Guideline and standards for tTEM data collection, processing, and inversion

Version 1.1 - November 2020





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Version 1.1, November 2020

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Appendix 1 Documentation of the GEX file



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

ACIONYING	
Acronyms	
AEM	Airborne ElectroMagnetics
ATV	All-Terrain Vehicle (quad bike)
DOI	Depth of Investigation
EM-methods	Electromagnetic methods which induce electrical currents in the ground through the principle of electromagnetic induction
GFS	GeoFysikSamarbejdet, collaboration between The Danish Environmental Protec- tion Agency and the Department of Geoscience, Aarhus University
HGG	The HydroGeophysics Group at the Department of Geoscience, Aarhus University
LCI	Laterally Constrained Inversion
SCI	Spatially Constrained Inversion
TEM	Transient Electromagnetic
tTEM	Towed TEM
UTC	Coordinated Universal Time
QC	Quality Control

Acronyms



1 REVISION HISTORY

The latest version of this guide is available on the web page of the HydroGeophysics Group: <u>www.hgg.au.dk</u>

Version 1.0 - September 2020

This is the first version of the *Guideline and standards for tTEM data collection, processing, and inversion*. This version of the guide reflects the present stage of the tTEM-system, the processing software, and the inversion algorithms. (August 2020).

The tTEM guideline report version 1.0 was reviewed by *Miljøstyrelsen* (The Danish Environmental Protection Agency) prior to release.

Version 1.1 – November 2020

Minor edits in section 4.1 and 4.2 regarding temperature variations in the tTEM transmitter unit.



Figure 1. The tTEM system in action.



2 INTRODUCTION

The tTEM system is a compact, highly efficient, towed TEM-system, designed for detailed 3D geophysical mapping of the shallow subsurface, approximate 0-80 m. The purpose of this guide is to ensure uniform and high quality standards for the tTEM data collection, the data processing and inversion, and the survey reporting, but this guide also serves as a description of the workflow as well as documentation for the data formats of the tTEM system.

The standards presented here are aligned to standards and requirements set to other geophysical data collected for hydrogeological mapping in Denmark. In general, despite the *Danish context* of this guide, the guide provides a review of the different steps in a tTEM mapping campaign in regard to workflow, quality control, data processing, and inversion.

The following describes the three roles in a tTEM survey:

- **Instrument Owner**: The company/institution that owns the tTEM instrumentation and rents it out for tTEM surveys.
- **Contractor**: The person(s)/company that performs the data collection (operates the tTEM system) and performs the data processing/inversion and reporting to the Client. Typically, a consultant company.
- **Client**: The company/institution that ordered the tTEM survey and receives the survey reporting and the mapping results, e.g. The Danish Environmental Protection Agency or a water plant.

Requirements in this guide will be referenced to one of the three defined roles. In this guide it is assumed that data collection, processing, and inversion is carried out by the same contractor and that required documentation of the different steps is incorporated in a survey report to the client.

In case the requirements cannot be met, the reasons for this must be stated clearly in the final report and, where relevant, the involved parties must be informed in time. It is required that the contractor and client have open and frequent dialogues about important irregularities or issues during mapping and data processing.

The guide provides a number of typical/recommended processing and inversion settings. The typical/recommended processing and inversion settings are not requirements, and the settings must be adjusted to the specific survey/target.

It is assumed and recommended that data processing and inversion is conducted with the Aarhus Workbench software, since Aarhus Workbench holds modules specific designed for tTEM data processing, inversion, and



data upload to the Danish National geophysical database. Thus, this guide holds direct references to specific Aarhus Workbench processing and inversion settings. Also, general experience and knowledge of TEM data collection, processing, and inversion is assumed. Thus, this guide is not a training guide or an operation manual for the tTEM instrument and data processing.

The tTEM system also comes in a FloaTEM version, operated on water. Section 8 holds details and additional requirements for the FloaTEM system.

The *Notes* provided in the sections are primarily guides/hints to specific settings or steps in the workflow.

References for this guide are grouped under the different topics in the reference section (9), with no direct references in the text.



3 THE TTEM-SYSTEM, DATA COLLECTION, AND DATA FORMATS

In the following sections we present the tTEM system, provide recommendations regarding survey planning and data collection, and provide documentation of the different tTEM data formats.

3.1 THE TTEM-SYSTEM

The tTEM-system is a towed, ground-based, transient electromagnetic system, designed for highly efficient data collection and detailed 3D-mapping of the shallow subsurface (the upper ~80 m). The present layout of the tTEM system is shown in Figure 1 and Figure 2. The main development of the tTEM-system was conducted in 2016-2018, building on the high expertise and experience within the HGG-group regarding all aspects of the TEM-method: from instrument design, testing and calibration, to data surveying, processing, and inversion of EM-data.

The tTEM-system (Figure 2) consists of an ATV carrying the instrumentation and towing the transmitter frame (Tx coil) and the receiver coil (Rx coil) in an offset configuration. The Tx and Rx coils are mounted on sleds for a smooth ride over rough fields/terrain. The frame and sleds are built of non-electrically conductive fiberglass and composite materials and are assembled with 3D printed, carbon-strengthened, parts.



Figure 2. Schematic layout out of the tTEM system (2020).

The operational speed of the tTEM system is up to 20 km/h and depending on terrain and surface conditions the actual speed will vary accordingly. When surveying on farmland, the service tracks in the fields are used as driving guides to minimize crop impact. The production rate strongly deepens on: Line density, condition of the fields, field sizes, and accessibility/connectivity of the fields. The production rate, therefore typically spans from 50-250 hectares/day (0.5-2 km²/day).



Navigation and data collection are monitored and controlled by the driver using a tablet PC. The navigation software (Aarhus Navigator) provides a real time display of the survey path, line numbers, status parameters, and various alarms from the instrumentation. Pre-planned survey lines and GIS maps can be loaded into the navigation system. The geographical position of the data is recorded by one SBAS (Satellite Based Augmentation System) GPS placed on the Tx-frame. In the later data processing, the GPS data are lagcorrected to position the data/resistivity model at the midpoint between the transmitter and receiver loops.

The tTEM system is operated by one person, but a second person is required for mobilization/demobilization, on-site survey planning, data quality control, and field safety. Mobilization as well as demobilization is quite fast and takes approximately 20 min. Transportation wise, the $2 \times 4 \text{ m}^2$ frame fits on a long car trailer. Placing the ATV in the back of the van makes transportation a single car job. Additionally, the system can be disassembled and palletized for longer transportation and shipment.



Figure 3. The tTEM system packed on the transport trailer. The ATV and all instrumentation fit inside the van.



3.2 SURVEY PLANNING AND NAVIGATION

A tTEM survey requires ground access, and the ground surface needs to be drivable for the ATV towing the tTEM system. Most often, there will be subareas in the survey region that cannot be mapped due to lack of access permission or non-drivable ground. This could be wet meadow areas, forest areas or farmland with (too much) livestock. Even if a dense mapping cannot be obtained in some subareas, it will, most often, be beneficial to have a few scattered lines in these areas e.g. obtained by driving on small pathways in forest areas or similar.

It is preferable that a survey is carried out in one continuous campaign, since seasonal variations in the resistivity of the shallow layers cannot be ruled out.

Line spacing and resolution

The footprint of the tTEM system is quite small in the top ~20 meters compared to other TEM systems, and it is recommended to aim for a general line spacing of maximum 25 m. A line spacing of less than 10 m will not increase the resolution due to the footprint size. Depending on the target and purposes of the mapping, the line spacing must be set accordingly.

Before the survey, client and contractor agree on a target line spacing, and since the distance between the service tracks in some cases dictates the line spacing, moderate deviations from the target line spacing must be expected.

Survey layout

In the tTEM navigation program, Aarhus Navigator, you can upload pre-prepared driving routes, with the desired line spacing to follow during the data collection. This approach is mainly useful if you have open land where you are free to drive anywhere.

When mapping in farmland areas, the normal approach is to map the survey area field by field and it is good practice (sometimes a demand from the farmer) to use the service tracks in the fields. In this case the line spacing is limited to the distance between service tracks or multiples thereof. Figure 4 shows an example of mapping in a farmland area.





Figure 4. Example of tTEM data mapping in farmland. Red + black dots marks the mapping lines. Black dots mark data rejected during data processing.

If service tracks are not available it is most convenient to use the plowing structure of the field as direction guidance, and the line spacing guide circle (see Figure 5) in the navigation program to obtain a constant line spacing.



Figure 5. Screen capture from the tTEM navigator program. The radius of the yellow circle can be set to the desired line spacing.



Driving speed

The driving speed should be kept fairly constant. An uneven driving speed will result in an uneven spacing of the resistivity models along the lines, since data are stacked in equidistant time intervals. The normal target speed is 20 km/h for the tTEM system, and one should not exceed a driving speed of 25 km/h for safety reasons and to limit vibration noise. In noisy areas (highly resistive areas), it can be beneficial to lower the speed to increase the data stack, especially if the focus is on deep mapping. On rough terrain, the speed should be adjusted accordingly to minimize vibrational noise and to ensure instrumentation/driving safety. In case of rough terrain, on small forest trails etc. the mapping speed will often be reduced to 5-10 km/h. Reducing the speed might also be needed in forest areas to obtain a good GPS-signal.

Line shift - start/end line procedure

It is important that the rope between the transmitter coil and the receiver coil is fully extended, as a constant distance between transmitter and receiver coil is assumed in the modeling of the data. Furthermore, the ATV will cause distortion in the data if it is too close to the transmitter/receiver coils. At U-turns (when shifting lines) the system operator must give an '*End Line*' indication in the navigation program (see Figure 5) when the turning starts. It is equally important that the '*Production*' (start line) indication for the next line is not given before the towing rope is fully stretched and the transmitter and the receiver are aligned. Data between an '*End Line*' and the next '*Production*' indication are automatically removed in the later data processing. Missed *End line*/*Production* marks can normally, be corrected manually in the later processing, since data are recorded/saved no matter which *Production/End of line* state the instrument is set for. If a stop on a line is needed, the operator must give an *End line* mark.

With a total system length of ~15 m, some data loss at the beginning and end of the fields/lines is unavoidable. Furthermore, when operating in service tracks the line turning will normally start 10-15 m before the end of the field where the farmer also makes turns with his farm machinery. A skilled U-turning technique, by overshooting the turn slightly, will result in a quicker alignment of the system and less data loss when turning.

In general, it is preferable to drive in straight lines. Smooth changes in driving direction can be conducted without initiating the described end/begin line procedure, and it is acceptable that the receiver coil slides ~1 meter from side to side while driving.

Measurement script

The measurement script controls the repetition frequency, the low moment/high moment (LM/HM) cycle, key data normalization factors, etc. The



measurement script must be designed to stack out the power line frequency noise (50/60 Hz).

Note:

• Noise measurements (transmitter off) are normally not included in the measurement scripts.

Change of system components might require adjustment in the measurement script.

3.3 DATA FORMATS

This section describes the output files from the instrument and additional setup files required to perform the data processing in Aarhus Workbench. This section also serves as documentation for the different file formats, thus a high level of detail in this section.

Instrument output files:

- Line number file
- Rwb file
- SPS files (two types)

Instrument modeling and setup files

- System geometry file
- Filter file

Line number file (*.lin)

The line number file holds the production time intervals associated with a line number, a line type, start/end UTM position of each line, and an optional comment. Only data within the specified time intervals in the line number files are imported in the processing software. The Line number file is created during data acquisition, based on the system operator's begin/end line indications as described in section 3.2. Figure 6 holds an example of a part of a line file.



Date	Time	Line	UtmX	UtmY	DataFolder	Comment	
27-03-2020	10:53:31	20000	503789.31	6283318.81	!Run1 "	TestPoint,	start"
27-03-2020	10:53:47	20000	503789.32	6283318.81	!Run1 "	TestPoint,	end"
27-03-2020	11:09:20	100	503820.19	6283310.34	!Run3 "1	Production,	start"
27-03-2020	11:10:06	100	503959.47	6283324.15	!Run3 "1	Production,	end"
27-03-2020	11:10:40	110	503940.05	6283274.35	!Run3 "1	Production,	start"
27-03-2020	11:12:02	110	503790.80	6283247.99	!Run3 "1	Production,	end"
27-03-2020	11:17:44	120	503818.06	6283239.65	!Run3 "1	Production,	start"
27-03-2020	11:18:39	120	503957.89	6283253.10	!Run3 "1	Production,	end"
27-03-2020	11:21:44	130	503957.85	6283253.12	!Run3 "1	Production,	start"
27-03-2020	11:22:46	130	503957.83	6283253.13	!Run3 "1	Production,	end"
27-03-2020	11:23:26	140	503957.82	6283253.14	!Run3 "1	Production,	start"
27-03-2020	11:26:09	140	503792.35	6283204.59	!Run3 "1	Production,	end"

Figure 6 Line file example. Blue header text is not part of the file.

Each tTEM-line is defined by two text lines (start and end) in the file. The line number increment is +10 starting from line number 100, hence the order of the line numbers reflects the data recording order. The operator can set the line number manually in the field at the start of each line or make corrections directly in the line file post survey. A more geographically based ordering of the line number naming is preferable, but at present, no automatic line file un-scrambler routine/software exists.

The automatically generated comments indicate if data are *Testpoints* or *Production*. The *Testpoints/Production* stage is set by the operator during the data collection and serves only as a bookkeeping tool; no automatic filtering with respect to the *Testpoints/Production* comment is performed in the later data processing.

RWB files (*.RWB)

The RWB-file is the tTEM-instrument output file containing the TEM data (the db/dt responses) in a binary format. The RWB-file holds an Ascii header, which is an exact duplicate of the system configuration, holding information about measuring scheme, amplification, gating, etc. (copy of script.idx, script.ini). Under no circumstances should changes be made to the ascii header of the RWB-files, since these settings represent how data *were* recorded.

The RWB-file names are date-time tagged (UTC time) and a new RWB-file is created when the data recording program (PaPC) is started and at any instrument re-starts.

Aarhus Workbench is compatible with the RWB-file format.

GPS-file (*NavTTem.sps)

The NavTTem sps-files hold the GPS-data. Figure 7 shows four GPS-lines from a NavTTem.sps files. Only lines starting with G12 in the file are used.



1	2	3	4	5	6	7	8	9	9A	9в	10
G12	2020	06	10	08	57	04	655	\$GPGGA,0	85705.20,5627.	3624751,N,00940.	.6469218, E, 2, 18, 0.6, 9.087, M, 39.291, M, , *66; \$GPVTG, 0.00, T, , , 0.01, N, 0.03, K, D*77;
G12	2020	06	10	08	57	04	858	\$GPGGA,0	85705.40,5627.	3624748, N, 00940.	.6469230, E, 2, 18, 0.6, 9.077, M, 39.291, M,, *6D; \$GPVTG, 0.00, T,,, 0.02, N, 0.03, K, D*74;
G12	2020	06	10	08	57	05	061	\$GPGGA,0	85705.60,5627.	3624747,N,00940.	.6469232,E,2,18,0.6,9.073,M,39.291,M,,*66;\$GPVTG,0.00,T,,,0.02,N,0.03,K,D*74;
G12	2020	06	10	08	57	05	249	\$GPGGA,0	85705.80,5627.	3624758, N, 00940.	.6469167,E,2,18,0.6,9.075,M,39.291,M,,*63;\$GPVTG,0.00,T,,,0.03,N,0.06,K,D*70;

Figure 7 NavTTem sps-files example. Blue header text is not part of the file. See Table 1 for explanation.

The explanation of the G12 line is given in the table below.

Colum	GPS-devise
1	GPS sting type: G12
2-8	UTC, [yyyy mm dd hh mm ss zzz]
9	Standard \$GPGGA string. <u>http://aprs.gids.nl/nmea/#gga</u> for detailed info.
9AB	Latitude and longitude coordinates in Degrees Minutes DecimalMinutes [degmm.mm]. EX: 5640.0122390 = 56° 40.0122390 minutes
10	Standard \$GPVTG string. <u>http://aprs.gids.nl/nmea/#vtg</u> for detailed info.

Table 1 Explanation of the columns of the NavTTem sps-files in Figure 7.

The GPS data is an essential part of the tTEM-data set, and GPS dropouts of more than ~4 s will result in data loss in the later processing.

TX-current (*_PaPc.sps)

The transmitter current is measured for each transient and stored for each HM and LM data sequence in the PaPC.sps file. The PaPC.sps also holds a number of transmitter status/QC parameters like temperature and battery voltage.

Figure 8 shows eight lines of a PaPC.sps file with the parameter explanation in Table 2. Note is it only the *Mean current* (column 20, see Table 2), that is used in the data processing for data normalization.



1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	
TXD	2020	04	01	07	56	09	900	422	2 0	0	211	211	0.01	0.01	33.86	0	1	422	5.27	0.00	0.00	0.00	
TXD	2020	04	01	07	56	09	900	252	2 0	0	126	126	0.01	0.01	34.53	0	1	252	30.27	7 0.00	0.00	0.00	
TXD	2020	04	01	07	56	10	500	422	2 0	0	211	211	0.01	0.01	34.05	0	1	422	5.27	0.00	0.00	0.00	
TXD	2020	04	01	07	56	10	500	252	2 0	0	126	126	0.01	0.01	33.56	0	1	252	29.85	5 0.00	0.00	0.00	
TXD	2020	04	01	07	56	11	100	422	2 0	0	211	211	0.01	0.01	33.19	0	1	422	5.27	0.00	0.00	0.00	
TXD	2020	04	01	07	56	11	100	252	2 0	0	126	126	0.01	0.01	34.23	0	1	252	29.98	3 0.00	0.00	0.00	
TXD	2020	04	01	07	56	11	700	422	2 0	0	211	211	0.01	0.01	33.74	0	1	422	5.27	0.00	0.00	0.00	
TXD	2020	04	01	07	56	11	700	252	2 0	0	126	126	0.01	0.01	32.82	0	1	252	30.02	2 0.00	0.00	0.00	

Figure 8. Part of PaPC.sps file. Blue header text is not part of the file. See Table 1 for explanation.

Row	Transmitter, TXD-devise
1	Device type [TXD]
1-8	UCT-PC-time, [yyyy mm dd hh mm ss zzz]
9	NumberOfShots: The total number of LM or HM transients
10	NumberOErrors: Indicates a missing pulse detection. The integer states the num- ber 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].
21	Max_Current: Not in use
22	Min_Current: Not in use
23	RMS_Current: Not in use

Table 2. Explanation of the columns of the PaPC sps-files in Figure 8.



The system geometry file (GEX-file)

The GEX-file contains essential information about the specific tTEM system/configuration, which is required in the data processing and inversion in Aarhus Workbench. Below the main content of the GEX-file is listed, while appendix 1 provides a complete documentation of the GEX-file.

The geometry file contains information about:

- The x,y position of the devices and transmitter/receiver coils as shown in Figure 9. The x,y origin is defined at the center of the transmitter coil. The z-axis is zero ground level and positive downwards. This results in the z-coordinates in the GEX-file being negative for coils and devices.
- The nominal transmitter current.
- The size and area of the transmitter coil and number of turns.
- Calibration constants in the form of time shift and db/dt factors
- Specification of the first usable gates of each channel
- Low-pass filters
- The front gates time. The front gate must occur a minimum of 1 μ s before the first usable gate opens.
- Parameters describing the transmitter waveform (the turn-off time before the front gate time).
- A uniform data uncertainty. As standard, 3% is used.
- Gate center times, gate factors, and gate opening and closing times.

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



Figure 9. tTEM configuration, coordinate orientation.



The filter file (*.TFI)

During import, the data is convolved with a filter that removes 50/60 Hz noise and DC offset and reduces the vibration noise. The filter also includes a lowpass filter. A filter for both LM and HM is stated in the filter file (see example in Figure 10). The Instrument owner provides the filter file.

```
[FilterSwCh1] /LM
Periodtime = 4.740e-04 /Period time
Filter = 4.79644195210675e-5 3.66167329277456e-5 -5.20872599689183e-5 ... /Filter coefficients
[FilterSwCh2] /HM
Periodtime = 1.587e-03 /Period time
Filter = -5.73009583716962e-6 2.13149258960294e-5 1.30906210105234e-4 ... /Filter coefficients
```

Figure 10. Filter file example. Normally the filter holds 50 filter coefficients. Text in blue is not part of the filter file.



4 INSTRUMENT VALIDATION/CALIBRATION

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

In the tTEM design phase, the system geometry, the position of the instrumentation and devices, the cabling and rigging, etc. were carefully designed and tested to ensure an acceptable system noise/bias level. Therefore re-rigging, changing of the cabling, or the positioning of the instrumentation/devices etc. of the tTEM-system should not be carried out without expert knowledge and potential re-testing/calibration.

Results of some of the general system validation tests and a comprehensive validation from the national TEM test site are found in the reference list listed under *TEM-test site calibration and validation*.

4.1 PRE-SURVEY CALIBRATION/VALIDATION

TEM test-site calibration

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

The general test site calibration procedure is descried in *Foged et.al*, 2013. The following guidelines are set for the tTEM calibration, calibration frequency, etc.:

- The tTEM system must be configured as in production mode for the calibration measurement.
- The tTEM receiver coil is positioned in the center of the TEM test site with the transmitter south of the receiver coil.
- Calculation of the tTEM specific reference response from the reference model must be with the exact same system parameters (the GEXfile settings) that are to be used in the later modeling of the data, except for the calibration parameters to be obtained.
- After calibration, the measured tTEM response must match the reference response within 5% (late time apparent resistivity data transformation) for low noise time gates.
- The obtained calibration parameters are valid for a specific transmitter instrument using a specific receiver coil type.
- Documentation of the calibration is provided in the form of plots showing the match between the reference response and the measured data.



- Instrument calibration based on test site measurements must be performed in the period between fourteen days before/after the survey period.
- For multi day surveys instrument stability is documented by:
 - Test site measurements/calibration before and after the survey, resulting in consistent calibrations parameters.

and/or

- By obtaining consistent data responses from repeating measurements at a local site inside the mapping area.
- For single day surveys the initial calibration at the test site is sufficient.
- In connection with instrument reconfiguration/adaptation a new test site calibration is required.

Transmitter Waveform

The transmitter waveform describes how the current ramps up and down in the transmitter coil and needs to be known in detail for precise modeling of the data. The tTEM system facilitates an accurate temperature and current regulation, which results in a constant transmitter waveform within the needed modeling precision. The tTEM transmitter waveform can therefore be measured once in detail for a given tTEM system.

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

Guidelines for the waveform measurement:

- The system must be configured as in production mode, though the ATV and the receiver coil can be omitted.
- Separated waveform measurements for turn-on and a turn-off part, and the LM and HM are performed.
- The measured waveforms are approximated with a number of linear segments to be used for the data modeling.
- The resulting waveforms, stated in the GEX-file, must include both a negative and a positive waveform, separated with the correct period of time and normalized to a peak amplitude of -1, 1.
- The determination of the waveform is documented with plots of the measured waveforms and the segmented waveforms used in the GEX-file.



• The measured waveform is specific for a given tTEM transmitter instrument, output current, and transmitter loop.

ATV distance test

The tTEM frame and sleds are built of non-conductive components to avoid coupling and bias signals. The ATV with the instrumentation is therefore placed ~3 m away from the front of the transmitter frame to minimize interference. The tTEM system has been operating with different ATVs and no issues with the 3 m ATV distance has been observed for any of the different brands of ATVs. If other types of pulling vehicles than an ATV is used, or by any doubt of possible interference from the ATV, we recommend that the *ATV test* described below is conducted. The *ATV test* should be conducted where the earth signal is low (resistive ground) since minor ATV interference is only detectible in this case.

ATV test procedure:

- 1. Set up the system as normal, but place the instruments, in the normal layout, on the ground or on plastic boxes at the end of the towing rope, instead of on the back of the ATV.
- 2. Important: Make sure that the transmitter and receiver cables are separated by a minimum of ~40 cm as when the instruments are mounted on the ATV.
- 3. Move the ATV far away (>30 m) and record one minute of data. Make a note of the line number/time interval. This is the *Baseline response*.
- 4. Move the ATV as close to the front of the transmitter frame as possible (*0 m separation*). Change the line number and record for one minute in this position with the ATV engine on.
- 5. Move the ATV in steps of ~1 m away from the transmitter front towards the instrument boxes and record one minute of data at each ATV location and note line number, time, ATV separation at each position. Continue this procedure until the ATV is ~5 m away from the transmitter front. Remember to make a measurement at the normal ATV position.
- 6. End the sequence as stated with the ATV far away.
- 7. Import the data to Aarhus Workbench. Set the stack width to 40 s and turn off filters that eliminate data.
- 8. Plot the stacked data curve (AVE data) at the center time of the time interval for each ATV distance and compare them with the base line measurements.
- 9. You should observe that when the ATV is close to the frame the curve is disturbed, compared to the base line response.
- 10. If no systematic dissimilarities between the response at the normal ATV distance (and longer distances) and the base line response are



observed, the ATV - TX-coil distance is sufficient for the specific ATV. You can evaluate the natural fluctuations of the TEM response by comparing the start and end baseline responses. Do not shorten the ATV-transmitter frame distance even if your test results show it is possible.

4.2 DAILY INSTRUMENT/DATA VALIDATION

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

System geometry

The system geometry: TX-RX distance and TX and RX heights above the surface are used in the later modeling of the data and are therefore needed. The skids on the sleds are gradually worn down, changing the height of the TX and RX coils. Also, the TX-Rx distance may change over time, especially if the towing ropes are repaired or replaced. It is therefore important to check the system geometry regularly, at least at the start and end of a survey, and when the towing ropes or skids are replaced or repaired.

The RX-TX distance and the RX and TX heights stated in the GEX-file must be within +/- 2 cm of the actual geometry. If this is not possible throughout the survey, the dataset must be split up and assigned different geometry/GEX-files accordingly. Minor variation of the distance to the ATV is of no importance.

The geometry measurements are carried out with the system standing on a smooth horizontal surface. The coil heights are measured from the ground to the vertical center of the coil. The RX-TX distance is the horizontal center-to-center distance of the coils. It is most accurate to measure the RX-TX distance from the back edge of the transmitter coil to the front edge of the receiver coil and then add half the coil widths to get the center-to-center distance.

Data QC

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

- Stable transmitter current, at the same level as for the measured waveform.
- Transmitter temperature
- Stable GPS signal/data
- Correct production intervals (Begin/end line marks)
- dB/dt data appear normal and are present where mapped
- Real time inversion results look plausible (if performed)



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



5 DATA PROCESSING

In the following, the overall requirements to data processing are outlined.

The data processing is performed in the tTEM processing module of the Aarhus Workbench.

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

- Review of the test site calibration
- Review of the geometry file
- Import of data to Aarhus Workbench, with the relevant information
- Processing of GPS-data
- Processing of dB/dt data automatic
 - Adjustment of filter settings for removal of coupling and noisy data.
 - Stacking width set via the Trapezoidal averaging filters
 - Final Sounding/model density (Sounding distance)
- Processing of dB/dt data manual
 - Visual assessment and editing along the lines
 - Elimination of coupled data in RAW stacks
 - Elimination of late time noise data after stacking (in AVE stacks)
 - Preliminary inversion to support the data processing

5.1 DATA IMPORT - CONVOLUTION, UNCERTAINTY ESTIMATION

During data import to Aarhus Workbench the single transient data curves are sign corrected and pre-stacked into *RAW*-data, with the frequency dictated by the LM-HM cycle time defined in the measurement script. Typically, this will result in a *RAW* sounding for each ~0.6 s. In the later processing, *RAW* data are further stacked/averaged to soundings (*AVE*-data), then set to the final spacing between the resistivity models.

During import, the data are also convolved with a filter that removes 50/60 Hz noise and DC offset and reduces the vibration noise. The filter also includes a low-pass filter. The filter is specified in the TFI-file and must match the used measuring script.

Finally, the error on the *RAW* gate values (the *RAW* data uncertainty) is estimated based on the pre-stacking, plus the uniform uncertainty stated in the GEX-file. The uniform data uncertainty is typically 3% (0.03).



Note

• The filters in the TFI-file and some of the parameters of the GEX-file cannot be updated/changed after the data import to Aarhus Workbench. Therefore, it is important that the tTEM data are imported with the correct setup.

5.2 GPS-PROCESSING

During data import the Lat-long GPS data are converted into the selected UTM coordinate system. Processing of the GPS data comprises filtering, lag correction, and re-sampling of the data to a fixed rate.

GPS data are a required data type and gaps of more than ~4 s in the GPS-data will produce gaps in the model space as well.

QC of the GPS processing is simply done by:

- Plot and zoom to layer for the processed GPS data.
- Check that the processed GPS plots on the map where expected.
- In case of unexpected gaps in the GPS data, then check the Workbench import log for GPS data lines skipped due to format errors.

Lag correction

The GPS-data is automatically lag corrected to the center of the TX-coil. For an offset configuration, the optimum position is at the middle between the RX- and TX coil. The user must therefore add an additional lag-correction of half the TX-RX distance (with a negative sign) in the *Move GPS in X-direction from frame center* setting in Aarhus Workbench. The lag correction is performed geometrically and based on calculation of the direction of movement. When holding still, the lag-correction therefore becomes inaccurate.

5.3 DB/DT DATA PROCESSING

The objective of the dB/dt data processing is to remove any coupled data, suppress the random noise by staking of RAW data, and finally to discard the very noisy late time LM and HM gates. Thus, we ensure that data entering the inversion do not include noise from man-made installations etc., and that the resulting resistivity model represents the geological structures of the subsurface.

Processing of the dB/dt data comprises, at a minimum, the following steps, which also represent a normal Workflow:



- 1. Automatic filtering of *RAW* data for removal of coupled data.
- 2. Data stacking of *RAW*-data to *AVE*-data using the trapezoid filter.
- 3. Automatic filtering of *AVE* data for removal of late-time noisy data points.
- 4. Visual assessment of all dB/dt data and manual corrections to the automatic filtering of *RAW* data.
- 5. Visual assessment of all dB/dt data and manual corrections to the automatic filtering of *AVE* data.
- 6. Evaluation and adjustment of the data processing based on preliminary inversion results.

cf. 1) Automatic filtering of RAW data

The purpose of *RAW* data filtering is primarily to reject coupled data, so they do not enter the later stacking. Aarhus Workbench utilizes some filters that are designed to detect and reject coupled data, working by evaluating the smoothness of the data curves and by detecting sign change. Settings for these filters must be adjusted/customized to the individual survey/area to work properly. Regardless, the automatic filtering should not be expected to work perfectly for removal of the coupled data and therefore a visual examination and manual data editing is normally needed.

Note:

- The filters in Aarhus Workbench working on the RAW data are called *CAP**** filters, since they are designed primarily to removed capacitive coupling.
- The automatic filtering can provide false positives.
- Settings for the automatic filtering of *RAW* data, do not need to be constant for the full survey, but can be optimized with processing experience of the specific dataset.

cf. 2) Stacking of RAW data

The purpose of stacking the RAW data is to improve the signal-to-noise ratio. The stacked RAW-data are called *AVE*-data (averaged) in Aarhus Workbench. The software has the option of using a trapezoidal shaped averaging kernel as shown in Figure 11. The trapezoidal shaped averaging results in larger stack size/better noise suppressions for the late-time data.



1e+01



Figure 11. Principle sketch of trapezoid-shaped averaging kernel, shown for three HM neighboring soundings along a data section.

The choice of the averaging filter width is a trade-off between suppressing random noise at late times and lateral resolution. 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 advantageous if you are handling noisy data or if you want to maximize the depth of investigation. A limited averaging filter width is preferable where the signal-to-noise ratio is good and in situations where lateral resolution is a priority.

The averaging widths and the resulting *AVE*-data distance (*Trapez sounding distance*) are user-defined settings and are stated in time (s), and they therefore need to be related to the driving speed to obtain the corresponding distances.

We recommended that the trapezoidal filters are set with the following guidelines:

- *Trapez sounding distance* should be approximately 10 m (2.0 s at ~20 km/h)
- Same filter width for LM and HM.
- For early times, we recommend the averaging filter width to be the same as the sounding distance, i.e. no overlap, as shown in Figure 11.
- For the late times we recommend some overlap in the averaging kernel depending on the signal-to-noise and the mapping target.
- Use the same averaging kernel for the entire survey
- Synchronization of LM and HM moments data position (*Trapez Sync. location of sound = ON*).



Typical *Trapez* filter settings for a driving speed of 20 km/h are stated in Figure 12.

Trapez Filter	ON
Trapez Sounding Distance [s]	2
Trapez Gate Time 1 [s]	1e-5
Trapez Gate Time 2 [s]	1e-4
Trapez Gate Time 3 [s]	1e-3
Trapez Width 1 [s]	2
Trapez Width 2 [s]	5
Trapez Width 3 [s]	10
Trapez Spike Factor	20
Trapez Min. No. Gates [%]	20
Trapez Min. No. Gates per sound.	7
Trapez Sync. location of sound.	ON
Trapez Require left/right sound.	ON
	-

Figure 12. Typical LM/HM Trapez filter settings for a driving speed of 20 km/h, mapping on field in Denmark.

cf. 3) Automatic filtering of AVE data

The aim of the filtering of the *AVE* data is to discard the very noisy late time data points that are too noisy to enter the inversion. Aarhus Workbench uses filters that are designed to discard the noisy late time data points, working by setting a threshold value for the data uncertainty or by evaluating the smoothness of the data curves. Settings for these filters must be adjusted/customized to the individual survey/area to work properly. Manual edits/correction to the automatic *AVE*-data filtering is normally needed.

Note:

- The filters in Aarhus Workbench working on the *AVE* data are called *AVE**** filters.
- The automatic filtering can provide false positives.
- Settings for the automatic filtering of *AVE* data, do not need to be constant for the full survey, but can be optimized with processing experience of the specific dataset.
- The LM data curve only needs to overlap the HM data curve with a few data points, so late time LM data points might be discarded. Optionally the discarding of late LM data points can be set during data import.



cf. 4) Manual processing - RAW data

Manual processing comprises a visual inspection and edits of all dB/dt data in profile view. The automatic *RAW*-data filtering normally only detects and discards the very heavily disturbed data part of a coupling. Therefore, the objective of the manual processing is to adjust/correct the results of the automatic processing, so any remaining parts of coupled data are removed. In practice this will normally result in areas with coupled data extended by manual cuts in the data. For survey areas with infrastructure/couplings sources, the manual editing is normally the most time-consuming part of the data processing.

Couplings are normally recognized as particular data patterns observed when viewing a few minutes of the *RAW* data. The evaluation of possible couplings in data is performed in connection with the geographical position of the data and distance to potentially coupled sources (the power grid, gas pipes, wind turbine electrical fences, etc.).

Note:

- If a data curve is clearly coupled, the full data curve is normally discarded.
- Galvanic types of coupling might not be detected by the automatic filtering, and these couplings therefore need to be spotted and removed manually.
- Driving parallel to fences can result in couplings that increase the signal level for the entire line, so comparison to the neighboring line data might be needed to detect this type of coupling.
- Experience with TEM data processing in general is needed for identification and optimal removal of couplings.

cf. 5) Manual processing - AVE data

Proper setup of the automatic filtering of AVE-data normally removes very noisy late-time data points. Regardless, some manual editing must be expected. This editing could also include increasing the data uncertainty for slightly noisy data points just above the noise-level; typically increasing the data uncertainty to 5-20%.

- Discarding of the noisy late time data must be performed on the *AVE*-data (not on the *RAW*-data)
- After processing, the *AVE*-data curve should generally be smooth enough that the data can be fitted within the error bars.



cf. 6) Evaluation of data processing based on preliminary inversion

Based on a preliminary inversion, the processing is evaluated and adjusted normally with respect to:

- Data misfit. Large misfits could be an indication of coupled and/or very noisy data entering the inversion.
- Resistivity sequences/structures. Do the results have unrealistic resistivity sequences/structures for the given survey area?
- The geographical position of the models in relation to expected coupling sources. Resistivity structures following infrastructure could be a result of coupled data entering the inversion.

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



6 INVERSION

Modelling of tTEM data

Modelling of tTEM system must comprise modelling of:

- Transmitter-receiver geometry
- The transmitter and receiver height above ground
- Instrument front gate
- Low-pass filters of receiver instrument and receiver coil
- Shape of transmitter waveform
- Data fit weighting with respect to the individual data uncertainties
- Estimations of depth of investigation (DOI) for the single resistivity models
- Laterally/spatially constrained inversion setup

The inversion code AarhusInv used in Aarhus Workbench is designed to model the tTEM system in full detail with high precision.

Inversion setup Aarhus Workbench

The final inversion of the tTEM data is performed with the spatially constrained inversion scheme (SCI inversion) as standard. If the survey or part of the survey is conducted as single scattered lines, the laterally constrained inversion (LCI) scheme can be applied here instead. Final inversion types (smooth, blocky, sharp, layered) are agreed upon with the client. It is recommended that both a smooth plus a sharp or a blocky inversion is conducted and reported.

A SCI inversion setup is composed of:

- Selecting type of inversion (Smooth, Blocky, Sharp, Layered)
- Vertical model discretization and number of layers
- Start model resistivity
- Lateral and horizontal constraints
- Lateral constraints scaling width distance

Typical values for the key inversion settings for smooth and sharp inversion are listed in Table 3.



Item		Value
Model setup	Number of layers	30
	Starting resistivities (Ωm)	Area dependent
	Thickness of first layer (m)	1.0
	Depth to last layer (m)	~120.0 (area dependent)
	Thickness distribution of layers	Log increasing with depth
	Constraints distance scaling	1/distance ^{0.75} (power =0.75)
Smooth model:	Horizontal Constraints, resistivities (factor)	1.5
Constraints	Vertical constraints, resistivities (factor)	2.0
Sharp model:	Horizontal Constraints, resistivities (factor)	1.05
Constraints	Vertical constraints on resistivities (factor)	1.08
	Sharp vertical constraints	100
	Sharp horizontal constraints	200

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

Note:

- The data must be assigned a surface elevation prior to the inversion.
- As a minimum the model should be discretized roughly to the deepest DOI-*standard* values.
- In conductive areas, the inversion might need to be conducted in linear-data space instead of log-data space, because an offset TEM-configuration can produce a partly negative data curve in this setting.
- The inversion configuration settings regarding approximate Jacobian computation are not in use for tTEM data.

Inversion QC

QC of final inversion results should at minimum comprise:

- Evaluation of data misfit.
- Evaluation of resistivity structure based on cross-sections and mean resistivity maps (horizontal/depth slices) in relation to location of in-frastructure, fences etc.



7 REPORTING

7.1 GEOPHYSICAL SURVEY REPORT

The geophysical survey reporting of a tTEM survey must as a minimum account for the data collection, data processing, and inversion. Furthermore, conditions or issues that have had significant influence on the data collection, processing, or inversion results must be included in the reporting as well.

The sections below list the minimum documentation needed in the geophysical survey report for the different steps in a tTEM survey.

Data Collection

The contractor must include information on/documentation of:

- Specific conditions and problems, which may affect data quality, processing, and/or inversion of the data.
- Number of line kilometers conducted and target line spacing.
- Reason for planned, but unmapped, sub-areas, e.g. livestock on the field, crops too high, ground too soft to drive.
- System calibration at the TEM test-site in form of plots of the reference response overlain by the recorded data after calibration, and specification of the obtained time shift and factor shift.
- Measurement and determination of transmitter waveform.
- Key system parameters, like:
 - LM and HM specification
 - Measurement script
 - System Geometry
- Instrument ID numbers.

Data processing

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

- An overview of key processing parameters.
 - Trapezoidal filter, averaging widths
 - Sounding/model distance
- Maps showing
 - o Survey lines/data location
 - Location of used/discarded data (coupled/un-coupled data)



Inversion

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

- Key settings for inversion setup
 - o Inversion type
 - o Layer discretization,
 - Vertical and lateral constraints setup
 - Start model resistivity
- Set of QC- maps for each inversion result
 - Data fit plot (data residual)
 - Number of data points per sounding curve
 - o DOI value

The inversion results are typically presented as cross sections, and horizontal slices (mean resistivity maps in depth or elevation intervals). Key settings for the different maps must be specified in the report or annotated on the maps; e.g. interpolation method, search radius, grid cell size, DOI blinding, etc.

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

7.2 REPORTING TO GERDA

For Danish tTEM surveys, raw data, processed data, and inversion results must all be reported to the national GERDA database in accordance with the applicable standards. A separate guide for reporting tTEM data to the national GERDA database via Aarhus Workbench is included in the reference list.



8 FLOATEM

The tTEM system also comes in a FloaTEM version, operating on water as shown in Figure 13. The main difference to the tTEM-system is that the transmitter loop is mounted on pontoons (stand up paddleboards), the receiver coil on an inflatable boat, and the instrumentation and operator in a towing boat. Instrumentation wise tTEM and FloaTEM are identical, except that the FloaTEM-system may be equipped with an echo sounder recording the water depth continuously.

The general requirements described for the tTEM-system apply to the FloaTEM-system as well, with the exceptions/add-ons reviewed in this section.



Figure 13. Layout of the FloaTEM system (2020), 2x4m² transmitter loop.

System

• The FloaTEM system can also be rigged with a 4x4m² transmitter loop doubling the transmitter moment. The larger transmitter loop/moment is often needed when surveying on saline water, since the conductive water column reduces the depth of investigation significantly. It is also a possibility to add more turns on the transmitter-loop to further increase the moment.

System calibration

• Pre-survey instrument calibration is carried out at the National TEM test-site, but pontoons and boats can be left out.



• If a large metal boat and/or a significantly larger boat engine than a standard ATV engine is used, onshore test of the transmitter-boat distance like the *ATV distance test* described in section 4.1 must be conducted.

Data collection

- The operation speed of the FloaTEM system will normally be slower than the tTEM-system, typically 5-10 km/h depending on the boat and the engine size.
- A very slow operating speed (<~2 km/h) is not recommended since the nominal system geometry will easily be violated it this case.
- An echo-sounder recording the water depth can be connected to the data recording system. The echo-sounder data are stored as DDB data strings in the NavTTem sps-file, see Figure 14 and Table 5-5 for documentation.
- The vertical offset of the echo sounder transducer to the waterline can be specified in the data logger software. The specified offset is written as a COZ data-string in the NavTTem sps-file (se Figure 14). The offset can be changed during surveying, generating a new COZ datastring in the SPS-file. Aarhus Workbench will correct the water depth with the offset value(s) from the COZ-string(s), thus the offset value(s) can be corrected manually in the sps-files prior to data import, if specified wrong while surveying.

 1
 2
 3
 4
 5
 6
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 8
 9
 10
 11
 12

 COZ
 2020
 04
 22
 08
 39
 25
 963
 \$GECOZ,0.00,0.00, -.70

 DDB
 2020
 08
 24
 07
 58
 21
 291
 \$SDDBT,3.34,f,
 1.02,M,
 0.55,F*31

 DDB
 2020
 08
 24
 07
 58
 21
 628
 \$SDDBT,3.34,f,
 1.01,M,
 0.55,F*31

 DDB
 2020
 08
 24
 07
 58
 21
 628
 \$SDDBT,3.34,f,
 1.02,M,
 0.55,F*31

Figure 14. COZ and DDB strings in NavTTem sps-files. Water depths (m) are marked with red and the echo sounder vertical offset is marked with green. See Table 5 and 5 for a detailed explanation.

Colum	Echo sounder-devise
1	Type: COZ
2-8	UTC, [yyyy mm dd hh mm ss zzz]
10-11	Vertical offset of GPS1 and GPS2 to waterline (m). Positive above water line.
12	Vertical offset of echo sounder transducer to waterline (m). Negative when transducer is in water.

Table 4. Explanation of COZ-string of the NavTTem sps-files.



Colum	Echo sounder-devise
1	Type: DDB
2-8	UTC, [yyyy mm dd hh mm ss zzz]
9	Standard \$SDDBT string. <u>https://www.eye4software.com/hydro-</u> magic/documentation/nmea0183/ for detailed info.
12	Water depth in meters.

Table 5. Explanation of DDB-string of the NavTTem sps-files.

Data processing and inversion

- Pre-processing of the echo-sounder data outside Aarhus Workbench might be needed to filter out bad/false data points e.g. due to aquatic plant vegetation.
- The operation speed must be taken into account when setting up the stacking of the data. The resulting sounding/model distance should be approximately 10 m.
- Water depth from the echo-sounder or from an external bathymetry grid can be added as prior information on the depth to first layer interface in the inversion setup.
- If measured, the conductivity of the water column can also be included as prior information in the inversion.



9 REFERENCES

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GERDA upload

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APPENDIX 1 DOCUMENTATION OF THE GEX FILE

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

For tTEM, only the full geometry file in gex-format is supported.

The format of the GEX –file is defined in an *.ini format and is explained in the example below. The GEX-file is split up in a **[General]** block, a **[Channel1]** (LM), and **Chan-nel2]** (HM) block and is keyword based. The order of the parameters/keywords within a block does not matter.

The brown colored parameters in the GEX-file example are settings that can be looked up in the RWB/SPS-files, while black colored parameters are values obtained by external measurements, or other data/modeling settings.

```
/gex file for import of tTEM data to Aarhus Workbech
/Note: SI-units are used for all variables
/Text after a forward slash '/' are comments and are automatic skipped by the importer
/'[General]' or '[Channel#]' marks the start of the different sections in the gex file
[General]
Description=tTEM2 Offset
DataType= GroundTEM
/----- Device positions -----

      GPSPosition1=
      2.00
      0.00
      -1.20
      /x,y,z (m) (z positive downward)

      RxCoilPosition1=
      -9.28
      0.00
      -0.43

      TxCoilPosition1=
      0.00
      0.00
      -0.50

/----- Low pass filter definition ------
RxCoilLPFilter1= 0.7 450E+3 /Damping ratio Gaussian filter,Cut-off frequency
FrontGateDelay=1.9E-06
                                      /Time (s) added to front gate time specified in the
                                      /script, due to delay in the TX-RX commination
/---- Transmitter loop (Tx) definition ------
LoopType=72
                              /Controls the source type. See remark below
NumberOfTurnsLM=1
                                      /Number of Tx-loop turns, low moment
                                      /Number of Tx-loop turns, high moment
NumberOfTurnsHM=1
TxLoopArea=8.00
                                     /Area of Tx-loop (m2)
                -02.00 -01.00
TxLoopPoint1=
                                     /Knee points x y (m) - clockwise order
                02.00 -01.00
TxLoopPoint2=
TxLoopPoint3=
                 02.00
                           01.00
TxLoopPoint4= -02.00 01.00
Continues on next page ...
```

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- Mics. GateNoForPowerLineMonitor=15 /Gate number to use for power line monitor FreqForPowerLineMonitor=50.00 /Frequency for power line monitor /1=Estimate uncertainty on raw stacks CalculateRawDataSTD=1 ----- Waveform definition -----/Low moment points Time (s) Normalized amplitude [0;1] TXRampLM= WaveformLMPoint01= -6.7400e-04 WaveformLMPoint02= -6.6150e-04 -0.000 -0.638 WaveformLMPoint38= 2.7000e-06 0.000 Normalized amplitude [0;1] /High moment points Time (s) TXRampHM= WaveformHMPoint01= -2.0370e-03 -0.000 WaveformHMPoint02= -2.0089e-03 -0.376 WaveformHMPoint40= 4.5000e-06 0.000 /----- Gate Time table (raw times)-----/Gate num Center Open Close (s) GateTime01=2.190E-06 3.800E-07 4.000E-06 GateTime29=7.247E-04 6.434E-04 8.060E-04 GateTime30=9.092E-04 8.064E-04 1.012E-03 /----- Low Moment, Z-coil channel -----[Channel1] RxCoilNumber=1 /Receiver coil number GateTimeShift=-1.4E-06 /Time shift of gate times and frontgate time, (s) /Factor shift of db/dt values (factor) /Automatic disabling of time gate 1 to GateFactor=1.05 RemoveInitialGates=6 RemoveInitial Gates in Aarhus Workbench PrimaryFieldDampingFactor=1 /Primary field damping factor, used in the modelig/iversion of the data UniformDataSTD=0.03 /Relativ uniform STD for db/dt-data (all gates) E.g. 0.03 = ~3%/Numbers of gates (from Gate Time table [1;NoGates]) /Repetition frequency /Frontgate time (0=No front gate) NoGates=15 RepFreq=1055 FrontGateTime=2.0E-6 /Frontgate time (U=NO front gate, /LowPass filter in Transmitter instrument /Transmitter moment type (LM, HM, or Noise) /Approx. transmitter current. Must be within 25% of TiBLowPassFilter=1 6.79E+5 TransmitterMoment=LM TxApproximateCurrent=5.2 ReceiverPolarizationXYZ=Z /Receiver Polarization (X, Y, or Z) /----- High Moment, Z-coil channel ------[Channel2] RxCoilNumber=1 /Receiver coil number GateTimeShift=-1.4E-06 /Time shift of gatetimeand font gate time, (s)

Zero time definitions

In Aarhus Workbench (WB) and in the GEX-file all times are with zero time reference at the begin of turn-off ramp (=transmitter turn off time).

In the RWB file the times in the section [MOMENTID_##] are related to zero time at transmitter turn-on, while the SAMPLECENTERTIME are with zero reference at transmitter turn off.