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# An integrated processing scheme for high-resolution airborne electromagnetic surveys, the SkyTEM system

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**Abstract.** The SkyTEM helicopter-borne transient electromagnetic system was developed in 2004. The system yields unbiased data from 10 to 12 μs after transmitter current turn-off. The system is equipped with several devices enabling a complete modelling of the movement of the system in the air, facilitating excellent high-resolution images of the subsurface.

An integrated processing and inversion system for SkyTEM data is discussed. While the authors apply this system with SkyTEM data, most of the techniques are applicable for airborne electromagnetic data in general. Altitude data are processed using a simple recursive filtering technique that efficiently removes reflections from trees. The technique is completely general and can be used to filter altitude data from any airborne system. Raw voltage data that are influenced by electromagnetic coupling to man-made structures are culled from the dataset to avoid uncoupled data being distorted by coupled data, and geometrical corrections are applied to correct for pitch and roll of the transmitter frame. Data are de-spiked and averaged using trapezoid-shaped filter kernels. A Laterally Constrained Inversion using smooth models is actively used to evaluate the processing, and the final inversion is tightly connected to the processing procedures.

**Key words:** airborne electromagnetic, altitude processing, constrained inversion, SkyTEM.

## Introduction

Large airborne electromagnetic surveys are a logistical challenge, not only in carrying out the field operation, but also in the subsequent data handling. The data handling can be divided into four steps: management, processing, inversion and, finally, presentation. These four steps involve many different techniques, but common to all of them is a complicated logistic data flow.

The SkyTEM system is a relatively new helicopter-borne transient electromagnetic system (Sørensen and Auken, 2004; Auken et al., 2007*a*). It was originally developed for high-resolution surveys targeting freshwater hydrological problems, but over the past few years it has been utilised in a wider range of applications including mapping buried iron ore palaeochannels (Reid and Viezzoli, 2007) and salinity (Viezzoli et al., 2007; Munday et al., 2007). On the Galapagos Islands the system gave high-resolution data forming the basis of a very comprehensive hydrological and geomorphological understanding of the Santa Cruz Island (d'Ozouville et al., 2008). The SkyTEM system differs from other systems in two ways. First, the system measures very early time data that are unbiased (unbiased means voltage data which at all time gates have less than 1% primary response). Second, the geometry of the system is completely described and the entire movement of the system in the air is at all times monitored.

In this paper we will discuss the implementation of the data-handling logistics for SkyTEM data. The implementation is based on our background in hydrogeophysics, where minor changes in data can change the outcome of the investigation from success to failure. Therefore, the need for not only high-precision unbiased data, but also high-quality processing, is inevitable. The processing entails using appropriate data averaging schemes, removing distorted data, and having accurate altitude estimates. First, we will briefly present the SkyTEM setup and then, in greater detail, describe the data-handling system. This will include presentation of a scheme for processing the specific inputs, e.g. correction of altitude or voltage data due to the tilt of the frame as it moves in the air, removal of bad reflections from laser altimeter data, and design of the data filtering and averaging schemes. The latter ensures that maximum lateral information is preserved while still obtaining a high penetration depth. As inversion of SkyTEM data has been the subject of several other papers, it will only be summarised here in order to make the paper complete and to demonstrate how the processing is actively used in the inversion algorithm and vice versa.

## The SkyTEM system

SkyTEM is a time-domain, helicopter-borne electromagnetic system originally designed for hydrogeophysical and environmental investigations. The system is shown in operation in Figure 1. It is carried as an external sling load independent of the helicopter. The transmitter (in normal configuration), mounted on a lightweight wooden lattice frame, is a four-turn 314 $m^2$ octagonal loop divided into segments for transmitting a low moment in one turn and a high moment in all four turns.


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The transmitted current pulse is bipolar with an exponential turn-on ramp and a turn-off ramp consisting of a linear part and a small exponential part. The system operates with alternating moments, which give the possibility of using a low current with a very fast turn off as one source moment while the other source moment allows a high current with a slower turn-off. This is crucial for obtaining data at very early times while at the same time maintaining the high moment essential for obtaining data at late times. As of 2009 the low moment (LM) is ~7 A with a turn-off time of a few µs; the high moment (HM) transmits ~100 A and has a turn-off time of ~38 µs. All times are measured from the beginning of the turn-off ramp. The first LM gate centre time is 10–12 µs whereas the last HM gate is 7 ms. These numbers are valid for 50 Hz power line frequency operation. The gates are approximately logarithmically spaced with 10 gates per decade, although at the very early times the gates are sampled every microsecond. Under normal conditions, the latest gate with usable signal is 2–4 ms, but this is strongly dependent on the overall resistivity of the subsurface and on the level of background noise in the survey area. The receiver loop is rigidly mounted on the side of the transmitter loop, and therefore the system can be regarded as a central-loop configuration with a 1.5 m vertical offset between the transmitter and the $z$-component receiver. The total weight of the system is less than 350 kg, and typical flight speed is 70–90 km/h. There are no instruments mounted inside the helicopter (except for a small navigation panel) and the system has its own power supply. The operation altitude is as low as possible, 30–35 m on flat fields, higher over forest. Measurement, processing, and inversion of the $x$-component data are subjects of ongoing intensive research (Auken et al., 2007*b*).

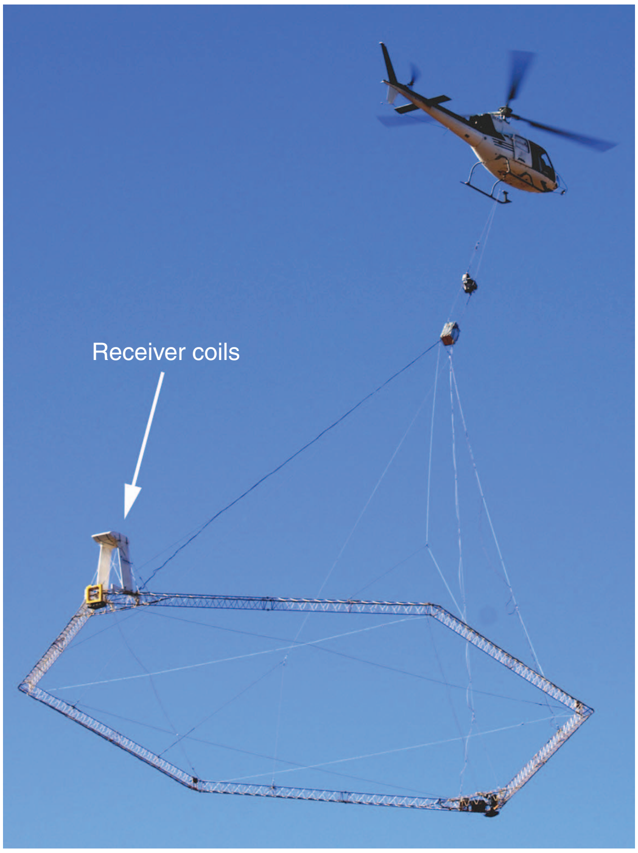


**Fig. 1.** The picture shows the SkyTEM system in operation. The transmitter wires are attached to the octagonal lattice frame. The $z$-component receiver coil is mounted on the top of the tail fin while the $x$-component coil is mounted behind the fin in the plane of the transmitter frame.

Whereas the configuration just discussed is designed for general mapping purposes, balancing lateral resolution with sufficient vertical resolution, the SkyTEM system exists in two other configurations emphasising either shallow mapping, with laterally densely sampled data, or very deep mapping. The deep mapping configuration has a 492 $m^2$ transmitter loop yielding a magnetic moment of ~187 000 a.m.$^2$ (compared to ~125 000 a.m.$^2$ for the normal system). The shallow mapping system is designed specifically for mapping from the surface to depths of 100–120 m. The configuration has only one turn in the transmitter coil and alternates between a super low moment (SLM) transmitting 7 A and a LM transmitting 80 A. The SLM + LM system gives very densely sampled near-surface soundings.

The system stores every transient in a binary format. This yields ~50 and 115 Megabytes of data per hour for the normal and the shallow systems, respectively. The difference is caused by the difference in system repetition frequencies, as the shallow system constantly transmits 400 transients per second, whereas the normal system transmits 50 transients per second for three-quarters of the time, and only in the last quarter of the time does it transmit at 400 transients per second. Recording of the data from every transient is important because it allows full reprocessing of the raw voltage data in the event that even better processing algorithms are developed in the future.

The measured navigation data form a comprehensive dataset describing the full movement of the transmitter frame in the air. The normal location of the devices is shown in the outline of the transmitter frame in Figure 2. The GPS position is measured every second, and the pitch and roll (tilt) of the frame is measured both in the front of the frame and at two positions at the back of the frame. Each tilt device outputs one measurement each second. The altitude is measured using two lasers mounted directly on the frame, sampled 20 times per second per laser. All these data are stored unprocessed in ASCII format. All devices are duplicated, i.e. there are two GPSs, two lasers etc.

All data (voltage and navigation data) are marked by time stamps, basically the GMT mean time obtained from the GPS devices. The accuracy of the time stamp is in the order of a few milliseconds.

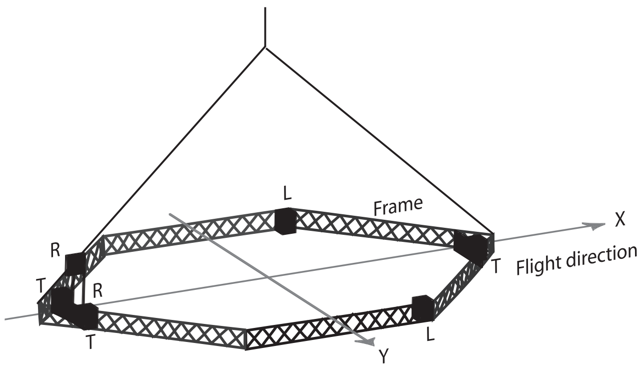


**Fig. 2.** The figure shows an outline of the transmitter frame with attached devices, tilt (T), lasers (L) and receiver coils (R). The GPS devices were before 2009 mounted on the instrument box located between the frame and the helicopter (not shown in the figure). Since 2009 they are mounted at the front part of the frame. Two of the tilt devices are mounted on the stiff tail fin, which also carries the receiver coils.

In the design and development of the SkyTEM system, the aim has been that the data quality should be the same as or better than the data quality of ground-based systems. One way of accomplishing this is to take several different ground-based systems to a reference site and make them reproduce each other. Based on measurements from more than 10 different Geonics Protem/TEM47 systems a ‘standard curve’ and a ‘standard model’ have been established at a test site in Denmark. For the verification of the SkyTEM system we have calculated a reference curve for the standard model from which data are generated for the different dimensions of the SkyTEM transmitter loop, low-pass filters (Effersø et al., 1999),

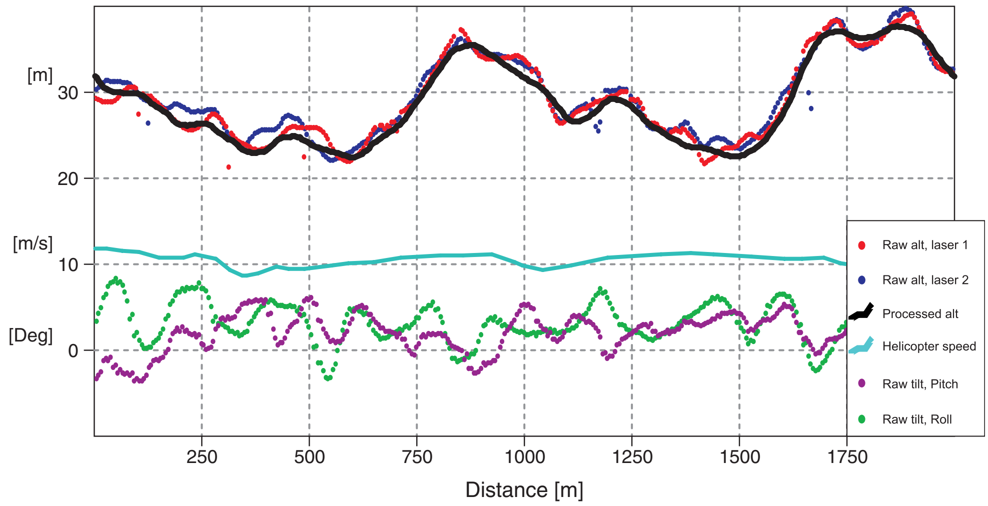


**Fig. 3.** The figure shows a typical integrated plot of navigation data. Raw altitude data from the two lasers are shown in blue and red, the processed and tilt corrected transmitter altitude in black. The helicopter speed is blue/green while the raw tilt data from one of the tilt devices are shown in purple (pitch) and light green (roll).

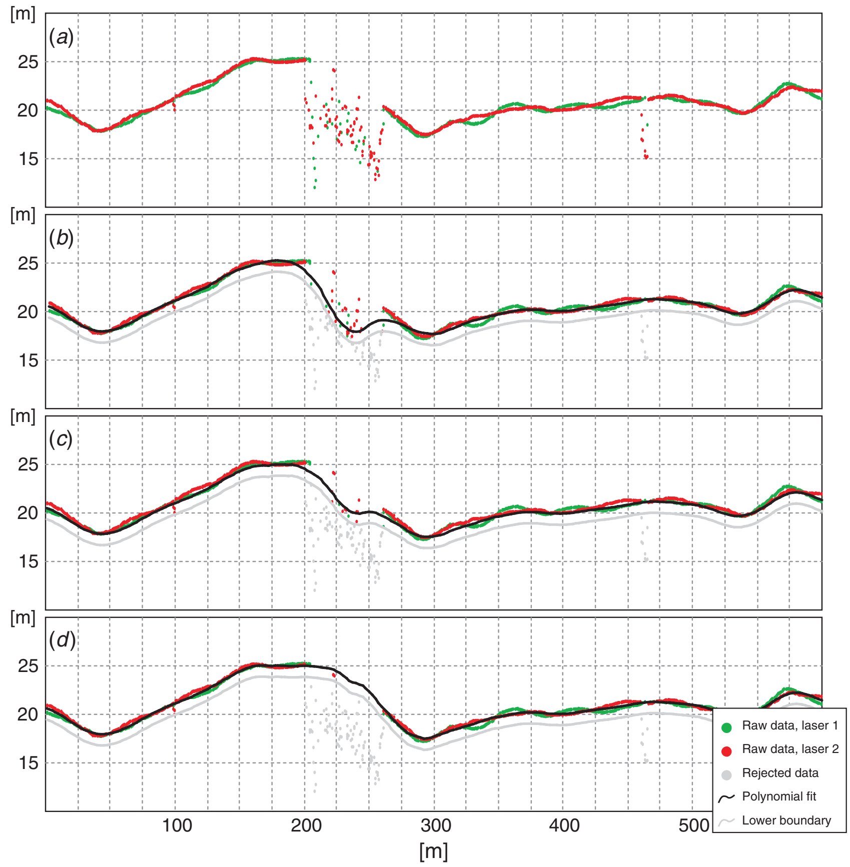


**Fig. 4.** The figure shows 600 m of laser altitude data. Panel (*a*) shows raw data stacks; between 200 and 275 m along track the helicopter passes across a small pine stand. According to the laser reflections, the trees are 5–10 m high. At 465 m, a windbreak is passed. Panel (*b*) shows the processed altitude after iteration 1 of the altitude processor, panel (*c*) shows the processed altitude after third iteration. Panel (*d*) shows the final output of the altitude processor.

ramps, and altitude. When acquiring data at different altitudes we can show that the SkyTEM response compares to better than 5% to the response of the standard model (Sørensen and Auken, 2004) at any of these altitudes.

The data for the SkyTEM system consist of navigation data and voltage data. The processing is implemented as a module in the Aarhus Workbench (Aarhus Geophysics, 2009), which is software developed in-house. The Aarhus Workbench is a common platform for working with geophysical, geological, and GIS data. It includes fully integrated modules for generating geophysical thematic maps, geo-statistic modelling, and visualisation on GIS maps. The SkyTEM processing system is fully integrated with the GIS component (MapX, MapInfo Inc.). This is extremely important when working in densely inhabited areas where long data sequences often have to be culled because data are severely biased by coupling to man-made conductors (Danielsen et al., 2003).

SkyTEM data processing is a four-step process: 1) navigation data are filtered and averaged automatically, and manual corrections may also have to be applied to the altitude data; 2) voltage data are processed automatically, i.e. filtered and averaged, and standard deviations based on the data stacks are calculated; 3) voltage data are evaluated manually for further refinement of the processing (necessary in areas with cultural responses); and finally 4) a fast inversion using a smooth model is used to fine-tune the processing done in steps 1 to 3. The automatic processing of SkyTEM data (steps 1 and 2) is done using several routines that work on the different data types. Each of the steps described above is addressed individually in the following sections.

## Navigation data processing

As mentioned above, navigation data are filtered and averaged automatically, and manual corrections are applied to the altitude data if needed.

The result of the automatic processing is inspected using profile plots of flight time versus data value (tilt, altitude, voltage data, etc.). This is illustrated in Figure 3. The plot also shows various quality control parameters, e.g. flight speed, topography, tilt (pitch and roll), etc. Other parameters like topography, transmitter current, transmitter temperature etc. can also be displayed. A key feature in the processing is the use of an integrated interactive GIS map where the helicopter location is highlighted. Combined with proper GIS themes, it is in most cases possible to explain most features in data, e.g. that the sudden increase in altitude and somewhat coherent noise is an effect of the helicopter crossing a power line, that the lasers get bad reflections because the helicopter is moving across a forest, etc.

Since navigation data are gathered with different time stamps and recorded with different sampling intervals, it is convenient to have the output of the navigation data processors interpolated to common fiducial times, at an interval which is typically set to 0.5 s or 1.0 s depending on the flight speed. The GPS positions are simply fitted with a 2nd order polynomial with a length of 10 s thereby interpolating them so that there is one GPS position per fiducial time. Positions are also relocated so they correspond to the centre of the transmitter frame.

### *The frame tilt processor – pitch and roll*

The tilt is measured both in front of the frame and at the back of the frame. The tilt measurements are important for the correction of the altitude measurements and as input to the inversion when inverting both *x*- and *z*-component data.

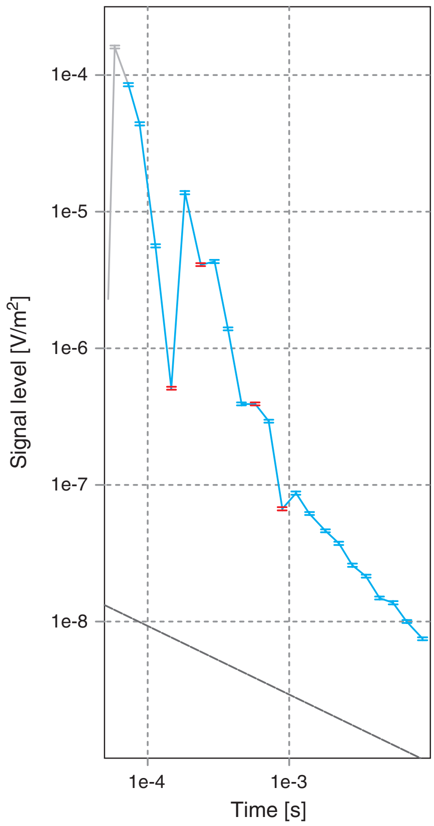


**Fig. 5.** The figure shows a capacitively coupled dataset being culled because the sounding has sign changes (error bars shown in red) in the interval before the signal reaches the noise floor. The noise floor is survey specific, but here it is 5e-9 V/m$^2$ at 1 ms and defined as being proportional to $t^{-1/2}$. A typical noise level seen in surveys from around the world is in the interval 5e-9–1e-8 V/m$^2$.

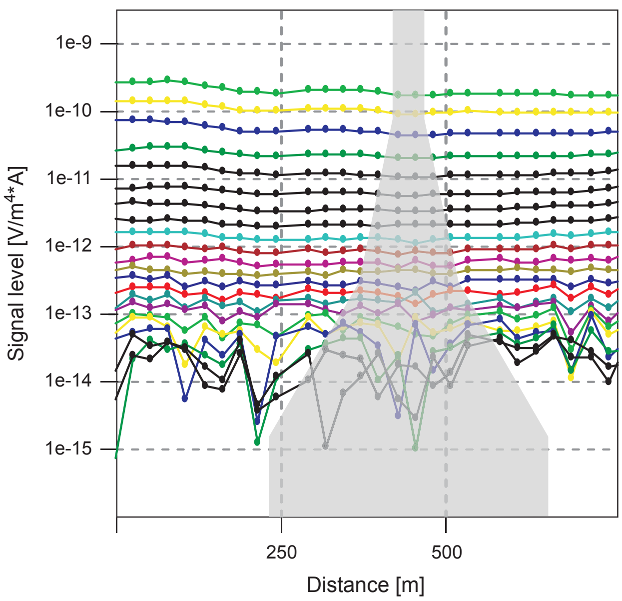


**Fig. 6.** Illustration of the trapezoidal average windows seen as a grey transparent polygon along with the raw data stacks. Averages are narrow at early times to avoid lateral smoothing of the near-surface geology and wide at late times where the signal/noise ratio needs to be increased to obtain the desired depth of penetration.

Data from the two tilt meters mounted on the stiff platform carrying the receiver coils (Figure 2) are normally used for the data processing. The tilt data are smooth and slowly varying due to the low frequency movements of the frame (see Figure 3). They are simply median filtered over intervals typically of 3 s and then interpolated to the fiducial times.

### *The altitude processor*

The altitude of the transmitter frame and receiver coils is measured to distinguish the substratum from air, especially in highly resistive areas. Good altitude estimates are necessary as they 1) prevent shallow, false highly resistive artefacts in the model and 2) give an accurate starting parameter and thereby help stabilise and speed up the inversion. Most problems in determining the correct altitude using lasers are caused by the laser beam not being reflected from the surface of the ground but from leaves. These reflections are seen as abrupt reductions in altitude as illustrated in Figure 4*a*.

To eliminate these reflections and to correct for the laser beam not always being vertical, several correction steps are taken. First, the altitude has to be calculated at the centre of the transmitter frame, second the altitudes need to be filtered, and third they are averaged and the altitude of the receiver coils are calculated.

The first step is a simple geometric calculation. The second step deals with altitude filtering. The challenge is to design a robust filtering scheme, which picks only the highest reflections assuming they come from the ground surface (through small holes in the leaf-cover), and at the same time do not remove the real altitude variations of the frame. We have designed a very simple recursive filtering scheme, which has proven to be robust even over dense forest with few reflections from the ground. Leaf reflections are simply removed by repeatedly fitting a high-order polynomial to the altitudes while removing outlying data. Typically, a 9th order polynomial is fitted in a least-squares sense to a length of 40–60 s of data. All data of range one metre less than the polynomial prediction are culled, and the process is repeated, typically 7–9 times.

As seen in Figure 4, panels *b*, *c*, and *d*, the filter gradually finds the maximum reflections in the along-track interval 200–275 m while leaving all other data untouched. The reflections from the windbreak at 465 m are removed almost immediately. The length of the polynomial and the order are normally adjusted manually by trial and error, and one set of settings are determined for the entire survey. The time interval has to be sufficiently long to cover long strips with tree top reflections, and the polynomial degree must be sufficiently high to leave the actual variations untouched by the filter. The recursive filtering is very fast and the trial and error process does not take much time.

After running the recursive filter on each of the lasers, data from both lasers are merged and fitted with a 9th order polynomial of length 40 s, and the altitude of the transmitter coil is calculated at the fiducial times. Finally, the altitudes

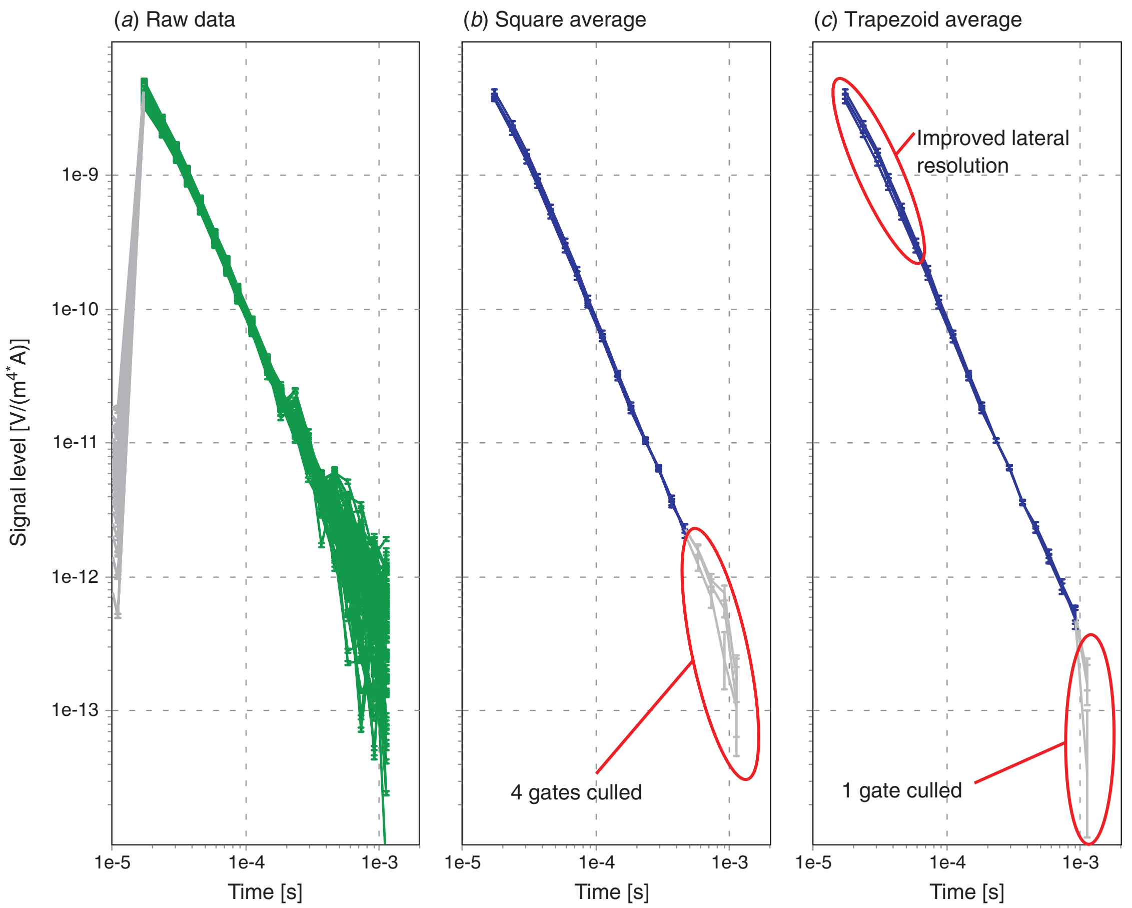


**Fig. 7.** The figure shows the effect of different averaging strategies. Panel (*a*) shows raw data stacks from a stretch of ~600 m, panel (*b*) shows the effect of using a 'square' averaging window of 150 m, while panel (*c*) shows the effect of using an averaging window of 25 m, 100 m, and 450 m at times 0.01 ms, 0.1 ms, and 1 ms, respectively. As seen in panel *c*, the benefits of using the trapezoid averaging is two-fold: an improved lateral resolution at early times and an increased signal-to-noise ratio at late times.

of the *x*- and *z*-receiver coils are calculated using the *x*-tilt (the pitch).

In a few cases, over very densely leaf-covered areas, the recursive filter does not output a reasonable estimate of the altitude, and in this case the user is free to manually draw the altitude he or she prefers. However, our experience is that it is better in these cases to let the altitude be determined in the inversion (see below).

## Processing of voltage data

High-quality data processing is a must in hydrogeophysical surveys; however, our experience shows that the same approaches can successfully be applied to most other types of surveys.

Voltages are divided into categories according to their processing stage: 1) instrument data, e.g. raw un-stacked transients from the receiver; 2) raw data, e.g. stacks of transients (instrument data); and 3) averaged data, e.g. averages of raw data stacks.

The raw voltage data are collected with a certain number of transients in the stack. The number of transients in the stack is set according to the desired signal-to-noise ratio and, equally important, the power line frequency (and its most powerful harmonics) is rejected. A typical stack size for the HM is 96 transients, and for LM and SLM it is 160 or 320 transients. It takes 1.92 s (HM) and 0.64 s (LM and SLM) (1.28 s if 320 transients) to complete these measurements and ~50 ms to change between the moments. When operating with the SLM and LM, an almost continuous sampling of the subsurface is achieved.

While the system alternates between LM + HM or SLM + LM in sequences of typically 10 pairs the 11th pair is used to measure the natural background level to assist the manual data processing, as discussed below. This is simply done by turning off the transmitter while the system still runs. In more remote areas the noise measurements are typically done for each 20th or 30th pairs of moments.

While densely sampled data increase the amount of data to handle, it also makes it possible to track rapidly shifting signal levels often seen in mineral exploration. SkyTEM voltage data from the instrument are by default stacked during import, i.e. a raw data stack is created with the number of transients mentioned above. However, depending on the target type, it is possible to make a subdivision of the data stacks: i.e. to create a raw data stack for every 8, 16 or 32 transients. The application of filters to the raw transients before stacking, to further increase the signal-to-noise level, is the subject of ongoing research. The *x*-component data, especially, show significant noise spikes, which are not efficiently suppressed by averaging only. Very useful noise-suppression techniques are discussed by Macnae et al. (1984).

Data from areas with a significant amount of infrastructure, such as pipes, power lines, and metal fences, unfortunately require a significant amount of manual processing, even though filters have been designed to help cull disturbed data. These data are

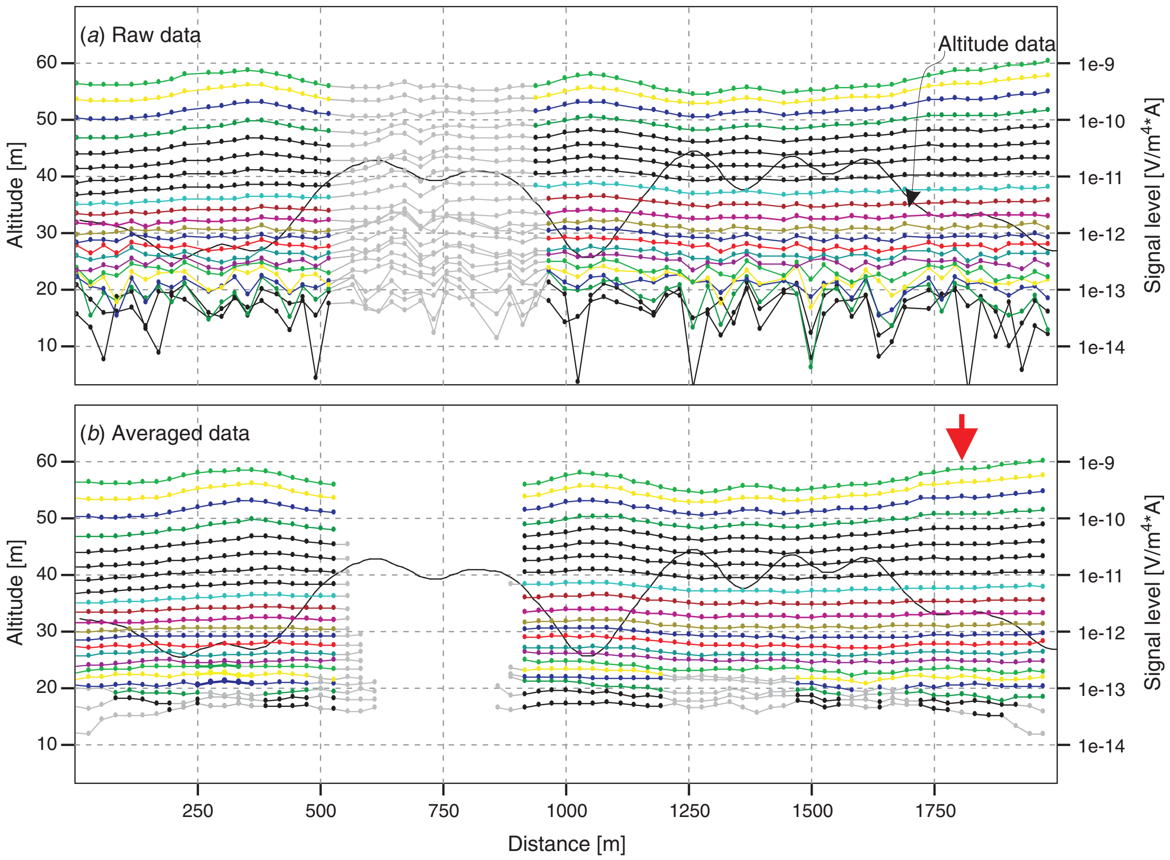


**Fig. 8.** The figure shows 3 min of HM data corresponding to ~2000 m on the ground. The time gates range from 7.18e-5 s to 8.8e-3 s. The flight altitude is illustrated with the black line in both panels. Panel (*a*) shows raw data while panel b) shows averaged data. The filtering width increases from 5 s to 12 s from the time gate in the interval 1e-4 s to 1e-3 s, then increases to 28 s at gate 1e-2 s. The non-spike filter removes ~20% of the raw data. A removed capacitive coupling is seen from 500 m to 850 m. The flanks of culled averaged data seen in panel (*b*) from 520 to 540 m and 820 to 840 m are caused by the trapezoidal averaging filter. The arrow indicates the location of the data shown in Figure 7*c*. The results of inversion of this data are shown in Figure 9.

removed entirely from the raw stacks, as they will otherwise be smeared out and significantly degrade the quality of the data that are not influenced by coupling. Danielsen et al. (2003) discuss the physics behind the galvanic and capacitive coupling phenomena. Designing filters to detect galvanic coupling is not considered viable as the signal level is simply raised and does not show oscillation. A filter for detection of capacitive coupling, which shows oscillations and possible sign changes, is easier to design. The capacitive coupling detection filter works by examining both the raw data stacks for changes in curve slopes and sign changes within the time interval where a useful signal is to be expected. In other words, the detection filter is executed from the first gate of the sounding until the signal reaches the noise floor. This is illustrated in Figure 5.

In most cases the entire data curve is removed even where only the late time gates (with signal above the noise level) are disturbed visually, i.e. they oscillate. This is done because we often see an unrealistic rise in signal (galvanic effect) before the actual oscillations. The noise level is estimated from the measurements of the background noise.

Typically, all data within a distance of 100–150 m from roads, power lines, windmills, slurry tanks etc. must be culled. The exact distance depends on the subsurface conductivity. A low-conductive ground produces a low electromagnetic response, which increases this distance, whereas a high-conductive ground produces a large signal, and the coupling distance is decreased.

The raw data stacks are corrected for the reduction in the effective of the transmitter and receiver when coils when the coils are tilted. For the $z$-component data this is

$$\frac{db}{dt_{cor}} = 2\frac{db}{dt}\cos(\alpha_{pitch})\cos(\alpha_{roll}), \tag{1}$$

where $db/dt_{cor}$ is the tilt corrected voltage, $db/dt$ is the voltage, $\alpha_{pitch}$ is the pitch angle and $\alpha_{roll}$ is the roll angle. Both the area of the transmitter and the receiver loops are reduced, hence the factor of 2. In itself this correction is just an area correction of the data, and it does not take into account the horizontal components of the tilted transmitter, nor does it correct for the horizontal magnetic field in the receiver loop as described for helicopter frequency domain data (HEM) in Fitterman and Yin (2004). However, forward modelling of the full system response has shown that, when the pitch and roll is below 15–20 degrees, the area correction is less than ~5% compared to the full solution which includes both $z$- and $x$-transmitter loops. For the normal operation, the pitch and roll is less than 15 degrees, and the correction is therefore negligible.

## *Designing an optimal data averaging scheme*

The standard approach for airborne TEM is that data are averaged over the same distance at early times and late times. The downside of this approach is that it is not possible to maintain a high resolution at early times (corresponding to the near surface), where the signal-to-noise ratio is usually relatively high, and still obtain a reasonable signal-to-noise ratio at late times, i.e. at a large penetration depth. Furthermore, for quasi-layered environments, it must be stressed that a small sounding distance, e.g. 5 m, does not necessarily correspond to a high lateral resolution if data are still averaged over long time spans or distances, e.g. 150 m. It just means a high level of redundant information.

Our approach is to use trapezoidal average windows so that early-time data are averaged less than late-time data, as illustrated in Figure 6. This approach is actually an image of the nature of the electrical fields in the substratum itself. If a sounding is produced e.g. at each 30 m, the very early time data will not be averaged over more than 30 m, whereas late-time data may be averaged over e.g. 300 m. By doing this we 1) maintain the optimal resolution of the near-surface resistivity structures, where the current system in the ground is relatively small and the signal-to-noise ratio good, and 2) obtain a reasonable signal-to-noise ratio at late times, thereby maintaining the desired penetration depth. Deeper lying structures are averaged both by the larger current system and by the filters, but the amount of redundant information is minimized.

The actual width of the trapezoidal average filter is normally chosen as narrow as possible for the early-time gates to give the highest possible unsmeared resolution of the near-surface resistivity structures. The late-time gates are averaged so that the desired depth of penetration is obtained while still retaining lateral resolution of the geological layers. Simulation of the averaging filter has been carried out on synthetic 3D data generated over buried channel structures, data presented in Auken et al. (2008). The results show that late-time data averaged over up to 200 m laterally do not change the inverted model significantly.

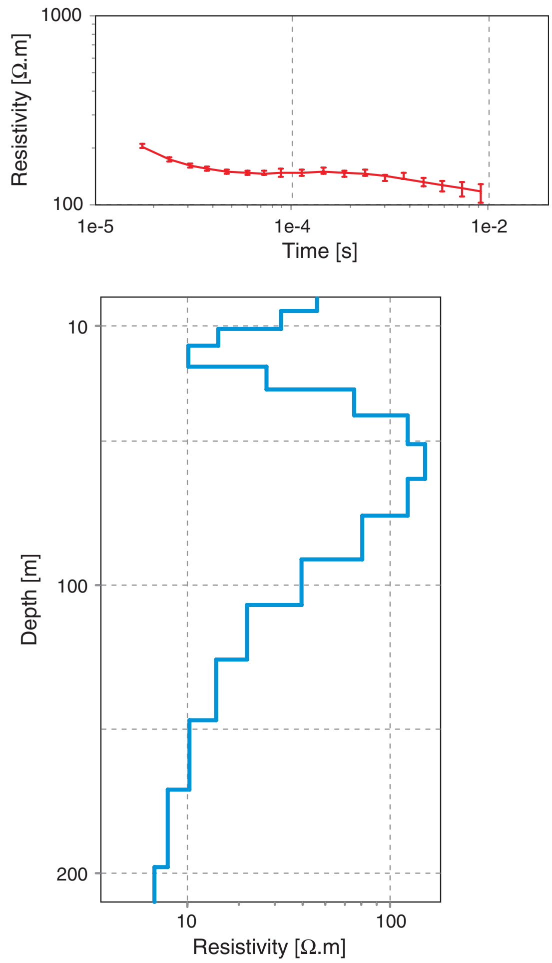


**Fig. 9.** Model curve showing the sounding from Figure 7*c* (red error bars) along with the forward response (red line). As seen, data are generally well fitted. The model shows a thin (~10 m) uppermost layer with a resistivity of ~40 Ω.m, underlain by a layer of similar thickness and a resistivity of 10 Ω.m. Below this layer is found a thick high resistive layer (~100 Ω.m) overlaying a ~10 Ω.m layer. Geologically the model reflects from the top; till, clay rich till, sand/gravel (aquifer), and tertiary clay (aquitard).

The effect of late and early time averaging is illustrated in Figure 7. The raw data in Figure 7*a* are filtered and averaged using a square averaging windows (Figure 7*b*) where data are averaged over ~150 m at both early and late times, and a trapezoidal averaging window (Figure 7*c*) where data are averaged over ~25 m at 0.01 ms, 100 m at 0.1 ms, and 450 m at 1 ms. As expected, the increased averaging at late times increases the signal-to-noise ratio considerably, as indicated by the grey data points showing which gates would be culled in a normal processing phase because of not meeting the desired signal-to-noise ratio. In this case only one is culled for the trapezoidal scheme and four for the square scheme. Furthermore, the use of a relatively wide averaging core at early times, which is necessary to maintain at least a reasonable signal-to-noise ratio at late times, means loss of resolution at early times in the square case.

During this filtering the raw voltage data are not corrected for variations caused by varying altitude over the averaging window. Such a correction would require a full inversion of the raw datasets, which would then be used for calculating a set of correction factors to bring the response to a nominal flight altitude. It can, however, be shown that the error introduced by using an average can be neglected for altitude changes less than 20 m in the averaging window.

The average soundings are formed by applying a de-spike filter for each time channel. Typically 20% of the raw data stacks (at each channel) are removed, and the rest are averaged while also calculating the standard deviation. Our experience shows that the de-spiking is important, especially on *x*-component data where the raw data are characterised by noise spikes of high amplitude and short duration. A typical data profile is shown in Figure 8. From 500 to 850 m along track the helicopter crosses a road, and capacitive coupling is seen. These data have been removed from the raw data stacks as seen in Figure 8*a*. The last usable time gate in the averaged data (Figure 8*b*) is 0.88 ms.

## Inversion

Inversion of SkyTEM data is the subject of several other papers and abstracts (Viezzoli et al., 2007; Auken et al., 2008), and the intention of the following is therefore just to tie together the processing and the inversion.

### *Using a smooth inversion for post processing of voltage data*

Both in situations where a large part of the data are culled because of coupling, and in situations where the main noise source is the

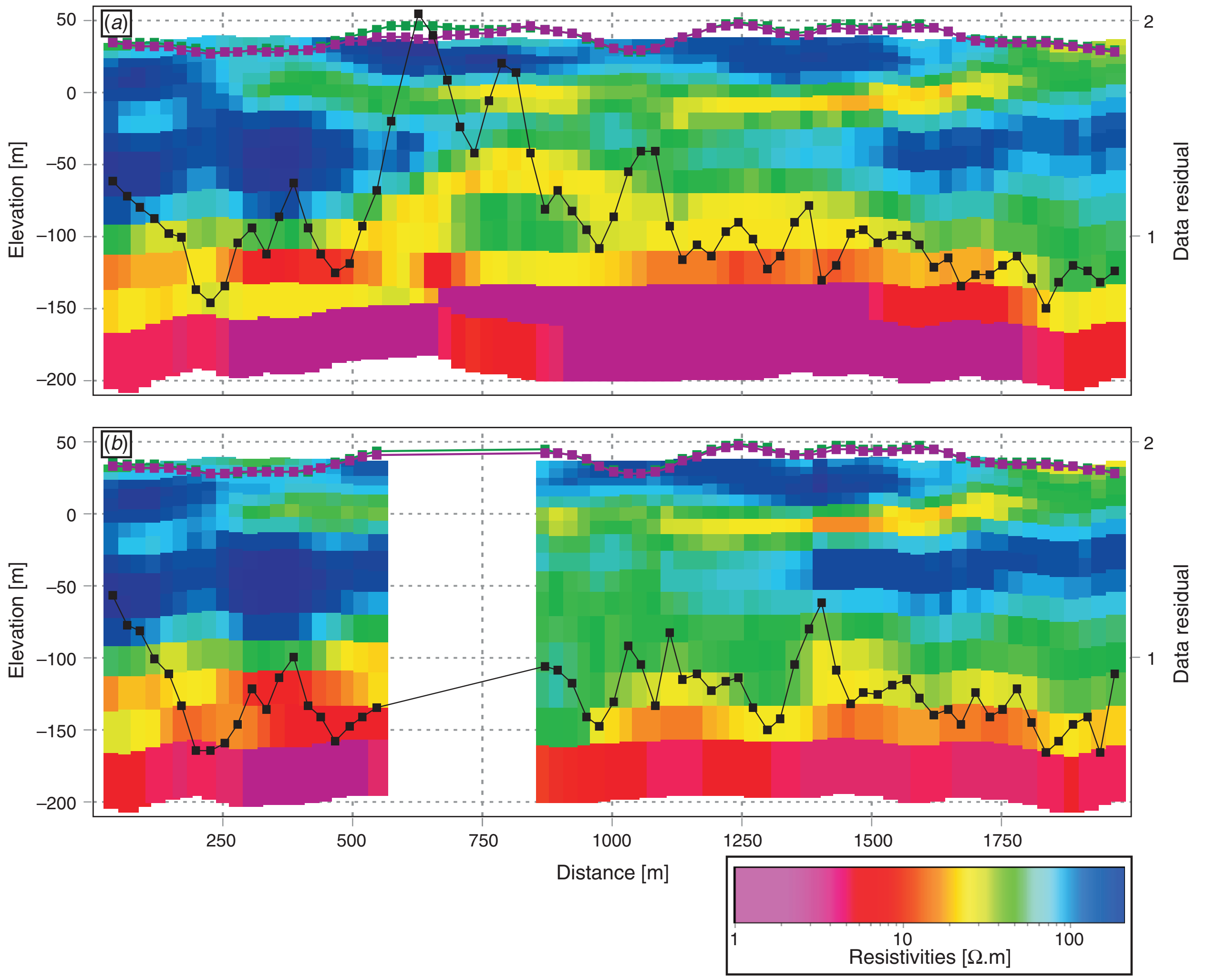


**Fig. 10.** The figure shows an inverted section of the data shown in Figure 8 plus the LM moment. Inversion has been run on data including coupled data (panel *a*) and where the data had to be removed because of the crossing of a road (panel *b*). The distortion is seen in panel (*a*), mainly as a conductive body that migrates to the surrounding areas through the lateral constraints.

natural background noise, we find it useful to run a smooth inversion of the average data as the final step in the processing. We use the Laterally Constrained Inversion (LCI) algorithm (Auken et al., 2005) for this. This inversion is used to remove outlier data that, for some reason, have not been removed in the automatic filters or the manual processing. Such data always occur at late times where the signal-to-noise level is low. Typically, data that deviate more than twice the data standard deviation to the forward response of the inverted models are removed. As an example of a smooth inversion Figure 9 shows the results of inverting the data in Figure 7*c*. Data are converted to late time apparent resistivity to make it easier to evaluate the data fit. Data are well fitted at early as well as late times.

### *Final inversion of data*

The data standard deviation calculated from the data stack enters the inversion scheme and is used basically to weight the individual data points. The flight altitude is also treated as an inversion parameter, with an a priori uncertainty set at a fixed number, typically $\pm 3$ m. Constraining the altitude no more than 3 m allows the inversion to move the altitude to its correct value, thereby not compromising the validity of the model.

The inverted section of the data in Figure 8 plus the LM data (not shown), are shown in Figure 10 along with data residuals (black line/dots) and input altitude (green line/dots) and output altitude (purple line/dots). The model has sixteen layers with fixed thicknesses, and the LCI algorithm was set up with a lateral variation from model to model of a factor of 1.5 for resistivities. The inversion was run both on data for which the distorted data around 500–850 m had not been removed (Figure 10*a*) and on data for which they had (Figure 10*b*). As expected, the major difference in the results is around the centre of the distortion, which is seen mainly as a conductive body in panel a. In the LCI, due to averaging and the lateral constraints, this unwanted information migrates laterally to the surrounding areas thereby degrading the quality of these data. It is also seen from the data residual that data in this area are poorly fitted and that the inversion routine actively moves the altitude in order to fit data. In Figure 10*b*, it is seen that data are generally fitted without needing move the altitude.

## Conclusion

We have discussed the entire workflow of processing SkyTEM navigation and voltage data. The navigation data include data from GPS receivers, frame pitch and roll, and frame altitude. Several steps are taken to obtain maximum data quality and by this to get the most detailed possible resolution of the resistivity structure of the subsurface. At all stages in the processing it is know by the user what is done to the data and no system or processing parameters are proprietary.

Even though the raw voltage data are bias free, they need to be corrected to account for the reduced horizontal transmitter and receiver areas when the frame moves in the air. Data are averaged using trapezoidal average filters, and data are also de-spiked. The filters are designed so that the lateral resolution of resistivity structures is least possible smeared. With this design the lateral resolution of the shallow subsurface is maintained through a narrow averaging of early-time data, whereas the optimal penetration depth is achieved through a wider average.

We have argued that data which are influenced by coupling to man-made installations on the ground surface must be culled before entering the averaging scheme as, otherwise, good data are degraded. It is important that this is done by the geophysicist processing the data, as he or she has the source information necessary to decide whether data are coupled or not. This information is not readily available after averaging and inversion.

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