Helmholtz-Zentrum Potsdam
Deutsches
GeoForschungsZentrum

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Scientific Technical Report STR12/05 - Data

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Content

1. Introduction

Electrical resistivity methods, either in vertical electrical sounding mode or lateral mapping mode, assess the resistivity distribution in the subsurface. Electrical resistivity tomography (ERT) has been successfully applied to image fluid-flow processes at various length scales and depths, mainly with electrodes deployed at the surface (e.g. Storz et al., 2000, Michot et al., 2003, Daily et al., 2004). Further developments showed that permanently installed electrode arrays in cased holes offer the possibility for almost continuous time-lapse measurements with a much larger radius of investigation than borehole logging tools. A wide range of engineering, exploration and environmental problems has been addressed by this technique, as e.g. air sparging and steam injection (Daily et al., 1995; Ramirez et al., 1995), evaluation of drainage efficiency in oil and gas reservoirs (van Kleef et al., 2001) and monitoring of vadose zone water movement (Liu et al., 2004). Geoelectrical methods are particularly suitable for monitoring CO_2 storage in deep saline aquifers due to the significant conductivity contrast between CO_2 and brine. They provide independent information about the electrical resistivity of the fluid-bearing rock that can be interpreted in terms of the relative CO_2 and brine saturation. In this context, Ramirez et al. (2003) and Christensen et al. (2006) presented promising modeling study results of geoelectrical monitoring for CO_2 plume detection.

A practical application of the ERT monitoring technique was demonstrated at the geological CO_2 storage site in Ketzin (Germany) (Schilling et al., 2009; Würdemann et al., 2010; Martens et al., 2011), where time-lapse surface-downhole ERT measurements as well as cross-hole ERT measurements have been carried out during a CO_2 injection experiment.
In the frame of the multidisciplinary monitoring concept, a combination of surface-downhole (SD) geoelectric measurements was tested (Kiessling et al., 2010) with the objective to enlarge the near-wellbore area, and to address limitations of the individual survey techniques. The geoelectric measurements at the Ketzin site comprise the following survey types (Figure 1):

- 3D SD-ERT: Current injection and voltage acquisition are performed at the surface using sparse circular dipole geometry (surface-surface). Additional voltage acquisition is conducted in the three wells (surface-downhole) using the vertical electrical resistivity array (VERA) system.

- 2D SD-ERT: Current injection and voltage acquisition are performed by dipoles that are arranged along two separate profiles intersecting each other near the injection location (surface-surface). Additional voltage acquisition is conducted in the wells Ktzi201 (surface-downhole) using the VERA system. 2D SD-ERT surveys have been carried out in the CO_2 injection phase exclusively.

- Crosshole ERT: Both, current injection and voltage acquisition, are performed by the downhole VERA system.

The present data publication is focused on the 3D SD-ERT data sets only. Practitioners have the opportunity to assess SD-ERT data in two main steps: The raw field data (voltage and current time-series) and the preprocessed apparent resistivities. If one decides for the first option, the raw field data can be used to apply own preprocessing procedures in order to determine apparent resistivities. If one intends to reproduce our pre-processing, one will find the relevant information in section 4 ('Raw field data'). If one decides to begin with the pre-processed apparent resistivities, it is possible to start right away into the resistivity inversion. The relevant information on the apparent resistivities are given in section 5 ('Preprocessed data'). In the context of these data, we recommend also the publications of Kiessling et al. (2010) and Bergmann et al. (2012).

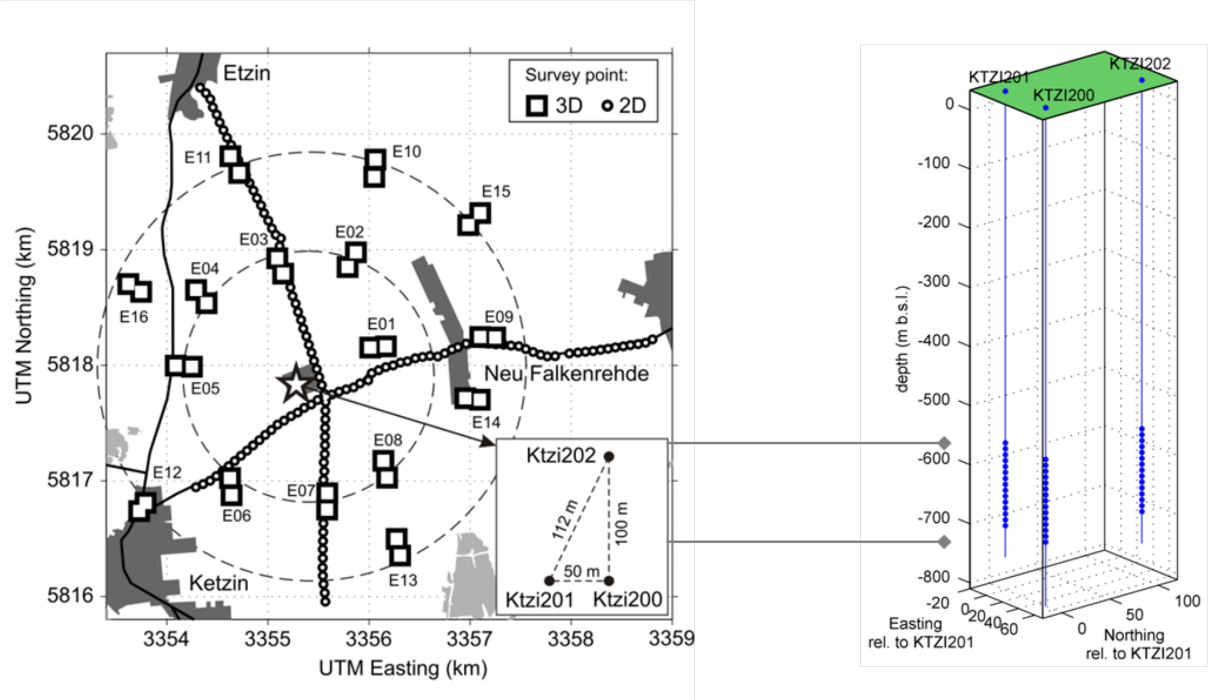


Figure 1: Schematic of the particular survey types carried out at the Ketzin CO2 storage site: ☐ 3D SD-ERT measurements, ○ 2D SD-ERT measurements (left side), and ● cross-hole measurements via the permanent installed downhole VERA system (right side) (after Bergmann et al., 2010).

2. Data collection

Survey periods

The 3D SD-ERT survey periods (Table 1) were performed as close to the arrival times of the CO_2 at the observation wells (Figure 2) as operational circumstances allowed.

Table 1: Periods of the SD-ERT surveys (without mobilization and initial layout)

	Period
Baseline 1	08.10.-12.10.2007
Baseline 2	21.04.-23.04.2008
Repeat 1	28.07.-30.07.2008
Repeat 2	24.11.-27.11.2008
Repeat 3	27.04.-29.04.2009

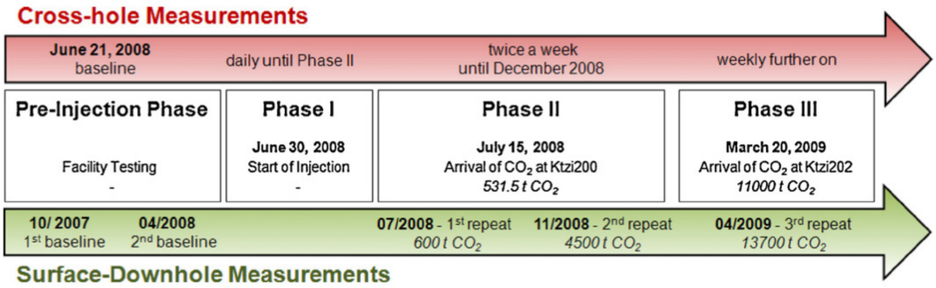


Figure 2: Overview on the SD-ERT measurements during the CO_2SINK project (time bar at bottom) (Kiessling et al., 2010)

Surface geometry

The surface geometry of the SD-ERT surveys consists of 16 surface dipoles which are approximately deployed on two concentric circles. These circles are centered on the injection location (Figure 3) and have a radius of 800 m and 1500 m, respectively. The dipoles have a length of 150 m and are used for current injection and voltage acquisitions. Coordinates were surveyed with GPS handhelds that provided accuracy in the order of meters. Table 2 gives relative coordinates, with the well Ktzi200 as reference point (see Table 4). Variations in ground elevation have been neglected due to the relatively flat surface topography and the low (vertical) GPS accuracy. Consequently, surface locations are assumed to be located on a uniform datum plane which equals the surface elevation at the observation well Ktzi200.

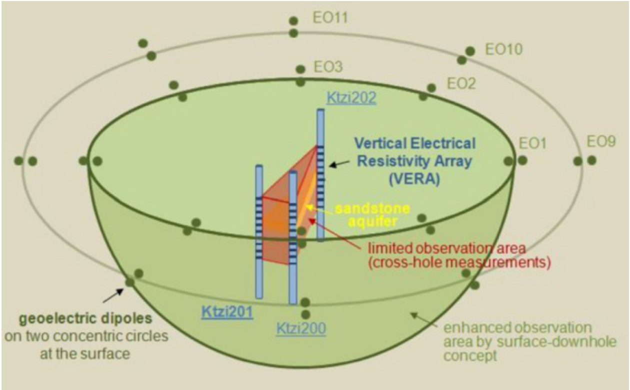


Figure 3 Schematic illustration of the 3D SD-ERT measurements carried out at the Ketzin site (Kiessling et al., 2010).

Table 2: Relative coordinates (in meters) of the surface electrodes. Base of the coordinate system is given by the location of the well Ktzi200.

Number	Easting	Northing
EO01a	718	351
EO01b	873	362
EO02a	494	1048
EO02b	577	1175
EO03a	-142	991
EO03b	-201	1123
EO04a	-901	735

Number	Easting	Northing
EO09a	1806	443
EO09b	1954	438
EO10a	758	1827
EO10b	770	1977
EO11a	-577	1862
EO11b	-664	2006
EO12a	-1503	-993

EO04b	-1004	850
EO05a	-1045	185
EO05b	-1205	194
EO06a	-668	-778
EO06b	-653	-926
EO07a	293	-909
EO07b	292	-1051
EO08a	849	-629
EO08b	885	-775

EO12b	-1567	-1063
EO13a	980	-1304
EO13b	1014	-1448
EO14a	1659	-87
EO14b	1802	-100
EO15a	1688	1410
EO15b	1806	1515
EO16a	-1547	833
EO16b	-1674	901

Downhole geometry (VERA electrodes)

Voltage registration in the Ketzin boreholes was conducted via the electrodes of the permanently installed Vertical Electrical Resistivity Array (VERA). The VERA system provides 45 electrodes (15 per well) which are installed in the depth range of about 590 to 740 m with a vertical spacing of 10 m (Figure 4).

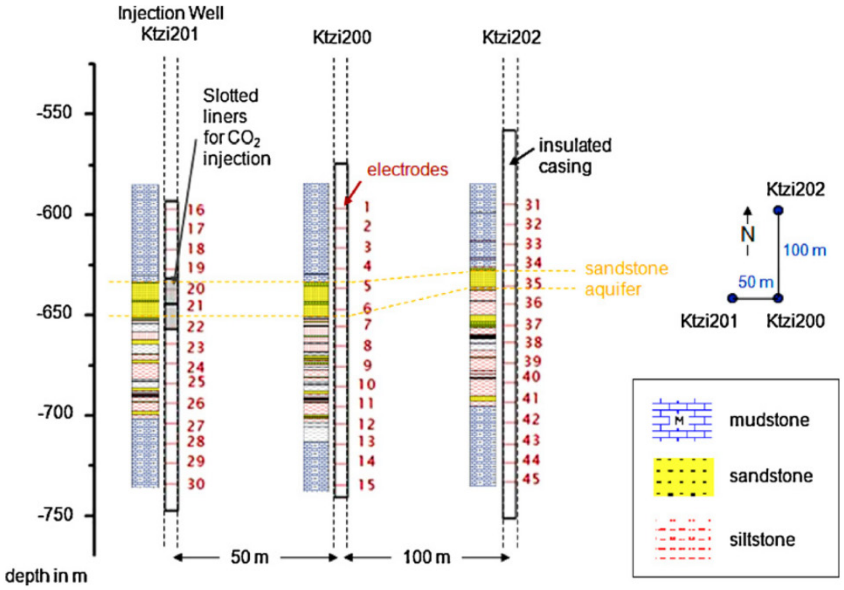


Figure 4: Arrangement of electrodes in the VERA (Kiessling et al. 2010) with the lithology after Norden et al. (2008).

For details on the technical specification and installation procedure of the VERA electrodes the reader is referred to Prevedel et al. (2009); Kiessling et al. (2010); Schmidt-Hattenberger et al. (2011). The relative coordinates of the VERA electrodes are given in Table 3 and the respective reference coordinates in Table 4. It is important to note that the coordinates in Table 3 do not reflect lateral or vertical displacements, e.g. due to deviations in well tracks.

Table 3: Relative coordinates (in m) of the downhole electrodes. Base of the coordinate system is given by the surface position of the well Ktzi200 (Table 4).

Ktzi200 (Observation well)

NB	E	N	D
1	0	0	-595
2	0	0	-605
3	0	0	-615
4	0	0	-625
5	0	0	-635
6	0	0	-645
7	0	0	-655
8	0	0	-665
9	0	0	-675
10	0	0	-685
11	0	0	-695
12	0	0	-705
13	0	0	-715
14	0	0	-725
15	0	0	-735

Ktzi201 (Injection well)

NB	E	N	D
16	-50	0	-595
17	-50	0	-605
18	-50	0	-615
19	-50	0	-625
20	-50	0	-635
21	-50	0	-645
22	-50	0	-655
23	-50	0	-665
24	-50	0	-675
25	-50	0	-685
26	-50	0	-695
27	-50	0	-705
28	-50	0	-715
29	-50	0	-725
30	-50	0	-735

Ktzi202 (Observation well)

NB	E	N	D
31	0	100	-590
32	0	100	-600
33	0	100	-610
34	0	100	-620
35	0	100	-630
36	0	100	-640
37	0	100	-650
38	0	100	-660
39	0	100	-670
40	0	100	-680
41	0	100	-690
42	0	100	-700
43	0	100	-710
44	0	100	-720
45	0	100	-730

Table 4: Coordinates of the Ketzin wells from CO_2SINK drilling reports. Eastings and Northings are given for UTM (ETRS 89) reference system.

	Ktzi200	Ktzi201	Ktzi202
Full name	CO2 Ktzi200/2007	CO2 Ktzi201/2007	CO2 Ktzi202/2007
Type	Observation	Injection	Observation
Easting	3355292.7	3355242.7	3355296.8
Northing	5817801.6	5817803.7	5817901.4
Elevation a.s.l. (m)	33.6	33.5	33.5

Current source

The used current injection was a TSQ-4 (Scintrex Limited, Canada) power source (max. power of 10 kW, max. electrical current 20 A at a max. voltage of 3.3 kV) which is owned and operated by the Institute of Geophysics and Geology, University of Leipzig. Injection was performed by a repeated square-wave direct current (DC) with changing polarity (4 s +on, 4 s off, 4 s -on, 4 s off). Electric currents were injected for a period of approximately 45 minutes at each surface location.

Voltage registration

Voltage registration at the surface dipoles and the borehole electrodes was realized by Texan-125 recorders (Refraction Technology Inc., USA) operated and owned by the Institute of Geophysics and Geology, University of Leipzig. Voltages at the VERA electrodes were performed for neighboring electrodes:

Ktzi200: 1-2, 2-3,… 14-15
Ktzi201: 16-17, 17-18,… 29-30
Ktzi202: 31-32, 32-33,… 44-45

The 45 min current injections were divided into three intervals which were used for sequential voltage acquisition in the three wells. This was due to the limited number of recording units in use, which caused the use of 14 recording units for the VERA electrodes. After measuring potentials in the first well for a period of 15 minutes, they were connected to the second well. After another period in the second well they were connected to the third well. Subsequently the current source was moved to the next current injection point.

Current registration

The current registration was performed by a shunt resistor of 10 mΩ and dedicated Texan -125. The registered voltage signals have to be multiplied by a factor of 100 to transfer the scale to Ampere.

3. Workflow of data processing

In the field surveys, voltage time-series with a length of 15 minutes were obtained, which would result in an average cycle count of 56 (due to the used 1/16 Hz current wavelet). However, because of adjustments and interruptions in the start/end phase of the current sweeps, a count of 30-40 cycles was most generally achieved. In order to determine apparent resistivities and error estimates from the voltage and current time series, a preprocessing routine ("pre_processing_script") was implemented in Matlab (we used Matlab in the version R2011b and higher). The functionality of the preprocessing script is schematically illustrated in Figure 5.

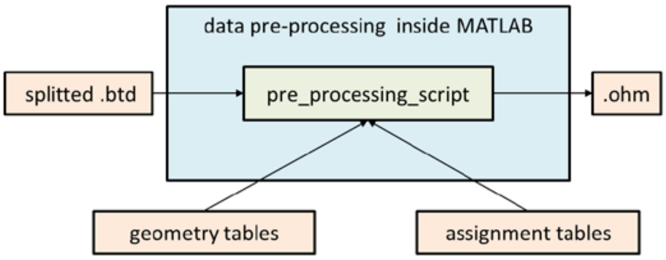


Figure 5: data pre-processing inside Matlab

Figure 6 depicts a more detailed block structure of the preprocessing routine. Because of galvanic and self-potential effects, the voltage time-series are often affected by asymptotic and drifting (long-wavelength) signal components. The long-wavelength signals were addressed by a (convolution) high-pass filter with cut-off frequency of 1/32 Hz. The filter was also used to reduce bias components in the voltage time-series. Subsequently, a selective stacking procedure (following Storz et al., 2000) was applied in order to sum the multiple voltage periods into an averaged signal of a single (16 s) period. The selective stacking is an alpha-trimmed mean summation in which a selected percentage of largest and smallest samples are excluded.

The resulting voltage signals have been notch filtered for frequencies of 2.8 Hz, 8.5 Hz, and 16.6 Hz, which we found to be the dominant periodic noise signals in the data. The first baseline survey contains particular noise due to pulsed electrical anti-corrosion currents of a nearby gas pipeline. Finally, a phase correction was carried out, because the voltage recorders are not fully synchronized. The programming unit does not allow the simultaneous connection to all voltage recorders and therefore the simultaneous setup with a sufficient timing accuracy is not given. For synchronizing the internal time the PC time of the host computer was used. Further, as the current supply uses a smooth roll-in and roll-out it was not possible to reconstruct the true phase information. The phase correction is carried out to align voltage signals and current signals by means of the cross-correlations. Since this gives rise to potential cycle skips, which introduce spurious sign switches, we proceeded with the absolute values for the apparent resistivities.

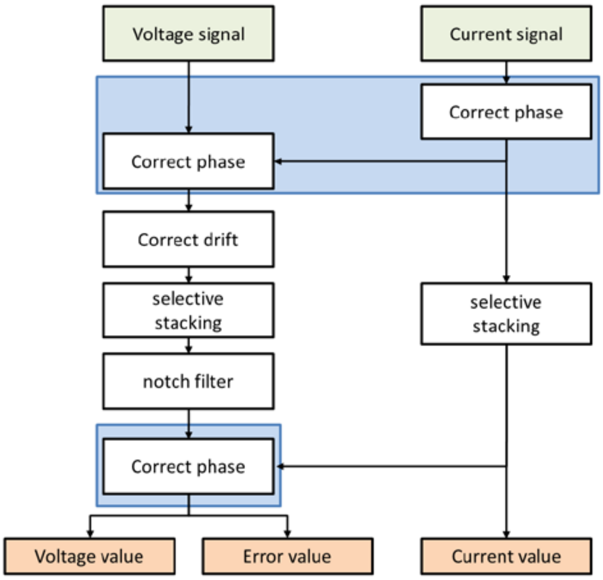


Figure 6: Schematic of “pre_processing_script”

The determination of the apparent resistivity from the stacked and phase corrected voltage signal was performed by analysis of two time gates (see Figure 7). Averaged voltages were deduced from the time gates, which are indicated by the green boxes. These gates cover the second half of each signal plateau in order to reduce the impact of the asymptotic signal components.

The error estimation is based on the maximum and minimum voltages of the complete plateaus (red boxes). The difference of minU_3 and maxU_1 is used to deduce a minimum voltage U_{min}. The difference of maxU_3 and minU_1 is used to deduce a maximum voltage U_{max}. Based on the U_{min}, U_{max}, and the averaged voltage, we estimated a percent error according to:

```
% snippet from MATLAB script “get_resistance.m”
% ...
```

```
dU = abs(maxU1 - minU1) / 2;
dU = dU + abs(maxU3 - minU3) / 2;

r = abs(voltage / current);

rmax = (abs(voltage) + dU) / (abs(current));
rmin = (abs(voltage) - dU) / (abs(current));

dr = abs(rmax - rmin) / 2;

if (r > 0)
      error = ((dr * 100) / r) / 1;
else
      error = 1e+999;
end

% ...
```

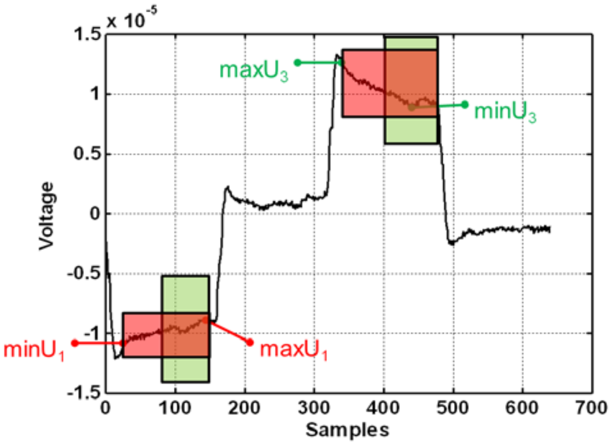


Figure 7: Voltage and error estimation from time signal

The injected currents were measured as voltage time-series by means of a 10 mΩ shunt resistor. Current values were determined in the same manner as the voltage values.

4. Raw field data

Assignment table

The assignment tables are used as a digital protocol which was translated from the handwritten field protocols. These tables specify the allocations of current injection times, electrode numbers and digital recorder units. All tables are created with Microsoft Excel Professional Plus 2010.

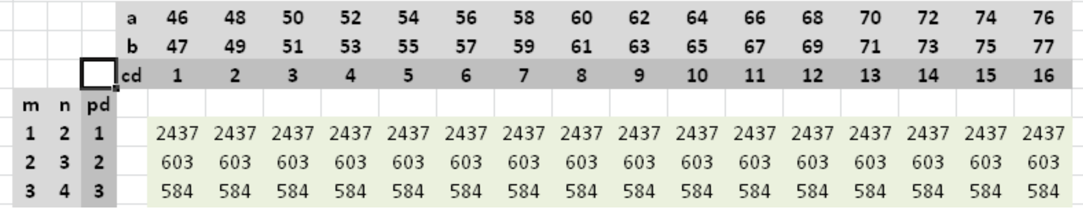
Table 5: Abbreviations used in the assignment table

a,b	current electrodes (range: 46-77)
m,n	potential electrodes (range: 1-77)
cd	Current dipole: alias name of combined current electrodes a and b (range: 1-16)
pd	Potential dipole: alias name of combined potential electrodes m and n (range: 1-58)

series	“Series” was introduced to measure more potential electrode combinations pd for the same current electrode combination cd then digital recorder units are available. The measurements are done to different times.
sh	Start hour of measurement
sm	Start minute of measurement
eh	End hour of measurement
em	End minute of measurement
date	Date of measurement
current	Injected current displayed on Scintrex transmitter unit
voltage	Actual voltage applied to electrodes a and b (measured by Scintrex transmitter unit)
index	Index number
day_julian	Day of the year of measurement
recorder_p	Digital recorder unit for voltage (potential) acquisition
recorder_c	Digital recorder unit for injection current acquisition

Table sheet “mapping” is divided into two sub spreadsheets.

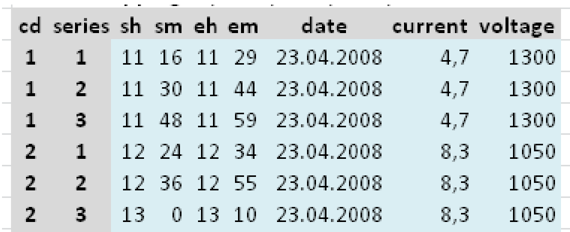
Spreadsheet 1 is used to map the Texan-125 digital acquisition units to the potential electrodes numbers. For each current dipole cd, the respective set of acquisition units is defined, which were used for measure the potential dipole pd (see Figure 8). Numbering of cd (1-16) and pd (1-58) was conducted independently and consecutively and, therefore, do not indicate identical electrode combinations when cd and pd occur with the same number.



			a	46	48	50	52	54	56	58	60	62	64	66	68	70	72	74	76
			b	47	49	51	53	55	57	59	61	63	65	67	69	71	73	75	77
			cd	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
m	n	pd																	
1	2	1		2437	2437	2437	2437	2437	2437	2437	2437	2437	2437	2437	2437	2437	2437	2437	2437
2	3	2		603	603	603	603	603	603	603	603	603	603	603	603	603	603	603	603
3	4	3		584	584	584	584	584	584	584	584	584	584	584	584	584	584	584	584

Figure 8: spreadsheet 1 example mapping cd, pd and recorder units

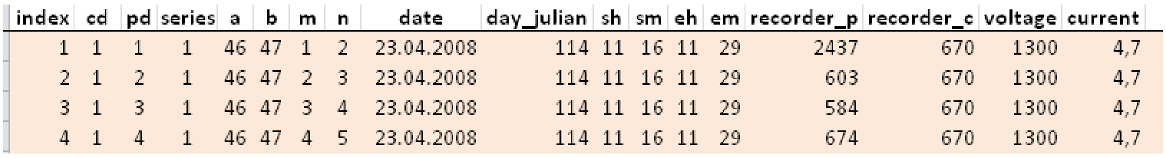
Spreadsheet 2 is used to map the injection time and date to the current dipoles cd. Additionally, the current and voltage values, displayed on the Scintrex transmitter during current injection, are denoted (see Figure 9). For every current dipole cd, three times and dates are specified (marked with series 1 to 3) representing the voltage measurements sequentially carried out in the three wells (see also Chapter “Voltage registration”).



cd	series	sh	sm	eh	em	date	current	voltage
1	1	11	16	11	29	23.04.2008	4,7	1300
1	2	11	30	11	44	23.04.2008	4,7	1300
1	3	11	48	11	59	23.04.2008	4,7	1300
2	1	12	24	12	34	23.04.2008	8,3	1050
2	2	12	36	12	55	23.04.2008	8,3	1050
2	3	13	0	13	10	23.04.2008	8,3	1050

Figure 9: spreadsheet 2 example mapping cd, series, time and date

In **table sheet “data”** all information from sheet “mapping” are merged together. The “data” table contains all measurements and specifies electrode numbers, time and date information, and recorder numbers (see Figure 10). For completeness, the “data” table contains also configurations with similar electrode combination for a-b and m-n (e.g. a-b-m-n: 1-2-1-2). However, because these configurations represent current injection and voltage registration at identical locations they are to be ignored. The “data” table is further used for the automated preprocessing routine in Matlab (see “Workflow of data processing”)



index	cd	pd	series	a	b	m	n	date	day_julian	sh	sm	eh	em	recorder_p	recorder_c	voltage	current
1	1	1	1	46	47	1	2	23.04.2008	114	11	16	11	29	2437	670	1300	4,7
2	1	2	1	46	47	2	3	23.04.2008	114	11	16	11	29	603	670	1300	4,7
3	1	3	1	46	47	3	4	23.04.2008	114	11	16	11	29	584	670	1300	4,7
4	1	4	1	46	47	4	5	23.04.2008	114	11	16	11	29	674	670	1300	4,7

Figure 10: table sheet data example

Table sheet “data_sorted” is a copy of table sheet “data” but is sorted with respect to the fields “series” and “recorder_p”. This table is not mandatory for operation of the following processing routines but improves data import times, because data input will be carried out only once.

Geometry table

The geometry table defines the electrode names and positions, and is also used for automated processing. Table 6 gives the used abbreviations.

Table 6: Abbreviations used in the geometry table

protocol_name	Inherited electrode names from the handwritten protocol
alias_name	Renamed protocol_name for counting and automation
x	X position of electrode
y	Y position of electrode
z	Z position of electrode
Well 200	Electrode names and positions for well Ktzi200
Well 201	Electrode names and positions for well Ktzi201
Well 202	Electrode names and positions for well Ktzi202
ring	Electrode names and positions for surface ring electrodes
profile WE current	Electrode names and positions for surface profile current electrodes
profile WE potential	Electrode names and positions for surface profile potential electrodes
profile NS current	Electrode names and positions for surface profile current electrodes
profile NS potential	Electrode names and positions for surface profile potential electrodes

Data Formats

In order to proceed with the field data throughout the preprocessing some format conversions have to be carried out (Figure 11).

The Texan-125 units store the field data in the TRD format. This format is converted by “125_SEGY.EXE” to the RSY format, which is very similar to the seismic SEGY format (e.g. Barry et al., 1975). The wrapper tool “TRD2RSY.EXE” can be used to convert multiple TRD files more conveniently. In the final step, RSY files are converted to the BDT format via “RSY2BTD.EXE”, which we introduced to allow for efficient and simple handling of the data in Matlab.

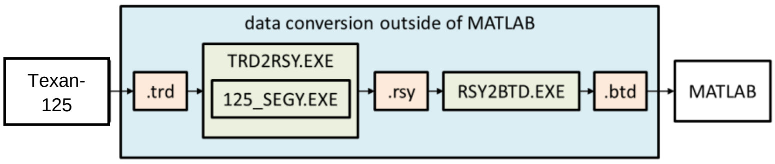


Figure 11: data conversion outside Matlab

In order to reduce storage requirements and increase processing speed, the BTD files are split into the current injection intervals as specified in the assignment tables. For this purpose, the splitting procedure is implemented in the Matlab script “split_data_script” (see Figure 12), which generally retains the BDT format.

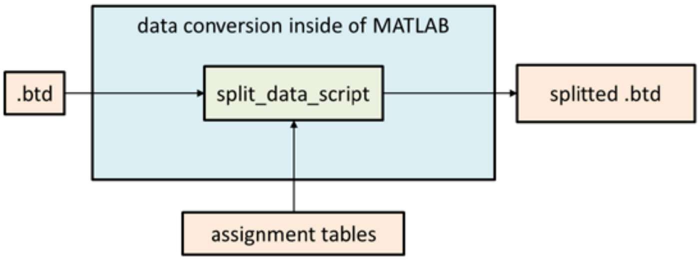


Figure 12: data conversion inside Matlab

BTD file format

The BTD format is a simple binary file format with header information. All values are stored as 4 byte floating point (IEEE 754) little-endian (PC) format. This file format consists of three types of blocks, the header block, the time stamp blocks, and the data blocks. Table 7 gives detailed information about the value positions and Figure 13 illustrates the block structure of a BDT file.

The BDT file is initialized with the header information, which specifies the header length, sample rate, and total number of samples. Subsequently, time stamp blocks and data blocks are alternating. Each time stamp block specifies the year, month, day, hour, minute, second, and millisecond of the first data sample in the following data block. Because each data block stores one second of field data, the length of a data block is equal to the sample rate. Another time stamp following a data block indicates the existence of further samples.

Table 7: BTD file format

Position in file	**Value position**	**Description**	**Default value**
1	1	Header length (start of header block)	100
4	2	Sample rate	40
8	3	Sample count	-
12-396	4-99	Reserved fields (end of header block)	0
400	100	Year (start of times stamp block)	-
404	101	Month	-
408	102	Day	-
412	103	Hour	-

416	104	Minute	-
420	105	Second	-
424	106	Millisecond (end of times stamp block)	-
428	107	Data value 1 (start of data block)	-
432	108	Data value 2	-
…	…	…	…
584	147	Data value 40 (end of data block	-
588	148	Year (start of times stamp block)	-
592	149	Month	-
…	…	…	…

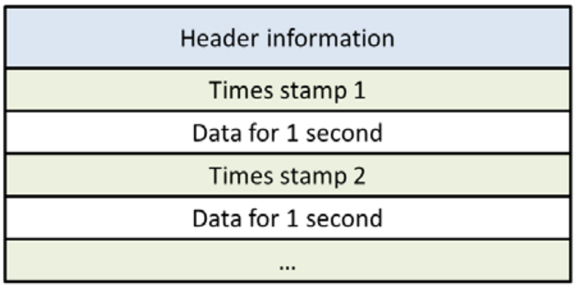


Figure 13: Schematic BTD file structure

SEGY file format

Finally, we amended the data workflow illustrated in Figure 14 by a SEGY file export in order to simplify the access to the data. Since this format is specialized for storing seismic (time-series) data, we adopted the following changes for the SEGY trace header definitions for our purpose (Table 8). For export SEGY files, we use the Matlab script “export_segy_script”. We used the textual file header to store comments and filled the file header fields “sample format” and “sample interval”. The first trace in the SEGY file is always reserved for storing the current time series, whereas traces 2-30 are used for potential time series.

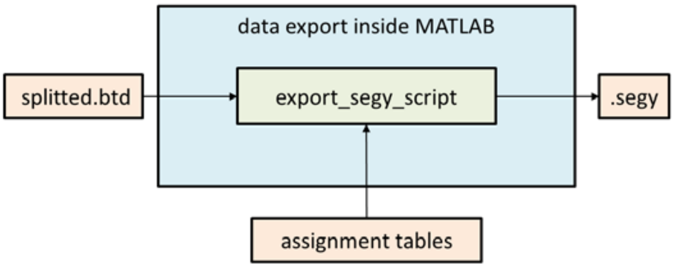


Figure 14: data SEGY export inside Matlab

Table 8: SEGY trace header specification used for the SD-ERT data.

Original field name and position	**Renamed field**
SourceX coordinates (Bytes 73-76)	for trace number 1: electrode a for trace number greater 1: electrode m

SourceY coordinates (Bytes 77-80)	for trace number 1: electrode b for trace number greater 1: electrode n
Original field record number (FFID) (Bytes 9-12)	Index in assignment table

For reading and writing of SEGY files with Matlab we use the open-source package SegyMAT, which can be accessed from http://segymat.sourceforge.net/.

5. Preprocessed data

On the basis of the BDT files or SGY files, one can carry out the determination of the apparent resistivities, which are used for the resistivity inversion. Practitioners who would like to skip the previous steps can use the apparent resistivities, we obtained from the procedure described in section 3 (‘Workflow of data processing’). For the apparent resistivities we use the plain text format that is recommended for the usage in BERT (see Inversion scripts). A detailed description of this so-called OHM file format can be assessed from www.resistivity.net. In the following a description of the OHM file format is given as reported there:

Every data set consists of two mandatory parts: electrode definitions and arrangement definition. Subsequently the number of electrodes, their positions (x z for 2D, x y z for 3D), the number of data and their definitions are given. Comments may be placed after the # character. After the number of data the definition for each datum can be given row-wise by the electrode numbers for the current electrodes A and B (C1 and C2) and the potential electrodes M and N (P1 and P2). They may be followed by other attributes (see list below). Standard is the apparent resistivity and optional the relative error as exemplified for a tiny dipole-dipole survey.

```
6 # Number of electrodes
# x z
0     0
1     0
2     0 # loose ground
3     0
4     0
5     0
6 # Number of data
#a b m n rhoa
1   4   2   3   231.2 # A Wenner point
1   2   3   4   231.2 # Dipol-dipole sequence
2   3   4   5   312.8
3   4   5   6   12.1  # possibly an outlier
1   2   4   5   256.7
1   0   5   6   199.7 # Pole-dipole
1   0   5   0   246.2 # Pole-pole
```

The token string in the **line after the number of data** can be omitted for the order A B M N rhoa (error). Otherwise it is used to specify the given columns The token may be followed by a slash and a physical unit. The following tokens are allowed (case insensitive).

Tokens	**Meaning**	**Possible units**
a c1	electrode number for A (C1)	
b c2	electrode number for B (C2)	
m p1	electrode number for M (P1)	
n p2	electrode number for N (P2)	
Rhoa rho_a Ra	apparent resistivity	Ohmmeter
R Z rho	Resistance/Impedance	Ohm
err error std	Error/standard deviation	1(default),%,Ohm
Ip	IP measure	mRad(default),°,FE,MF
I	Current	A(default),mA,uA
U V	Voltage	V(default),mV,uV
Sp	self potential	V(default),mV,uV
T	topography effect	1

The following sample contains voltages, currents and a percentage error.

```
...
6 # Number of data
# a b m n U I/mA err/%
1   2   3   4  -0.5305165 102.2 2.4
2   3   4   5  -0.5305165 99.9  1.4
1   2   4   5  -0.1326291 100.1 7.6
...
```

Topography may be given in two ways.
1. Each electrode can be given a height value as z position (preferred by webinv).
2. Alternatively, the data may be followed by a topo list (preferred by DC2dInvRes).

```
...
1   2   5   6  -0.05305165  7.5
4# Number of topo points
# x h for each topo point
0 353.2
12 357.1
19 359.9
24.5 350
```

Buried/borehole electrodes vs. topography

There might be confusion about using z for surface topography or buried/borehole electrodes, (DCndInvRes understands z usually as depth, whereas DCTopo reads it as topography) In order to distinguish between both we provide different tokens for the electrode list: Besides x and y used for real coordinates, h (for height) and d (for depth below surface) can be provided. So the definition is unique, furthermore it is possible to combine both. A z will still be interpreted problem-dependent.

6. Inversion scripts

Inversion of the data had been carried out with the open-source software BERT (Boundless Electrical Resistivity Tomography, www.resistivity.net). For users not acquainted with BERT we strongly recommend the tutorial document which can be downloaded from www.resistivity.net and the examples that accompany the code.

The second step (after the previous data preprocessing) to run the inversion is to create the mesh:

This is carried out by running bert.cfg (>>bert.cfg meshes) which retrieves the relevant geometrical information (e.g. model depth, lateral model size) from the data (here baseline2b.dat) and initializes the triangularization.

The complete inversion procedure is carried out by:

```
rhoMax=1000
errorMax=1000
lambda=20
zweight=0.9

dcedit baseline2a.ohm -o baseline2b.dat --rMin=0.1 --rMax=$rhoMax --errMax=$errorMax
dcedit repeat1a.ohm -o repeat1b.dat --rMin=0.1 --rMax=$rhoMax --errMax=$errorMax
dcedit repeat2a.ohm -o repeat2b.dat --rMin=0.1 --rMax=$rhoMax --errMax=$errorMax
dcedit repeat3a.ohm -o repeat3b.dat --rMin=0.1 --rMax=$rhoMax --errMax=$errorMax

dcedit baseline2b. ohm -o baseline2b.dat --filter=n=10 --filter=n=11 --filter=n=38 --filter=n=39
dcedit repeat1b.ohm -o repeat1b.dat --filter=n=10 --filter=n=11 --filter=n=38 --filter=n=39
dcedit repeat2b.ohm -o repeat2b.dat --filter=n=10 --filter=n=11 --filter=n=38 --filter=n=39
dcedit repeat3b.ohm -o repeat3b.dat --filter=n=10 --filter=n=11 --filter=n=38 --filter=n=39

cp baseline2b.dat baseline2a.dat
cp repeat1b.dat repeat1a.dat
cp repeat2b.dat repeat2a.dat
cp repeat3b.dat repeat3a.dat

python delElectrodes.py baseline2b.dat
python delElectrodes.py repeat1b.dat
python delElectrodes.py repeat2b.dat
python delElectrodes.py repeat3b.dat

echo "repeat1b.dat" > timesteps.dat
echo "repeat2b.dat" >> timesteps.dat
echo "repeat3b.dat" >> timesteps.dat

bert bert.cfg meshes

dcinv -SJvvv -i20 -l $lambda \
   -z $zweight \
   -b 0.1 -u 2000 \
   -T -t timesteps.dat \
   -p mesh/mesh.bms baseline2b.dat
```

This inversion script makes use of delElectrodes.py

```
#!/usr/bin/env python

import sys
import pygimli as g

def removeE( N, e ):
```

```
   N.remove( g.find( N('a')==e ) )
   N.remove( g.find( N('b')==e ) )
   N.remove( g.find( N('m')==e ) )
   N.remove( g.find( N('n')==e ) )

def removeEs( N ):
#    N.remove( g.find( g.abs( N('n') - N('m') ) > 15 ) )
   removeE( N, 10 )
   removeE( N, 38 )
   removeE( N, 39 )
   removeE( N, 40 )
   removeE( N, 41 )
   removeE( N, 42 )
   removeE( N, 43 )
   removeE( N, 44 )
   N.removeUnusedElectrodes()

def readData( name ):
   N=g.DataContainer( name )
   print "loaded:", N
   removeEs( N )
   print min( N.err() ), max( N.err() )
   N.save( name )
   print "saved:", N
   return N

if __name__ == '__main__':
   readData( sys.argv[-1] )
```

bert.cfg

```
DATAFILE=baseline2b.dat
DIMENSION=3
TIMESTEPS=timesteps.dat
# Mesh options
SURFACESMOOTH=1 # makes a nicer surface
PARA3DQUALITY=1.12   # defines how fast the mesh is growing (1.1-slow,2-fast)
PARAGEOMETRY='. ./mkpara.sh'  # user-defined parameterisation producing mesh/mesh.poly
```

mkpara.sh

```
#!/usr/bin/env bash
# mandatory name for the resulting PLC
mkdir -p mesh/
MESH=mesh/mesh
nElecs=`head -n 1 $DATAFILE`
head -n $[ nElecs + 2 ] $DATAFILE | tail -n $nElecs > usedElectrodes.xyz
# create world ( 0km x 20km x 10km)
polyCreateWorld -x 20000 -y 20000 -z 10000 -m1 -d3 $MESH
# create parameter domain ( 5km x 5km x 2km )
polyCreateCube -m2 para
polyScale -x 5000 -y 5000 -z 2000 para
polyTranslate -z -1000 para
# merge parameter domain into the world
polyMerge $MESH para $MESH
# add electrode positions
polyAddVIP -f usedElectrodes.xyz -m -99 $MESH
# apply $PARAMAXCELLSIZE flag
```

```
polyAddVIP -a $PARAMAXCELLSIZE -R -m2 -x 0 -y 0 -z -600 $MESH
# remove temporary stuff
rm para.poly
```

In general, we cannot guarantee a numerical upward compatibility of the BERT code. Therefore, practitioners who intent to strictly reproduce our results, should inform the BERT developer Carsten Rücker about their aim when requesting the software via www.resistivity.net.

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References:

Barry, K.M., Cavers, D.A., Kneale, C.W., 1975, Recommended standards for digital tape formats: Geophysics, 40, 2,344-352.

Bergmann, P., Schmidt-Hattenberger, C., Kiessling, D., Rücker, C., Labitzke, T., Henninges, J., Baumann, G., Schütt, H., 2012, Surface-Downhole Electrical Resistivity Tomography applied to Monitoring of the CO_2 Storage Ketzin (Germany): Geophysics, submitted.

Christensen, N.B., Sherlock, D., Dodds, K., 2006, Monitoring CO_2 injection with cross-hole electrical resistivity tomography: Explor. Geophys. 37, 44–49.

Daily, W., Ramirez, A., LaBrecque, D., 1995, Electrical resistance tomography experiments at the Oregon Graduate Institute: Journal of Applied Geophysics, 33, 227-237.

Daily, W., Ramirez, A., Binley, A., LaBrecque, D., 2004, Electrical resistance tomography: The Leading Edge, 438–442.

Kiessling, D., Schmidt-Hattenberger, C., Schütt, H., Schilling, F., Krüger, K., Schöbel, B., Danckwardt, E., Kummerow, J. and the CO_2SINK Group, 2010, Geoelectrical methods for monitoring geological CO_2 storage: First results from cross-hole and surface-downhole measurements from the CO_2SINK test site at Ketzin (Germany): International Journal of Greenhouse Gas Control, 4, 5, 816-826.

Liu, S. and Yeh, T.-C.J., 2004, An Integrative Approach for Monitoring Water Movement in the Vadose Zone: Vadose Zone Journal, 3, 2, 681-692.

Martens, S., A. Liebscher, F. Möller, H. Würdemann, F. Schilling, M. Kühn, and Ketzin Group, 2011, Progress report on the first European on-shore CO_2 storage site at Ketzin (Germany) - Second year of injection: Energy Procedia, 4, 3246-3253.

Norden, B., Förster, A., Vu-Hoang, D., Marcelis, F., Springer, N., Le Nir, I., 2008, Lithological and petrophysical core-log interpretation in CO_2SINK, the European CO_2 Onshore Research Storage and Verification Project. In: SPE 115247, SPE Asia Pacific Oil and Gas Conference and Exhibition, Perth, Australia, October 20–22.

Prevedel, B., Wohlgemuth, L., Legarth, B., Henninges, J., Schütt, H., Schmidt-Hattenberger, C., Norden, B., Förster, A., Hurter, S., 2009, The CO_2SINK boreholes for geological CO_2-storage testing: Energy Procedia, 1, 1, 2087-2094.

Ramirez, A.L., Daily, W.D., Newmark, R.L., 1995, Electrical Resistance Tomography for Steam Injection Monitoring and Process Control: J. Environ. Eng. Geophysics 1, 39, 39-51.

Ramirez, A.L., Newmark, R.L., Daily, W.D., 2003, Monitoring carbondioxide floods using electrical resistance tomography (ERT): Sensitivity studies: J. Environ. Eng. Geophys. 8(3), 187–208.

Schilling, F.R., G. Borm, H. Würdemann, F. Möller, M. Kühn, and CO_2SINK Group, 2009, Status report on the first European on-shore CO_2 storage site at Ketzin (Germany): Energy Procedia, 1, 2029-2035.

Schmidt-Hattenberger, C., Bergmann P., Kiessling, D., Krüger, K., Rücker, C., Schütt, H. and Ketzin Group, 2011, Application of a Vertical Electrical Resistivity Array (VERA) for monitoring CO_2 migration at the Ketzin site: First performance evaluation: Energy Procedia, 4, 3363-3370.

Storz, H., Storz, W., Jacobs, F., 2000, Electrical resistivity tomography to investigate geological structures of the earth's upper crust: Geophysical Prospecting, 48, 455-471.

Van Kleef, R., Hakvoort, R., Bushan, V., Al-Khodhori, A., Boom, W., de Bruin, C., Babour, K., Chouzenoux, C., Delhomme, J.P., Manin, D., Pohl, E., Rioufol, M., Charara, M., Harb, R., 2001, Water flood monitoring in an Oman carbonate reservoir using a downhole permanent electrode array. In: SPE Middle East oil show, Proceedings Society of Petroleum Engineers, vol. SPE-68078, CD-ROM, 11.

Würdemann, H., F. Möller, M. Kühn, G. Borm, F. Schilling, and CO_2SINK-Group, 2010, The Field-Laboratory for CO_2 Storage “CO_2SINK” at Ketzin (Germany): Site Preparation, Baseline Surveys and the First Year of Operation: International Journal of Greenhouse Gas Control, 4, 938-951.

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