Numerical modelling of electromagnetic coupling effects in EIT borehole measurements

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The measurement of the impedance of low-polarizable soils and rocks in the mHz to kHz range with sufficient phase accuracy requires advanced data correction methods in addition to a sophisticated EIT measurement system. Several different electromagnetic effects currently limit the useable upper frequency range of the measured impedance to some tens of Hz in borehole EIT applications. In this presentation, we aim to discuss how improved EIT data acquisition and effective error correction procedures can be used to achieve higher phase accuracy for borehole EIT measurements in the frequency range between 10 Hz to 45 kHz.

EIT data acquisition was performed using a prototype spectral EIT system optimized for field applications. The prototype is based on a laboratory spectral-EIT measurement system with high phase accuracy. This laboratory system uses electrode modules with amplifiers for potential measurement and relays for current injection in order to minimize the capacitive load at the electrodes and to improve measurement accuracy. For EIT borehole measurements, similar electrode modules were integrated in electrode chains that consist of 25 m long shielded multicore cables each with eight electrode modules with a separation of one meter. In addition to the optimized system design, model-based numerical correction methods are used to remove several errors introduced by amplification errors, signal drift, current measurement errors, the propagation delay of the signal due to the long cables and other system dependent sources. Although these corrections improve the quality of the EIT measurements, a main source of errors in EIT field measurements above 10 Hz is the electromagnetic coupling associated with the long electrode chains and this error source will be treated in this study. Electromagnetic coupling consists of phase errors introduced by inductive coupling between the wires of electrode chains and phase errors due to capacitive coupling between the cable shield and the electrically conductive subsurface.

In the case of inductive coupling, the injected current induces a voltage in the wires used for potential measurement. This voltage is linearly added to the resulting voltage of the 'true' subsurface impedance Z_s, but with a phase shift of 90° and it therefore introduces a large phase error. The additional part of the induced voltage in the measured transfer impedance $Z = Z_s + j\omega M$, which is the quotient of the measured voltage and the injected current, is the mutual inductance M between the wires used for current injection and potential measurement. This shows that the measured transfer impedances can be corrected to obtain the subsurface impedance of interest by determining the mutual inductance. Therefore, we developed a method to determine the mutual inductance based on numerical modelling combined with calibration measurements. We differentiate two cases: i) coupling between wires in one borehole cable with small separations in the mm range and ii) coupling between different borehole cables with large separation in the m range. The mutual inductances between wires of different chains can be calculated numerically based on the position of the cable layout in the field. Sensitivity studies showed that the cable positions need to be known with cm accuracy only. To determine the inductance between wires in one chain, a calibration method is used because numerical calculations were not accurate enough due to insufficient knowledge of the positions of the wires in a multi-core cable. This calibration only needs to be performed once, since the mutual inductance is independent of the subsurface electrical conductivity and the wire positions are fixed within a single multi-core cable. In order to correct the measurements of any configuration with two or more electrode chains, the different contributions to the mutual inductances are combined in a single universal pole-pole matrix. This enables the simple calculation of the mutual inductance for EIT field measurements using two electrodes for current injection and two electrodes for voltage measurement, because the mutual inductance now is a simple linear combination of the elements of the pole-pole-matrix corresponding with the current and potential electrodes.

The second source of errors is due to the capacitive currents between the soil and the shield of the cables. Due to the thin isolation of the multicore cables, these capacitances are relatively large (~1200 pF/m). The effect of this capacitance on the measured transfer impedances cannot be corrected a priori as in the case of inductive coupling because these parasitic currents depend on the unknown subsurface electrical conductivity distribution. To account for capacitive coupling, the complex admittance matrix of the forward electrical model is enhanced with additional admittances of the capacities of the cable segments. This enhanced admittance matrix is used for the forward modelling of the potential distribution in order to reconstruct the subsurface electrical conductivity.

In a first step, the developed correction methods were verified with borehole EIT measurements in water. The achieved accuracy in this controlled set-up was 1 mrad at 10 kHz using one electrode chain and 1 mrad at 1 kHz using two electrode chains. To demonstrate the method for actual subsurface characterization, borehole EIT measurements were made in a heterogeneous aquifer at the Krauthausen test site. The depth profiles reconstructed with 3D forward modelling and 1D inversion clearly showed the necessity of the correction for inductive coupling. The effect of the correction for capacitive coupling is also noticeable but much smaller (see figure 1). The presented work clearly is a major step towards more accurate borehole EIT measurements for frequencies above 10 Hz.

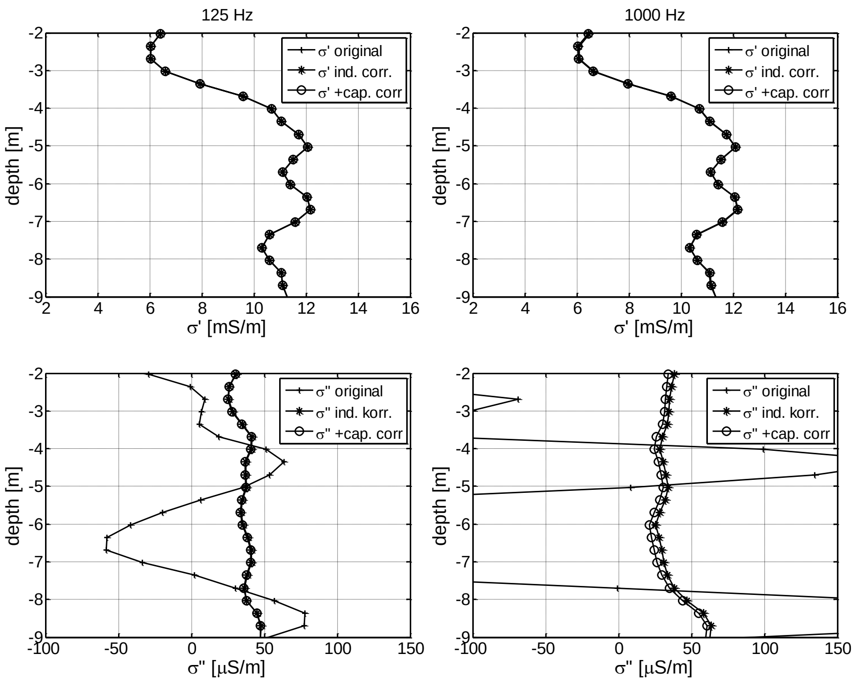

Fig. 1: Depth profiles of real (top) and imaginary (bottom) conductivity at 125 Hz (left) and 1 kHz (right) as obtained from borehole EIT measurements at the Krauthausen test site with and without corrections for inductive and capacitive coupling using a 1D inversion scheme.