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The superparamagnetic response of transient AEM data

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SUMMARY

Several lines of VTEM data flown at different system elevations across a known sulphide body and surface cover with elevated superparamagnetic (SPM) properties were analysed with MAXWELL, layered-earth inversions, LEROIAIR and LEROI. The SPM material was modelled with frequency-dependent magnetic susceptibilities at shallow depth.

Due to their slow late-time decay, SPM responses can be confused with responses of deep conductors and vice versa. Depending on the parameter weighting used, 1D inversions model all late-time responses as deep conductive material or as surficial SPM material. However, the joint 1D inversion of data acquired at different system elevations manages to recover a deep conductor from the sulphide anomaly and elevated SPM values at the location of the SPM response. For the modelled parameters, the VTEM data sets from two elevations (at 70 and 80 m) require a vertical separation of about 10 m to allow for the discrimination between the SPM and sulphide responses. For lower system elevations, less sensor separation is necessary due to the strong gradient of the SPM response.

We suggest that two vertically separated receivers could be used to measure the AEM gradient and depending on the flying height of the transmitter, the vertical offset of the receivers should be between 2 and 40 m.

Key Words: Airborne electromagnetics, EM data modelling, EM gradiometer, inversion, superparamagnetism.

INTRODUCTION

The effects of superparamagnetic (SPM) material on transient EM data has been well documented and analysed for ground EM surveys in mineral exploration (Buselli, 1984; Lee, 1984; Barsukov and Fainberg, 2001), archaeological studies (Tabbagh and Dabas, 1996) and UXO detection (Billings *et al.*, 2003; Pasion *et al.*, 2002). SPM is mainly caused by the presence of very small particles of iron oxide, which generally occur at the surface but can also be found in palaeochannels at considerable depth. With the increased use of time-domain helicopter-borne AEM systems, SPM effects have recently been analysed for VTEM data (Mutton and Mortimer, 2009; Mutton, 2012; Kratzer *et al.*, 2013). Since spatially limited SPM responses can be confused with EM responses of discrete conductors, due to their slow late-time decay, they can represent a challenge for mineral exploration and UXO detection.

The SPM response can be modelled with a frequency-dependent magnetic susceptibility. Lee (1984) defines a complex susceptibility ranging from a static susceptibility χ_0 (at ω=0) to zero (at ω=∞), separated by a transition zone determined by two time constants, τ_1 and τ_2:

$$\chi(\omega) = \chi_0\left[1 - \frac{1}{\ln(\tau_2/\tau_1)}\ln\frac{(1+j\omega\tau_2)}{(1+j\omega\tau_1)}\right] \qquad (1)$$

With this formulation of $\chi(\omega)$ implemented in a layered-earth algorithm for a circular transmitter loop (Ward and Hohmann, 1987), we have derived SPM parameters from two VTEM data sets to determine typical SPM values. The AEM data were acquired across a known sulphide body and an area of elevated SPM material. The main objective was to determine if SPM responses and discrete conductor responses could be identified through the analyses of the values of derived SPM parameters. Discrete conductor modelling with MAXWELL (Duncan, 1987) was also conducted to test if model discrimination between these two types of responses can be achieved.

Since the examined AEM data profiles had been repeated at different system elevations, we were able to evaluate the usefulness of vertically separated AEM data with layered-earth inversions (LEI) and MAXWELL. Besides being very useful in identifying SPM effects, the extra data improved the model resolution of the LEI. The receiver coil separation of a vertical EM gradient system necessary for the discrimination between the sulphide and SPM material was derived.

VTEM SURVEY DATA

Two z-component VTEM data sets acquired in Africa in 2011 with a base-frequency of 25 Hz were analysed. One data set was acquired during the helicopter take-off over a laterally extensive patch of near-surface SPM material, providing the EM response for a system elevation from 0 to 150 m. The helicopter moved laterally by about 1 km during the climb so that the surveyed ground slightly changed during the acquisition of these AEM data. The second data set contains repeat lines acquired at different system elevations (70, 80, 95, 109 and 128 m) across a known sulphide body and a wide pocket of surficial SPM material. The occurrence of SPM material was confirmed with a portable magnetic viscosity meter by taking measurements along the surface and on core samples (Mutton, 2012; Kratzer *et al.*, 2013).

Helicopter take-off data

The VTEM data in the first data set, shown in Figure 1, display strong late-time responses at lower system elevations, due to the SPM effect. Results of an Occam LEI (Constable *et al.*, 1987) are shown when SPM parameters are not taken into account. The achieved data fit is excellent, but the inversion models place conductive material at depth for lower system elevations. With increasing ground clearance, the SPM response drops off fast, and a more reasonable conductivity-depth model is recovered.

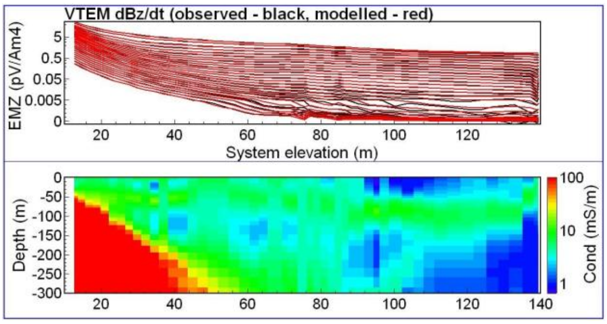

Figure 1. VTEM response (observed in black, modelled in red) as a function of system elevation above known SPM material. The conductivity-depth section was derived by LEI, ignoring SPM parameters.

Barsukov and Fainberg (2001) determined SPM decays to be proportional to $1/t^{1+\delta}$ with $-0.2 < \delta < 0.2$. The SPM decay recorded at 40 m elevation and shown in Figure 2 agrees with these results, matching the VTEM response from mid- to late time with a $1/t^{1.2}$ decay. For comparison, Figure 2 also shows the decay recorded at 120 m elevation, which appears unaffected by SPM and is matched by a $1/t^{2.5}$ decay, as expected for dBz/dt data above a half-space (Spies and Frischknecht, 1991).

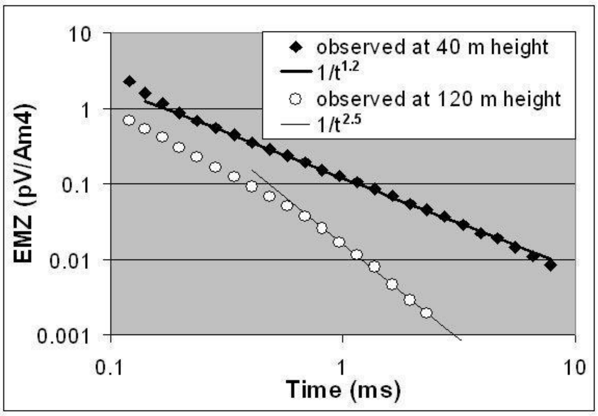

Figure 2. VTEM decay response recorded 40 m and 120 m above SPM material with time dependences of $1/t^{1.2}$ and $1/t^{2.5}$ indicated.

Assuming a power-law decay $1/t^k$ at late time, the power-law index k was derived from the data shown in Figure 1. The determined k-values are shown as a function of system elevation in Figure 3. These results indicate how the EM data change from SPM responses (k=1.2) for elevations between 10-30 m to half-space responses (k=2.5) for elevations above 100 m. In the elevation range 70-75 m, the k-curve flattens, with k-values taking on a value of 2.1. Lacking any other explanation, we assume this behaviour to be the result of noisy data.

Figure 4 shows the LEI result when SPM parameters, as expressed in Equation (1), are included in the inverted parameters. The SPM parameters were modelled at constant values from the surface to a depth of 5 m, the depth extent of the SPM soil being indicated by borehole data (Mutton, 2012). Taking into account the SPM parameters, no conductive material is modelled for shallow system elevations, and the modelled conductivity structure is fairly constant for the range of system elevations. The recovered SPM parameters are constant for lower system elevations, but for ground clearances above 120 m the inversion struggles to extract reliable values, because the SPM response is too small to be resolvable.

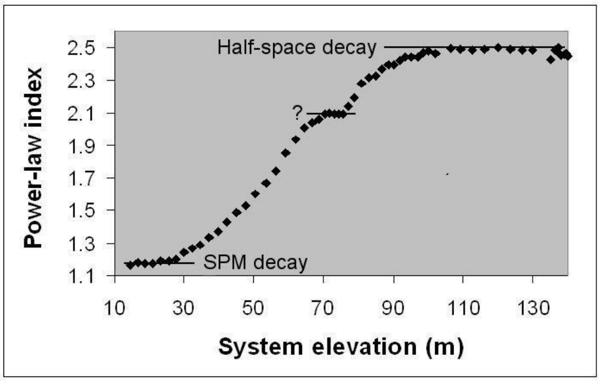

Figure 3. Power-law index k of the relation $1/t^k$ inverted from the late-time channels of the VTEM data shown in Figure 1. The determined k-values indicate SPM responses at lower elevations (10<z<30 m, k=1.2) and half-space responses at high elevations (z>100 m, k=2.5). The cause for the k-curve to become flat in the elevation range 70<z<75 m is unclear.

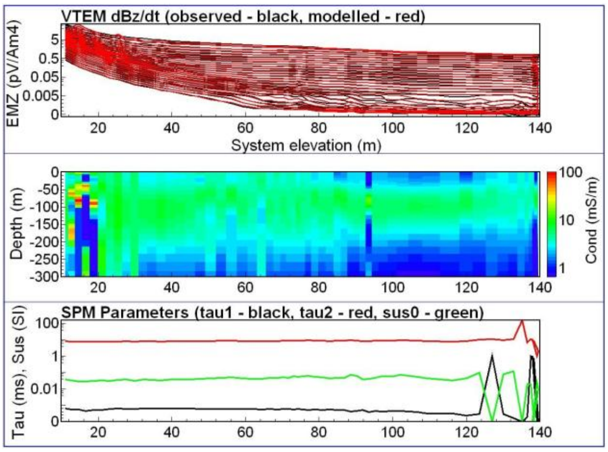

Figure 4. VTEM response as shown in Figure 1, with conductivity-depth section, derived by LEI, inverting for the SPM parameters τ_1 (black), τ_2 (red) and χ_0 (green) as shown in the bottom panel.

The above inversion results suggest that the layered-earth algorithm with a magnetic susceptibility implemented as defined by Equation (1) can be used to model SPM responses, matching the response drop-off with elevation and the strong late-time responses for lower ground clearances. Average derived SPM values are τ_1=0.8 ms, τ_2=8 s and χ_0=0.04 (SI).

Repeat line of lowest ground clearance

VTEM data acquired at a 70 m flying height were inverted with and without allowing for a SPM response. Figure 5 shows the results with no allowance for SPM. The known sulphide body and the SPM material model as conductive material at depth. The inclusion of SPM parameters in the LEI (see Figure 6) results in the absence of mapped conductive material at depth. Even the sulphide response however is modelled with a near-surface SPM response.

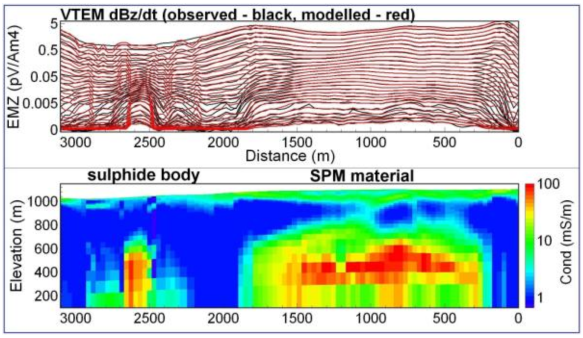

Figure 5. VTEM response and derived conductivity-depth section. A known sulphide body is at 2500 m and a broad area with near-surface SPM material is between the 100 m and 1800 m interval.

For the sulphide response, the data fits are comparable between the models of Figures 5 and 6, and the SPM parameter values for the sulphide are comparable to those of the SPM anomaly. This suggests that a 1D inversion algorithm that allows for the inversion of SPM parameters does not provide the necessary information to discriminate between sulphide and SPM responses.

The result of MAXWELL modelling of the same AEM profile is shown in Figure 7. Since MAXWELL is using a more appropriate algorithm than the LEI for computing the response of a finite conductor, the data fit of the sulphide response is excellent. Surprisingly, the SPM response can also be fitted very well. If x-component data were available for this data set, the use of MAXWELL might lead to the confirmation of the plate model for the sulphide and the rejection of the plate model solutions for the SPM response.

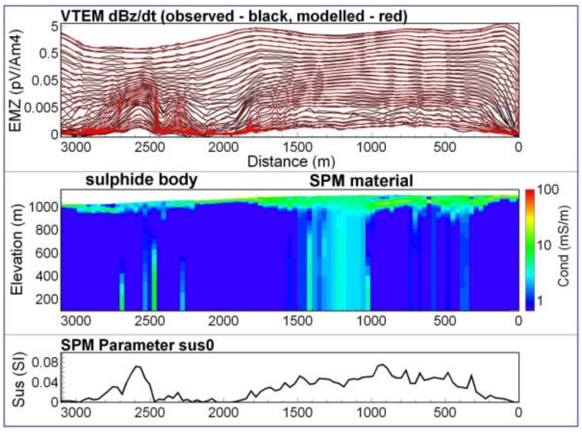

Figure 6. VTEM response as shown in Figure 5, with derived conductivity-depth section, that takes into account SPM parameters. Note the absence of deeper conductive material and the elevated χ_0 mapped at the sulphide location.

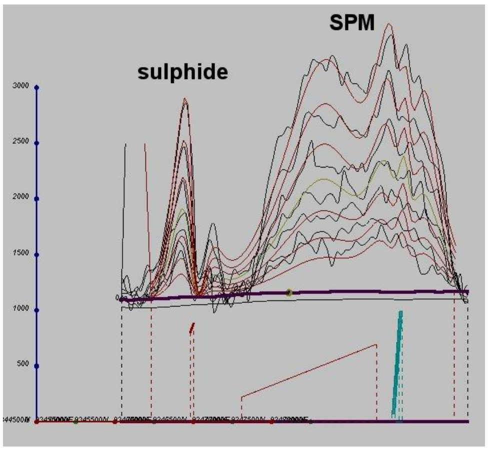

Figure 7. MAXWELL modelling of low-elevation (70 m) VTEM response, with derived plate solutions. Even though the plates are inappropriate models for the SPM anomaly on the right, the data can be fitted well. The plate parameters for the sulphide target on the left are: conductance 100 S, depth 157 m, depth extent 100 m, strike length 170 m, dip angle 160 degrees.

Vertically separated repeat lines

The AEM profile recorded 58 m higher than the data discussed in the previous section is shown in Figure 8 together with the MAXWELL responses as predicted from the plate parameters of Figure 7. Clearly, the sulphide response is predicted much better than the SPM response. This indicates that the signal drop-off with system elevation is quite different for the two zones, and vertically separated EM data could provide the information needed to discriminate between them.

The EM responses of the flight lines with mean system elevations of 70 and 80 m were inverted jointly with an LEI, including the inversion of SPM parameters for the top 5 m. The result shown in Figure 9 indicates that the sulphide and the SPM responses of both profiles are fitted well. At the location of the SPM response, the inversion derived elevated χ_0 values. The conductivity–depth section indicates some structure at mid-depth that is not clear from the previous inversions on single-elevation data (see Figure 6). Probably, the additional data resulted in the improved resolution of the inverted model.

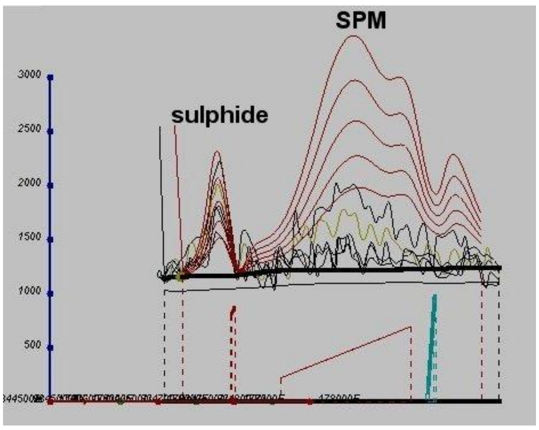

Figure 8. High-elevation (128 m) VTEM response. Shown are the observed AEM profile and the responses predicted for the plate models of Figure 7. The agreement between observed and predicted data is

excellent for the sulphide body and poor for the SPM anomaly.

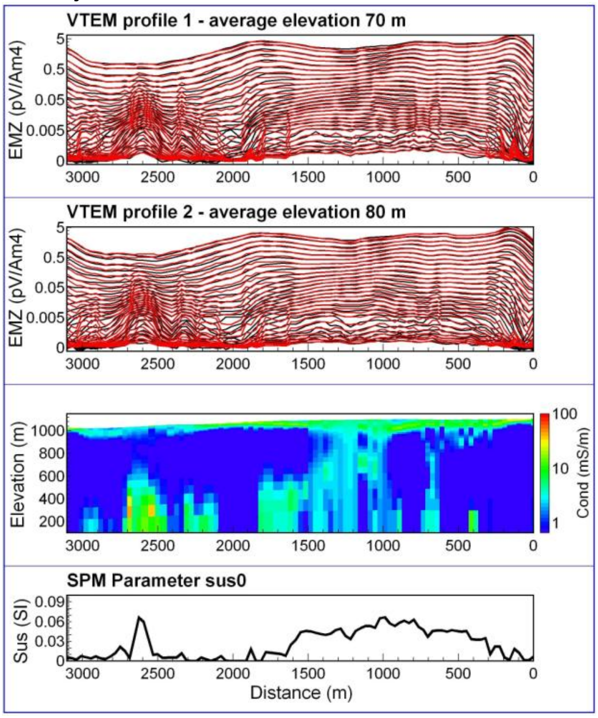

Figure 9. LEI results for inverting jointly VTEM data acquired at mean elevations of 70 and 80 m, respectively. Note the presence of deeper conductive material at the sulphide location, the elevated SPM values across the sulphide and SPM responses, and the subtle structure being mapped mid-depth below the SPM response.

Moderately conductive material is indicated at the location of the sulphide body, but at a deeper depth. The depth overestimate is expected for the 1D inversion of a discrete conductor. Elevated SPM values, assumed to be incorrect, were determined above the sulphide. However, it would have been difficult to model the sulphide response of the two lines with a layered-earth inversion without SPM parameters, as we will explain in the following paragraph.

The signal drop-off with elevation above the sulphide is explored in Figure 10. The channel 25 amplitude (recorded 5.5 ms after the transmitter turn-off) of the observed sulphide response is shown at five system elevations. Also shown are the corresponding channel 25 amplitudes computed by LEIs with and without SPM and by MAXWELL modelling done at a 75 m system elevation. The models derived at that elevation were then used to predict the responses at lower and higher elevations, which are also shown. Figure 10 shows that the layered-earth response without SPM drops off much slower with elevation than the observed sulphide response, which in turn drops off slower than the layered-earth response with SPM. This shows, in order to compensate for the inappropriate 1-D model, the LEI introduced elevated SPM values to fit the sulphide responses of Figure 9. Using a more appropriate model, such as a plate in a layered-earth host would be expected to explain the data without the requirement to elevate the SPM values at the sulphide location.

The drop-off predicted by MAXWELL matches the observed sulphide response drop-off very well. Responses for LEROIAIR (Raiche, 2004), which match the observed and the MAXWELL responses, are also shown for an extended range of system elevations. Taking into account the noise level of the VTEM system, the data from Figure 10 can be used to predict the vertical separation needed for being able to discriminate between the sulphide and SPM responses discussed above. With derived LEROIAIR and SPM layered-earth responses being almost identical for the system elevation of 75 m, Figure 11 shows how the difference between the two responses changes as the system's height is raised or lowered from 75 m. For that difference to exceed the indicated noise level of channel 25, the second system has to be at least 10 m below or 20 m above the first VTEM system at 75 m elevation.

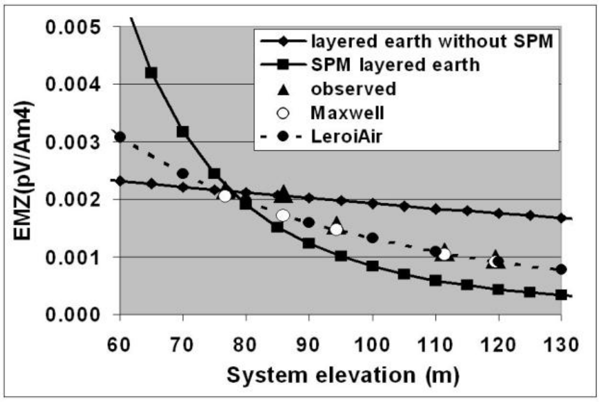

Figure 10. Observed VTEM channel 25 (5.5 ms) above sulphide for 5 system elevations and predicted signal drop-off for layered earth without SPM, discrete conductor (MAXWELL, LEROIAIR) and layered-earth with SPM.

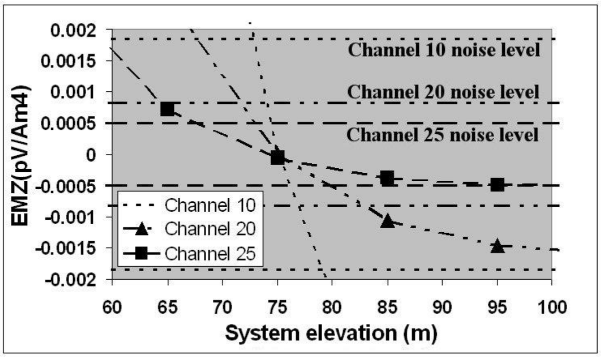

Figure 11. Difference between the plate and SPM layered-earth responses of Figure 10 for VTEM channels 10 (0.4 ms), 20 (2.3 ms) and 25 (5.5 ms). Since the parameters of the plate and SPM responses were derived from the AEM data at 75 m elevation, the difference is zero at 75 m. The shown difference curves are the result of the different signal drop-off with elevation for the two responses as the system is moved above or below 75 m. Estimated noise levels are shown as dotted and dashed lines.

Gradient system

Rather than acquiring AEM data at two different elevations it makes more economic sense to acquire gradient EM data using two vertically separated EM receivers. For an in-loop system, such as VTEM, the second sensor could be attached to the tow cable above the first sensor. Assuming the cable at an angle of 40 degrees during flight, the offset of the second receiver was modelled in the range from dx=0.8 m, dz=1 m to dx=42 m, dz=50 m. The plate responses were computed with LEROI (Raiche, 2004) rather than LEROIAIR, since the latter models the transmitter loop as a dipole, which results in highly inaccurate responses when modelling a non-zero horizontal receiver offset. For the SPM and plate models of Figures 10 and 11, the separation was computed at which the difference between the SPM and plate responses was equal to three times the system's noise level for the respective channel. This minimum separation for plate-SPM discrimination is shown as a function of transmitter height in Figure 12. For low ground clearances (z < 40 m) the SPM response has a strong vertical gradient and a small receiver separation is needed (dz < 2 m). For system elevations in the range 40 m < z < 70 m, the SPM response and the associated gradient are weaker, requiring a wider sensor separation (2 m < dz < 40 m). Above 80 m, the SPM gradient is too weak to allow SPM-plate discrimination with a gradiometer system for the modelled system noise level. As indicated in Figure 4, above 120 m the SPM response will be too weak to be detectable and a second receiver will not be necessary. These results indicate that in the presence of SPM, unlike a single-receiver system, a gradient system is best flown at low ground clearances, with a wide sensor separation.

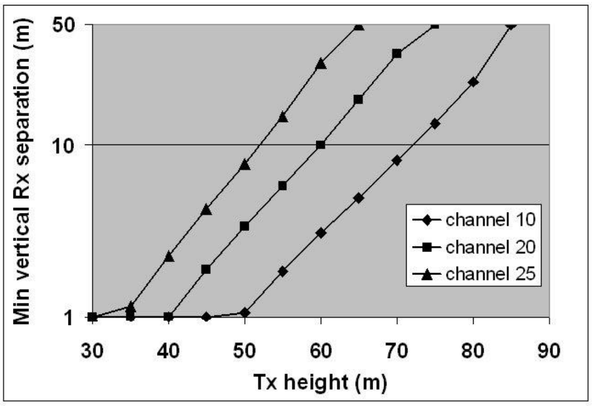

Figure 12. Minimum vertical separation between receiver coils of vertical gradiometer, as a function of system elevation, for the difference between SPM and plate responses to exceed 3 times the VTEM channels' noise levels.

CONCLUSIONS

Depending on the parameter weights used, layered-earth inversions modelled the sulphide and SPM EM anomalies, acquired during a VTEM survey, as either deep conductors or as shallow SPM material. Model discrimination was achieved when making use of AEM data acquired across the same anomalies at different system elevations.

In order to reduce the modelled SPM responses significantly, transient AEM surveys should be flown with a transmitter height above 80 m. An AEM gradiometer system is likely to offer the necessary information for discrete conductor – SPM discrimination for survey elevations below 80 m. Wider vertical receiver separations are preferable over small separations, but, depending on the flying height of the transmitter, separations between 2 and 40 m would be adequate.

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