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Full-waveform analysis of soil and sensor characteristics on EMI sensitivity and investigation depth

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Electromagnetic induction (EMI) is a popular technique which has been intensively used for more than 30 years for rapid and non invasive characterisation of soil physico-chemical properties through the measurement of soil apparent electrical conductivity. Soil apparent electrical conductivity is influenced by several factors, mainly soil water content, clay content, salinity and temperature, and to a lower extent, mineralogy, porosity, structure, cation exchange capacity, organic matter and bulk density. This integrative dimension of soil apparent electrical conductivity makes EMI useful for a wide range of environmental applications implying the assessment of one or several of these soil properties and their spatiotemporal distribution at the field scale. The vertical spatial sensitivity of the EMI sensor to soil electrical conductivity and the depth of investigation are key factors for quantitative analyses in such studies. Classically, the response signal of the instruments is processed using an asymptotic approximation of Maxwell's equations valid for low-induction-number (LIN) conditions, corresponding to a very small value of the ratio between the transmitter-receiver coil separation and the skin depth (i.e., the depth at which the primary magnetic field has been attenuated to 1/exp of its original strength). Under the LIN assumption, the ratio of the secondary magnetic field to the primary magnetic field is linearly proportional to the soil apparent electrical conductivity, and the sensor vertical spatial sensitivity and investigation depth only depend on coil spacing and orientation (i.e., vertically or horizontally oriented). However, divergences from LIN conditions are likely to arise in moderately high conductive soil areas and the preceding statements may not hold anymore. In particular, influences of the soil electrical conductivity and frequency on the vertical spatial sensitivity and investigation depth are theoretically possible in such situations, leading to erroneous analyses and data interpretation if not properly accounted for.

We conducted synthetic experiments in order to investigate and quantify the effects of the different factors likely to affect EMI sensor vertical spatial sensitivity and investigation depth and to identify conditions for which the LIN approximation holds. The EMI signal was modelled from an exact solution of the three-dimensional Maxwell's equations for wave propagation in a horizontally multilayered medium. For this analysis, we examined different configurations for a two-layered subsurface, considering contrasted values for the two layer electrical conductivities within the range encountered for soils and varying the thickness of the first layer. For each of these configurations, several frequencies and transmitter-receiver coil separations were studied, encompassing the ranges of corresponding parameters found for the current EMI systems. Moreover, the effects of the orientation and of the height of the instrument above the soil surface were also analysed. These results bring interesting insights on the influence of both soil and sensor characteristics on the sensitivity with depth of the EMI signal and on the investigation depth, and point out situations for which the LIN approximation should be carefully considered. This study situates in the framework of the development of a new EMI approach, based on zero-offset co-planar coils and full-waveform inversion for exact parameter retrieval.