

Evaluation of a correction procedure to remove electrode contact impedance effects from broadband SIP measurements

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Accurate measurements of the complex electrical conductivity using spectral induced polarization (SIP) in the mHz to kHz frequency range require sophisticated impedance spectrometers and carefully designed sample holders with appropriate geometry. Data correction procedures can be used to further improve the accuracy of the SIP measurements. A source of error in laboratory SIP measurements that has not yet been addressed is the effect of the contact impedance of the potential electrodes. This effect is particularly strong when SIP measurements are made on unsaturated porous media with a low electrical conductivity using high-impedance non-polarizing electrodes. In such a case, the accuracy of the imaginary part of the electrical conductivity is strongly affected by the high electrode contact impedance for frequencies above 100 Hz. Therefore, the aim of this study is to develop a correction procedure to remove electrode impedance effects from broadband SIP measurements and to evaluate this new correction procedure using measurements on water with known electrical conductivity and unconsolidated porous media.

Our proposed correction procedure is based on the electrical model of the sample and the measurement system shown in Fig. 1. Here, Z_x is the unknown sample impedance, Z_{e1} and Z_{e4} are the contact impedances of the current electrodes that also include part of the sample material, and Z_{e2} and Z_{e3} are the contact impedances of the potential electrodes. The model also considers the approximately known parasitic capacitances C_v of the amplifiers that lead to possible leakage currents during the SIP measurements. The aim of any SIP measurement is to estimate Z_x from the unknown voltage U_x and current I_x (Fig. 1). In previous work, we have shown how I_x can be accurately determined. So far, we have not yet considered procedures to correct U_x for the effect of Z_{e2} and Z_{e3} . Instead, we have attempted to minimize Z_{e2} and Z_{e3} to allow accurate measurements of U_x and Z_x , which is not always possible as detailed above. The electrical model shows that at least two measurements are required to estimate the five unknown impedances. We propose to use normal and reciprocal measurements where the current and potential electrodes are switched (Fig. 1). For the reciprocal measurement, we use a current injection with low intensity in order to avoid non-linear electrode processes. The contact impedance of the potential electrode Z_{e2} can then be determined from the voltage between node 5 and 2 and the associated known injected current in the reciprocal measurement. The potential at node 2 can be measured directly, and we assume that the potential at node 5 is identical to the measured potential at node 1, which is a reasonable assumption because of the high input impedance of the spectrometer. The electrode impedance Z_{e3} can be calculated in an analogous manner. Once the electrode impedances Z_{e2} and Z_{e3} are known, the unknown voltage $U_x = U_5 - U_6$ in the normal measurement can be calculated using:

$$U_x = U_2(1 + Z_{e2}j\omega C_v) - U_3(1 + Z_{e3}j\omega C_v) \quad (1)$$

where j indicates imaginary units, ω is the angular frequency, and U_2 and U_3 are the measured potentials at the electrodes. The corrected impedance can now be calculated using $Z_x = U_x / I_x$.

There are several challenges associated with the proposed correction method. First, the use of the low current intensity in the reciprocal measurement results in a low signal-to-noise ratio for the measured impedances, and it is clear that a compromise needs to be made between accurate impedance measurements and using a low enough current density to avoid non-linear electrode processes. Second, the electrode impedance is frequency dependent because of electrode polarization effects. However, initial analysis has shown that the electrode contact impedances are

relatively independent of frequency above 1 kHz, and we opted to use the mean electrode impedance between 1 and 2 kHz in our correction procedure. We neglect the frequency dependent behaviour because the observed low-frequency dispersion is not relevant for the correction of the SIP data because of the term $j\omega$ in Eq. 1.

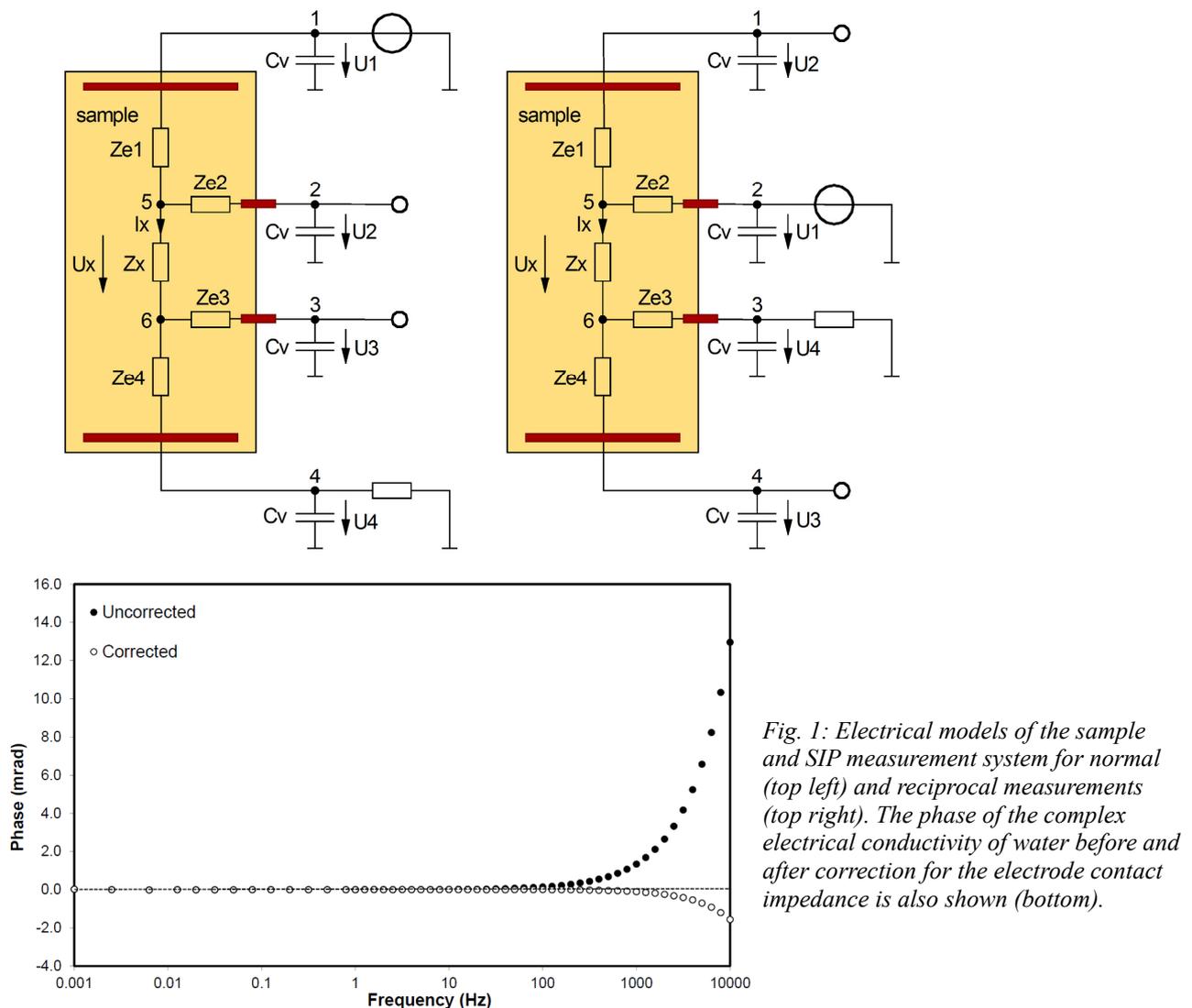


Fig. 1: Electrical models of the sample and SIP measurement system for normal (top left) and reciprocal measurements (top right). The phase of the complex electrical conductivity of water before and after correction for the electrode contact impedance is also shown (bottom).

The procedure to estimate the electrode impedances was tested using measurements on water with a known electrical conductivity of 0.0895 S m^{-1} . The uncorrected phase in Fig. 1 shows that the contact impedance of the potential electrodes introduced an error for frequencies higher than 100 Hz. The error was about 1 mrad at 1 kHz and increased to 13 mrad at 10 kHz. After correction, the increasing phase with frequency largely disappeared and the phase became negative for frequencies above 1000 Hz. This indicates that the required correction of the SIP measurements was slightly overestimated. When considering the potential error sources in the estimation of the electrode contact impedance, we estimate that the accuracy can be improved up to a factor of 10. However, greater improvement is not likely because of the need to know C_v with high accuracy. This estimated maximum possible improvement in accuracy is in reasonable agreement with the deviation of the corrected and the known phase of water at 10 kHz. The developed correction procedure was also applied to SIP measurements on unconsolidated porous media with variable water saturation. The corrected phase spectra were considerably below the uncorrected phase spectra for frequencies above 100 Hz. However, a direct validation of the corrections is not straightforward in this case because of the unknown contribution of the sample to the measured phase. We conclude that the developed correction procedure resulted in a considerable improvement of the SIP measurement accuracy.