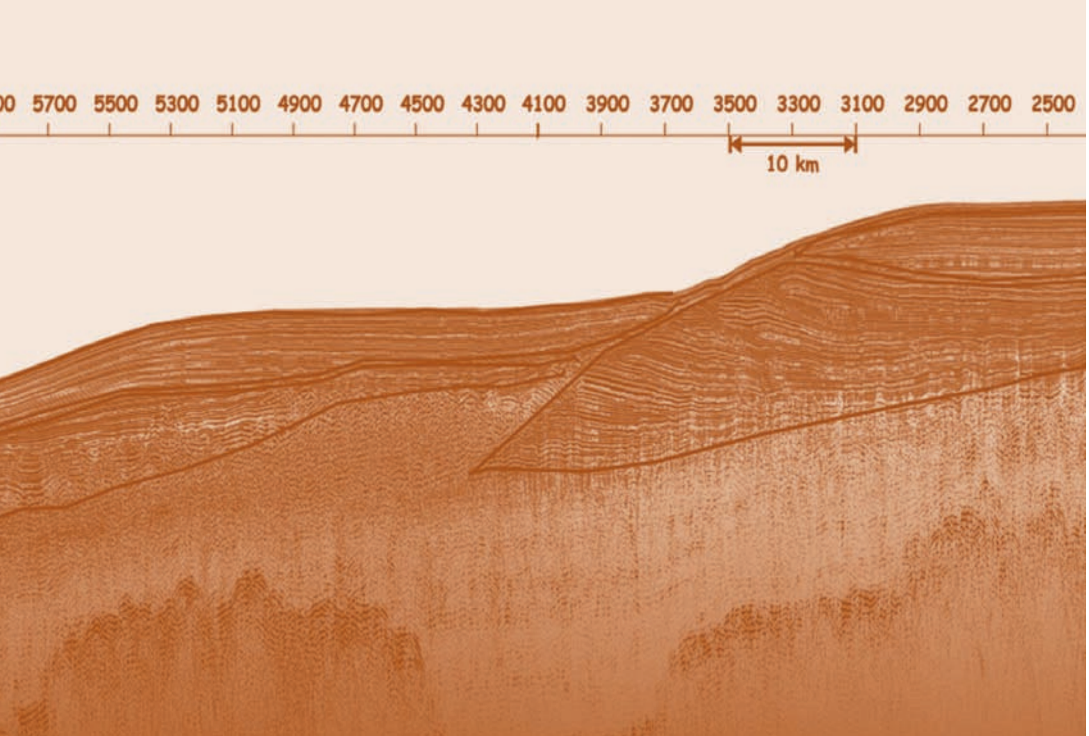

GEOTECHNOLOGIEN

Science Report

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Tomography of the Earth's Crust – From Geophysical Sounding to Real-Time Monitoring

Status Seminar
2 May 2011
GFZ, German Research Centre for Geosciences, Potsdam

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Preface

The zone near the surface on our planet is the interface between geo-, bio-, hydro- and atmosphere and the basis for our daily life. Water, natural resources (salt, ore, oil and gas) and energy/heat for example are exploited from this zone. Increasingly, waste and other material will be stored underground. We do not only use the surface for infrastructure but rather we increasingly expand construction to the subsurface for example relocating traffic to tunnels.

Suitable exploration and monitoring technologies are therefore of enormous importance to mitigate danger and damages in this economically and ecologically sensitive area.

Despite methodical progress especially in mathematical and numerical geophysics during the last years, so far the various methods are often used independently due to economical reasons. However the concerted combination and/or the enhancement of different methods would allow new prospecting strategies. A deficit still exists in the combination and evaluation of the various data sets and models received from different methods.

The research work on the topic of »tomography of the Earth's crust – from geophysical sounding to real-time monitoring« will focus on the development of cross-scale multi-parameter methods and their technological application together with the development of innovative field techniques. Seismic wave field inversion theory, diffusion and potential methods are to be developed and optimized with respect to cost and benefit aspects.

Nine different joint projects are currently funded by the German Federal Ministry of Education and Research in the framework of the R&D programme GEOTECHNOLOGIEN.

Ute Münch
(Head of the GEOTECHNOLOGIEN coordination office)

Hans-Peter Harjes
(Chair of the advisory committee)

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MINE, Mining Environments: continuous monitoring and simultaneous inversion

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Abstract

Continuous monitoring of fracturing processes in mine environments and the consequent characterization of the damage induced during mining exploitation is of primary interest both for mining engineering and civil protection. The development of improved monitoring and imaging methods is of great importance for salt mines as potential reservoirs for CO_2 sequestration. Imaging tools able to handle continuous data streams and providing fast reliable information about stress perturbations and fracturing state will offer important new information to support local authorities in decision-making processes. The monitoring framework will manage continuous datasets, including acoustic, seismic, deformation and thermal data, give access to different inversion and modelling techniques. Continuous data acquisition and storage and automated routines for data analysis will be implemented to image the time evolution of 3D structures at a very local scale. Acoustic and seismic data, whose routinely use in mining survey is typically limited to estimate location and magnitude, will be more widely analysed thanks to full waveform analysis, learning from seismological applications at larger scales. Automated processing will include triggering, source location, moment tensor and extended source parameters inversion. This knowledge can be subsequently used to derive local stress perturbations. A set of different tools, based on statistical analysis of spatiotemporal crack distribution, will be applied to identify rupture clusters and fracturing processes. Local earthquake tomography, which couples source location and seismic velocity inversions, will be applied and interpreted to image the velocity structure. The inclusion of data from cavity deformation, thermal and chemical monitoring will complement acoustic and seismic information, providing a multidisciplinary dataset. The coupling of different data and joint interpretation/inversion methods within a common surveying framework will finally provide high-resolution 3D and 4D tomographic images of the mining area and a continuous monitoring of fracturing processes.

1. Introduction

Human activity and mining exploitation may produce significant damages to the surrounding rocks and locally induce seismic activity, with rupturing process scales ranging from mm-long microcracks up to hundreds of meters rupture lengths of induced earthquakes. It is important to monitor the dynamics of rupturing processes and the perturbation to the background stress field in order to detect weakened regions and evaluate risks of further dangerous ruptures or changes in hydraulic permeability. The development of new monitoring tools that are economically and ecologically rentable, able to handle continuous and multi-stream data processing, and derive underground models by a combined interpretation/inversion of different observations, would offer a chance to substantially improve the imaging of the subsurface 3D structure and permeability and its time evolution.

Common geophysical mining monitoring techniques include acoustic, seismic and deformation data. Acoustic data acquisition is done by piezoelectric sensors, which detect high-frequency radiation associated to microcracks. Geophones and broadband seismometers sometimes complement acoustic sensors to detect larger events. The standard approach of seismic-acoustic surveys consists of the analysis of discontinuous recordings, based on event triggering (e.g. JAGUAR project, deep gold mines in South Africa). Typically, only arrival time information is saved and only in rare cases, for larger events, short time windows are stored. Due to discontinuous and incomplete waveforms, data interpretation is often limited to source location and magnitude estimation. Limitation towards continuous recording related to computational requirements are nowadays overcome, as storage devices can now handle multi-trace continuous records for periods of some weeks. Continuous acoustic and seismic data would allow the implementation of automated full waveform analysis tools. Full acoustic waveform inversion can be used to derive source location, magnitude and moment tensor (e.g. Manthei et al. 2001).

Waveform modelling of seismic data is routinely used in seismological approaches at local to teleseismic distances. Real-time moment tensor solutions procedures are well established. Fast automated routines to derive extended source parameters have been implemented by German projects Kinherd and RAPID (Cesca et al. 2010, Heimann 2011). Applications in mine environments included source estimation of mining induced seismicity (Dahm et al. 1998, 1999, Fletcher & McGarr 2005). Local earthquake tomography (LET) is a powerful tool to invert the local 3D velocity structure and simultaneously improve hypocentral locations. Limits of LET applicability may arise by poor distribution of travel paths and significant diffractions at galleries. LET applications to mining monitoring are rare until now, but successful applications at local scale have been carried out. Mine environments, with small study regions and convenient receiver configurations, are a favourable case study to successfully implement these techniques. If source location, modelling and LET allow monitoring the time evolution of fracturing processes, stress inversion is helpful to evaluate further rupturing risks. Stress field data, based on average regional scale estimations, have been included within mine models. However, local stress perturbations, which are likely to be significant in highly heterogeneous ruptured regions, are typically not considered. Seismic source modelling provides valuable information to estimate local stress perturbations. Existing tools for stress inversion, developed within the field of local-scale seismology, can be adapted for mining applications (Maxwell & Young 1992, Marsan et al. 1999, Urbancic & Trifu 2000).

Information concerning induced seismicity can be also learned by statistical analysis of detected events, following acoustic and seismic triggers. A wide set of statistical techniques have been implemented, providing a standard and useful approach to evaluate acoustic emission in mines. Spatial and temporal event clustering and anomalous behaviour of induced seismicity indicators, such as the b-value (Hainzl & Ogata 2005, Becker et al. 2008), can be derived by statistical analysis.

Finally, additionally available datasets including deformation, thermal and chemical monitoring should be coupled within a common monitoring system. Free surface and internal deformation, recorded by GPS sensors and strainmeters allow the monitoring of surface, cavities and tunnel deformations. These data may help to constrain seismic data and acoustic emission interpretation. Thermal survey is often carried out at mines to preserve structural conditions. Small temperature variations may be related

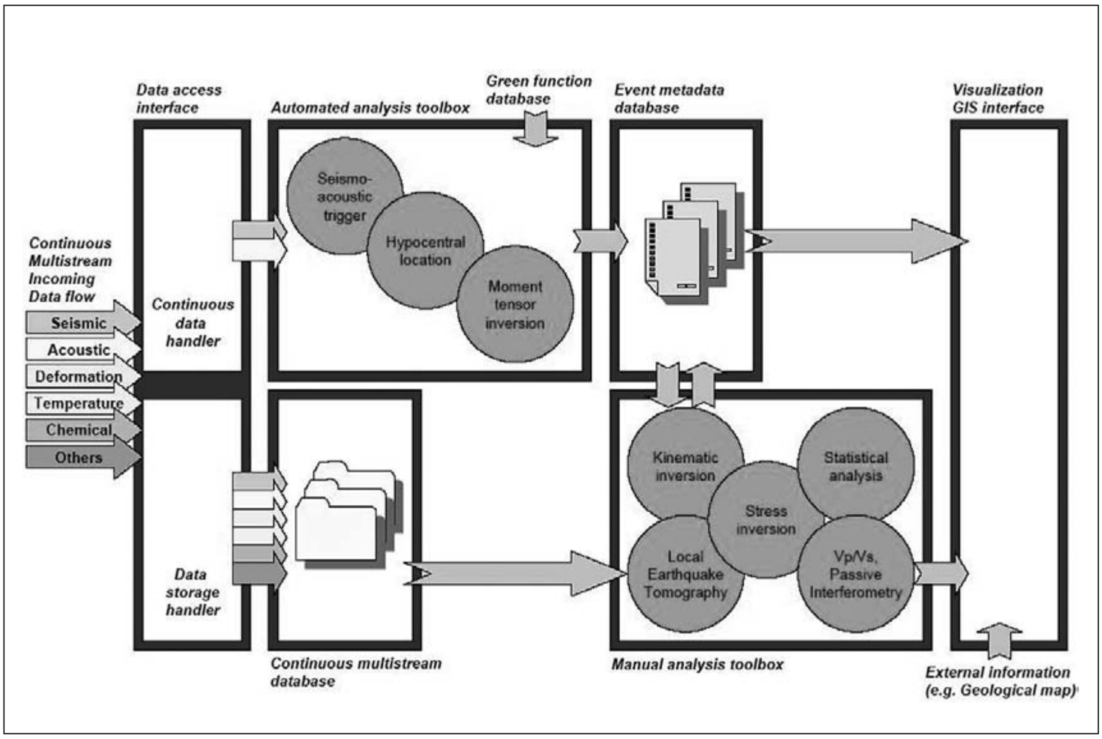

Figure 1: Planned structure of the MINE toolbox

to mining activity and stress perturbations. Chemical and radioactive survey may add information to detect degassing activity and may complement the information concerning the dynamic of fracturing processes.

2. Objectives

We plan to develop a new framework for the access, processing and analysis of continuous multi-stream data in mining environments, with the final purpose of monitoring and evaluating the fracturing process and the stress field evolution at a very local scale.

Developed package modules will provide opportunity for future extensions and inclusion of other data streams. Algorithms portability, parallelization and respect of standard data exchange protocols will be accounted, in order to ensure easy implementation and usage of the package. The package structure (Fig. 1) planned for an extended duration of the project of 6 years will include the following components: data access interface (acquisition of continuous multi-stream data), Green's functions database, event metadata database, continuous multi-stream database, manual and automated analysis toolboxes, visualization interface.

3. Project structure and collaborations

The project is structured in 4 Work Packages (WPs); 4 research positions (1 leading scientist, 3 PhDs) are encharged for the scientific and technical aspects of each WP. Researchers also act as link with our scientific partners. Main tasks, research lines and preliminary results of each WP are summarized at the end of this report. PhD supervision is carried out in collaboration with different partners (Fig. 2).

The collaboration with partner institutions and the private company GMuG will ensure data availability to test developed tools. We have identified different mines as possible test locations. Salt mines data access will be granted by collaboration with the Bundesanstalt für Geowissenschaften und Rohstoffe (BGR) and

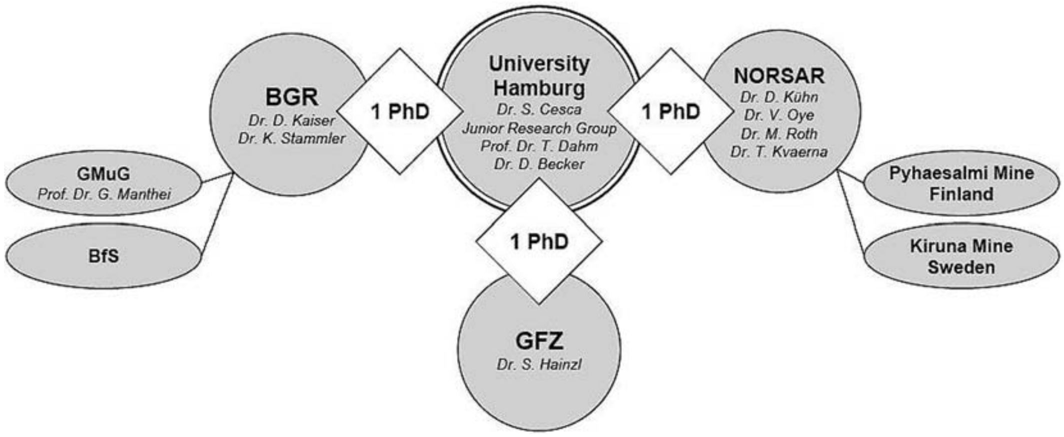

Figure 2: Structure of the Junior Research Group and planned collaborations

the Bundesamt für Strahlenschutz (BfS). Iron ore mines will be monitored in collaboration with NORSAR. Reduced continuous datasets will be collected at different test sites to simulate real time applications with continuous data streams. The collaboration with GMuG in data recovery and software development will ensure private company participation and promote further implementation of the developed package within industry.

4. WP1 Automated event detection and location in mining environments using continuous multi-stream waveform data

4.1 Introduction

Locally induced seismic activity involves a range of rupturing process, with spatial extensions varying from mm-length microcracks to hundreds of meters rupture lengths of induced earthquakes. Under such circumstances, it is important to continuously monitor the time evolution of rupturing processes. A detection of all range of events, an early location and an event characterization will allow for the detection and imaging of weakened regions, which is needed to evaluate risks of dangerous ruptures at both the underground mining area and the upper surface. The development of new monitoring tools, able to handle continuous records and multi-stream data processing would offer a chance to substantially improve the tomographic imaging of the subsurface 3D structure and its time evolution.

A significant improvement of detection and location techniques, as well as the combination of different approaches, can provide an early image of the local seismicity and its evolution. The combination of the location information with tools for a fast characterization of seismic event, as recently derived within the BMBF/DFG Exupery project, may then provide a first tomographic image of the mining structure, indicating areas were major weakening occur and different fracturing processes taking place. In order to use location and event characterization (including magnitude estimation) results with a tomographic aim, the first main goal is to derive specific tools focused on the generation of a complete seismic catalogue. The generation of such a complete catalogue within mining environments has to account for different problems. First, it requires tools for the detection and location of a range of different fracturing process and events magnitudes, possibly combining the information retrieved using different sensors. A second problem concerns the detection and identification of different events occurring within a short time gap, which can be significant in mining environments, owing to the possible presence of crack migrations. Finally, the identification and early characterization of different kind of events (e.g. creeping, crack processes within fractured fluid-filled host rocks), which may not be identified by standard triggers depending on their slower rupturing processes and/or the absence of sharp onsets, may increasingly complete new catalogues. The adoption of a continuous recording approach would give the opportunity to develop different detection and location techniques, based on full waveform, which are better suited to solve some of the highlighted problems. Novel full waveform location techniques have the potential for automated triggering and location applications, and has never been applied neither within mine monitoring nor to a 3D problem.

4.2 Detection and location of microearthquakes in a gas field using a single borehole array

The techniques previously described can be applied in other contexts, such as microseismic monitoring of reservoirs. To show the applicability of such methodologies, we developed specific applications to analyse a microseismic dataset from a gas field in Northern Europe. In the beginning of the project, we focus on the problem of detection and location of induced microseismic events at gas fields. Detection and location of microseismicity are important challenges in reservoir monitoring and characterization. High resolution location allows to estimate the distribution and the orientation of the faults and pore pressure changes inside the reservoir. Standard location methods use only arrival times of the main phases (P and S) of a seismic wavefield and can be succesfully used when these phases are clearly observable. If a dataset is mainly composed by small seismic events with low S/N ratio, these methods may have a poor resolution, and the problem of correct picking of P and S phases is non trivial. Our goal is to develop an automatic, picking independent, earthquake location method that make use of all the information contained in a complete seismic waveform (full-waveform approach).

For our intents we used one month of continuous data recorded using a single vertical array of 90 m, with six three-component geophones deployed at the end of deep borehole at about 2 km of depth. A software module for the detection of seismic events was first implemented, adopting a recursive STA/LTA algorithm (e.g. Withers et al. 1998) of the total energy trace to pick the first P-phase arrival. The cumulative envelope function (Baranov 2007) is used to set the ending time of the event. In this way we avoid to pick later phases and obtain a rough estimation of the duration magnitude of the seismic event. Since the sensors are not aligned and their absolute orientations are not known, sensor are aligned using an innovative technique based on a complex linear least square method.

The geometry of this network requires the development of an "ad hoc" location technique. We use polarization analysis to overcome the ambiguity of the azimuth and full-waveform inversion to improve the resolution of the location. To test the reliability of the methods, the alignment and location techniques are applied to synthetic and real data, and results compared to those obtained with other techniques.

4.3 Preliminary results

The STA/LTA is first applied to the total energy trace and then the relative characteristic function is computed. A STA/LTA recursive algorithm was chosen, because the exponential decaying impulse response was suitable for detecting purposes and requires less data storage. When an event is detected, the trigger algorithm should be temporarily interrupted to avoid more picks than the first arrival. To overcome this problem, we used the cumulative envelope function that allows to estimate the ending time of the event when this function become non positive.

The determination of the absolute and relative geophone orientations is a common problem that affect acquisition procedure of borehole data. Standard techniques used to solve this problem are generally based on polarization analysis or signals cross-correlation. Here, we

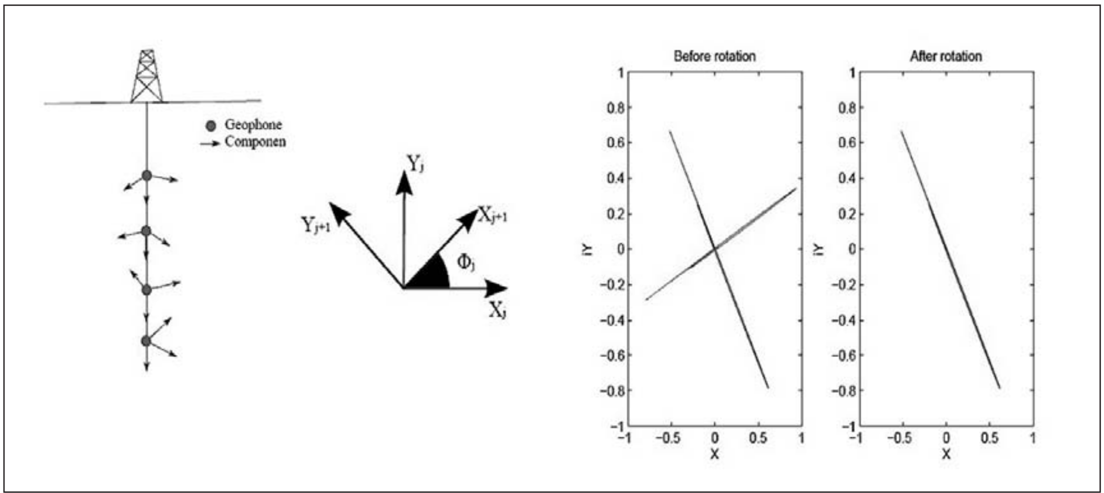

Figure 3: Receivers geometry (left), sketch of the inversion problem (center) and rotation results (left, complex trace hodograms show the polarization of the signal at two different sensors, before and after the rotation is performed).

present an alternative method using a complex algebra approach. In the Complex field, a two dimensional vector can be written as a complex number whose real and imaginary parts are respectively components of the vector itself. Rotations can be performed by simple multiplication of the complex number itself with a complex exponentials whose phase is the rotation angle. Defining the "complex trace" as a complex valued vector whose real part is the X-component seismic trace and the imaginary part is the Y-component seismic trace we can apply these concepts in order to align multi-component seismic traces.

Synthetic tests have been performed first, using the E3D software to generate a synthetic dataset with a borehole-type acquisition geometry. Satisfactory results have been obtained, by applying the developed method to align sensors with respect to a reference one (Figure 3). The polarization analysis of the stacked trace can then be used to derive the backazimuth and reduce the location problem to the bidimensional case (distance-depth). Currently, the last step of the location, using full-waveform to locate the event in the 2D case is being developed.

5. WP2 Source characterization of micro-seismicity in mining environments

5.1 Introduction

Earthquake source characterization is important to detect fracturing and shear processes, understand local seismotectonics, correctly evaluate stress field perturbations and early predict fracturing risks associated to seismicity. The development of fast automatic routines for the retrieval of point source parameters of medium to large earthquakes was convincingly established within the last decades, for tectonic earthquakes at teleseismic and regional distances. Further extension to small scale problems have been investigated in a wide range of environments, including seismic activity at volcanoes, mining induced seismicity, and induced seismicity in salt rock.

The standard approach to describe the seismic source is by a point source, using a moment tensor representation. Moment tensor inversion techniques include a variety of approaches. In addition to point source parameters, recent studies (Cesca et al. 2010, Heimann 2011) have successfully investigated the possibility of fast and automated kinematic inversions. Source inversion problem in mines are complicated by the heterogeneous velocity structure and the small size of acoustic emission and microcrack sources. While geophones and seismometers can record low frequency waveforms, which may be well reproduced with standard 1D earth models, high-frequency records are affected by structural heterogeneities (see Kühn et al., 2009). Modelling and inversion of these waveforms require prior computation of GFs and synthetic seismograms for specific 3D models. In particular, when focusing the application towards mine environments monitoring, void spaces (cavities and galleries) should be considered. The recent implementation of a 3D finite difference code and an eikonal solver H. N. Garti at our partner institute NORSAR provide specific tools which can be used for the quick generation of GFs. The code quickness enables its implementation for the generation and further modification of the GF database, which is important at mines, since mining activities may significantly affect the 3D structure of the area with time.

5.2 Coal mining induced seismicity at the Ruhr region

Coal mining in the Ruhr region, Western Germany, has been monitored continuously over the last 25 years by the Ruhr University Bochum. About 1000 seismic events with local magnitudes ML between 0.7 and 3.3 have been located every year. In 2006 a dense temporary network (HAMNET) was deployed to monitor the active longwall mining close to the town of Hamm. The HAMNET network includes 9 short period and 6 broad-band stations. From July 2006 to July 2007 more than 7000 events with magnitudes ranging from ML -1.7 to 2.0 were located with this dense network configuration. Out of this dataset, more than 900 events have magnitudes equal or larger than 0.0. Source depths are constrained in a narrow band, centered at about 1km depth.

Epicentral locations and depths mostly correspond to the region of active longwall mining. However, different clusters at further distances have also been observed. The spatial and time distribution of induced seismicity show a high correlation with the mining activity. We perform a moment tensor inversion for the largest recorded events, using a full waveform inversion technique and double couple constrain. We first generated Green functions databases for different 1D layered models.

The Kiwi inversion tools, which were developed and successfully applied in recent years to perform moment tensor inversion at regional and teleseismic distances, have been adapted here to carry out the inversion at a local scale (the maximal source-receiver distance is 3km). It is done tests to determine the suitable model and bandpass range. The inversion is carried out at different steps. First, a frequency domain moment tensor inversion is performed, fitting amplitude spectra of the full waveforms at frequencies between 0.1 and 4Hz. Then, a time domain inversion is used to solve the polarity ambiguity and to determine the best centroid location. As a result, we obtain information about the centroid location, source depth, scalar moment and best double couple (DC) focal mechanism.

5.3 Preliminary Results

Before applying the inversion to a larger dataset, we tested different velocity models and range of frequencies using a subset of events (2 months, 58 events). In this way, we investigate the performance and stability of the inversion approach.

(a) A layered model shows a consistent better performance than a homogeneous velocity model. In the following we use only the layered model.
(b) Inversion stability and quality of fit are best for frequency in the range 0.5 to 4 Hz. We choose to adopt 2 frequency ranges (0.5-2Hz and 1-4Hz) to investigate focal mechanisms of event in the magnitude range Ml 0,5-2,0. This choice limits the inversion to broadband station data only.

We then processed 12 selected events. Only solutions showing an amplitude spectra L2 misfit below 0.5 have been considered. Results

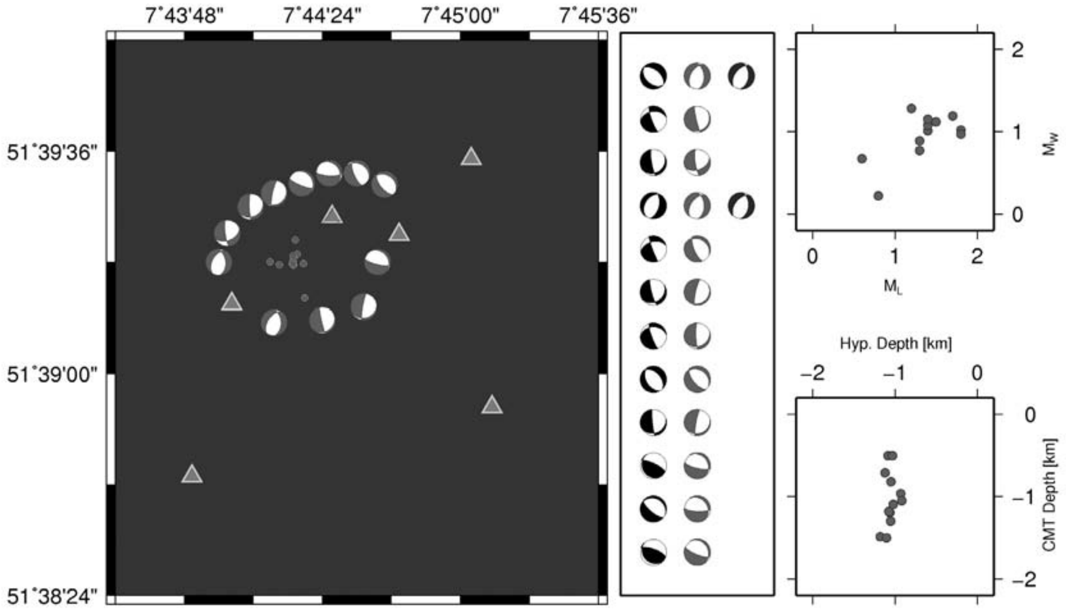

Figure 4: Comparison of 12 event results. Reference solution (left), full waveform inversion at 0.5 – 2.0 Hz (middle) and 1 – 4 Hz (right)

are summarized in Figure 4, and indicate low misfits and general agreement with reference solutions.

6. WP3 Statistical analysis of seismic catalogs in mining environments

6.1 Introduction

The imaging of stress perturbation and weakening zones and its time evolution, thus a 4D stress tomography, is extremely important for a safe monitoring of mining environments and an efficient hazard assessment at different time scales. Detection of daily/hourly stress perturbation, for example, may be used within short time scale decision-making processes, in order to secure the safety for workers. Long-term stress variations on the other hand may indicate the beginning of mining activity in a structurally instable part of the mining and may used for further planning. Finally, precursory stress localizations might be indicative of subsequent bursts or rock-falls.

The imaging of rock damaging at the first step will carried out on the base of statistical analysis of seismicity spatialtemporal evolution, clustering and event characterization. Local seismicity can be studied using statistic approaches by analysing standard indicators, such as the b-value or the volumetric release of seismic moment. Statistical and clustering analysis for different event subsets can support new information. Stress modelling and aftershock evaluation can be study based on the results that would be provided by statistical studies. Apart from the analysis of seismicity patterns, stress inversion can be also carried out based on focal mechanisms determination. The provision of focal mechanism information by WP2, would make possible the adoption of a similar approach and the combination of the two stress inversion methods (based on seismicity and focal mechanisms) resulting finally in a joined stress inversion and 4D tomography.

Goals of Work Package 3 are to establish and carry out a multi-step analysis, using seismic, acoustic and deformation data, which will finally bring to a 4D stress tomography tool. In the first step we have focused on seismicity studies in mining environments using real and synthetic catalogs.

6.2 Mc and b-value estimations

The size distribution of earthquakes in a seismogenic volume can often be adequately described over a large range of magnitudes by a power law relationship. The commonly used form of the power law relates the cumulative number N of earthquakes with magnitude equal or above M, and constants 'a' and 'b'. The parameter 'a' describes the productivity of a volume, while 'b' describes the slope of the frequency-magnitude distribution (FMD). The first step in this WP is extracting information on the b-value in mining environments. The minimum magnitude of complete recording, Mc, is an important parameter for most studies related to seismicity. Mc is defined as the lowest magnitude at which most of the events in a space-time volume are detected. It is well known that Mc changes with time in most catalogs, usually decreasing, because the number of seismographs increases and the methods of analysis improve. If a seismicity dataset strictly follows the Gutenberg-Richter law, Mc can also be defined as the magnitude at which the cumulative Frequency-Magnitude Distribution departs from the linear trends. In order to derive the b-value in the region of study, we first estimate Mc with different methods. Different techniques have been tested so far to derive Mc and b-value of seismicity catalogs. These include the maximum curvature technique (MAXC), the Goodness-of test (GFT), the Mc and b-value stability method (MBS) and the Entire-magnitude range technique (EMR). All these methods have advantages and disadvantages, and the adoption of a specific method may be recommended, depending on which type of catalogue is used. In general, different techniques may give different estimates of the completeness magnitude.

6.3 Preliminary results

At now, the mentioned different methods have been applied to derive Mc and b-value from different catalogs. First, the developed algorithms have been tested on synthetic catalogues (with and without noise). Tests were successful, and catalog parameters could be satisfactorily retrieved for both catalogs. At a further stage, the methods have been applied to a real catalog from a mining region. For this purpose, we use a data catalogue from Pyhäsalmi ore mine in Central Finland. This is the oldest operating metal mine in Finland and the deepest in Europe extending to a depth of 1441 m. Data are recollected and provided by NORSAR, that performs a microseismic monitoring, using 18 sensors, including 6 three-component stations, leading to source-receiver distances of 60 to 400 m. The network has been operational in a continuous mode since January 2003. Until March 2004, about 18,000 events were detected. About two thirds of those events were identified as mining blasts, the remaining events are microseismic activity. The range of magnitudes is -1.8 to 2. Because of some gaps in the catalog, we focus on a one-year subset from 01.08.2003 until 31.07.2004. Additionally, we have tested our analysis with two synthetic catalogs which resamble location and magnitude range of the real catalog.

7. WP4 Local earthquake attenuation tomography in mining environments

7.1 Introduction

The development of tomographic methods cover a wide part of seismology and in the last decades a large effort was done to develop and apply tomographic methods at very different spatial scales, ranging from local applications, able to image limited regions to teleseismic application to resolve the whole Earth structure and long time scale processes. The resolution of structural details is important to better determinate physical phenomena occurring at depth, and to evaluate transient processes. Tomography applications at mines may be then used to monitor fracturing processes and fluid migration, which is important for the hazard assessment, within the goals of the MINE project. Local earthquake tomography (LET) can be combined with active seismic tomography for the planned application, using waveforms generated both by microseismic events and mining blasts. Different LET approaches have been developed to either resolve the velocity or attenuation structure. Both attenuation and velocity anomalies may reveal fractured regions and fluid presence. Attenuation tomography is of special interest here because it can image fractured regions, which we intend to monitor. The attenuation of seismic waves when travelling through fractures and fluid-saturated rocks is generally higher than in dry rocks in most of the frequency bandwidth, and changes in the spectral and amplitude characteristics of the seismic signal have been associated with the presence of fluids and fractures. Laboratory measurements of wave attenuation have been performed at several frequency levels, generally showing how factors such as porosity, permeability, and clay content are responsible for wave attenuation (Del Valle-García & Ramírez-Cruz 2002). The basic data for studying the attenuation structure are the Fourier amplitude spectra of seismogram phases, the phase amplitudes on filtered waveforms using different range of frequencies, and the pulse width of seismogram phases (Iyer & Hirahara, 2001, and references therein). The availability of information concerning the seismicity (WP1), the focal mechanisms and the adopted 3D velocity structure (WP2), may be used to further develop full waveform tomography techniques. If tomography has been one of the main research field within seismology, mining applications have been mostly confined to controlled-source tomography, with most applications only involving the processing of arrival times of direct waves.

The potential of tomographic application in mining exploration has been investigated to identify different ore structures. The planned application has indeed a different aim, being focused on the identification of weakened and fractured regions, which could provide advance warning of mining hazards, or the early detection of regions of stress concentration, which may be indicative of rock burst risks. In this sense, a successful application was carried out by Cotten & Geldmacher (1990) at the Illinois basin, where a reduction of seismic velocity was identified and associated to a limited region of structural weakening above a worked coal seam, whereas a region of stress concentration (higher seismic velocity) was detected above the caved zone.

7.2 Preliminary results, adaptation of attenuation tomography techniques to mining areas

We are in the process of adopting and we plan to further develop local earthquake attenuation tomography methods, including the information provided by full waveform acoustic and seismic data. The application of these methods to the different datasets will provide tomographic images of the mining attenuation structure, which can be then interpreted in terms of the dynamic of fracturing processes. As a starting point, we are adapting and implementing a methodology based on the spectral ratio approach, as described by Monna and Dahm (2009), who successfully modelled the regional crustal structure beneath the Thyrrenian sea (Monna and Dahm 2009).

Acknowledgements

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Seismic Observations for Underground Development (SOUND)

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Objectives and Concept

In the past decades, a rapid progress in tunneling and underground construction has taken place. Large-scale projects of long distances (tunnels >50km) and large diameters (>13m) are currently planned or realized. Many of these projects are located in geologically complex areas or under a thick overburden. Consequently, a detailed geotechnical exploration and rock mass classification in the run-up to the construction work is possible to a limited degree only. Such large-scale projects as well as underground construction in urban areas (with diverse and mostly small-scale obstacles) require technologies for high-resolution prognosis. To this end the new technologies need to be integrated into the tunnel boring machine (TBM) or the conventional drill-and-blast method. In recent years the technical pre-conditions for the realization of seismic measurements have been established. The technological requirements for an efficient seismic exploration in tunneling are mainly brought into existence (e.g. during the former GEOTECHNOLOGIEN projects OnSITE and AUTOSEIS). However, futher research is needed to achieve a sound tomographic imaging of the underground constructions` near field. Here, high-resolution seismic measurements have got the potential to provide essential information about the mechanical stability of the tunnel wall and face in a fast and non-destructive way. To this end elasto-dynamic properties of the rock can be determined via wave propagation velocities of the P- and S-wave that in turn are estimated by analyzing the direct wave or surface waves. These methods enable us to map existing tunnel walls with relatively small effort and to identify potentially risky sectors before damage occurs.

We will focus on:

(a) the development of new imaging and inversion strategies and

(b) on the optimization of acquisition strategies.

As to (a) we will focus on reflection tomography and the integration of geophysical and geotechnical parameters and regarding (b), the emphasis lies on the utilization of noise from the TBM as a source on the one hand and the provision of optimized broad band seismic sources on the other hand.

State of the Art in Science and Technology

During the projects AUTOSEIS and OnSITE hardware for seismic acquisition on TBMs was optimized and modeling as well as data processing steps have been developed. The latter two have improved our understanding of the seismic wave field behavior around tunnels substantially. Apart from some smaller attempts to apply geoelectric measurement techniques, research and development in the past years have concentrated on seismic methods. These show high resolution and broad coverage and are additionally applicable in damp and reinforced (TBM, reinforced concrete lining) environments.

In tunneling several exploration methods are known. The „Tunnel Seismic Prediction" (TSP) System from Amberg Technologies AG has been developed for the drill and blast method in hard rock tunneling with an open TBM (Dickmann & Sander, 1996). The „Sonic Softground Probing" (SSP) System from Herrenknecht AG (Kneib et al., 2000) consists of sources and receivers that are integrated into the TBM cutter head. It is mainly used in tunneling with mixed shields in water saturated soft soils. The „Tunnel Reflection Tomography" from NSA Engineering Inc. used to apply the drilling noise of the TBM cutter head (Neil et al., 1999), as does the „Tunnel Seismic While Drilling" technique (TSWD) (Petronio et al., 2007). So far, experience with the utilization of drilling noise has shown, that the localization of the noise proves difficult and that the signal is dominated by relatively low frequencies (dominant frequencies of under 100 Hz for distant receivers) leading to a poor resolution (Brückl et al., 2008). At the German Research Centre for Geosciences (GFZ) the concept of an „Integrated Seismic Imaging System" (ISIS) has been under development since 1999. The development is carried out in close cooperation with partners from the industry and scientific institutes (Borm et al., 2000, 2003).

The most important components of the system are pneumatic hammers acting as seismic sources, geophones that are integrated into rock anchors and a processing- and interpretation system. Latter is based on the concept of tunnel surface waves that are converted to shear waves at the tunnel face (Lüth et al., 2008b, 2008c, Bohlen et al., 2007). This system is patented and currently being further developed for commercial application by Herrenknecht AG in cooperation with the GFZ. The components of ISIS are also applicable to the investigation of the underground construction near field by means of high-resolution reflection seismic or tomographic analysis due to the modular construction of the system. This field of application has been demonstrated in several surveys in the Gotthard basis tunnel (Giese et al., 2005, 2006). The system has also been tested at a tunnel construction site in soft rock with segmental lining. The results show that under these circumstances a mechanical coupling between sources and receivers on the tunnel wall on the one hand and the host rock on the other hand, can be established as well (Lüth et al., 2008a).

Technical and methodical developments in the past years allow for the implementation of seismic exploration of the tunnel near field. Generally, tomographic methods (refraction waves and transmission measurements) and seismic reflection imaging are used respectively (Giese et al., 2006, Lüth et al., 2008b). The technical realization has focused to a great deal on the implementation of in-house production (high frequency) signal sources as the reproducibility of the signals was a primary objective. Even though, various application trials with different tunnel advance methods using this concept have shown a high variability of the coupling conditions depending on the surrounding geology and the applied tunnel advance method, respectively. For a reliable imaging of the tunnel near field of an underground construction site a good signal quality and also a high data coverage in the space domain is important. This can be achieved by using the constructive overlap of as many measurements as possible.

In machine driven tunneling the cutter head of the tunnel boring machine can be regarded as a source with the highest possible coverage of measurement points as it is by definition active along the entire tunnel length. The technical design that evolved from the GEOTECHNOLOGIEN project OnSITE is aimed primarily at the seismic acquisition with active sources but also allows for a mostly automated „passive" acquisition with the TBM-cutter head as a seismic source (Fig. 1). In Figure 1 the general set-up of the source and receiver geometry for "passive" (at the cutter head) in comparision to „active" (at the tunnel walls) measurments is delineated.

LIAG extended the use of the vibroseis method for high resolution shallow targets since 2000 to shear wave applications (Polom, 2003), including the development of hydraulic and electrodynamic seismic sources. In 2002, GFZ and LIAG ratified a co-operation contract regarding a joint venture in the development of high frequency vibratory sources for hard rock and high resolution applications. First results of this joint venture are published in Polom et al. (2003) and Polom et al. (2004). Latest developments in magnetostrictive actuator control improvements are published in Hock & Polom (2008). A pilot project of an automated seismic monitoring system for tunnel applications has been published for the first time in Lang et al. (2009) using a LIAG developed shear wave source.

There is no direct link of the seimsic systems in use to geological and geotechnical data from preinvestigations or the logging of technical parameters of the tunnel boring machine (penetration, cutter head torque, or thrust force). To gain broad acceptance for geophysical exploration it is essential to convert geophysical results into a geotechnically relevant form. This may be achieved by means of data mining and pattern recognition algorithms that are linking the seismic data with rock mass classification systems (Q- or RMR-system) or primary rock mass characteristics (i.e. UCS) and TBM control parameters. The incorporation of the latter is important as the rock mass class might be estimated on the basis of TBM parameters in automated tunneling (Mitterlechner et al., 2007, Ribacchi & Fazio, 2005) and subsequently might be used when first-hand geological data is not available. As more and more tunnels are built in closed mode excavations the importance of TBM parameters for the interpretation of seismic results increases.

Project Structure

The collaborative project SOUND is subdivided into three working packages (WP) that build upon a common basis of acquisition and interpretation techniques.

- **WP 1** concentrates on the seismic and geotechnical exploration in tunneling.
- **WP 2** investigates the acquired data by means of inversion techniques that in one part are already existing and to another part will have to be further developed in cooperating projects (GEOTECHNOLOGIEN Project TOAST).
- **WP 3** provides seismic sources that allow for a broad band signal generation for high resolution tomography in cases where the utilization of TBM noise is not possible.

Geotechnical Characterization of Seismic Measurements and Technical Control Parameters (WP 1)

At the moment, mainly specialized active sources are used in the seismic exploration of tunnels as the usage of drilling noise bears uncertainties in the localization of the noise. Additionally, only low resolution has been achieved so far in surveys using the drilling noise. In WP 1 the acquisition techniques provided by ISIS will be used to realize cost effective passive acquisition campaigns on tunnel construction sites. The advantage of the ISIS-technology in comparison to hitherto applied techniques is that it can be integrated into the construction work without great logistical difficulties (Fig. 1 and 2). During the „TSWD-Campaigns" that where carried out so far, the seismic receivers were installed several hundred meters away from the cutter head. Now with the ISIS-technology we have the possibility to record the wave field in the immediate vicinity of the rock mass under investigation. Previous tests have been acquired with relatively long offsets of the seismic signals. This has put increased emphasis on low frequencies and thus reduced resolution (Brückl et al., 2008, Petronio et al., 2007).

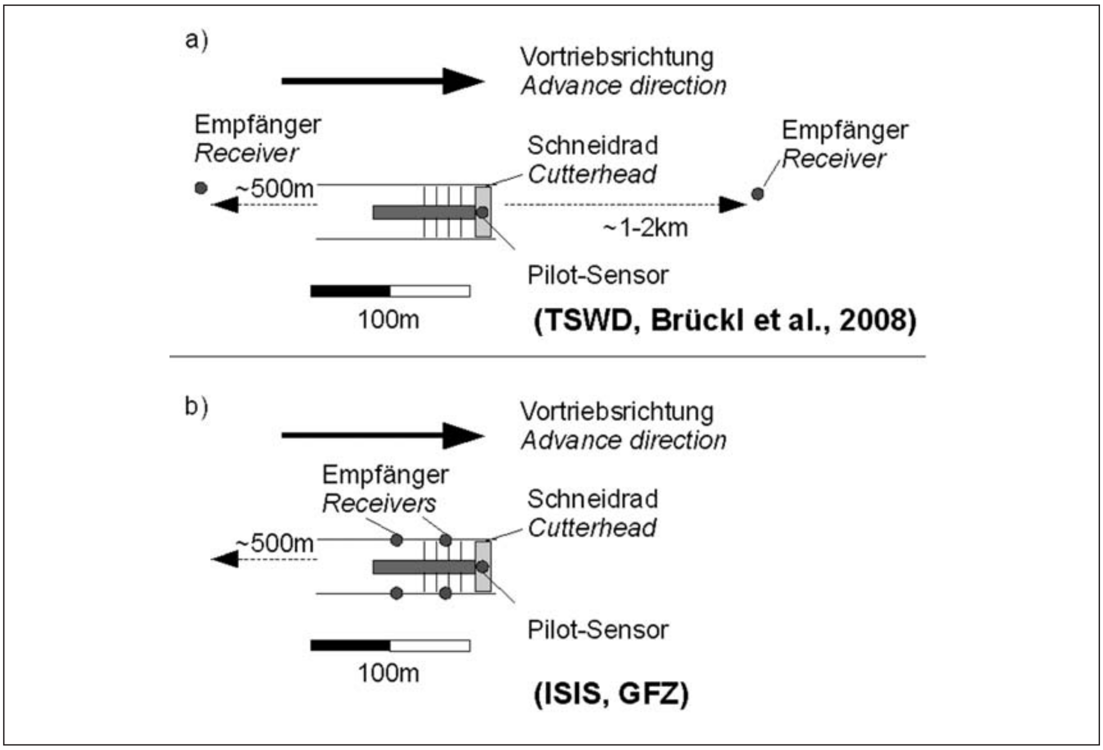

Figure 1: a) Typical acquisition geometry of „Tunnel Seismic While Drilling" (TSWD, after Brückl et al., 2008). A pilot-sensor is mounted at the tunnel boring machine close to the cutter head. Further receivers are mounted in tunnel adits or at the earth surface, resulting in offsets of several hundred meters.

b) Typical acquisition geometry for reflection tomography with ISIS. A pilot-sensor is again mounted close to the cutter head. Further receivers are mounted at the tunnel wall up to 50-100m behind the cutter head (far closer than in the set-up in a).

As a matter of principle the ISIS-technology can be used jointly with active broadband sources for the tunnel near field and passive source-signals from the TBM with higher coverage but slightly less resolution. New data processing steps are going to be developed that will particularly allow for the extraction of high frequency reflection signals from the tunnel near field. The objective of the development is a seismic system working continuously and in real-time with automated imaging. The modular hard ware components of ISIS allow for a quality in the data acquisition, that could not be reached in former attempts on continuous recording.

For the interpretation of the seismic data the simultaniously logged TBM-parameters are used as a basis for the verification of the results. Here, we revert to developments within the framework of the OnSITE project (Rechlin et al., 2009) that will be optimized in this project. The driving parameters of the tunnel boring machine are usually logged continuously at a 10s-interval during every tunnel construction leading to a huge amount of data. In this working package the exploration during tunnel advance by means of the cutter head shall be integrated into the ISIS-package (Borm et al., 2003). Against this background we pursue the strategy to enable seismic exploration as independently from the advance method as possible.

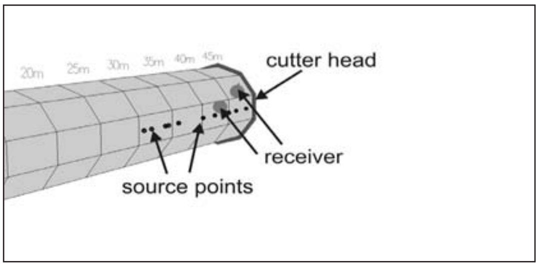

Figure 2: Measurement geometry in the seismic tunnel exploration (ISIS). The receivers are installed few meters behind the cutter head. The source points (during the usage of an active source) are situated 20 to 30m behind the cutter head.

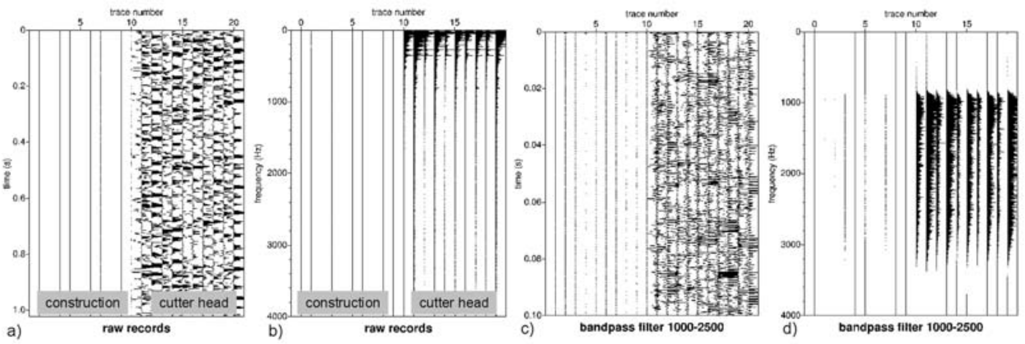

Figure 3: Seismic recordings from the construction site Neuer Schlüchterner Tunnel. a) Noise-recordings (radial component), unfiltered. The first 10 traces are recorded during the ring construction (installation of segmental lining). The traces 11 to 20 are recorded during tunnel advance (rotating cutter wheel). b) Amplitude-spectra of the data from a). c) Bandpass-filtered data. d) Amplitude-spectra from the filtered data in c).

Especially in closed mode advance with single- and double shield TBM an integration of additional active seismic sources is difficult. This is where the additional „passive" registration is advantageous. To this end the high-frequency signals need to be emphasized sufficiently though. The potential of passive measurements is pointed out in Figure 3. Here, seismic signals from quiet construction phases (ring construction) are compared with active tunnel advance (rotating cutter head). The active tunnel advance is mainly characterized by low frequency vibrations (f < 100Hz). but also contains a high signal strength in higher frequencies as becomes clear after filtering.

These high frequencies are suitable for high resolution exploration of the rock in tunnel advance direction. In the framework of a measurement campaign „passive" seismic monitoring data are logged. These consist of continuous waveform recordings during tunnel advance. The required technical equipment consists of 3-component receivers and a wireless data acquisition system. For this purpose the already established data acquisition system will be reprogrammed to a quasicontinuous acquisition (unlike the trigger-controlled acquisition with active sources). The data acquisition should be carried out over at least 300m to 500m, with about 2 month duration. The seismic recordings are subsequently processed with appropriate filter- and correlation techniques. Thus reflection signals are extracted and their attributes (i.e. envelope, instantaneous frequency, among others) are combined with TBM control parameters for an integrated rock mass classification.

High resolution tomography in the subsurface (WP 2)

A central position in this project is taken by the WP 2 as the seismic data from the TBM-acquisition (WP 1) and the broadband seismic sources (WP 3) are merged and subsequently analyzed by suitable imaging methods. However, a major element of WP2 will be synthetic wave field modeling. By means of 2-D and 3-D elastic Finite Difference (FD) methods, tunnel seismic data is gained which will be the first step of applying, adapting and developing imaging and inversion methods to reconstruct the geological structure of the tunnel surrounding.

The objectives of WP2 can be separated as follows:

1) Simulations of the elastic 3D wave field required for the support/understanding of the

passive seismic monitoring (WP 1) as well as the optimization of cascading vibration sources (WP 3). Beside of standard force applied at the tunnel wall surface, seismic noise excited by the TBM cutter head will be modeled.

2) Full waveform tomography of diving waves (P- and S-waves) and tunnel surface waves for high resolution imaging of the elastic parameters (P- and S-wave velocities, density, attenuation, possibly anisotropy) of the excavation damage zone (EDZ).
3) Application of an adapted reflection seismic body wave tomography and finally full waveform tomography. Thereby, high frequency body waves with a high resolution but small reach excited actively by controlled vibrator sources are combined with passive drilling noise of the cutting wheel with a smaller resolution but a larger reach.

The imaging potential of existing and new acquisition geometries will be investigated in very simplified geological settings as well as in realistic model scenarios with modeled data sets. The modeled data will be first processed with the common seismic processing methods and later on full waveform tomography. The results will then be compared with the input models. This is an important requirement to understand the properties of acquisition and analyzing methods with respect to their ability to image existing structures and the danger of giving artifacts geological or geotechnical importance. Basis of the modeling is a parallelized finite difference code (Bohlen, 2002; Sänger und Bohlen, 2004).

Beside the look ahead monitoring of tunnel excavation, the characterization of the surroundings in the underground becomes more important, particularly for existing older tunnels or galeries. For the stability of a subsurface construction, the development of the excavation damage zone (EDZ) due to the tunneling, for example, is important. For older constructions, repeated investigations to assess long-term damages are important to define the requirements of restoration or reparation. In this context, a fast and non-destructive monitoring method is necessary. Measurements along seismic profiles potentially with fixed installed sources and/or receivers can be an attractive alternative to exploration wells if suitable tomographic analyzing methods are available to evaluate the measured data in a short time and to illustrate the results in terms of geotechnical relevant models. Especially the tomographic inversion of diving waves and surface waves allowing the reconstruction of several elastic parameters of the excavation damage zone with high resolution will contribute together with geological mappings of the tunnel wall and the monitoring of the TBM-parameters to an improved geotechnical characterization of the direct surroundings of the tunnel.

Some first results of the 3-D seismic wave field modeling are displayed in Figure 4. On the basis of a random media model that accounts for both small and large scale heterogeneities in the elastic parameters a simplified tunnel model has been created (see Figure 1. a and b). A lithological boundary is dipping at a low angle with respect to the tunnel axis (yellowish color). The tunnel (dark blue color) is surrounded by an excavation damage zone (halo around the tunnel tube). The tunneling is simulated by an advancing tunnel face that is approaching the lithological boundary. For each tunnel face position, wave propagation is simulated while the source position is progressing as much as the assumed tunneling is. The corresponding seismic common-source-gathers for both, the tunnel face at position 40m and 100m are displayed in Figure 4 a-b. Please note, that the receiver lines are covering the whole model in length. For a realistic data processing an offset range within the tunnel is selected.

Common seismic processing as well as available full wave tomography tools are currently implemented in 2-D. For comparison, a separate 2-D wave simulation on the basis of the same model and measurement geometry has been performed. The immediate first step is

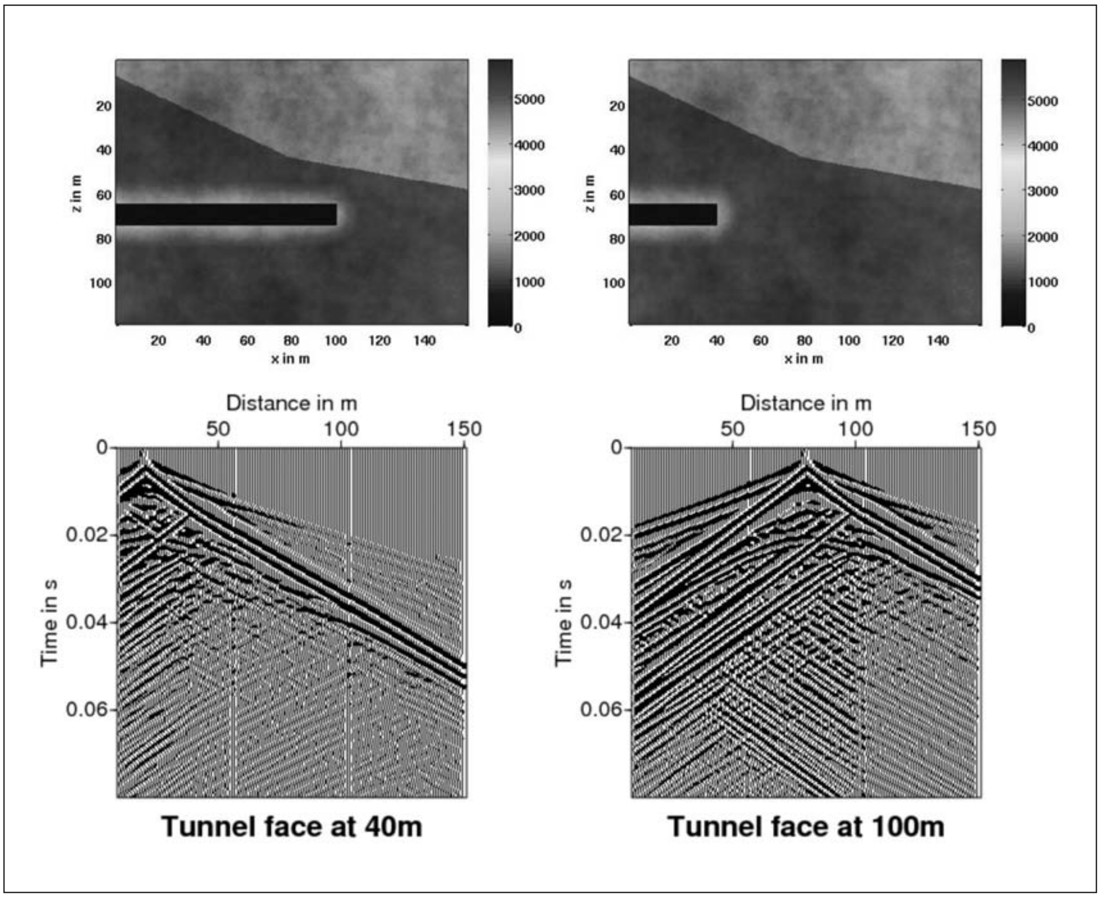

Figure 4: 2-D slices of a 3-D p-wave velocity model with a tunnel face position of a) 40 m and b) 100 m, respectively. According to these models a 3-D elastic wave simulation has been performed Receiver lines parallel to the tunnel axis record the wave field excited by a force source applied to the tunnel wall with a distance to the tunnel face of 20 m. Below, the common-source-gather of the vertical component (z-component) are displayed with a source position at c) 20 m and d) 80 m.

therefore a 3-D to 2-D correction of the seismic data. The standard seismic processing is independently applied to both field datasets. If the 3-D to 2-D correction is sufficiently working or the 3-D wave propagation effects can be neglected, the standard processing and even the full waveform tomography can be operated in 2-D as well. This will save both computational and developing time in order to adapt for the 3-D wave propagation.

Generation of broad band seismo-tomographic datasets using position-adaptive controlled vibration seismic souces (WP 3)

The WP 3 will improve and optimize the cascading vibroseismic actuator-system that has been established during the OnSITE project with regard to the target of a tomographic application. The system will be mainly implemented in safety-related and economically relevant enquiries. Possible fields of application include, e.g., the exploration of cavities, 3D-tomography between tunnels and adits as well as automated long-term monitoring with permanently installed systems. Especially the directed excitation of defined body waves (compression and polarized shear waves) will be optimized in cooperation with the WP 2.

Due to the theoretic full space approach, seismic tomography methods are a sophisticated methodic tool for exploration aims in an underground environment. However, from a practical point of view, all tomographic techniques based on travel time require highly reproducible signals of stable timing and steady wave forms. This fundamental condition is presented in many publications by images of symmetrically and equally spaced ray path diagrams combined with homogenious wavelet signatures. Is the target extended towards wave form analysis additionally, local influences of seismic source coupling need to be compensated for or even eliminated. These conditions can be achieved easily e.g. in medical computer tomography or in synthetic modelling, however, real conditions in underground construction strongly differ from these scenarios. Here, Ecavation Damage Zones (EDZ), heterogeneous surfaces, and highly variable surface pavements constitute leading edge technical challenges for the successful application of tomographic investigations.

The position-adaptive seismic vibrator source control system developed previously for amplitude and phase control of cascaded source systems offers seismic signal generation of a high-quality level, which is presently superior to all impulsive seismic sources available for underground construction investigations. The vibroseis method enables non invasive generation of precisely defined and reproducible seismic signals including the technical options of remote control and automated application. Based on realistic application conditions, the significant advantage of the method compared to a high quality impulsive signal generation has been demonstrated (Fig. 5). These source systems and their broad variability towards signal adaption represent a key technology for high-resolution seismic investigation in the environment of a so called »Excavation Damage Zone« (EDZ) and for the application on various paved surfaces in underground construction. Based on the modular concept, the system offers target-adapted high-resolution tomographic structure investigation in an underground construction evironment. To test the system and monitor time-variable changes in the rock mass, we will carry out a long-term field study in the underpround laboratory of the GFZ in the research and education mine »Reiche Zeche« in Freiberg. The study takes place during the drill & blast excavation of an adit with weekly blasta and just as many seismic measurments, starting in March 2011.

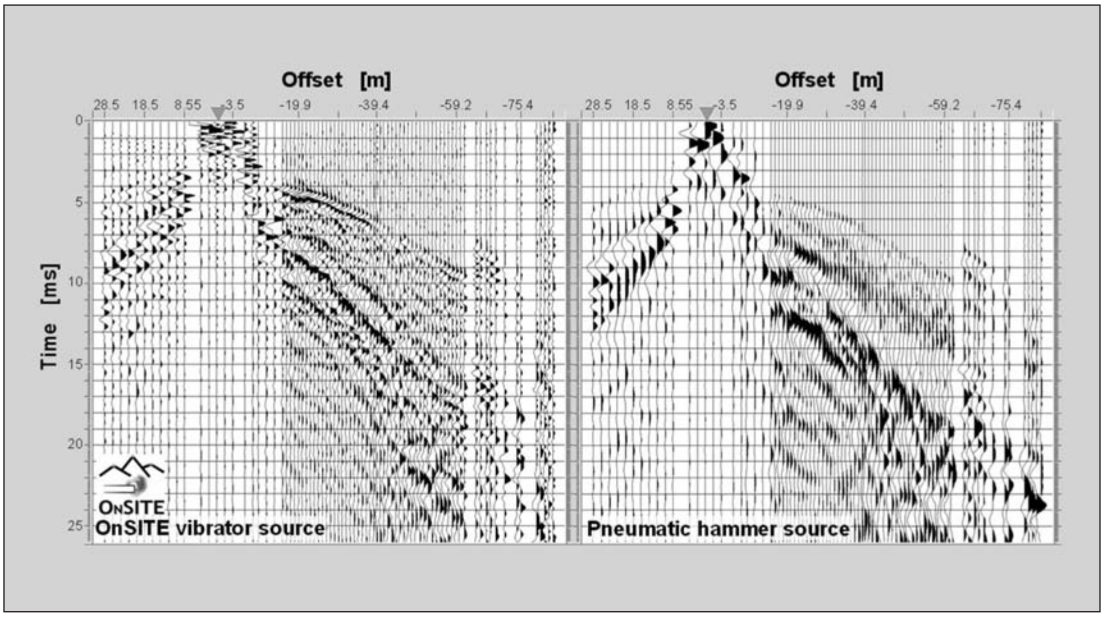

Figure 5: Comparison of seismic recordings using a vibrator source (left, OnSITE source) and a pneumatic hammer source (right, ISIS source) applied on a shotcrete paved surface in hard rock environment. (Piora adit, triangles flag source position). The vibrator source clearly achieves improved structure resolution for the whole section by excellent synchronous timing and clear reduction of absorption effects.

In the previous project OnSITE a target adapted modification was realized for the cascaded vibroseismic source system. Thus, the vibroseismic source can now be used to generate highly reproducible and time stable broad band seismic data sets from the environment of underground constructions. These datasets will be used for a verification of the tomographic inversion development and testing in WP 2 using body waves and surface waves.

Furthermore, modifications should be applied to generate broad band shear wave signals to get improved structure information from polarized shear waves and to get shear wave velocity as an indicator for rock classes. Task of the work package is the application-adapted dataset generation. These will be used for the further development and validation of tomographic methods for seismic prediction ahead and surround investigation in underground constructions. The task is splitted into:

1) geophysical exploration for the expansion of underground constructions, and
2) structure safety investigations of existing constructions.

Safety monitoring systems are not available on the market yet. In 2007, NORSAR together with the Norwegian Road Authority (Satensvegvesen) initialized a research program for tunnel safety observation systems. Accidents in other underground constructions worldwide show the need for structure safety inspection methods useful subsequently to e.g. fire or structural accidents for detailed structure improvements after damages of the construction. For long-term aspects, commercial application of semi-automated tomographic prediction ahead and sourround tunneling becomes evident.

Conclusion

In previous R&D activities a target adapted modification was realized for the cascaded vibroseismic source system. Thus, the vibroseismic source can now be used to generate highly reproducible and time stable broad band seismic data sets from the environment of underground constructions. These datasets will be used for a verification of the tomographic inversion development and testing in WP 2 using body waves and surface waves.

Moreover, the seismic data constitutes the basis for the tomographic imaging of the ahead lying rock as well as the surroundings of underground constructions. The seismic data used in this project is either obtained from already completed surveys, partly financed through GEOTECHNOLOGIEN within the OnSITE project, but also from pilot measurements that shall take place in the time frame of the presented project. The results of these measurements will be combined with geotechnical parameters (i.e. TBM-control) via an efficient data management and interpretation system. Optimized seismic broadband-acquisition as well as modeling and inversion of these data sets will be employed for a fast and nonetheless high-resolution characterization of tunnel- and adit walls.

Up to now, neglecting the full space situation, an integrated approach of diving wave tomography along tunnel walls and geologic-geotechnical observations of the tunnelling process is applied in ISIS. The special underground adapted acquisition and interpretation system will now be expanded using modified inversion methods for hard and soft rock developed in SOUND or similar research projects.

Acknowledgements

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Multi-scale S-wave tomography for exploration and risk assessment of development sites (MuSaWa)

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General Motivation and Objectives

Knowledge of the spatial distribution of geotechnical parameters relevant for the exploration of development sites and corresponding risk analyses is essentially required for the sustainable use of the near-surface underground, the reliable foundation of large buildings as well as for site specific geotechnical risk assessment. The depths of interest vary according to the specific geotechnical issue to be addressed and extent from a few meters to several hundred meters. Traditionally, geotechnical surveying and analysis tools are used at selected locations to address these issues. However, the high spatial heterogeneity of near-surface unconsolidated sediments is usually not reliably captured by the commonly sparse geotechnical measurements. Hence, additional geophysical surveys are carried out, which enable the 1D, 2D, and, depending on the invested operational effort, 3D tomographic imaging of physical parameters, such as seismic wave velocities.

Nowadays, almost exclusively seismic P-wave tomography is employed for high-resolution, local-scale exploration of development sites. However, the geotechnical benefits resulting from P-wave tomography are rather limited, since additional knowledge about the spatial variation of S-wave velocities is required to derive geotechnical parameters (e.g., shear strength) relevant for engineering applications and risk assessment from these physical velocity parameters. A key objective of this project is therefore the enhancement of S-wave tomography aiming on the routinely applicability of S-wave tomography for local-scale development site exploration. The overall concept of this project comprises technological innovations required for improved economical acceptance of the method as well as the enhancement and evaluation of efficient data acquisition approaches and cooperative/joint inversion methodologies allowing for a quantitative appraisal of tolerance limits and velocity model uncertainties. Additionally, the acquisition of geotechnical parameters by Direct Push (DP) technology required for ground truthing and its comparability to tomographically derived parameters as well as the validation of tomographically reconstructed velocity models shall be advanced. Existing data integration approaches allowing for the spatial interpolation of sparse geotechnical information on the basis of tomographic surveys shall be enhanced within the scope of this project.

Another fundamental goal is the development of a reliable methodology for site specific regional risk assessment. Traditionally, this is done by performing passive seismic experiments employing receiver arrays placed at selected locations within the surveying area. Such experiments provide usually only 1D information about the

S-wave velocity distribution at intermediate to larger depths. The combined analysis of active and passive seismic surface wave experiments is not routinely done, but may improve the resulting models particularly for shallow penetration depths. Employment of seismic 3D arrays realized by commonly using three-component borehole and surface-planted seismometers allows for ambient seismic noise tomography to overcome the 1D limitations of the surface wave analysis towards a full passive 3D tomographic imaging of the subsurface. Again, integrated analysis of ambient seismic noise tomography and sparse geotechnical measurements is strived as well as the quantitative appraisal of model errors. Figure 1 summarizes the overall concept of the project, the linkage between the subprojects and project partners and the key objectives addressed by the subprojects.

With accomplishment of this project an efficient multi-method multi-scale data acquisition and data analysis methodology for S-wave tomography shall be provided suitable for routinely applicability reaching from high-resolution local scale site exploration to regional scale site specific risk assessment studies. Especially at the early project phase, enhanced modelling and joint/cooperative inversion algorithms enabling the quantitative appraisal of model errors and tolerance limits will be developed employing synthetic data as well as already existing multi-method, multi-scale field data bases. At later project stages, the focus will move towards the validation of the daily-use-suitability of the technological and methodological developments.
In the following, we will introduce the individual subprojects dealing with local scale S-wave tomography, regional scale S-wave tomography, DP based validation and equipment development. This will be followed by reviewing the state of current research in the fields addressed by the subprojects.

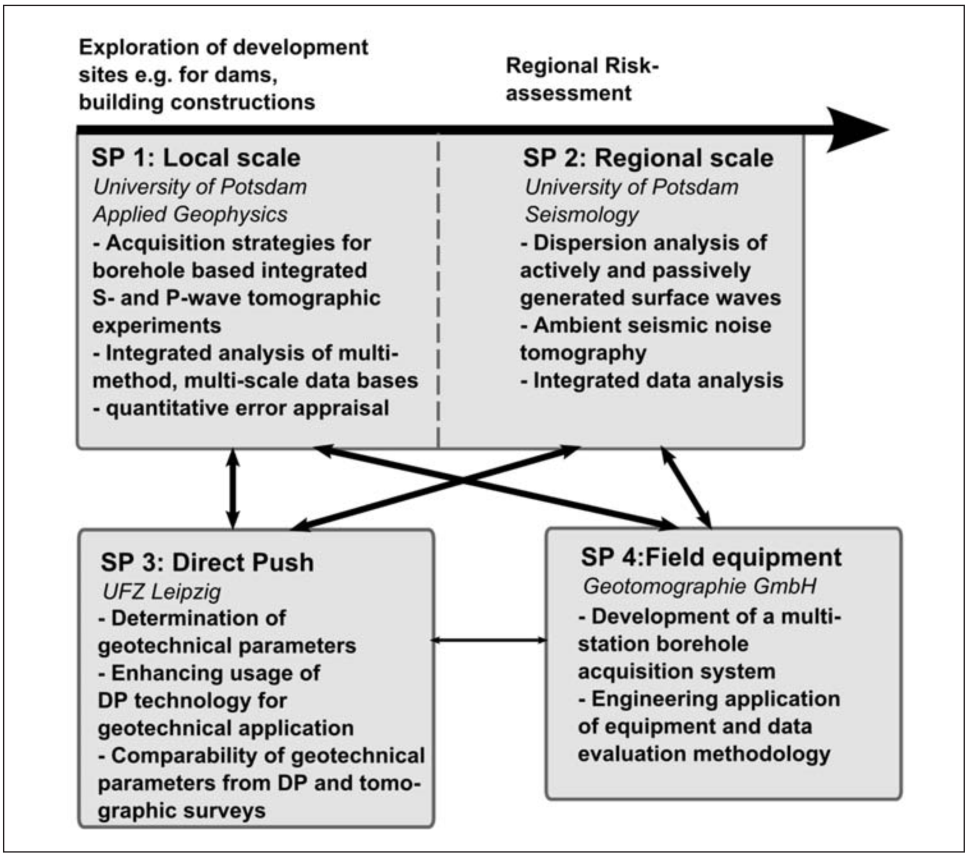

Figure 1: Overall concept illustrating the linkage of the subprojects and project partners as well as the spatial scale covered by the proposed project.

Goals

Subproject 1: S-wave tomography - the local scale

In contrast to high-resolution S-wave tomography, during the recent 1-2 decades P-wave tomography has become an integrated tool routinely used for surveying development sites considered for major building projects, such as dams and building constructions. However, the geotechnical relevance of exclusively applied P-wave tomography is limited, since knowledge about S-wave velocity is essentially required to derive parameter of high geotechnical relevance, e.g. shear strength or Poisson's ratio.

The standard P-wave tomographic acquisition geometries multi-offset VSP, crosshole and refraction tomography are generally applicable for high-resolution S-wave tomography. Refraction tomography is probably the most efficient acquisition geometry, since cheap high-quality sources and receivers are widely available. Existing surface and borehole S-wave sources inevitably generate strong P-waves, offering the feasibility to perform P- and S-wave tomography within one field experiment. Traditionally, different acquisition geometries, even if commonly applied at the same test site, are considered and processed individually.

Furthermore, cooperative or joint inversion of S- and P-wave tomographic data allows reducing the inherent ambiguity of tomographic reconstruction techniques. Frequently used regularized inversion approaches enable the determination of plausible S- and P-wave velocities, but such deterministic approaches do not allow for quantitative judgement of the reliability of the obtained velocities. Hence, geotechnical parameters derived from S- and P-wave tomographic surveys can also not be quantitatively judged regarding their confidence level, which significantly limits their suitability for a reliable geotechnical appraisal of development sites.

Within the scope of this project we want to develop and enhance acquisition strategies for borehole-based high-resolution S-wave tomography and their integration with P-wave tomographic experiments within one field experiment. Furthermore, we want to develop a cooperative inversion approach, which enables the automated and quantitative incorporation of geotechnical a priori information as for instance obtained from DP cone penetration test (CPT) measurements. This cooperative inversion approach shall provide quantitative information about the confidence interval of the obtained velocities throughout the model area. Based on such velocity confidence information it is possible to provide confidence intervals for geotechnically relevant parameters derived from S- and P-wave velocities.

Subproject 2: S-wave tomography - the regional scale

Knowledge regarding the lateral distribution of shear-wave velocities and shear strength in the shallow or middle deep sediment and bedrock (depth range of 10 to a few hundred meters) is a necessary prerequisite for the evaluation of the structural safety of buildings. This information is not only needed for local geotechnical pre-exploration of a specific locality but also in the assessment of regional hazard and risk up to a distance of a few kilometres. Active generation of shear waves with deep penetration and to such wide distances is still costly. Passive monitoring of the natural ambient noise wavefield with seismological array techniques allows obtaining phase velocity curves of surface waves rather cost efficient. From these curves 1D shear velocity models can be constructed. Depending on the source spectrum and on the subsurface structure shallow as well as middle deep structures can be analysed. The geometries of the arrays used have to be adjusted for each wavelength to achieve optimal resolution and should be supplemented by active shear wave velocity measurements if possible. 1D model interpretations can therefore be seen as average models of the regional structure. In this sense the ambient noise technique results in proxy parameters for the S-wave velocity on a wide aperture scale which may be combined with results of local high-resolution shear wave tomography in the shallow subsurface structure.

The 1D assumption made a priori is a severe limitation for the inversion of phase velocity curves. In the planned project we will therefore use additionally 3-component borehole sensors to add in-depth information regarding the incoming wavefield to the inversion algorithm. The simultaneous observation of the wavefield with a seismological array at the surface will allow high resolution wavefield decomposition in Rayleigh-, Love- and bodywave constituent parts. We will also use the 3D array (surface array plus borehole sensors) for a passive seismic interferometry experiment towards a full 3D velocity structure analysis. To evaluate the passive observations a small number of active calibration measurements is required.

Subproject 3: Direct-push based seismic and geotechnical validation

For quantitative evaluation of geotechnical parameters the exact determination of seismic velocities and the knowledge of site specific correlations between seismic and geotechnical parameters are required. In this context, Direct Push (DP) technology (Figure 2) offers an innovative approach for the investigation of these requirements. DP tools allow the in situ record of depth profiles of geophysical, geohydraulic, or geotechnical parameters. Furthermore, DP technology enables the installation of temporary wells for measuring and monitoring purposes and the instrumentation with geophysical equipment.

Figure 2: Direct-Push equipment.

Based on the available equipment and the overall objectives of the project, this subproject aims at the design, further development and evaluation of DP based measuring concepts for S-wave tomographic seismic surveys, and at the geotechnical validation of deduced parameter correlations. The goals in detail are following:

– Measurements of vertical seismic profiles (VSP) following the requirements concerning spatial resolution of local and regional scale tomography

– Development of efficient and practicable geometries for acquisition of S-wave tomographic data in cooperation with subproject 1

– Optimization of post-processing and interpretation of in-situ measuring technologies (e.g. CPT and hydraulic methods) for a better understanding and comparison with seismic parameters

– Improvement of the knowledge of correlations between seismic and geotechnical parameters by the analysis of available data

– Development of procedures for multivariate data analysis of different soil parameters in combination with seismic data considering site-specific conditions

– Evaluation of measuring concepts and methods by means of field studies, e.g. validation of tomographic models by active seismic measurements and acquisition of in-situ geotechnical parameters

Subproject 4: Development of a multi-station borehole receiver array for S-wave tomography

High-resolution tomographic investigations between boreholes are routinely applied for the exploration of development sites considered for larger building projects, e.g., power stations, dams and high-rise buildings. Currently, almost exclusively P-wave tomography is employed in geotechnically oriented tomographic surveys. As contractors are always expecting monetary return, numerous technological innovations and enhancements were made during the last decades towards effective borehole tomographic acquisition systems.

Recently developed sources and receivers suitable for crosshole P-wave tomography, such as sparker sources and hydrophone chains, enable very competitive P-wave crosshole tomographic experiments in the water saturated zone, although boreholes have to be installed. However, the geotechnical benefits of P-wave tomography are rather limited and information about S-wave velocity distribution is additionally required to derive geotechnically relevant parameters, such as shear strength, from the tomographically reconstructed P- and S-wave velocities. Up to now, only little efforts have been made to develop equipment enabling the competitive acquisition of S-wave crosshole tomographic data.

In our opinion, there are three major barriers to economical acceptance and routinely use of borehole based S-wave tomographic techniques:

1) the need for a robust and powerful borehole source generating high-frequency shear waves
2) the need for a borehole receiver chain suitable for S-wave tomography
3) the need for specific data analysis and inversion software suitable for commercial S-wave tomography

The first of these barriers has recently been overcome with the market launch of an SH-wave borehole source developed by Geotomographie GmbH. The ultimate goal of this

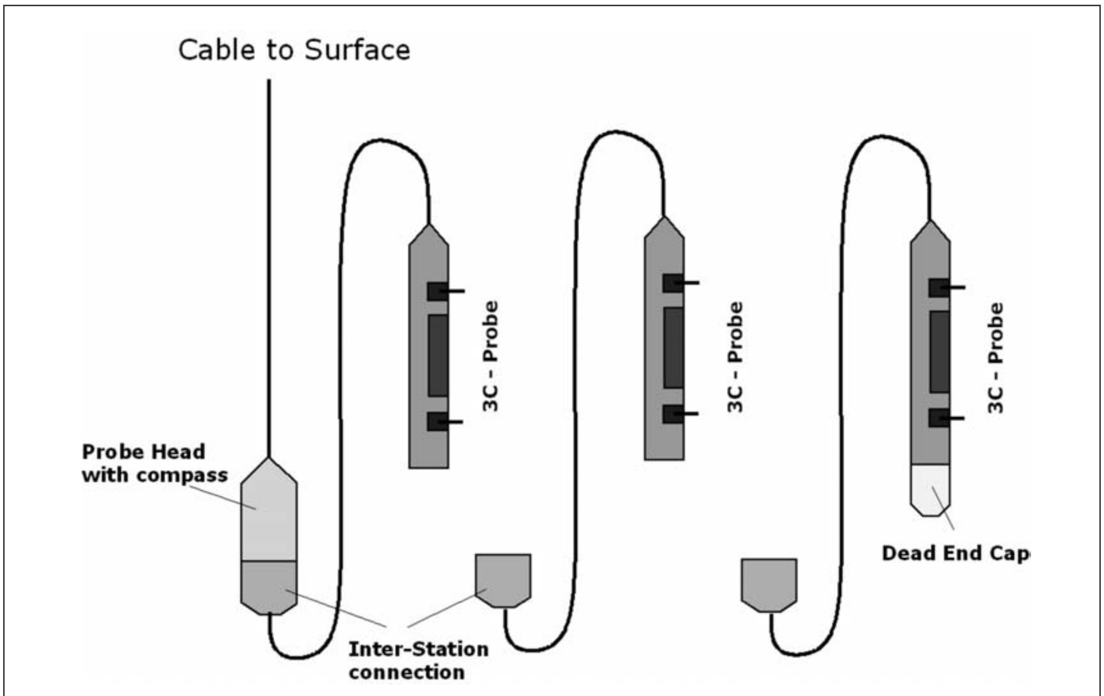

Figure 3: Sketch of the modular composition of the multi-station borehole-based S-wave acquisition system.

subproject is therefore the development of a multi-station borehole acquisition system (MBAS) for efficient recording of S-waves in boreholes. Subproject 1 is concerned with the development of S-wave tomographic data analysis software suitable for routinely use in geotechnical site explorations.

Within this research project a multi-station borehole acquisition system (Figure 3) shall be developed comprising at least 4 to 8 single receiver elements, each of it having 3 components (X, Y, Z). The system shall be applicable for shallow tomographic experiments in dry or watered boreholes up to 100 m depth. Contrary to standard borehole geophones using ordinary displacement sensors, we will employ accelerometers covering a very broad frequency range of 0.1 Hz to 8000 Hz, which is a prerequisite for using the MBAS system in combination with surface-planted receiver arrays for passive ambient seismic noise tomography on the regional scale.

State of Research

Internationally and nationally, S-wave tomography is employed in a relatively limited number of studies predominately motivated by academic interests. Mostly, this can be explained by the lack of technically mature and economical equipment, particularly for borehole-based acquisition geometries. However, the available academic studies indicate the outstanding economic and scientific potential of S-wave tomography for geotechnical and engineering applications, which may also incorporate aspects of regional risk assessment. Currently, 2D S-wave refraction tomography and 1D analysis of seismic surface waves (MASW) are probably the best established methodologies. In most cases, S- and P-wave tomographic field experiments are technically separated and employ different equipment. Combination of different acquisition geometries, e.g. refraction seismic and multi-offset VSP is not done when collecting S-wave tomographic data.

The S-wave tomographic data evaluation is separated according to the employed methodology, acquisition geometry and spatial scale. Cooperative or joint tomographic reconstruction of S- and P-wave velocities is rarely done. The same applies to the automated and quantitative incorporation of a priori information obtained from borehole measurements in the model generation process. Non-linear inversion approaches are, with certain restrictions regarding the 1D analysis of surface waves, up to now not used for the evaluation of S-wave tomographic data. Hence, a quantitative appraisal of geotechnically relevant parameters derived from tomographically reconstructed P- and S-wave velocity models by means of petrophysical or multivariate statistical analysis tools is not possible yet.

Subproject 1

Currently, no acquisition system is available that enables the economic recording of S-waves in boreholes. Most likely, this is the reason for the very limited number of available crosshole high-resolution near-surface S-wave tomographic studies (e.g. Angioni et al., 2003; Daley et al., 2004; Dietrich and Tronicke, 2009). For the same reason, VSP acquisition geometries are hardly used in combination with S-wave sources (Jarvis and Knight, 2000) and not yet employed for 2D tomographic velocity reconstruction. However, multi-offset RSVP measurements employing a DP P-wave source prove that such acquisition geometries allow for the reliable tomographic reconstruction of 2D velocity models, which are advantageous in their imaging capabilities compared to velocity models obtained from traditional refraction tomography (Paasche et al., 2009). S-wave tomography combining different acquisition geometries has not yet been done, but encouraging results of related P-wave tomographic studies may be transferable (Paasche et al., 2009). A few successful experiments have been reported, in which crosshole S- and P-wave tomographic data have been acquired within a single field experiment (Angioni et al., 2003; Daley et al., 2004).

Usually, linear or linearized regularized inversion algorithms are employed for the tomographic reconstruction of S-wave velocities. Such inversion algorithms do not allow for a quantitative confidence appraisal of the determined S-wave velocities. Non-linear inversion strategies, e.g. based on simulated annealing (SA) algorithms, enabling the evaluation of velocity confidence are currently only used on an individual basis for P-wave tomography (e.g., Velis, 2008). The cooperative inversion of crosshole S- and P-wave tomographic traveltimes employing regularized inversion algorithms is generally possible (Linder et al., 2010) and applicable to other acquisition geometries. The structural link used by Linder et al (2010) to cooperatively invert S- and P-wave traveltimes is based on multivariate statistical analysis tools and enables the efficient incorporation of structural a priori information, e.g. obtained from DP logging data. This structural link is generally capable to realize a non-linear cooperative inversion of S- and P-wave tomographic data.

Traditionally, approaches for the determination of geotechnical parameters on the basis of S- and P-wave tomographic surveys rely on petrophysical relations (Angioni et al., 2003). More recently, encouraging approaches replacing petrophysical relations by multivariate statistical analysis tools have been developed (Dietrich and Tronicke, 2009; Linder et al., 2010). However, a confidence interval of geotechnical parameters derived from S- and P-wave tomography, regardless whether obtained using petrophysical or statistical tools, can not be defined as long as no quantitative confidence appraisal for the tomographically reconstructed S- and P-wave velocities is available.

Subproject 2

The analysis of ambient seismic noise is since several decades a rapidly growing field in the seismological research related to site effect characterization. The H/V or Nakamura technique is a famous example due to its simplicity and cost efficiency and is widely and globally used since the early 90ies. The H/V method is primarily used to analyse resonances in unconsolidated sediment structures (Bard, 1998). The interpretation of H/V spectra in terms of Rayleigh wave ellipticity allows potentially the derivation of 1D shear wave velocity profiles (Fäh et al., 2003; Arai and Tokimatsu, 2004). The robustness of the interpretation is significantly enhanced by adding passive observations of the wavefield with seismological arrays (Asten and Boore, 2005; Boore, 2006). Several array techniques (Figure 4) were tested in various EU projects SESAME 2001-2004 (Ohrnberger et al., 2004, Ohrnberger, 2005), SISMOVALP

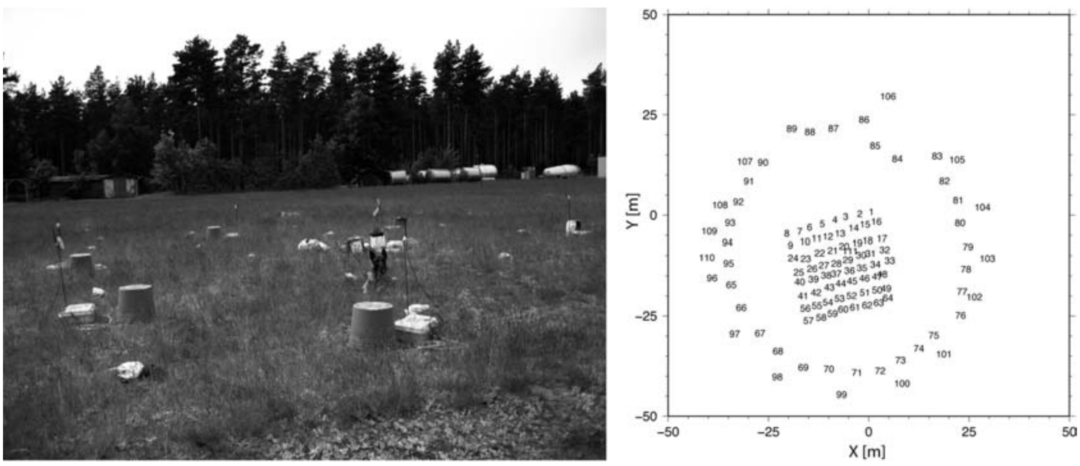

Figure 4: Seismological array for regional S-wave tomography.

2003-2006, and NERIES 2006-2010 and in internationally organized blind studies (Asten and Boore, 2005; Cornou et al., 2006) with synthetic and real data sets. All these studies show that the analysis of surface wave dispersion with passive methods allow a consistent and accurate retrieval of the 1D subsurface structure. The different methods like f-k (Capon, 1969), spatial autocorrelation (Aki, 1957) or enhanced correlation methods (Gouedard et al., 2008; Yokoi and Margarvan, 2008) can be successfully used within their method specific limitations. However, there is a high probability for misinterpretation due to the high degree of non-linearity and non-uniqueness of the inversion problem. This situation can only be improved by taking additional information into account (Wathelet, 2005). Arai and Tokimatsu (2005) suggest combining H/V spectra and dispersion curves in a joined inversion. An additional possibility is to use H/V ratios measured with borehole sensors at depth (measurements of the eigenfunctions of the analysed surface waves) and to use this information in the inversion.

The recently developed seismic interferometry method was successfully used to image the velocity structure on different scales (Gouedard et al., 2008; Picozzi et al., 2009). Chaves-Garcia and Raptakis (2008) showed that the method can be used with vertical borehole data and transient signals. Till now this correlation based method was not applied to ambient noise recorded simultaneously at borehole sensors and a surficial seismological 3D array.

Subproject 3

Commonly, geotechnical parameters are provided by local tests, such as plate-loading test or static penetration test, or by laboratory analysis. Static penetration test, also called Cone penetrating test (CPT) are used for in situ determination of cone resistivity, sleeve friction and pore pressure in soft sediments. These specific values enable the estimation of subsoil lithology and the evaluation of geotechnical parameters (e.g. Robertson and Campanella, 1983; Robertson, 1990). CPT soundings represent a standard practice within DP based methodologies (Dietrich and Leven, 2006). Most modern electronic CPT cones now also employ a pressure transducer with a filter to gather pore water pressure data. However interpretation of these data is still topic of research. The sampled region of CPT investigations is bounded to the close surrounding of the cone, i.e. the data set provided is a 1D depth profile at the cone-push location. For further characterization of the construction ground (2D profiles), different seismic methods are applied. In doing so, the derivation of geotechnical parameters by determination of the P-wave and/or S-wave velocities from vertical seismic profiling (VSP) or tomographic approaches is possible. Commonly, one or two boreholes equipped with seismic sources or/and receivers are used for these measuring concepts. Alternatively, DP technology offers the possibility to perform VSP measurements more flexible, or at sites, where no boreholes are available. Few studies have shown the potential of 1D cone-based geophysical imaging by an integrated application of a seismic S-wave receiver mounted on a CPT cone (Jarvis and Knight, 2000; Knight and Pidlisecky, 2005). Regarding a seismic 2D tomography based on S-waves, the technical requirements of an efficient source as well as of receiver arrays practicable for borehole measurements have not been available for a long time. In contrast to boreholes, the (further) development of S-wave sources and receivers practicable for DP technologies represent a current challenge for extend the field of operation and the flexibility of S-wave tomography. In this context, first results of multi-offset reverse VSP measurements under employment of a seismic P-wave source driven into the underground by DP technology have demonstrated to be a feasible method for 2D determination of seismic velocity (Paasche et al., 2009)

Besides technical issues there exist uncertainties regarding the quantitative evaluation of geotechnical parameters from seismic tomography. While seismic velocities can be feasible determined by combined inversion of P- and S-waves, there has been no quantitative evaluation tool to check the validity of seismic velocities. The consideration of a priori information on ground properties provided by DP technology and parameter correlations should help to better quantify both seismic velocities and geotechnical parameters

Subproject 4

Borehole geophones are commonly used for VSP applications. Usually, these are single receiver stations with only one three-component geophone. Coupling to the borehole wall or casing is realized either by mechanical clamping, a spring system or a pneumatic air bladder. Only a few companies currently offer such single-station borehole geophones

– Geostuff/USA, http://www.geostuff.com
– Pasi/Italy, http://www.eng.pasigeophysics.com
– Olson Instruments / USA, http://olsoninstruments.com
– Geotomographie GmbH / Germany, www.geotomographie.de.

Multi-station borehole acquisition systems are only available for hydrocarbon exploration purposes and therefore limited to deep boreholes as usually employed by the oil industry

– Oyo Geospace / USA, http://www.oyogeospace.com
– Vibrometric / Finnland, http://www.vibrometric.com.

Multi-station borehole acquisition systems for geotechnical and engineering applications in slim and shallower boreholes are not yet available.

Acknowledgements

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Tomographic Methods in Hydrogeology

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Summary

The extraction of groundwater for drinking water purposes is one of the most important uses of the natural subsurface. Sustainable management of groundwater resources requires detailed knowledge of the hydraulic properties of the subsurface. Typically, these properties are not directly accessible. We are convinced that the evaluation of hydraulic properties necessitates applying hydraulic stimuli (e.g., injection and extraction of groundwater, tracer tests, etc.). In this context, tomographic assemblies and inversion strategies originally derived for geophysical surveying and meteorological data assimilation can be transferred to hydraulic applications. In addition, time-lapse geophysical surveying techniques may be used to monitor hydraulic tests. The latter requires fully coupled hydrogeophysical inversion strategies, accounting for the entire process chain from hydraulic properties via flow and transport to the geophysical surveying program.

The current project includes:

(1) the development of a geostatistical inversion method for transient tomographic data of multiple hydraulic investigation techniques including the geoelectrical monitoring of salt-tracer experiments using the 4-D variational approach

(2) the comparison of this method to the inversion of temporal moments

(3) the model-based optimal design of tomographic surveys

(4) the development of modular assessment equipment for efficient execution of tomographic surveys in a hydrogeological context

(5) the performance of tomographic field tests at the research site Lauswiesen in Tübingen using the model-based design and providing data for the inversion.

1. Introduction

The natural subsurface is characterized by high spatial variability. This has direct consequences on the management of shallow aquifers used for the provision of drinking water and other purposes. The spatial variability of hydraulic conductivity causes solute transport to be quite nonuniform which impedes the assessment and remediation of contaminated aquifers and causes uncertainty in risk assessment and design of protective measures. Therefore a comprehensive assessment of hydraulic properties of the subsurface and their spatial variability is mandatory for management and protection of groundwater resources.

The project Tomographic Methods in Hydrogeology deals with the acquisition and inversion of hydraulic data, obtained in hydrogeological field studies using tomographic layouts. The main objective is the development of coupled tomographic surveying and inversion strategies, combining hydraulic and geophysical measurements to obtain three-dimensional distributions of hydraulic aquifer properties. This involves (1) the development of low-cost, re-usable field equipment and of assessment strategies in the field, and (2) the development of fully coupled hydrogeophysical inversion methods using high-performance computing methods to be implemented in the software package DUNE, a leading platform for parallel solution of partial differential equations. We test and compare two different geostatistical inversion strategies: one based on an extended Kalman filter approach, and another based on four-dimensional data assimilation techniques. The numerical models will be used for designing the experiments, and the experimental data will be inverted by the new inversion codes. The interplay between experimental and numerical studies will facilitate jointly optimizing the experimental strategy and the numerical inversion. In particular, the following objectives are addressed in the framework of the project:

– For **joint inversion of multiple data sets** the different hydrogeological data sets will be considered: (1) pumping tests and slug tests in tomographic arrays, (2) flowmeter data, (3) temperature measurement in experiments, in which heat is used as tracer, and (4) data from the geoelectrical monitoring of tracer tests. The combination of several investigation techniques depending quantitatively on the distribution of hydraulic conductivity will improve the resolution and decrease the uncertainty in the three-dimensional estimation of hydraulic subsurface properties.

– To meet previous objective, **a three-dimensional, fully coupled hydrogeophysical inversion on parallel computers** is envisioned. We develop a new geostatistical inversion method based on the four-dimensional variational approach (Zupanski and Mesinger, 1995), which is a regularized conjugate-gradient method tailored for inverting full time series of transient data. The software will be implemented in the software package DUNE which includes efficient parallel discretization methods and solvers for partial differential equations. It will be modular so that different combinations of data sets can be analyzed.

– **Model-Based Optimal Design of Tomographic Field Surveys:** The expected data worth of a particular tomographic field set up will be quantified by the expected reduction of conditional uncertainty (Cirpka et al., 2004). This metric will be used to choose the best set up of several candidates and to optimize the experimental setup (e.g. location of probes, pumping rates or other continuous design parameters) by automatic maximization routines.

– **Development and Test of Coupled Tomographic Assessment Strategies in the Field:** The intended tomographic assessment strategy includes different tomographic approaches (e.g. hydraulic and tracer tomography) that will sequentially be applied at the test site Lauswiesen of University of Tübingen and will be developed to reliable and mature field technologies. At the Lauswiesen site, comprehensive data of previous studies already exist. These data sets will be used for the design of experiments and included in inversion. In particular, we want to develop the method of heat-tracer tomography to a ready-to-use tomographic field technique. The field studies also include pumping and slug test based hydraulic tomography, and geoelectrical monitoring of salt tracer tests with three-dimensional electrode arrays. We can use existing boreholes, but also intend to use cost efficient and simple to remove direct-push probes for the monitoring of the experiments. In addition, the intended tomographic assessment strategies will be applied and validated with already existing data from the Boise Hydrogeophysical Research Site.

– **Development of Direct-Push Probes for Three-Dimensional Tomographic Surveying** The geoelectrical monitoring of salt-tracer tests in alluvial systems with fine-grained cover layers require the installation of vertical electrode chains below the layer of fines. Rather than installing additional observation wells and equipping them with probes, we want to push probes with direct-push rods into the subsurface that can be re-used after retrieval. This is especially important as often the retrieval of in-situ installation is required after termination of an investigation. For this purpose, we want to develop a modular technique which is easy to install, withstands the mechanic stresses of the hammering, and can be retrieved from the subsurface for reuse. The probes will be applied in the field experiments at the test site Lauswiesen and thus significantly contribute to the integrated tomographic assessment strategy.

2. The Test Site Lauswiesen

Within the project we will collect new and use existing data from the test site Lauswiesen of the Center for Applied Geoscience at University Tübingen, which has already extensively been studied and used to develop and test several site assessment strategies and technologies (Neuman et al., 2007; Riva et al., 2008; Riva et al., 2006; Sack-Kühner, 1996). The site is located close to the city of Tübingen at River Neckar. The unconfined aquifer consists of unconsolidated material with medium gravel and medium to coarse sand and is overlain by a 1-2 m thick layer of loamy alluvial fines. The bedrock below 10 m depth consists of marl and clay stone of the Middle Keuper formation. The aquifer can be divided into two major zones: The upper zone ranging 2 - 6 m below ground surface has a spatially varying hydraulic conductivity. This zone is more homogeneous than the lower zone ranging 6 - 10 m below ground surface. Based on pumping tests, a mean transmissivity of $1.71 \cdot 10^{-2}$ m^2/s with a standard deviation of $1.56 \cdot 10^{-3}$ m^2/s was estimated (Neuman et al., 2007). Figure 1 shows logs of

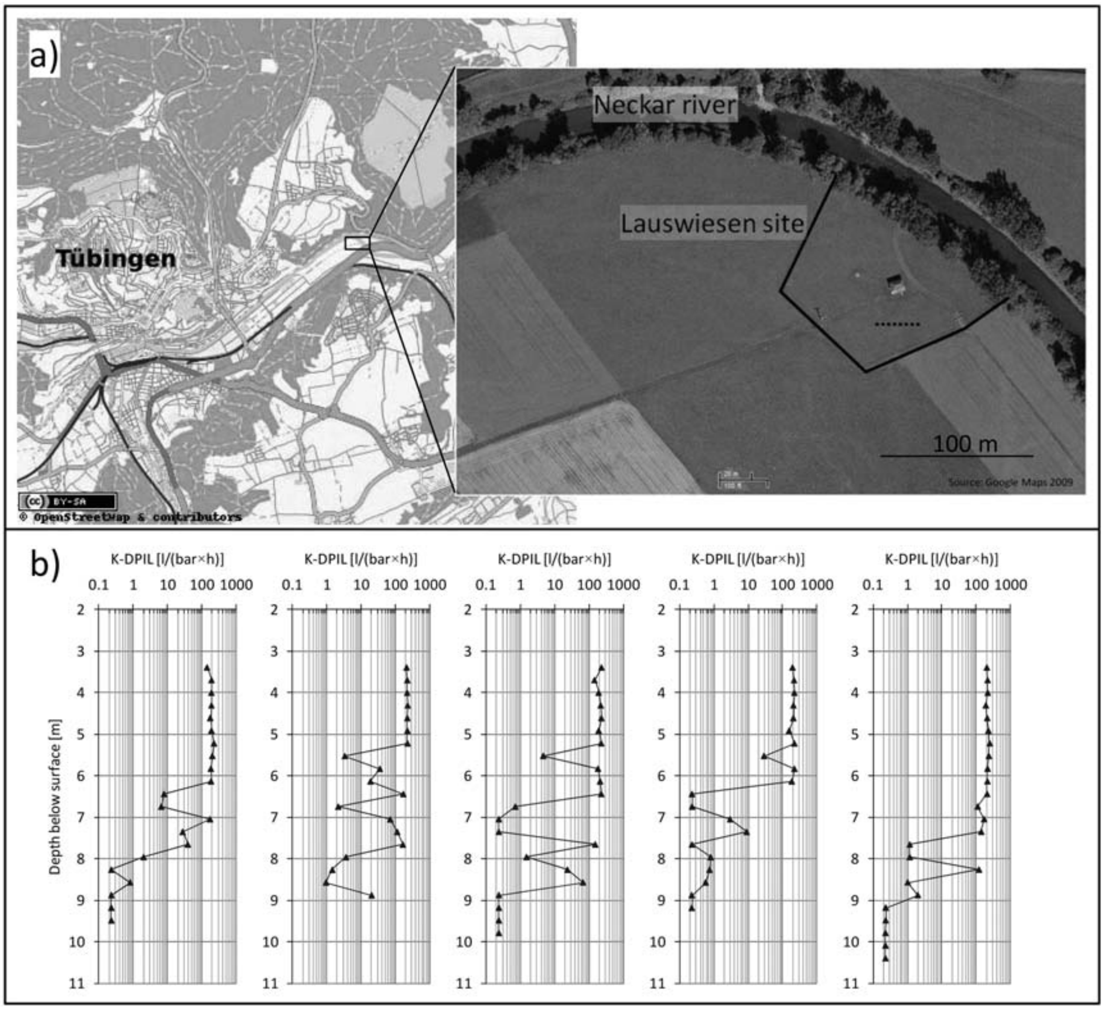

Figure 1: a) Location of the Lauswiesen site near Tübingen at River Neckar. b) Vertical logs of relative hydraulic conductivity derived from direct-push based hydraulic profiling ("injection log").

the vertical distribution of relative hydraulic conductivity derived from a direct-push based site investigation campaign at the Lauswiesen site. From the vertical distribution of relative hydraulic conductivities (resulting from so-called injection logging, (Dietrich et al., 2008)) the heterogeneous nature of the aquifer can be deduced.

The water table at the site is about 4 m below ground surface and the natural gradient is approx. 0.3%. The test site is equipped with multiple vertical observation wells and a horizontal borehole which may be used for tracer injection or other experimental studies such as integration into experiments for hydraulic tomography.

3. Work Packages

To approach the objectives described in section 2, four different work packages with their working tasks are defined and are described in more detail in the following:

Work Package 1:
Joint Geostatistical Inversion of Hydraulic Tomography, Heat-Tracer Tomography, and Geoelectrical Tomography Obtained during Salt-Tracer Experiments

Model-Based Design of Tomographic Field Experiments:

The design of tomographic experiments in hydrogeological applications include injection rates, placement of observation points, choice of tracer concentrations, and the layout of geophysical surveying devices. Numerical modeling of the entire assessment chain, using the current state of knowledge about the field site, will be used to predict the expected outcome of surveys. The simplest optimization of experimental design is based on studying variants and forms the basis for designing the first set of field experiments. In subsequent optimization studies, the data worth of additional measurements will be analyzed by the expected reduction of the estimation uncertainty (Zupanski and Mesinger, 1995). The geostatistical inversion framework allows evaluating this metric of data worth in the sense of linearized Bayesian updating (reduction of conditional uncertainty by additional conditioning). This technique will be applied in the design of field experiments in an advanced stage of the project.

Inversion of Heat as Tracer in Tomographic Surveys:

In the field experiments, heat will be used as tracer for tracer-tomographic surveys. In this technique, hot (or cold) water is injected into an injection well and the temperature time curve is monitored at observation points. In principle, these data can be analyzed by the same methods as data from solute tracer experiments. In particular, the distribution of log hydraulic conductivity can be inferred from the temporal moments of the breakthrough curves. The existing inversion code will be extended to account for such data. The inversion of heat-tracer experiments additionally demands inferring the distributions of heat conductance and heat capacity. Inverting heat-tracer experiments alone may lead to difficulties of distinguishing between effects of heat capacity and hydraulic conductivity. Thus the joint inversion of multiple experiments is desired. The developed code will first be tested using synthetically generated data and subsequently applied to field data.

Comparison of Inversion Approaches:

The inversion approaches based on temporal moments and on the analysis of full time series (see work package 2) will be jointly compared with respect to accuracy and convergence behavior using selected synthetical test cases.

Application to the data from field experiments:

The geostatistical inversion and optimal-design methods will be tested for applicability in practice by analyzing the field experimental data from the test site Lauswiesen of the University of Tübingen. We anticipate that the field application will lead to modifications of the inversion strategy, like the inversion of the data will feed back into the design of further experimental studies.

Work Package 2:
Inversion of Transient Tomographic Measurements by 4D-VAR Methods

Implementation of Forward and Adjoint Models for Transient Groundwater Flow, Solute and Heat Transport, and Geoelectrical Monitoring:
The implementation of parallel solvers for transient groundwater flow, solute and heat transport is greatly facilitated in DUNE by the module PDELab. Additionally the concentration-dependent Poisson equation describing geoelectrical monitoring of salt-tracer tests has to be coupled to the flow and transport code. For the preparation of inversion methods, interfaces efficiently extracting modeled monitoring data will be implemented. Developments are also necessary to account for data obtained by highly resolved direct-push based geohydraulic characterization of the subsurface. In order to apply 4D-VAR approaches to hydrogeophysical inversion, transient adjoint equations must be formulated and implemented. A particular challenge lies in data management of computed transient states throughout the domain and time, which need to be stored in order to compute the sensitivity of the objective function with respect to the spatially distributed parameter fields. This requires the development and implementation of fast distributed data access strategies using an efficient parallel file system, and if possible compression or reduction of the amount of data to be stored.

Development and Implementation of a 4D-VAR Inversion Scheme for Transient Hydraulic Tomography:
The 4D-VAR approach is a data assimilation/inversion approach based on conjugate gradients using adjoint states to obtain derivatives of the objective function. In contrast to meteorological data-assimilation applications, the target variable will not be the spatial distribution of previous states but that of material properties of the subsurface. For regularization, we will consider the target variables to be autocorrelated in space. This requires efficient techniques of computing the prior term of the objective function (conjugate gradient with circulant preconditioning). Intensive testing is necessary how linearized sensitivities affect convergence. It is also necessary to balance the amount of data which has to be stored during the forward model runs and the simplifications in the adjoint model with their influence on the speed of convergence. The first model system will only consider hydraulic heads and be tested using synthetically generated data sets.

4D-VAR Inversion of Transient Heat-Tracer Tomography:
The 4D-VAR approach will be extended to indirect inversion problems in which temperature measurements obtained during heattracer tests are considered as data. This requires a more complex evaluation of adjoint states and derivatives of the objective function with corresponding extensions in data management. The method will intensively be tested with a joint inversion of heat-tracer data and hydraulic heads using synthetically generated data sets.

4D-VAR Inversion of Time-Lapse ERT Data Obtained during Tracer Tests:
Time-lapse ERT data obtained during tracer tests are even more indirect with respect to the identification of hydraulic conductivity than (heat-)tracer measurements, since they involve an additional measurement equation depending nonlinearly on concentration. This will further increase the complexity of evaluating adjoint states, sensitivities of the objective function, and data management of intermediate quantities. This method will also be tested intensively using synthetically generated data sets.

Work Package 3:
Field Experiments of Coupled Hydraulic Tomographic Methods in an Alluvial Aquifer

Highly Resolved Geohydraulic Characterization:
For highly resolved geohydraulic characterization of aquifers, the approach of hydraulic tomography under transient conditions will be developed as field technique which has so far be applied mainly on a theoretical basis or in fully controllable lab experiments. Special focus has to be devoted to the experimental design in terms of temporal resolution and optimal positioning of observation points. The acquired time series of hydraulic head may be analyzed by their temporal moments or peak arrival times. We aim at the joint analysis of the different tests in order to exploit the different information content of the measurement results and to reduce the uncertainty of the inversion. The goal is to provide time-dependent data for inversion, and to develop a reliable field technique for hydraulic tomography under transient flow conditions. The concept of hydraulic tomography will also be extended by direct-push (DP) based in-situ measurements. In this context, vertical profiles of hydraulic conductivity by DP-based injection logging, and flowmeter measurements are measured. Direct-push based multi-well slug tests will be performed in tomographic arrays to be able to increase the resolution and data density with respect to hydraulic conductivity and storativity on two dimensional cross sections. The results of the DP based investigations will be included in the joint inversion. The DP technology can also be used to install additional observation points efficiently and cost effectively. This makes it possible to adapt the experimental investigation program and design based on the results of the inversion and associated data-worth analysis.

Development of a Tracer-Tomographic Method Using Heat as Tracer:
The method of tracer tomography has so far been tested only in virtual experiments (Yeh and Zhu, 2007). We develop this approach to a reliable field technique which requires the use of a tracer that is "attenuated" quickly after every tracer experiment. In this way, consecutive tracer experiments can be conducted without being influenced by preceding tests. For this purpose, we want to inject heated or cooled water as repeatedly usable tracer, and measure temperature changes. Thus, we avoid injecting an artificial tracer compound into the subsurface, which could accumulate, and are able to perform identical tests under modified boundary conditions. The experimental setup is similar to conventional tracer experiments, in which the heated or cooled water is injected into the aquifer by an injection well. For recording of temperature changes, thermometer profiles will be installed in the direction of flow and perpendicular to it. The experiments will be setup with the injection and extraction over limited sections of the wells to obtain tomographic data sets. The development of the experimental method includes (1) the generation of a sufficient temperature signal, (2) the comparison of several methods for temperature measurements (namely thermocouple chains in DP rods and fiber-optic distributed temperature sensing), and (3) automatic data acquisition.

Geoelectrical Monitoring of Salt-Tracer Experiments:
Non-invasive observation of salt tracer tests can be done with electrical resistivity tomography (ERT). In contrast to heat tracer tests, the salt tracer test itself is difficult to repeat multiple times with different hydraulic boundary conditions. That is, the tomography is restricted to geoelectrical monitoring for the observation of the distribution of the tracer plume along different transects and to different times (e.g. as time lapse tomography). In order to achieve a good vertical resolution, although the test site is covered by a layer of alluvial fines, ERT monitoring must be performed by 3-D electrode arrays. For this purpose, we make use of the modular DP probes developed in work package 4. The flexibility and efficiency of DP technology

allows to re-install the reusable electrode rods, so that multiple geoelectrical tomograms may be performed along various profiles during the salt-tracer experiment. The horizontal borehole at the site may be used for tracer injection, and a successive combination with thermal tracer and geohydraulic experiments is intended. The analysis of the salt-tracer tests will be performed using the fully coupled hydrogeophysical inversion approaches. The test site will sequentially be assessed by hydraulic tomography, heat-tracer tomography and ERT monitoring of salt-tracer tests, especially making use of the DP-based probe system. The acquired data will be jointly inverted. The proposed tomographic assessment strategy will be developed to a mature field technique and will be tested at the test site Lauswiesen.

Work Package 4:
Development of Modular Direct-Push Probes for Three-Dimensional Geoelectrical and Hydraulic Surveys

Performing tomographic measurements within the project requires the further development of direct-push probes for the three-dimensional assessment of the shallow subsurface. Within the project, the focus is on the development of direct-push based electrode chains for direct-current geoelectrical tomography performed during salt-tracer experiments. The adaptation of the probe technology has to meet requirements for simple, quick and reliable use in practice. The probes must be robust against mechanical stresses occurring during the direct-push installation, which is the most cost-efficient way of installing such monitoring devices. Particularly, the constructive design has to account for the possibility to reuse the rods equipped with electrodes. This is especially important, as often the retrieval of in-situ installation is required after termination of an investigation. We will facilitate synchronous performance of heat and salt-tracer experiments, so that there should be the option to have modules containing both electrodes for ERT and thermometers. Finally, additional integration of pressure transducers would make it possible to use the same modular system for joint hydraulic, geoelectrical, and heat-tracer tomographic surveys. The testing and application of the different probe variants will be done at different development stages to obtain the most reliable probe type with respect to data accuracy and precision, efficiency, and applicability for field use. In addition, the field applications and test measurements will be used to identify conceptual and constructive deficits, which will lead to further development of the prototypes in an iterative manner until a fully applicable measurement system is ready for pre-serial production.

4. Experience of the Applicants in Geostatistical Inversion Methods

This project builds upon the experience of the applicants in geostatistical inversion methods for hydrogeological problems. The key of geostatistical inversion is the assumption that the underlying parameter field (here hydraulic conductivity) is a random, auto-correlated spatial function. Then, dependent quantities (such as hydraulic heads, or temporal moments of a tracer) are also random fields correlating with the parameter fields. In this framework, inversion is conditioning procedure which is accessible by Bayesian statistics. The basic approach used in WP 1 is the quasi-linear geostatistical inversion approach (Kitanidis, 1995), which is a Gauss-Newton method, with several modifications introduced for efficiency and stability of the scheme (Nowak and Cirpka, 2004; Nowak et al., 2003). With sufficient data coverage, the geostatistical meta-parameters can be estimated from the measurements of dependent quantities together with the parameter fields themselves.

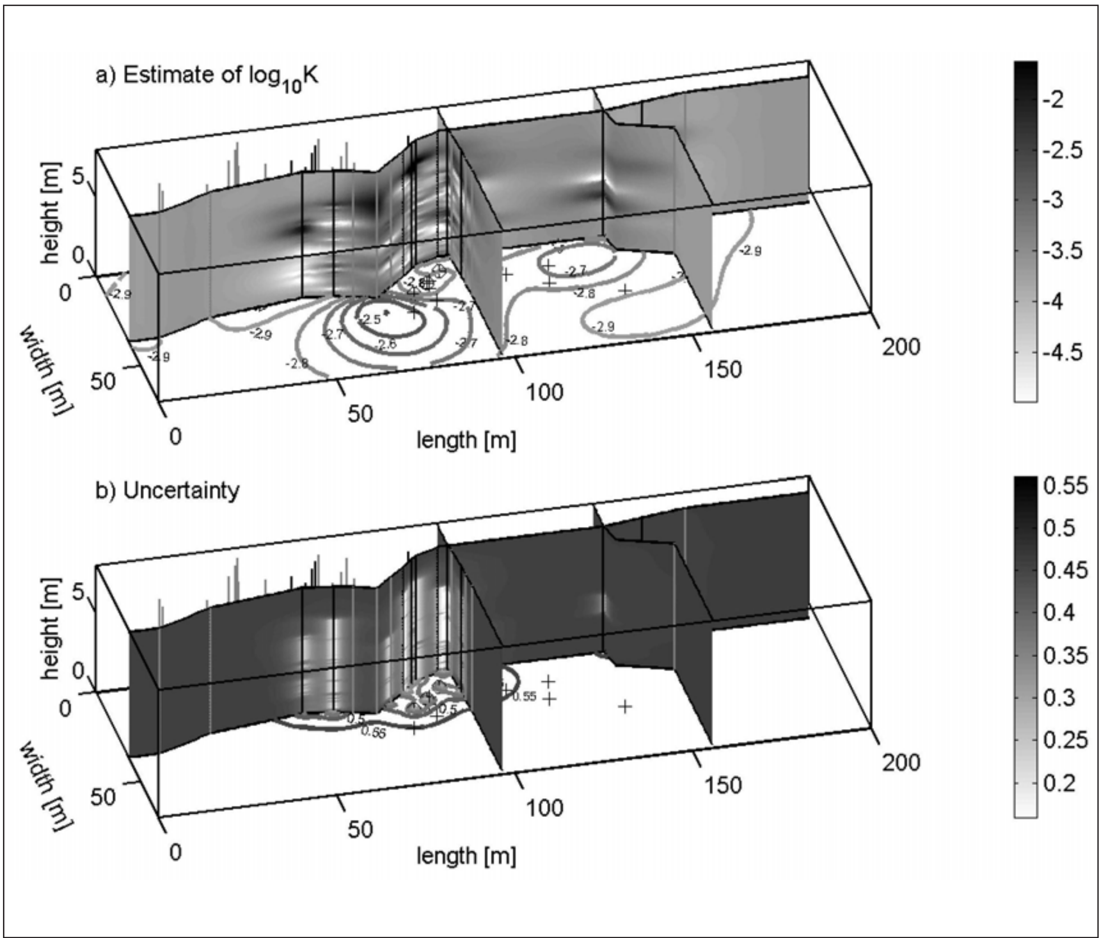

Figure 2: Example of estimated hydraulic conductivity field and associated uncertainty using data from multiple pumping tests and flowmeter tests (Li et al., 2008).

Figure 2 shows an example of coupled 3-D inference of hydraulic conductivity from pumping-test and flowmeter data collected at the Krauthausen site of Research Center Jülich (Li et al., 2007; Li et al., 2008). In the transient pumping-test analysis, temporal moments of drawnow were inverted (Li et al., 2005). For linear transient conservation laws, temporal-moment generating equations can be formulated, which are equivalent to steady-state partial differential equations. Temporal moments for point-like concentrations were successfully inverted to obtain hydraulic conductivity fields (Cirpka and Kitanidis, 2000) and dispersivities (Nowak and Cirpka, 2006). The latter study included the application to intermediate-scale laboratory data (Jose et al., 2004).

The approach of inverting temporal moments has been extended to the analysis of time-lapse ERT data obtained during salt-tracer tests (Pollock and Cirpka, 2010). The moment-generating equations for the perturbations of electrical potentials measured during such a test reuires linearization of the Poisson equation (Pollock and Cirpka, 2008). Figure 3 shows the inversion results of a virtual two-dimensional study (Pollock and Cirpka, 2010). The method has successfully been applied to laboratory data, which are not yet published.

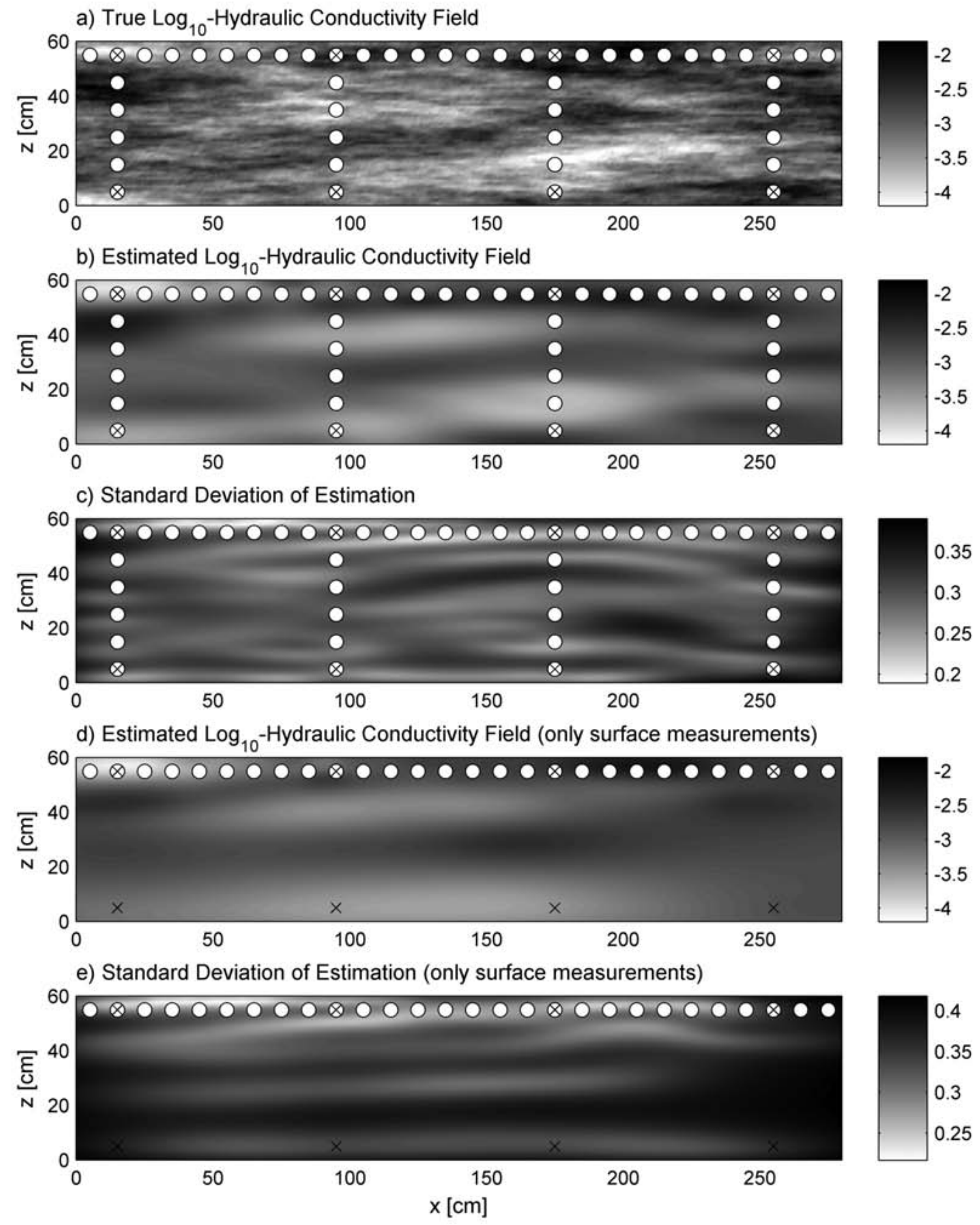

Figure 3. Example of estimated hydraulic conductivity field and associated uncertainty in a virtual test case of fully coupled hydrogeophysical inversion (inverting temporal moments of potential perturbations obtained by time-lapse ERT monitoring of a salt-tracer test).

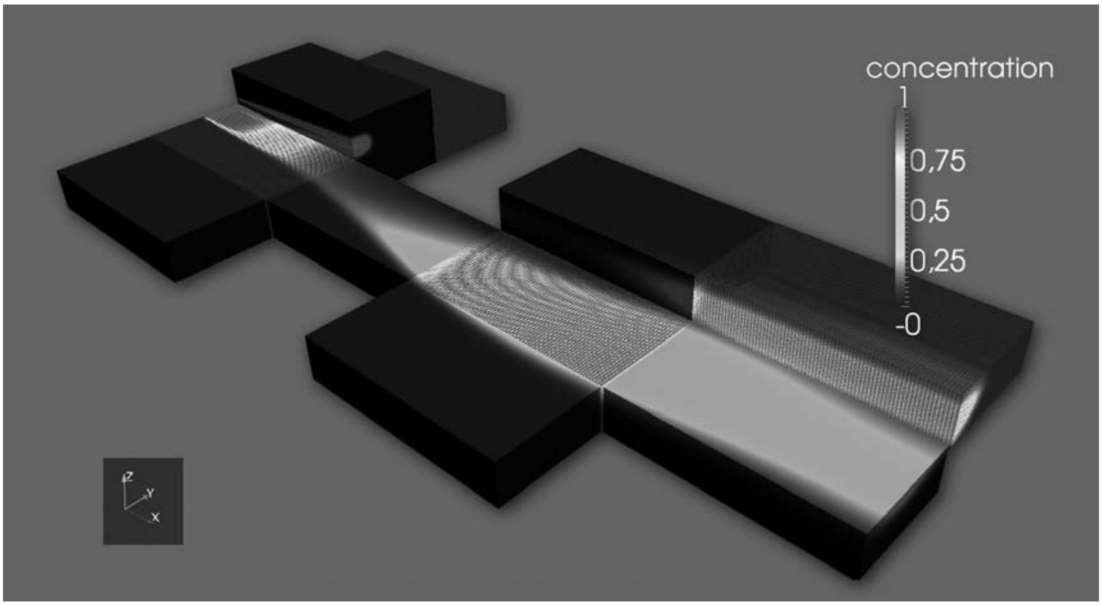

Figure 4: 3-D simulation of steady-state transport using the DUNE framework on 32 processors.

The geostatistical inversion method based on temporal moments has already successfully been transferred from Matlab to the Distributed Unified Numerics Environment (DUNE) for high-performance computing (see Figure 4).

Inversion on computer clusters is needed:

(1) for domain decompositioning of large 3-D domains as shown in Figure 4
(2) parallel evaluation of sensitivities for multiple measurements in Gauss-Newton type inversion
(3) parallel evaluation of condit ional realizations in conditional Monte Carlso simulations.

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Three-dimensional Multi-Scale and Multi-Method Inversion to Determine the Electrical Conductivity Distribution of the Subsurface Using Parallel Computing Architectures (Multi-EM)

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1. Objectives

Geophysical methods are applied to investigate the Earth's interior. We obtain models of the Earth by imaging physical parameters such as density, electrical conductivity, or elastic properties using a range of techniques. Here, we consider geophysical techniques exploiting natural and controlled-source electromagnetic (EM) fields to reconstruct the electrical conductivity structure at depth. During the last years, these techniques have experienced rapid development for exploration purposes of the drillable subsurface. For instance, active controlled-source electromagnetic (CSEM) techniques are now frequently used together with seismic techniques to characterize resistive hydrocarbon reservoirs in offshore petroleum exploration. Deep saline aquifers exhibit high electrical conductivities and constitute one of the prime targets for electrical imaging methods, making these techniques one of the most important geophysical tools to characterize target horizons for CO_2 storage or geothermal reservoirs.

In this project, we attempt to optimize the resolution capabilities of geoelectric potential field and electromagnetic diffusion methods covering a wide range of scales from boreholes to regional or lithosphere dimensions. To reach these goals, we pursue an inter-disciplinary concept, integrating research groups from applied and numerical geophysics, information technology and numerical mathematics. The project partners come from university and non-university research institutions.

For tomographic imaging of a single physical parameter, the electrical conductivity, a number of well-proven techniques are available. In this project, we combine geoelectric methods (direct current - DC), transient electromagnetics (TEM), natural-source magnetotellurics (MT) and controlled-source magnetotellurics (CSMT) (see Fig. 1). The resolution power of the individual methods depends on the experimental design, the strength, geometry, and frequency content of the source fields and the characteristics of the induced current systems. Multi-scale, multi-method inversion strategies yield complementary but usually higher sensitivities when compared with existing inversions of the individual methods. Hence, a combina-

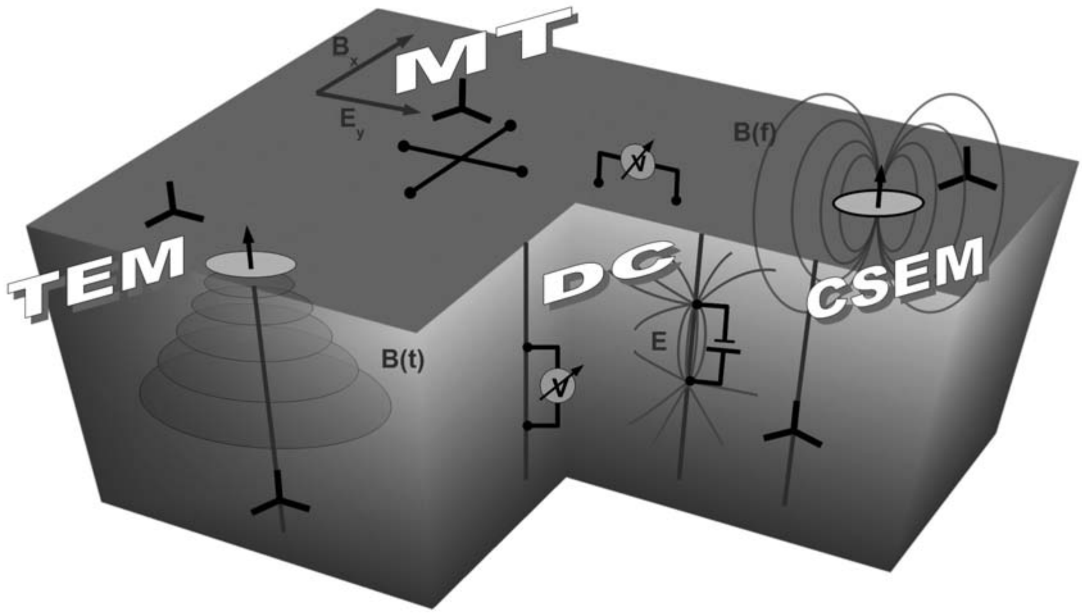

Figure 1: A combination of four electric and electromagnetic methods to enhance the reconstruction of the subsurface conductivity structure. Transient electromagnetics (TEM), DC resistivity, controlled-source electromagnetics (CSEM) and natural-source magnetotellurics (MT) cover a wide range of spatial scale lengths and provide individual and complementary sensitivity patterns.

tion of the various sensitivity patterns is expected to result in

– a better coverage of the model space
– a more complete and better resolved reconstruction of the conductivity structure
– a reduction of model ambiguities.

An effective implementation of multi-method, single-parameter inversions is a prerequisite for subsequent development of multi-method, multi-parameter inversions (e.g. a joint inversion of MT and seismic).

Realistic predictions of structures and materials at depth require three-dimensional modelling. The underlying differential equations can only be solved with numerical approaches, usually using finite difference (FD), finite element (FE) or integral equation (IE) techniques. The subsurface and the physical fields are discretized on grids, which in the three-dimensional domain easily consist of millions of individual cells. The number of these grid cells and associated computations determines the requirements for memory and CPU time. However, a comprehensive image of the subsurface is only obtained with sufficiently fine discretization on a correspondingly large mesh. Solving these complex equation systems requires extremely powerful computers and highly optimized algorithms, which are often beyond the realms of individual working groups.

Considering the enormous numerical complexity of "normal" single-method three-dimensional inversions, the new algorithms will be designed from the beginning for massively parallel computing architectures. Initially, local computer clusters will serve as development environments, but integration with D-GRID or similar international structures is envisaged. The overall goal is to transfer the newly gathered knowledge and infrastructure to the wider geosciences community.

2. Introduction

The inversion of an electromagnetic data set to determine the electrical conductivity structure of the subsurface requires numerical methods. In three dimensions and for practically relevant models, several tens of thousands of data and model parameters are involved. Presently, such computationally intensive problems require high performance or supercomputers. Börner (2010) and Avdeev (2005) review state of the art three-dimensional electromagnetic numerical simulation and inversion strategies.

FD methods simulating the diffusion of transient fields in three-dimensional structures were first developed in the late 1980s (Newman et al., 1986). Wang and Hohmann (1993) introduced a time-stepping approach to compute the electromagnetic fields on a staggered grid (Finite Differences in the Time Domain, FDTD). The FDTD method is attractive because explicit time-stepping methods avoid solving linear equation systems. Commer and Newman (2004) demonstrated a numerical solution of the FDTD method on parallel computers.

A different approach to solving the TEM forward problem was presented by Druskin and Knizhnerman (1994), who introduced the spectral Lanczos decomposition method (SLDM). Here, Maxwell's equations are approximated on an FD grid, which leads to a system of ordinary differential equations. The solution of this system is reduced to the products of functionals of the stiffness matrix and a vector containing the initial conditions. Börner et al. (2008) developed the method of model reductions in the frequency domain (MRFD), which extends the SLDM method by combining it with the advantages of the FE methods on unstructured grids.

Adaptive grids with local refinements have predominantly been applied for FE methods (e.g. Franke et al. 2007; Rücker et al, 2006, Li and Key, 2007, Schwarzbach, 2009). For all of these methods the subsurface is subdivided into a large number of homogeneous cells organized in ordinary or staggered grids (Yee, 1966) for which Maxwell's equations are solved.

Over the last few years, approaches to solve the 3D inverse problem have been suggested based on Newton, Quasi-Newton-, Gauss-Newton and non-linear conjugate gradient methods (Rodi and Mackie, 2001; Newman and Boggs, 2004; Commer and Newman, 2008, Avdeev and Avdeeva, 2009). All-at-once approaches attempt to solve the forward and the inverse problem simultaneously, applying an approximation to the forward solution (Haber et al., 2004). If the amount of data is less than the amount of model parameters, transformation to the data space can be advantageous (Siripunvaraporn and Egbert, 2005). Most inversion procedures are based on Gauss-Newton approaches using various forms of regularization (Smith and Booker, 1991; Oldenburg and Ellis, 1991; Sasaki, 2001; Günther et al., 2006). Often, the objective function represents a trade-off between optimum data fit and minimum structure of the model based on some smoothness constraint (de Groot-Hedlin and Constable, 1990). Newton techniques have favourable convergence characteristics, but require computationally costly second order derivatives of the objective function or derivatives of the sensitivities with respect to the model parameters.

Previous attempts to fit electromagnetic observations by 3D inversion include Patro and Egbert (2008) for magnetotelluric, Haber et al. (2007) for TEM, and Newman et al. (2010) for CSEM data. Commer and Newman (2009) consider the joint inversion of MT and CSEM data.

3. Work plan

Multi-method inversions of geoelectric and electromagnetic data require optimized and parallelized algorithms for the forward simulation which have to be well adapted to the specific resolution and model regularization of a particular method. The efficiency and suitable parallelization strategies for forward operators depend on the particular electrical or electromagnetic method. Inversion strategies, in contrast, can be developed largely independently of the individual methods. Nevertheless, multi-scale, multi-method inversions depend strongly on the regularization and model resolution of the individual methods. We therefore divide our work packages into tasks that can be addressed separately before being merged in a second step.

Multi-scales are introduced by different spatial resolution capabilities of the methods under consideration. Borehole tomography, for instance, can image the direct vicinity of a well at very high resolution, whereas MT measurements conducted at the surface of the Earth cannot provide additional information at this scale. Conversely, well-logging cannot reveal structures of the subsurface at larger distances from the borehole. When combining both methods, the overlapping resolution domain is small and the multi-scale information content of the data is large. A common model that is consistent for both methods will be resolved in separate regions at dissimilar scales depending on the individual methods. The expression of the transition between resolved model domains and their inherent scales in the final model depends strongly on the regularization.

MT and CSMT are frequency domain methods using virtually identical sensor technology and similar survey geometry. Whereas passive MT

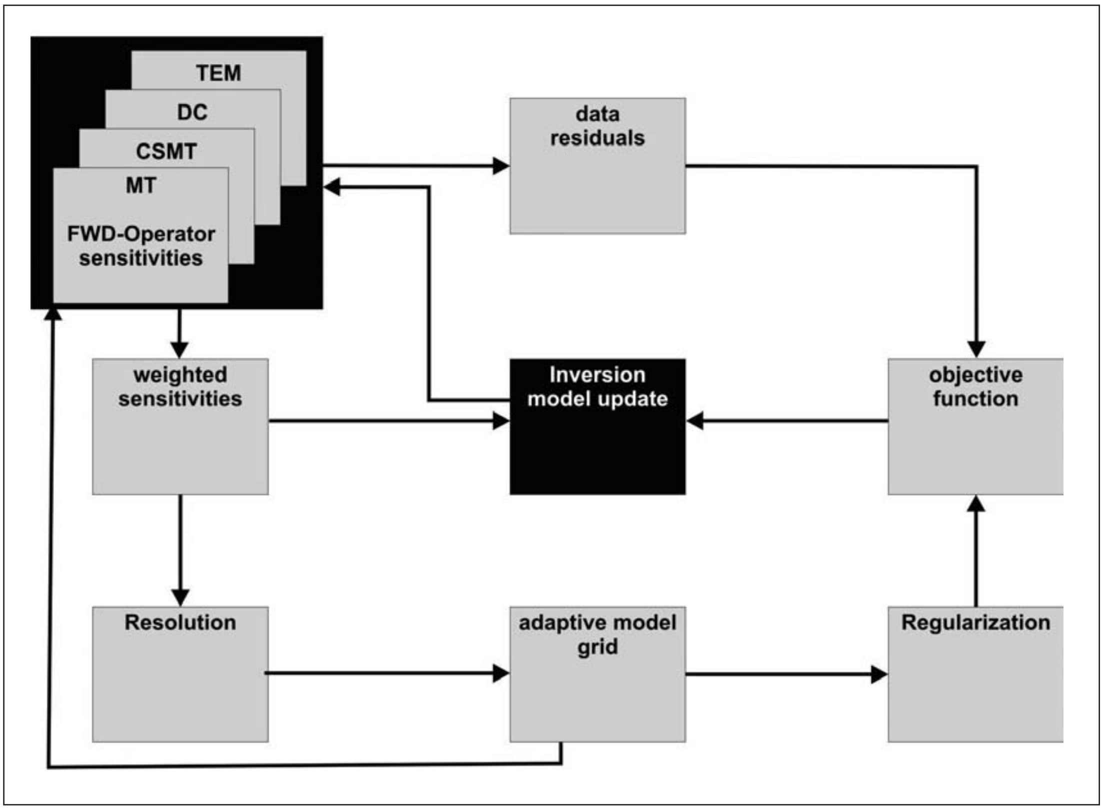

Figure 2: Flow chart of a multi-scale, joint EM inversion. In non-linear inversion, an objective function is defined, representing a measure of the distance between measured and synthetic data (i.e., data residuals). Synthetic data and data residuals are computed by applying a forward operator to a parameter model. Generally, the objective function is extended by a regularization term, which stabilizes the system and limits the solution space more or less arbitrarily. For joint inversion, we have to consider additional issues related to combining the methods. These include different resolutions (handled by using weighted sensitivities), optimized model discretizations (adaptive grids), and appropriate regularization techniques.

sources are usually assumed to be plane waves, in processing CSMT data, the geometry of the source and the near-field characteristics of the excited EM fields have to be considered. CSMT and classical MT have overlapping resolution domains on similar spatial scales. However, their sensitivities with respect to conductivity structures differ and are partly complementary. Due to the excitation of different current systems in the subsurface in MT and CSMT, MT has a high resolution potential for lateral conductivity variations, whereas CSMT has a comparatively better vertical resolution power for horizontal layering and for poor conductors. A combination of both methods by joint inversion should therefore be well-suited to increase the overall resolution beyond that of the individual methods, independently of the applied regularizations (Commer and Newman, 2009).

In subproject I (see below) the GFZ Potsdam group concentrates on the above mentioned combination of MT und CSMT. First, a 3D joint inversion of "normal" surface MT and CSMT data shall be developed (WP 1.02 – 1.04). Subsequently, this inversion will be extended by introducing resolution- and scale-dependent regularization strategies (WP 1.05) to facilitate, e.g., an integration of borehole data.

The main focus of the Freiberg working group is the combination of transient electromagnetics (TEM) and the DC resistivity method in subproject II. In WP 2.1 and WP 2.2 the specific sensitivity patterns of the individual methods are combined to enhance the resolution power for a given target area (WP 2.6). Both, DC resistivity and TEM can be applied from the surface or within boreholes. Using sensitivity and resolution analyses (WP 2.4, WP 2.5), optimum transmitter/receiver configurations can be determined to optimize experimental designs. In the mathematical part of WP 2.3, procedures will be developed to increase the efficiency of the geophysical interpretation techniques. Particularly, we will address model reduction in the frequency domain (MRFD), the spectral Lanczos decomposition method including restarts, so called thick restarts, rational Lanczos methods, and multigrid techniques.

The enormous complexity of three-dimensional inversions calls for the use of massively parallel computing architectures. In addition to the parallelization of numerical algorithms (WP 1.03, 1.09), this requires the development of scheduling algorithms to coordinate the execution of computing jobs in a distributed computing environment (WP 1.10). Job scheduling is particularly important when grid architectures are used as a computing resource (Fernandez-Quiruelas et al., 2009).

Subproject 1: Joint inversion of CSMT and MT, implementation of concepts for distributed computing.

WP 1.01

Benchmarking of various existing 3D MT and 3D CSMT forward and inversion codes.

WP 1.02

Extension of a 3D code for joint inversion of CSMT und MT:

The development of the joint inversion will combine the modular, open source code from Egbert (Egbert et al., pers. communication), which presently includes a range of options for MT modelling and more generally applicable inversion schemes, with existing CSEM modelling codes (Streich, 2009; Streich and Becken, 2011). In addition, optimized strategies for regularization and design of the inversion meshes for a joint CSMT and MT inversion must be defined, considering the different and complementary sensitivities of the two methods (WP 1.04). Furthermore, global weighting of the individual methods as described by Commer and Newman (2009) can be used.

WP 1.03

Efficient parallelization of implemented algorithms:

We will develop and implement parallelization strategies that are specific to each individual method. For instance, when using iterative solvers, the MT forward problem can be computed in parallel for each period and polarisation, and the sensitivity matrix can be computed for all receivers autonomously. We will also utilize parallelized direct solvers, initially for CSEM modelling and inversion. Direct solution approaches are memory-intensive, but advantageous if solutions for many sources and sensitivities for many receivers are required. Inversion techniques which so far have been considered impractical because of the large number of forward modelling solutions required may thus become feasible. In addition to these different levels of parallelization within our modelling and inversion algorithms, we shall also use and possibly adapt parallelized algorithms for matrix operations, such as PETSc, PSBLAS or ScaLAPACK (see also WP 1.09 and 1.10).

WP 1.04

Multi-grid methods and adaptive meshes for multi-scale problems:

Scaling properties of CSMT and MT models may be comparable, but the spatial behaviour of the associated electromagnetic fields differs significantly between the two methods. Whereas the external magnetic source fields in MT can be treated as quasi-homogenous plane waves, the source fields and secondary currents in the vicinity of a CSMT transmitter are extremely heterogeneous and exhibit strong gradients. Consequently, numerical CSMT simulations generally require much finer meshes than MT simulations, and local mesh refinements near the source can be advantageous for CSMT simulations. To generate optimized meshes that permit accurate computations of EM fields using as few cells as possible but as many as necessary, adaptive methods for grid refinement shall be applied in the forward computations. Similarly, for the inversion, we will develop adaptive methods that adjust the mesh according to the model sensitivities. Adaptive inversion meshes will also be used in the multi-scale inversion of combined borehole and surface measurements (see also WP 1.05).

WP 1.05

Optimisation of regularisation schemes:

All electrical and electromagnetic inverse problems are ill-posed and require regularization. Common regularization schemes impose smoothness constraints on the electrical conductivity structure. The solution is then determined as a trade-off between the model norm (or an a priori defined semi-norm) and the data residuals. Usually, model structure is penalized with a (weighted) global constraint, which may lead to over-regularisation of well resolved model domains and under-regularization of badly resolved regions. Such global penalties are inappropriate for multi-scale inversion algorithms. We therefore aim to develop a posteriori regularization strategies that depend on the model resolution on a local scale, possibly making use of strategies similar to Scherzer et al., 1993; Kaltenbacher and Schicho, 2002; Raus and Hämarik, 2009, which are not yet widely used for EM inversion.

In multi-grid approaches, a resolution-dependent regularization can be found by discretizing the model space depending on the resolution and defining the regularization operator in the model space: Well-resolved model regions are finely discretized and thus require little regularization. Kaltenbacher and Schicho (2002) show that such an approach converges for ill-posed non-linear problems. In this work package, we attempt to develop an implicit local regularization by adaptive model parameter discretization for multi-scale problems, such as the joint inversion of surface and borehole data. This first requires testing strategies for adaptive model refinement (see also WP 1.04).

WP 1.06

Wavelet parameterisation:

To reduce the number of degrees of freedom in the model and the associated size of the inverse problem, the model parameters can also be represented in the wavelet domain. A major challenge in using wavelet parameterisation is identifying the significance of coefficients, as predicting the significance of coefficients for the next iteration will be necessary when solving nonlinear equation systems iteratively. For an efficient inversion, these predictions must be achieved without explicitly computing the wavelet coefficients. To this end, we attempt to transfer methods for adaptive model discretization of WP 1.04 to the wavelet domain.

WP 1.07
Application to existing field data:
The newly developed inversion schemes will be applied to and tested with existing field data. MT data sets with areal site coverage that are suitable for 3D inversion are available from various projects (Namibia, South Africa, Dead Sea Transform, San Andreas Fault, North-German basin, Groß Schönebeck). Within the ongoing GeoEn project, the GFZ working group has acquired a large CSMT data set in the vicinity of the CO_2 sequestration test site near Ketzin. Since MT data were also collected in the same survey, these data may be used for testing the multi-scale joint inversion.

WP 1.08
Communication Platform:
Implementation of a web-based communication platform that will serve as a tool for an exchange of experiences, to publish best practice guides, and to document project and administrational matters. The platform will be available throughout the project and after the project has ended.

WP 1.09
Implementation of parallel computing and open source packages on the compute cluster:
For the development of parallel algorithms, several Message Passing Interface (MPI) software packages, which are capable of using the infiniband network, and compatible Fortran and C compilers (Intel, Portland, GNU) are installed on the GFZ computer cluster. In this work package we will investigate the combination of distributed memory, MPI-based and shared-memory (OpenMP) parallelization that can be used within multi-core cluster nodes.

WP 1.10
Development of scheduling algorithms for distributed computing:
In addition to the compute cluster of the GFZ, the project aims to facilitate the use of Grid computing technologies, such as the D-GRID network (Klump and Häner, 2005). Besides parallelization of algorithms, the distributed nature of the Grid requires development of scheduling algorithms to orchestrate distributed compute jobs dispatched to remote Grid computing nodes. The Grid resources will be made accessible through a web portal. The results of this work package will be disseminated to the project partners and a wider user community via the workshops and the project communication platform (WP 1.08). A longer-term goal of this work package is to facilitate access to the compute and storage resources of the Grid for the geosciences community to provide computing resources which are well beyond the current means of individual research groups. We have initiated discussions to coordinate these efforts with the BMBF-funded WissGrid project.

Sub-project 2:
Joint inversion of transient electromagnetic and DC resistivity methods

WP 2.01
Further development and parallelization of forward modelling operators for DC resistivity methods: (see WP 2.02).

WP 2.02
Further development and parallelization of forward modelling operators for transient electromagnetic (TEM): The working group in Freiberg have developed their own, fast forward operators for DC electrics (Rücker et al., 2006) and TEM (Börner et al., 2008). Both codes use an unstructured grid finite element approach (Lagrange type for DC resistivity and Nédélec type for TEM), such that given structures can be transferred to synthetic models in great detail. These codes are powerful tools for practical use. Within this work package we want to

assess if the originally sequentially structured codes can be parallelized or have to be reengineered to facilitate efficient parallelization.

WP 2.03

Further development of the spectral Lanczos method: The interpretation software for TEM data, which has been developed during the last three years within the DFG project 'Numerical simulation of the propagation of transient electromagnetic fields for the exploration of the subsurface', is based on the finite element discretization of the three-dimensional quasistatic Maxwell's equations in space (Nédélec elements) and the solution of the semi-discrete problem by advancing the spectral Lanczos decomposition method (SLDM) using restarts (Eiermann and Ernst, 2006). Restarted algorithms reduce the memory requirement of SLDM significantly (or supersede a second run of the Lanczos algorithm, respectively). However, they converge generally slower than the variant without restarts. Another newly developed approach called 'thick restarts' may compensate the loss of speed without waiving the advantages of restarts. This technique will further accelerate our forward solver. In recent years, so called rational Lanczos methods were investigated at the Institute of Numerical Analysis and Optimization as an alternative to the classical Lanczos method. The crucial advantage of this method is the fact that its convergence rate does not depend on the size of the problem (at least for the problems at hand). Whereas classical SLDM needs additional iteration steps with increasing resolution to reach a given accuracy level, the number of iterations remains constant for the rational Lanczos method – an important advantage for the solution of very large problems. Since for the rational Lanczos method one linear system of equations of the type $(A - \lambda I)x = b$ has to be solved in each iteration step with A being the discrete version of Maxwell's equations and possibly including a complex shift λ, fast solvers are an essential prerequisite for the application of these methods. Therefore, we need to apply multi-grid methods that are specifically developed for the curl-curl operator and have been shown to exhibit robust convergence rates with respect to the choice of the shifts.

WP 2.04

DC resistivity method:

resolution analyses, optimization of the experimental design (see WP 2.05).

WP 2.05

TEM: resolution analyses, optimization of the experimental design:

Apart from the actual simulation, the computation of sensitivities is complicated and numerically very costly. Günther et al. (2006) und Baranwal et al. (2007) have developed working inversion codes which have increased our knowledge about resolution characteristics of the DC and TEM methods (see also Spitzer, 1998). For both applications, we employ adjoint field techniques, which have partly been implemented (Ullmann, 2008), but require further development and adaptation to large and powerful computers. The envisaged modular, flawless inversion code would simplify an efficient parallelization. By means of a joint DC/TEM inversion we can investigate the resolution characteristics of different experimental designs in order to optimize the resolution power of field experiments. In other words, we intend to develop a tool telling us where to place receivers and sources to obtain an optimal (with the highest resolution) image of the target structures (see Stummer et al., 2004).

WP 2.06

Combination of both methods in a joint inversion:

After developing the individual inversion algorithms for TEM and DC, we will start implementing a joint inversion scheme. In this context, problems with the combined parameterizations have to be solved. By means of sensitivities we can compute resolution matrices to assess the resolution characteristics of the individual methods and subsequently of their combination.

Common sub-project III: Synthesis, knowledge transfer and publications

WP 3.01
Definition of interfaces:
For combining the modules developed in sub-projects I and II, suitable interfaces have to be defined and incorporated into the developed codes. The interfaces will initially be defined in the workshops at project commencement. Necessary extensions and adjustments will then be agreed upon during consecutive workshops (WP 3.03) and using the communication platform (WP 3.04).

WP 3.02
Synthesis of DC, TEM, MT and CSMT:
Questions concerning parameterization, modularization, implementation and parallelization of the individual methods and eventually their combination will be examined in close cooperation between all working groups of sub-projects I and II. Once the separate inversions are running, they will be combined into a common joint inversion scheme. All working groups will be involved in this task.

WP 3.03
Workshops:
Part and parcel of this cooperation are regularly held workshops where project partners and their associated working groups meet. These workshops will be held every 6 months, alternating between Freiberg and Potsdam. The workshops participants will report on the status of the ongoing work, develop common inversion strategies, and use synergies to parallelize and implement inversion codes.

WP 3.04
Information platform:
In addition to the workshops, communication between project partners will be supported by web-reporting and web-based tools (see WP 1.08). Information will be processed by project participants and made available to all partners.
WP 3.05
Scientific results obtained within this project will be presented at national and international conferences and published in international, peer-reviewed journals.

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

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Introduction and overall objective

Spectral induced polarization (SIP), more generally known as electrical impedance spectroscopy (EIS), is a geophysical method in which the frequency-dependent, complex electrical conductivity (or its inverse, complex resistivity) of soils and rocks is measured, typically in the mHz to kHz range. In the absence of electronically conducting minerals, the complex electrical conductivity is a measure of ionic conduction in the water-filled pores and along the water-mineral interfaces (real part of complex conductivity) as well as ionic polarization in the vicinity of electrically charged mineral surfaces and constrictions in the pore space (imaginary part of complex conductivity) as response to an electric field (e.g., Leroy et al., 2008). Recent research has demonstrated that EIS has enormous potential for improved lithological and textural characterization (e.g., Vanhala, 1997; Slater and Lesmes, 2002), direct hydraulic conductivity estimation (e.g., Binley et al., 2005; Zisser et al., 2010), and for elucidating biogeochemical processes associated with remediation treatments (e.g., Williams et al., 2009). This potential arises from the fact that the complex conductivity is directly affected by pore space geometry, pore fluid chemistry and mineral surface properties. In principle, the 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-

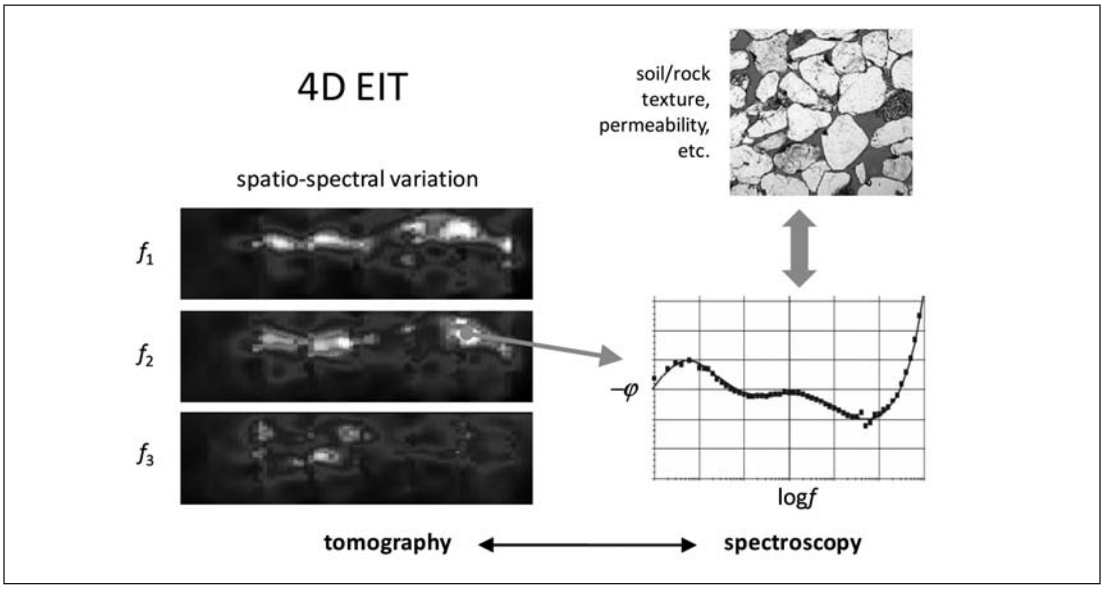

Figure 1: Concept of 4D (3D space plus frequency) electrical impedance tomography. Left: spatial tomograms of resistivity phase (φ) at different measurement frequencies (f_i). Right: Local resistivity phase spectrum and soil/rock characterization options.

sion of spectral data based on an appropriate regularization in the frequency domain. The latter should account for the typical, or expected (a-priori information), electrical relaxation behaviour as described by established phenomenological models. Thus, for 3D parameter variation in space a 4D inverse problem with spatio-spectral regularization results. The development, implementation and testing of an inversion algorithm for 4D spectral EIT is the focus of SP1.

The diagnostic capability of EIS generally requires broadband spectral information, typically in the range of 1 mHz to 1 kHz, with a high phase accuracy (in the order of 1 mrad) of the collected impedance data. Unfortunately, capacitive and inductive effects inherent to the EIT instrument or associated with the wire layout superimpose the response of the subsurface and typically start dominating the signal above 10 Hz. This circumstance limits the useful frequency band of available instruments to below 10 Hz, in turn putting severe constraints on the soil/rock characterization capabilities (e.g., silts and clays are most responsive above 10 Hz). However, the different coupling effects, including those originating in the instrument, can 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

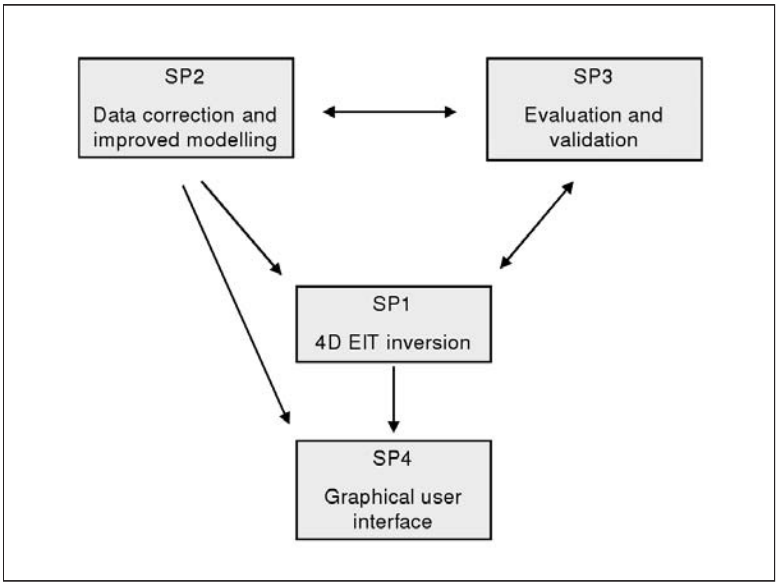

Figure 2: Main tasks of and interactions between subprojects.

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.

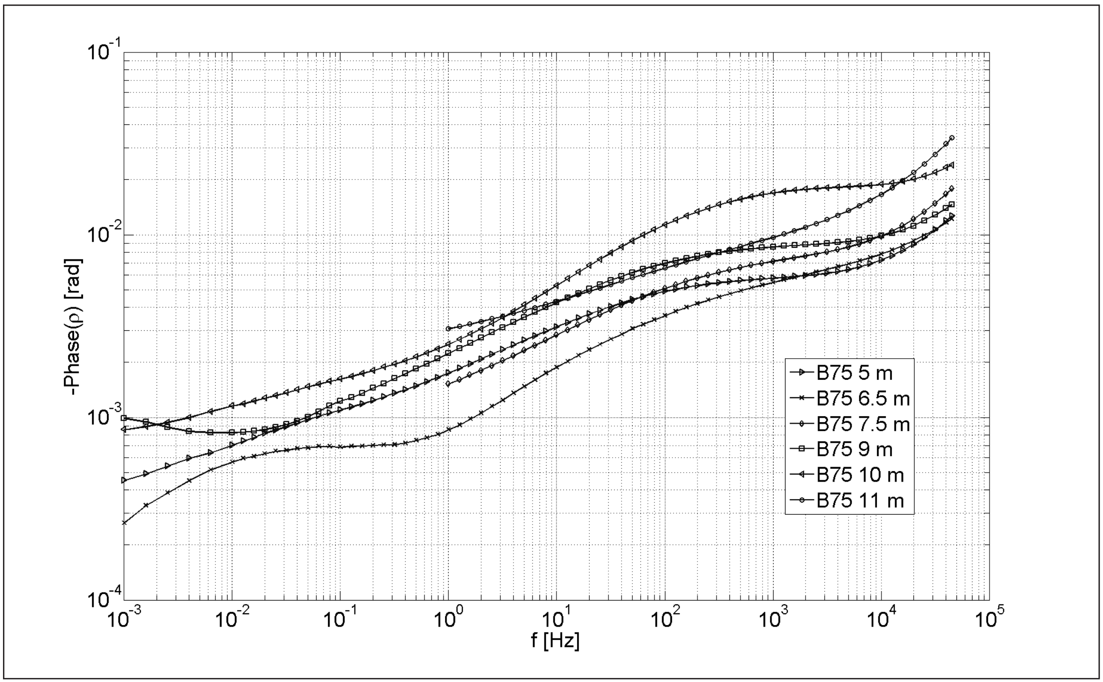

Figure 4: Resistivity phase spectra as measured on material from different depths from the Krauthausen test site in the laboratory using an impedance spectrometer with high phase accuracy.

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

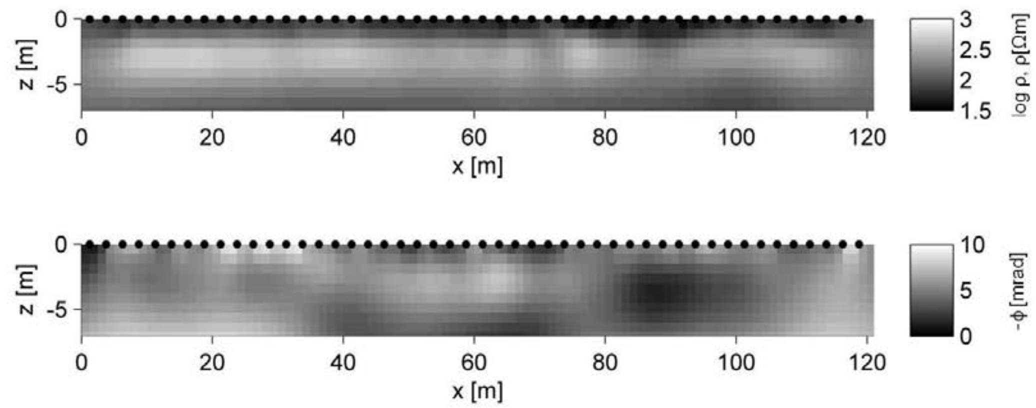

Figure 5: Images of resistivity magnitude (top) and phase (bottom) inverted from EIT data collected at the Krauthausen test site using the commercial measurement system SIP256C by Radic-Research.

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 standalone 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.

Acknowledgement

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TOAST
(TOolbox for Applied Seismic Tomography)

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Abstract

The time has come to exploit the full richness of broadband, three-component waveforms. The inversion of full seismograms leads to a tremendous improvement in imaging resolution due to the ability to map structures that are smaller than the seismic wavelength. In addition, it provides important constraints on density and attenuation. State-of-the-art software for full waveform tomography is available in scientific environments but is not yet accessible to the practitioner. The Toolbox for Applied Seismic Tomography (TOAST) will open a new window to seismic inversion. Due to advances in available computational resources and recent developments in high performance and parallelized computing, 3D inversion of full seismograms is within reach. By combining tested code collections for waveform modelling and the solution of large inverse problems, complemented by experience in the management of large software projects and by sound expertise in the inversion of elastic waves from the centimeter to the kilometer scale, the cooperation of the TOAST project partners will provide a unique knowledge base for implementing flexible and efficient tools for full waveform tomography and to transfer the knowledge to industrial practice. The TOAST project pursues the concept of modularization. It will provide modules that interact through standardized interfaces and thereby can be re-combined in application-specific and efficient ways. The Toolbox for Applied Seismic Tomography will prove its worth through application to surveys from commercial practice. Existing data from seismic experiments at different scales (e.g., monitoring of embankments, CO_2 sequestration studies) and newly aquired shallow seismic and ultrasonic data will serve as case studies to validate the functionality of the toolbox.

Introduction

For an improved estimation of subsurface parameters we need to exploit the full information contained in threecomponent seismic waveforms. Of particular importance is the estimation of the independent elastic parameters that characterize the properties of the subsurface. Waveform tomography is a cutting-edge inverse method that accounts for the full seismic waveform recorded over a broad range of frequencies and apertures. It iteratively retrieves multiparameter models of the subsurface by solving the full viscoelastic wave equations each time. It allows for a mapping of structures on spatial scales down to less than the seismic wavelength, hence providing a tremendous improvement of resolution compared to travel-time tomography based on ray theory.

Many examples published in recent years demonstrate that waveform tomography can image the interior of the earth and of material specimens on a wide range of scales. It has successfully been applied to seismological scales (Friederich, 2003), subduction zones (Operto et al., 2006), basalt structures (Chironi et al., 2006), shallow environments (Forbriger 2003; Gao et al., 2007), material testing (Pratt 1999), and even breast tissues (Pratt et al., 2007). We can therefore anticipate a rich future of this approach for a wide range of applications.

Tomographic problems are commonly solved using highly-specialized monolithic computer applications at the expense of flexiblity, transparency, portability and extendibility. Within the TOAST project, a flexible and modular toolbox for 1D, 2D, and 3D full waveform inversion will be created.

Existing software that has been developed and maintained by the participating partners will be assembled and grouped into three modules, which will interface through appropriate definitions of data and parameterization formats, input/output routines and parameter file translation tools. The whole collection of software will establish the toolbox which will be used to design and solve applied inverse problems. The toolbox will also contain components to prepare initial models from field data for subsequent waveform inversion. It will further contain tools to explore the null-space of the model, as well as tools to perform a quantitative resolution analysis. A deliberate definition of the representation of model parameters will allow for future extension to non-seismic observables, which is beyond the scope of the present project.

On one hand, the toolbox strives to facilitate access to tomographic methods for users from fields of applied science and engineering. On the other hand, it is designed to assist the expert scientist in solving highly demanding inverse problems. To all users, the added value of a modular product such as TOAST will be the freedom to start data exploration with very basic tools, and to gradually escalate the level of sophistication as their experience, the amount and understanding of their data, and their computational resources increase. Studies on the spatial scales adressed by TOAST will benefit in particular because they often start from a very vague understanding of the structure under investigation. Here, the modular toolbox will develop its full strength by supporting the scientist from the first simple model to a final high-end waveform tomography.

The success of this approach relies on professional code management. Format definition standards and best practices must be established. Interaction between working groups will be supported by a version-controlled software repository and documentation standards. Parallelized code must be implemented on several platforms. Code benchmarking and scalability will be accounted for.

The toolbox will be benchmarked through application to field data. Within the project, it will be tested on different scales from centimeters to meters in ultrasonic studies, and over tens of meters to kilometers in seismic studies. The requirements for seismic inversion at different scales differ significantly. While solutions to 1D problems on the seismological scale are standard nowadays, they are still challenging on the shallow seimics or ultrasonic scale, where initial models are missing for each individual sample or site. The variety of heterogeneity encountered (predominantly horizontal layering, full 3D heterogeneity, or even holes in the samples) calls for very flexible inversion tools.

The results of these studies will be compared to other observations (dynamic probing, resonant columns, etc.), thus providing a benchmark and calibration of seismic results to petrophysical parameters. Through close cooperation with industrial partners, exemplary datasets for all spatial scales will become available to the project. Additionally, exemplary data sets will be acquired at low cost in a field laboratory, and optimal acquisition strategies for waveform inversion will be developed. In return, the industrial partners will benefit from the tools created by the project for their future applications.

Structure of the project

The structure of the project is visualized in Fig. 1. The core of the project is work package WP1 where the actual toolbox will be created. Software implementations of inversion modules are prepared within three tasks. WP1 is complemented by work package WP2, where the toolbox is applied and tested on different scales in two tasks. WP2 provides calibration and benchmarking on field data and establishes the transfer of knowledge and tools to companies and industrial practice. Work package WP0 is the substratum for the success of the whole project. Professional management of code and information based on seismological expertise is required to foster a frictionless cooperation of all tasks and an enduring final product.

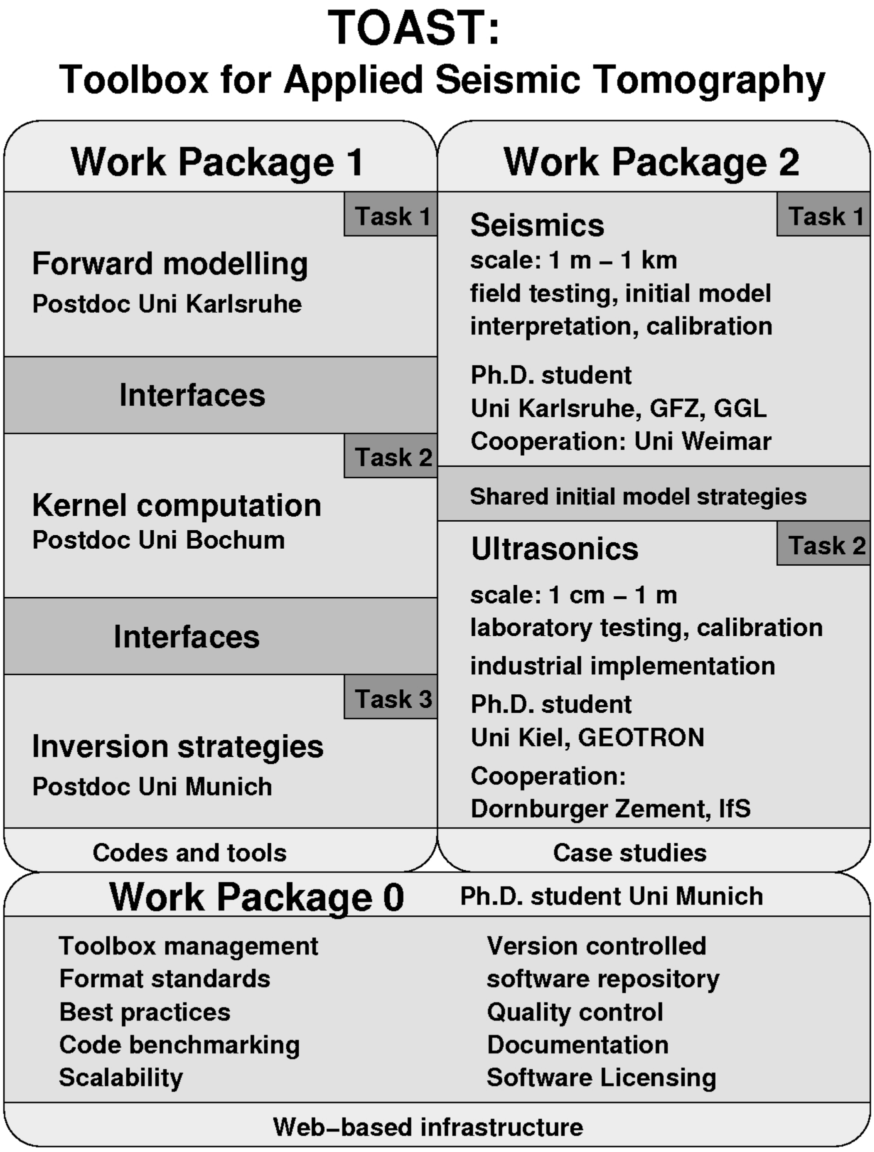

Figure 1: Structure of the project and work package interaction

Work package 0: Management of the Toolbox for Applied Seismic Tomography

Development and maintenance of a central web-based IT infrastructure that serves as a platform for the software development, distribution of project relevant information amongst partners, and dissemination of project results and software products. The key objectives of this work package are:

– to define common standards for seismic data and model formats in line with international developments
– to establish a version-controlled software and documentation repository
– to establish quality control (e.g., through benchmarking) of the software products

Work package 1: Design and implementation of the Toolbox for Applied Seismic Tomography

Work package WP1 provides the actual toolbox. The toolbox realizes a modularization of the inverse problem into its basic components forward modelling, sensitivity kernel computation and equation system solving including resolution and uncertainty analysis (Fig. 2). The tasks defined below reflect this structure. Each of the tasks will be coordinated by one postdoc with experience in scientific computing. Their essential duties will be the collection, implementation and testing of existing codes and the design of interfaces that guarantee a seamless flow of data between codes inside each building block. To realize the interfaces, several standards must be defined: a format for the

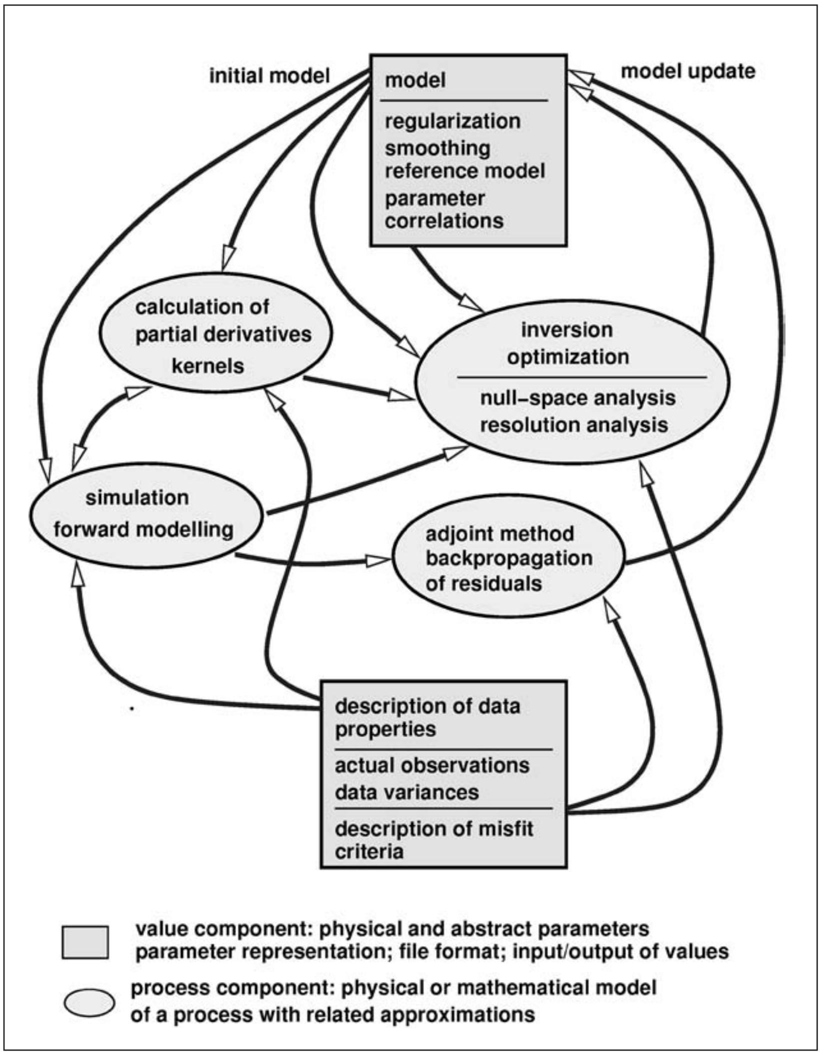

Figure 2: The components of the toolbox reflect the structure of the generic geophysical inverse problem

data and the aquisition geometry, several ways to parameterize the earth model and schemes for the regularization of the inverse problem. The software will be managed through a web-based infrastructure developped in working package WP0.

WP1 Task 1: Forward modelling

Precise forward modelling is not only the key to reliable inversion, it is also valuable in parameter studies and in the search for initial models. Existing codes for full wavefield elastic modelling, ray-tracing, Green's function and traveltime calculations will be collected, documented, and tested using benchmark models. The toolbox will contain forward modelling codes for 1D media (e.g. GEMINI, reflectivity method, normal mode summation), and for 2D and 3D (visco-)elastic media (e.g. Finite differences, spectral elements, ray-tracing, Born approximation, eikonal solver). For the modular application (1) formats and interfaces for measuring geometry will be defined and implemented in order to ensure interoperability with respect to survey geometry, (2) model exchange will be allowed by the implementation of specific conversion routines between structural parameterizations and computational grids. Both will be defined and implemented in close cooperation with Tasks 2 and 3 as well as WP0.

Full waveform inversion requires very accurate forward modeling. So far benchmark tests were accomplished by comparing finite difference results with analytical solutions and results from wavenumber integration methods. A comparison of the finite difference code in use (Bohlen, 2002) showed a very good agreement with analytical solutions.

To avoid artefacts due to numeric wave reflections from the boundary of computational model grid, Perfectly Matching Layers (PML) according to Komatitsch & Martin (2007) were implemented in this code. This turned out to be necessary for the accurate calculation of surface waves. These layers are designed in a way, that the reflection coefficient is zero for analytical solutions. Compared to exponential damping within the absorbing boundary, PMLs can suppress reflections much more effectively. They also work well for large incident angles and surface waves

WP1 Task 2: Kernel computation

Applications for the computation of partial derivatives of the seismic wavefield with respect to perturbations of density, seismic velocities and eventually petrophysical quantities (so-called sensitivity kernels) will be implemented and tested. Four different applications are considered:

– waveform sensitivities based on Green functions for 1D and 3D background media
– waveform sensitivities based on normal modes for 1D background media
– partial derivatives of surface wave phase velocities and finally
– finite-frequency sensitivity kernels of amplitude and traveltimes based on ray theory

Input data are Green functions, normal modes or travel times provided by the different forward modelling codes in the toolbox. The codes will provide sensitivities for wave propagation problems on very different scales and for background models of different complexity. The sensitivity output will be adjusted to the model parameterization schemes defined in Task 3. In addition, interfaces to the aquisition geometry and the equation solvers as well as appropriate conversion routines for experimental and synthetic data will be provided.

To date, a kernel calculation program was assembled which calculates 3D kernels based on synthetic displacements and Green functions for 1D or 3D background media. First simple routines for plotting the kernels were integrated. The program provides a flexible modularized structure that allows the use of arbitrary 1D or 3D forward modelling methods, as well as different parameterizations. For some 1D and 3D forward modelling methods, namely

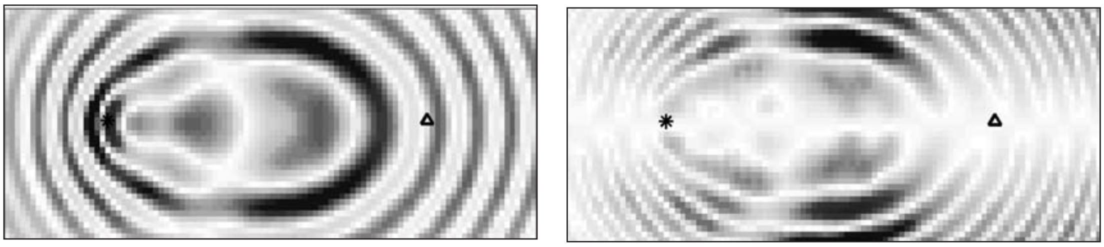

Figure 3: Horizontal cross section below source and receiver through a kernel which provides the sensitivity of the vertical (left) and transverse (right) displacement spectrum to changes of P-velocity. The star and the triangle mark projections of the source and receiver positions, respectively.

GEMINI (1D) and SPECFEM (3D), we produced suitable output for calculating the kernels. The figures below show a horizontal cross section below source and receiver through a kernel which provides the sensitivity of the vertical (left) and transverse (right) displacement spectrum to changes of P-velocity. The star and the triangle mark projections of the source and receiver positions, respectively. Sensitivity of a specific wavelength, which here is one ninth of the length of the area shown, is plotted. A simple 1D gradient model was used for the simulations.
The kernel code will be extended to FD forward modelling codes and veryfied by comparing results for one selected benchmark reference model.

WP1 Task 3: Inversion strategies
Here we deal with the final steps of every tomographic study: finding solution(s) to the inverse problem and assessing their quality. We will design and implement a reasonable number of parameterization standards (»earth models«) onto which the sensitivity kernels of Task 2 can be cast. Regular and unstructured grids will be supported, as well as joint inversion of multiple data types, or inversion for multiple parameters. Parallelized versions of a few tested, iterative solvers will be provided. Assessing a solution's non-uniqueness and resolution are crucial challenges, in terms of computational cost as well as intuitive grasp of the analysis. Tools will be implemented to generate various resolution tests and nullspace analyses for the supported model formats. They will be accompanied by interactive visualization tools for intuitive exploration of the results.

The inversion strategy tested during the first year of TOAST at LMU is a Monte Carlo based approach, and specifically the Neighbourhood Algorithm, a global search procedure (Sambridge 1999a, 1999b). This technique allows us to sample properly the whole model space and to extract robust information about the probability density functions, together with the uncertainties, of model parameters. Each sampled model is associated with a misfit function which measures the discrepancy between observed and predicted seismograms. The latter are evaluated from solving the forward modelling which is given by the Gemini code of Friederich & Dalkolmo (1995).

A crucial disadvantage of this present approach is the high computational cost with increasing the number of model parameters due to the curse of dimensionality. Indeed, the space grows exponentially with large unknowns and so does computational time. For this reason a full space sampling approach is practical only for defining elastic properties of 1-D models (layered subsurface structures).

In the context of TOAST, a very fruitful application of the Neighbourhood Algorithm concerns the ultrasonic scale. After having implemented and tested both, the serial and parallel version of Neighbourhood Algorithm and Gemini codes together, we applied this technique to ultrasonic data, thus inferring the elastic properties of a block of Plexiglas (data are provided by partners in WP2 Task 2). We tested different densities of sampling the model space in order to set up the whole code efficiently by trial and error. Furthermore, we used various geometries of the model to study the behaviour of ultrasounds within the block of Plexiglas.

Full waveform inversion for shallow seismic surface waves on 2D structures is in preparation. The use of surface waves is particularly interesting because they dominate the wave field in shallow seismics. A further advantage is their sensitivity to the S-wave velocity. The underlying inversion code was developed by Daniel Köhn (2011), using a finite difference adjoint inversion conjugate gradient approach. To obtain good results, a thorough preconditioning of the gradient is essential. In spite of this, due to the small scale, high amplitudes which occur close to source and receiver cause problems in the inversion and cannot easily be eliminated by preconditioning in the case of the inversion of surface wave. First tests are applied to 1D synthetic data of one layer over half space. The results show a good reconstruction of the discontinuity. As a next step, the method will be tested for 2D models and is then planned to be applied to field data.

Work package 2:
Evaluation and field test of the Toolbox for Applied Seismic Tomography

Software for geophysical data analysis may perform nicely in numerical tests. Its true value, however, must be proven by successful application to field data. Work package WP2 will therefore apply testing and benchmarking to the toolbox at different scales. The inversion will be applied to datasets from applications in different areas in close cooperation with industrial partners. Experience, tools and knowledge will be transfered to the industrial partners. The work packages will be complemented by a shallow seismic field laboratory and studies of exemplary laboratory samples. The application on different scales will be conducted by two tasks. Task 1 applies the toolbox to seismic recordings from the scale of shallow seismics to 1 km depth in the context of CO_2 sequestration. Application to ultrasonic recordings in material testing is studied in Task 2. Interaction between the tasks will yield synergy effects, since strategies to obtain initial models and to explore the resolution provided by the data are similar in seismics and surface ultrasonics.

WP2 Task 1: Evaluation and tests on a meter to kilometer scale

nversion strategies that are supported by the toolbox will be applied to studies on scales from shallow seismics to 1 km depth. Data sets are available for example from the monitoring of embankments, CO_2 sequestration studies and from previous shallow seismic studies. Within the task, a field laboratory will be set up to record data on exemplary sites and to develop optimal acquisition strategies and quality control with respect to the subsequent inversion. Field sites will be selected together with partners from industry and civil engineering. Waveform data will be made accessible with all necessary metadata (receiver coordinates, source properties, intrument's transfer characteristics, etc). In a first step, 1D full seismogram inversion must be implemented and applied, which has not yet been done in shallow seismics. This leads to the preparation of initial models for a 2D or 3D inversion, which is applied in a second step. The results will be compared with other observations (e.g. drilling and laboratory measurements) for calibration, further geotechnical characterisation, and benchmarking purposes. Descriptions of existing data are collected on a web-based platform and are made accessible to all partners.

Site surveys in the area of Karlsruhe were carried out for the field laboratory. And first 1D datasets but also datasets on a 2D structure were gathered (Stelzer 2010). We focussed to find appropriate sites for basic tests of the toolbox and to get starting models for the

waveform inversion. Further shallow seismic measurements are planned for this 2011.
In preparation of 2D inversions of field data, the transformation of wavefield recorded with a point source (hammer blow) to equivalent line-source data (as implictely calculated by 2D finite difference algorithms) currently is implemented and tested. The used method was successfully applied to synthetic data and is presently tested with field data.

Existing programs for preprocessing shallow seismic datasets and for the inversion of Fourier-Bessel expnasion coefficients to initial models for waveform inversion are made accesible to all partners. TOAST partners have agreed on commonly using the SeismicUnix data format for field data. Meanwhile input and output routines for SeismicUnix data are implemented in most shallow processing tools as well as in reflectivity modelling code (wavenumber integration for 1D structure).

WP2 Task 2: Evaluation and tests of waveform inversions on a centimeter to decimeter scale

At ultrasonic frequencies, seismic investigations are used for non-destructive testing of concrete and natural stone. At present, mostly transmission experiments are carried out and only times of first arrivals are measured. That means only a very limited part of the waveform is parametrized and analyzed. Here, we propose to analyze ultrasonic waveforms measured at the surface of the object under investigation. This approach has two main advantages: it is applicable if only one side of the object is accessible for measurements and the information of ultrasonic waveforms is explored to a much greater extent. The enormous potential of ultrasonic surface measurements can only be exploited if algorithms are developed that are robust and relatively easy to apply for the users. The aim of the project is therefore:

– to adopt waveform inversion tools to ultrasonic surface measurements
– to develop user-friendly algorithms that are implemented into ultrasonic analysis software (Geotron Elektronik)
– to test these software tools together with potential users (dornburger zement GmbH & Co. KG, Institut für Steinkonservierung e.V. Mainz).

Algorithms for ultrasonic waveform inversions that are suitable for the investigation of the upper centimeters and decimeters of concrete and natural stone are to be tested by WP2T2. Tools developed by WP1 will be applied and modified to ultrasonic surface measurements together with cooperation partners from the Institut für Steinkonservierung Mainz and dornburger zement GmbH & Co. KG. Algorithms for the detection of weathering layers with a thickness of up to a few centimetres are to be developed. Ultrasonic measurements of surface wave propagation along a profile at the surface will be used for this purpose. First tests indicate that velocities of elastic waves as well as their attenuation are strongly affected by weathering layers. Synthetic tests show that the corresponding waveforms are highly sensitive to superficial weathering layers. At the beginning of the project algorithms for the determination of group and phase velocities of fundamental modes and their attenuation have been modified for ultrasonic measurements. In order to test these algorithms they are to be applied to measurements of artificially weathered samples of natural stones and concrete. The corresponding samples have already been supplied by the cooperation partners and a first version of the optimized equipment for field measurements has been developed and provided by Geotron Elektronik. First tests indicate that the obtained ultrasonic measurements are broad band in a frequency range between about 50 kHz and 300 kHz. The measurements are replicable and robust and therefore well suited for our purposes. In a next step, measured phase and group velocities of fundamental Rayleigh modes are to be inverted for 1D models of S-wave velocity. Corresponding algorithms are to be developed together with WP1.

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MIIC – Monitoring and Imaging based on Interferometric Concepts

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1. Overview

Recent years have witnessed the emergence of a new field in seismology (Courtland, 2008). New concepts from mesoscopic physics have dramatically changed the seismologists' view on ambient noise and seismic coda. Being disturbing signals that hinder the detection of earthquakes only six years ago these wave fields become a major source of information that is used with seismic interferometry.

The goal of MIIC is to develop new imaging and monitoring strategies that are based on these new concepts to make use of scattered waves and ambient seismic noise in a broader set of applications that extends beyond seismology. We will develop an analysis tool that integrates real time data handling, interferometric processing and novel simulation and inversion strategies to combine the monitoring and imaging approaches into a dynamic tomography that gives 4D information about the structure of the target and its temporal changes. This concept is illustrated in figure 1.

With this tool we will provide the opportunity to use the advantages of seismic interferometry in many disciplines that are concerned with elastic waves.

The special requirements of the interferometric concepts in the data acquisition will be met by optimized instruments that will be developed within the project. From the combination of active and passive seismic techniques with new imaging and monitoring technologies

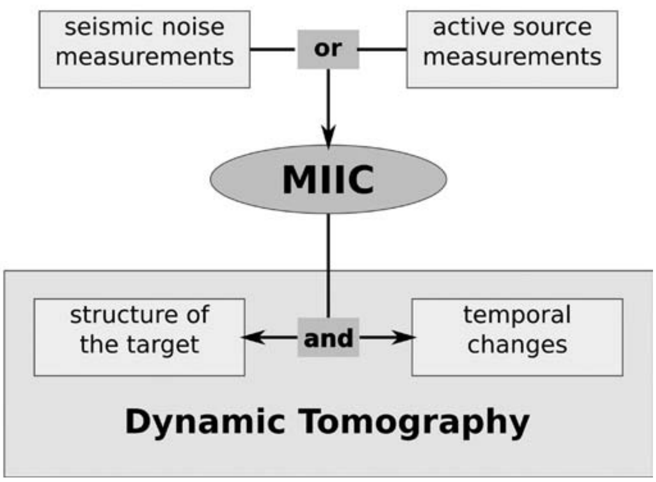

Figure 1: Illustration of the concept of MIIC. The use of interferometric concepts allows to simultaneously retrieve information about the structure of the target and its temporal changes resulting in a dynamic tomography (4D).

that will be developed in the project we expect progress that is strongly required in the fields of building-ground investigation (seismic risk, Eurocode 7), subsurface monitoring (mining safety and subsurface storage) and geo-hazard evaluation (volcano and landslide monitoring).

2. Goals of the project

MIIC is a joint effort of research institutes, a university and private companies. It combines scientific and technical goals with the economic goal of commercially usable results.

Scientific goals

- Detailed investigation of the potential of seismic interferometry for monitoring material changes on different scales and in different environments
- Comprehensive understanding of the effects of localized changes in the propagation medium on phase shifts, de-correlation of the wave form and amplitude variations of the scattered wave field
- Inversion of phase shifts and wave form changes in the scattered seismic wave field for the location and amplitude of spatially localized changes in the target material
- Utilization of seismic three-component data for joint inversion of Rayleigh and Love waves from ambient noise
- Utilization of stationary non-synchronized noise sources for imaging and monitoring
- Investigation of the benefit of a structurally coupled inversion of surface wave dispersion measurements with seismic refraction and geoelectric measurements

Technical goals

- Development of a software for the integrated analysis of seismic noise and scattered waves from active sources for monitoring and imaging
- Implementation of an inversion routine to locate medium changes based on variations of the scattered wave field
- Application and test of the software with data from various environment that are candidates for later commercial application of the methodology
- Development of seismic sensors for continuous recording with wireless real time access to the data and integration in the software for real time analysis.

3. Project Structure

The workload in the joint project MIIC is divided into two activities reflecting different approaches to the ultimate goal of the a 4D dynamic tomography.

3.1 Activity I: From Monitoring to Dynamic Tomography

State of research

Monitoring with acoustic or seismic waves has been limited to the monitoring of sources for a long time. In nondestructive testing the acoustic emissions can yield information about the damaging process and earthquake locations studied in seismology picture the tectonically active features in the earth’s crust. Temporal changes in the wave propagation have generally been neglected since these variations are usually very weak, i.e. smaller than the spatial variability. However, changes of the wave velocity or attenuation may provide valuable information about ambient stress changes, the opening and development of cracks, temperature changes or chemical alteration. The key to detect these temporal variations of the wave field is to use interferometry of scattered waves. This provides an accuracy that is far superior to traditional travel time measurements. During the long time that scattered waves propagate, they accumulate the effects of changes in the medium (e.g. phase delays due to velocity changes). Figure 2 illustrates this advantage.

The concept of detecting temporal changes with interferometry of scattered waves in seismic coda was presented by Poupinet et al. (1984) under the term Moving Window Cross

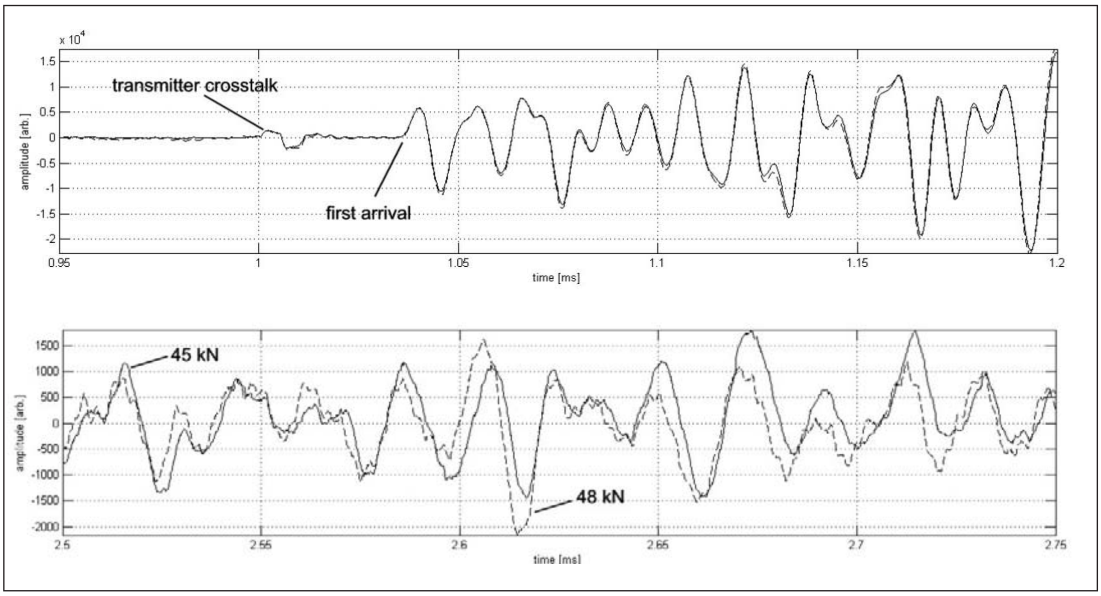

Figure 2: Ultrasonic transmission through concrete sample at different loads. Straight line : 45 kN load, dotted: 48 kN load. The slight load change has almost no effect on the time of flight of the direct wave (top) but in the coda a clear phase shift can be observed (bottom). From Stähler et al. (2009)

Spectral Analysis. A number of studies applied this technique to identify temporal changes in fault zones and volcanoes. Snieder et al. (2002) presented some more theoretical consideration of this approach and coined the term Coda Wave Interferometry (CWI). Following this, CWI was applied to monitor velocity changes in the medium, movement of scatterers, and differences in source locations. The concept was also used with active source experiments e.g. Nishimura et al. (2005). Grêt et al. (2006) reported on stress induced changes in a mining environment that were detected with CWI. These investigations suffered from the irregular temporal sampling induced by uncontrolled or expensive sources. In Sens-Schönfelder and Wegler (2006) we introduced a new concept termed Passive Image Interferometry (PII) that revolutionized the research on temporal changes. We demonstrated the possibility to retrieve scattered waves from ambient noise. This allowed to continuously monitor temporal changes with ambient noise independent of irregular or expensive sources. The method was applied to data from Merapi Volcano (Indonesia) were the changes of the local ground water level were observed on a daily basis. Figure 3 shows the Green's functions that are retrieved from noise on Merapi. The temporal changes in the medium result in the variable travel time of the coda phases in figure 3. In combination with independent precipitation data our modeling proved the applicability of the concept. In Wegler and Sens-Schönfelder (2007) and Wegler et al. (2009) we applied the method to the fault region of a Japanese earthquake and could estimate a clear co-seismic velocity drop. To increase that accuracy of the interferometric measurements, we presented a new technique based on dilatation and compression of the coda time axis that considerably stabilizes the measurements (Sens-Schönfelder and Wegler, 2006). In Sens-Schönfelder and Larose (2008) we analyzed temporal changes in the lunar crust that are induced by variations of the surface temperature. Based on our developments Brenguier et al. (2008b) observed pre-eruptive velocity changes at Piton de la Fournaise volcano. At the San Andreas fault Brenguier et al. (2008a) observed the post-seismic relaxation after two earthquakes. These prominently published applications helped to initiate investigations in seismology around the world. This approach is a completely new area of research.

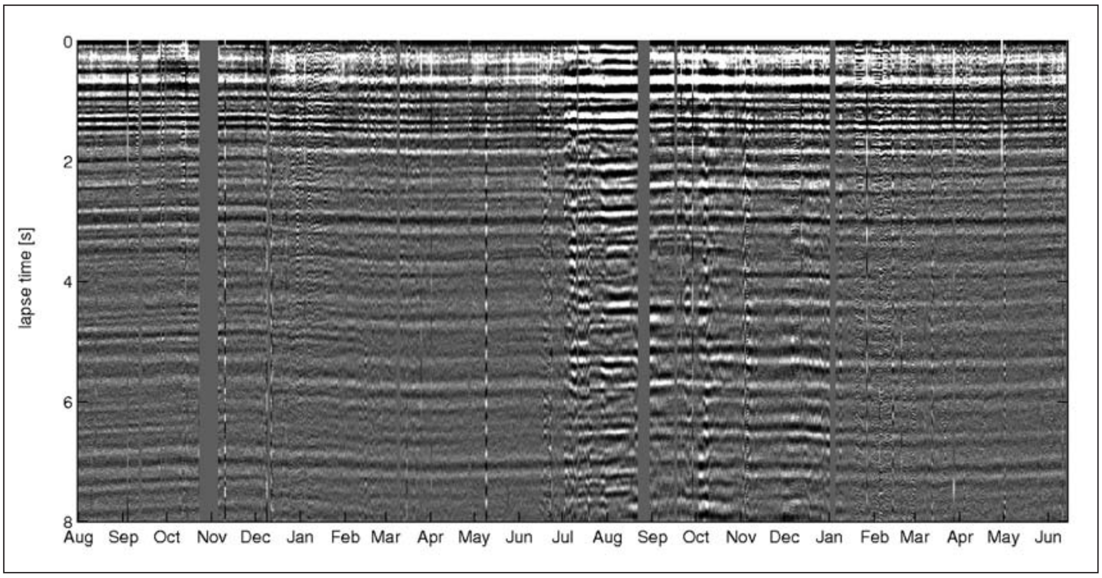

Figure 3: Noise retrieved Green's functions from Merapi volcano for each day as used by Sens-Schönfelder and Wegler (2006). Travel time is on the vertical, time of the year on the horizontal axis and amplitude is color coded. The change in the medium is reflected by the variable travel time of the coda phases, e.g. at 7 s lapse time.

The only theoretical approaches to the problem of locating velocity variations via travel time perturbations in the seismic coda were presented by Pacheco and Snieder (2005) for diffuse waves and by Pacheco and Snieder (2006) for single scattered waves. Brenguier et al. (2008b) used a heuristic regionalization concept that is not based on the physics of wave propagation to assign detected travel time changes to some region.

In Sens-Schönfelder and Wegler (2006) we presented the first approach to detect spatially heterogeneous velocity changes with scattered waves. In Sens-Schönfelder and Larose (2008) we modeled the heterogeneous velocity change in the lunar soil. The application of interferometric methods is not limited to geosciences. As Larose and Hall (2009) as well as Stähler et al. (2009) have pointed out, the concept can for example be applied in non-destructive testing of concrete and other materials.

Work plan

Activity I will focus on monitoring techniques with seismic coda waves because they provide superior temporal resolution of variations from relative measurements. Use of this advantage is currently limited to the scientific community. Also the type of change in the coda of seismic signals that is analyzed for medium changes is currently restricted to phase shifts which correspond to changes of propagation velocity. Finally the superior sensitivity and temporal resolution of monitoring with scattered waves comes at the cost of difficulties to locate the changes. This defines the main goal of activity I:

- The experience based development of software that allows the easy application of the interferometric methodology in the geophysical, geotechnical- and engineering communities.
- The application of the methodology to a number of targets ranging from seismological monitoring of volcanoes over geotechnical sites like mines or tunnels to nondestructive testing of concrete samples to investigate the potential of interferometric processing in different ares.
- Comprehensive study of the relation between changes of different wave field properties (amplitude, de-correlation) and their underlying variations of the propagation medium with theoretical modeling, lab experiments, and field data.

- The development of a tomographic approach to image the temporal changes. This will be fundamentally different from traditional tomography with direct waves. By adding spatial resolution to the monitoring technique we will approach the aim of a dynamic (4D) tomography starting from the temporal variations.
- The validation of analysis and inversion tools with model experiments

The activity is divided into four work packages. In work package 1.1 the processing and analysis software is developed that is used by the other work packages. Work package 1.2 is devoted to a broad interdisciplinary application of the monitoring technique. In work package 1.3 we will develop methodology for localizing the changes that are measured with scattered waves. With the model experiments that are performed in work package 1.4 we will validate and calibrate analysis and inversion strategies.

3.2 Activity II: From Imaging to Dynamic Tomography

State of research

During the last few years, the analysis of seismic noise recorded by arrays has been found to be particularly successful in deriving the S-wave subsoil structure below an investigated site. Innovative tools based on seismic noise analysis have been developed and tested in a broad set of targets and proved to be particularly suitable for the urban area, and especially Megacities. In particular, using just a few minutes of seismic noise recordings and combining this with the information coming from the well known horizontal-to-vertical spectral ratio, it was shown by Parolai et al. (2005) that it is possible to investigate, with a sufficient resolution, the average 1D velocity structure below an array of stations in urban areas to depths that would be prohibitive with active source surveys, and hence avoiding very expensive invasive measurements (boreholes). After successful applications of this method to several urban areas (e.g. Istanbul, see Picozzi et al., 2009 b), the possibility of deriving 3D structures by simply using some minutes of seismic noise recordings is now to be explored.

The pioneering work of Shapiro et al. (2005) showed that seismic interferometry from seismic noise recording in the frequency band below 0.5 Hz allows the retrieval of the 3D structure of the Earth at regional scales. Following applications of this Ambient Noise Tomography (ANT) were presented also in exploration geophysics (e.g. Bakulin and Calvert, 2006), focusing generally on noise above 10 Hz, and therefore a portion of subsoil of few meters.

Recently, Picozzi et al. (2009 a) applied the ANT technique for engineering seismology purposes (frequencies between 0.2-10 Hz), aiming to fill the gap between the seismological and exploration geophysics scales in the subsoil characterization. Please note that the change of frequency range from seismology to engineering seismology scale does not imply a trivial scaling. In fact, in the frequency range between 0.2-10 Hz, seismic noise sources are different (mainly anthropic), the attenuation in the considered material is larger and the distance between stations is much shorter with respect to the wavelength of the signal, complicating the estimation of the propagation time. The results obtained, showed that with just a few tens of minutes of seismic noise recording, it is possible by seismic interferometry to obtain 3D images for few tens of meters of the subsoil structure. As it can be imagined, this technique might result in a small revolution in geophysical investigations of shallow geology. Differently from the standard active source method, it allows obtaining images of the subsoil mechanical properties and the possibility of continuously monitoring also at sensible site like landslides and megacities.

A crucial point of ANT applications is that a large number of stations to be deployed in the field is required. This opens some main issues: (1) the costs of the standard seismological equipment to be used would be very high; (2) the dimension, weight and function of the standard seismological equipment make it not suitable for this kind of experiment; and (3) the analysis of data is generally performed only in a post-survey timeframe, which represents a severe drawback for some applications, as for example the landslides monitoring and early warning. For these reasons it is necessary that the equipment (i.e. hardware and software) we can dedicate to this kind of experiment is at the same level of excellence as the methodology we proposed.

Therefore, during the project, it will be necessary to develop and tests ad-hoc equipment. For this purpose, we can take advantage of the experience gained in building up wireless sensing instruments for the SOSEWIN Early Warning System for Istanbul, Turkey (Fleming et al., 2009), which have been developed by the Helmholtz-Zentrum Potsdam GFZ German Research Centre for Geosciences and Humboldt University of Berlin (HUB) within the framework of the European projects Seismic eArly warning For EuRope (SAFER, http://www.saferproject.net) and Earthquake Disaster Information systems for the Marmara Sea region, Turkey (EDIM, http://www.cedim.de/EDIM.php).

In the surroundings of construction sites or other industry, non-synchronized sources like vibrations of machinery may be used for imaging. Indeed they have to be used because dominant stationary sources destroy the random character of the ambient noise and hinder the use for ambient noise tomography. Seismic imaging with the noise of a tunnel boring machine or with drill bit noise are examples of taking advantage of the non-synchronized but known sources (Ashida, 2001). Non-synchronized means here that the source signal is unknown but the position of the source is known. This possibility can be extended by purposeful generating noise. Such an approach was used by Gouédard et al. (2008) for a surface survey. They worked with a continuously recording array and used human steps as non-synchronized sources. These records can be used similarly to the noise records in ANT. From cross-correlation between the signals from two sensors the impulse response can be obtained as if one receiver was a source. The advantage of using the active (non-synchronized) sources compared to ambient noise is the better convergence towards the Green's function since the "noise" can be generated in line of the receiver pair which is preferable for the cross-correlation.

Besides the improvement of the seismic methods a further possibility to improve the subsurface imaging is the combination with other geophysical methods. Irrespective of the kind of geophysical data they all have their common origin in the geological structure under investigation. This allows to couple independent geophysical data via a common subsurface structure and jointly invert and interpret the measurements. Compared to a separate inversion with subsequent common interpretation, the significant advantage is the unique structure that is used to explain the different data sets. It may significantly improve the subsurface image by combining advantages of different methods e.g. abilities of resolve layer properties (seismic surface waves, electrical measurements) or abilities to locate interfaces (seismic reflection or refraction measurements).

Work plan

Activity II will approach the dynamic tomography by augmenting imaging techniques with temporal resolution. The new concept of small scale seismic imaging with noise or non-synchronized sources is advantageous if active sources are prohibitive as in megacities or on landslides or in the presence of strong active non-synchronized sources of vibrations like machinery. The application of this new approach requires new field equipment and new analysis tools that are developed in activity II. It has the following goals:

- The development of wireless 3-component seismic sensors for continuous data acquisition and real-time transmission.
- The development of analysis software for small scale ambient noise tomography of 3-component data.

– The development of a tool for small scale subsurface investigations with seismic waves emitted from non-synchronized sources.
– The integration of an approach for the structurally coupled inversion of seismic surface wave dispersion curves with other geophysical measurements.

Activity II is divided into two work packages. Field instruments will be developed in work package 2.1. that allow real time data transmission of continuous recordings. New approaches of interferometry for better constraining underground models by using Love waves and estimating attenuation will be developed. Repeated imaging will open the possibility to detect temporal changes. In work package 2.2 we will develop a new approach to use seismic interferometry in combination with active non-synchronized sources. This will result in an easy-to-use tool for surface wave analysis of the shallow subsurface. It will be integrated in an algorithm for the structurally coupled inversion with other geophysical methods.

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AIDA – From Airborne Data Inversion to In-Depth Analysis

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1. Overview

The rising competition in land use especially between water economy, agriculture, forestry, building material economy and other industries often leads to irreversible deterioration in the water and soil system (as salinisation and degradation) due to over-exploitation which results in a long term damage of natural resources. A sustainable exploitation of the near subsurface by industry, economy and private households is a fundamental demand of a modern society. To fulfil this demand, a sound and comprehensive knowledge on structures and processes of the near subsurface is an important prerequisite. A spatial survey of the usable underground by aerogeophysical means and a subsequent ground geophysics survey targeted at special locations will deliver essential contributions within short time that make it possible to gain the needed additional knowledge. The complementary use of airborne and ground geophysics as well as the validation, assimilation and improvement of current findings by geological and hydrogeological investigations and plausibility tests leads to the following key questions:

a) Which new and/or improved automatic algorithms (joint inversion, data assimilation and such) are useful to describe the structural setting of the usable subsurface by user specific characteristics as i.e. water volume, layer thicknesses, porosities etc.?
b) What are the physical relations of the measured parameters (as electrical conductivities, magnetic susceptibilities, densities, etc.)?
c) How can we deduce characteristics or parameters from the observations which describe near subsurface structures as ground water systems, their charge, discharge and recharge, vulnerabilities and other quantities?
d) How plausible and realistic are the numerically obtained results in relation to user specific questions and parameters?
e) Is it possible to compile material flux balances that describe spatial and time dependent impacts of environmental changes on aquifers and soils by repeated airborne surveys?

2. Goals of the project

In order to follow up these questions raised the project aims to achieve the following goals:

a) Development of new and expansion of existent inversion strategies to improve structural parameter information on different space and time scales.
b) Development, modification, and tests for a multi-parameter inversion (joint inversion).
c) Development of new quantitative approaches in data assimilation and plausibility studies.
d) Compilation of optimised work flows for fast employment by end users.

e) Primary goal is to solve comparable society related problems (as salinisation, erosion, contamination, degradation etc.) in regions within Germany and abroad by generalisation of project results.

3. Project structure

Two main focuses »Development of new inversion strategies« and »Development of new simulation techniques« are laid out in five subprojects (SPs). Existing and new data from airborne and ground geophysics are merged in one structural model, tested for plausibility and interactively visualised in a low cost graphic cave (CAU). BGR provides existent and preprocessed data from airborne geophysics (Elbe river marshes, Cuxhaven glacial channel, Bode river catchment area, etc.). For each project only the three most important tasks are stated below.

SP1: Aero-Ground-Joint-Inversion (University of Cologne)

- Development and preparation of in-house algorithms for 1D-inversion of HEM data of BGR plus TEM and RMT data for joint inversions.
- Development of a forward modelling tool for UAV based VLF/LF measurements as a base for further inversion programs.
- Achievement of common conductivity models based on data of different measurement techniques as an input for model coupling (SP2) and 3D-models in SP3, SP4 and SP5.

SP2: Model coupling HEM 1D+ (Federal Institute for Geosciences and Natural Resources in Hannover)

- Development of a method to combine large scale HEM data sets with more local data from ground geophysics, geology and hydrogeology.
- Investigation of types of anomalies with regard to modelling: complex structures need a full 3D-inversion.
- Development of methods for segmentation of complex anomalies and a combination of 3D-models in a quasi 1D-environment with little lateral conductivity changes.

SP3: HEM 3D-Inversion (TU Bergakademie Freiberg)

- Solution of large, sparse, strongly structured linear systems of equations arising from the discretised forward problem of electromagnetics.
- Adaption of techniques from numerical algebra (Krylov and Block-Krylov methods) to solve linear systems of equations with multiple right-hand sides typical for HEM applications.
- Development and implementation of iterative equation solvers, and multi-grid methods for large-scale 3-D-problems

SP4: Evolutionary algorithms for the 3D-inversion of geophysical fields (Christian Albrechts University Kiel, Technical University Dresden)

- Development of »evolutionary algorithms« to solve automatic multi-parameter inversions applying approaches from bio-informatics via adaption of principles of natural evolution: recombination – mutation – selection – isolation.
- Implementation of a 3D-optimisation of geophysical target functions via $(\mu + \lambda)$ and / or (μ , λ) evolution strategies with covariance matrix adaption (CMA-ES).
- Development of knowledge based optimisation and consideration of semantic constraints for topology and model geometry preservation.

SP5: Model development and validation of results (Christian Albrechts University Kiel, Leibniz University Hannover)

- Development of two synthetic GoCAD® models to demonstrate the architecture of a sedimentary system and a complex tectonic setting as an error free data basis for common tests in the joint research project.

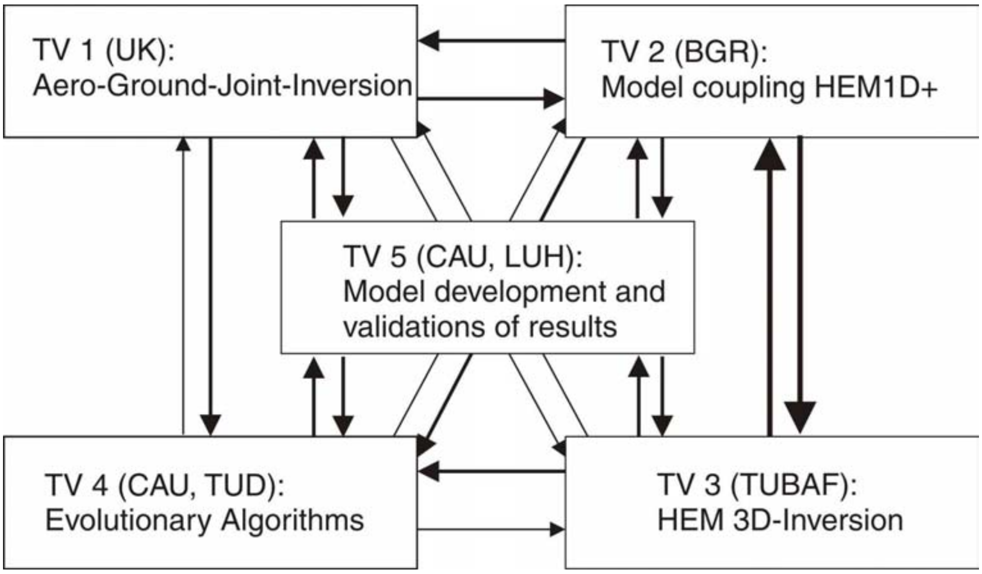

Figure 1: Networking between sub-projects; the thickness of the arrows represent the level interaction (UK = University of Cologne, BGR = Federal Institute for Geosciences and Natural Resources in Hannover, TUBAF = Technical University of Freiberg, CAU = Christian-Albrechts-University in Kiel, TUD = Technical University of Dresden), LUH = Leibniz University in Hannover).

– Check and comparison with inversion and modelling results of the joint research as well as development of statistical methods for automatic classifications.
– 3D-low cost graphic cave visualisation of joint research results by forward modelling and inversion.

Figure 1 visualises the cooperation, networking and information flows of the AIDA sub-projects.

3.1 Sub-project 1: Aero-ground joint inversion

Aims of the sub-project

The aim is the development of innovative algorithms for the joint interpretation of helicopter-borne electromagnetic (HEM), transient electromagnetic (TEM), and radiomagnetotelluric (RMT) data sets. The proposed concept of the joint inversion takes advantage of each single method, which in most cases consists of a dense measuring grid (HEM and RMT) and on the other hand provides the capability to resolve near surface (RMT) and deeper electrical conductivity structures (TEM). Our joint inversion concept yields quasi-2D images of the electrical conductivity over a large depth range and provides ancillary information for SP2 (model coupling) and for the compilation of 3D-models in SP3. In addition to RMT ground data and existing TEM and helicopter borne EM data, we propose a new deployment of a so called Unmanned Aerial System (UAS; Fig. 2), an innovative platform for airborne VLF/LF-measurements. It requires integration of a VLF/LF sensor, such as is provided by Metronix GmbH, the so-called Super High Frequency Triple (SHFT). In combination with our new interpretation algorithms, we are convinced that this innovative measuring platform will allow an efficient approach to map the electrical conductivity.

State of the art

The inversion of HEM- and TEM data sets are usually accomplished using simple 1D conductivity models which consist of layer conductivity and thickness. Several measuring points of the grid are combined by the application of smoothness conditions (Siemon et al., 2007; Auken et al., 2004). 2D as well as 3D inversion codes are still not standardised in the interpretation. But 3D forward modelling codes are widely used to simulate EM data, esp. TEM-data. At the moment, there is no inversion method available which enables the joint interpretation of HEM, TEM, and RMT data. In former studies at the University of Cologne TEM data, however, were successfully combined and inverted with DC and RMT soundings (Eckardt, 1993; Schwinn, 1999).

An UAS shall be utilized to perform geophysical surveys on a flying measuring platform. The utilization of UASs enables the performance of a time and cost-effective measuring platform to acquire high resolution images of geophysical parameters of electrical conductivity. Since many decades VLF measurements have been a well established method in exploration geophysics on the ground as well as in airborne geophysics. These qualitatively provide an indication about lateral changes of the electrical conductivity of the ground. Gharibi and Pedersen (1999), Becken and Pedersen (2003), and Oskooi and Pedersen (2006) developed a transform function to enable the determination of the electrical conductivity value on each point of a measuring grid.

Figure 2: Autonomouse UAS test flight near Cologne (Tezkan et al., 2011, Unmanned Aircraft Systems: A new geophysical measuring platform for aeromagnetic surveys, First Break - in Print).

UASs have the potential to open new possibilities concerning the organisation and performance of geophysical exploration. This sensor was already deployed in a Swedish airborne geophysical survey performed by Pedersen und Dynesius (2008).

Scientific-technical working aims within the project

At first, the 1D numerical inversion codes, which were developed by the Cologne geophysics group as a tool for the interpretation of single methods (TEM, RMT), need a comprehensive modification and must be extended to accomplish the numerical joint inversion with the HEM data. In addition, a VLF/LF forward modelling code shall be developed for the interpretation of UAS-borne measurements. This code is essential for the development of a VLF/LF inversion code. All codes will be initially tested with synthetic data. Usually, the measuring grids of different sounding methods do not overlap which makes it inconvenient to accomplish the joint inversion. Therefore, we propose a method which combines individual grids to a joint grid. There are two ways to harmonise these different grids: first by composing the model parameters using smoothness conditions, secondly to apply interpolation routines in order to estimate the interpolated data on the joint grid. A comparison of both approaches shall reveal the optimum way to generate the desired joint grid. In addition, we plan to conduct extensive ground RMT measurements and UAS-borne VLF-LF-measurements in areas which were already surveyed and geophysically characterised from BGR by HEM and TEM soundings.

3.2 Sub-project 2: Model coupling HEM1D+

Aims of the sub-project

This sub-project aims to develop methods enhancing the inversion of helicopter-borne electromagnetic (HEM) data. In particular, a program package will be created that coordinates all tasks related to HEM data inversion, data import, model coupling and model export. Important sub-goals are joint inversion of different data sets (SP1), integration of a priori data in HEM 1D inversion and evaluation of the resulting conductivity distribution with respect to 3D effects. These laterally strongly varying conductivity structures (anomalies) will be selected, classified and forwarded to SP3 to be 3D modelled (3D inversion). Afterwards, the resulting 3D models will be integrated into a quasi 1D environment and the combined 1D/3D conductivity models will be forwarded to SP5 for crosschecking with hydro-geological and geological models.

State of the art

HEM data sets contain information about the spatial conductivity distribution in the subsurface. Due to the huge amount of data and the complexity of the numerical algorithms, however, an accurate 3D inversion of the HEM data of an entire survey area is not feasible and, instead, stitched together 1D inversion models are used to approximately display the 3D conductivity distribution. In case of strong lateral conductivity variations the 1D inversion yields contorted results and 3D modelling is mandatory. HEM 3D inversion of SP3 requires background and starting models to be derived from the 1D inversion models optimised in SP2. The search algorithm to be developed should work on a grid or voxel basis in order to identify conductivity anomalies being independent of the flight line orientation. The anomalies detected in such a manner are structurally classified using a »moving window« technique. HEM data sets are generally inverted using layered earth models (»Single Site Inversion« SSI). That is only a weak constraint for conductivity distributions varying slightly on the horizontal scale with respect to the area in the subsurface affecting a single HEM measurement (foot print). Thus, 1D inversion of HEM data is still state of the art (Hodges & Siemon, 2008). Recent developments concentrate on using additional model parameters (Huang & Fraser, 2003; Yin & Hodges, 2005) as well as several data sets (»Laterally Constrained Inversion«LCI: Siemon et al., 2007; »Spatially Constrained Inversion«SCI: Viezzoli et al., 2008) for the HEM inversion. Multi-dimensional inversion of HEM data is currently restricted to approximate calculations (Cox & Zhdanov, 2008; Christensen et al., 2009; Cox et al., 2010) or not applicable to huge survey data sets (Sasaki, 2001).

Scientific-technical working aims of the project

The quality of the HEM inversion results at single sites will be enhanced using additional data. Besides already tested approaches, such as the laterally or spatially constrained inversion connecting the layer parameters of neighbouring models using constraints, the feasibility of using different data sets will be evaluated and compared to standard procedures. While SP1 focuses on a joint inversion of airborne and ground geophysical data, SP2 tries to integrate additional data into the HEM inversion using a priori constraints. In addition, a method has to be developed that connects the large-scale HEM data with rather local ground geophysical, geological or hydrogeological data sets.

A search algorithm has to be developed that browses the HEM 1D inversion models of an entire survey area in order to identify, select and classify conductivity anomalies. In case of complex structures a full 3D inversion is required. Due to the rather small footprint (< 250 m) valid for HEM measurements the space to be modelled can be restricted to rather small sub-spaces, but is has to be investigated how complex anomalies are subdivided and how the resulting 3D models can be combined and integrated into a quasi-1D environment where the conductivies are varying smoothly.

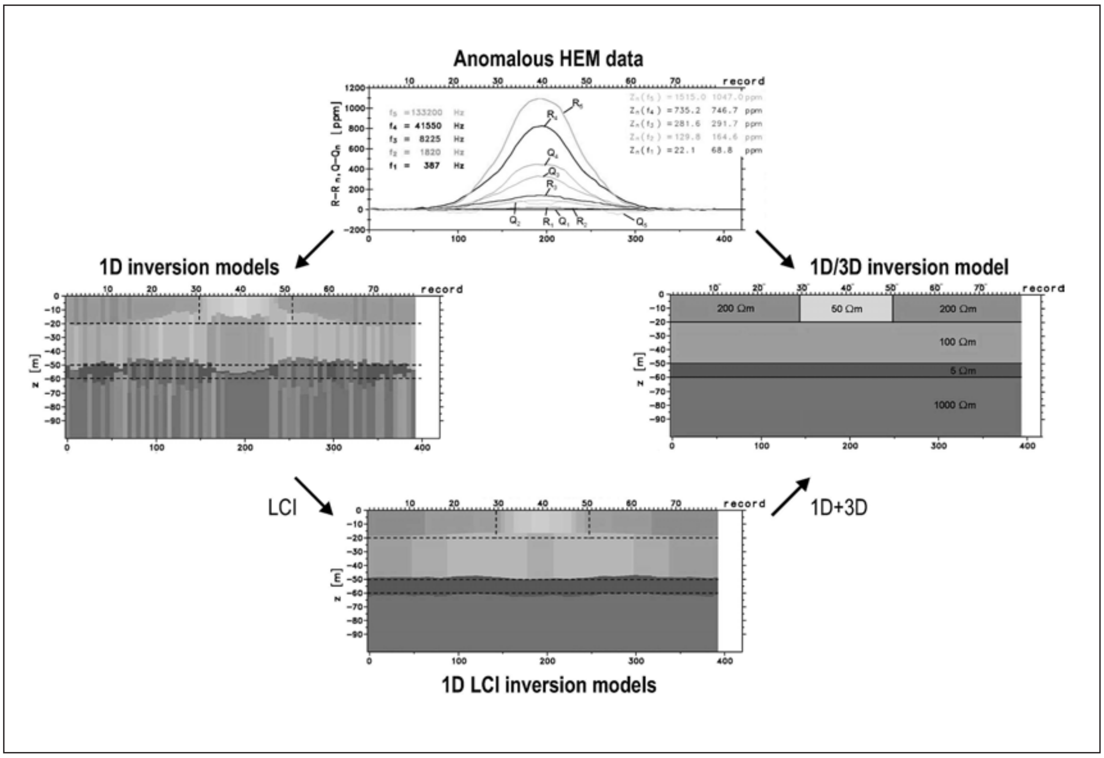

Figure 3: Combination of 1D background HEM inversion models with local 3D inversion model. Only the anomalous part of the HEM data will be used for 3D inversion.

3.3 Sub-project 3: HEM-3D inversion

Aims of the sub-project

The sub-project SP3 aims at the development of methods for the three-dimensional inversion of helicopter electromagnetic (HEM) data. For this purpose, numerical algorithms have to be developed and implemented. These numerical algorithms utilize a recently developed fast and accurate 3-D forward operator for the reconstruction of the spatial distribution of the main petrophysical parameter, the electrical conductivity. It is clearly not advisable to invert a complete HEM dataset. Instead, a properly chosen subset of the data has to be defined. To this end, an indicator has to be defined which provides those parts of the dataset that cannot be interpreted using conventional 1-D inversion methods. Sub-project SP2 selects parts of the full dataset, which indicate strong lateral variations in the models obtained by a local 1-D interpretation. The reduced partial datasets, which are essentially smaller than the full dataset, will be inverted in a subsequent step by SP3. The obtained local 3-D model will then be integrated into the quasi-1-D models of SP2.

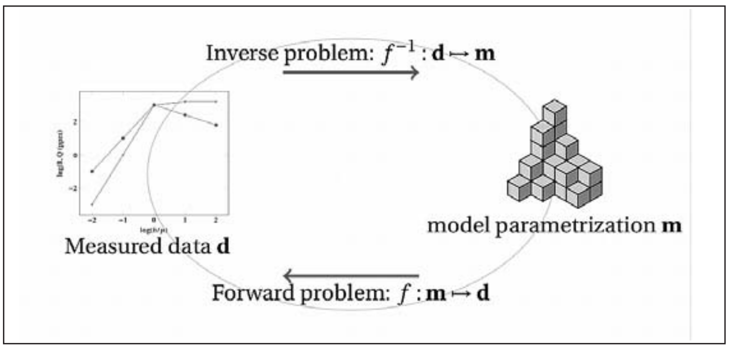

Figure 4: Framework of geophysical data interpretation.

State of the art

Up to now, HEM data have been interpreted using simple layered models. HEM data over complex geological structures, however, can only be explained by three-dimensional conductivity models. This requires the numerical simulation of the induction phenomena in three-dimensional conductivity structures. The Freiberg research group has developed a 3-D finite element code (Schwarzbach et al., 2008), which is far superior with regard to performance and flexibility to the more traditional finite difference codes (Newman und Alumbaugh (1995), Sasaki (2001)) or integral equation codes (Avdeev et al. (1998)) commonly used in this field. In addition, we have developed model reduction methods for efficient multi-frequency simulation (Börner et al. (2008). For 3-D DC resistivity and 2-D magnetotelluric inversion, the Freiberg group has already implemented codes and published results (Günther et al., 2006; Baranwal et al., 2007).

Scientific-technical working aims of the project

The 3-D inverse problem of HEM data interpretation is underdetermined and ill-posed. Moreover, HEM datasets are spatially incomplete and noisy. State-of-the-art inversion methods are predominantly based on regularized Gauß-Newton methods. The penalty functionals involved that have to be minimized typically comprise linear combinations of a data residual, and a model norm. The major objective of this research is to decide which variants of known 3-D inversion methods are particularly suited for the interpretation of HEM data. The solution of the discrete forward problem of electromagnetics leads to linear equations systems with large, sparse, and structured coefficient matrices. Among the most important are iterative solvers, which seem attractive due to their low memory requirement when 3-D large scale problems are considered. Recently, multigrid methods become an interesting alternative to the generally slowly convergent iterative methods. We plan to solve systems with multiple right-hand sides with Krylov methods and their block-related variants. For the solution of the linearized sub-problem, regularized Gauß-Newton methods require the construction of the sensitivity matrix of partial derivatives of the model response with respect to small model parameter perturbations. However, only the action of this matrix on a vector is required.

3.4 Sub-project 4: Evolutionary algorithms

Aims of the sub-project

The application of evolutionary algorithms in the context of 3D-inversion of geophysical field data - here of potential fields and their derivatives (gradients) - is the principal purpose of sub project SP4. Closely related is the optimisation of target functions for three-dimensional modelling of susceptibility, density and conductivity distributions by evolution strategy (ES). After the implementation of the algorithms and several tests with synthetic data sets, they will be used for the interpretation of real world data. A special aspect is knowledge-based optimisation, which goes beyond well-known methods and for the first time it will be possible to include (1) semantic constraints and (2) topology preservation. A further aim is the examination of the applicability of the algorithms to inversion of electrical fields for the AIDA partners. We will focus on a combined (multidisciplinary) inversion of gravity and magnetic data and their derivatives/ tensors (in cases where tensor data are available). We also envisage an applicable integration and the consideration of constraints/ boundary conditions. For this purpose we will create an applicable start model based on geological and hydrogeological models.

State of the art

Today, inversion methods for highly nonlinear problems of potential theory exist for two-dimensional procedures on the basis of statistical concepts. 3D-modelling is limited to prism models, whereby the lateral extension of the prisms is optimised. I. Rechenberg (1994) is considered the founder of evolutionary-biological algorithms and an advancement of evolution strategy is the covariance matrix adaptation strategy (CMA-ES) (Hansen and Ostermeier, 1997). Evolution strategy procedures for local (Hansen and Ostermeier, 2001) and global optimisations (Hansen and Kern, 2004; Auger and Hansen, 2005; Hansen, 2006; Kern et al. 2006; Jastrebski and Arnold, 2006; Hansen et al. 2009) are particularly proven and competitive. The application to 3D problems to optimise geometry, position and physical parameters (density, susceptibility, electrical conductivity, velocity and more) has not previously been tackled and will be pursued for the first time in this subproject.

Scientific-technical working aims of the project

An important aim is the optimisation of quality functions of 3D models of susceptibility, density and conductivity distributions with the aid of new algorithms incorporating evolution strategy. Evolutionary algorithms solve problems of automatic multi-parameter inversions using concepts from bio-informatics (adaptation of the principles of natural evolution: recombination - mutation - selection - isolation).After the implementation of these algorithms and diverse tests with synthetic data, they will be adopted for interpretations of real world data sets. Subproject SP4 aims to develop and test new inversion and modelling methods for improved user-oriented spatial interpretations of the shallow subsurface for investigations of resources and environmental changes.

We seek a topology-conserving procedure that excludes these disadvantages. We do not want to change the model, but rather deform the model space. Thus, the model is not better optimised, but the space, the embodied model will be deformed whilst conserving topology (Fig. 3). The model to be optimised is pulled through with a regular tetrahedron grid. Then, the grid is changed in such a way that the geometry of the model becomes optimal in the sense of the quality function. Any grid modification is performed along the edges of tetrahedron, which should not become less than zero-length because the grid would intersect itself and the original topology would be destroyed. Therefore, the optimisation of model parameters is shifted on the optimisation of the length of the grid sides. The refinement of the grid controls the numerical resolution and the number of optimisation parameters of the magnetic and gravity fields and/or their derivatives/tensors.

3.5 Sub-project 5: Model development and evaluation of results

Aims of the sub-project

Synthetic models will be generated, which are geologically and hydrogeologically consistent and provide great variety in all datasets. In contrast to real world models synthetic models are error-free. Thus, different results from inversions and forward modelling can be better compared with each other. In addition, we can implement complex tectonic structures, such as fault zones, which will cause numerical problems for inversion or modelling procedures. Likewise we will also test constraining data and boundary conditions for inversion and modeling (a-priori-parameter) and their controlling factors for the results (a-posteriori-parameter).

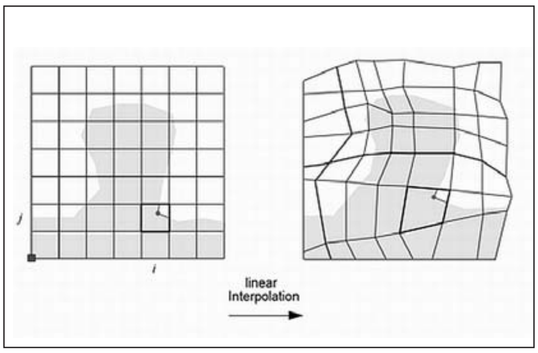

Figure 5: The optimization of model parameters will be shifted to the optimization of grid cells lenghts (Alvers, 1998).

The SP team ensures that selected data sets are compatible with the used software components and provides program interfaces if necessary. For purposes of exchange of results and for mutual and consistent comparisons the in-house CAU software package IGMAS+ (e.g Schmidt et al., 2007) will be modified for 3D-visualization of the results.
Therefore interfaces between IGMAS+ and GOCAD and/or other user software in the AIDA project will be developed and implemented. Data and 3D-modeling results will be visualized together with their specific uncertainties in one low cost »graphic cave« (Geowall Consortium, http://www.geowall.org 2008/12/12). The aim of this sub-project is to iteratively connect the heterogeneity distribution within the synthetic models with airborne geophysical data and to test and evaluate the plausibility of these models. Ambiguities will be reduced and the quality of the results will be enhanced. The use of airborne geophysical data in geological and hydrogeological simulations is a central issue, because these multi-parameter datasets can help to complete the often insufficient data base of the user-models (BurVal 2007, Working Group 2006).

Correlations of boreholes have been mainly based on conventional lithostratigraphic methods, leading to the connection of genetically different sediment bodies and the reconstruction of unrealistic facies and aquifer models. Therefore the understanding of the geometry of depositional systems, architectural elements and its internal lithofacies construction is critical. Particularly in sensitive coastal regions and special hydrogeological settings, a detailed knowledge of saltwater distribution and dynamics is important.
The missing feedback of geophysical models and user models complicates effective interpretations and hinder the use of airborne geophysical data. Since long interoperable graphics applications in the framework of interpretations of geodata and constraining information are inherent parts of 3D-interpretations and visualizations in »graphic caves«.

State of the art

Integration of geophysical, sedimentological and petro-physical data is a well established method in the frame work of hydrocarbon exploration, but has been applied to the analysis of groundwater aquifers only in the last few years. In particular modern sequence stratigraphic concepts for the interpretation of Quaternary depositional systems are often lacking. The architecture of sedimentary bodies determines the heterogeneity of many reservoirs and therefore the spatial distribution of hydraulic properties. Various scales of heterogeneities are distinguished, in-cluding lithofacies (0.01m – 1m), architectural elements (1m – 10m) and larger-scale lateral and vertical stacking patterns of depositional systems (10m – >100m). Tectonic processes lead to the formation of compartments, which are bounded by faults. The faults can be impermeable for fluids. Both, formation of compartments and faulting create a very heterogeneous subsurface geometry. This affects the fluid-flow, as well as the distribution of the effective geophysical parameters (e.g. Heinz et al., 2002; Fossen et al. 2005).
In most cases a feedback of geophysical models and user models is missing. Established part of 3D interpretations are interoperable visualization techniques. Since a couple of years visualization in »graphic caves« have been made available even in the low cost sector. Caves provide excellent conditions for visuable plausibility checks

Scientific-technical working aims of the project

From existing BGR data and partners sub areas are selected for application in inversion and modeling tools. These data will be transferred into a consistent model, which can fulfil the criteria of geology and hydro geology. This consistent model will help to adjust the results of the inversions and modeling later. Here we will investigate the possibilities of automatic classifications for geological interpretations. This task is to be noticed by two graduate student places (at LUH and CAU by help of BGR).

For 3D visualisation forward modeling and inversion a system will be developed permitting the presentation of all or most results of both inversion and modeling in a low-cost graphic cave. For comparison of inversion results with the forward modelling substantial modifications must be made in in-house program IGMAS+, and new interfaces have to be developed and implemented. Afterwards tests of sensitivity and errors at individual data sets will be visualized in combination with inversion and modelling results, in order to achieve an optimal combination from geophysical datum and its modelling. For this two synthetic models will be constructed.

Figure 6: Visualization of complex geological structures - here the underground of Schleswig-Holstein - in the Visualization Centre of the Helmholtz Centre for Environmental Research - UFZ, Leipzig. 3D Model: F. Hese, LLUR, Flintbek; Foto/ Visualisierung by B. Zehner, UFZ, Leipzig.

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Tomography of the Earth's Crust – From Geophysical Sounding to Real-Time Monitoring

The intensive usage of the underground with respect to exploitation, storage of disposals, energy source, and infrastructure as well as tunnel construction requires new or enhanced technologies and methods. High resolution time dependent images are necessary to receive important information about the subsurface.

The objective of this research topic is the refinement of tomographic methods and their application to geological processes. A lot of technological developments and innovations have been made in recent years like the real-time data acquisition and evaluation in addition to computer-aided visualization programmes.

But there is still the need to integrate und combine different methods in particular inversion methods.

This volume summarizes the scientific goals and first results presented during the kick-off seminar at the GFZ German Research Centre for Geosciences in May 2011. The articles reflect the interdisciplinary approach of the research topic.

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