MHz, which is not consistent with the text. The lowest frequency in which Vivaldi antenna can operate with a high signal to noise ratio is 500 MHz for a small size of antenna. At 3 GHz the day and night effect in the top 0-2.5 cm soil should be clearly visible, which cannot be seen in any figure. The reason may be the big discretization (2.5 cm) for such a wide range of frequencies.

Reply: In the revised version, the figure 3b, d, f will be replaced by the new one with a frequency range of 1 – 3 GHz so it appears consistent with the text. The smaller discretization (1 cm) will be applied in the revised version to improve the day and night

effect in the top soil layer.

10. Page 1595 L 13: The sub figure 4a represents that the synthetic soil moisture profile at initial time (0 h). It is sure that the initial profile was considered as a constant with depth equal to 0.2 cm^{3}cm^{-3} (already discussed on page 1593 Line 17-18). How the synthetic profiles at initial time (0 h) was constructed for clay, loam sand and silt? Please provide more explanation.

Reply: The same initial soil moisture profile was assumed for all soil types ($\theta = 0.2cm^3cm^{-3}$). This is popular assumed conditions that were used by several synthetic studies (for example, Walker el al., 2002).

11. Page 1599 Paragraph 3.2: Please mention in the text somewhere that how much time it takes to complete one simulation with 5, 30 and 50 h.

Reply: Because this data assimilation belong to the optimization approach (with the nonlinear gradient conjugate algorithm), there is no exact computation time for each simulation. It depends on the initial value and the soil type.

12. If possible please include more recent references from HESS and cite the following two recent articles, related to the use of GPR for the estimation of soil hydraulic parameters to construct soil moisture profiles.

Dagenbach, A., J. S. Buchner, P. Klenk K. Roth, 2013. Identifying a parameterization of the soil water retention curve from on-ground GPR measurements. Hydrol Earth Syst Sci 17(2):611-618 doi:10.5194/hess-17-611-2013. Jadoon, K. Z., L. Weihermüller, B. Scharnagl, M. B. Kowalsky, M. Bechtold, S. S. Hubbard, H. Vereecken S. Lambot, 2012. Estimation of Soil Hydraulic Parameters in the Field by Integrated Hydrogeophysical Inversion of Time-Lapse Ground-Penetrating Radar Data. Vadose Zone Journal 11(4) doi:10.2136/vzj2011.0177

Reply : The two above articles will be cited in the revised version.

Reference:

Jadoon, K.Z., Lambot, S., Slob, E.C., Vereecken, H. (2011), Analysis of Horn Antenna Transfer Functions and Phase-Center Position for Modeling Off-Ground GPR, IEEE Transactions on Geoscience and Remote Sensing, 49(5), 1649 – 1662.

Tran, A.P., Mohammad Reza Mahmoudzadeh, A., and Sebastien, L. (2012), Coupling of dielectric mixing models with full-wave ground-penetrating radar signal inversion for sandy-soil-moisture estimation, Geophysics, 77, H33–H44, 2012.

Walker, J. P., Willgoose, G. R., Kalma, J. D. (2002), Three-dimensional soil moisture profile retrieval by assimilation of near-surface measurements: Simplified Kalman filter covariance forecasting and field application, Water Resources Research, 38 (12),13.

Zupanski, D., and Zupanski, M. (2006), Model error estimation employing an ensemble data assimilation approach, Monthly Weather Review, 134 (5), 1337–13541.

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