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A new electromagnetic induction sensor using Vector Network Analyzer technology for accurate characterisation of soil electrical properties

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Electromagnetic induction (EMI) has been widely used since the 70s to retrieve soil physico-chemical properties through the measurement of soil electrical conductivity. Soil electrical conductivity integrates several factors, mainly soil water content, salinity, clay content and temperature, and to a lesser extent, mineralogy, porosity, structure, cation exchange capacity, organic matter and bulk density. EMI has been shown to be useful for a wide range of environmental applications. EMI is non invasive and individual measurements are almost instantaneous, which permits to characterise large areas with fine spatial and/or temporal resolutions.
Nevertheless, current EMI systems present some limitations. First, EMI usually operates at a single or at a limited number of fixed frequencies, which limits the information that can be retrieved from the subsurface. In addition, the calibration of existing commercial sensors is generally rather empirical and not accurate, which reduces the reliability of the data. Finally, the data processing techniques that are used to retrieve the soil electrical properties from EMI data often rely on strong simplifying assumptions with respect to wave propagation through the antenna-air-soil system.

Performing EMI measurements with Vector Network Analyzer (VNA) technology would overcome a part of these limitations, allowing to work simultaneously at a wide range of frequencies and to readily perform robust calibrations, which are defined as an international standard. On that basis, we have developed a new algorithm for off-ground, zero-offset, frequency domain EMI based on full-waveform inverse modelling. The EMI forward model is based on a linear system of complex transfer functions for describing the loop antenna and its interactions with soil and an exact solution of Maxwell's equations for wave propagation in three-dimensional multilayered media. The approach has been validated in laboratory conditions for measurements at different heights above a perfect electric conductor (copper sheet). Although VNA technology has a relatively wide dynamic range, regular loop antennas do not have a sufficient efficiency to ensure enough sensitivity to the soil electrical conductivity in zero-offset, off-ground mode. For higher efficiency, we have designed a specific transmitting antenna based on two coils in series together with a variable capacitor to modify the resonant frequency. The two coils have different diameters and are placed in the same plane, centred on the same point. The current in the inner coil is travelling in opposite direction compared to the outer coil, leading to two magnetic fields with opposite polarity. This produces a magnetic cavity in the middle of the coils (the magnetic field tends to zero), where a regular receiving coil is situated. This set up permits to strongly decrease direct coupling between the antennas, thereby increasing the dynamic range of the system. In addition, a wideband amplifier is used to further strengthen the received wave. The results obtained with this new method show great promise for quantitative and accurate characterization of the soil electrical conductivity with EMI.