4D Spectral Electrical Impedance Tomography – a diagnostic imaging tool for the characterization of subsurface structures and processes (4DEIT)

Kemna, A. (1), Huisman, J.A. (2), Zimmermann, E. (3), and Fechner, T. (4)
(1) Bonn University, Applied Geophysics, Steinmann Institute, Nußallee 8, D-53115 Bonn, Germany, kemna@geo.uni-bonn.de
(2) Forschungszentrum Jülich GmbH, Institute for Bio- and Geosciences – Agrosphere (IBG 3), D-52425 Jülich, Germany, s.huisman@fz-juelich.de
(3) Forschungszentrum Jülich GmbH, Central Institute for Electronics (ZEL), D-52425 Jülich, Germany, e.zimmermann@fz-juelich.de
(4) Geotomographie GmbH, Am Tonnenberg 18, D-56567 Neuwied, Germany, tfechner@geotomographie.de

EIS measurement approach can be implemented in a tomographic framework so that the diagnostic capability of EIS can be combined with the spatial resolution benefits of electrical impedance tomography (EIT) (e.g., Kemna et al., 2000). The present project pursues such an integrated methodological approach and aims at developing broadband spectral EIT technology in 4D (3D space plus frequency). The new tomographic technique with spectroscopic capability will enable the improved non-invasive characterization of subsurface structures and processes at depth scales ranging from 1 m to 100 m, in particular for hydrogeological and environmental applications (Figure 1).

Project structure and objectives
The development of spectral EIT comprises three major tasks, which will be addressed in subprojects (SPs) (Figure 2). Existing EIT codes are limited to the inversion of single-frequency data, or the independent inversion of multi-frequency data. However, the successful exploitation of the relatively weak frequency dependence of soil/rock electrical properties for improved soil/rock textural, hydraulic or biogeochemical characterization in an imaging framework requires the integral inver-
be quantitatively described and corrected for to a significant degree. The modelling of the different effects as well as the development of effective correction approaches (both numerical and electronic) are addressed in SP2 with a view to maximizing the usable bandwidth of spectral EIT instruments.

A prerequisite for the establishment of a new imaging technology is a thorough evaluation and validation on both synthetic and field data. Importantly, a successful field validation requires the availability of independent information on the imaged properties – in the optimum case independently measured on soil/rock samples in the laboratory. To minimize corresponding efforts in the present project, we selected a demonstration field site (a heterogeneous sand-gravel aquifer) which has been extensively characterized in the past – including EIS lab measurements on a representative set of sediment samples – and which is thus well suited for validation of the new spectral-EIT technology. In addition, representative synthetic models will be studied to assess the potential and the limitations of the methodology; and adequate description and treatment of data errors will be investigated. Evaluation, validation and data

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error treatment will be pursued in SP3.

In addition to the above key SPs for 4D EIT development, a fourth SP (SP4) is intended to start paving the way for a commercialization of the new technology – and thus making it available to potential end-users in the different fields of possible application (e.g., hydrogeological, environmental, geotechnical) – by involving an industry partner for the design and programming of a graphical user interface for the different routines developed in this project. It is expected that the availability of easy-to-use inversion software is essential for widespread acceptance and use of 4D EIT technology.

Development of spectral-EIT inversion (SP1)

Current complex-resistivity imaging approaches are limited to the inversion of single-frequency data (e.g., Kemna et al., 2004; Blaschek et al., 2008), or the independent inversion of multi-frequency data sets (Kemna et al., 2000). Such an approach significantly limits the characterization capabilities of EIT because there is no control on the spectral behaviour in the inverse procedure, resulting in considerable ill-posedness with respect to the retrieval of spectral characteristics. This subproject aims at the development, implementation and testing of a spectral-EIT inversion code. The necessary regularization to overcome the inherent ill-posedness of the inverse problem will be extended from a purely spatial constraint to a spatio-spectral conditioning honouring in particular the typical, expected or known electrical relaxation behaviour. The latter will be accounted for in the regularization operator in form of an adapted smoothness constraint or, alternatively, by means of established phenomenological relaxation models (such as Cole-Cole, or a superposition of Cole-Cole models).

Depending on the dimensionality of the inverse problem with respect to space, where both 2D and 3D models will be considered, the new spectral-EIT inversion defines a 3D or 4D inverse problem. Although the development will first be undertaken and tested based on 2D spatial models, i.e., in 3D, the overall goal is the development of a 4D EIT code for full spatio-spectral inversion. In the new inversion code, the forward models for the prediction of instrumental coupling effects provided by SP2 will
also be incorporated, if these effects cannot be removed from the data prior to inversion. A spin-off of the above development is an inversion tool that also allows the integral processing of time-lapse EIT, as collected in many monitoring application (e.g., monitoring of biogeochemical system alterations in the course of remediation treatments). If based on a smoothness constraint, the spatio-spectral regularization can likewise be applied as a spatio-temporal regularization, i.e., frequency and time can be interchanged as additional dimension in the inversion. Therefore, the developed inversion tool will also offer improved process characterization capabilities in time-lapse EIT applications. In the spatio-temporal regularization, the contributions with respect to space and time will be optionally linked via the mean velocity of the process under investigation, if the latter is known or can be reasonably estimated beforehand.

Data correction and improved modelling for spectral-EIT measurements (SP2)

For geophysical applications of spectral EIT, relatively high phase accuracy of the measurement system is required given the relatively low polarizability of soils and rocks. In the absence of minerals with electronic conductivity, such as for sedimentary rocks, typical phase values lie between 1 and 20 mrad only, and the frequency range of interest ranges from 1 mHz to some kHz. In contrast to medical applications, where EIT imaging is often of qualitative character only and high frame rates are used (e.g., Yerworth et al., 2003; Oh et al., 2007), for geophysical applications quantitative imaging is of highest interest, even if this means that data acquisition times are long. In order to image the spectral phase response of low-polarizable objects such as soils and rocks, a laboratory spectral-EIT measurement system with sufficient accuracy has been developed (Zimmermann et al., 2008) based on a previously developed high-accuracy laboratory EIS system (Zimmermann et al., 2008b). Recently, tests with a first prototype for spectral EIT data acquisition at the field scale, also suitable for borehole measurements, were performed (Figure 3).

Figure 3: Prototype spectral-EIT measurement system allowing borehole measurements in action at the Krauthausen test site.
To improve the accuracy of spectral EIT field measurements, it is not sufficient to only optimize the measurement equipment. In addition, appropriate data acquisition, data correction and improved forward modelling concepts are required. Capacitive coupling causes parasitic currents that distort the phase accuracy at higher frequencies. Therefore, the first objective is to develop a correction procedure to account for these effects. For this, the actual current that is injected and the actual voltage at the electrodes will be estimated, which is difficult because of the varying contact impedances of the electrodes. In addition, the propagation delay of the signal along the cables will be corrected. A second issue is inductive coupling of the cables. Because of the excitation currents in the cables, it is possible that electrical voltages are induced that again cause phase errors. Therefore, a second objective is to correct for these inductive coupling errors. This is possible if it is assumed that the magnetic field due to electric currents in the ground is small compared to the magnetic field due to excitation currents in the cables. In addition, the cable positions need to be known accurately. A third issue is the secondary electric field induced by the magnetic field associated with the current distribution in the subsurface. This is typically not considered because the change of the magnitude of the resulting field is negligibly small. However, this is typically not true for the phase of the electric field. The third objective is to develop an appropriate approximation that accounts for this secondary field. In addition, the unwanted induced voltages in the cables due to the subsurface current distribution will be corrected. A final issue are capacitive currents from the subsurface to the cables that can also distort the phase accuracy. In case of EIT this effect can be substantial because of the multitude of electrodes and cables. Therefore, the final objective is to include these currents directly in the forward model. This correction needs to be performed directly in the EIT forward model because these currents will depend on the subsurface potential distribution, which is not known a priori.

**Evaluation and validation of spectral-EIT technology (SP3)**

The main objective of this subproject is to evaluate and validate the developed data correction and 4D imaging strategies using synthetic model studies and field EIT measurements. In particular, 4D-EIT technology will be demonstrated and validated at the Krauthausen test site, operated by the Forschungszentrum Jülich GmbH. One focus of research at this test site is the development and use of electrical imaging methods to obtain hydrologically relevant soil and aquifer properties (e.g., Kemna et al., 2002; Vanderborght et al. 2005; Müller et al., 2010).

The test site is equipped with 76 observation wells. Basic aquifer properties, such as porosity and grain-size distribution, were determined at a large number of locations and used to estimate the variability of hydraulic conductivity. The latter was also investigated with borehole flowmeter data, pumping experiments and cone penetration tests (Tillmann et al., 2008). In addition, laboratory SIP measurements made on material obtained during installation of the observation wells are available (Figure 4) and first EIT measurements with commercially available equipment were performed (Figure 5).

Both the laboratory and the preliminary field measurements confirm that the measured resistivity phase values at the Krauthausen test site are low (absolute values mostly below 10 mrad, see Figures 4 and 5). For such a low polarizability, the accuracy of the measurement equipment is a critical issue. Accordingly, an important focus in this subproject is the application of the high-accuracy prototype EIT measurement system (Figure 3). The field evaluation of the data correction and improved forward modelling concepts developed in SP2 is indispensable to determine the relative merit of the proposed methods to improve the phase accuracy of EIT measurements. It is expected that this field evaluation will provide additional insights into the various sources of errors in field EIT measurements.
The results of geophysical imaging are strongly influenced by errors in the data and the underlying forward modelling. For electrical imaging, the random fraction of these errors is typically estimated using reciprocal measurements where current and potential electrodes are switched. This reciprocal error is used in the inversion and, therefore, has a strong impact on the resulting images. Although the reciprocal error is a convenient error measure, it might be plagued by systematic EIT measurement errors. An important objective thus is to better understand and characterize the various sources of error in order to come up with a practical method for improved error quantification, which will ultimately lead to enhanced image quality. This new error quantification approach should also be applicable to measurement systems that do not allow reciprocal measurements.

The field evaluation and validation will be supported by synthetic model studies, which will investigate how the 4D-EIT technology translates known subsurface heterogeneity and intrinsic spectral characteristics (based on the Krauthausen test site) into electrical images given different data acquisition strategies, varying error levels and error descriptions, and different regularization strategies in the spatio-spectral inversion (SP1).

**Development of graphical user interface for spectral-EIT inversion (SP4)**

There are various commercial software packages available for modelling and inversion of resistivity and induced polarization (IP) data. In addition, there is a number of freely distributed software mainly for the use on a non-commercial basis for students and universities. Today, two major trends for commercially available resistivity software are observed, i.e., software which runs with almost any resistivity equipment and software which is more or less adapted to a specific instrument. Commercially available software packages allow the modelling of IP data based on either classical time-domain chargeability (an integral measure of IP) or on certain electrical relaxation models (e.g., Cole-Cole model). However, there is no

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Figure 4: Resistivity phase spectra as measured on material from different depths from the Krauthausen test site in the laboratory using an impedance spectrometer with high phase accuracy.
software available accounting for (i) general frequency-domain, broadband EIT data and (ii) the various effects generated by EIT instruments (e.g., capacitive/inductive coupling).

The aim of this subproject is to develop a customer-friendly interface to model and invert spectral EIT data sets in 2D or 3D space. Modelling and inversion are based on the concepts developed in subprojects SP1 and SP2. Furthermore, an option will be included to extend the software to the processing of time-lapse (i.e., monitoring) data. The software will be a stand-alone tool dedicated to spectral/time-lapse EIT measurements. It will also include features for data correction following the procedures developed in SP2 and SP3, which might depend on instrument design.

Conclusions
The 4DEIT project aims to develop broadband 4D spectral EIT for the improved non-invasive characterization of subsurface structures and processes in various fields of application. The development of spectral-EIT technology will pave the way for a quantitative interpretation of inverted tomograms by means of available petrophysical, physicochemical and/or biophysical models and by this is likely to lead to a breakthrough in the spatially highly resolved characterization and diagnosis of subsurface lithology, hydrogeology and biogeochemistry at depth scales ranging from 1 m to 100 m.

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