Guidelines and standards for sTEM data - HydroGeophysics Group - Aarhus University

# Guidelines and standards for sTEM data collection, processing, and inversion

HydroGeophysics Group
AARHUS UNIVERSITY

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Aarhus University, Department of Geoscience, HydroGeophysics Group (HGG), Aarhus, Denmark, December 2025.

This *Guideline and standards for sTEM data collection*, was prepared within the framework of *GeoFysikSamarbejdet* (GFS), which is a collaboration between the Groundwater Division of the Danish Environmental Protection Agency (DEPA) and HGG at the Department of Geoscience, Aarhus University.

**Abbreviations**

| Acronyms | |
|---|---|
| EM | Electromagnetic methods which induce electrical currents in the ground through the principle of electromagnetic induction |
| TEM | Transient Electromagnetic |
| tTEM | Towed TEM |
| Tx | Transmitter |
| Rx | Receiver |
| LM | Low moment |
| HM | High moment |
| sTEMprofiler | Offset system |
| DOI | Depth of Investigation |
| LCI | Laterally Constrained Inversion |
| SCI | Spatially Constrained Inversion |
| UTC | Coordinated Universal Time |
| QC | Quality Control |
| GERDA | National Geophysical Database |
| GFS | GeoFysikSamarbejdet, collaboration between The Danish Environmental Protection Agency and the Department of Geoscience, Aarhus University |
| HGG | The HydroGeophysics Group at the Department of Geoscience, Aarhus University |
| DEPA | Danish Environmental Protection Agency |

# 1. REVISION HISTORY

The latest version of this guide is available on the web page of HGG: www.hgg.au.dk

**Version 1.0 - December 2025**
This is the first version of the *Guideline and standards for sTEM data collection, processing, and inversion*. This version of the guide reflects the present stage of the sTEM system, the processing software, and the inversion algorithms (December 2025).

# 2. INTRODUCTION

The sTEM platform is a modular, single-site TEM system supporting multiple transmitter (Tx) - receiver (Rx) loop configurations for flexible shallow-subsurface mapping. The purpose of this guide is to ensure consistent, high-quality standards for sTEM data collection, processing and inversion, and survey reporting. In addition, this guide serves as a workflow description and documentation for the different sTEM data formats.

The standards presented here are aligned with requirements for other geophysical data collected for hydrogeological mapping in Denmark. Although, the guide is written in a Danish context, it provides a general overview of the steps involved in a sTEM mapping campaign, including workflow, quality control, data processing, and inversion.

The following describes the three roles in an sTEM survey:

- **Instrument Manufacturer**: The company or institution that builds and sells the sTEM equipment.
- **Contractor**: The person(s) or company (user(s)) who owns the sTEM equipment and is/are responsible for data collection (operation of the sTEM system), as well as data processing, inversion, and reporting to the Client. This is typically a consulting company or an Academic institution.
- **Client**: The company or institution that orders the sTEM survey and receives the survey report and mapping results (e.g. DEPA).

Requirements in this guide are referenced to one of these three roles. It is assumed that data collection, processing, and inversion are carried out by the same Contractor and that all documentation for these steps is included in the survey report to the Client.

If any requirements cannot be met, the reasons must be clearly stated in the final report, and relevant parties should be informed in a timely manner. Contractors and Clients are expected to maintain open and frequent communication regarding any significant irregularities or issues that arise during mapping and data processing. This guide also provides typical or recommended processing and inversion settings. These settings are not mandatory and should be adapted to the specific survey and target.

All the sTEM systems discussed in this guide are commercial products sold by an Instrument Manufacturer, in this case TEMcompany. The intention of this guide is to guide the Contractors on properly acquiring data, processing data, and reporting data rather than to provide instructions for operating these systems.

Data processing and inversion are assumed to be conducted using SPIA or Aarhus Workbench software, both commercial products sold by Seequent, which contain modules specifically designed for sTEM data processing, inversion, and uploading to the National Geophysical Database (GERDA). Therefore, this guide includes direct references to specific SPIA and Aarhus Workbench settings. A general understanding of TEM data collection, processing, and inversion is assumed; this guide is **not** intended as a training manual or operation manual for sTEM instruments and related software.

For the purpose of training, we make use of a sTEM dataset (Madsen et al., 2025) from north-western Denmark, on the Salling Peninsula in the Limfjord area, which is open for training purposes. We recommend the Contractor(s) to train on that dataset before any other application. The dataset can be downloaded from https://zenodo.org/records/16894039 and has the DOI 10.5281/zenodo.16894038. All maps and figures presented in this report have been generated using this dataset.

# 3. THE STEM PLATFORM, DATA COLLECTION, AND DATA FORMATS

In the following sections, we present the sTEM platform with different system configurations, provide recommendations for survey planning and data collection, and document the various sTEM data formats. Note that data collection and formatting are similar across all configurations and will therefore be discussed together.

## 3.1 THE STEM-PLATFORM

The sTEM platform supports three central-loop coil configurations, here referred to as sTEM20, sTEM40 and sTEM80, as well as an offset-loop configuration referred to as the sTEMprofiler. In this document, we will not include discussions on the sTEM20 version. All configurations operate using the same Tx–Rx hardware suitcase. The layouts of the systems are shown in Figure 2.

For more information on sTEM components, assembly and disassembly procedures, and field operation guidelines, Contractors are referred to the manufacturer of the TEM equipment.

In the central-loop configuration, a large Tx loop (40 m or 80 m side length) is paired with a 3 × 3 m Rx loop placed at its center. Both loops are connected via a Tx–Rx hardware suitcase positioned adjacent to the Tx loop. The sTEMprofiler, consists of two separate loops placed side by side at a distance of 10 m from edge to edge. The sTEMprofiler loops are typically mounted on plastic frames to maintain their shape and size, allowing easier deployment. They are connected via a hardware suitcase positioned between them, closer to the Rx. See figure 1 for the schematics of the system layout.

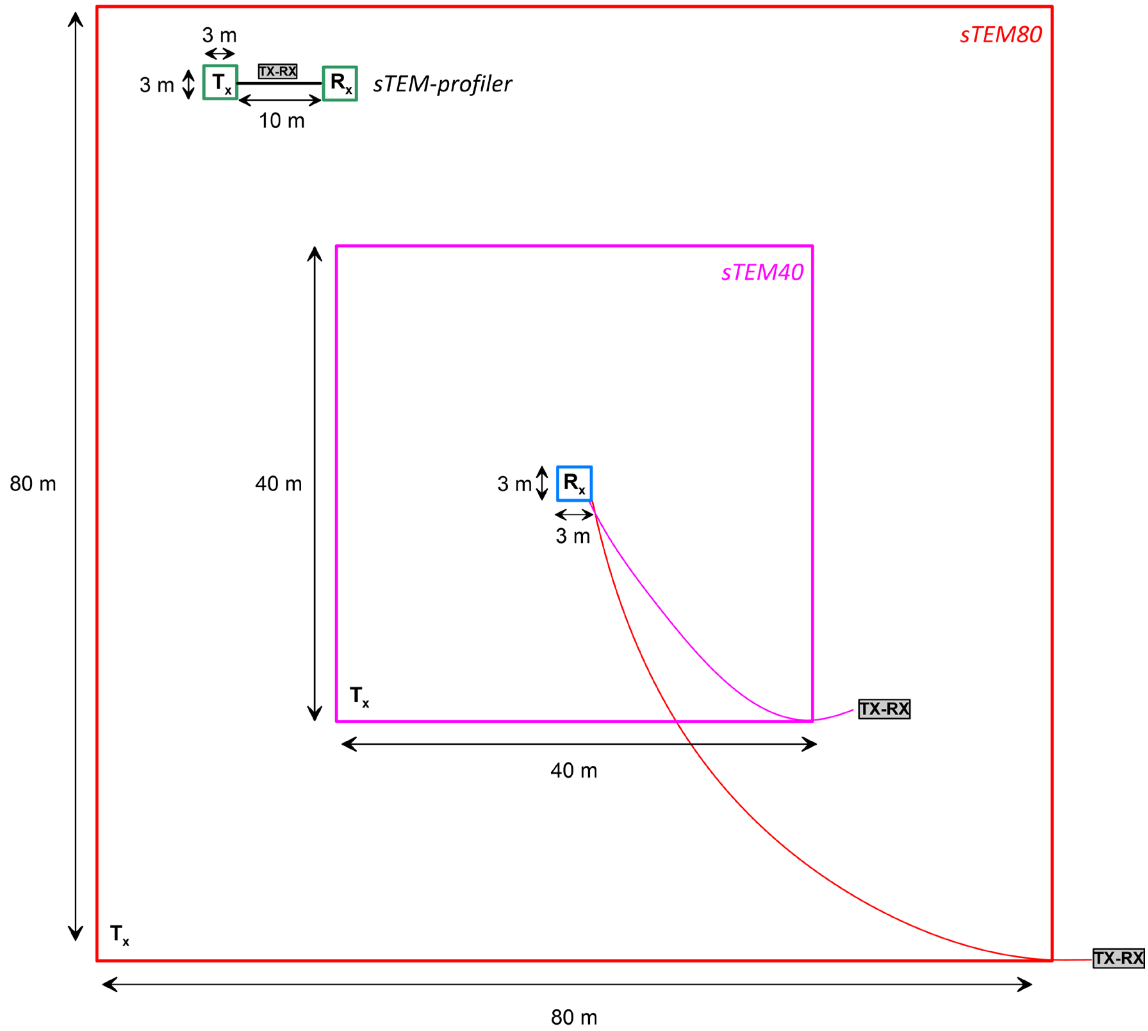


*Figure 1. System layouts of (a) central-loop sTEM with 40 × 40 m and 80 × 80 m Tx loops, and (b) sTEM-profiler. The receiver coil (Rx) is shown in blue. System components are connected via cables, with instrument (labeled TX-RX) control managed through sTEM Controller app.*

An sTEM survey can be carried out by a crew of two to three people. The operational speed of the central-loop systems depend on loop size, crew number, and terrain conditions. With two people, deployment and setup of any central-loop configuration generally take 10 to 15 minutes. For the sTEMprofiler, the operational speed is significantly higher, as the crew only needs to move the frames with the loops and the hardware suitcase before starting the measurement. Transportation wise, all the sTEM systems can fit in a normal car.

The production rate depends strongly on the choice of sTEM system, line density, stacking size, field conditions, field size, and accessibility. As a result, production typically ranges from 10–20 soundings per day for the central-loop configurations, and up to 100 soundings per day for the sTEMprofiler.

*Table 1: Specifications of the low-moment (LM) and high-moment (HM) transmitter waveforms for the central-loop configurations and the sTEMprofiler using the 10 Ampere sTEM. These specifications can be found in the GEX-file.*

| | **Central-loop sTEM 40 x 40 m** | **Central-loop sTEM 80 x 80 m** | **sTEM profiler** |
|---|---|---|---|
| Tx current (LM/HM) | 1 / 10 A | 1 / 10 A | 1 / 10 A |
| Effective transmitter area | 1600 $m^2$ | 6400 $m^2$ | 18 $m^2$ |
| Maximum transmitter moment | 16,000 $Am^2$ | 64,000 $Am^2$ | 180 $Am^2$ |
| Transmitter turn-off time (LM/HM) | 7 / 13 µs | 12 / 20 µs | 4 /5 µs |
| Number of gates (LM/HM) | 20 / 27 | 18 / 29 | 6 / 22 |
| First gate center time (LM/HM) | 11.2 / 28.7 µs | 11.2 / 28.7 µs | 9.6 / 19.4 µs |

Navigation and data collection are monitored and controlled by the user via the sTEM Controller app on a phone or tablet. The sTEM Controller app provides a real-time display of the measurements, sounding numbers, stacking time, status parameters, and various instrumentation alarms (e.g., temperature, current). In addition, the sTEM Controller app may include real-time 1D pseudo-inversion of the data.

## 3.2 SURVEY PLANNING AND NAVIGATION

An sTEM survey requires ground access for deploying the system components. For the sTEMprofiler, the required area is significantly smaller compared to the 40 × 40 and 80 × 80 configurations. Most often, there will be areas in the survey region that cannot be mapped due to lack of access permission or limited ground space. This may include wet meadows, forested areas, or farmland with livestock. Even if dense mapping is not possible in some subareas, a few scattered measurements, e.g., along small pathways in forests, are often still beneficial. In addition to ground access, suitable survey sites should have limited infrastructure (e.g., building, roads, powerlines, gas pipes, wind-turbines) and avoid nearby metallic objects such as fences or vehicles, which can introduce electromagnetic coupling and degrade the data.

For one-time surveys, it is recommended to complete the campaign in a single session (e.g., within a few days period), to avoid the effects of seasonal variations in the resistivity of shallow layers. If this is not possible, repeated measurements at identical positions are recommended to account for potential variations.

It is recommended that the survey planning be carried out by the Contractor is in alignment with the survey objectives. During the survey, deviations from the original plan may occur due to factors such as unexpected terrain or weather conditions, in which case the Contractor’s expertise and field experience should be relied upon. Proper documentation for any deviations and argumentations for deviations from the initial survey planning should be provided in the form of a daily logbook.

**Sounding spacing and resolution**

Sounding spacing should be determined based on the target and purpose of the survey, as well as the time available for the survey and terrain conditions. The sounding spacing should account for the footprint size of the chosen system (Figure 2). Figure 2 shows a general sketch of the footprint sizes of sTEM40 and sTEM80. For example, it shows that the approximate footprint for a 40 × 40 central-loop covers a horizontal distance of ~210 m at 50 m and increases to ~1250 m at 350 m depth. For central-loop configurations we can generalize this to a simple rule-of thumb; 1) When the survey objective is to detect shallow targets, the maximum station spacing should be 1.5–3 times the loop size; 2) For deeper targets, approximately 4–6 times the loop size, is reasonable, depending on the target's depth.

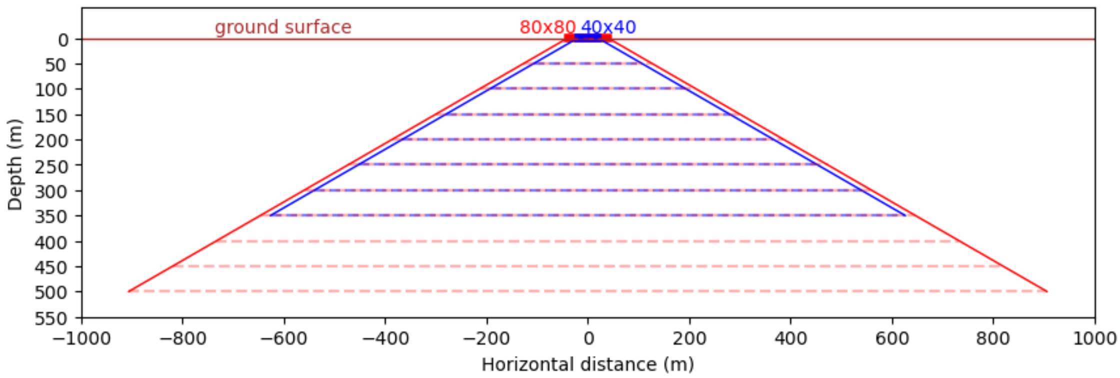


*Figure 2: General footprint dimensions of a typical 40 x 40 m (blue) and an 80 x 80 m (red) central-loop.*

Figure 3 shows these considerations in more detail. It shows footprint coverage of 40 x 40 m central-loops for different sounding spacings, L2 is one loop size (40 m) from L1, while L3 is positioned six loop sizes (240 m) from L1. Using geometrical considerations from Figure 3 we can generalize the rule-of-thumb from above to estimate a recommended maximum sounding spacing $S_{distance}$, for a system with loop side length, $L$, based on an assumed target depth, $d_{target}$:

$$S_{distance} \approx L + 3.4 \times d_{target}$$

As an example, using an sTEM40 with a main target at 50 meter depth gives us a *maximum* sounding spacing of 210 meter.

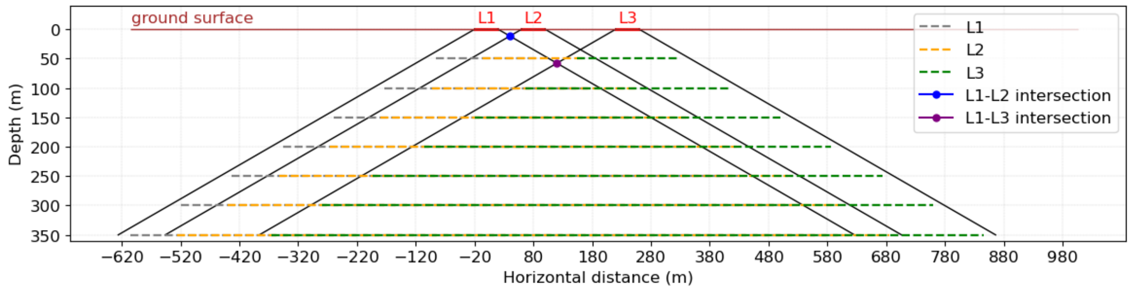


*Figure 3: General footprints of three 40 × 40 m central loops (L1, L2, and L3). Loop L2 is positioned one loop size (40 m) from L1, while L3 is positioned six loop sizes (240 m) from L1. The blue and purple circles denote the L1-L2 and L1-L3 intersections at depth that can be used to estimate maximum sounding distances for targets at those depths.*

Before the survey, the Client and Contractor should agree on the nominal sounding spacing, considering the entire survey.

**Survey layout**

In a sTEM survey, there is no strict requirement for a specific sounding layout (e.g., soundings arranged in straight lines); however, a sub-linear layout is recommended when aiming to produce 2D resistivity sections. This should be planned in accordance with the project's objectives.

The main objective is often to maximize area coverage and data density to capture the relevant geological variations while avoiding sources of noise such as power lines/cables, railways, fences, buildings, gas pipes, wind-turbines, cars, etc. The required distance from such noise sources will vary depending on the type of source and the ground conductivity but keeping a minimum distance of at least 100 m helps avoid unusable data.

Actual sounding positioning will always need to be adapted to the terrain, access restrictions, and field conditions. In practice, this often means soundings in irregular patters, but the maximum sounding spacing should be followed to ensure adequate spatial coverage to resolve the subsurface structures of interest.

The real-time inversion feature in the sTEM Controller app can provide a preliminary view of the subsurface resistivities, which may help guide the placement of subsequent sounding positions in real time.

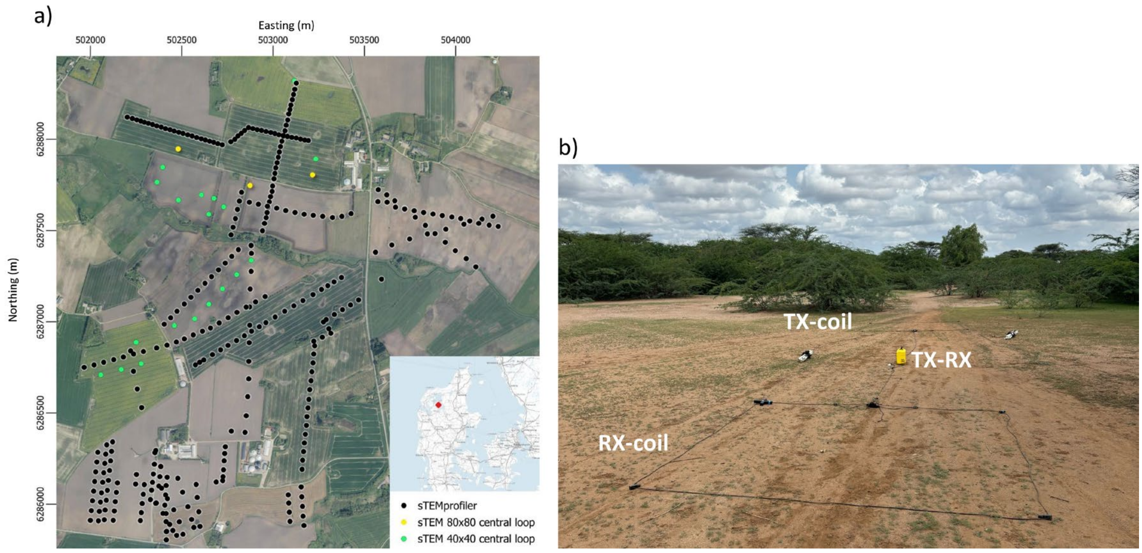


*Figure 4: (a) Example of sTEM data mapping dataset (Madsen et al., 2025) collected to map buried glacial valley structures using the sTEMprofiler, and the stationary central-loop sTEM with 40 x 40 m and 80 x 80 m loops. The data were collected on the Salling Peninsula, in the Limfjord area, and (b) photo of an sTEM system in the field.*

## 3.3 DATA COLLECTION

The measurements in the field are controlled by the sTEM Controller app running a certain measurement script.

### Measurement script

The measurement script controls the repetition frequency, the low moment/high moment (LM/HM) cycle, key data normalization factors, etc. The measurement script must be designed to stack out the power line frequency noise (50/60 Hz). <u>While the Contractor can modify the script if needed, it is recommended that only experienced Contractors make changes or that the Instrument Manufacturer be consulted</u>.

Note:

- Noise measurements (transmitter off) are normally not included in the measurement scripts.
- Change of system components might require adjustment in the measurement script. As of instance:
    - Positioning change of Tx and/or Rx – due to repairs or other modifications
    - Positioning change of GPS
    - Different waveform, on-time, stack size among others, than the ones provided by the Instrument Manufacturer

**sTEM Controller app**

The sTEM Controller app can be used to control the sTEM system. It only requires a phone/tablet device to connect with the system. Once the system is connected to the app, the Contractor can select the measurement script, define the stacking time, and monitor system parameters such as temperature, current, and responses, as well as view the real-time inversion results. Note, that while the sTEM Controller app stores position information, it does not provide any real-time visual geographical information; therefore, Contractors are encouraged to use an external mapping app or a manual map for navigation and survey tracking while measuring.

**Data export**

Upon completing the data collection, Contractors can export the data using the *TEM Data Manager* program. The program also updates the instrument firmware, measurement scripts, etc.

## 3.4 DATA FORMATS

This section describes the output files from the instrument and additional setup files required to perform the data processing in SPIA and in Aarhus Workbench. This section also serves as documentation for the different file formats. It is noted that each instrument gathers a large amount of data in each location. These data are then stacked together to produce an average sounding for each location referred to as the raw data.

The sTEM dataset consists of (1) the instrument (raw data) output files, (2) modelling setup files, and (3) output files from SPIA or Aarhus Workbench containing processed data, predicted data, and resistivity models.

**Instrument output files:**

- Station (*.stn) file
- Universal Sounding Format (*.usf) file
- STB (*.stb) file

**Software modeling and setup files:**

- System geometry (*.gex) file
- System data export (*.xyz) file

**Station file (*.stn)**

This file contains the location of each station (sounding), including the line number, station number, latitude, longitude, and heading. By default, the line number assumes that the soundings are arranged in a line, but no issues arise if the soundings are not aligned.

**Universal Sounding Format file (*.usf)**
This file contains all the information on data acquisition for each sounding and is preferable for importing in SPIA. This file serves as the primary output from the sTEM instrument for further processing and inversion. The information is listed as:

*Metadata*: includes instrument type/ID, file version, date/time, loop geometry, and coordinate reference system;

*Sounding Information*: Name, loop size, coil location, and station coordinates (latitude, longitude, elevation), and sweep count;

*Sweep Details*: each sweep block specifies: excitation current and frequency, ramp time and time delay, Tx waveform (as time-voltage pairs), channel number, low-pass filter configuration;

*Gating Data*: Each sweep includes gate center times, measured voltages, error bars, quality flags, and exact gate open/close times;

*Noise and Calibration*: Sweep blocks indicate noise flags, field shift factors, and instrument-level timing parameters.

**STB file (*.stb)**
An Aarhus Workbench compatible file containing information extracted from the USF file.

**System geometry file (*.gex)**
This file defines the system configuration required for data processing and inversion in Aarhus Workbench. It includes:

*Geometry*: The x, y, z positions of the transmitter/receiver coils. The origin is centred on the transmitter coil; the z-axis is zero at ground level and positive downward, resulting in negative z-values for coils and devices;

*Transmitter Settings:* Nominal current, coil size and area, number of turns, and waveform parameters (e.g., turn-off time before the front gate).

*Calibration Constants*: Time shifts and dB/dt factors;

*Gating Configuration*: Gate center times, opening/closing times, gate factors, and specification of the first gates per moment;

*Filters and Uncertainty*: Low-pass filters and a standard uniform data uncertainty (typically 3%).

The instrument owner must provide the GEX-file with the instrument, while the operator must QC and update the GEX-file if needed.

**System data export file (*.xyz)**
The XYZ file contains processed sTEM measurement data. It includes metadata for each sounding–such as project name, line and station numbers, coordinates, and elevation–along

with transmitter currents, multiple receiver channel measurements (dB/dt), and their corresponding standard deviations. This structured format allows the data to be used directly for mapping, visualization, or inversion in TEM data processing software.

# 4. INSTRUMENT VALIDATION

This section concerns instrument validation to ensure high and uniform data quality.

In the sTEM design phase, the system geometry, the position of the instrumentation and devices, the cabling and rigging, etc. were designed and tested to ensure an acceptable system noise/bias level. This means that the sTEM instruments are delivered calibrated by the Instrument Manufacturer and no need for calibration is required by the Contractor. However, if any modifications in the sTEM system are performed, such as repairing, re-rigging, changing of the cabling, or the positioning of the instrumentation/devices etc. the Contractor should be responsible for re-testing/calibration. It is advised that the Contractor calibrate the system(s) at least once every six months, especially for frequently used systems or prior to large-scale surveys.

## 4.1 PRE-SURVEY CALIBRATION/VALIDATION

**TEM test-site calibration**

The objective of calibrating the sTEM systems is to establish the absolute data level to facilitate precise data modelling. The calibration is carried out at the National TEM test-site west of Aarhus (56°09'39.2"N 10°02'15.5"E).

The general test-site calibration procedure is described in *Foged et.al, 2013*; but more information can be found in GFS (2019) and HGG reports (2012). The following guidelines are to be used for sTEM calibration, including calibration frequency and related requirements.:

- The sTEM system must be configured in production mode (see Figure 1 and sTEM Manual) for the calibration measurement.
- Calculation of the sTEM-specific reference response from the reference model must use the exact same system parameters (GEX-file settings) as those intended for later surveys, except for the calibration parameters to be obtained.
- After calibration, the measured sTEM response must match the reference response within 5% (late time apparent resistivity data transformation) for low-noise time gates.
- The obtained calibration parameters are valid for the specific transmitter-receiver pair used during calibration.
- Documentation of the calibration is provided in the form of plots showing the match between the reference response and the measured data.
- Instrument calibration in relation to large survey campaigns must be performed in the period between fourteen days before/after the survey period.
- For multi-day surveys instrument stability is documented by:
    - Test site measurements/calibration before and after the survey, resulting in consistent calibrations parameters, and/or
    - Obtaining consistent data responses from repeated measurements at a local site within the mapping area.

- For single-day surveys, the initial calibration and recurring half-year calibration check at the test-site is sufficient.
- Any instrument reconfiguration or adaptation requires a new test-site calibration.

**Transmitter waveform**

The transmitter waveform describes how the current ramps up and down in the transmitter coil and needs to be known in detail for precise modeling of the data. The sTEM system facilitates accurate temperature and current regulation, which results in a very stable transmitter waveform. The sTEM transmitter waveform therefore only needs to be measured once in detail for a given sTEM system. Even though this action is provided by the Instrument Manufacturer, and no further actions are necessary by the Contractor, we provide the steps needed to measure the waveform.

The transmitter waveform can be split into a turn-on and a turn-off part. The turn-on part is relatively slow and can be measured directly as the currents flow in the transmitter coil. The turn-off part takes only a few microseconds and needs to be measured with a device capable of sampling the signal fast enough– typically a small pickup coil measuring the time derivative of the current in the transmitter loop is used.

Guidelines for the waveform measurement:

- The system must be configured as in production mode.
- Separated waveform measurements for turn-on and a turn-off part, and the LM and HM are performed.
- The measured waveforms are approximated with a number of linear segments to be used for data modeling.
- The resulting waveforms, stated in the GEX-file, must include both a negative and a positive waveform, separated by the correct off-time period, and normalized to a peak amplitude of -1, 1.
- The determination of the waveform is documented with plots of the measured waveforms and the segmented waveforms used in the GEX-file.
- The measured waveform is specific for a given sTEM transmitter instrument, output current, and transmitter loop (e.g., Figure 5).

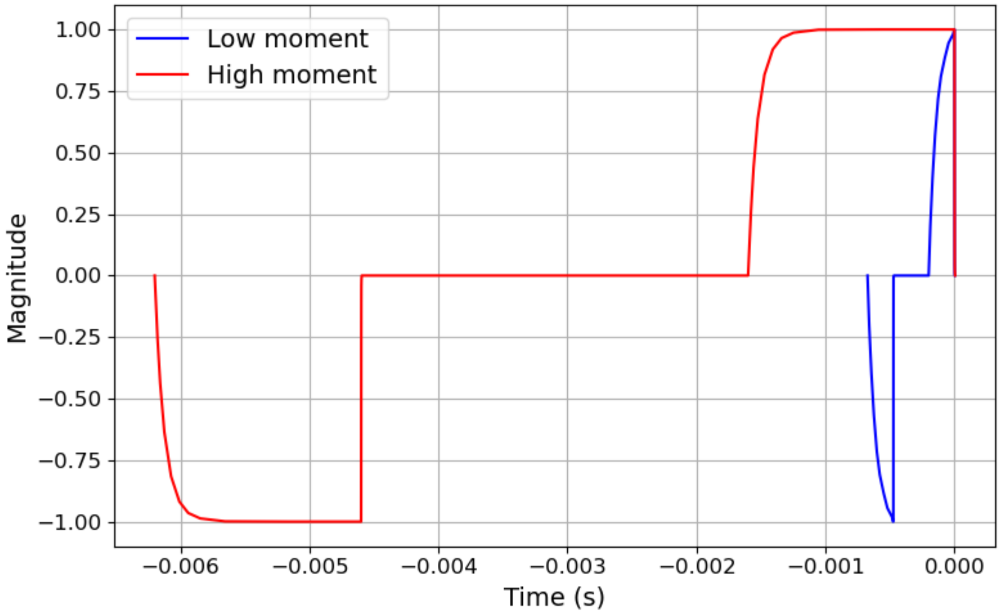


*Figure 5: Waveforms for low (blue) and high (red) moment for the sTEMprofiler. Both waveforms include a negative and a positive part and are normalized to a peak amplitude of -1 and 1, respectively.*

## 4.2 DAILY INSTRUMENT AND DATA VALIDATION

This section deals with instrument and data Quality Control (QC) conducted in the survey period and is performed by the instrument operator.

On a daily basis, QC of the data normally includes checks of:

- Stable transmitter current, at the same level as for the measured waveform
- Transmitter temperature
- Stable GPS signal/data
- dB/dt data appear normal
- Real-time inversion results look plausible (if performed)

Some of these parameters can be followed in real time in the sTEM Controller app while mapping, and the sTEM Controller app gives various alarms in case of irregularities in the different data streams.

During survey periods, it is recommended to perform repeated measurements at the same location regularly to ensure instrument stability and data consistency.

# 5. DATA PROCESSING

Processing of sTEM data should follow the same principles regardless of the TEM software used. In this guide, the procedure is demonstrated using SPIA and Aarhus Workbench. The general requirements for data processing are outlined below.

Generally, the following should be performed in the processing steps of the sTEM data.

- Pre-processing steps
  - Review of the test-site calibration
  - Review of the geometry file and calibration factors
  - Import of data to either SPIA or Aarhus Workbench (or any other compatible TEM software)
- Processing steps
  - **Automatic pre-processing** of dB/dt data
  - **Manual processing** of dB/dt data
    - Visual assessment and editing of all soundings
    - Remove negative gates
    - Remove coupled data that deviate significantly from a smooth data decay (Figure 6).
    - Preliminary inversion to support data processing

Manual processing can be performed in either SPIA (one sounding per time) or Aarhus Workbench (multiple soundings at once). The same rules applied in both cases and the primary task concerns removing outliers caused by coupling noise sources. Contractors should inspect the map carefully to identify areas affected by such coupling noise sources while checking the quality of the raw data. This is because, in some cases, noise cannot be identified only by looking at a dB/dt curve (e.g., Figure 8), and thus, inspecting the map for potential noise sources often helps cleaning the data. In contrast, background EM noise is typically random and does not exhibit spatial patterns.

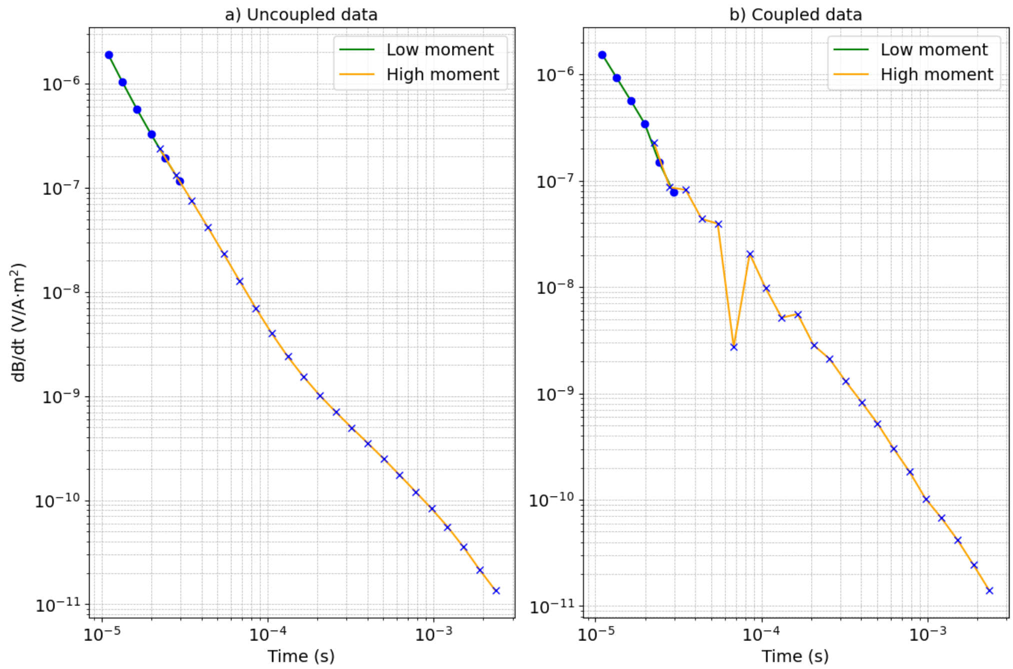


*Figure 6: Example of raw a) uncoupled and b) coupled data for sTEM-profiler. For the uncoupled data the training file L001_S001_2025_0327_081212.usf was used, while for the coupled data the L001_S021_2025_0327_092920.usf.*

## 5.1 AUTOMATIC DATA PRE-PROCESSING

Automatic pre-processing is supported by both SPIA and Aarhus Workbench. Contractors may adjust the processing settings according to their expertise; however, the default settings are often suitable.

Table 2 describes the pre-processing setting options available in SPIA and Aarhus Workbench with the default values. There are two settings: (1) average slope filter which removes data based on the change in slope on the dB/dt curve (i.e., curvature), and (2) the average standard deviation (STD) filter, which identifies and removes data points with high variability across repeated measurements (i.e., stacked measurements). Note that the average slope filter can be applied to a specified number of data points (using back step) surrounding the "noisy" ones; however, it is generally recommended to discard the entire sounding by default to ensure data consistency and avoid "hidden" couplings.

*Table 2: Description of the pre-processing settings and their default values available in SPIA and Aarhus Workbench. Note that back step should be a number higher than the number of gates so the entire sounding is discarded.*

| | | Value |
|---|---|---|
| **Average Slope Filter:** *Disables averaging when the 2nd-order derivative of the dB/dt sounding curve falls outside two specified threshold values. Smaller thresholds (closer to zero) allow less variability before the filter is applied.* | **From time (s):** *Data points (gates) before this value are not evaluated by the filter.* | 1.00E-05 |
| | **Min slope:** *The smallest acceptable 2nd order derivative of the dB/dt sounding curve.* | -0.7 |
| | **Max slope:** *The largest acceptable 2nd order derivative of the dB/dt sounding curve.* | 0.7 |
| | **Back step:** *Number of additional gates backwards to disable from the sounding curve when the filter is triggered.* | 50 |
| **Average STD Filter:** *Disables averaging when the standard deviation (STD) of a gate exceeds the maximum acceptable STD value.* | **From time (s):** *Gates before this value are not evaluated by the filter.* | 1.00E-05 |
| | **STD max:** *Defines the largest acceptable STD value.* | 1.2 |

Figure 7 shows an example of the application of the average slope filter (Figure 7a), where the entire sounding is discarded, and the average STD filter (Figure 7b), where only points with STD values exceeding the acceptable threshold (i.e., 20%) are removed.

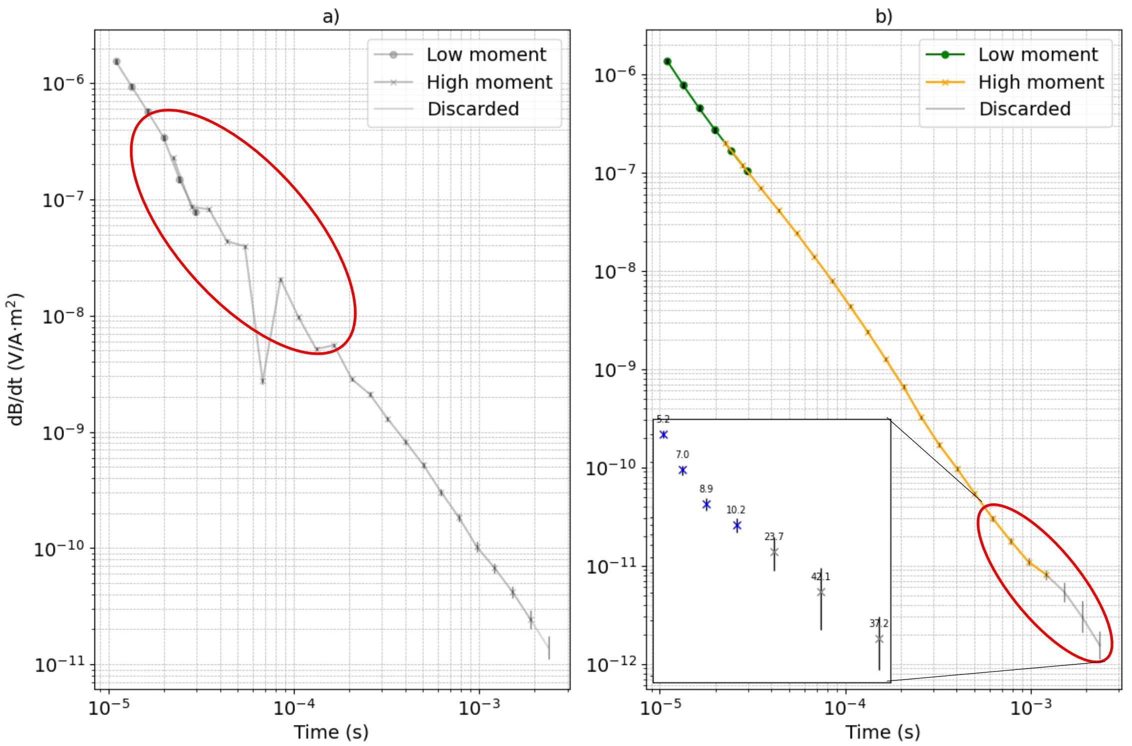


*Figure 7: Example of data filtering using (a) the average slope filter applied to L001_S021_2025_0327_092920.usf, where the entire sounding is discarded. The red circle defines the gates that exceed the acceptable threshold, and (b) the average STD filter applied to L001_S027_2025_0327_100210.usf, where only points with STD values exceeding the acceptable threshold (20%) are removed. All data points are plotted with their associated error bars. The close-up shows the last 7 gates with the number indicating the STD values at individual gates.*

## 5.2 MANUAL DATA PROCESSING

The objective of the dB/dt data processing is to remove any coupled (noisy) or negative data. Contractors must ensure that data entering the inversion do not include noise from man-made installations etc., and thereby that the resulting resistivity models represent the structures of the subsurface.

Manual processing involves visually inspecting and editing all dB/dt data, either individually or in profile view. The main objective is to adjust or correct the results of the automatic processing, ensuring that any remaining coupled data are removed. In survey areas affected by infrastructure or coupling sources, manual editing is typically the most time-consuming part of data processing and must always be performed carefully. Thus, the evaluation of possible couplings in data is performed in connection with the geographical position of the data and distance to potentially coupled sources (the power grid, gas pipes, wind turbines, etc.).

Couplings are typically identified as distinctive data patterns or abrupt changes in the signal that deviate from a smooth decay (see Figure 7a). If there is uncertainty about whether certain data are affected by coupling, it is recommended to perform a preliminary inversion and then re-evaluate the results.

Note:

- If a data curve is clearly capacitively coupled, the full data curve is normally discarded.
- Galvanic types of coupling might not be detected by automatic filtering, and these couplings therefore need to be spotted and removed manually.
- Experience with TEM data processing in general is needed for identification and optimal removal of couplings.

Figure 8 provides an example of coupled data that might not be captured by automatic processing. While both the average slope and average STD filters are applied, the average slope filter does not discard any data since the sounding falls within the acceptable slope limits, whereas the average STD filter identifies and removes the noisy late-time gates. In that case, careful manual processing is required to identify the noise source and either clean part of the sounding or eliminate the particular sounding.

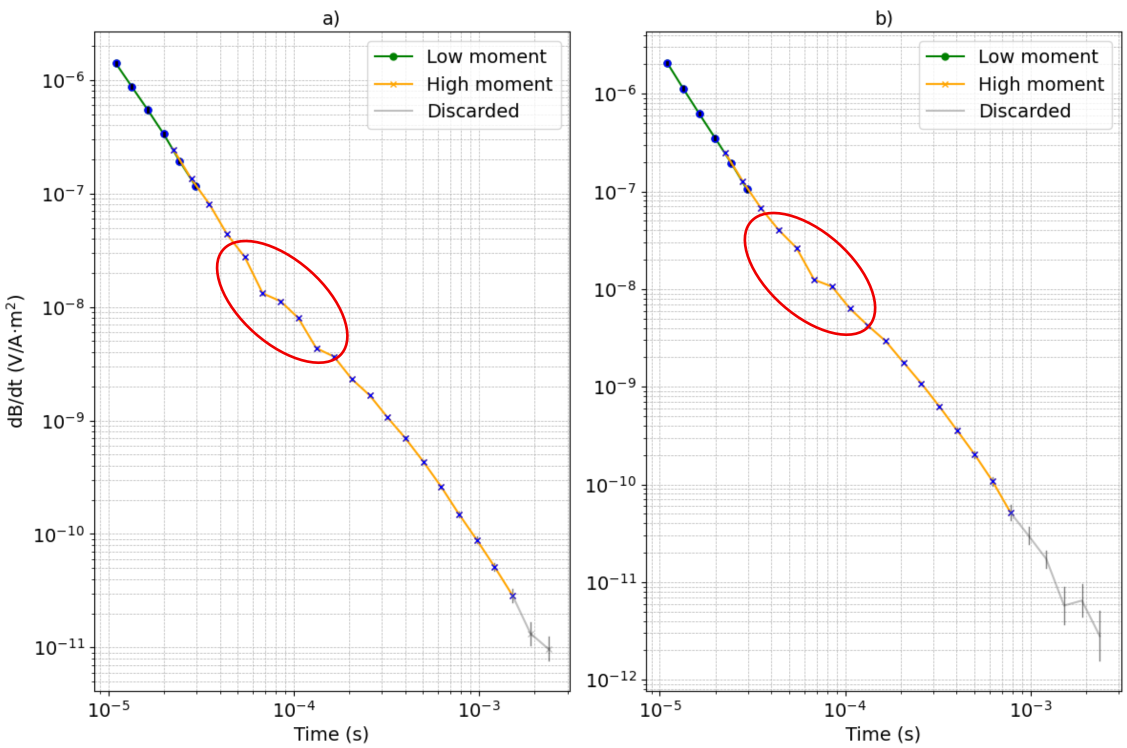


*Figure 8: Examples of coupled data from the training dataset for sTEM-profiler files: a) L001_S020_2025_0327_092313.usf, and b) L001_S023_2025_0327_094139.usf. The red circle highlights the gates potentially affected by noise not captured by automatic processing.*

## 5.3 EVALUATION OF DATA PROCESSING

It is recommended to perform a preliminary inversion after automatic pre-processing and before manual processing. The preliminary inversion can give an idea on how well the automatic pre-processing performed and to what degree additional manual processing is needed. That said, after every processing cycle (whether it is automatic or manual), it is recommended to perform an inversion and evaluate the results.

Based on an inversion, the processing is evaluated and typically adjusted with respect to:

- **Data residual:** Large residuals may indicate that coupled or very noisy data have entered the inversion.
- **Number of data points:** A limited number of data points after processing restricts the depth of the investigation and indicates that the TEM measurements were conducted in a noisy environment. Conversely, a significant number of data points after processing suggest more reliable measurements and allows for a more detailed interpretation.
- **Depth of investigation:** Shows to which depth the resulting resistivity model can be interpreted.
- **Resistivity sequences/structures:** Are the resulting resistivity sequences or structures realistic for the surveyed area?
- **Geographical position of the models relative to expected coupling sources:** Resistivity structures that follow infrastructure may result from coupled data affecting the inversion.

This assessment can be carried out section-wise and/or by generating miscellaneous QC-maps and resistivity slices. In most cases, data processing and QC will be an iterative process.

# 6. INVERSION

In this section we discuss the different inversion setups for the sTEM systems, i.e., type of inversion, constraints, starting model, number of layers, etc. Following, we will outline the "imaging" steps that should be performed for evaluation of the inversion results and finally their presentation in technical reports.

In this guide, we limit our discussion to 1D constrained inversion in SPIA and Aarhus Workbench. However, 2D and 3D inversion options are also available and can be utilized, though their complexity requires experienced Contractors.

## 6.1 INVERSION WORKFLOW SETUP

Inversion should be performed after each processing cycle, either automatic (pre-processing) or manual processing. For the final inversion, the Contractors need to ensure that the data are processed to the necessary level and that the residuals are acceptable.

The following are recommendations for the Contractors to follow during an inversion:

**Selection of inversion type**

- Perform non-constrained or/and laterally constrained inversion (LCI) for preliminary inversion results and to determine appropriate inversion settings.
- Perform spatially constrained inversion (SCI) inversion as the final inversion product.
- If the survey or part of the survey includes evenly scattered sTEMs, the non-constrained scheme or the LCI scheme can be presented as the final inversion product.
- Choose between smooth, sharp, or layered model types depending on the geological context and interpretation objectives. It is recommended that at least smooth and sharp model types are delivered for the final inversion results.

**Model parameterization**

- If possible, include a high-resolution digital elevation model (DEM) for improved vertical positioning.
- Define the number of layers, layer thickness distribution, and depth to the last layer to capture key geological features.
- Ensure the starting resistivities and constraints distance scaling reflect the expected geological variability across the area.

**Constraints and regularization**

- Apply appropriate horizontal and vertical constraints (resistivity, thickness, sharpness) based on the inversion type.
- For smooth models, maintain medium constraints to achieve gradual resistivity transitions. In most cases medium constraints is a suitable option, but in very resistive or rapidly changing geological environments (mapping fracture zones etc.) loose constraints may add value to allow for larger resistivity changes.

- For sharp models, adjust constraints to highlight distinct interfaces. Sharp models inherently promote simplified, blocky models and cannot easily be forced to produce additional layers beyond what is justified by the data.
- For few-layered models, ensure that the number of layers is appropriate and relevant to the geological setting and supported by the data. The model should use as few layers as possible while still providing an adequate fit to the data.

**Quality control and convergence**

- Monitor the data residual and total residual after each inversion. Large residuals may indicate unhandled noise contributions, poor initial models, or improper constraints. A data residual:
    - < 1 – the data are fitted within the errorbars; acceptable
    - > 1 – the data are not fitted within the errorbars; acceptable only under certain circumstances and depending on context:
        - Assess the gates separately by checking the dB/dt curves; determine whether the data error is high in specific gates or randomly distributed
        - Assess whether the data errors cover several soundings in the same region or are randomly distributed
            - In a very resistive setting or 3D environment (for instance an sTEM line along a beach) one would expect elevated data residuals, but still in the range of 2-3.
- Compare inversion results across model types (smooth, sharp, layered) to evaluate model robustness and geological plausibility.

**Documentation**

- Document inversion parameters (layer setup, constraints, convergence criteria) in technical reports.
- Document quality control maps and provide a paragraph on the quality: discuss why, in certain areas, the data residuals are high or the number of data points is low. Assess whether high data residuals are related to low or high moments, whether they occur in specific gates, or whether they are randomly distributed.
- Document both the inversion models and residual statistics for reporting or further interpretation.

## 6.2 INVERSION TYPES

When performing 1D inversion in SPIA and Aarhus Workbench, there are three types of constraints supported: (1) non-constrained, (2) LCI and (3) SCI.

(1) When performing a non-constrained inversion, each sounding is inverted separately without any connection (constraints) to other soundings. This is the fastest inversion type (typically a few seconds) and should always always be performed for data assessment. The non-constrained inversion can be the final product when the soundings are scattered.

(2) LCI inversion shares information only from adjacent soundings to ensure lateral consistency between neighboring models. This approach is quick and can provide a first interpretation of the subsurface, making it suitable preliminary inversion runs. However, due to its simplified treatment of lateral constraints, LCI results should not be considered final and are typically refined through subsequent inversions. After finalizing an LCI then the Contractors can proceed with SCI inversion. LCI can be used as the final result if soundings are collected only along lines and not for spatial coverage.

(3) SCI inversion extends the concept of LCI by allowing information sharing among all surrounding soundings within a defined spatial neighborhood. This method enhances the spatial coherence of the resulting model and typically yields a more geologically consistent representation of subsurface structures. SCI inversion is therefore recommended for detailed interpretation and final modeling once data quality and processing parameters have been verified.

## 6.3 INVERSION SETTINGS

Table 3 summarizes the typical inversion settings, including the different model types used in sTEM data inversion (i.e., *smooth*, *sharp*, and *layered* models).

*Table 3: Key inversion settings. Typical settings for smooth and sharp SCI setup.*

| Item | Parameters | Value |
|---|---|---|
| Model setup | Number of layers<br>Starting resistivities (Ωm)<br>Thickness of first layer (m)<br>Depth to last layer (m)<br><br>Thickness distribution of layers<br>Constraints distance scaling | 30-40<br>Area dependent<br>$2.0^{\text{sTEMprofiler}}/2.5^{40 \times 40\text{ m}}/4.0^{80 \times 80\text{ m}}$<br>$\sim 200^{\text{sTEMprofiler}}/250^{40 \times 40\text{ m}}/400^{80 \times 80\text{ m}}$<br>(area dependent)<br>Log increasing with depth<br>$1/\text{distance}^{0.75}$ (power =0.75) |
| **Smooth model:**<br>Constraints | Horizontal Constraints, resistivity (factor)<br>Vertical constraints, resistivity (factor) | 1.5<br><br>2.0 |
| **Sharp model:**<br>Constraints | Horizontal Constraints, resistivity (factor)<br>Vertical constraints on resistivity (factor)<br>Vertical sharpness<br>Horizontal sharpness | 1.04<br><br>1.12<br><br>100<br>200 |
| **Layered model:**<br>Constraints | Horizontal Constraints, resistivity (factor)<br>Horizontal Constraints, thickness (factor) | 1.30<br><br>1.30 |

For the sharp inversion settings some fine-tuning may be needed to achieve satisfying results. In the tuning process the GFS (2018) can be used as a guideline.

Note that few-layered inversions are mostly recommended for 40 × 40 m and 80 × 80 m soundings, or scattered soundings, in addition to smooth and sharp inversions.

It is important to discretize the model to suitable depths, because the sounding curve will always contain information about both shallow and deep geology. The DOI calculation can also be used to guide how deep one has information in the sounding. The model discretization should go slightly beyond the DOI.

## 6.4 QUALITY CONTROL (QC)

After each inversion, QC maps with relevant themes should be generated for evaluating the inversion. The thematic QC maps should be at least:

(1) Number of data points for the individual soundings, potentially for the individual moments at each sounding
(2) Data residual (data fit) for the individual models (typically normalized with the data STD)
(3) Conservative/standard depth of investigation (DOI)

Note that if one of the moments (LM, HM) indicates anomalies, the Contractor should investigate this further and generate separate QC maps for each moment. Often, QC maps other than those listed above may be required, depending on the context and data quality.

Figure 6 shows an example of QC maps generated for the training dataset including 40 × 40 m, 80 × 80 m and sTEMprofiler soundings. Similar QC maps, along with the background map, should be included in the final reports to ensure detailed documentation. When only a small number of sTEM soundings are measured the measured values can be reported directly in tables or similar.

The QC maps results should be carefully evaluated. Contractors are responsible for examining areas with low DOI, a low number of data points, or poor data residual, in order to identify potential unhandled noise sources or otherwise problematic soundings or models.

Contractors must clearly justify the acceptance or rejection of data, explicitly stating the criteria used and the underlying reasons. Major features and anomalies evident in the QC maps should be discussed (e.g., see high residual in Figure 9b or discarded data in all panels), including their impact on the final inversion results. The analysis should demonstrate how the QC evaluation informed decisions made for the final inversion.

Additional QC themes beyond those listed above may be included where relevant; the maps and analyses described here represent the minimum required QC deliverables. Upon completion of the final inversion and subsequent evaluation of the results, profiles and mean resistivity (MR) maps should be generated to assess the models and data from a geological perspective.

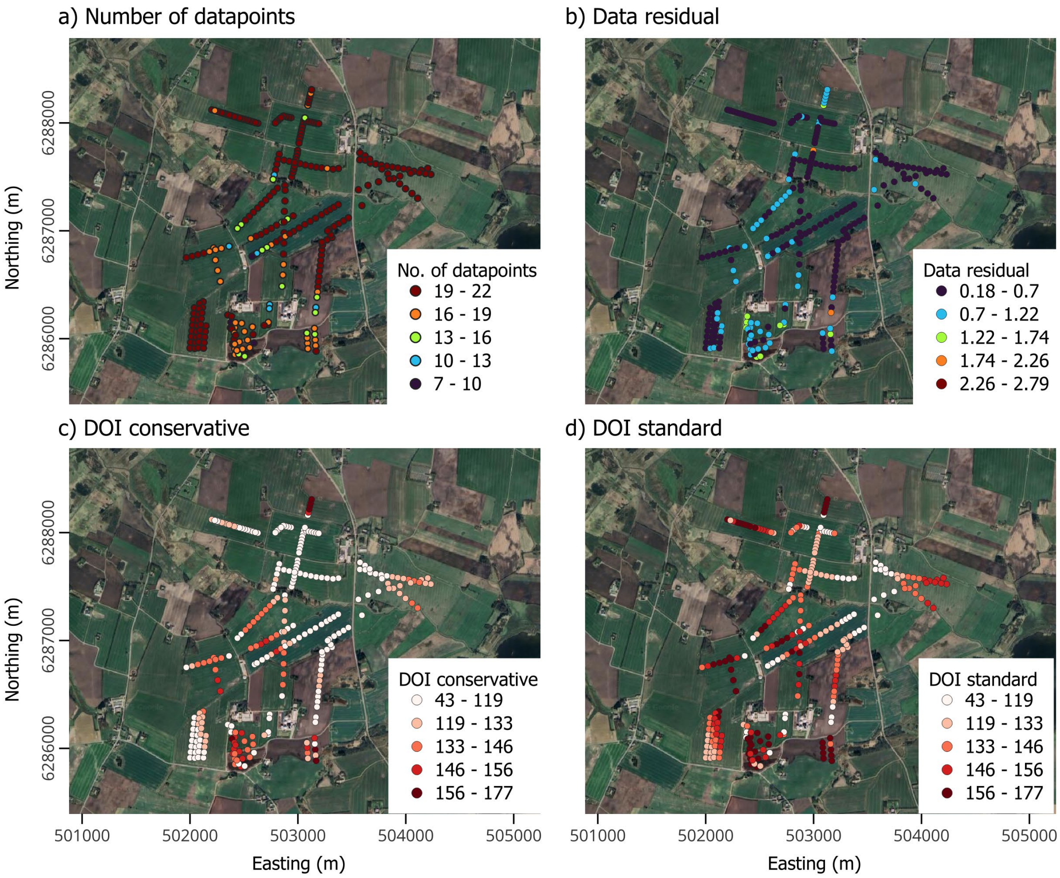


*Figure 9: a) Number of datapoints for each sounding after processing; b) data residual for each sounding for the final inversion result; c) conservative depth of investigation (DOI) and d) standard DOI of each sounding computed based on the inversion results.*

## 6.5 RESISTIVITY SECTIONS

Resistivity sections are constructed from profile lines connecting a number of sTEM sounding models to build an image of the lateral and vertical variations of the subsurface resistivity. The orientation of the sections as well as the DOI and data residual of each sounding should always be marked. Location and orientation of the profiles depend on the sTEM coverage and the goal of the survey.

Figure 10 shows an example of a resistivity section along an sTEMprofiler line oriented from East to West. The Contractor should prepare multiple resistivity sections that cover the entire study area and are oriented in different directions.

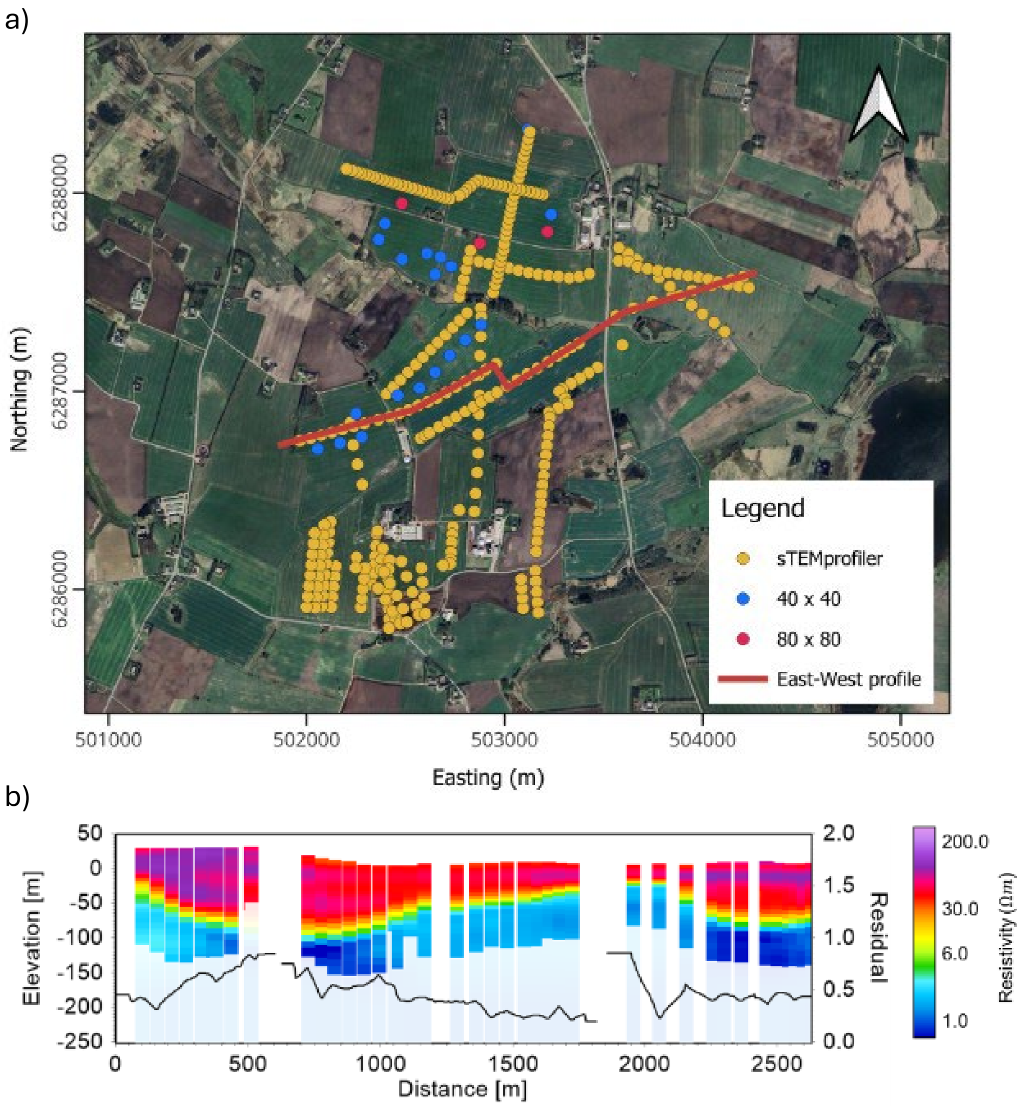


*Figure 10: a) Map showing sTEM soundings and b) an East-West profile section derived from the training dataset (Madsen et al., 2025). The individual model bars are blanked by DOI standard, and the black line shows the data residual for the individual models/soundings.*

## 6.6 MEAN RESISTIVITY (MR) MAPS

The MR maps represent the average/mean resistivity of an elevation or depth interval covering the entire mapping area. They are useful for visualizing lateral variations in resistivity over the maped area. MR maps should be produced for each model type (smooth, sharp, layered).

For sTEM data, it is recommended to produce MR maps by elevation (or depth) with 5 m intervals for the top 30 m, followed by 10 m and later 20 m intervals down to the DOI. The search radius used for construction the maps should be at least twice the general sounding spacing.

Regarding the interpolation method, both SPIA and Aarhus Workbench support Inverse Distance and Kriging interpolation. We recommend to use the Kriging interpolation as it can be shown to produce the best estimates (GeoFysikSamarbejdet 2003; Sandersen et al. 2018).

The results should appear without artifacts and be consistent with the expected geological setting, i.e., without abrupt or unrealistic changes in resistivity that lack geological justification. For more information about interpolation settings, the reader is referred to GeoFysik-Samarbejdet (2003).

Figure 7 presents an example of MR maps for the elevation intervals: (a) 0 to 10 m, (b) -20 to -30 m, (c) -50 to -60 m, and (d) -90 to -100 m.

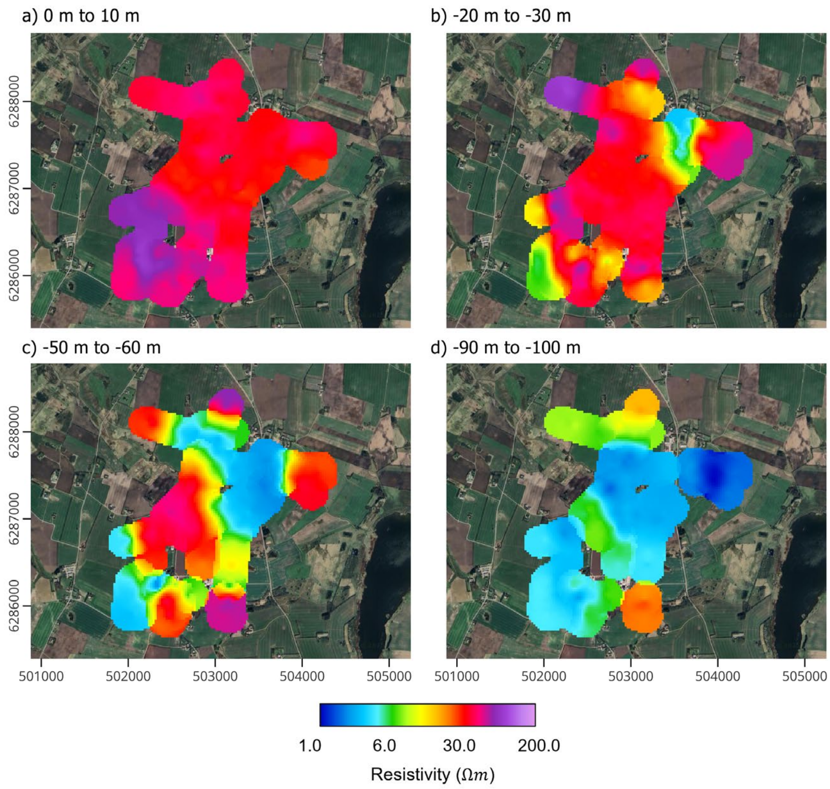


*Figure 11: Mean resistivity maps derived from the training dataset (Madsen et al., 2025) for elevation intervals: a) 0 m to 10 m, b) -20 m to -30 m, c) -50 m to -60 m, and d) -90 m to -100 m.*

# 7. REPORTING

## 7.1 GEOPHYSICAL SURVEY REPORT

A geophysical survey report for an sTEM survey must, at a minimum, document data collection, data processing, and inversion procedures with all the parameters involved. Additionally, any conditions or issues that have significantly influenced data acquisition, processing, or inversion results should be included in the report.

The sections below outline the minimum documentation required in the geophysical survey report for each step of an sTEM survey.

**Data Collection**

The Contractor must include information on/documentation of:

- System calibration at the TEM test site with dates, presented as plots of the reference response overlain by the recorded data after calibration, along with specification of the obtained time shift and factor shift.
- System validation at local test-site (if appropriate)
- Measurement and determination of the transmitter waveform.
- Sounding spacing, number of soundings, approximate area coverage, and survey duration.
- Specific conditions and problems that may affect data quality, processing, or inversion.
- Reasons for planned but unmapped sub-areas, e.g., livestock on the field, crops too high, or ground too soft.
- Key system parameters, including:
  - LM and HM specifications
  - Measurement script
  - System geometry
- Instrument ID numbers.

**Data processing**

Reporting related to processing must, at a minimum, account for the following:

- An overview of key processing parameters.
  - Automatic pre-processing settings
  - Example of used and discarded data
- Maps showing
  - Survey area and data locations
  - Location of used/discarded data (coupled/un-coupled data)

**Inversion**

Reporting related to the inversion must, at a minimum, account for the following:

- Key settings for inversion setup

    - Inversion type
    - Layer discretization,
    - Vertical and lateral constraints setup
    - Start model resistivity
- Set of QC- maps for the final inversion result with short discussions
    - Data fit plot (data residual)
    - Number of data points per sounding curve
    - DOI value
- Selected profiles in different directions covering the entire area
- MR maps for the different model types
    - Documentation of parameters for the MR maps.

The inversion results are typically presented as cross sections, and mean resistivity maps in depth and/or elevation intervals. Key settings for the different maps must be specified in the report or annotated on the maps; e.g. interpolation method, search radius, grid cell size, DOI blinding, etc. All the inversion results should generally be presented with the same color scale and limits.

The inversion results are normally delivered digitally in form of an Aarhus Workbench Workspace, a standard PC-GERDA database, or in xyz-files (ascii-files).

## 7.2 REPORTING TO GERDA

After completion of sTEM surveys in Denmark, the Contractor is required to report the raw data, processed data, and inversion results, as well as the processing and inversion settings, to the national GERDA database (see GeoFysikSamarbejdet (2020) for more details). This is a requirement for all work conducted on behalf of the DEPA and ensures compliance with national standards, while also allowing other projects to benefit from the collected data.

# 8. TRAINING

The training dataset used in this document is found on this link. This sTEM dataset consists of the instrument (raw data) output files, modelling setup files, and output files from Aarhus Workbench containing processed data, predicted data, and resistivity models in XYZ-format.

The dataset was collected to map buried glacial valley structures using an sTEM profiler and the stationary central-loop sTEM with 40 × 40 m and 80 × 80 m loops (Madsen et al., 2025). The measurements were carried out in northwestern Denmark, on the Salling Peninsula in the Limfjord area (see Figure 2a).

The purpose of this dataset is to provide sTEM operators with realistic training material to practice data handling, processing, and interpretation.

# 9. REFERENCES


### sTEM-system

Madsen, L. M., Almpanis, A., Hansen, F. S., & Pedersen, J. B. (2025). sTEM_Salling_2025 [Data set]. Zenodo. https://doi.org/10.5281/zenodo.16894039

### TEM-test site calibration and validation

Foged, N., E. Auken, A. V. Christiansen, and K. I. Sørensen, 2013, Test site calibration and validation of airborne and ground based TEM systems, *Geophysics*, 78, 2,E95-E106. https://mapwater.stanford.edu/sites/g/files/sbiybj21546/files/media/file/foged2013.pdf

GeoFysikSamarbejdet, 2019: The tTEM System - System validation and comparison with PACES and ERT. https://hgg.au.dk/fileadmin/HGGfiles/Reports/tTEM_Validation_2019.pdf

HGG report, 2012: Refinement of the TEM reference model at Lyngby. https://hgg.au.dk/fileadmin/HGGfiles/Reports/Refinement_TEM_RefModel_June_2012.pdf

### Inversion

GeoFysikSamarbejdet, 2018: Sharp model inversion setup for inversion of geophysical data – Guidelines and examples, 2018, HydroGeophysics Group. https://hgg.au.dk/fileadmin/HGGfiles/Reports/Sharp_report.pdf

### Interpolation

Sandersen, P., Jørgensen, F., Kallesøe, A., Møller, I., 2018: Opstilling af geologiske modeller til grundvandsmodellering. De Nationale Geologiske Undersøgelser for Danmark og Grønland, GEUS, København, https://data.geus.dk/pure-pdf/Geovejledning%202018-1.pdf

GeoFysikSamarbejdet, 2003: Anvendelse af TEM-metoden ved geologisk kortlægning. https://hgg.au.dk/fileadmin/HGGfiles/Reports/DK_reports/TEM_metoden_geologiskkortlaegning.pdf

### GERDA upload

GeoFysikSamarbejdet, 2020: Reporting tTEM and SkyTEM data/models to GERDA using Aarhus Workbench. https://hgg.au.dk/fileadmin/HGGfiles/Reports/GERDA_upload_Workbench_v4.pdf