Inversion of SPECTREM AEM data for conductivity and system geometry

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SUMMARY

We evaluate the use of airborne electromagnetic data from the $SPECTREM_{2000}$ system flown for ore body detection, regolith mapping and assessment of aquifers. Since the position and orientation of the receiver bird are not measured, the primary field at the bird cannot be known and removed precisely. In order to successfully invert the AEM data, and produce conductivity–depth models, we first reinstate the removed primary field estimate and convert the data from ppm units to Teslas. We then simultaneously inverte the X and Z component data, to solve for a 1D layered conductivity model and receiver position.

The SPECTREM system has flown many line kilometres in other parts of the world but substantially less in Australia. Through further processing and inversions we have resolved conductivity–depth structures very similar to those previously obtained from other well-established AEM systems flown under Australian conditions. We also present a section of AEM data with logged drilling core data as a means of assessment of our inversion models against an independent data set.

Key words: Airborne EM, inversion, geometry, SPECTREM, electrical conductivity.

INTRODUCTION

One of the significant problems with all AEM systems is that the total response measured in the receiver coils (Rx) can never be perfectly decomposed into 1) its primary response, due to direct induction from the transmitter loop (Tx), and 2) the secondary response, due to eddy currents induced in the ground. If the relative offsets and orientations of the Tx and Rx (i.e., the system geometry) could be measured dynamically in flight with sufficient accuracy, the primary contribution could be analytically calculated and subtracted from the total response to yield an accurate secondary response. Additionally, even for an AEM system that only records in the off-time, when there is theoretically no primary, the system geometry still needs to be known for proper quantitative interpretation of the secondary ground response.

Imprecise knowledge of the Tx-Rx offsets and orientation of the Rx bird are a particular problem for fixed-wing towed receiver (bird) systems (e.g., TEMPEST, GEOTEM, SPECTREM) whose geometry varies continuously throughout flight. For these systems, the Tx height above ground and orientation (roll, pitch and yaw) can typically be measured. However, despite efforts to monitor the bird offset and orientation in fixed-wing systems (e.g., Smith, 2001a), this has not so far been achieved with sufficient precision to allow accurate primary field removal.

Schemes used for estimating the primary and secondary contributions in GEOTEM (Smith, 2001b), TEMPEST (Lane *et al*., 2000) and SPECTREM (Leggatt *et al*., 2000) data processing, all make assumptions, implicit or otherwise, about subsurface conductivity. When estimated secondary field data from such processing schemes are input into quantitative conductivity depth imaging (CDI) or layered earth inversion (LEI) algorithms it is routinely found that the X- and Z-component data cannot simultaneously be fitted with a realistic conductivity model consistent with prior information. Or, in some cases, no conductivity model can be fitted to the data. Sometimes the X- and Z-component data can be fitted independently, but to different conductivity-depth models. The problem usually stems from inaccurate decomposition of the primary and secondary field in the initial data processing and the subsequent inaccurate estimate of the system geometry calculated from the poorly determined primary field.

Various inversion algorithms have been developed to deal with this problem by solving for unknown elements of the fixed-wing AEM system geometry (or primary field) in concert with a conductivity model (e.g., Satell, 2004; Lane *et al*., 2004). Of course these algorithms also involve assumptions. However, their advantage is that fitting of both X- and Z-component data to a realistic conductivity model, that is consistent with prior information, is not precluded by previous imprecise primary field removal. In other words the methods have the advantage of being able to deal with the egg before it has been scrambled.

In this paper we discuss the inversion of final processed $SPECTREM_{2000}$ data using Geoscience Australia's GA-LEI inversion algorithm (Lane *et al.*, 2004). $SPECTREM_{2000}$ (Figure 1) is a fixed wing, time domain AEM system which has flown many thousands of line kilometres mainly in Canada and Africa. Its current operational state is described by Leggatt *et al.* (2000). The SPECTREM system has reportedly successfully mapped and been able to discriminate targeted geological units to depths of hundreds of metres in the presence of conductive cover (Leggatt *et al.*, 2000; Pare *et al.*, 2012). The system has been specifically designed to map both high-conductance bodies and near-surface conductors, although resolution is still dependent on the specific electrical properties and lateral and vertical extent of target bodies.

SPECTREM employs a bipolar, approximately square-wave, 100% duty cycle current waveform with a selectable base frequency of 25 Hz or higher. The transmitter current and the voltages in the X- and Z-component receiver coils are continuously recorded (streamed) at 76.8 kHz. Through a

sequence of data processing steps (Leggatt *et al.*, 2000) each 0.2 s (~15m) stack of streamed voltage data, which contain both primary and secondary contributions, are ultimately transformed into soundings or decays representing the estimated secondary magnetic B-field. Each sounding contains 10 windows (gates) with centre times ranging from 0.02604 to 16.654 ms. The processed secondary field data are presented in units of parts per million (ppm) of the corresponding X- or Z-component of the high altitude reference primary magnetic B-field.

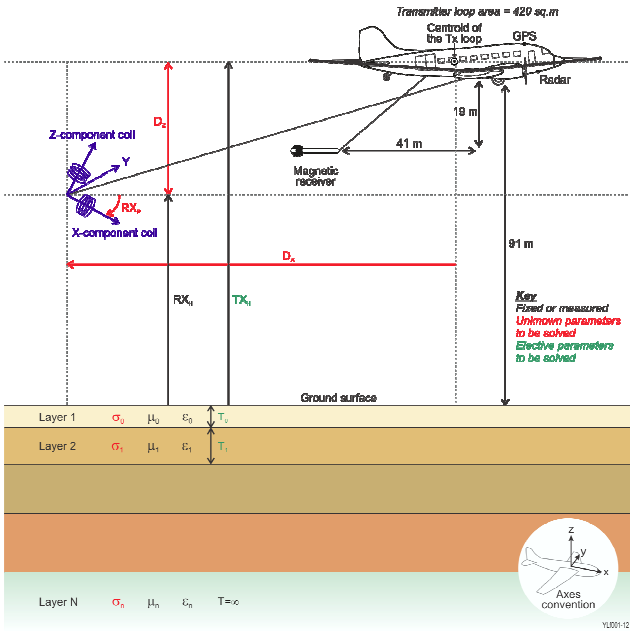

Figure 1. SPECTREM AEM system axes convention, sensors geometry, rotation and input and output parameters for inversion.

METHODS

The GA-LEI inversion algorithm is capable of inverting total (primary plus secondary) field data to solve for the Tx-Rx horizontal and vertical offsets as well as the Rx pitch along with a 1D conductivity model. In doing so it circumvents the potential pitfalls, summarized earlier in the introduction, of estimating the primary field and quantitative interpretation in two sequential steps. Therefore prior to inverting the data, we first need to reinstate the primary field that was (possibly erroneously) removed during the original data processing.

In the original processing of the SPECTREM dataset considered here, the kth window of the X-component sounding X_k^{ppm} is given as an estimated secondary field in units of parts per million (ppm) of the unipolar (i.e., zero-to-peak) primary field measured on the high altitude reference line X_{ref}. It is calculated as,

$$X_k^{ppm} = 10^6 \left(X_k - X_{10} \right) / X_{ref} / 2 \,, \qquad (1)$$

where X_k is the total survey altitude response in the kth window prior to primary field removal and conversion to ppms. Thus, the primary field estimate X_{10} is just the total response in the last (10th) window. Hence, usually only nine windows of ppm data are delivered since the tenth will always be zero. The division by 2.0 simply converts the bipolar (peak-to-peak) current step to a unipolar (peak-to-zero) current step response. The removed primary was delivered in the dataset in the so-called coupling channel, given by,

$$X_{couple}^{ppm} = 10^6 X_{10} / X_{ref} \,, \qquad (2)$$

which is used later to reconstruct the total response.

For the SPECTREM system, there are two unknown amplitude scaling factors that would relate a given transmitter current to resulting X- and Z-component receiver responses. They are dependent on the amplifier gains and other conversions (Braam du Plooy, pers. comm., June 2012). Without these scaling factors, or alternatively exact knowledge of the Tx-Rx offsets, we cannot convert the data from relative ppm units to the required absolute B-field units (e.g., in Teslas). Note that this is somewhat different to the case for our inversion of TEMPEST data. According to Lane (2000), the TEMPEST system has been calibrated such that it allows conversion of the processed data to absolute units of Tesla.

We therefore used the average high altitude reference line Tx-Rx horizontal and vertical offsets, D_X^{ref} =-121 m and D_Z^{ref} =-41 m, that were estimated by SPECTREM Air Ltd (using cameras and knowledge of the tow cable length) to constrain the unknown scaling factors. Using these offset values along with the measured Tx roll and pitch angles and assuming a straight and level Rx bird (i.e., zero roll, pitch and yaw), we calculated the theoretical unit magnetic dipole field at the receiver in units of femtoTesla (fT) for the X and Z-components as X_{ref}^{fT} and Z_{ref}^{fT}.

Since the ratios of the survey altitude fields to the high altitude reference fields are independent of the units used, that is,

$$X_k^{fT} / X_{ref}^{fT} = X_k / X_{ref} \,, \qquad (3)$$

by combining equations 1, 2 and 3 we can reconstruct the total field in units of femtoTeslas as,

$$X_k^{fT} = (2X_k^{ppm} + X_{couple}^{ppm}) X_{ref}^{fT} / 10^6 \,. \qquad (4)$$

An exactly analogous reconstruction is performed for the Z-component data,

$$Z_k^{fT} = (2Z_k^{ppm} + Z_{couple}^{ppm}) Z_{ref}^{fT} / 10^6 \,. \qquad (5)$$

Equations 4 and 5 give the reconstructed total magnetic B-field in units of femtoTeslas (/Am^2) that we input into the GA-LEI algorithm. In doing this we have had to assume that the estimated high altitude reference line geometry was correct. However in our GA-LEI inversion, we also solve for new values of the horizontal (D_X) and vertical (D_Z) offsets as well as the receiver pitch (RX_P) for every sounding, simultaneously with a 1D conductivity model. Parameters used during the inversion routine are shown in Figure 1.

RESULTS

Synthetic modelling

Accurate knowledge of the position and orientation of the receiver bird is important, as previously discussed. As the bird position fluctuates, so will the primary and secondary fields at the receiver. The (Tx–Rx) coil separations for each sounding can vary considerably and are very dependent on flight conditions. If these offsets are not measured they can have considerable impact, in particular on the modelling of the near surface.

We computed a suite of forward responses over a common conductivity model for a range of Tx-Rx offsets. The responses

are shown in Figure 2, from which it can be seen that the effect of geometry variation on ground response is particularly strong in the early time channels. Here we used our estimated SPECTREM noise levels, and fixed all other nominal parameters including rotations.

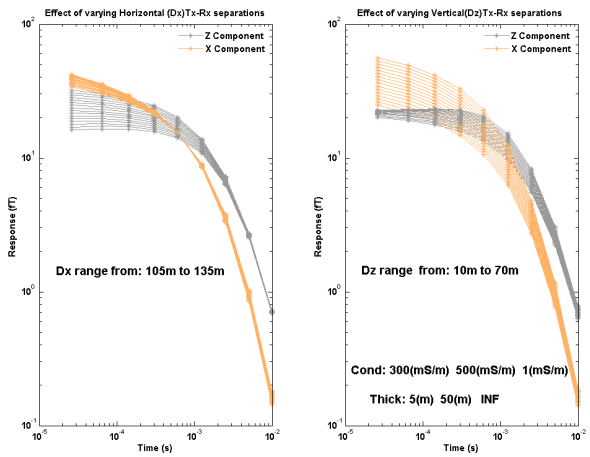

Figure 2. Responses of a synthetic three-layer model calculated by varying the Tx-Rx horizontal (Dx) separation in 2 m increments from 105 to 135 m (left) and vertical (Dz) separation in 4 m increments from 10 to 70 m (right).

Inversion assessments on production data

Assessment of channels of AEM data is commonly carried out qualitatively on profiles of soundings which are plotted as a continuous profile. Anomalous amplitudes and shapes are then visually compared to the responses from simple bodies such as thin sheets, plates, spheres and other geometric shapes. Further analysis is done by parametric modelling which allows calculation of strikes, dips and other geometric dimensions. Using AEM data exclusively for isolated anomaly modelling undervalues the method's full potential. The high density and spatial coverage of AEM data enables regional geological mapping, particularly if there is sufficient contrast in the responses of subsurface formations. AEM window data can be transformed to estimates of subsurface conductivity and depth by inversion which, in contrast, permits a quantitative assessment of the changes in the geo-electrical properties of the subsurface materials.

Inversion and processing of SPECTREM data previously described was carried out as part of a program to analyse data sets from several systems being employed to support mineral exploration, develop hydro-geological conceptual models, and groundwater resource assessment in different parts of Western and South Australia. The work has required the re-processing of historical AEM data sets, including TEMPEST, HOISTEM and VTEM. New SkyTEM508 and $SPECTREM_{2000}$ data have recently been flown co-incident with TEMPEST and VTEM lines. This presents a unique opportunity to assess the systems over the same terrain.

To demonstrate the possible effects of geometry we show X and Z-component SPECTREM data, with their associated error bars in grey and black, on the left hand panel of Figure 3. The data were inverted to 30 layer models in two inversions. In the first inversion, the geometry was fixed at the high altitude reference geometry. The best fitting conductivity model and its forward response are shown, in blue, on the right and left panels respectively. The system geometry was solved for in the second inversion, and the best fitting model and its response are shown in red. The better fitting model results from the inversion where the system geometry was allowed to vary because the reference geometry is not consistent with the observed data.

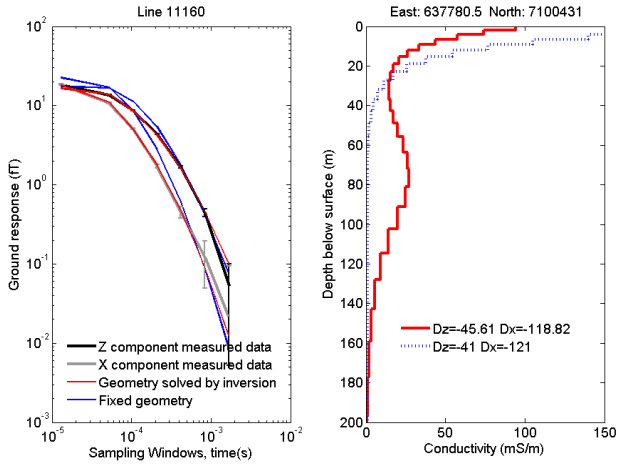

Figure 3. The grey and black decays on the left hand panel are reconstructed X and Z component total field data. Also shown are the best fitting 30 layer models resulting from inversions where the geometry remained fixed (blue), and was solved for (red) in the inversion. The right hand panel shows the corresponding best fit models in the same colours.

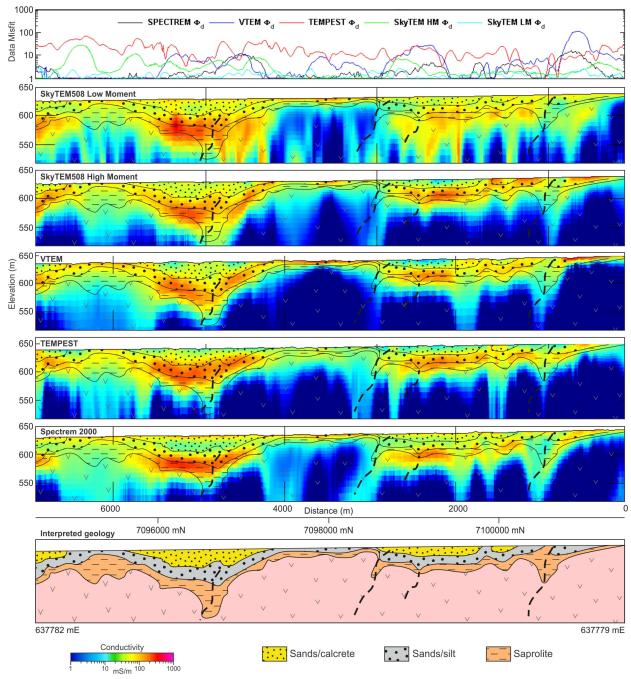

Figure 4. Conductivity depth sections from inversion of SkyTEM, VTEM, TEMPEST and SPECTREM data (Munday and Ley-Cooper 2012)

We have processed and inverted AEM data acquired along a coincident flight line by a range of systems. A section of inversion results from these systems is shown in Figure 4. A suitable comparison was facilitated by using the same model parameterization and a common inversion kernel, specifically the GA-LEI. In general all systems recover similar structures, although there are some subtle differences regarding extensions, lateral variations and depths of the mapped layers which are yet to be validated by ground-truth.

Note that the TEMPEST data acquired in (1998) did not provide enough elements required to calculate the system's geometry, hence separations could not be included in the inversion; which may have compromised the fitting. For the VTEM data, we needed to omit the first three data channels in order to achieve a reasonable fit to the early time channels. The omission of these three channels from the inversion has clearly hindered the VTEM's resolution of layers in the near surface. We are also aware that combining the SkyTEM low- and high-moment data would improve the system's vertical coherency.

To further assess our inverted conductivity models of SPECTEM data; in Figure 5 we have projected lithologies obtained from logging rotary air blast drill (RAB) holes onto a flight line conductivity section of inverted SPECTREM data. RAB drilling is usually logged up to the depth at which further drill penetration is prevented. Thus it may give some indication of regolith thickness. Our assessment is that an interpretation of the regolith thickness attained from the profile of drill holes is in good agreement with the boundary that would be picked from the sharp conductivity contrast on the conductivity section.

CONCLUSIONS

The full inversion process has provided us with a better understanding of the SPECTREM system and its capabilities. We have implemented a procedure to model and invert SPECTREM data. Tx–Rx separations can be estimated during inversion to allow acceptable data fits. The implications of not properly taking into account Tx–Rx separations are that the early time responses are affected, which hinders the system's ability to correctly resolve near-surface regolith variability.

Through further processing and inversions we have resolved conductivity–depth structures very similar to those previously obtained from other well-established AEM systems flown under Australian conditions. Good agreement between the inverted conductivity model and available drillhole information on regolith thickness has been demonstrated.

Implications for exploration

An important outcome is predicting areas where drilling will encounter thicker regolith cover. Inverted AEM products can be utilized as fundamental elements to plan further exploration campaigns and assist in determining areas where geochemical sampling of the surface may be less fruitful.

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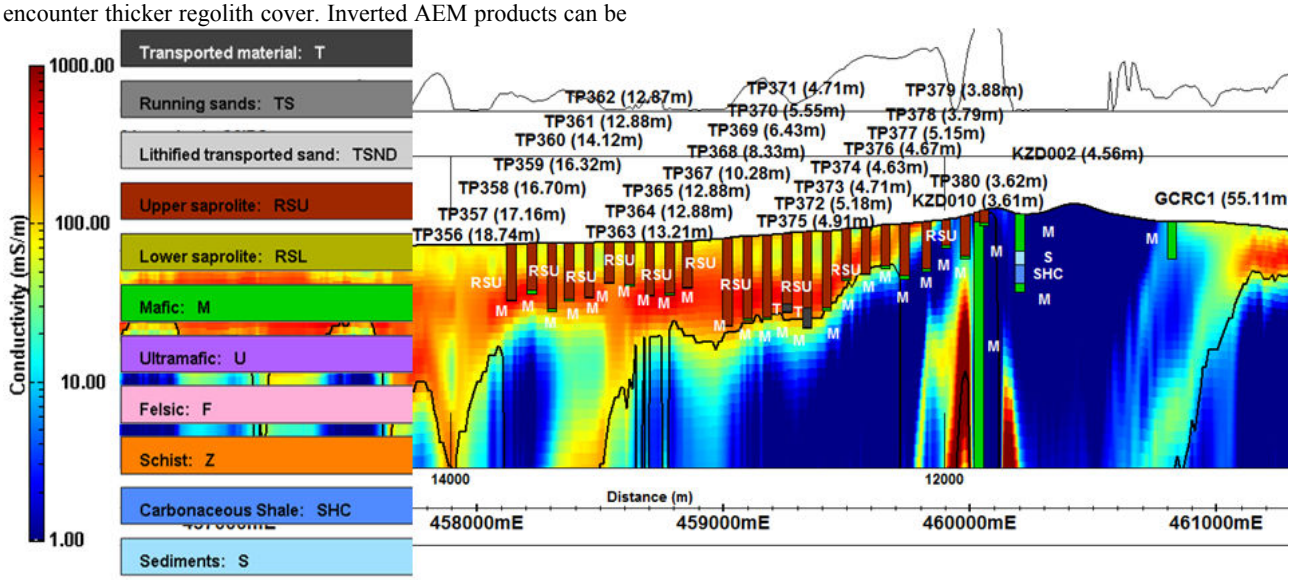

Figure 5 Conductivity section along a portion of a flight line with several drill holes. RAB holes (TP prefix) are usually drilled to the base of the regolith, which here show a good correspondence with the main (orange-red) conductive unit on the inverted section. The diamond holes, which have been drilled into outcrop, correspond with resistive material (blue) at the surface in the section.