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Test-site calibration and validation of airborne and ground-based TEM systems

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ABSTRACT

Validation and calibration of airborne and ground-based time-domain electromagnetic (TEM) systems are important to obtain high-quality data and thereby reliable and reproducible results. Validation and calibration become even more important when the TEM systems are to be used for low-anomaly groundwater and environmental applications. The recent extension of the Danish TEM test site has made it possible to perform detailed validation of airborne TEM systems and calibrate airborne TEM systems that cannot make hovering measurements. We evaluated the Danish TEM test site and used a test site calibration scheme recommended for ground-based as well as airborne TEM systems. Furthermore, we discovered an extended data set from the airborne TEM system, SkyTEM, from the test site, used for an extensive validation of the SkyTEM system. This validation included repeatability tests at different heights and comparisons with the reference sections obtained with ground-based measurements. The validation and comparison were performed directly on the inversion results and in data space, down to the single data gate values. The extensive validation of the SkyTEM system at the TEM test site revealed a very stable and reliable system. The data repeatability of the SkyTEM system at different heights and directions was, in general, well within the standard deviation (STD) of the data. The agreement between the ground-based reference model sections and the SkyTEM model section from different recording heights was very good. Likewise, the match between the ground-based reference data and the SkyTEM data was good and, in general, within 1.5 times the STD on the data. The positive outcome of the extensive validation also confirmed that data processing and modeling were performed at the highest standard.

INTRODUCTION

For groundwater and environmental applications, airborne time-domain electromagnetic (ATEM) data are used quantitatively to reveal fine geologic details, and as a consequence, the reliability of the model parameters obtained by inversion is crucial. This calls for high-quality data, careful data processing, accurate forward modeling, and precise and robust inversion. As Christiansen et al. (2011) discuss, minor errors in data as well as in the modeling of ATEM systems will introduce errors into the model results and in the subsequent geologic interpretation.

Calibration and validation are performed on different levels for ATEM systems to improve the data quality and to ensure valid results. Corrections and calibration of individual system parameters are performed regularly. This can be calibration or correction of system geometry-related parameters (e.g., transmitter-receiver positioning, bird swing, altimetry) and calibration or correction of system-related inaccuracies (e.g., transmitter waveform, transmitter-receiver timing, low-pass filters; Davis and Macnae, 2008; Christiansen et al., 2011).

Comparison of ATEM results to other geophysical and/or geologic results are often used for validation (Anderson et al., 1993; Smith et al., 2001). Steuer et al. (2009) show detailed comparison examples of airborne frequency-domain and airborne time-domain results with ground-based resistivity and TEM results.

Test sites and test lines for validation and calibration play an important role to obtain the needed high-quality, reliable data (Vrbancich and Fullagar, 2004, 2007; Witherly et al., 2004; Davis et al., 2010; Lavoue et al., 2010). The Reid-Mahaffy test site (Irvine et al., 2000) for airborne systems is an example of this. The Reid-Mahaffy site is used to demonstrate that the system is operational and for testing the different systems' capabilities of mapping certain

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confined conductors. The validation of the systems is therefore primarily performed in the data space as a test of the ability of a system to reproduce data patterns (Witherly et al., 2004) and not as a test of absolute data values or mapped resistivity values.

The Danish TEM test site (Auken et al., 2011) is used in a more direct way for the calibration of TEM systems to absolute data and resistivity levels. This calibration is essential when results from different mapping areas and different TEM systems at varying ages are stitched together to form common geophysical maps (Møller et al., 2009). The calibration scheme for TEM instruments we present here is similar to the calibration of the ground conductivity meter data that Lavoue et al. (2010) present. In both cases, system-specific forward responses are calculated from known resistivity models and calibration constants are obtained by matching measured data to the forward responses.

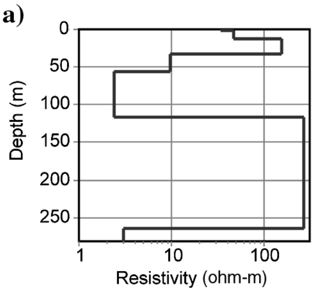
In this paper, we work with a unique data set obtained from the helicopter TEM system SkyTEM (Sørensen and Auken, 2004) flown over the Danish TEM test site. We present a detailed validation of the SkyTEM system and the associated data processing and data modeling. The SkyTEM validation data set from the TEM test site consists of two orthogonal test lines, with several repeated flights flown at different recording heights for each line.

First, we introduce the Danish TEM test site and the general test site calibration scheme and show an example of ground-based TEM data. Second, we present a detailed validation of the SkyTEM system. This includes comparison of model sections from the different line repetitions at different altitudes to the ground-based reference sections and comparisons in data space between the ground-based responses and the SkyTEM data with respect to the data uncertainties. Also, a repeatability study of the line repetitions of the SkyTEM data is carried out. To make the validation in data space, the SkyTEM data must be brought to a common nominal altitude for which an upward-continuation scheme based on the TEM-system's transfer function and the resistivity model is used.

Because the validation involves modeling of the different TEM systems to a high degree, the results presented here are not only an evaluation of the data quality of the SkyTEM system, but also an evaluation of the processing and modeling scheme applied to the SkyTEM data.

To date, only the SkyTEM and VTEM (Witherly et al., 2004) airborne systems have been operated at the Danish TEM test site. Unfortunately, data and results for the VTEM system have never been reported and have not been made available for this paper.

a)



b)

Layer	Resistivity		Thickness		Depth (top layer)	
	(Ωm)	STDF	(m)	STDF	(m)	STDF
1	33.8	1.20	2.1	2.5	0	
2	47.7	1.11	11.0	1.16	2.1	2.5
3	155.2	1.11	19.5	2.0	13.1	1.16
4	9.8	1.07	23.0	1.03	32.6	1.07
5	2.4	1.05	61.1	1.25	55.5	1.04
6	270.6	>10	148.3	3.0	116.7	1.14
7	3.0	>10			265.0	1.6

c)

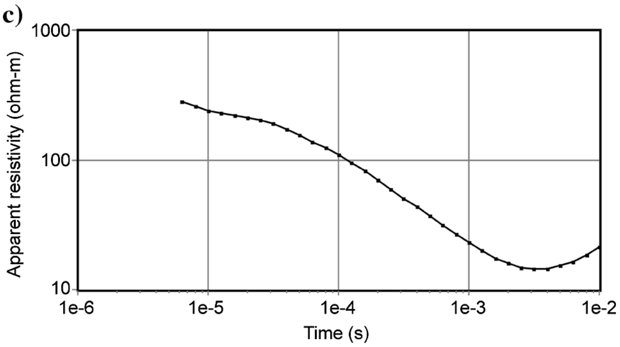


Figure 1. (a and b) The 2011 point reference model of the TEM test site. The STDF columns hold the model parameter uncertainties stated as STD factors. (c) Typical ground-based forward response of the reference model (central loop configuration, 40×40 m^2 transmitter loop) plotted as late-time apparent resistivity for a smaller dynamic range and easier inspection.

The Danish TEM test site

The Danish TEM test site was established in 2001, with the aim of getting the nine different ground-based Geonics TEM47/PROTEM systems (Geonics Limited, 2012) operating in the Danish groundwater mapping campaign to produce the same TEM responses at a given point location, which was far from the case initially. After instrument repairs, updates, and minor time and data shifts, it was possible to get the nine TEM systems to produce consistent TEM responses within a deviation of roughly 3% for the low-noise part of the sounding curve. Based on these nine responses, an average response was calculated and appointed as the reference response for the test site. The reference response was then used for continuously monitoring and calibration of the nine individual systems.

With the introduction of other TEM systems such as HiTEM (Sørensen et al., 2005) and SkyTEM, a resistivity model for the test site was needed to calculate system-specific forward responses for calibration. The reference response was therefore inverted to a five-layer resistivity model, and this model was appointed to be the TEM reference model for the site.

The upper ∼15 m of the reference model has recently been refined based on shallow electrical resistivity tomography (ERT) measurements and a detailed electrical conductivity log (Geoprobe System, 2012). The reference model has also been extended in depth with an additional conductive bottom layer. This layer was picked up by the HiTEM system and the WalkTEM system (Nyboe et al., 2010) using long stacking times. Figure 1 shows the 2011 TEM reference model and a typical ground-based TEM forward response plotted as late-time apparent resistivity (Ward and Hohmann, 1988).

The model parameter analysis stated as standard deviation factors (STDFs) (Auken et al., 2005), for the reference model, is shown in Figure 1b. It provides an estimate on the uncertainty of the model parameters. Because the reference model is a model stitched together from ERT and TEM models, the parameter analysis is simulated doing a joint inversion of an ERT and a TEM sounding for the given reference model. The uncertainties are mainly dictated by the ability of the geophysical method to resolve the individual parameters considering noise on the data, which results in model equivalences. The calibration scheme presented later on is therefore based on matching responses and not resistivity models because equivalent models result in equivalent responses.

No deep geologic borehole has yet been drilled at the test site, and the reference model is therefore purely a resistivity model representing resistivity information corresponding to the footprint of a TEM sounding. However, the layer sequence of the reference model matches the known geologic setting of the area based on the Danish national borehole database (Geological Survey of Denmark and Greenland, 2012): clay till (layers 1–2), meltwater sand (layer 3), heavy Paleogene clays (layers 4–5), freshwater saturated chalk (layer 6), and saltwater saturated chalk (layer 7).

The TEM test site has recently been extended to include two orthogonal lines approximately 1 km long each. This extension was needed to test and validate ATEM systems under production conditions and to enable calibration of ATEM systems that cannot make hovering measurements, e.g., the VTEM system and all fixed-wing systems. Two test lines were set up to explore the heterogeneity of the area and to ensure at least one operational test line regardless of wind direction. The extension was carried out with a precalibrated ground-based TEM system, WalkTEM (Nyboe et al., 2010). At precalibration, the WalkTEM system reproduced the reference data set at the original test site to within ~1%. The red squares in Figure 2 show the positions of the ground-based TEM soundings along the two orthogonal test lines. The original local test site with the detailed reference model from Figure 1 is exactly at the line intersection. The WalkTEM soundings were carried out in a central-loop configuration using a 40×40 m^2 transmitter loop placed edge to edge resulting in 40-m spacing between soundings. Data were obtained from approximately 8 µs to 10 ms, with a maximum transmitter moment of 13,000 Am^2. Data were then inverted with a least-squares inversion approach, modeling the full system response and using the laterally constrained inversion (LCI) concept by Auken et al. (2005). A six-layer model was used and the LCI setup includes lateral constraints on resistivities and depths to the layer boundaries. The inversion results for the two profiles are shown in Figure 3. The two reference sections do not reveal the thin (~2 m thick) top layer in the point reference model because the TEM soundings cannot resolve it properly and ERT measurements were not made over the full length of the test lines to confirm the general presence.

Several ground-based TEM instruments from USA, Australia, France, Germany, Switzerland, and Italy have been validated and calibrated over the years at the Danish TEM test site. This includes the ground-based TEM systems TEM47/57 (Geonics Limited), TEM-Fast (AEMR), SIROTEM (CSIRO), and NanoTEM (Zonge International). So far, SkyTEM and VTEM are the only two ATEM systems that have been operating at the test site. Access to the test site can be arranged through the Hydrogeophysics group, Department of Geoscience, Aarhus University (www.hgg.au.dk) together with assistance on data calibration and modeling.

Figure 2. Detailed map of the Danish TEM test site. Red squares mark the two reference lines (ground-based TEM soundings). The point reference site is at the line intersection. Black, blue, and cyan dots mark the different SkyTEM repetitions from the validation data set.

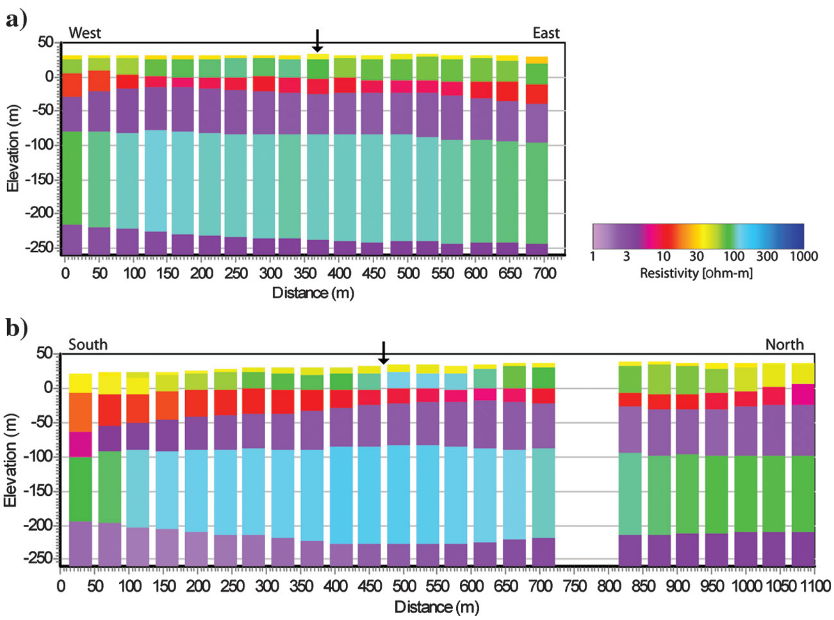


Figure 3. Resistivity sections of the two test lines. (a) West–east profile and (b) south–north profile. The arrows mark the position of the point reference site, which is also where the lines intersect.

TEST SITE CALIBRATION

This section provides a detailed description of the current test site calibration procedure for the SkyTEM system, which we propose as a general calibration procedure for all TEM systems. As such, the presented procedure can be applied to airborne TEM systems as well as ground-based TEM systems.

Precalibration

Prior to the calibration of the SkyTEM system at the test site, different system parameters are determined by laboratory measurements, e.g., transmitter waveform, transmitter-receiver timing, and low-pass filters. These parameters are all part of the system transfer function, and knowing these are essential to obtain accurate modeling and inversion of the data (Christiansen et al., 2011).

At the test site, a high-altitude test is performed, in which the system is flown to above 1000 m where the earth response is negligible. Measurements carried out while transmitting current sequences (high-altitude responses) and with the transmitter off (noise measurements) are performed to quantify any bias signals, and it is verified that the bias response is negligible compared to an average response at production height. Figure 4 shows stacked high-altitude responses (black curves). The random noise in the high-altitude responses is reduced significantly due to the stacking (2-min stack), and the system bias response is clearly identified. The bias response demonstrates an exponential decay, until it drops down into the background noise (light gray curves). The exponential decay indicates that the bias signal is a decaying primary field from the transmitter loop (coil response) and not bias noise from the instrumentation itself. Time gates before 10–12 μs are normally discarded because of the strong influence of the coil response.

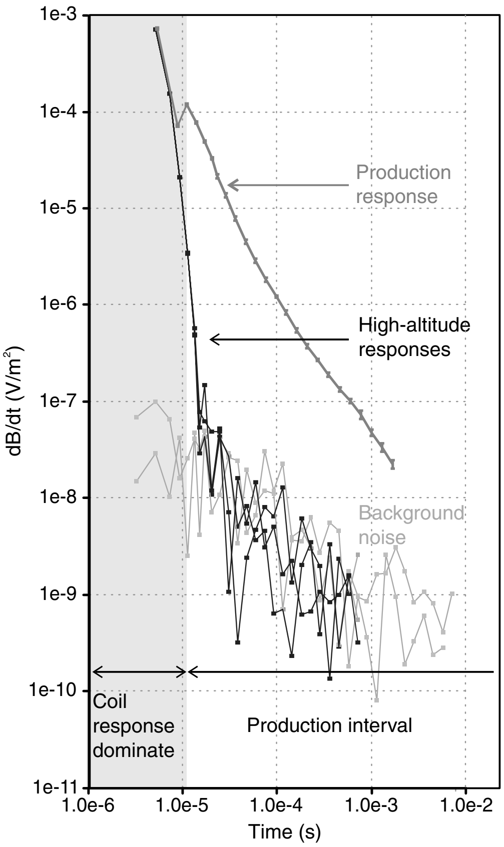


Figure 4. Low-moment data from a high-altitude test. Black curves are sequences of 2-min data stacks from altitudes above 1000 m (transmitter on). Light gray curves are noise measurements from above 1000 m (transmitter off). The dark gray curve is a typical production response from a height of ~25 m. Time gates before 10–12 μs are normally discarded because of the strong influence of the coil response. In this case, the coil response is negative resulting in a negative production response for gates before 10 μs. The dB/dt responses are normalized with the receiver area only.

Calibration scheme

For the SkyTEM system, the calibration is performed with data from hovering measurements over the point reference model (Figure 1). The test site calibration scheme is illustrated in Figure 5. First, a SkyTEM forward response of the reference model is calculated using the SkyTEM system transfer function. The forward response is calculated at the exact height of the measured data and is then referred to as the system-specific reference response. The system-specific reference response is directly comparable with the measured data. Second, the calibration is finalized by applying small uniform level and time shifts to the measured data curve to obtain the best possible fit to the reference response. For the SkyTEM system, the calibration is carried out at least three different heights, typically in the interval from 10 to 40 m, and the obtained calibration shifts must be the same for all calibration heights.

Hovering measurements are preferable for the calibration because large data stacks can be obtained. For systems that cannot make hovering measurements, the calibration can be done on either the data obtained when passing the point reference location or a calibration at each of the test-line model locations to determine the best set of calibration parameters.

The calibration procedure for ground-based systems is similar to the calibration scheme detailed here for SkyTEM, with the exception that only a ground-based reference response has to be calculated. However, it is still necessary to apply the system transfer function to get the system-specific reference responses for the test-site model.

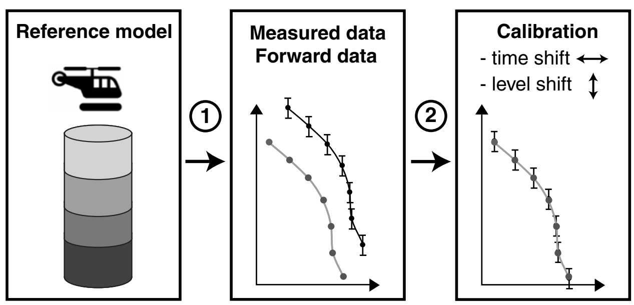


Figure 5. The calibration scheme (1) a system-specific forward response is calculated from the reference model and compared with measured data. (2) Time and level shifts are applied to the measured data curve to obtain the best possible fit to the reference response. Error bars indicate measured data, whereas dots are forward data.

Calibration examples

Figure 6 shows a calibration example for the ground-based TEM-FAST system (Barsukov et al., 2006). The TEM-FAST data in the example were recorded at the test site using a 25×25-m coincident loop configuration with a transmitter current of 2 A. First, the factor shift is determined by evaluating the center part of the sounding curve, where minor timing errors are negligible and the signal-to-noise ratio (S/N) is good. A factor of 1.06 was required in this case to fit the level of the reference response. Second, a small time shift of 0.3 μs was applied to get a good fit for the early time gates. Figure 6a and 6b shows the TEM-FAST data before and after calibration, compared with the test site reference response. The responses are plotted as late-time apparent resistivity (Ward and Hohmann, 1988) for a smaller dynamic range and easier inspection. The same late-time apparent resistivity transform is used for the airborne SkyTEM data in Figure 7. The poor fit to the reference response for the late-time gates after calibration may be explained by underestimated noise on the late-time gates. The noise estimates were given by the instrument. Thus, in this case it is advisable to assign larger standard deviations (STDs) to the late time gates before inversion.

Figure 7 shows a comparison of the reference responses and measured SkyTEM data from three different heights after the test site calibration. With common time and level shifts, a good fit is obtained for all three heights. The time and level shifts for the SkyTEM system are typically in the order of a few microseconds and a few percent in level. The time and level shifts are related to the different parts of the electronics in the transmitter, which cannot be measured accurately in the laboratory.

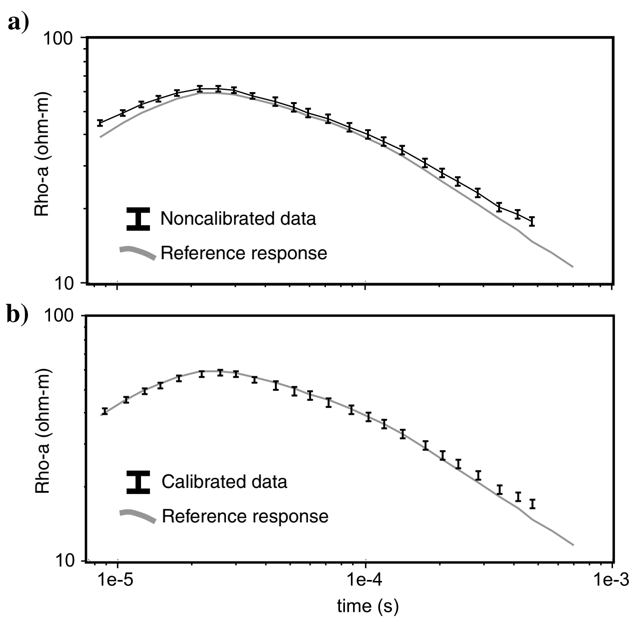


Figure 6. The TEM-FAST data (error bars) are compared with the test site reference response (gray curves) (a) before calibration and (b) after calibration. The calibrated data in (b) have been shifted 0.3 μs in time and a factor of 1.06 in dB/dt space, to fit the reference response as close as possible. The responses are plotted as late-time apparent resistivity for a smaller dynamic range and easier inspection.

VALIDATION OF TEM SYSTEMS

Validation of TEM systems can be done in model space as well as in data space. A visual model space validation is straightforward, but it can be influenced by equivalent models, which will not be the case for a careful data space validation. The validation procedures

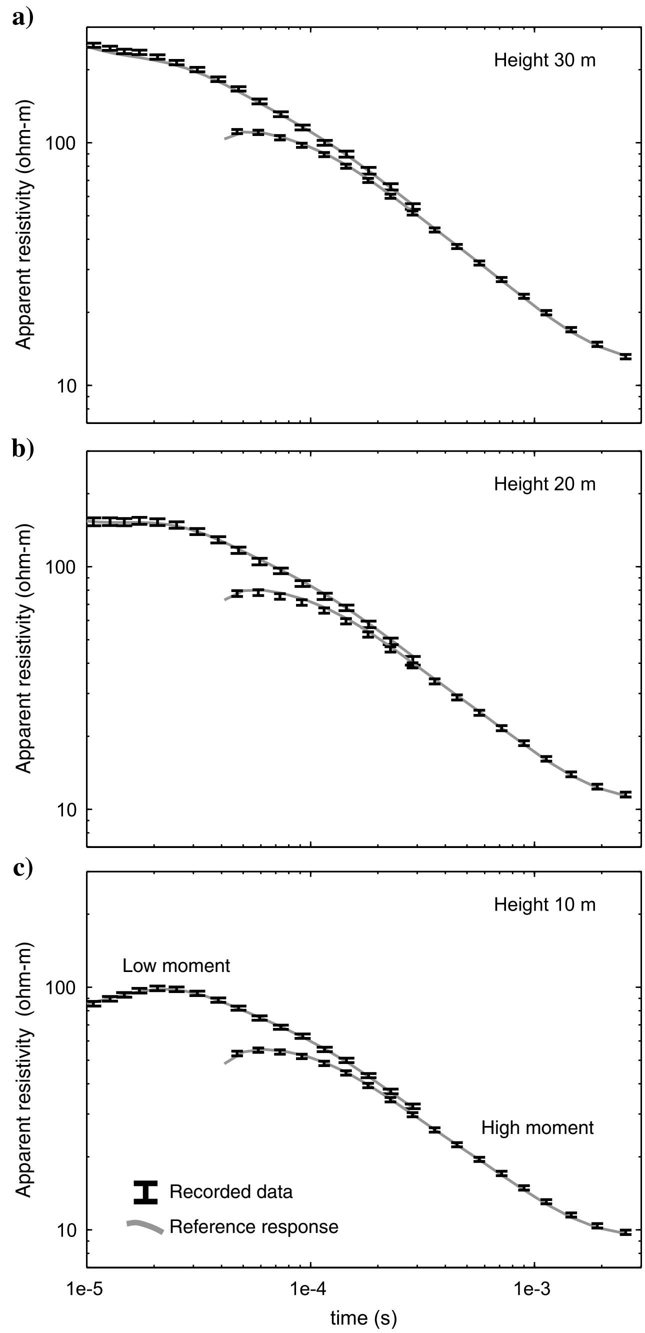


Figure 7. A comparison between reference responses (gray curves) and recorded high-moment and low-moment SkyTEM data (black error bars) after calibration. (a-c) Recording heights of 30, 20, and 10 m, respectively. The responses are plotted as late-time apparent resistivity for a smaller dynamic range and easier inspection. The SkyTEM data are hovering measurements over the point reference site, with a stack size of typically 30–60 s, depending on how steady the pilot could keep the frame.

outlined in the following sections all use data and models obtained from the test lines and not the point reference, which was used for the calibration procedures described above.

Upward continuation of data to a nominal height

The recording height influences responses strongly (Figure 8a and 8b), and it is therefore necessary to normalize data to a nominal height to carry out data comparisons from different repetitions (Figure 8c). This is done by what we term "upward continuation," but in fact this also includes "downward continuation" for data recorded above the nominal height.

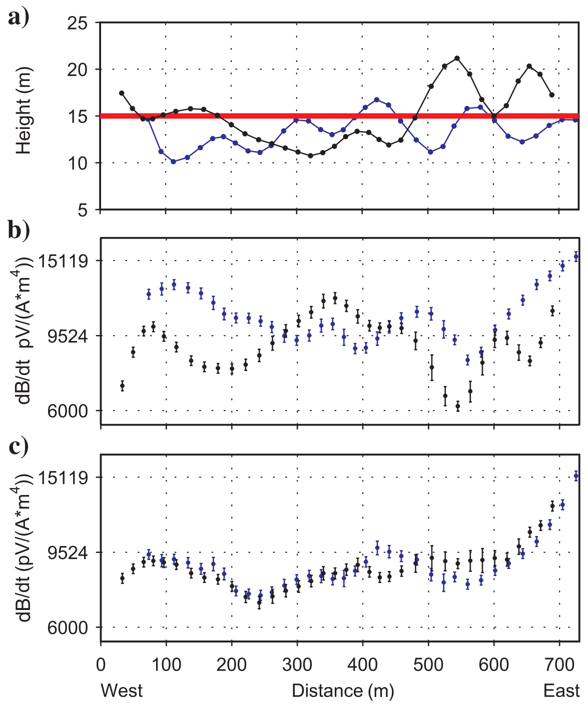


Figure 8. Altitude influence on data. (a) Height variations (center of transmitter frame, Tx-height) along the west–east profile for two repetitions at approximately 15 m. Note that variations in the receiver coil height can be larger that the Tx-height variations due to a pitch angle of the frame. (b) Recorded SkyTEM data for the time gate at 14.5 μs for the two repetitions. (c) Upward-continued data at a nominal height of 15 m. A direct data comparison of the two repetitions is now possible. The y-axis is logarithmic in (b) and (c) and represents exactly half a decade. The dB/dt responses are normalized with the transmitter moment and receiver area.

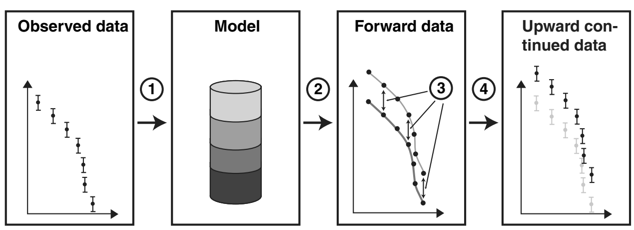


Figure 9. Flow chart illustrating the upward-continuation concept. The observed data are inverted into a model (1) from which forward responses are calculated in the nominal height and in the recorded height (2). Based on these, correction factors are calculated (3) to move the recorded data to the nominal height (4).

The upward continuation to a nominal height is done individually for all the soundings based on a gate-by-gate correlation of the forward response from the resistivity model with the height. The upward-continuation scheme is illustrated in Figure 9 and includes the following four steps:

Inversion of the observed data to a 1D-layered resistivity model.

1) calculation of the SkyTEM forward responses, using the full system transfer function in the recorded height, FR_{rec}, and in the nominal height and with nominal geometry, FR_{nom}
2) calculation of a correction factor C_n gate by gate from the two forward responses:
3)
$$C_n = FR_{\mathrm{rec},n}/FR_{\mathrm{nom},n} \qquad (1)$$
4) the upward-continued data in the nominal height D_{nom} are then calculated by applying the correction factors to the recorded data D_{rec}
$$D_{\mathrm{nom},n} = C_n \cdot D_{\mathrm{rec},n}. \qquad (2)$$

With this scheme, the height variations in the responses are removed, whereas the noise characteristics of the individual data points are kept. Figure 8b and 8c shows data for one gate time for two repetitions of the S/N profile before and after the upward continuation. For the SkyTEM system, the receiver coil (Rx-coil) is placed nominally 2.2 m above the frame and offset approximately 16 m from the center opposite the flight direction. A pitch angle of the frame causes the Rx-coil to move up or down, while the transmitter (Tx) height (center of frame) stays the same. This effect is important to include in the modeling of SkyTEM data in general because a pitch angle of, e.g., 7° results in a height displacement of the Rx-coil of approximately 2 m from the nominal geometry, which has a significant influence on the response. The upward-continuation scheme for the SkyTEM data therefore includes bringing the system to nominal geometry.

An upward continuation of the ground-based reference sections to the three nominal altitudes is also needed to validate the SkyTEM data against the reference sections in data space. The upward-continuation scheme for the reference sections is simple and is performed by calculating SkyTEM specific forward responses for the reference sections, at the nominal height, using the SkyTEM system transfer function.

SKYTEM VALIDATION RESULTS

System setup and processing

The SkyTEM data set for validation from the Danish TEM test site was carried out on 5 August 2009 by SkyTEM Surveys ApS. The SkyTEM data were recorded with a standard setup using the largest transmitter frame at the time of approximately 500 m^2. Data were obtained from approximately 10 μs to 10 ms using a low and a high transmitter moment sequentially. Table 1 shows a brief overview of key system parameters.

The full SkyTEM data set consists of data from the two intersecting lines at altitudes of 15, 25, and 35 m, all repeated twice in both directions, which in total result in 12 repetitions per line.

The flight paths of all 2 × 12 repetitions are shown in Figure 2. Electrical installations and fences associated with the highways to the east and south and a power line to the north, just outside the map window, cause coupling interferences in the data when the system is too close. During the processing, the coupled data have been removed and their positions do not appear in Figure 2.

In general, the different flight lines and the ground-based reference line are coinciding nicely and always within 25 m. On the north part of the north–south profile a small water hole and a group of trees result in small line deviations for the repetitions in 15- and 25-m heights. The data from 35-m height had no treetop clearing problems and therefore no line deviation. The SkyTEM data deviating from the lines are kept and inverted as well, and this needs to be taken into account in the later comparisons. Also, note that there is no ground-based reference sounding at the water hole.

Data processing and inversion were carried out in the Aarhus Workbench software (Auken et al., 2009), using the AarhusInv code for inversion (Christiansen and Auken, 2009). The processed data were sampled to soundings at even time steps resulting in approximately one sounding per 20 m. The assigned data uncertainty (STD) arises from the data stacking plus a uniform STD of 3% (Auken et al., 2009). The SkyTEM data were inverted with the same LCI approach as for the ground-based TEM data. For the SkyTEM data, this also includes modeling of the actual transmitter and receiver heights. The line repetitions were inverted in separate LCI sections, using a five-layer model. The data residual normalized with the data error (Auken and Christiansen, 2004) is, on average, ~0.6, which means that the data, in general, are fitted well within the data error. An example of a single SkyTEM sounding curve and data fit is plotted in Figure 10. A full SkyTEM model section is show in, e.g., Figure 11a.

Comparison of inversion results

The first validation step of the SkyTEM system at the Danish TEM test site is a simple visual comparison of the inversion results. This is done with respect to repeatability at the same height, different heights, different flight directions, and agreement with the ground-based reference sections.

Resistivity sections for two repetitions of the west–east profile at a height of 25 m flown in opposite directions are shown in Figure 11a. The agreement between the two sections is very good with only minor dissimilarities. In Figure 11b, a comparison of two SkyTEM repetitions at heights of 15 and 35 m are shown, revealing an equally good match as for the two 15 m repetitions in Figure 11a. Figure 11c shows the comparison of a SkyTEM section from a height of 25 m (background) with the ground-based reference section (bars), in this case for the S/N profile. The dissimilarities are a little bit larger especially in the southern end, but the general agreement is still good.

The model parameter analysis, in the form of a STDF (Auken et al., 2005) for a single SkyTEM model at height 25 m is listed in Table 2. The model parameter analysis provides information on the uncertainty of the model parameters. An STDF below 1.2 indicates a well-determined parameter, whereas an STDF above two indicate an undetermined parameter. Note that the poorly determined and undetermined model parameters are the resistivity of layer five, resistivity and thickness of layer one.

Comparing the different model sections in Figure 11a and 11c, it is clear that the largest dissimilarities between the sections are seen for the poorly determined and undetermined model parameters. This indicates that the observed model variations in the different repetitions are likely to be model-equivalence issues.

We observe a high model repeatability in the SkyTEM sections (Figure 11a and 11b) for all four repetitions at the three different altitudes. Likewise, we obtain a consistent good agreement to the ground-based reference sections (Figure 11c). We therefore conclude that the model repeatability of the SkyTEM system with

Table 1. Key parameters for the SkyTEM system setup.

Type	Value	
Helicopter speed	~45 km/h	
Tx-height	~15 m, ~25 m, ~35 m	
Line repetition	Four times of each line in all heights (twice in both directions)	
	Low moment	High moment
Transmitter moment	~45,000 Am^2	~180,000 Am^2
Transmitter, on time	1.0 ms	10 ms
Transmitter, off time	1.25 ms	10 ms
Gate center time	10 μs to 1 ms	0.14 to 9 ms
Turn-off time	5.6 μs	53 μs
Turn-on time	0.9 ms	3.2 ms

Note that the gate center times are referenced to the beginning of the turn off.

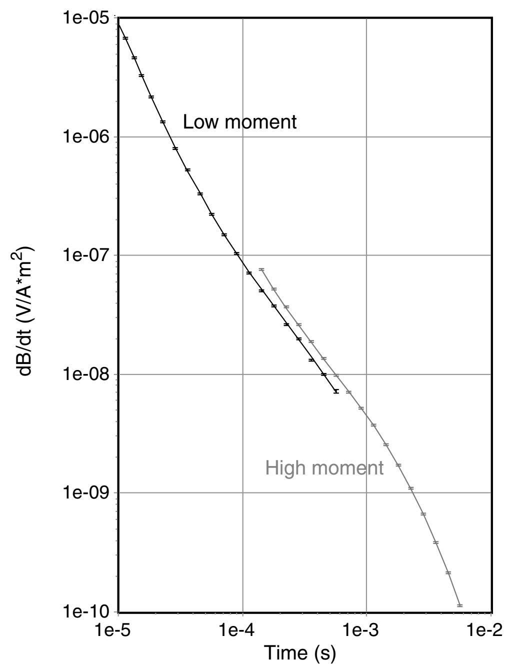


Figure 10. Single SkyTEM sounding from the east–west profile at 250 m, altitude 25 m. The error bars mark the recorded data, whereas the line is the forward response from the inverted model. The data residual normalized with the data error for this sounding is 0.45. The dB/dt response is normalized with the transmitter current and receiver area.

respect to different heights, and flight directions are very good. Furthermore, these results indicate that the resolution capabilities of the SkyTEM system are not noticeably affected by different recording altitudes in the interval from 15 to 35 m for a layer sequence of this type.

Comparison in data space — Single gate times

For the comparisons in data space, the upward-continued SkyTEM data are used. The comparisons are carried out with respect to an average SkyTEM response (purple line in Figure 12) and the upward-continued ground-based response (red dots in Figure 12). The average SkyTEM response is calculated as a noise-weighted running mean value over the SkyTEM repetitions in the given height. The data STD will normally increase with gate time, as the TEM response gets closer to the background noise.

Figure 12a and 12b shows the data comparison for the two time gates at 20 μs (low moment) and 0.9 ms (high moment), for a recording height of 15 m. For the late time gate (Figure 12b), we observe an overall good agreement between the responses. The individual repetitions are all very close to the average curve (magenta), which in turn shows a good agreement with the upward-continued ground-based reference data (red dots). Data from the early time gate (Figure 12a) are more scattered and especially at the ends of the profile the agreement with the ground-based reference response is poorer than seen for the late gates.

Figure 13 shows a similar comparison, in this case for data from the south–north profile at a recording height of 35 m. The overall trend is the same as in Figure 12, but the fit to the ground-based response for the early time gate is slightly better in this case.

Comparison in data space — Total misfit

To quantify the agreement between the SkyTEM and ground-based data in general, a total misfit between the two responses is calculated. A cubic spline was used to interpolate the ground-based response to the exact SkyTEM recording positions for the misfit calculation. Furthermore, a misfit calculation between the SkyTEM data and the average SkyTEM response was performed to quantify the SkyTEM system's repeatability in general.

The SkyTEM data have nonuniform uncertainties, and the misfit Q is therefore normalized with respect to the data STD on single data points:

$$Q = \frac{|\log(d_{\mathrm{SkyTEM}}) - \log(d_{\mathrm{ref}})|}{\log(1 + \mathrm{STD}_{d\_\mathrm{SkyTEM}})}, \qquad (3)$$

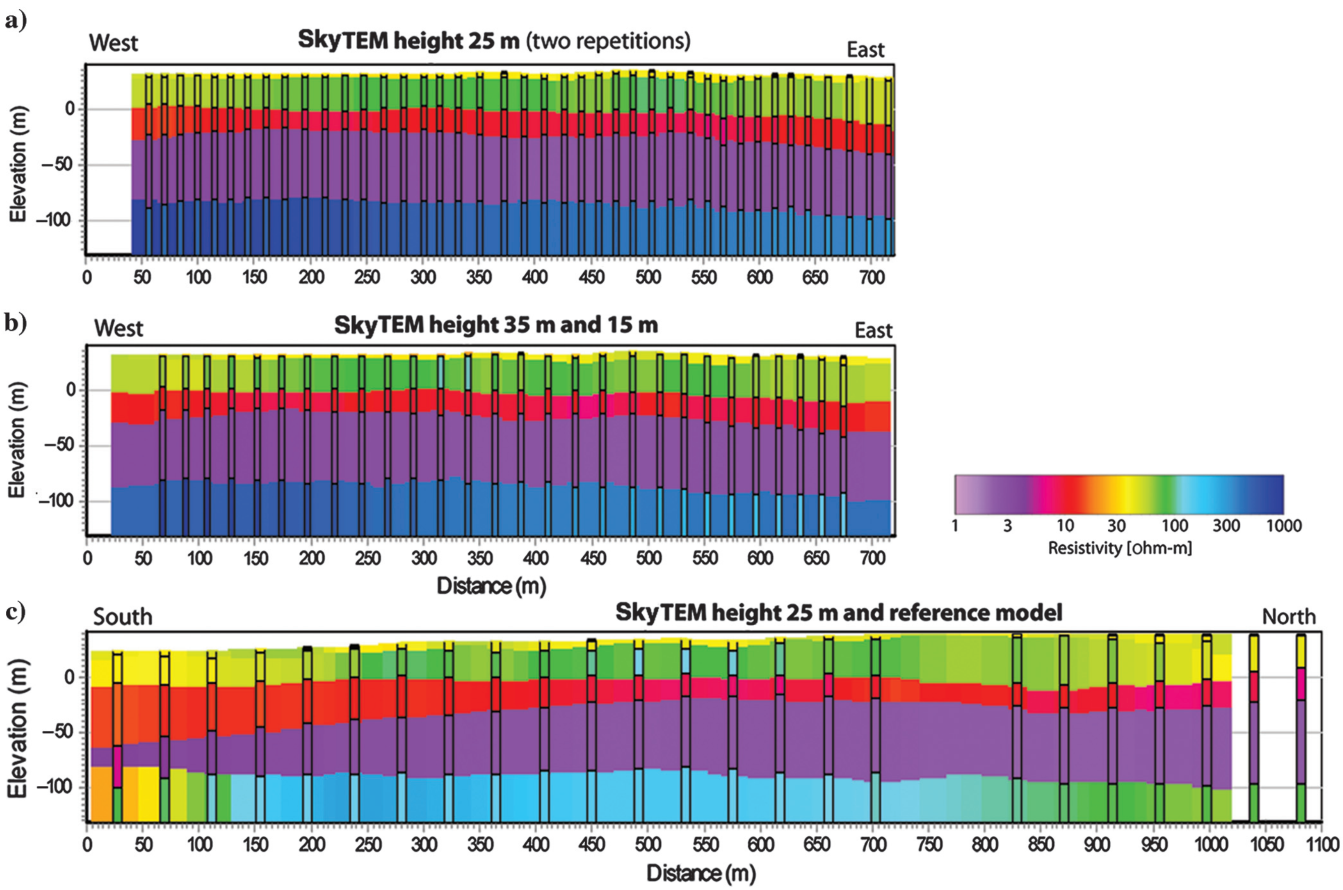


Figure 11. (a) Two model sections from the east–west profile, recording height of ∼25 m. The background is a stitched section of repetition one, whereas front bars with borders are repetition two in opposite flying directions. (b) Model section from an east–west profile at two different recording heights. Background section is from a height of ∼35 m, whereas front bars are a height of ∼15 m. (c) Model sections from the S/N profile where the background is the SkyTEM results from a height of ∼25 m, and front bars show the ground-based reference model. All sections are plotted with no vertical exaggeration, and the elevation axis is meters above sea level.

where d_{ref} is reference data, which can be either the ground-based response or the average SkyTEM response, d_{SkyTEM} is the recorded SkyTEM data with the data STD, $\mathrm{STD}_{d\_\mathrm{SkyTEM}}$, stated as a fraction (e.g., 0.05 = 5%). A misfit of one corresponds to a fit equal to the STD. The Q values smaller than one indicate fits within the data STD and Q values larger than one indicate fits outside the STD. The Q value is always calculated in the log space.

The light gray bars in Figure 14a show the mean misfit of the SkyTEM responses to the average SkyTEM responses for all line repetitions and all gates with respect to the three different heights. The mean misfit to the average SkyTEM response is below one for all heights. In Figure 14b, the mean misfit with respect to different gate times is plotted, disregarding height and line direction. The light gray bars in Figure 14b again show that for all gate times, the individual SkyTEM gate data have a misfit to the average SkyTEM response close to or below one. Based on Figure 14, we conclude that the repeatability is generally well within the assumed data noise.

The dark gray bars in Figure 14a and 14b show the misfit of the SkyTEM responses to the ground-based responses. Overall, the misfit is ~1.7 (Figure 14a, last dark gray bar). This indicates that the SkyTEM system reproduces the ground-based measurements within less than two STDs.

Figure 14a shows that the misfit to the ground-based responses is slightly decreasing with increasing altitude. Intuitively, the opposite is expected, because the footprint of the ground-based and the airborne measurements becomes more alike with decreasing height. The opposite trend we observed may therefore indicate that our data uncertainty becomes too pessimistic with increasing height, which results in a better normalized misfit.

Figure 14b reveals that the misfit is significantly larger for the early time gates (<30 µs) than for the late time gates. This is most likely caused by the high sensitivity of these gates to deviations in the geographical position, due to a smaller footprint. Also, the fact that the underling assumption of a layered 1D earth with homogenous and isotropic resistivity layers is never 100% fulfilled, will have a larger impact on the early time gates in the comparisons.

The validation results for the SkyTEM system at the Danish TEM test site set the standards for the data quality expected for an airborne system to qualify for the Danish national groundwater mapping campaign. A complete report of guidelines and standards for SkyTEM measurements, processing, and inversion in the Danish national groundwater mapping campaign is available online (Foged et al., 2011).

DISCUSSION

Test site

As mentioned, the Danish TEM test site was refined in the upper 15 m in 2011. In the refining of the test site model, based on ERT measurements, two aspects needed to be addressed: electrical anisotropy and footprint size. The TEM method maps the horizontal resistivity ρ_{H} of a given layer, whereas the layer resistivity from the ERT method ρ_{ERT} is influenced by the horizontal resistivity and vertical resistivity ρ_{V} of the layer ($\rho_{\mathrm{ERT}} = \sqrt{\rho_{\mathrm{H}} * \rho_{\mathrm{V}}}$). Hence, the macro (structural) electrical anisotropy must be known to correct the ERT resistivities before using them in the TEM reference model. The detailed electrical conductivity log has been used to estimate anisotropy (Christensen, 2000). The footprint size issue has been addressed by calculating a mean ERT resistivity model from 10 ERT sections placed in a 65 × 65-m fence grid centered at the point

Table 2. Model parameter analysis for a single model (SkyTEM model in Figure 11c at distance 450 m, flight height ~25 m).

	STDF resistivity	STDF thickness	STDF depth top of layer
Layer 1	1.62	4.05	—
Layer 2	1.14	1.28	2.02
Layer 3	1.11	1.05	1.05
Layer 4	1.02	1.04	1.04
Layer 5	4.23	—	1.01

The STDF columns contain the model parameter uncertainties stated as STD factors.

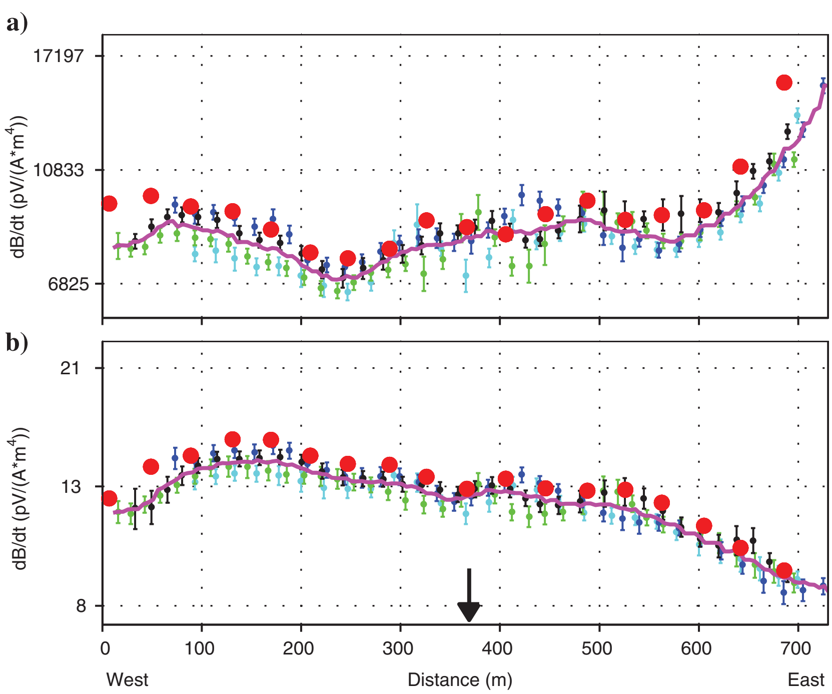


Figure 12. West–east profile at a nominal height of 15 m. (a) Responses for gate time 20 µs (b) responses for gate time 0.9 ms. Colored error bars, upward-continued SkyTEM data of the four repetitions. Purple line, weighted average of the upward-continued data. Red dots, upward-continued response of the ground-based reference section. The y-axis is logarithmic and represents exactly half a decade in both plots. The dB/dt responses are normalized with the transmitter moment and receiver area. The arrow marks the crossover point of the test lines.

reference model (Auken et al., 2011). The 65 × 65-m area is in the same order as the footprint size of a TEM measurement at early times.

A single deep borehole at the test site, including geophysical logs (resistivity logs, gamma log, etc.) would, to some degree, strengthen the confidence in the reference model. However, a borehole only provides point information in the horizontal plane and cannot capture the horizontal heterogeneity within the TEM footprint. A deep borehole can therefore only confirm the overall resistivity structure of the reference model, but it cannot be used to update/refine the reference model, which needs to include the heterogeneity as seen by the TEM method. The reference model can bee seen as a forward generator for the different TEM systems, and therefore only need to represent the resistivity of the subsurface as seen by a TEM sounding.

Some of the model parameters of the reference model have large uncertainties, e.g., the resistivity of the high-resistivity layer, but this will not affect the calibration and validation. Minor changes of the poorly determined parameters have a negligible effect on the TEM response, because equivalent models result in equivalent responses. This is the reason for preforming the calibration in the data space and not in the model space.

To establish a test site, we have identified at least the following important issues:

- The site must be accessible throughout the year, and accessibility should be ensured for years ahead.
- The subsurface should be reasonably 1D, within the footprint and along the lines.
- Close proximity to infrastructure such as fences, power lines, and railroads should be avoided.
- Yearly variations on the resistivity model should be negligible.
- Signal-to-noise levels should be high enough to achieve late-time data.
- The reference model should be obtained with a precalibrated instrument, e.g., one that has been calibrated at the Danish site.

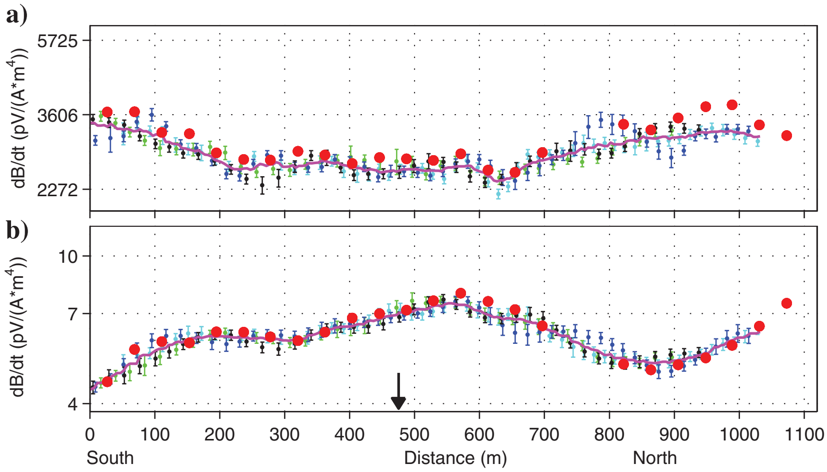


Figure 13. South–north profile 35 m. (a) Responses for gate time 20 μs; (b) responses for gate time 0.9 ms. Colored error bars, upward-continued SkyTEM data of the four repetitions. Purple line, weighted average of the upward-continued data. Red dots, upward-continued response of the ground-based reference section. The y-axis is logarithmic and represents exactly half a decade in both plots. The dB/dt responses are normalized with the transmitter moment and receiver area. The arrow marks the crossover point of the test lines.

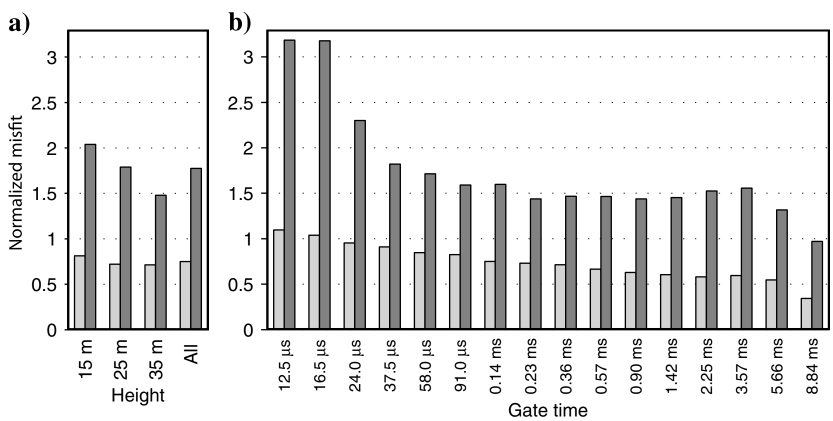


Figure 14. (a) Mean misfit for all repetitions at the three different heights (All = sum of all heights). (b) Mean misfit for selected time gates. Light gray bars show mean misfit to the average SkyTEM response, and dark gray bars show the mean misfit to the average upward-continued ground-based response.

TEM calibration

A TEM calibration resulting in time and level shifts is only valid if the errors for which the shifts compensate can be approximated with a time and/or level shift. For airborne systems, this is examined by performing the calibration at different heights, corresponding to having different calibration models and thereby ensuring that the calibration is model independent. For ground-based systems, this model independence test is not possible and we have to rely on the single calibration result.

To use the calibration globally, one also needs to assure that system drift problems are negligible. Drift in the instrumentation is not observed for the SkyTEM system (Sørensen and Auken, 2004). The calibration on the Danish test site is therefore global for a given SkyTEM instrument setup/configuration. To document the repeatability of the SkyTEM system throughout a survey, repeated measurements on a local reference site are performed for each flight during the survey. Similar repeatability tests are recommended for any TEM survey.

Finally, with the SkyTEM system, several high-altitude tests are carried out during the survey period to document that the system bias signal is constant and negligible compared to the earth signal level at production height.

Validation

The upward continuation of airborne TEM data to a nominal height with high precision is only possible because the resistivity model is known.

Therefore, the described upward-continuation concept can not be used for transforming airborne electromagnetic (AEM) data in general to a nominal height prior to an inversion scheme that needs data at a common height. The upward continuation of SkyTEM data in this paper is applied only to be able to perform comparisons in data space.

The upward continuation of the reference section (the ground-based TEM results) to perform the validation of the airborne TEM system only makes sense if the following criteria are met: first, the reference section must resolve the subsurface equally as well as or better than the TEM system that is validated; second, the mapping method for the reference section and the TEM system must be based on the same physical principles, e.g., EM to EM, and only EM to DC if anisotropy issues have been addressed. For the SkyTEM validation, both criteria are met, although issues that are not related to system errors still remain. First, the size of the footprint is not the same for the ground-based and airborne measurements and the footprint varies with altitude (Beamish, 2003; Reid et al., 2006). This implies that, if we have lateral resistivity variations, the ground-based and airborne measurements at the exact same position will not result in the exact same response and resistivity model. Second, we have minor deviations in geographical data positioning of the different line repetitions. It is difficult to quantify the effect of footprint size and positioning deviations in the inversion results and data responses, but the effect is clearly largest for the early time gates in which the averaging volumes are smaller. This explains, at least partly, the larger misfit between the SkyTEM data and the ground-based data observed for the early time gates (Figure 14) compared to the late-time gates.

In many cases, people consider ground-based geophysical measurements more valid than AEM results without taking the quality control scheme and documentation for the different methods and instruments into account. In this paper, we have also established the ground-based TEM results as the reference to compare against. However, in our case, the quality control scheme is equally good for the ground-based and airborne systems. The SkyTEM data set included 12 repetitions of the test lines and the ground-based-only one, suggesting that the SkyTEM responses and results are better consolidated than the ground-based data. So, in principle, we could have evaluated the ground-based data against the SkyTEM responses and not the other way around.

CONCLUSIONS

Over the past decade, the Danish TEM test site has proven to be of great value in ensuring uniform and high-quality data required to obtain consistent results for the different TEM systems used in the Danish groundwater mapping campaign. The described test site calibration procedure for TEM systems together with well-documented processing procedures and accurate modeling has made it possible to stitch together results as the mapping progressed over more than 15 years forming seamless geophysical and geologic maps.

With the recent extension of the TEM test site to two test lines, it is also possible to validate airborne TEM systems that cannot make hovering measurements.

The comprehensive test and validation of the SkyTEM system at the test site confirms a high data quality of the SkyTEM system. The original Danish TEM test site required hovering measurements, whereas this validation extends the conclusions to lines and survey conditions for the SkyTEM system. The validation is also a validation of the processing, modeling, and inversion schemes applied to the TEM systems involved.

The direct comparison of inversion results revealed that the model repeatability of the SkyTEM system is good at the same height and at different heights. Also, no lag or heading errors are observed in the inversion results. The agreement with the ground-based reference sections is good, showing that the SkyTEM system yields data of the same high quality as the ground-based system.

The validation of the SkyTEM system in data space was set up to examine the responses gate by gate, which, among other things, rules out equivalent model issues in the comparison. An upward-continuation scheme, including the TEM systems transfer function and the resistivity model, for scaling AEM data to a nominal height, was applied to be able to make the data comparison. The different comparisons in the data space show that the SkyTEM system repeats the test lines equally good at the different heights. The statistical summation revealed that the EM responses from the SkyTEM system, in general, are reproducible to within the data STD.

The agreement to the ground-based reference responses is good and in general within 1.5 times the data STD. For the very early time gates, the mismatch to the reference responses are approximately three times the data STD. The larger disagreements for the very early time gates are partly related to deviations in footprint size and line deviations.

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