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Mapping the soil hydrogeophysical properties using full-waveform inversion of proximal, zero-offset ground-penetrating radar based on vector network analyzer technology

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Ground-penetrating radar (GPR) has proven to have great potential for high-resolution, non-invasive mapping of the soil hydrogeophysical properties at the field scale. Common GPR techniques are usually based on ray-based travel time or reflection analyses to retrieve the soil dielectric permittivity and correlated water content. These methods suffer however from two major limitations. First, only a part of the radar data is used. Second, the adequacy of the electromagnetic wave propagation model is strongly limited. In order to maximize information retrieval capabilities from the radar data, it is necessary to resort to full-waveform forward and inverse modelling techniques. For the specific case of proximal GPR, where the radar antennas are off the ground, we have developed such an approach. The radar system is set up using vector network analyzer technology, for which the measured quantities represent a well-known international standard, and a highly directive horn antenna acting simultaneously as transmitter and receiver. Assuming some distance between the ground surface and the antenna, so that the spatial distribution of the backscattered electromagnetic field taken over the antenna aperture does not depend on the soil properties, the antenna is modelled using frequency-dependent, complex linear transfer functions in series and parallel accounting for all antenna effects and antenna-soil interactions. The air-soil system is assumed as a three-dimensional multilayered medium for which an exact solution of Maxwell's equations is derived to describe electromagnetic wave propagation. A fast integration procedure permits to compute the spatial domain Green's function from the spectral domain counterpart. Signal inversion is formulated as a complex least-squares problem and is performed iteratively using advanced global optimization based on the multilevel coordinate search algorithm. The model has been shown to reach an unprecedented accuracy in controlled laboratory conditions and accurate estimates were obtained for both soil dielectric permittivity and electric conductivity. The proposed method is presently used for real-time mapping of surface soil moisture at the field scale, thereby bridging for the first time the scale gap between soil sampling and remote sensing. Integrated electromagnetic and hydrodynamic inversion of time-lapse radar data should further permit the identification of the shallow soil hydraulic properties governing water flow in the soil.