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Full-waveform modeling of Zero-Offset Electromagnetic Induction for Accurate Characterization of Subsurface Electrical Properties

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Water is a vital resource for human needs, agriculture, sanitation and industrial supply. The knowledge of soil water dynamics and solute transport is essential in agricultural and environmental engineering as it controls plant growth, hydrological processes, and the contamination of surface and subsurface water. Increased irrigation efficiency has also an important role for water conservation, reducing drainage and mitigating some of the water pollution and soil salinity. Geophysical methods are effective techniques for monitoring the vadose zone. In particular, electromagnetic induction (EMI) can provide in a non-invasive way important information about the soil electrical properties at the field scale, which are mainly correlated to important variables such as soil water content, salinity, and texture. EMI is based on the radiation of a VLF EM wave into the soil. Depending on its electrical conductivity, Foucault currents are generated and produce a secondary EM field which is then recorded by the EMI system. Advanced techniques for EMI data interpretation resort to inverse modeling. Yet, a major gap in current knowledge is the limited accuracy of the forward model used for describing the EMI-subsurface system, usually relying on strongly simplifying assumptions.

We present a new low frequency EMI method based on Vector Network Analyzer (VNA) technology and advanced forward modeling using a linear system of complex transfer functions for describing the EMI loop antenna and a three-dimensional solution of Maxwell's equations for wave propagation in multilayered media. VNA permits simple, international standard calibration of the EMI system. We derived a Green's function for the zero-offset, off-ground horizontal loop antenna and also proposed an optimal integration path for faster evaluation of the spatial-domain Green's function from its spectral counterpart. This new integration path shows fewer oscillations compared with the real path and permits to avoid the singularities. We tested the model in controlled laboratory conditions for EMI measurements at different heights above a copper sheet, playing the role of a perfect electrical conductor. Good agreement was obtained between the measurements and the model, especially for the resonance frequency of the loop antenna. The loop antenna height could be retrieved by inversion of the Green's function. For practical applications, the method is still limited by the low sensitivity of the antenna with respect to the dynamic range of the VNA. Once this will be resolved, we believe that the proposed method should be very flexible and promising for accurate, multi-frequency EMI data inversion.