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On the value of including x-component data in 1D modeling of electromagnetic data from helicopterborne time domain systems in horizontally layered environments

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ABSTRACT

Helicopter borne time domain EM systems historically measure only the Z-component of the secondary field, whereas fixed wing systems often measure all field components. For the latter systems the X-component is often used to map discrete conductors, whereas it finds little use in the mapping of layered settings. Measuring the horizontal X-component with an offset loop helicopter system probes the earth with a complementary sensitivity function that is very different from that of the Z-component, and could potentially be used for improving resolution of layered structures in one dimensional modeling. This area is largely unexplored in terms of quantitative results in the literature, since measuring and inverting X-component data from a helicopter system is not straightforward: The signal strength is low, the noise level is high, the signal is very sensitive to the instrument pitch and the sensitivity function also has a complex lateral behavior.

The basis of our study is a state of the art inversion scheme, using a local 1D forward model description, in combination with experiences gathered from extending the SkyTEM system to measure the X component. By means of a 1D sensitivity analysis we motivate that in principle resolution of layered structures can be improved by including an X-component signal in a 1D inversion, given the prerequisite that a low-pass filter of suitably low cut-off frequency can be employed. In presenting our practical experiences with modifying the SkyTEM system we discuss why this prerequisite unfortunately can be very difficult to fulfill in practice. Having discussed instrumental limitations we show what can be obtained in practice using actual field data. Here, we demonstrate how the issue of high sensitivity towards instrument pitch can be overcome by including the pitch angle as an inversion parameter and how joint inversion of the Z- and X-components produces virtually the same model result as for the Z-component alone. We conclude that adding helicopter system X-component to a 1D inversion can be used to facilitate higher confidence in the layered result, as the requirements for fitting the data into a 1D model envelope becomes more stringent and the model result thus less prone to misinterpretation.

1. Introduction

Airborne time domain electromagnetic systems can be divided into two categories; helicopter and fixed wing systems. Helicopter systems such as SkyTEM (Sørensen and Auken, 2004), VTEM (Witherly et al., 2004), AeroTEM (Balch et al., 2003) and HoistEM (Boyd, 2004) carry the instrument as a sling load beneath the helicopter. These systems have relatively fixed transmitter/receiver geometries with loops that remain close to horizontal during operation. This type of controlled geometry operating almost parallel to the ground is very well suited for measuring the component of the secondary field perpendicular to the ground, i.e. the Z-component, which is most often the component of interest. The characteristics of the field component along the flight direction, i.e. the X-component, are very different from those of Z since the signal is weaker, decays faster with time, has a higher noise level, and is more sensitive to minor changes in geometry.

Fixed wing systems such as GeoTEM (Annan, 1991), Spectrem (Leggatt et al., 2000) and TEMPEST (Lane et al., 2000) have a transmitter mounted around the aircraft itself and carry a set of receiver coils being towed in a "bird." This implies that the relative transmitter/receiver geometry is constantly varying and the receiver coils are often exposed to significant movement (pitch, roll and yaw). For such systems, the field components can be of almost equal magnitude and hence all 3 field components are typically measured in modern instruments. Historically, fixed wing systems have used the X-component to qualitatively locate discrete conductors, since this component couples strongly with vertical conductors as discussed by Smith and Keating (1996). These authors further describe how the Z-component is more appropriate in the case of layered target structures, but examples of X-component data used for mapping of layered environments also exist, e.g. Huang and Palacky (1991) and Palacky and West (1973). Regardless of target structure, the

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receiver coil orientation can greatly influence the measured field components, making it necessary to account for geometry in any quantitative analysis. Rotation of receivers will cause a projection of field components into each receiver coil, effectively making each coil measure a superposition of the X-, Y- and Z-components. Since such geometric effects can be substantial it is desirable to have highly accurate measures of pitch, roll and yaw, which can require sophisticated monitoring and processing methodology (Davis et al., 2009). Assuming accurate geometric information is available it can be accounted for in different manners. This includes relatively simple geometric data correction techniques (GEOTEM, Smith and Annan, 1997), joint inversion of all field components including geometric model parameters with prior information (TEMPEST, Lane et al., 2004) and inversion of the total field amplitude (GEOTEM, Christiansen and Christensen, 2003). Field amplitude inversion provides the benefit of being independent of receiver rotation and was suggested by Macnae et al. (1991).

1.1. The sensitivity function of the X- and Z-components

In this paper we study what we will refer to as helicopterborne offset loop systems. In Fig. 1 we show the X- and Z-component normalized sensitivity functions for such a system (Niels Bøie Christensen, personal communication). The figure is a straight forward extension of the work on frequency domain sensitivity functions by Tølbøll and Christensen (2007) transformed into the time domain (Hördt, 1998). Based on the significantly different properties of the respective sensitivity functions, it is seen that additional complementary information can be extracted using multiple field components. The Z-component sensitivity function is almost strictly positive and close to being symmetric, whereas the X-component sensitivity function has multiple sign changes and is more localized at the surface. This implies that including the X-component could potentially improve near-surface vertical resolution, due to the addition of a more near-surface confined sensitivity function. In the case of lateral resolution the influence of including X component data is likely to be even stronger, as the sign-changes of the sensitivity function essentially differentiate lateral conductivity variations. As for the temporal trends of the sensitivity functions these can be visualized by comparing the early and later time plots of Fig. 1. Here, the lobes formed by contour lines illustrate how most of the X-component sensitivity is initially located immediately beneath the helicopter, and it further shows how the sensitivity smears out with time as a result of diffusion. From this type of comparison it is also clear that the sensitivity towards lateral variation should be highest at early times.

It has previously been shown that X-component data from helicopterborne systems can be used successfully for the mapping of discrete conductors and other 2D/3D structures (Smith et al., 2009), however, to our knowledge no quantitative studies of the effect on mapping of 1D layered structures appear in the literature. In the fixed wing literature X-component data also finds little use for detailed mapping of layered structures, but Ley-Cooper et al. (2010) show its importance for mapping sharp discontinuous boundaries with a TEMPEST instrument and Lane et al. (2004) show how X-component data is in fact necessary in order to include pitch as a model parameter in 1D inversion of TEMPEST data. Taking the existing literature into account we find it very relevant to quantitatively investigate the potential use of helicopterborne system X-component data for mapping of structures that are normally regarded 1D. After all, there is no doubt that the information contained in the X-component is complimentary to that of the Z-component and we hypothesize that the use of X-component data could be used for improving near surface resolution.

The scope of our study is to investigate the effects of including X-component data from helicopterborne systems in the mapping of layered structures, performed within the established practice of one dimensional (1D) forward and inverse modeling. Very recently, Cox et al. (2010) showed that 3D inversion is in fact computationally feasible at a survey scale, however, we believe that there are several obstacles to be overcome before full 3D inversion will become common practice at a survey scale (Viezzoli et al., 2010).

We start by presenting our reference airborne TEM system, our forward modeling and inversion methodologies, followed by the results of a synthetic study of layered resolution. Following the synthetic study we describe how we have modified an actual SkyTEM system for measuring X-component data, present our experiences from a practical point of view and show results from an actual field example. The paper is rounded off by a discussion of the practical and theoretical implications of X-component data from a 1D modeling point of view with concluding remarks.

2. Reference AEM system

We consider the case of helicopterborne offset loop systems, using the characteristics of the SkyTEM system (Sørensen and Auken, 2004). This system utilizes a horizontal transmitter loop mounted on a rigid wooden frame, which is also equipped with a receiver platform holding the offset-position Z- and X-component coils, as shown in Fig. 2. Both receiver coils are located in positions where the primary field from the transmitter loop can be safely neglected for production surveying situations. For the Z-component coil this is about 1.9 m

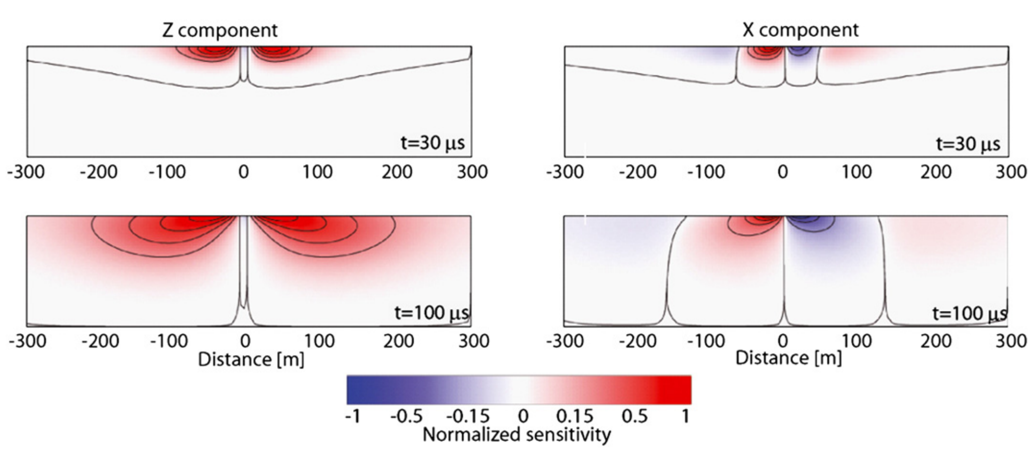

Fig. 1. Z and X component normalized sensitivity functions on a homogenous halfspace at 30 and 100 µs. The plots are normalized to the maximum at the respective time and are for the step response of a circular loop transmitter centered at an altitude of 25 m, ie (x,y,z) = (0,0,25), and a vertical magnetic dipole receiver located at (x,y,z) = (-12,0,25). Arbitrary contour levels (including zero) are added to emphasize shapes.

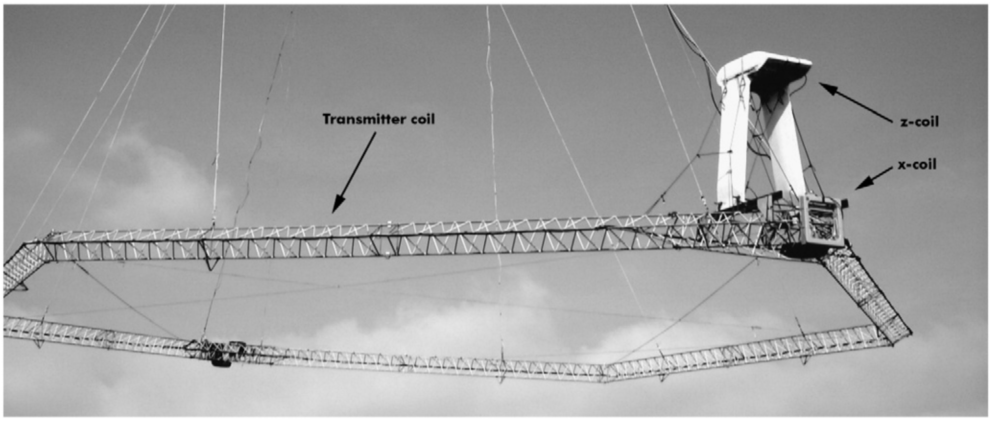

Fig. 2. Picture of the SkyTEM transmitter frame. The X- and Z-receiver coils are located where the primary field from the turn-off ramp is zero for each of the components. The transmitter is attached along the frame and has 1–4 turns, depending on the transmitter moment. The system is made as rigid as possible and even more importantly, the platform carrying the receiver coils is constructed in one stiff unit to ensure constant geometry of the coils at all times.

above the transmitter loop, whereas the X coil zero-position is in the plane of the transmitter. Locating the receiver coils in the two zero positions not only protects the receiver electronics from saturating during the transmitter turn off, but more importantly ensures that the measured signal does not include any primary field which would otherwise bias the measurements. During operation the system uses dual alternating transmitter moments, a low and a high moment, ensuring high resolution of near surface structures as well as providing a large depth of investigation. In the system as of 2008 we drive 40 A of current through one turn of the transmitter loop to generate the primary field of the low moment and 90 A through 4 turns for the high moment. Normally, the system utilizes a 340 kHz low-pass filter and measures the Z-component only, but for the purposes of the studies presented here we have also equipped the system with an experimental filter configuration using a 60 kHz filter for the X-component. The addition of this experimental filter is the result of simulations and experimentation in optimal acquisition of X-component data.

3. Modeling

3.1. Forward modeling

Our 1D forward model as implemented in em1dinv (Christiansen and Auken, 2009) is based on the theory of Ward and Hohmann (1988) and applies to most airborne EM systems. Our code allows for full system modeling including transmitter geometry, waveform and receiver low-pass filters, which can all be source of serious modeling errors when improperly described (Christiansen et al., 2011).

The systems being investigated are helicopterborne sling load systems, for which it is safe to assume that the transmitter structure is rigid and pitch and roll angles can be kept small given the right operating conditions. This includes weather conditions being reasonable, an adequately skilled pilot and that the helicopter speed remains sufficiently low during data acquisition. We strive always to fulfill these criteria for our own surveys and we provide characteristic numbers for pitch and roll of the SkyTEM system during operation in Section 5.

Assuming that the system geometry is well behaved we use the vertical projection of the transmitter moment for our further calculations, i.e. account for the small system rotation angles by means of a geometric factor. This is an approximation that has been proven highly accurate in the case of frequency domain systems (Yin and Fraser, 2004). As for the receiving part of the system we have to take the pitch and roll angles more directly into account. When a receiver coil is rotated with respect to the ground it will detect a superposition of all field components, as illustrated for a rotated X receiver coil in Fig. 3. The measured "contaminated" response, dB'_x/dt, is given by a simple projection of the actual field components given a pitch angle, α:

$$\frac{dB_x'}{dt} = \frac{dB_x}{dt} \cdot \cos(\alpha) + \frac{dB_z}{dt} \cdot \sin(\alpha) \tag{1}$$

In this equation the sign of the Z-component contribution to the contaminated X-component signal follows the sign of α, which allows the signal to go negative and also makes it highly sensitive to α. This angular dependency can also be observed from the synthetic

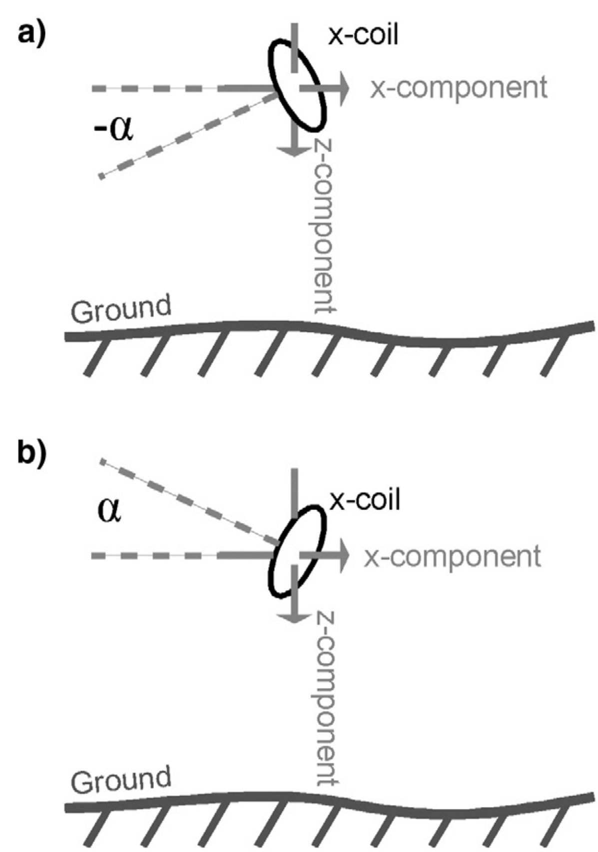

Fig. 3. Illustration of field component mixing for a rotated receiver coil. (a) and (b) illustrates negative and positive pitch angles α, respectively.

responses of Fig. 4a. Here, we simulate the helicopterborne offset-loop SkyTEM system (Sørensen and Auken, 2004) fitted with an X-component receiver coil, as described previously. We use the SkyTEM system as basis for our simulations, but also emphasize that the results apply to any small offset loop system. For such a system we find that the typical Z/X-component ratio for various half-spaces is in the order of 5 for early times and greater than 10 at late times, as seen in Fig. 4b. Using Eq. (1) we see that a tilt measurement error of just 1°, e.g. from 5 to 6°, will result in approximately 6% data error for the early time gates where the z-response is around 5 times larger than the X-component response. Such extreme sensitivity represents a challenge, since it can be difficult to monitor pitch with an accuracy of 1° during operation. The issue of determining pitch will be discussed in more detail later in Section 5, but for now we will consider two ways of overcoming this issue: (1) Including the pitch as a model parameter with prior information in the inversion and (2) transforming to field amplitude (total field). The field amplitude is defined as:

$$\frac{dB_{FA}}{dt} = \sqrt{\frac{dB'_x(\alpha)}{dt} + \frac{dB'_z(\alpha)^2}{dt}} \tag{2}$$

Here, the Z-component is simply the Z-component equivalent of Eq. (1), making the field amplitude independent of pitch, since vector norms are invariant under rotational translation. Note that the X-component contribution to the Z-component can be safely neglected in actual numerical calculations, since the X signal is relatively weak and α is small.

3.2. Inverse modeling

For inversion we use the Laterally Constrained Inversion (LCI, Auken et al., 2005) scheme, extended to include system pitch and altitude as model parameters (Auken et al., 2009a). This inversion scheme solves the non-linear inversion problem in a linearized iterative manner, conceptually outlined in the following. First, the non-linear forward response **g** is linearized using a first order approximation for mapping model space vectors, **m**, into observed data space, $\mathbf{d}_{\text{obs}}$:

$$\mathrm{d}_{obs} + e_{obs} \cong g\left(m_{ref}\right) + G\left(m_{true} - m_{ref}\right) \tag{3}$$

In this equation $\mathbf{e}_{\text{obs}}$ is a stochastic vector representing the error on the observed data, $\mathbf{m}_{\text{true}}$ and $\mathbf{m}_{\text{ref}}$ are the true model vectors and some reference vector, respectively, and **G** is the Jacobian matrix. Rewriting Eq. (3) in terms of model updates for an iterative solution scheme the inversion problem becomes:

$$G\delta m_{true} = \delta d_{obs} + e_{obs} \tag{4}$$

We solve this equation iteratively in a least squares sense, by minimizing the L_2 misfit functional Q in Eq. (5) using a Gauss-Newton style minimization scheme with a Marquardt modification (Marquart, 1963).

$$Q = \left(\frac{1}{N}\left[\left(\delta d_{obs}^T C^{-1} \delta d_{obs}\right)\right]\right)^{\frac{1}{2}} \tag{5}$$

Here, **C** is the covariance matrix describing the error on the observed data and N is the number of data points. Finally, the scheme allows for calculation of linearized uncertainty estimates on the resulting model parameters in the form of the covariance matrix of the model estimate:

$$C_{est} = \left(G^T C^{-1} G\right)^{-1} \tag{6}$$

The full inversion scheme also integrates regularization in the form of lateral and vertical smoothness, as well as support for prior

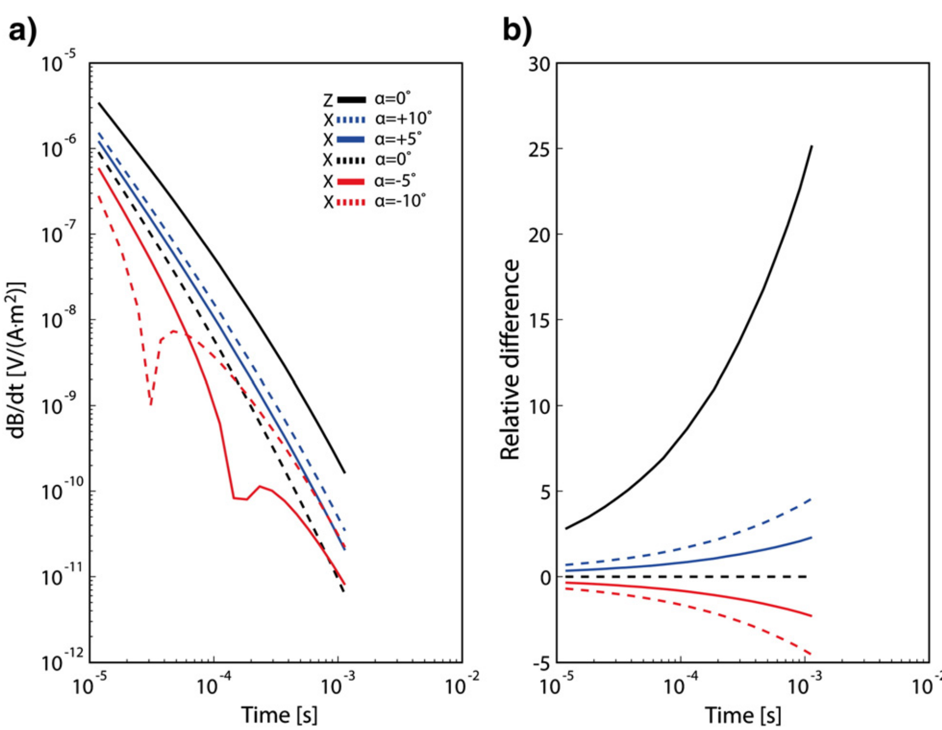

Fig. 4. Illustration of the influence of pitch angle α. The synthetic data is calculated at an altitude of 30 m over a 50 Ωm half space using a transmitter loop of 314 m². In (a) actual sounding curves are shown, whereas (b) shows the relative signal difference with respect to the X component response for α = 0° (i.e. the difference to this reference response divided by this reference response). Note how the Z-component signal is generally much larger than the X-component, which also drops off faster with time, and how the X responses for α = −5 and α = −10 include sign changes.

information, by adding more systems of equations of the type seen in Eq. (4). For the results presented here we use the LCI constraining scheme where we invert multiple sounding at a time, having the model parameters of adjacent soundings connected by a series of distance normalized constraints. This regularization technique is used to impose the assumption of smooth lateral variation onto the solution, not only for the model parameters of a layered 1D earth but also for instrument altitude and pitch as discussed by Auken et al. (2009a). For brevity, we refer to Auken and Christiansen (2004) and Auken et al. (2005) for the full details on the formalism, which has proven a reliable way of constraining profile lines of 1D models for producing pseudo 2D sections.

4. Model parameter resolution

4.1. Vertical model sensitivity analysis

Our quantitative investigation of the effect of including X-component data starts by considering the effect on vertical resolution, by means of single site 1D model parameter analysis using the described forward modeling and inversion methodologies. In order to make the simulation as realistic as possible we choose to model the characteristics of the SkyTEM system, but this could apply to any other helicopterborne TEM system with a similar offset. The output of the model parameter analysis is conveniently viewed as a relative measure of uncertainty, since our inversion scheme operates in log space. The absolute analysis values from log space translates into a standard deviation factor in linear space, such that 1 is equal to perfect resolution and 1.1 is approximately equal to a standard deviation of 10%. In rough terms, model parameters can be considered well determined when the analysis factor is less than 1.2, reasonably well determined for factors of 1.2 to 1.5, poorly determined for factors of 1.5 to 2 and undetermined when larger than 2. It should also be noted that single site sensitivity analysis results should not be viewed as a direct benchmark of what cannot be resolved in an actual survey. Single site 1D sensitivity analysis provides a simple and useful tool for simulating the influence of instrumental modifications, but it does not fully reflect the properties of an LCI inversion of entire flight lines at a time. In this case LCI constraints are used to entangle the parameters of neighboring models, which facilitates propagation of information along the profile and generally improves the degree of model parameter determination. As such, the results of the following simulations should be viewed as a relative metric, since many models appearing unresolved in this type of analysis will actually be well resolved in a LCI inversion.

One main prerequisite in performing a realistic sensitivity analysis is to first specify a realistic noise model. Assuming there is no coupling to manmade installations, the noise can be described by a power function decaying with time and with a significant level difference between the vertical and horizontal components. The space between the earth and the ionosphere acts as a spherical waveguide for ambient noise, making the horizontal noise component in the order of 5–10 times larger than the vertical component (McCracken et al., 1986; Spies, 1988). For the purposes of our investigation we assume an optimistic difference of a factor of 4, in order to simulate ideal conditions. The used baseline noise level for Z transmitter moments is $4{\cdot}10^{-9}\,\mathrm{V/m^2}$ at 1 ms, decaying with a power of -0.5 (e.g., $t^{-0.5}$), whereas the X noise is 4 times larger at 1 ms and decays as -0.7 based on empirical measurements of noise levels. In order further to make the noise levels resemble the outcome of an actual data processing (Auken et al., 2007) we add an additional uniform noise contribution of 3%.

In Fig. 5 the analyses of 4 different simulated setups are shown for 2 different layered models, representative of our findings in experimenting with different models. The first model simulated in Fig. 5a, includes a very clear resistivity contrast at the near surface, whereas the contrasts in the second model in Fig. 5b are more subtle. For each model parameter the figure shows the result of simulations of Z-component data only, Field Amplitude (FA), joint Z + X and joint Z + X including experimental filters. The latter configuration uses experimental low-pass filters with a cutoff of 60 kHz for X, whereas the rest of the configurations use standard SkyTEM low-pass filters with a cutoff of 340 kHz. The simulation is run for an altitude of 30 m, a pitch angle of 2 degrees and the first time gate in 18 μs. Note that for brevity we show results for altitude and thicknesses in Fig. 5a only. We omit these parameters in later figures as the use of multi component data has insignificant influence on the sensitivity towards instrument altitude and that the effect on resolution of layer thicknesses can be derived from the depth results.

Comparing the results of Fig. 5a and b it is clear that the impact of including the X-component is model dependent, which is to be expected given the more near surface localized sensitivity function. In Fig. 5a the near surface resistivity contrast is so pronounced that it is already reasonably well resolved by the Z-component alone, which is not the case for the model in Fig. 5b. Here, the Z-component sensitivity analysis indicates that most model parameters are undetermined or poorly determined in terms of the rule of thumb classifications discussed in the beginning of this section. In both cases joint inversion with experimental filters prove to be the only configuration bringing substantial resolution improvements over the Z-component alone. We also find minor improvements for joint inversion using standard filters, but the effect is generally much more subtle. For FA we find that the vertical resolution capability is virtually identical to that of the Z-component alone, which is also what is to be expected. The X contribution to the norm is very small and noisy and the main reason for using FA is avoiding the high sensitivity towards rotated geometry.

In Fig. 6 we examine the model of Fig. 5b in more detail, since this is the hardest model to resolve. Here, we repeat the simulation using earlier time gates starting from 12 μs and in Fig. 6b we further double the base noise level to $8{\cdot}10^{-9}\,\mathrm{V/m^2}$ at 1 ms. Comparing Figs. 5b and 6a it is clear that earlier time gates provide substantial improvements towards resolving the model. Most importantly, we note that using the Z-component alone with earlier time gates as in Fig. 6a, provides an improvement comparable to that of the joint inversion with experimental filters in Fig. 5b. This is an important observation, since it proves difficult to reliably measure the X-component for very early times. We finally note that the tendencies remain the same for different baseline noise levels as seen in Fig. 6b.

5. The skytem system and x

In the synthetic resolution study of the previous section we have shown how including measurements of X-component data in principle can be used to improve the resolution of layered structures for helicopterborne time domain systems. In particular, we have shown how vertical resolution can be improved considerably by using both Z and X-component data in conjunction with low-pass filters with a low cutoff frequency. We will now shift our focus from theory to practice and go into the details about what can be accomplished in practice using an actual airborne EM system; in this case the SkyTEM system.

For the purposes of including X-component data to the system, we have shown that the signal is extremely sensitive to the pitch angle making it necessary to measure this angle accurately. During operation the pitch of the SkyTEM system normally varies within +/- 5 degrees of a general offset from horizontal of up to 10 degrees, depending on the wind speed and the flight direction. The roll (i.e. the tilt measured perpendicular to the flight direction) is normally very close to 0 degrees. For acquisition of pitch data we have equipped the system with dual tilt meters, mounted on the transmitter frame as close to the receiver coils as possible. Even though the

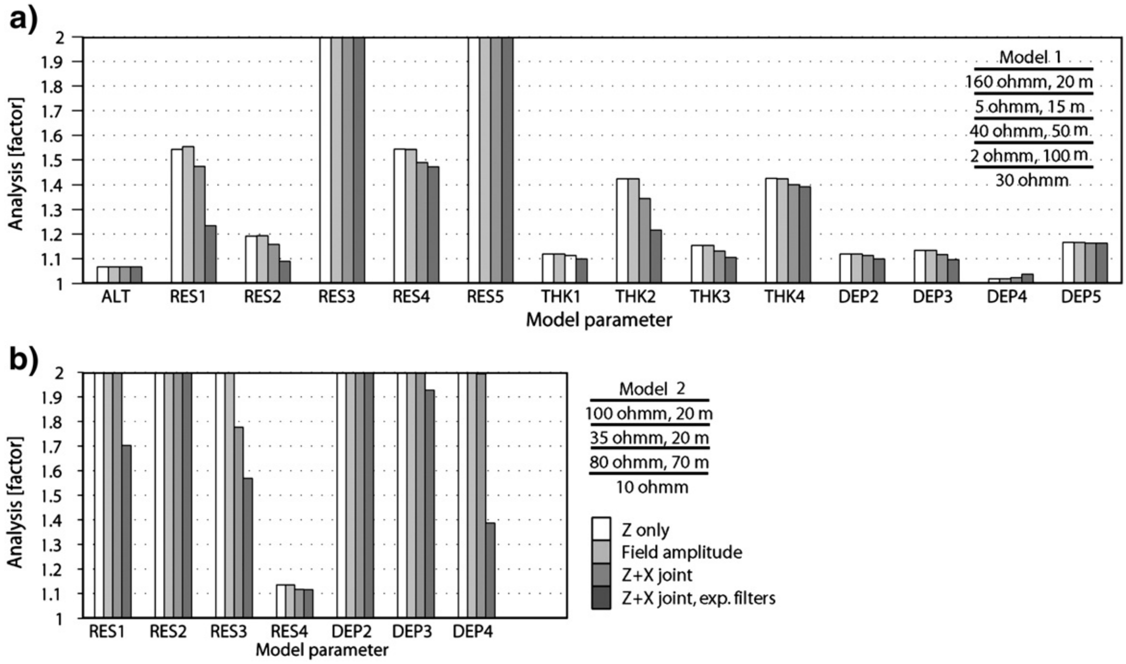

Fig. 5. Model resolution analysis for 2 characteristic models. For each model parameter the bars show results for Z, FA, Z + X jointly and Z + X jointly with experimental filters (from left to right, respectively). The simulations are run using the characteristics of a SkyTEM system with the first gate at 18 μs at an altitude of 30 m and a pitch angle α = 2°.

specified accuracy of the tilt meters is well below one degree, we find that there are several issues making it difficult to determine the tilt within a one degree precision in practice. First of all the frame is not perfectly rigid, causing small local variations in pitch measured around the frame, which obviously serves as a source of error. One further issue is related to data processing. In order to obtain a reasonable signal to noise ratio some number of soundings is stacked, resulting in soundings averaged over a time interval in the order of a few seconds (Auken et al., 2009b). This type of stacking is particularly relevant in the case of X-component data, as this signal is much weaker than the signal for the Z-component. As the instrument pitch will typically vary slightly within the timeframe of a stack, data processing becomes one further source of added uncertainty. Obviously, the most accurate inversion would be done given an extremely accurate pitch, but since this is not possible we propose to include the pitch as an inversion model parameter with a good prior estimate, or alternatively invert for field amplitude.

One further geometric problem is the receiver coils deviating from the zero position. Small deviations from the perfect geometry, e.g. twists and vibrations in the frame etc., cause bias response in the receivers. The X receiver coil is more prone to such effects as the secondary signals are much weaker than for Z. In practice this means that the X response cannot be considered unbiased for as early time gates as the Z response. Working with the experimental 60 KHz low-pass filters in practice revealed further bias issues. As low-pass filters contain capacitors they effectively act as integrators, ie. they are charged by a signal that is then measured during discharge, essentially providing information about the signal at earlier times than when the measurement is made. Using the experimental filters the bias response at very early times becomes integrated into the first time gates, effectively rendering them useless. Such bias issues are extremely difficult to resolve, implying that the significant theoretical improvements to vertical resolution of layered structures found in Section 4.1 can be extremely difficult to take advantage of in practice. In the following we provide an example of what can be obtained in practice from measuring X component data in a field situation of high signal level.

6. Toolibin field example

In 2006, a small 340 line km SkyTEM test survey was flown over Toolibin Lake in southwestern Australia (Reid et al., 2007). The lake and its catchment are located in the upper part of the Blackwood-Arthur River Catchment, approximately 250 km south-east of Perth. This area serves as a good candidate for test flights, since the Earth generally provides a high signal level, extremely little coupling to

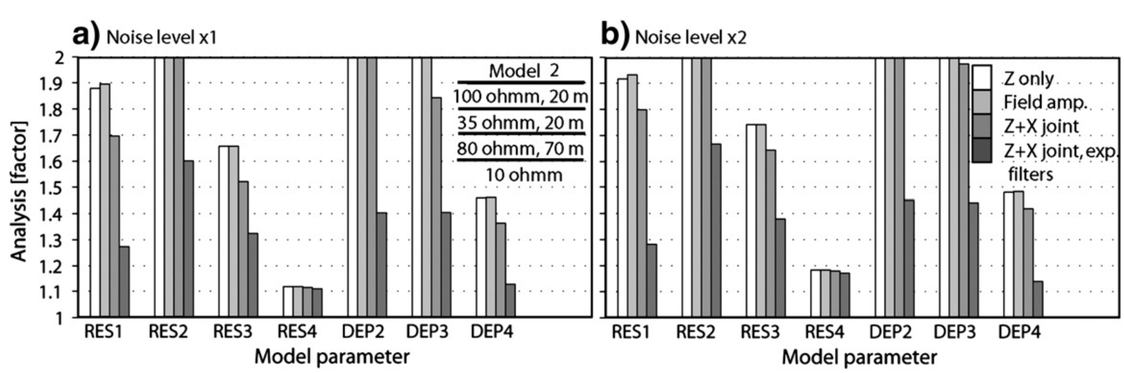

Fig. 6. Model resolution analysis for earlier time gates. The simulation is the same as in Fig. 5b, only this time with the first gate at 12 μs and in (b) also twice the base noise level.

man made installation can be found, and it is one of the most investigated areas in Western Australia. This is both in terms of groundwater, surface water hydrology and salinity management exploration (Dogramaci et al., 2003). The geology in the area consists of Quaternary and Tertiary sediments covering a basement of Archaean granite and granite gneiss cut by Proterozoic dykes. Average thickness of the sediment layer is 25 m, ranging up to 60 m. Previous exploration has shown the regolith layer to be highly conductive (down to around 1.4 Ωm) due to elevated groundwater salinity, whereas the Archaean basement is found to be highly resistive.

The collected data was processed using the Aarhus Workbench (Auken et al., 2009c), implementing the methodology of Auken et al. (2009b), and inverted using the methodology presented in Section 3, including instrument pitch and altitude as inversion parameters. The survey was conducted at an average helicopter speed of around 22 m/s, measuring both the Z- and X-components for high and low transmitter moments and processed for resulting soundings approximately every 50 m. More survey specific details are given by Reid et al. (2007).

In Fig. 7 we show a typical model section from the survey along with characteristic plots of data fits for soundings both with and without X-component data. The shown results are for survey flight line 9 ranging from (X,Y) = (554163,6354385) to (X,Y) = (558054,6365073) GDA94 MGA Zone 50. Based on knowledge from previous studies in the area we see the results reveal bedrock covered by sediments of very low resistivity (blue colors), whereas the resistivity of the bedrock itself is known to be high and appears underestimated at depth (green colors). This is due to the limited depth of investigation in such highly conductive regions, and the fact that the signal level generated by the bed rock will be relatively low and noisy. Near the center of the profile bedrock rises to the surface, showing its true resistivity signature. In the surroundings of these features the overall residual level rises, as the very high resistivity decreases the signal to noise ratio significantly. Note how Fig. 7b and c shows different parameters of the same joint Z- and X-component inversion, in order to accommodate display of all relevant model parameters: data residual, measured altitude, inverted altitude, measured tilt and inverted tilt. When comparing the model sections in Fig. 7a and b the first thing to note is that they appear virtually identical. The main difference is seen as features in (b) appearing slightly more jagged and less smooth compared to (a), and also by the data residual level being around 30% higher. This is due to the added contribution of information from the X component data on lateral resistivity variations. The most pronounced residual increases are for the low moment, which is also to be expected as the sensitivity towards small lateral variation is highest at early times. Despite this slight increase in data residual we find that all 4 sounding curves can generally be fitted well jointly as seen in Fig. 7c. We finally note that this example is for an area of very high signal, providing useful X-component gates at much later times than can be expected for more resistive areas.

7. Discussion

From our investigations we find a changed perspective on the use of helicopter system X-component data in 1D layered modeling, as compared to what was suggested by our initial hypothesis. Our study of the effect on vertical resolution shows that only minor improvements can be expected from including the X-component, since it proves too technically difficult to implement low-pass filters of a suitably low cut-off frequency due to bias response issues. In our field example we show what can actually be obtained from real world X-component data, acquired over an area of high signal. Ley-Cooper et al. (2010) have previously shown how the addition of X-component data to a 1D inversion makes it harder to adequately fulfill the 1D assumption, which is also evident from our results. For our dataset we find that including the X-component in an inversion produces virtually the same result as for the Z-component alone, except that the general data residual level is around 30% higher due to 2D/3D effects. In this sense one can argue that including the X-component in a joint 1D inversion facilitates an equally good model result, but further introduces a more sensitive intrinsic measure of how well the 1D assumption is fulfilled. Ley-Cooper et al. (2010) further shows how 1D modeling of Z-component data acquired in areas of 2D/3D conductivity variation can lead to serious errors when interpreting the model result, which can obviously be of major concern in many cases of decision making. As such, there are many scenarios where more stringent requirements towards fulfilling the 1D assumption can be useful and the added measure of model trustworthiness facilitated by adding the X-component can be highly valuable.

While including the X-component can prove useful in certain cases, it is also important to note that it comes at the price of overhead in terms of computations and data processing. When including the X-component in a joint scheme three forward responses need to be calculated: Z- component in the Z receiver and both X- and Z-components in the X-component receiver (assuming non-zero pitch). Even though this does not necessarily imply three times the computational effort, as the reflection coefficient in the mathematical solution is the same, it slows down the solution of an already time consuming problem. Also, for surveys conducted in inhabited areas where couplings need to be manually removed from the data, the additional work involved in processing the X data channels is not to be underestimated.

We finally note that despite having limited immediate impact, instrumental innovations leading to reliable measurements of the X-component signal using helicopterborne systems can prove very important at a later stage. The use of X-component data provides a much higher sensitivity towards lateral conductivity variation and there is no doubt that modern computer technology will allow for routine inversion of large datasets in 2D or 3D in the not so distant future. When such techniques have matured, the distinct characteristics of the X-component can become an important asset in improving lateral resolution of layered targets.

8. Conclusions

We have investigated the hypothesis that resolution of layered structures measured from helicopterborne TEM instruments can benefit from including X-component data in a layered 1D inversion. The hypothesis takes its theoretical basis in a sensitivity analysis, where we show that resolution of layered structures can be significantly improved by including the X-component in a layered inversion. The prerequisite for this improvement is that the X-component is measured using a low-pass filter of low cut-off frequency, which we unfortunately find very difficult to implement in practice. We conclude that X-component signal can indeed be measured from a slight offset helicopter system, but that bias response becomes even more of an issue than for the Z component. This problem is due to the X-component signal being relatively weak for small receiver offsets, which in turn makes the relative influence of bias response much greater than for the Z-component. In practice it implies that the X-component cannot be reliably measured for as early times as the Z-component and it further prohibits implementing the actual setup of the sensitivity analysis forming the basis of our original hypothesis. If the bias problems can be overcome, however, our results show that there is improvement to be gained in vertical resolution capability.

Being unable to reliably acquire X-component data using the low-pass filters of our simulation, the results show little improvement in terms of resolution of layered structures. On the other hand, there are still many scenarios where the additional effort of including the X-component could prove worthwhile. These are scenarios that make use of the added sensitivity to lateral conductivity variation of

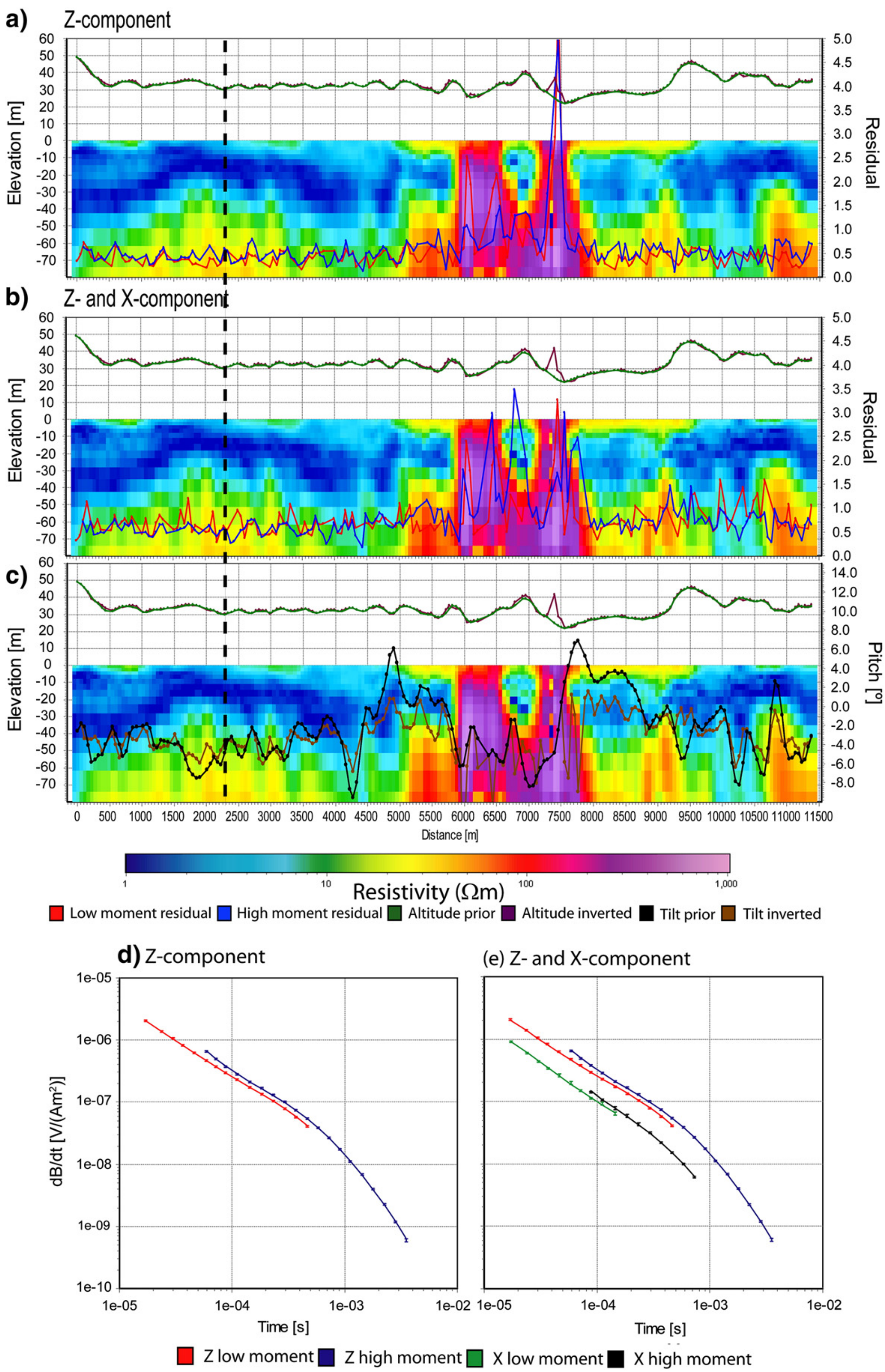

Fig. 7. Comparison of inversions of field data using the Z-component only (a) and both Z- and X-component jointly (b)–(c). Note how (b) and (c) show the same section twice in order to display how both data residual, altitude and tilt correlate with the model. Figure (d) and (e) show data with error-bars and inverted model responses in solid lines, all collected at the position indicated by a black vertical line.

the X-component, making it more difficult to fit within a 1D modeling envelope. As such, one can put more confidence in a 1D model fitting the Z- and X-components simultaneously, as it imposes much stricter criteria for what can be fitted in a 1D model envelope. Such added confidence can prove useful in many cases of decision making based on model results.

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