



GUIDELINE AND STANDARDS FOR SKYTEM MEASUREMENTS, PROCESSING AND INVERSION

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VERSION 2.5

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1 REVISION HISTORY

This guideline has been updated and revised repeatedly. In the following, we summarize the main revisions made.

Version 1.1

Changes to averaging filter widths.

Minor changes made in the processing section, including averaging filter widths.

Minor changes made in the inversion section, including recommended model setup.

Specification of the repetition frequency in the raw data report.

Version 2.0

The guideline was thoroughly revised and restructured. The guideline was amended to reflect the currently used SkyTEM equipment including updated specifications and method & data collection requirements. The processing and inversion sections were expanded and updated.

Furthermore, based on experiences with the previous guideline and performed SkyTEM mappings, a number of details were clarified concerning data collection, processing, inversion and reporting of mappings.

Main changes and amendments to the current version:

- A description of the various SkyTEM setups and their uses was added to the manual
- In a number of places, text and sections were reorganized slightly to achieve a more consistent presentation
- Sections on calibration including bias and altitude testing were added
- New sections were added on line numbering and positioning of flight lines.
- Requirements for the processing and inversion of SkyTEM data were described
- Appendices with detailed SkyTEM setup options and processing and inversion system settings were added
- The SkyTEM file formats were documented.

The changes are so comprehensive that the manual was presented to all interested parties at a meeting in January 2010.

Version 2.1 – 5 August 2010

A new appendix was added to this version - Appendix 7 - comprising a detailed description of the standard map types included in data reports. References to the new appendix were added to section 8.2.

Version 2.3 – December 2010

Extension of appendix 5 with SCI-settings

Minor changes on pages 22, paragraph "noise processing"

Appendix 1 SkyTEM-setup: The gate width for time gate in the interval 6 μ s to 13 μ s SLM is changed resulting in more robust gates.

Version 2.4 – January 2011

A new setting for the processing of the GPS-data in Aarhus Workbench is added. This setting enables the user to shift the GPS-position in flight direction to obtain the optimum geographical positions for the data/models. Appendix 4. has been updated with this setting inc. comments and recommended values. The inversion code em1dinv has been updated to handle larger LCI-sections/SCI-cells. Recommended LCI-sections/SCI-cells sizes have therefore been updated in Appendix 5.

Version 2.5 – November 2011

In chapter 4.1 it is now specified that the calibration has to be performed with the refined national TEM reference model from Aarhus testsite.
Minor corrections in Appendix 3. , regarding the geometry file.

2 INTRODUCTION

This report is a translation of the Danish version of the “Guideline and standards for SkyTEM measurements, processing and inversion”. The intention is to keep the English version up-to-date with the Danish version. The Danish version is valid for the partners involved in SkyTEM surveys in Denmark.

The helicopter-borne transient electromagnetic measurement method, SkyTEM, is the leading geophysical method used for groundwater mapping in Denmark. This guideline was made as a quality assurance measure to ensure the quality of the procedures performed during SkyTEM data collection and processing. The standards presented herein are tailored to Danish geological conditions and to local Danish requirements concerning data quality and inversion.

The manual is comprised by two main sections: Data collection, validation and documentation are detailed in sections 3-5. Processing, inversion and reporting to GERDA are described in sections 6-8. Furthermore, the manual contains a number of appendices detailing various instrumentation and processing parameters. These appendices may be useful in connection with the drafting of agreements.

As the measurement equipment and inversion software are improved over time, the manual will be updated, as needed.

The requirements to field work and data processing presented in the manual are standard requirements. In case these requirements cannot be met, the reasons for this shall be stated clearly in the final report and, where relevant, the involved parties shall be informed. The guideline also provides a number of recommended processing and inversion settings.

The guideline was circulated for comment in GEUS and among consulting engineers. All interested parties were invited to a meeting held at the Department of Earth Sciences in January 2010.

Please note that the percentages provided in section 4.3 are presently instructive only. Final determination of the percentages presupposes thorough investigation.

Version 2.0 of the manual came into force on 15 February 2010. The newest version is available from the web page of the HydroGeophysics Group: www.gfs.au.dk

3 SKYTEM CONFIGURATION AND MEASUREMENT STRATEGIES

Below we present the various SkyTEM configurations, positioning of flight lines and determination of flight speed and altitude. The SkyTEM method is also described in ref. /8/.

3.1 SkyTEM configurations

Generally, the SkyTEM system measurement configuration needs to be adjusted to fit the mapping area and purpose. The system may be adjusted in a number of ways to facilitate mapping of very surface-near geological structures, profound structures or intermediary layers. Appendix 1 comprises a number of standard configurations, optimized for each of the mentioned mapping purposes.

The system uses a combination of two moments, super low moment (SLM) and high moment (HM). Previous versions of the SkyTEM also used low moment (LM). This is not currently the case, as LM was replaced by SLM. The SLM and HM have the following characteristics:

Super low moment (SLM)

One turn is employed on the transmitter frame, and a current of approx. 10 A is used. The first usable gate time depends on the choice of HM and is somewhere in the 10-15 μ s interval. SLM yields maximum resolution of surface-near geological structures.

High moment (HM)

The maximum transmitter current is 110 A in 1 to 4 turns. The first usable gate time occurs at approx. 30-70 μ s. Two frame sizes are available, measuring approx. 314 m² and 494 m². When the smaller frame is used, configurations with 1 (HM1), 2 (HM2) or 4 (HM4) turns are possible. If the larger frame is employed, four turns are always used.

The larger frame is mainly used for mappings requiring a substantial mapping depth (up to 300 m), while the smaller frame is used where mapping depths of up to 200 m are needed. If HM1 and HM2 are used, the mapping depth is more limited (100-150 m) as measurements are limited to 1.2-4 ms (versus the normal 10 ms) period.

In two or four turn configurations, SLM will not yield as early gate times as when using one turn with a single turn.

Moment combinations and lateral resolution

SLM in combination with HM1 and HM2 yield a very dense lateral data sampling resulting in a very high resolution of surface-near geology. By combining SLM and HM4, considerable mapping depth is achieved, but as transmission occurs at a lower frequency and over a longer period of time, lateral data sampling is less dense and the geology of very surface-near therefore somewhat limited.

For approx. every 20th shift of moment, the HM background noise is measured at a reduced stack size. This measurement is used during processing to assess the noise.

3.2 Flight lines

Generally, the positioning of flight lines is agreed upon by SkyTEM ApS and the client.

Flight line positioning

Lateral resolution will always be greater along the flight lines than perpendicularly to these. Normally, it will therefore be beneficial to place the lines so that they cross any known/expected geological structures. Wind and weather conditions experienced while mapping may affect the orientation of flight lines. However, at higher line densities, the impact of line orientation on mapping results is more limited.

Flight lines are positioned as straight lines. Lines which run along ground installations over long distances and at a distance not exceeding 100 m are not measured as they result in coupled data. However, the distance depends on the specific geology, as a high resistivity in the upper layers will entail a need for further distance to any installations. Experience shows that a distance of the above-mentioned 100 m is needed at resistivities ranging from 30 to 80 Ωm , while the distance needed at resistivities above 200-300 Ωm may exceed 200 m.

The actual flight lines may deviate somewhat from the planned straight flight lines, as the actual route taken is decided by the helicopter pilot in accordance with safety considerations. For instance, the pilot will need to avoid buildings and some types of farm animals, tall trees and high-voltage power lines.

Placing flight lines at short intervals will provide a high lateral resolution of the geological layers. A maximum line distance of 200 m (5 line kilometres per km^2) when a large mapping depth is a priority, and approx. 170 m (6 line kilometres per km^2) when structures nearer to the surface are to be mapped. In special priority areas, it may be relevant to reduce line distance to as little as 50 m.

3.3 Flight speed, altitude and frame angle

Flight speed

The selected flight speed is a trade-off between lateral resolution, mapping depth and costs. A low speed leads to a high data density, which results in an improved lateral resolution and a higher mapping depth.

Generally, flight speed should be maintained as constant as possible. Major speed fluctuations over short distances distort subsequent data processing with regard to mapping depth and lateral resolution. The flight speed target should be 45 km/t (12,5 m/s) and fluctuations to above 55 km/t for more than a few consecutive minutes should be avoided. If the flight speed/average speed deviates from what was agreed, this requires the acceptance of the client. Given the current system configurations, the stated flight speed is considered optimal for Danish conditions.

Flight altitude

The flight altitude has considerable impact on the size of the ground response, particularly in early time measurements. All things equal, the signal-to-noise ratio will be lower at low altitudes. For reasons of safety, the target altitude in open terrain is approx. 30 m, with fluctuations ranging from 25 to 45 m. Over

woodland and installations, the altitude is increased by the height of the objects overflown.

Generally, the altitude should be maintained as low and as constant as possible. Major altitude fluctuations over short distances cause erroneous data processing and in some cases data must be discarded completely.

Frame angle

The frame should be maintained as horizontally as possible during flight. In practice, the frame cannot be maintained completely horizontal due to shifting winds and changes in flight direction and speed. Whenever possible, the frame should be suspended in such a manner that the angles (pitch and roll) do not exceed +/- 10 degrees in production scenarios. Angles exceeding 20 degrees in periods of less than 20 s are acceptable.

4 VALIDATION PROCEDURES

This section describes the validation procedures for SkyTEM equipment in connection with mapping.

During any validation procedure, the SkyTEM system shall be configured as in the corresponding production scenario. The client shall be informed of any configuration changes and of their influence on the validation of the equipment. If changes are significant, the equipment shall be revalidated.

4.1 Calibration – National test site Aarhus

The objective of calibrating the SkyTEM system at the National test site near Aarhus is to establish the absolute data level to facilitate precise data modelling.

In connection with adaptation of the instruments, calibration measurements are always performed. Furthermore, calibration measurements shall have been performed three months or less before any mapping. The calibration has to be done with the refined TEM reference model from the National test site, as stated in /11/

Determination of any time or level displacement is established by comparing a measured SkyTEM response to the forward response from the geophysical ground model at the Aarhus test site. This is done for a minimum of three altitudes, typically approx. 10, 20 and 30 m. The forward responses are calculated on the basis of the actual altitude and the entire SkyTEM system (transmitter waveform, filters, front gate, etc.) is modelled. Thus, the waveform shall be determined prior to the calculation of forward responses. If the waveform is altered, new forward responses shall be generated and used for calculation of calibration constants. This procedure is known as *upward continuation*.

Documentation of the calibration is provided in the form of a plot showing the forward data and the measured data at the selected altitudes. A frame angle of approx. 0 degrees is the target. If the angle differs significantly from 0 degrees, adjustments should be made. The determined calibration constants should be identical for all measured altitudes.

The difference between an upward continued forward response for the model from the Aarhus test site and the measured response at every altitude shall not exceed 5% (rhoa data transformation) for data with a low noise level. Any deviations from this shall be presented to and accepted by the client.

Please refer to /10/ for a general description of the calibration procedure.

4.2 Determination of transmitter waveform

The objective of determining the transmitter waveform is to enable precise modelling of the measured data.

The transmitter waveform consists of a turn-on ramp and a turn-off ramp. Turn-on current is measured directly at the transmitter coil. The turn-off is measured

as the time derivative of the current. When the waveform is determined, the transmitter current shall have the same level as during production for the various moments. The waveform shall be scalable to the transmitter current because minor waveform fluctuations may occur during mapping, primarily due to temperature changes.

The turn-on ramp is defined in the geometry file by an exponential function and by placing “elbows” as shown in the upper half of Figure 1. The turn-off ramp is stated as a turn-off constant (A/s) for the linear avalanche process and an exponential constant for the free exponential decay (lower half of Figure 1). In the processing module of the Aarhus Workbench, the waveform constants from the geometry file are translated into straight line subsections describing turn-on and turn-off ramps, as shown by the straight lines in Figure 1.

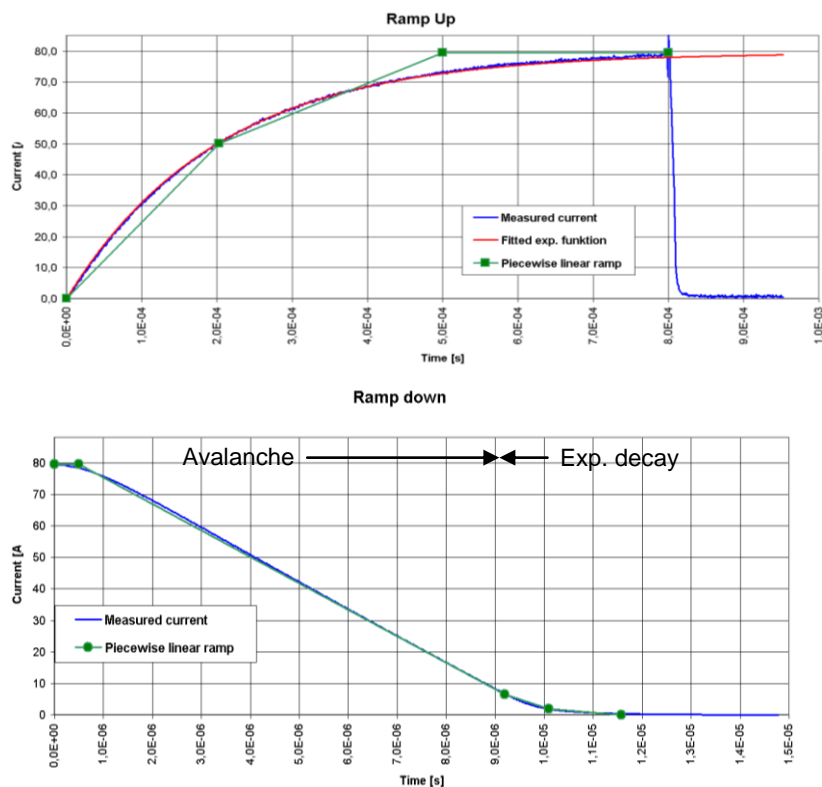


Figure 1. The figure shows the transmitter waveform and how the form is modelled in the Aarhus Workbench. Top - Turn-on ramp. The blue curve shows the measured current. The red curve shows the fitted exponential function (stated in the geometry file). The green line segments show the ramp used for inversion. These are calculated using the exponential constant and the relevant transmitter current. Bottom - Turn-off ramp. The blue curve shows the measured integrated turn-off currents. The green line segments show the ramp used for inversion. These are calculated using the exponential constant of the avalanche process, the exponential constant and the measured transmitter current.

The determination of the waveform is documented in the raw data report as a plot showing:

- The measured current data from the turn-on ramp with the selected exponential function

- The turn-off current with the selected exponential function. As data from the pick-up coil provides the time derivative of the actual current in the transmitter coil, a time-specific integration is performed to determine the parameters of the avalanche process and the exponential decay process.

Please refer to /4/ for a general description of the waveform calculation.

4.3 Local reference locality

The objective of testing at the local reference locality is to ensure that the system remains error-free after mobilization and mapping.

The local reference locality is established by performing five soundings using ground-based equipment. Before the soundings, this equipment shall have been calibrated at the Aarhus test locality. The soundings are performed as a cross by placing the centres of each set-up at 40 m- intervals, as shown in *Figure 2*

During the actual collection of production data - in connection with every flight and return flight - an approx. 30-second measurement should be performed at the local reference locality with the frame located at production altitude. By comparing these measurements, the repeatability of data is documented. Furthermore, by comparing the measurements to the ground-based measurements, data reproducibility is also documented.

The repeatability of all curves shall fall within 5% of the average value of every single gate (rhoa data transformation). The reproducibility of upward continued data from the ground model shall fall within 10% of the average value of every gate (rhoa data transformation). Both conditions apply to gates with a high signal-to-noise ratio. Any deviations from this shall be presented to and accepted by the client.

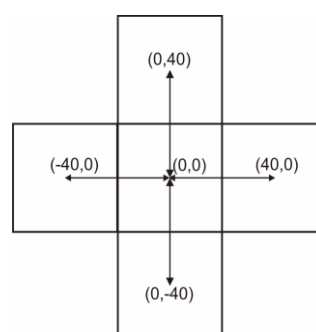


Figure 2. The local reference locality consists of five soundings with 40 m between the centres of each set-up.

4.4 Bias test during production flight

The objective of the bias test is to establish the bias level of early time measurements to facilitate the removal of any biased data. To establish any

changes in the bias response, access flights as well as return flights shall reach an altitude of min. 300 m or as high as the cloud cover permits. Such altitude should be maintained for a minimum of 15 seconds.

4.5 Measurements at high altitude - system response determination

The objective of the altitude test is to identify the system response. The altitude test is performed by measuring at an altitude at which the ground response is negligible, normally at approx. 1,000 m. One altitude test is performed in connection with every mapping and in close proximity to or within the mapped area.

The system response may not exceed approx. 2% (db/dt) of the ground response from the local reference locality at the normal production altitude. The size of the system response is documented in the form of combined plots showing data (db/dt) from a high altitude and data from the normal production altitude. A large stack size shall be used for the db/dt data collected at high altitude to eliminate random background noise and ensure that the system response is clearly discernible. On the background hereof, SkyTEM ApS shall state in the geometry file which gate times are applicable.

5 DATA REPORTING

The SkyTEM system produces various data files. The next sections describe the data types and requirements related to raw data reporting. Furthermore, the SkyTEM equipment calibration requirements are outlined.

The below section lists the instruments which collect the data that are subsequently processed and inversed. Figure 3 shows where the instruments are mounted.

Data types

SkyTEM shall supply all relevant data in accordance with the formats and conventions outlined below. Data shall be handed over as one comprehensive package.

The data recorded during SkyTEM mapping shall be reported in the following file formats:

- Geometry file
- SKB files
- SPS files
- Line number file

Geometry file

The geometry file contains information on the configuration of the SkyTEM system. This information is used during data processing and inversion. The geometry file is loaded with the remaining data to the Aarhus Workbench. It is a requirement that the final geometry file is handed-in along with the remaining data. A complete description of the geometry file is provided in Appendix 3. .

The geometry file contains information on:

- The placement of the various devices on the transmitter frame. The convention used for the system of coordinates is shown in Figure 3
- The expected transmitter current. Any deviation from the actually applied current may not exceed 25% of the expected transmitter current
- Size of the transmitter coil, number of turns and area covered
- Calibration constants in the form of time and db/dt factors and constants
- Specification of the first usable gates of each channel
- Low-pass filters
- The front gate's position in time. The front gate shall occur a minimum of 1 μ s before the first usable gate opens
- The estimated attenuation of the primary field from the zero position
- Repetition frequency. Note that the repetition frequency stated in the geometry file is calculated as: $\text{RepetitionFrequencyGeo} = 1/(4 \times \text{OnTime})$
- Parameters describing the waveform (turn-on and turn-off process) the turn-off process must be terminated before the front gate time (as stated above).
- Uniform data STD. As standard 3% is used
- Gate centre times, gate factors, and gate opening and closing times.

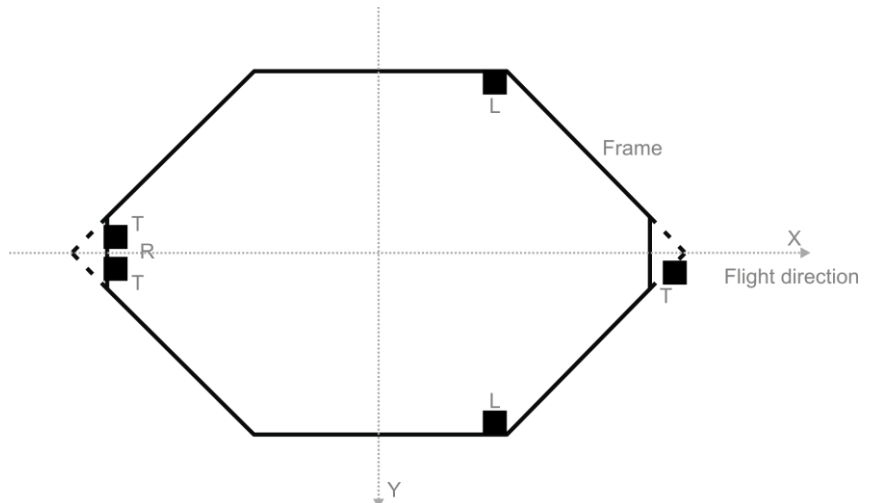


Figure 3. Sketch of the SkyTEM frame from above with indication of the primary instruments and definition of x and y directions. The x axis is the flight direction, the Y axis points to the right, and the Z axis points into the page.

SPS files

The SPS files contain:

- GPS data
- Pitch and roll (angle data)
- Altitude data
- Transmitter data, including transmitter current

The instruments used to measure these data are all duplicated (except for the transmitter). Where possible, data from both instruments should be used. However, when only one of the duplicated instruments has recorded a value, this is accepted.

All strings of the SPS file carry a GMT time stamp. The time recorded for each data type shall be stated consecutively in the files. The difference between system time (the time stamp) and the GPS time shall not exceed 2 seconds.

The system of coordinates used for the GPS data of the SPS file is lat./long. WGS84. GPS data shall have been measured by a minimum of one GPS, and any periods without recorded data shall not exceed 10 s.

The angle measurement devices shall be level (horizontal) with the transmitter frame/receiver coil and shall display 0° for the x and y angles in the horizontal position. The X angle (pitch) is the flight direction, which is positive when the front of the frame rises and its rear end moves downwards. The Y angle (roll) is the inclination measured perpendicularly to the flight direction. This angle assumes negative values then the right side tilts upwards (see Figure 3).

Angle data from a minimum of one angle measurement device shall be complete; however, a limited number of periods with no data is acceptable, provided these periods do not exceed 10 s each.

The flight altitude is normally measured using two independent lasers. The resolution is 1 cm and the uncertainty of measurements is in the order of 30 cm over a reflected surface. The laser provides a minimum of 9 measurements per second. Altitude data from a minimum of one laser shall be complete; however,

a limited number of periods with no data are acceptable, provided these periods do not exceed 10 s each.

The complete documentation of the SPS file format is provided in Appendix 2. .

SKB files

The SKB files contain the TEM data (db/dt responses). The data are stored in a binary format with an ascii header. The sign of the TEM data shall be positive for undistorted data.

The complete documentation of the SKB file format is provided in Appendix 2. .

Line number file

The line number file contains intervals connecting data to flight lines. Furthermore, the file holds a data category, the start/end UTM position of every line and an optional comment.

Line number file example (excerpt):

```
<date> <time> <line no> <.data category> <utm x> <utm y> <comment>
30-11-2009 09:30:06 911011.7 581886.11 5093810.78 !Flight 20091130.01 "Lokal ref, start"
30-11-2009 09:30:58 911011.7 581898.03 5093817.46 !Flight 20091130.01 "Lokal ref, end"
.....
30-11-2009 09:41:58 931011.8 581106.04 5092809.77 !Flight 20091130.01 "Bias test, start"
30-11-2009 09:42:34 931011.8 581981.25 5093680.87 !Flight 20091130.01 "Bias test, end"
.....
30-11-2009 09:43:48 100201.1 582063.04 5093561.63 !Flight 20091130.01 "Production, start"
30-11-2009 09:46:08 100201.1 580788.27 5092262.15 !Flight 20091130.01 "Production, end"
30-11-2009 09:47:16 100301.1 580465.36 5091680.92 !Flight 20091130.01 "Production, start"
30-11-2009 09:50:28 100301.1 582216.15 5093423.02 !Flight 20091130.01 "Production, end"
```

The line number convention is as follows:

- Line numbers are stated in a natural geographical order, e.g. from west to east and north to south
- Line numbers must be unique and the individual soundings of the mapping shall belong to one and only one line number
- When numbered, the flight lines shall have the same orientation. This means that the UTM position describing the starting point of all flight lines shall be placed at the same end of the line (e.g. from west to east - use left to right orientation where possible)
- The line number consists of six digits
- The first digit states the line type and sub area cf. the below line type table.
- Digits 2-5 are used for the specific line number. During planning, the numbering of neighbouring lines should be stated at intervals of 100, e.g. '100100', '100200', '100300', etc. If, during the data collection phase, it is decided that intermediate lines should be measured, these are given an intermediate number. For instance, the line placed between lines '100100' and '100200' will be called '100150'
- The final digit provides information on any line subsections. Line subsections occur when a flight line is split into several sections, e.g. because the line was completed during several different flights. The final digit is added after the data has been collected. When there are no subsections, the final digit is 1. Where subsections exist, each is numbered consecutively 1, 2, 3,...n.

The line types (the first digit) for production data are stated in the below table.

	Line type	Digit		
		1	2-5	6
Production data	Production area 1	1	Line no.	Any line subsection
	Tieline production area 1	2		
	Production area 2	3		
	Tieline production area 2	4		
	Production area 3	5		
	Tieline production area 3	6		
	Production area 4	7		
	Tieline production area 4	8		

The line types (1st and 2nd digits) for test and reference data are stated in the below table.

	Line type	Digit			
		1	2	3	4-6
Test and reference data (not production)	Test and reference data	9	X	X	X
	Repeated reference (point) Aarhus test site, local reference	9	1	Reference location	Consecutive number
	Repeated reference (line)	9	2		
	Bias test (~ 300 m)	9	3		
	Altitude test (> 800 m)	9	4		
	0 position test	9	5		
	Mag lag test	9	6		
	Mag heading test	9	7		
	---	9	8		
	Other test flights	9	9		

The line number file also contains a data category stated after the line number. This is used by the Aarhus Workbench to filter out any non-production data. The data category may hold the following values:

1. Production
2. Tieline production
3. Not in use
4. Not in use
5. Not in use
6. Repeated reference measurements (line)
7. Repeated reference measurements (point) - e.g. local reference locality or Aarhus test site
8. Bias test
9. Altitude test

Line number examples - production

118701.1= line subsection 1 of line 18700 in area 1
118702.1= line subsection 2 of line 18700 in area 1
305601.1= line subsection 1 of line 05600 in area 2
301651.1= line subsection 1 of line inserted between lines 01600 and 01700 in area 2

Line number examples - reference locality

911001.7= local reference locality 1000 measurement 1

911013.7= local reference locality 1000 measurement 3

5.1 SkyTEM ApS reporting

Generally, SkyTEM ApS shall supply error-free data and establish calibration and geometry constants that support optimal data interpretation. Furthermore, SkyTEM ApS shall document the validation/calibration performed on the employed SkyTEM equipment in the raw data report.

SkyTEM ApS reports data and mapping information in a raw data report. As a minimum, such report shall comprise information on:

- Specific conditions and problems which may affect data quality, processing or interpretation - e.g. increased flight altitude and/or speed and any temporary component malfunction
- A comprehensive data calibration statement
- The overall weather conditions, especially the wind speed and direction, and any rain shall be specified for the altitude test and for every production flight
- The position and numbering of every flight line
- Time intervals for production data, altitude data, etc. These data are provided as part of the line number file
- The localization of reference and landing localities, incl. GPS positions
Furthermore, it shall be specified which time intervals were used to collect reference data and where this was done. These data are provided by means of the line number file
- Maps (GIS), showing the flight speed, altitude, pitch and roll
- Number of collected line kilometres
- System parameters (see below).

All coordinates stated in the report shall be Euref89, UTM zone 32 (33). All statements of time shall be provided as GMT times.

Before the final hand-over of the raw data and the raw data report, it is checked that data can be loaded into the Aarhus Workbench from the files which will be handed over. This step does not, however, comprise data reporting to GERDA.

System parameters

The majority of the system parameters are stored in the geometry file. As a minimum, the raw data report should specify the following system parameters:

- GERDA identification numbers of the employed SkyTEM equipment including sub-components. The identification numbers should have been added to GERDA previously
- The employed measurement sequence
- Presentation of the parameters provided in the geometry file.

Unless otherwise agreed, the client shall complete any data quality assessment no later than 10 weeks after receiving the raw data report.

Calibration/validation of the employed SkyTEM equipment

Calibration and validation of the measurement equipment is performed by SkyTEM ApS. The validation shall, as a minimum, comprise the following:

- Calibration at the Aarhus test site. Data from the test site are provided with any information needed to assess and reproduce the calibration
- High altitude measurements to determine the system response
- Measurements at local reference locality for every flight. The above serves to document that the equipment was fully functional during the entire mapping session
- Bias tests performed in connection with access and return flights
- Measurement and determination of waveform (turn-on and turn-off ramps).

6 DATA PROCESSING

In the following, the overall requirements and measures related to data processing are outlined. Processing is performed using the SkyTEM processing module of the Aarhus Workbench. The recommended settings for each individual processor are stated in Appendix 4. Processing settings are also available from the web page of the HydroGeophysics Group: www.hgg.au.dk.

It should be stressed that the recommended data processing settings need to be adjusted to the relevant mapping area, specifically to the geology, flight speed, mapping focus, etc. of such area. The consultant who processes the data shall ensure that the used processing settings are adequate and have been adapted to the data set in question.

Generally, the following should be comprised by the processing of the SkyTEM data.

- Review of the raw data report from SkyTEM ApS
- Review of calibration soundings and reference measurements
- Review of the geometry file, which should also be compared to the raw data report
- Review of the line number file which should also be compared to the raw data report
- Processing of GPS angle and altitude data, including a visual assessment and editing along the profiles
- Processing of db/dt data - automatic
 - Adjustment of any settings needed to perform the automatic processing. This procedure takes into consideration the amount of removed data and the signal-to-noise ratio
 - Verification that all data are included and coincide with the data comprised by the raw data report
- Processing of db/dt data - manual
 - Visual assessment and editing along flight lines
 - Elimination of coupled data
- Preliminary smooth inversion to support processing.

An outline of the SkyTEM data processing is available in references /4/ and /10/. Furthermore, the help function of the Aarhus Workbench comprises a description of each processing setting.

6.1 Assessment in connection with data processing

Reporting related to processing should, as a minimum, account for the following:

- Choice of trapezoidal averaging filter widths
- Sounding density - sounding distance and relation to the selected averaging filter width
- Strategy used for elimination of coupled data
- Assessment of the choice of first gate in consideration of bias content.

6.2 GPS, angle and altitude data

GPS, angle and altitude data are loaded from the SPS files. Data are measured asynchronously and with different frequencies. The majority of the data processing is automatic, but always needs to be assessed by the person performing the interpretation.

GPS data

X and Y coordinates are filtered and averaged separately. GPS data are needed in order to use the db/dt data.

Angle data

The pitch and roll angle data are filtered and averaged using median filtering. If the numerical values for roll or pitch exceed 25 degrees, the db/dt data are excluded as the effect of a tilted transmitter and receiver coil cannot be filtered-out adequately. This trimming is performed manually.

Altitude data

During the processing of altitude data, reflections not stemming from the earth's surface are removed; therefore, such data do not form part of the averaged altitude series.

Processing comprises two steps. The first step is automatic data processing in which repeated polynomial fit is used to discard any reflections not originating from the earth's surface. Altitude data are adjusted during processing. This includes adjustment for the altimeter's deviation from a horizontal position. The second step is a visual assessment and manual adjustment of the automatic processing result.

Limited stretches which do not have any altitude data after the processing, e.g. due to dense forest or flight over water, are acceptable.

6.3 db/dt data

The objective of db/dt data processing is to remove any coupled and noisy data and to average data into soundings thereby suppressing any random noise in the data.

Processing of db/dt data comprises, as a minimum, the following steps:

1. Import of the geometry file and the SPS and db/dt data
2. Automatic processing, removal of noisy and coupled data and averaging of raw data to create average soundings
3. Visual assessment of all db/dt data and manual elimination of any noisy/coupled data.

cf 1) Data import

Instrument data are defined as data which have yet to be stacked. Raw data are defined as pre-stacked data with a stack size ensuring that any interference from the 50 Hz power grid is stacked out. Such pre-stacking is performed automatically during data import to the Aarhus Workbench. If a reduction of the raw data stacks is desired during the import, it should be checked that any interference from the 50 Hz power grid is still stacked out correctly. During processing, raw data are averaged to average soundings, which are subsequently interpreted to form geophysical models.

The db/dt data are ascribed a uniform 3% data uncertainty. The corresponding uncertainty in apparent resistivity (ρ_{a}) is determined by multiplying the db/dt uncertainty by 2/3. The uniform data uncertainty is ascribed to the data during data import and stored in the geometry file.

Some of the parameters of the geometry file cannot be adjusted after data has been imported to/processed in the Aarhus Workbench. Therefore, it is important that the geometry file is correct at the time of the import. Consequently, it may be advantageous to perform a minor inversion test on the data before initiating final data processing. This ensures that data are consistent and that inversion results are attainable given the employed system parameters.

cf 2) Automatic processing

During the automatic processing, a number of filters are used to remove any coupled and noisy data. Furthermore, data are adjusted to compensate for the altimeter's deviation from the horizontal position. The automatic processing should not be expected to remove all noisy/coupled data. Furthermore, in some cases the automatic processing discards usable data. It is therefore necessary to manually revise and adjust the automatic processing result. How many data the automatic filters discard depends on filter settings. To operate optimally, the filters need to be adjusted to the specific data set/area.

Additionally, during the automatic processing, the parameters are defined for the averaging of raw data to create soundings.

cf 3) Manual processing

Manual processing comprises a visual assessment of all db/dt data at profile and sounding levels. The objective is to optimize the results of automatic processing.

During manual processing, any remaining bits of coupled data are removed. Furthermore, the averaged soundings are trimmed when they coincide with the noise level. This manual revision of data is the most time-consuming step of the processing, but it is essential to achieve a good data quality and reliable inversion results.

6.4 Coupled data

Coupled data are unusable and should be discarded. Coupled data are removed at the raw data level, so that they do not form part of the data which are averaged to form soundings, and trapezoidal filters may be reapplied at subsequent data reprocessing. Couplings may normally be recognized in data by observing sounding curves and by studying the data development along the flight lines. Furthermore, it is important to constantly monitor the geographical localization to identify potentially data-disruptive installations (power grid, wind generators, animal fences, etc.).

As data are collected continuously along a profile, it is possible to obtain a good overview of data developments and any couplings. In some cases, it is possible to only eliminate the coupled part of a data curve.

Considerable experience and familiarity with data are required to identify couplings. As a minimum the segments (SLM, HM) are trimmed according to the following guidelines:

- If the coupling is present at gate times that overlap both segments, all data from both segments are removed. The overlap is defined as the time interval where one normal would keep data from both segments.
- If a coupling is present early times (before the overlap), all SLM data are removed. HM data may be preserved
- If a coupling is present a late time (after the overlap), the coupled data points and all subsequent data points are removed. SLM data may be preserved.

6.5 Averaging and trimming of data

The purpose of averaging raw data to create soundings is to improve the signal-to-noise ratio. For such purpose trapezoidal filter averaging is used, in which late-time data on the data curve are averaged over a greater interval than early-time data. This is shown in Figure 4.

The choice of averaging filter width is a trade-off between the desire to achieve usable, noise-free data and lateral resolution. The averaging filter width should therefore be limited as much as possible to achieve usable data; specifically, the width should be agreed with the client. It is recommended that the averaging filter width be determined in connection with the initial assessment of data. To assist in this decision, plots of raw and averaged data for various averaging filter widths may be made and also minor test inversions can be made to assess the result of deciding on a certain averaging filter width.

A large averaging filter width improves the signal-to-noise ratio, particularly for the last part of the data curve which is close to the background noise level. A large averaging filter width may therefore be an advantage if you are handling noisy data or want to map deeper-lying structures. A limited averaging filter width is preferable where the signal-to-noise ratio is good and in situations where lateral resolution is a priority. In addition to the averaging filter width, the noise level is a function of the flight altitude, stack size, transmitter moment and the average resistivity of the mapped area – specifically, a high average resistivity will result in a lower signal level.

Averaging of data is determined during data processing along with the sounding distance. Averaging width and sounding distance are stated in time and therefore need to be related to the flight speed. For early times, we recommend that the averaging filter width does not significantly exceed the sounding distance. Furthermore, it is recommended that no or only a very limited overlap exists between the averaging interval of adjacent soundings. Normally, the same averaging filter widths are used for the entire mapping. Data from the various moments are averaged to soundings from the same position/time (Aarhus Workbench: "Trapez Sync. location of sound." ON).

Noise processing

The late time gates of a data curve normally reach into the background noise. Very noisy data points that holds very limited earth response are removed. Slightly noisy data points just about the noise-level is assigned a larger uncertainty, typically 5-20%. The Aarhus Workbench program automatically calculated reasonable data uncertainties based on the data stack. Manual adjustments are needed in some cases. The noise processing must be performed on stacked data and not on raw data series.

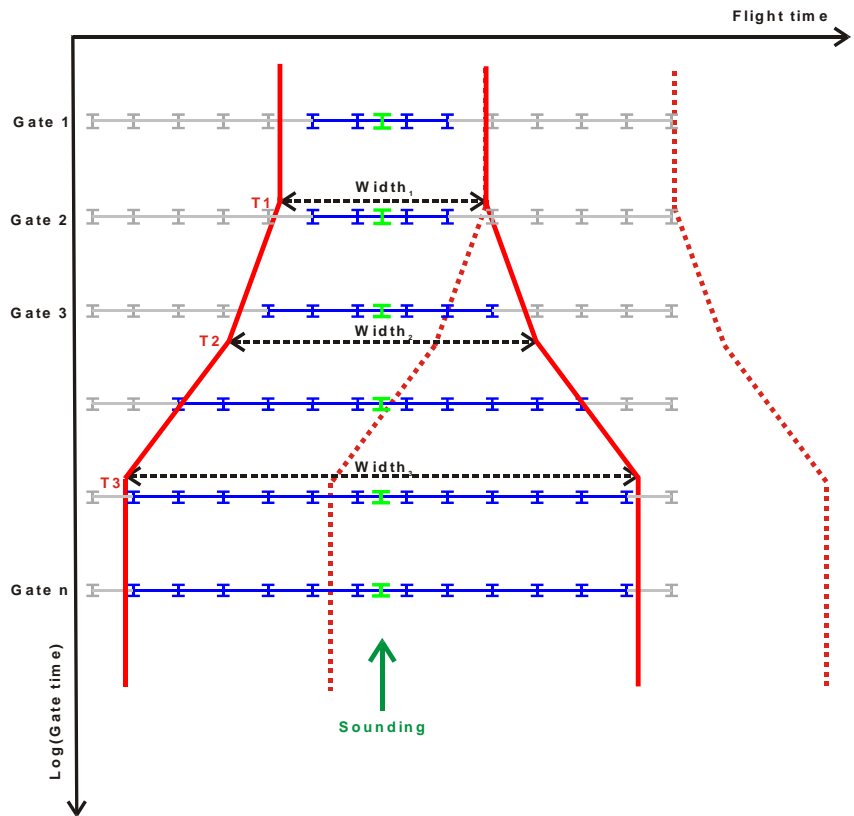


Figure 4. Principle sketch of trapezoidal filter averaging: The averaging core for the sounding is stated in red, thereby creating an averaged sounding. Subsequently, the trapezium is moved, and another average is calculated.

7 DATA INVERSION

This section details the requirements made to the geophysical data inversion. A presentation of SkyTEM data inversion is also provided in references /4/ and /5/.

The first section covers general issues concerning the inversion model and methods, while the final sections cover the more specific requirements to the SkyTEM inversion workflow.

Inversion is performed using the SkyTEM inversion module of the Aarhus Workbench. Elevation data should be added to the data model results. Recommended settings for the various types of inversion are provided in Appendix 5. Inversion settings are also available from the web page of the HydroGeophysics Group: www.hgg.au.dk. These guiding inversion settings shall be adapted/adjusted to the specific mapping area (its geology) sounding density, mapping focus, etc. It is always the person performing the inversion who carries the responsibility that the employed inversion settings are adequate /adapted to the relevant data set. The geophysical inversion may subsequently be complemented by an integrated geological/geophysical interpretation.

Generally, the following should be comprised by the inversion of the SkyTEM data.

- Preliminary LCI smooth inversion to support processing.
- Control and assessment of:
 - processing
 - inverted altitude versus processed altitude
 - data fit
- Final LCI/SCI smooth inversion, assessment of:
 - model reliability
 - inverted altitude versus processed altitude
 - data fit
- Final LCI/SCI few-layer inversion with estimation of the number of layers from the smooth inversion, assessment of
 - model reliability
 - inverted altitude versus processed altitude
 - data fit
- Thematic maps
- Calculation of depth of investigation (DOI)

7.1 Assessment in connection with data inversion

Reporting related to the inversion should, as a minimum, account for the following:

- The number of layers of the few-layer and smooth model
- Vertical and lateral constraints of smooth models and depth of discretization
- Lateral constraints of few-layer models
- Start model including layer boundaries and layer resistivities
- A priori models - if relevant.

7.2 Inversion model

System modelling

SkyTEM data inversion is performed using a 1D-model, either in an LCI setup (Laterally Constrained Inversion) or a SCI setup (Spatially Constrained Inversion). For SkyTEM inversion, the full SkyTEM system shall be modelled. This comprises modelling of:

- The segmented transmitter coil
- The receiver coil's position
- The front gate
- Low-pass filters before and after the front gate
- Primary field attenuation
- Turn-on and turn-off processes (the waveform)
- Data standard deviations
- Flight altitude as inversion parameter with a priori constraints and lateral constraints.

The underlying inversion code `em1dinv` (ref. /2/) was designed specifically to model the full SkyTEM system.

Few-layer models

Few-layer models are typically used for inversion of geophysical data in connection with hydrogeophysical mapping.

Few-layer models provide a geophysical model with sharp layer boundaries. In a layered geological environment, the geophysical layer boundaries are frequently correlated directly to distinctive geological layer boundaries, which assist the geological inversion of the geophysical results.

Besides the model result, a model parameter analysis is performed providing estimates of how well the model parameters (resistivities, thicknesses and depths) were determined, which is helpful for any further geological interpretation. Determination of the number of layers to include in the model (the model section, if LCI is used) is relatively time-consuming and as such decision cannot be made on the basis of purely objective criteria, but rather demands a manual assessment and selection based on several inversion results obtained with a different number of layers.

Smooth model

A smooth model typically consists of 15-20 layers with a set thickness. The large number of layers makes the model appear continuous. Consequently, the interpretation process is limited to establishing the electrical resistivity of the layers. The term *smooth model* is owed to the fact that resistivities change very gradually from one layer to the next. One of the primary advantages of smooth inversion is that it is frequently possible to identify complex geological structures such as inclined layer boundaries, which are harder to detect when using few-layer models. Furthermore, time-consuming and to some extent subjective selection/assessment of several model results is unnecessary.

The disadvantages of smooth inversion are that in some contexts layer boundaries are diffuse and that the depth of investigation (DOI) is unknown.

The uncertainty estimate of the model parameters of smooth models is significantly influenced by vertical as well as lateral constraints. Consequently, uncertainty estimates may only be used relatively and not absolutely as in a few-layer inversion.

A presentation of the inversion of smooth models and examples of few-layer and smooth models are provided in ref. /5/.

7.3 Constrained Inversion

All data inversion is performed using either LCI or SCI.

Lateral constraints

In LCI and SCI, lateral constraints are used. The lateral constraints are scaled with the distance between soundings.

Constraints are important during the establishment of the LCI section, as illustrated in Figure 5. Ideally, the lateral constraints reflect the geological variations of the area. Too tight a constraint will introduce erroneous information and may cause too few and too small variations in the section and possibly also poor data adjustment. Conversely, too loose a constraint may cause the information not to be forwarded from sounding to sounding so that the inversion is not stabilized.

LCI

LCI is performed by connecting layer parameters, normally resistivity and depths, to neighbouring soundings. The principle in LCI is illustrated in Figure 5. One of the main advantages of LCI is the achievement of continuity in the model sections and an improvement of the determination of the poorly resolved parameters. Data are interpreted in sections and sections are split wherever the distance between soundings exceeds a previously set value or when a section reaches a certain size. A reasonable section size is approx. 1000 model parameters per section, i.e. 125 models per section if using a four-layer model (1000/8 model parameters, 7 model parameters and a flight altitude). This section size expresses a trade-off between an acceptable calculation time and a desire to use large sections.

Detailed descriptions of LCI interpretation are also provided in refs. /3/ and /7/.

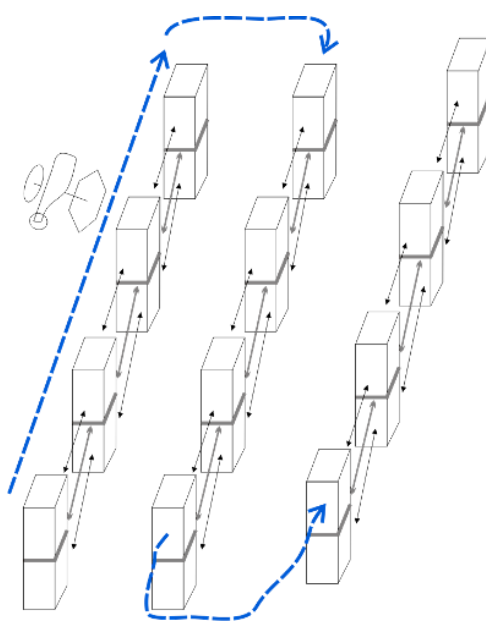


Figure 5. Illustration of the LCI principle. Lateral constraints connect the models along flight lines.

7.4 SCI

The introduction of lateral constraints connecting to the models of neighbouring lines comprises a natural development of the LCI method - particularly as shorter line distances of 170-200 m have become more common. This is shown in Figure 6 and the concept is known as SCI. The main difference between SCI and LCI is the manner in which lateral constraints are set. In SCI, the lateral constraints are set in a triangular system in which the connection is always made to the nearest neighbours. This method therefore comprises information on the geological information along as well as across flight lines. This generally leads to more coherent resistivity areas, and any striping effects of the LCI constraints which only extend along flight lines are not seen in SCI.

As in LCI, the mapping area is divided into sub areas which are inverted independently. Detailed descriptions of SCI are provided in refs. /9/ and /6/.

7.5 Inversion workflow

The typical inversion workflow may be described as follows:

1. Adjustment of the processing on the basis of the results from a preliminary smooth LCI
2. Final LCI/SCI with a few-layer and smooth model.

cf 1) Processing adjustment

On the basis of a preliminary inversion, the inversion result is assessed. This is done by visual revision of data and inversion results at the sounding and/or profile level. The revision serves, among others, to assess data fit, model and flight altitude (input and output flight altitude).

Smooth inversion is recommended for the preliminary inversion, as it is performed automatically. The following frequently need to be performed on the basis of the inversion:

- Adjustment of data processing - i.e. removal of very noisy data points and/or coupled soundings which were not identified during data processing
- If the flight altitude measurements from the altimeter and the altitude of the inversion result differ significantly, altitude processing may need adjustment or the difference detected may be an indication of data calibration issues
- The geographical position of the models in relation to expected coupling sources is assessed. In places where data are included in the interpretation, where coupling may be expected a priori (at major roads, high voltage power lines etc.), processing results are reassessed and in some cases more data need to be discarded.

cf 3) Final inversions

During the final inversions, it is important to ensure the continuity of model sections across section boundaries. In LCI, this is achieved by using the "Force continuous model section" facility in the LCI module of the Aarhus Workbench. In SCI, continuity is achieved automatically.

During the final inversion, it should also be checked that a satisfactory data misfit, etc., is achieved. The specific contents of the final inversions are agreed with the client: few-layer inversion and/or smooth inversion, LCI/SCI, etc.

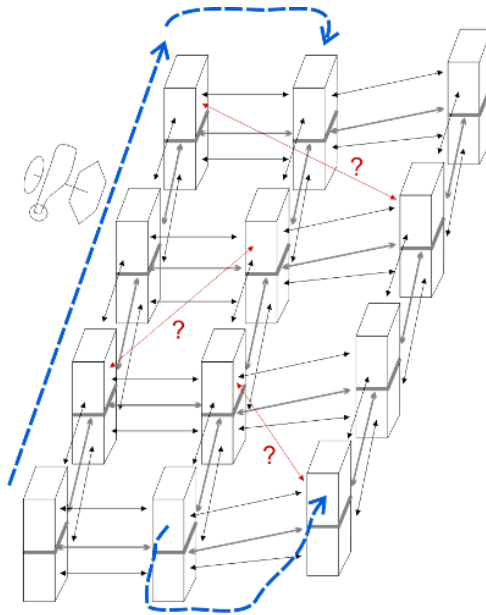


Figure 6. Illustration of the SCI principle. There are lateral constraints along and across flight lines.

8 REPORTING ON PROCESSING AND INVERSION

This section comprises minimum requirements to the geophysical data reporting.

The geophysical data reporting shall account for conditions which have had significant influence on processing, inversion and the results of the inversion.

8.1 Processing

The data processing report shall, as a minimum, comprise the following:

- An overview of the parameters used for processing.
- An account for the choice of:
 - Trapezoidal filter averaging widths
 - Sounding density - sounding distance and relation to the selected averaging filter width.
 - Strategy for elimination of coupled data
 - The first used gate time in consideration of the bias contents.
- An Aarhus Workbench Workspace with processing nodes.
- All data types are handed over digitally.

8.2 Inversion results

The inversion results are typically presented as sections, average resistivity maps and other relevant themes, e.g. elevation of the conductive subsurface. The map/report shall specify how the maps were made and which calculation method was used for the mean resistivity maps, search criteria, gridding methods, etc. All Danish maps are provided as Euref89, UTM zone 32 (33). Ref. /1/ contains general information on the presentation of TEM data.

The interpretation section of the report shall, as a minimum, comprise the following:

- An account for the choice of:
 - The number of layers in the few-layer inversion
 - The number of layers and the depth of discretization of smooth models
 - Start model including layer boundaries and layer resistivity values
 - Vertical and lateral constraints
 - A priori constraints - if relevant
- Maps, please find further specification details in Appendix 7.
- Aarhus Workbench Workspace with inversion results.

8.3 Reporting, GERDA

The raw data, processing and inversion results are reported to GERDA in accordance with the applicable convention for reporting to the GERDA database.

9 REFERENCES

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9. Viezzoli, A., Christiansen, A. V., Auken, E., and Sørensen, K. I., 2008, Quasi-3D modelling of airborne TEM data by Spatially Constrained Inversion: Geophysics, 73, F105-F113
10. Auken, E., A. V. Christiansen, J. A. Westergaard, C. Kirkegaard, N. Foged, and A. Viezzoli, 2009, An integrated processing scheme for high-resolution airborne electromagnetic surveys, the SkyTEM system: Exploration Geophysics, 40, 184-192.
11. Refinement of the national TEM reference model at Lyngby, November 2011.

Articles and reports are available from the web page of the HydroGeophysics Group: www.gfs.au.dk

APPENDIX 1

THE SKYTEM SYSTEM - DEFINITIONS

This Annex will be regularly updated so that it follows the development of the SkyTEM system.

Configurations and moments - Overview

The right part of the table below gives an overview of the main parameters of the super low moment (SLM) and the three variants of the high moment (HM). Note also that there are two sizes of the transmitter frame. The left part of the table shows the possible combinations of moment and the investigation depth a given combination has. In the following tables the different moment specifications are tabulated in detail.

Moment definitions						Two-moment configurations			
	Tx-area [m ²]	Number of turns	¹ Tx cur- rent [A]	² 1st gate time [μs]	³ Last gate time [ms]	A	B	C	D
SLM	314	1	10	12	1,0		X	X	X
	494	1	10	15	1,0	X			
HM1	314	1	100	30	1,0				X
HM2	314	2	100	35	2,7			X	
HM4	314	4	100	70	9,0		X		
	494	4	90	100	9,0	X			
Focus depth:						Deep	Near surface /deep	Near surface	Very near surface
Lateral resolution:						Medium	Medium	High	Very high
⁴ Approx. depth of investigation [m]:						~300	~200	~150	~100

¹ Approx. current.

² Approx. time for the first usable gate (gate with an acceptable low bias level). Depend on the resistivities of the survey area.

³ The last gate-center time recorded. The last gate-center time used in the processing will normally be earlier dependent on the resistivities of the survey area.

⁴ The depth of investigation is highly dependent on the resistivity distribution in the survey area.

Detailed moment definitions

The following tables contain detailed specifications for the various moments from the overview table. Furthermore a table showing standard software IDs for the various moments is present.

Super low moment (SLM)	
Number of turns, Tx-loop	1
Tx-loop area	314 m ² / 494 m ²
Current	~10 A
Tx moment	~3.200 Am ² / ~5.000 Am ²
Repetition frequency	222 Hz
On-time	1000 μs
Off-time	1200 μs
Waveform	Exponential ramp-up, followed by an exponential turn-off
Number of series per moment	160
Front-gate time	No front gate (0 μs)

High moment 1 (HM1)	
Number of turns, Tx-loop	1
Tx-loop area	314 m ²
Current	~100 A
Tx moment	~31400 Am ²
Repetition frequency	100 Hz
On-time	2000 μs
Off-time	3000 μs
Waveform	Exponential ramp-up, then linear turn-off followed by an exponential turn-off
Number of series per moment	64
Front-gate time	~35 μs (time in script file)

High moment 2 (HM2)	
Number of turns, Tx-loop	2
Tx-loop area	314 m ²
Current	~100 A
Tx moment	~62800 Am ²
Repetition frequency	100 Hz
On-time	2000 μs
Off-time	3000 μs
Waveform	Exponential ramp-up, then linear turn-off followed by an exponential turn-off
Number of series per moment	64
Front-gate time	~ 35 μs (time in script file)

High moment 4 (HM4)	
Number of turns, Tx-loop	4
Tx-loop area	314 m ² / 494 m ²
Current	~100 A / ~90 A
Tx moment	~125600 Am ² / ~179000 Am ²
Repetition frequency	25 Hz
On-time	10000 µs
Off-time	10000 µs
Waveform	Exponential ramp-up, then linear turn-off followed by an exponential turn-off
Number of series per moment	96
Front-gate time	~ 50 µs / Ca. 70 µs (time in script file)

Software channel ID	Moment ¹	Component	Signal/Noise
1	SLM	Z	Signal
2	HM	Z	Signal
3	SLM	X	Signal
4	HM	X	Signal
5	SLM	Z	Noise
6	HM	Z	Noise
7	SLM	X	Noise
8	HM	X	Noise

¹Because LM is not in use anymore the SLM is on channel 1, 3, 5, and 7.

Measuring sequence, gate times and system

The following tables contain settings for the measuring system

General measuring sequence	
Number of moments	2
Moment 1	SLM
Moment 2	HM
Noise measurement	HM, stack size 32
Moment sequence	Alternating SLM, HM and noise. A noise measurement is recorded for every 20th SLM and HM measurement

Gate times*/ gate distribution SLM, HM	
Time interval: 6 µs to 7 µs	1 µs gate width
Time interval: 6 µs to 13 µs	2 µs gate width
Time interval: 13 µs to 10 ms	10 gates per decade approximately logarithmically distribution
Gate-centre time definition	Arithmetic mean of gate-open and gate-close

* Approximate gate centre times after calibration correction

Navigation instruments	
Altimeters	Minimum data from one laser mounted on the Tx frame.
Frame inclination	Minimum data from one inclinometer mounted on the Rx platform
Positioning	Minimum data from one GPS

Receiver system – z-coil	
Coil area	5 m ² , effective area 100 m ²
Receiver coil low pass filter	450 kHz, 1st order
Receiver instrument low pass filter	300 kHz, 1st order
Nominal position	Null-position

The mapping

The following table contains settings for the actual field campaign

Flight lines and flight speeds	
Line distance	170 m - 250 m, to be agreed with the client
Line direction	To be agreed with the client
Average flight speed	45 km/h
Accepted variation of speed	+/- 10 km/h
General flight altitude	25-35 m, forest areas etc. will increase the altitude

Calibration and high-altitude test

The following tables contain settings for calibration and test of the system.

Local reference location measurements	
40x40 measurements on the ground	Five soundings in a cross.
Number of reference measurements, SkyTEM	1 per flight
Altitude at reference measurements	Production altitude, ~30m
Time at reference location	Min. 30 s

High-altitude test/Bias test	
High-altitude test	Minimum one high-altitude test is performed before production flights start
Min. altitude for high-altitude test	1000 m
Time at high altitude	Min. 30 s
Bias test	At outgoing and at incoming ferry flight for every flight
Min. altitude for bias test	300 m if the cloud cover permits it
Time at bias test	Min. 15 s

Calibration, Aarhus Test site	
Ramps	By SkyTEM ApS
Time shifts	By SkyTEM ApS
Factor shifts	By SkyTEM ApS

APPENDIX 2

DOCUMENTATION OF THE SKYTEM FILE FORMATS

SPS-fil

The following is a description of the format of the SPS file, version 3.

The *sps-file* contains data from the instruments listed in the table below. The line numbers in the table refers to the *SPS-file* example shown in Figure 1.

The data frequency in the SPS-file is different for the different instruments. All data lines in the SPS-file start with a device ID followed by a system GMT-time stamp. The format of the system GMT-time stamp is: [yyyy mm dd hh mm ss zzz] corresponding to [year month day hour minute second millisecond].

Line num.	De-vice	Comment
1	VER	SPS-filer version
2-4	MRA	Marks. Text string added by operator
5-6	SOF	Software version
7-8	HE#	Data from Laser altimeter number #
9-10	GP#	Data from GPS number #
11-12	TL#	Data from Inclinator number #
13	ANG	Duplicate of TL1 line (backward compatible reasons). Do not read this line.
14	TXD	Data from transmitter. Description of measurement cycle, transmitter currents
15	TX3	Data from transmitter, when running in multi moment mode

Line number	SPS-filer (short example)
1	VER 3
2	MRK 2009 05 02 09 51 32 015 PaPc id: 21
3	MRK 2009 05 02 09 51 32 015 PaPc Software version: Build: 3.0.1.40
4	MRK 2009 05 02 09 51 32 015 TxProc: Software version 2.0.1.6 and TX ID 8 CtrlID 505 Slice 498 485 455 454 453
5	SOF 2009 05 02 09 51 32 015 1 21 Build: 3.0.1.40
6	SOF 2009 05 02 09 51 32 015 3 8 2.0.1.6
7	HE1 2009 05 02 10 23 42 859 14.39
8	HE2 2009 05 02 10 23 42 968 14.58
9	GP1 2009 05 02 10 23 42 921 5534.9376 00920.9471 10:23:43 10 WGS84 7.3 1.4 0.8 0.0 72.7
10	GP2 2009 05 02 10 23 42 890 5534.9385 00920.9456 10:23:43 9 WGS84 7.2 1.5 0.9 0.0 72.4
11	TL1 2009 05 02 10 08 31 500 2.17 -2.31
12	TL2 2009 05 02 10 08 31 656 -0.41 -1.22
13	ANG 2009 05 02 10 08 31 500 2.17 -2.31
14	TXD 2009 05 02 10 08 32 859 64 0 0 32 32 70.67 70.62 32.48 0 1 64 92.53 93.18 91.66 -1.00
15	TX3 2010 01 15 16 31 46 260 160 1 22 0 0 22.62 22.62 23.04 7.66 7.92 7.52 0.00

Figure 1 SPS file example

The format of the data string for the different devices are listed in the tables below.

Row	Laser altimeter devise
1	Devise type [HE1 or HE2]
1-8	GMT-system time, [yyyy mm dd hh mm ss zzz]
9	Distance to the reflective object (~TX-frame height), [m]. Device returns

	99999.99 if no reflection/invalid reading (normal about ~200 m)
--	---

Row	GPS-device
1	Device type [GP1 or GP2]
1-7	GMT-system time, [yyyy mm dd hh mm ss zzz]
8-9	Latitude and longitude coordinates in degrees
10	GTM-Time from GPS-receiver, [hh mm ss].
11-12	Numbers of satellites connected to GPS-receiver
13	Coordinate system datum
14	Speed [m/s]
15-17	The delusion of precision of the GPS receiver. (HDOP, VDOP, PDOP)
18	Elevation, [m]

Note: Only Latitude, Longitude and elevation are used from the GPS-device in the data processing in Aarhus Workbench.

Row	Inclinometer
1	Device type [TL1 or TL2]
1-8	GMT-system time, [yyyy mm dd hh mm ss zzz]
9	Pitch. Tilt of the coils in direction X positive when the nose of the frame goes up [degree].
10	Roll. Tilt of the coils in direction Y, negative when the right side of the frame goes up (right side is in the positive y-direction), [degree].

Row	Transmitter, TXD-device
1	Device type [TXD]
1-8	GMT-system time, [yyyy mm dd hh mm ss zzz]
9	NumberOfShots: The total number of transients, NumberOfDatasets * NumberOfSerie.
10	NumberOfProtemErrors: Indicates a missing pulse detection. The integer states the number of missing pulses.
11	FirstProtemError: The position of the first missing pulse.
12	Nplus: The number of positive currents in stack.
13	Nminus: The number of negative currents in stack.
14	VoltageOn: The battery voltage measured during transmitter on time, [V].
15	VoltageOff: The battery voltage measured during transmitter off time, [V].
16	TxTemperature: The temperature of the transmitter, [°C].
17	VersionNo: Added to be able to add new elements to the frame. VersionNo 0 is without PolErr and VersionNo1 is with PolErr. VersionNo 3 adds Max_Current, Min_Current and RMS_Current.
18	NumberOfDatasets: The number of data sets.
19	NumberOfSeries: The number of series in each data set.
20	Mean_Current: The mean transmitter current for NumberOfSeries. Measured for before the ramp off, [A]. Current is looped over the NumberOf-Datasets.
21	Max_Current: The maximum current for NumberOfSeries measurements [A].
22	Min_Current: The minimum current, for NumberOfSeries measurements, [A].
23	RMS_Current: The RMS current for NumberOfSeries measurements. Not calculated !

Note: Not all TDX-parameters are used in the data processing.

Row	Transmitter, TX3-devise, for “multi moment” mode (not yet in production)
1	Devise type [TX3]
1-8	GMT-system time, [yyyy mm dd hh mm ss zzz]
9	NumberOfShots: The total number of transients, NumberOfDatasets * NumberOfSerie.
10	MomentID: Moment ID in instrument script file
11	DatSeqCount: Dataset counter from TX. Can be match with TIB data.
12	Nplus: The number of positive currents in stack.
13	Nminus: The number of negative currents in stack.
14	VoltageOn: The battery voltage during transmitter on time, [V].
15	VoltageOff: The battery voltage during transmitter off time, [V].
16	TxTemperature: The temperature of the transmitter, [°C].
17	Mean_Current: The mean transmitter current for NumberOfSeries. Measured for before the ramp off, [A]. Current is looped over the NumberOf-Datasets.
18	Max_Current: The maximum current for NumberOfSeries measurements [A].
19	Min_Current: The minimum current, for NumberOfSeries measurements, [A].
20	RMS_Current: The RMS current for NumberOfSeries measurements. Not calculated !

APPENDIX 3

DOCUMENTATION OF THE GEOMETRY FILE

The geometry file contains all information about the SkyTEM system, e.g. calibration factors, loop sizes, device positions, transmitter wire form etc. used during the processing and inversion of the data. The information from the geometry file is linked to the rawdata during import to the processing module in Aarhus Workbench.

The geometry file contains of header part and settings block for each software channel, e.g. Super low moment (SLM) z-data, High moment (HM) z-data, Low moment z-noise etc. All values in the geometry file are in SI-units.

The line numbers in tables below refer to the geometry file example in Figure 1.

Header part of geometry file, line 1-14

Line num.	Type	Column	Comment
1	Char		Free text
2	integer		Geometry file version
3	integer		Number of channels in the geometry file
4	integer		Not in use
5	Real		Instrument factor, 1 for SkyTEM-data
6	integer		Number of device in the in the following device block (line 7-14)
7-14	Char	1	Device types. GP=GPS, HE=Laser altimeter, AN=inclinometer, RX=Receiver coil, TX=transmitter instrument
	Integer	2	Sub-device number
	Real	3-5	x,y,z, position of the devices. Coordinate system orientation see figure 2
	Real	6	Rotation of the device. Not in use

Channel part, line 15-82

Line num.	Type	Column	Comment
15	Char		Free text. Used as display text in the Aarhus Workbench
16	integer		Software channel number matching the software channel number for the SkyTEM data
17	Real	1-3	x,y,z center position of transmitter frame. (0, 0, 0) for SkyTEM-setup
18	Real	1-3	x,y,z center position of receiver coil. Orientation of coordinate system (z-position negative upwards)
19	Integer		Receiver polarization. 1=x, 2=>y, 3=z
20	Integer		Rx device number, see the Rx device in the header table.
21	Real		Approximate transmitter current. Must be within 25% of the actual current.
22	Integer		Transmitter loop type. 72=segmented loop (SkyTEM setup)
23	Integer	1	Number of segment for transmitter loop
	Real	2	Transmitter loop area. Area must match the area of the polygon formed in line 24-31
24-31	Real	1-2	x,y coordinates of the wire segments of the transmitter loop
32	Integer		Number of transmitter loop turns
33	Integer		Number of time gates defined in the time gate data-block line 57-82
34	Real		Gate time shift, constant [s]
35	Real		Shift db/dt fields by a constant [V/m2]

36	Real		Shift db/dt fields by factor
37	Integer	1	Default disable gates 1 to N during data-import. If 0 no gates are disabled
	Integer	2	Default disable gates N to last gate during data-import. If 0 no gates are disabled
38	Integer	2	Not in use
39	Integer		Not in use
40	Integer		Not in use
41	Integer	1-3	Order of 3 possible low pass filers before the front gate. 1=first order filer, 2=second order filer, -1=Off.
42	Real	1-3	Cut off frequencies for the 3 low pass filers. If some of the 2 possible filters are switch off in line 41 the value is not used. 3 numbers must be specified.
43	Integer	1	Use front gate. 1=yes, 0=no
	Real	2	Front gate time (0 at begin of ramp)
	Real	3	Primary field damping factor
44	Integer		Order of low pass filter after front gate. 1=first order filter, 2=second order filter -1=Off. If Use front gate in line 43 is off this value is not used.
45	Real		Cut off frequencies for low pass filers. If Use front gate in line 43 is off or the filter is set off in line 44, this value is not used.
46	Real	1	Repetition frequency calculated as $1/(4 \times \text{transmitter on time})$
	Integer	2	Not in use
47	Integer		Transmitter wave form type 1=exponential, 2=piecewise linear
48	Real		Exponential decay constant for ramp on
49	Real		Percent of the current for locating the first piece wise linear transmitter wave segment
50	Real		Percent of the current for locating the second piece wise linear transmitter wave segment
51	Real		The slope on avelance part of the turn off ramp. [Amp/sec]
52	Real		Current level when the avelance part of the turn off ramp ends.
53	Real		Exponential decay constant for exponential part of ramp off.
54	Real		Percent of the current for locating the first piecewise linear transmitter wave segment
55	Real		Percent of the current for locating the second piece wise linear transmitter wave segment
56	Real		Relativ uniform STD for db/dt-data (all gates). E.g. 0.03 = 3%
57-82	Real	1-3	Gate center time, Gate start time, Gate width. The number of gate must match the specifies number of gate in line 33
	Real	4	Shift db/dt fields by factor (single gates).
	Real	5	Relativ STD for db/dt-data (single gates). E.g. 0.03 = 3%
83-...			Similar settings for channel next channel

Example of SkyTEM Geometry file for Aarhus Workbench

```

1 SkyTEM Geometry file for Aarhus Workbench
2
3
4
5
6
7 GP 1 15.32 0.98 -0.24 0 !FileVersion number {int}
8 GP 2 15.32 1.02 -0.24 0 !NChannel, number of channels.
9 HE 1 8.15 9.90 -0.10 0 !Not in use
10 HE 2 8.15 -9.90 -0.10 0 !InstrumentFactor, 1 for SkyTEM
11 AN 1 -15.87 0.50 -0.36 0 !NDevice, number of device
12 AN 2 -15.87 -0.50 -0.36 0 !DeviceName, DeviceNumber, X, Y, Z, Rot
13 RX 1 -16.06 0.00 -2.13 0
14 TX 1 16.48 -0.34 0.00 0
15 Ch. #1 - Super Low Moment - z component
16 1 !Channel Number
17 0.0 0.0 0.0 !TxPos, Relative position of Transmitter, negative in the air [m] {float}
18 -16.06 0.0 -2.13 !RxPos, Relative position of Receiver [m] {float}
19 3 !Receiver polarization (1->x, 2->y, 3->z)
20 1 !Rx device number {integer}
21 11 !Current interval (A) {float}
22 72 !LoopType, 72=Segmented loop
23 8 494.4 !if Loop=72: NumberOfWires, LoopArea [m2] (>=2 or <=16,int){>0,float}
24 -15.34 -2.03 !if Loop=72: 1st wire begin and end points (x0,y0) -> (x1,y1)
25 -7.13 -10.26
26 7.13 -10.26
27 15.34 -2.03
28 15.34 2.03
29 7.13 10.26
30 -7.13 10.26
31 -15.34 2.03 !if Loop=72: 8th wire begin point. Connects back to 1st wire begin point(x,y)
32 1 !NTurns, Number of turns in loop
33 26 !NGates, Number of gates
34 -0.7e-06 !Shift times by a constant [s]
35 0.0 !Shift fields by a constant [V/m2]
36 0.92 ! Shift fields by factor
37 5 0 !Default remove gates 1..X and Y..NGate, 0=no gates are removed
38 0 0 !Not in use. Default remove ... for noise datasets,0=no gates are removed
39 0 !Not in use. Median filter, number of data to remove from Low end (>=0, int)
40 0 !Not in use. Median filter, number of data to remove from High end (>=0, int)
41 1 1 -1 !SlopFilters before front gate, -1=no filter (3 numbers)
42 450E+3 300E+03 1 !Filter cut off frequency [Hz] (3 numbers)
43 0 0.5e-6 0.01 !Use Frontgate (1=yes, 0=no),FrontGate time[s], Primary field damping factor
44 1 !Lowpass filter after front gate, -1 or UseFrontGate=0 means no filter
45 300.0E+3 !FrontGateFilter cut off frequency [Hz] (1 numbers)
46 250.0 1 !Repetition frequency [Hz] and RepFreqID [1..NChannel]
47 1 !WaveformType, 1 for exponential, 2 for picewise linear
48 31000 !if WaveformType=1, TOn: Exp. decay constant (time constant)
49 65.0 !if WaveformType=1, TOn: 1st ramp [%] (>=0 <100, float)
50 95.0 !if WaveformType=1, TOn: 2nd ramp [%] (>=0 <100, float)
51 4.08E+006 !if WaveformType=1, TOff: Turn off time [Amp/sec]
52 3.0 !if WaveformType=1, TOff: End avelance mode - [Amp]
53 1.27E+06 !if WaveformType=1, TOff: Exp. decay constant (time constant) (>0, float)
54 25.0 !if WaveformType=1, TOn: 2nd ramp [%] (>=0 <100, float)
55 1.5 !if WaveformType=1, TOn: 3rd ramp [%] (>=0 <100, float)
56 0.03 !MinUniformNoiseSTD, minimum uniform noise (>0, float)
57 1.195E-06 0.39E-06 1.61E-06 1.0 0.0! [Gatecenter, Start, Width, GateFactor, GateSTD]
58 3.195E-06 2.39E-06 1.61E-06 1.0 0.0
59 5.195E-06 4.39E-06 1.61E-06 1.0 0.0
60 7.195E-06 6.39E-06 1.61E-06 1.0 0.0
61 9.195E-06 8.39E-06 1.61E-06 1.0 0.0
62 11.195E-06 10.39E-06 1.61E-06 1.0 0.0
63 13.195E-06 12.39E-06 1.61E-06 1.0 0.0
64 15.195E-06 14.39E-06 1.61E-06 1.0 0.0
65 17.195E-06 16.39E-06 1.61E-06 1.0 0.0
66 20.195E-06 18.39E-06 3.61E-06 1.0 0.0
67 24.695E-06 22.39E-06 4.61E-06 1.0 0.0
68 30.695E-06 27.39E-06 6.61E-06 1.0 0.0
69 38.195E-06 34.39E-06 7.61E-06 1.0 0.0
70 47.195E-06 42.39E-06 9.61E-06 1.0 0.0
71 58.695E-06 52.39E-06 12.61E-06 1.0 0.0
72 73.195E-06 65.39E-06 15.61E-06 1.0 0.0
73 91.695E-06 81.39E-06 20.61E-06 1.0 0.0
74 115.195E-06 102.39E-06 25.61E-06 1.0 0.0
75 144.195E-06 128.39E-06 31.61E-06 1.0 0.0
76 181.195E-06 160.39E-06 41.61E-06 1.0 0.0
77 227.695E-06 202.39E-06 50.61E-06 1.0 0.0
78 285.695E-06 253.39E-06 64.61E-06 1.0 0.0
79 359.195E-06 318.39E-06 81.61E-06 1.0 0.0
80 451.695E-06 400.39E-06 102.61E-06 1.0 0.0
81 568.195E-06 503.39E-06 129.61E-06 1.0 0.0
82 714.695E-06 633.39E-06 162.61E-06 1.0 0.0
83 Ch. #2 - High Moment - z component
84 ..
85 ..
86 ..
87 Ch. #6 - High Moment Noise - z component
88 ..
89 ..
90 SkyTEM Geometry file for Aarhus Workbench

```

Figure 1. Geometry file example

Software channel definitions

Software channel ID	Moment ¹	Component	Signal/Noise
1	SLM	z	Signal
2	HM	z	Signal
3	SLM	x	Signal
4	HM	x	Signal
5	SLM	z	Noise
6	HM	z	Noise
7	SLM	x	Noise
8	HM	x	Noise

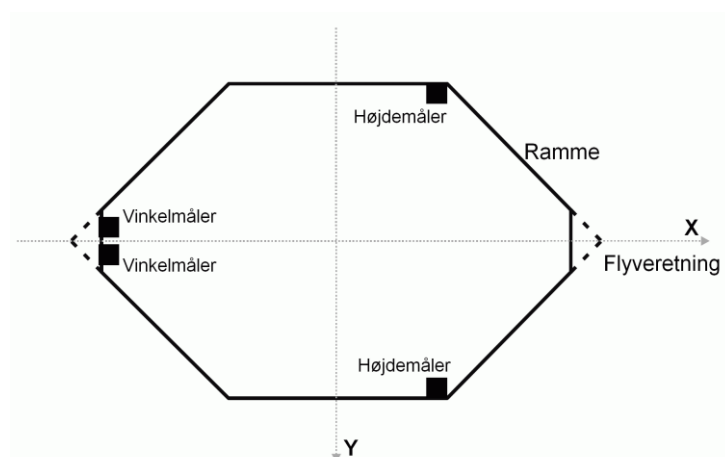


Figure 2. Sketch of the SkyTEM system. The x-axis is in the flight direction, the y-axis is towards the right while the z-axis is pointing into the paper

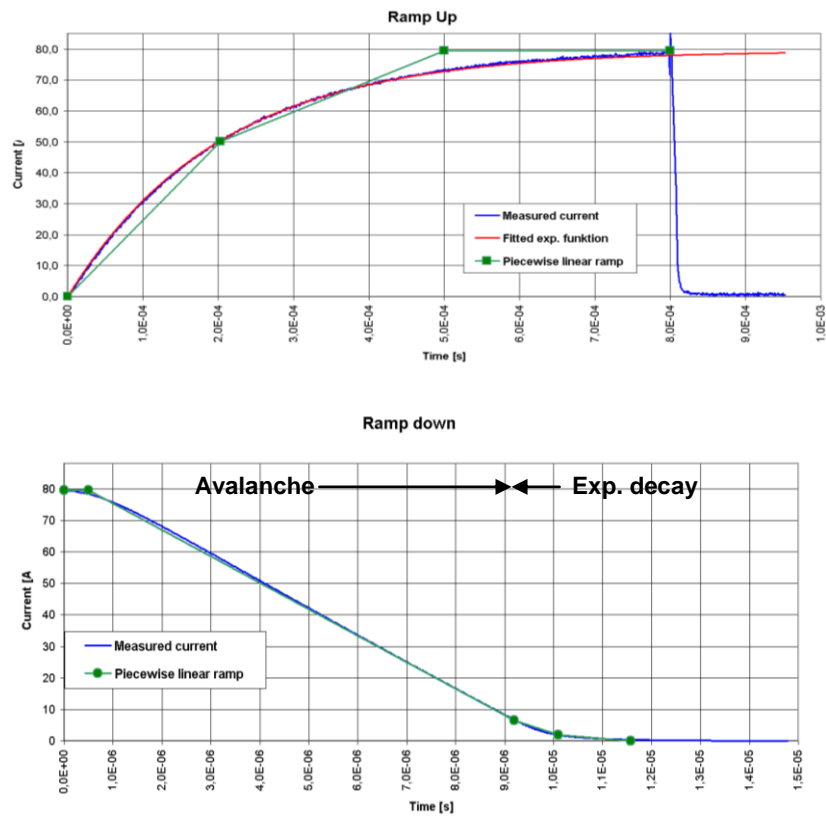


Figure 3 The figure shows the transmitter waveform and the modeling in the Aarhus Workbench. Top figure) Ramp up. The blue curve is the measured current. The red curve shows the fitted exponential function while the green curve shows the piecewise linear waveform modeled in the Aarhus Workbench. Lower figure) The figure shows the integrated turn off ramp, blue curve. The green curve shows the piecewise linear waveform modeled in the Aarhus Workbench.

APPENDIX 4 RECOMMENDED PROCESSING SETTINGS - AARHUS WORKBENCH

The following tables show recommended processing settings for the different data from the SkyTEM system

The settings must always be adjusted to the actual survey area, target geology, flight speed etc.

Settings for GPS data

GPS x- and y-positions are fitted stepwise to a polynomial of an order that can be specified in the processing phase. Furthermore the GPS-position can be shifted in the flight direction (x-direction) to position the data in the optimum lateral focus point for the actual SkyTEM-configuration. The lateral focus point for the SkyTEM-configuration is approximate 2/3 the distance from the frame center to Rx-coil position. This gives at negative shift of the GPS-data if the GPS-receivers are placed at nose of the frame (normal setup). The GPS-shift is based on calculations of the frame orientation from the GPS-positions. Hovering measurements result in a poor determination of the frame orientations, due to the uncertainty of the GPS-positions.

Parameters	Value	Comment
Device	All	Use one or all devices
Beat Time [s]	0.5	Sample rate for the time array which all navigation data are averaged into
Filter Length [s]	9	The length of the filter for each polynomial fit.
Polynomial Order	2	The order of the polynomial
Reposition in x-direction [m]	-20 / -26	Shift of the GPS-position in flight direction (x-direction). Working values for normal SkyTEM-setup: Small frame -20 m; Big frame: -26 m

Settings for Tilt data

Tilt data are filtered using a median filter to eliminate potential outliers. Tilt data are used to correct altitude and voltage data. Tilt data are measured as the deviation from normal in degrees in the x- and y-direction. It is presumed that the transmitter frame is rigid.

Parameters	Value	Comment
Device	All	Use one or all devices
Median Filter	ON	Turns the filter on and off
Median Filter Length [s]	3	Length of the filter
Average Filter Length [s]	2	Part of the data from Median Filter Length to use for in each step

Settings for Altitude data

The transmitter altitude is found using a number of lasers placed on the frame. The lasers measure the distance to the ground, but are also influenced by reflections from tree tops, bushes, etc., which results in a seemingly lower altitude. The main issue of altitude processing is therefore to remove reflections from the lasers. An automatic tilt correction is, however, also made. Furthermore, the final output is corrected for the fact that the lasers are not placed in the middle of the transmitter frame, while the position of the frame is defined as the center.

Filtering of altitude data is done using a two-step polynomial fit working separately on each device: Step one involves repeated cycles of fitting a polynomial to the data while continuously discarding outlying data, predominantly those of relatively low altitude. This results in an increasingly better data fit, where more and more undesired reflections are removed. The fit is done in steps where a certain amount of data is fitted at a time. Based on the fit, data are removed from a small portion of this interval after which the program

steps to the next time interval. The second step is a polynomial fit to the remaining data from pass 1, and data are sampled to Beat Time.

Parameters	Value	Comment
Device	All	Use one or all devices
Tilt Correction Threshold [s]	5	If no tilt data is found within this time span no tilt correction is made.
First Filter Poly Order	8	The order of the polynomial used in the first filtering of the altitude data
First Filter Number of Passes	8	Numbers of time (passes) the first polynomial fit is applied.
First Filter Shift Length [s]	6	Time interval that are used for evaluation (center par of Filter Length).
First Filter Length [s]	30	Time interval for each polynomial fit.
First Filter Lower Threshold [m]	1	Data that are below the polynomial minus the threshold value are discarded before the next pass. (reflections from tree tops etc.)
First Filter Upper Threshold [m]	30	Data that are about the polynomial plus the threshold value are discarded before the next pass. (incorrect readings from altimeter)
Second Filter Poly Order	8	Order of the polynomial used to fit the remaining data from the first filtering.
Second Filter Length [s]	30	Time interval for each polynomial fit.

Settings for Voltage data

In the table below recommended settings for the Voltage data Processor are listed. The settings most likely need to be adjusted to the current survey to result in an optimum processing of the data.

The time values given for the Trapez. Filters in the table match a flight speed of approximate 45 km/h (12.5m/s), and the values need to be adjusted if the flight speed differs significantly from this speed. The selected average widths (Trapez Width 1 2 3) are optimized based on the signal-to-noise ration for the survey area.

Note: For the Cap filters and the Ave filters, the assumed noise level, the min. and max. slope, and the back step value have much influence on the number of data that are automatically disabled.

Parameter	SLM/LM	HM	Comment
Noise Channel	OFF	OFF	Define if the Channel is a Noise channel or not.
Use 2nd order slope filters	ON	ON	ON: all Slope Filters will be based on the change in slope of the db/dt sounding curve ("2nd order derivate"). When set OFF all Slope Filters will be based on slope of the db/dt sounding curve.
Sounding Bin Spacing [s]	2	3	Not in use, but is included for compatibility reasons.
Current Time Distance	0.5	0.5	Not in use, but is included for compatibility reasons for old data.
Cap Sign Filter	ON	ON	Sign filters cull data if a sign change is found.
Cap Sign from time [s]	1.5e-5	1e-4	Data points before this time are not evaluated by the sign filter.
Cap Sign noise level (ms) [v/m2]	5e-7	2e-7	Defines the assumed noise level at 1 ms. Data points below noise function formed by the noise level and the noise slope are not evaluated.
Cap Sign noise slope	-0.5	-0.5	Defines the slope of the noise function
Cap Sign back step	30	30	Number of additional data points backwards to be removed from the data curve
Cap Slope Filter	ON	ON	Sets filter on/off. Slope filters cull data if the slope or the change in slope (2nd order slope ON) of the dB/dt sounding curve is not within specified min/max slopes interval

Parameter	SLM/ LM	HM	Comment
Cap Slope from time [s]	1.5e-5	1e-4	Data points before this value are not evaluated by the filter.
Cap Slope noise level (ms) [v/m2]	5e-7	2e-7	Defines the assumed noise level at 1 ms. Data points below noise function formed by the noise level and the noise slope are not evaluated.
Cap Slope noise slope	-0.5	-0.5	Defines the slope of the noise function
Cap Slope min slope	-0.6	-0.6	Defines the smallest acceptable 1st or 2 nd order derivate of the dB/dt sounding curve as selected with Use 2nd Order Slope filters
Cap Slope max slope	0.6	0.6	Defines the maximum acceptable 1st or 2 nd order derivate of the dB/dt sounding curve as selected with Use 2nd Order Slope filters.
Cap Slope back step	30	30	Number of additional data points backwards to be removed from the data curve.
Ave Sign Filter	ON	ON	Sets filter on/off. Sign filters cull data if a sign change is found..
Ave Sign from time [s]	1.5e-5	1e-4	Data points before this value are not evaluated by the filter.
Ave Sign back step	1	1	Number of additional data points backwards to be removed from the data curve.
Ave Slope Filter	ON	ON	Sets filter on/off. Slope filters cull data if the slope or the change in slope (2nd order slope ON) of the dB/dt sounding curve is not within specified min/max slopes interval
Ave Slope from time	1.5e-5	1e-4	Data points before this value are not evaluated by the filter.
Ave Slope min slope	-0.6	-0.6	Defines the smallest acceptable 1st or 2 nd order derivate of the dB/dt sounding curve as selected with Use 2nd Order Slope filters.
Ave Slope max slope	0.6	0.6	Defines the maximum acceptable 1st or 2 nd order derivate of the dB/dt sounding curve as selected with Use 2nd Order Slope filters.
Ave Slope back step	0	0	Number of additional data points backwards to be removed from the data curve
Trapez Filter	ON	ON	Always On, Off is included for compatibility reasons for very old data.
Trapez Sounding Distance [s]	2	2	Sets the distance in time between soundings.
Trapez Gate Time 1 [s]	1e-5	1e-4	Sets the time of Trapez Width 1
Trapez Gate Time 2 [s]	1e-4	1e-3	Sets the time of Trapez Width 2
Trapez Gate Time 3 [s]	1e-3	1e-2	Sets the time of Trapez Width 3
Trapez Width 1 [s]	3	6	Sets the width of the filter at Trapez Gate Time 1
Trapez Width 2 [s]	6	12	Sets the width of the filter at Trapez Gate Time 2
Trapez Width 3 [s]	12	36	Sets the width of the filter at Trapez Gate Time 3
Trapez Spike Factor	25	25	Median filtering of the data. E.g. Spike Factor = 20 removed the upper and lower 10% of the data with in the averring width for each gate
Trapez Min. No. Gates [%]	25	25	Minimum number of possible gates in the averaging interval that must be in use for an average sounding to be created.
Trapez Min. No Gates per Sound.	7	5	If less than Trapez Min. No. Gates per Sounding are in use after the filtering of the average data the sounding is removed.
Trapez Sync. location of sond.	ON	ON	Synchronize the location/time of the sounding from the different software channels.
Trapez Require left/right sound.	OFF	ON	If set to On raw data are required to both left and right side of the sounding time within the average interval for an average data point to be created. Off makes a more densely soundings/models sampling/averring possible without getting "holes" in the sounding array.

APPENDIX 5

RECOMMENDED INVERSION SETTINGS - AARHUS WORKBENCH

The following sets of tables states recommended LCI- and SCI-inversion settings. The settings must always be adjusted to the actual survey area, target geology, line spacing, etc. The horizontal constraints are stated for a sounding distance of 25-30 m.

LCI-INVERSION SETUP

LCI inversion settings, in general

Parameter	Value	Comment
Use soft channel inversion groups	1,2	software channel 1 (SLM) and 2 (HM) is inverted using one model
Altitude a-priori STD:	3	Defines the STD for the altitude in meters.
Altitude lateral constraint STD:	1.3	The lateral constraint on the altitude between two adjacent models.
A-priori altitude if not recorded [m]	50	Inversion start value for the altitude if no altitude is available
Max Number of Iterations	50	Maximum number of iterations before the inversion is stopped.

Setup of LCI 4-layer model

Parameter	Value
Resistivity [Ω m]	Auto scale or homogenous half space
Thickness [m]	20, 35, 65
Vertical constraints, resistivities	99 (not constrained)
Horizontal constraints, resistivities	1.3
Horizontal constraints, thicknesses	99 (not constrained)
Horizontal constraints, depths	1.35, 1.13, 1.06
Auto scaling, power	1
Max. Section length	250
Max. Distance before creating a new section [m]	300
Continuity between section boundaries	Force continuous: On

Setup of LCI 5-layer model

Parameter	Value
Resistivity [Ω m]	Auto scale or homogenous half space
Thickness [m]	15, 30, 50, 65
Vertical constraints, resistivities	99 (not constrained)
Horizontal constraints, resistivities	1.3
Horizontal constraints, thicknesses	99 (not constrained)
Horizontal constraints, depths	1.46, 1.16, 1.07, 1.04
Auto scaling, power	1
Max. Section length	250
Max. Distance before creating a new section [m]	300
Continuity between section boundaries	Force continuous: On

Setup of LCI-smooth model

Parameter	Value
Resistivity [Ωm]	Auto scale or homogenous half space
Number of layers	19 (maximum number)
Thickness first layer [m] ¹	4 m followed by logarithmic increasing thicknesses
Thickness A-priori constraint ²	1.001 (fixed), last layer 1.5
Vertical constraints, resistivities	2
Horizontal constraints, resistivities	1.3
Horizontal constraints, thicknesses ²	99 (not constrained)
Horizontal constraints, depths	99 (not constrained), last layer 1.05
Auto scaling, power	1
Max. Section length	100
Max. Distance before creating a new section [m]	300
Continuity between section boundaries	Force continuous: On

¹Last layer boundary is chosen so it covers the expected depth of investigation.

²Last thickness has a a-priori constraint of 1.5 and a horizontal constraint on the last depth of 1.05

SCI-INVERSION SETUP

Note: For SCI-setup the start model can be customized in subareas. The lateral constraints are in general set looser in a SCI-setup compare to a LCI-setup, since a SCI-setup in total holds more constraints - this is reflected in the tables below.

SCI inversion settings, in general

Parameter	Value	Comment
Altitude a-priori STD:	3	Defines the STD for the altitude in meters.
Altitude lateral constraint STD:	1.3	The lateral constraint on the altitude between two adjacent models.
A-priori altitude if not recorded [m]	50	Inversion start value for the altitude if no altitude is available
Max Number of Iterations	50	Maximum number of iterations before the inversion is stopped.

Setup of SCI 4-layer model

Parameter	Value
SCI-section size aprox.	240
SCI-section size min	170
Resistivity [Ωm]	Auto scale or homogenous half space
Thickness [m]	20, 35, 65
Vertical constraints, resistivities	99 (not constrained)
Horizontal constraints, resistivities	1.5
Horizontal constraints, thicknesses	99 (not constrained)
Horizontal constraints, depths	1.5, 1.2, 1.08
Auto scaling, power	0.75

Setup of SCI 5-layer model

Parameter	Value
SCI-section size aprox.	240
SCI-section size min	170
Resistivity [Ωm]	Auto scale or homogenous half space
Thickness [m]	15, 30, 50, 65
Vertical constraints, resistivities	99 (not constrained)
Horizontal constraints, resistivities	1.5
Horizontal constraints, thicknesses	99 (not constrained)
Horizontal constraints, depths	1.7, 1.2, 1.11, 1.06
Auto scaling, power	0.75

Setup of SCI-smooth model

Parameter	Value
SCI-section size aprox.	100
SCI-section size min	70
Resistivity [Ωm]	Auto scale or homogenous half space
Number of layers	19 (maximum number)
Thickness first layer [m] ¹	4 m followed by logarithmic increasing thicknesses
Thickness A-priori constraint ²	1.001 (fixed)
Vertical constraints, resistivities	2
Horizontal constraints, resistivities	1.5
Horizontal constraints, thicknesses ²	99 (not constrained)
Horizontal constraints, depths	99 (not constrained)
Auto scaling, power	0.75

¹Last layer boundary is chosen so it covers the expected depth of investigation.

APPENDIX 6

CALLIBRETION OF THE SKYTEM-SYSTEM

This Appendix will bee added later

Calibration at the Test Site

Local reference measurements

Waveform calibrations

APPENDIX 7 RECOMMENDED PRESENTATIONS

This appendix gives an overview of the basic maps and sections to be delivered together with the report for a SkyTEM survey.

All maps must be in Euref zone 32 (33) UTM coordinate system. Information about gridding method, search criteria for geological layers etc. is given in the report or in the map legends. Kriging is normally the preferred gridding method. Refer to 1 for general information about presentation of TEM-inversion results.

The basic maps are divided into three groups: Survey location, data, and inversion results. Specifications for the different theme maps are listed in the tables. All theme maps are composed with basic background maps e.g. KMS-map, air photos.

The tables below distinguish between digital maps (D) and printed maps on paper (A). Digital maps are delivered in the Aarhus Workbench survey workspace. Printed maps are printed on paper appearing in the report. They are also delivered in pdf format and present in the Aarhus Workbench Workspace. The themes can be either by color coded points (P) or gridded bitmaps images (G).

For some surveys it can be optimal to produce other/more theme maps.

Survey location

Theme	Digital/Paper	Point/Grid
Planned survey area and planned flight lines.	D	
Planned survey area, actual flight lines with overlay of coupling sources (roads, power lines etc.), landing location and local test site.	A	

Data

Theme	Digital/ Paper	Point/Grid
Flight altitude	A	P
Flight speed	D	P
Raw data positions overlaid by model positions (non-coupled data). This map shows where data have been excluded during the processing.	A	P
Presence of moments – with a two-moment system, the color code is: Both SLM and HM (green), SLM only (red) , HM only (blue).	A	P
Number of gates for each moment. One map per moment.	D	P

Inversion results

The maps are created for each inversion (one set of maps for smooth inversion, one set for the few-layer inversion).

Themes	Digital/ Paper	Point/Grid
Data residual.	A	P
Difference in measured and inverted altitude.	D	P

Inversion results – few-layer models

The following maps are delivered for few-layer models.

Note: Resistivity maps must be gridded on the logarithm to the resistivity.

Themes	Digital/ Paper	Point/Grid
Horizontal mean resistivity maps in 10 m elevation intervals.	D	G
Horizontal mean resistivity maps in depth intervals. 5 m intervals down to 20 m. 10 m intervals from 20 m to 50 m.	D	G
Elevation of the conductive subsurface (if present). The conductivity of the layer must be determined from histograms of the resistivity distribution in the deeper layers.	A	G
Resistivity of first layer	A	G
Thickness of first layer	D	G
Depth of investigation (DOI).	D	G

Inversion results – smooth-layer models

The following maps are delivered for smooth-layer models.

Note: Resistivity maps must be gridded on the logarithm to the resistivity.

Themes	Digital/ Paper	Point/Grid
Horizontal mean resistivity maps in 10 m elevation intervals.	A	G
Horizontal mean resistivity maps in depth intervals. 5 m intervals down to 20 m. 10 m intervals from 20 m to 50 m.	A	G
Depth of investigation (DOI).	A	G

Sections

Sections are typically created along flight lines. A number of sections illustrating central geological elements are selected. Typically, 10-20 sections are printed, and additional sections are present in the Work-space. The sections contain: resistivity models, boreholes, and DOI. There is a set for both smooth and layered models. Same scale and orientation are used for all sections.

Themes	Digital/ Paper	Point/Grid
Location of profiles inc. model and boreholes positions.	A	P
Sections for smooth and layer inversion results including boreholes and DOI.	A	