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Assimilation of Ground-Penetrating Radar Data to Update Vertical Soil Moisture Profile

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The root zone soil moisture has been long recognized as important information for hydrological, meteorological and agricultural research. In this study, we propose a closed-loop data assimilation procedure to update the vertical soil moisture profile from time-lapse ground-penetrating radar (GPR) data. The hydrodynamic model, Hydrus-1D (Simunek et al., 2009), is used to propagate the system state in time and a radar electromagnetic model (Lambot et al., 2004) to link the state variable (soil moisture profile) with the observation data (GPR data), which enables us to update the soil moisture profile by directly assimilating the GPR data. The assimilation was performed within the maximum likelihood ensemble filter (MLEF) framework developed by Zupanski et al., (2005), for which the problem of nonlinear observation operator is solved much more effectively than the Ensemble Kalman filter (EnKF) techniques. The method estimates the optimal state as the maximum of the probability density function (PDF) instead of the minimum variance like in most of the other ensemble data assimilation methods.

Direct assimilation of GPR data is a prominent advantage of our approach. It avoids solving the time-consuming inverse problem as well as the estimation errors of the soil moisture caused by inversion. In addition, instead of using only surface soil moisture, the approach allows to use the information of the whole soil moisture profile, which is reflected via the ultra wideband (UWB) GPR data, for the assimilation. The use of the UWB antenna in this study is also an advantage as it provides more information about soil moisture profile with a better depth resolution compared to other classical remote sensing techniques.

Our approach was validated by a synthetic study. We constructed a synthetic soil column with a depth of 80 cm and analyzed the effects of the soil type on the data assimilation by considering 3 soil types, namely, loamy sand, silt and clay. The assimilation of GPR data was performed to solve the problem of unknown initial conditions. We simulated a zero-offset antenna operating in the frequency domain in the range of 1-3 GHz with a frequency step of 6 MHz. The distance between the antenna and soil surface was 37 cm. The numerical soil moisture profiles generated by the Hydrus-1D model were used by the GPR model to produce the "observed" GPR data. The results show that the soil moisture profile obtained by assimilating the GPR data is much better than that of an open-loop forecast. Compared to the loamy sand and silt, the updated soil moisture profile of the clay soil converges to the true state much more slowly. Increasing update interval from 5 to 50 hours only slightly improves the effectiveness of the GPR data assimilation for the loamy sand but significantly for the clay soil. The proposed approach appears to be promising to improve real-time prediction of the soil moisture profiles and soil hydraulic properties at the field scale from GPR measurements.