Sub-surface imaging and vector precision from high resolution down-hole TEM logging

James Cull[1)] and Duncan Massie[1)]

Abstract: Filament inversion routines are highly effective for target definition whenever total-field DHTEM vectors can be obtained using three-component logging tools. However most cross-hole components contain significant noise related to sensor design and errors in observation of probe rotation. Standard stacking methods can be used to improve data quality but additional statistical methods based on cross-correlation and spatial averaging of orthogonal components may be required to ensure a consistent vector migration path. Apart from assisting with spatial averaging, multiple filaments generated for successive time-windows can provide additional imaging information relating to target geometry and current migration. New digital receiver systems provide additional time-windows to provide better tracking options necessary for high-resolution imaging of this type.
Keywords: down-hole geophysics, 3D logging, DHTEM, filament model, vector migration

1. Introduction

Three-component logging tools are now commonly available to assist with routine drilling and target selections in down-hole mineral exploration programs. The advantages of a full vector solution for interpretations based on filament inversion routines for down-hole time-domain electromagnetic (DHTEM) data have been clearly demonstrated by Duncan and Cull (1988) and Cull (1993). Similary, Hoschke (1985) has demonstrated the resolution and imaging capacity available using full-vector mapping of the natural magnetic field. To some extent both these methods have been merged in surveys for marginal conductors using the DHMMR technique (Purss *et al.*, 2003). High resolution surveys are now designed to combine the benefits of static-field magnetic surveys with the dynamic mapping capacity of the transient DHTEM filament method.

The objectives of a normal DHTEM survey are (a) to detect a target, (b) to provide vectors for subsequent drilling, and (c) to provide an indication of target structure and geometry for further interpretation. However probe performance, external noise, and sample density impose significant limitations on the quality and resolution available in any resulting model. Some types of external (atmospheric) noise can be reduced significantly by numerical processing and good results have been obtained using alternative digital survey systems (e.g. Duncan *et al.*, 1998). Unfortunately data quality can also be severely degraded by internal noise associated with electronic design and sensor limitations particularly for the cross-hole components. Probe rotation is most often measured using a combination of solid-state inclinometers while three separate induction coils (dB/dt) are used to determine the total DHTEM field at any depth.

The physical limitations in sensor performance and errors in probe rotation can result in significant scatter in estimates of the total field and vector migration used to define a general target response. However

1) School of Geosciences, Monash University, PO 28E, Clayton, Victoria 3800, Australia
E-mail: jim.cull@sci.monash.edu.au

model precision and resolution are further restricted by the available sample density and window width used to monitor filament migration paths associated with any specific structure. Consequently new data reduction methods are required to ensure internal consistency in the decay curves for each component as a function of depth. In particular high performance DHTEM survey systems can now be used to establish vector migration trajectories and eliminate deficiencies in crosshole profiles using the primary axial data as a major internal constraint.

2. Down-hole three-component TEM data

One example of three-component (3D) DHTEM data is given by Amann and Pietila (1998). There is a clear distinction in data quality for the crosshole vectors compared to the standard axial component (Fig. 1). The late time 'chatter' in the crosshole components does indicate an approach to true noise levels but the target signature is complicated by 'cross-overs' or overlapping trace effects in the profile plots. In contrast the standard axial component is relatively 'clean' and high quality data can be readily extracted for interpretation.

The quality of the available three-component DHTEM data has been a matter of concern for several years (e.g. Cull, 1996a). Apart from physical limitations related to the available crosshole receiver area there are additional sources of noise associated with measurements of probe rotation. Consequently crosshole DHTEM data are inherently less robust compared to the fixed axial component which is unaffected by rotation. In addition the axial component can be readily expanded in effective physical area by using long

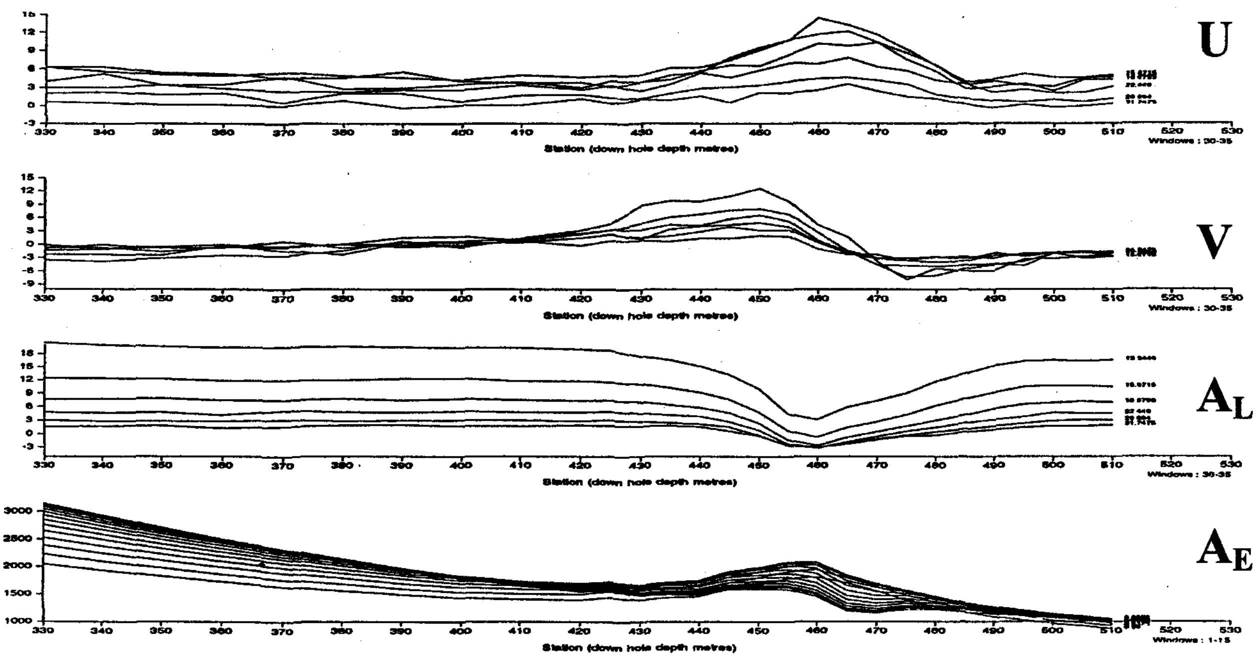

Fig. 1. Example of 3D DHTEM data indicating additional noise levels on cross-hole components (U, V) compared to axial data (A) for early times (E) and late times (L).

sections of core material with high permeability. Small plugs of this same material are much less effective for the shorter crosshole sensors giving only marginal gains in sensitivity (Cull, 1996b).

The initial performance of any crosshole sensor involves a trade-off between the number of turns required to achieve a significant receiver area and the corresponding linear resistance of the wire used in the coil assembly. The noise figure associated with the total resistance of the coil can be readily calculated providing a limit to survey resolution. However practical probe systems also contain other electronic components. In particular buffer amplifiers and multiplexers are used to address each orthogonal component in a 3D probe. Consequently the system response (V) can be characterized by the expression

$$V = \Sigma A + \varepsilon_R + \varepsilon_E \qquad (1)$$

Where A is the eddy current signal (dB/dt) and ε_R, ε_E are random noise factors associated with the resistive wire and the electronic components in the total system.

An efficient probe design will ensure that $\varepsilon_R > \varepsilon_E$ to optimize the S/N ratio. Any additional turns on the sensor coil will improve the physical area giving greater signal amplitude but these additional turns also contribute to the total noise and data quality remains unchanged. For example typical noise figures for the VECTEM 3D probe are determined by the amplifier design currently specified to be 2.2 nV/√hz. This source provides an input to a conventional receiver operating over a nominal bandwidth of 10 khz giving a total system noise level of 44 μV. However final noise values better than 0.6 μV can be obtained for typical mid-range windows after sample averaging and linear stacking (Fig. 2).

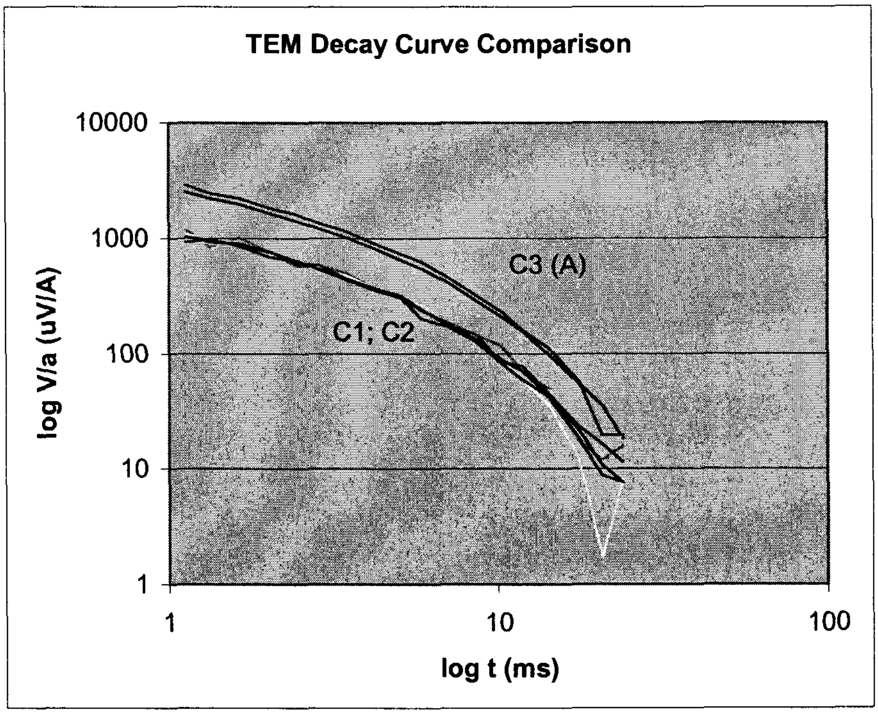

Fig. 2. TEM decay curves for VECTEM 3-component probe with each component oriented to the vertical (Z component offset for clarity). Additional noise on cross-hole sensors due to limited core length.

3. Vector rotation

Vector mixing caused by spasmodic probe rotation may introduce more serious errors than random internal electronic noise. In general survey tools are free to rotate about their longitudinal axis as they are lowered within the borehole. Consequently there is no fixed frame of reference for flux coupling with any eddy current system induced within a conductor. In order to obtain useful vectors to the target it is essential to measure the amount of rotation at any depth. In most 3D probes this is achieved using signals obtained from solid state inclinometers embedded in the sensor assembly. After calibration, angles of rotation can be calculated from the relative output of orthogonal pairs. However since each element depends on the gravitational force the accuracy varies with the angle of inclination. At the extreme there is no response obtained in vertical holes and angles of rotation are undefined.

For DHTEM surveys the drillhole axis provides a logical reference line. This axis is commonly labeled as the Z axis for logging surveys. Most operators refer to Z increasing down the hole from a zero point at the collar but the in-loop polarity is normally taken to be positive up. Two orthogonal axes must now be defined to formalise data obtained with a 3-component DHTEM probe. A rotation of the cross-hole vectors to the vertical plane can be readily accommodated and provides a consistent definition for the X component with a positive-up polarity. The second orthogonal cross-hole component Y is forced to be horizontal and completes a right-hand co-ordinate system. More recently an AMIRA convention has been adopted and these axes are described as U, V, and A in place of X, Y, and Z or their equivalent c1, c2, c3 (Fig. 3).

Output from the cross-hole sensors can be combined to give the required local vectors according to the expressions

$$\begin{aligned} V_U &= V_{c1}\cos\alpha + V_{c2}\sin\alpha \\ V_V &= V_{c2}\cos\alpha - V_{c1}\sin\alpha \\ V_A &= V_{c3} \end{aligned} \tag{2}$$

where α is the measured angle of rotation with respect to the vertical.

For many prospects the resulting 3D vectors can be used immediately to obtain a unique solution for a single eddy current system responsible for the total response in each of the observed orthogonal components (e.g. Barnett, 1984; Duncan, 1987). For an isolated conductor a single ring-filament or magnetic dipole source can be calculated for each time window of the DHTEM response. Furthermore the same inversion methods can be used to provide an interpretation of any static down-hole 3D magnetic data associated with the same body (Fig. 4).

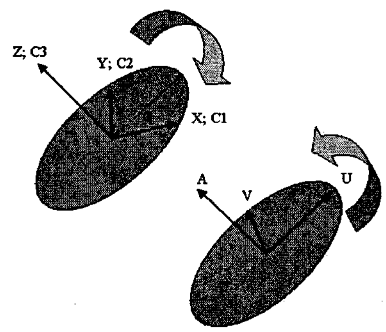

Fig. 3. Rotation conventions for 3D probe.

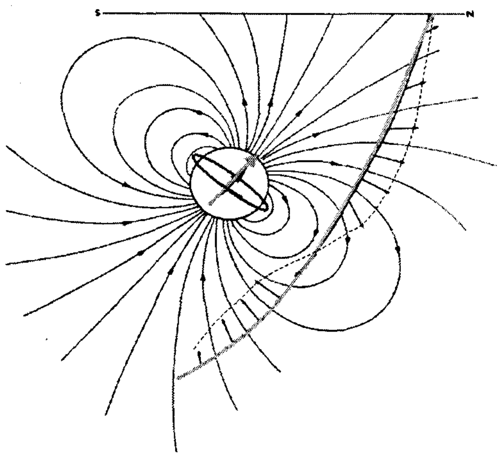

Fig. 4. Filament model for 3D magnetic or DHTEM data removing rotational ambiguity and providing unique vector response for down-hole dipole field.

4. Noise reduction and filament migration

Most TEM systems use variations of sample averaging and linear stacking to improve the quality of survey data. Average values in each window depend on sample interval and window length. Consequently the system noise is reflected in the standard deviation (σ) according to the expression

$$\sigma = \sqrt{[\,\Sigma\,(V_m - V_i) / W\,]} \qquad (3)$$

where V_m, V_i are the mean and point values of the TEM signal in each window extending over W samples. Linear stacking (repeated measurements) extends the data sampling and provides the equivalent of a standard error for the mean values in each window according to the expression

$$\sigma_m = \sqrt{[\,\Sigma\,(V_A - V_W) / N\,]} \qquad (4)$$

where V_A ,V_W are the stack average and window value for each of N stacks.

Normally N is much larger than W for most TEM systems and consequently noise levels depend primarily on (4). To a first approximation $V_W = V_i$ and the effect of amplifier noise can be readily established. However a progressive reduction in noise levels can rarely be achieved due to other non-random events in the environment (e.g. spikes or sferics) which degrade the stacking process. In addition there are financial penalties for extended stacking and the gains may be marginal for many applications. Consequently alternative techniques have been developed for noise reduction in routine surveys.

Duncan *et al.* (1998) have demonstrated the advantages of advanced signal processing techniques for fully digital TEM receiver systems. These combine the advantages of signal selection, filtering, and stacking based on the inspection and processing of raw time series data from full-wave continuous recording. However systems of this type are not commonly available and significant operator intervention is required to obtain optimum results. Other methods based on internal consistency, spatial averaging, and post-stack filtering of individual decay curves are well known and signal quality can be greatly improved at the risk of some distortion and lack of fidelity (e.g. Stolz and Macnae, 1998). However better solutions based on cross-correlation (Spies, 1988) and Hilbert transforms (Dass *et al.*, 1986) may be available for multi-component data including three-component down-hole probes.

Multiple inversions of data in successive time-windows may now provide an alternative 'brute-force' method for data averaging and noise reduction. The addition of the cross-hole vectors in a filament inversion provides the opportunity for a unique interpretation. Reasonable interpretations can be obtained from coarse starting models with very few iterations. Robust solutions are obtained even when there are random errors in rotation. Starting models based on a single filament (Barnett, 1984) act as a spatial filter providing stability in the statistical migration to a least-squares minimum. However some serious problems can be anticipated where there are multiple filaments corresponding to complex conductors or overburden/host distortion. Stripping techniques must be applied in these circumstances to isolate each separate response (in particular the overburden response) prior to inversion using a minimum number of filaments to suppress any residual noise or minor perturbations.

Several separate filament solutions have been obtained using successive decay-time windows in Fig. 5. Similar solutions are obtained for each window in spite of the variations in noise. All solutions require one filament fixed in the overburden with a second filament free to approximate the deeper target response. In addition to providing a data averaging or smoothing function the mapping of multiple filament solutions can also provide some information on target geometry and current migration. Late-time filaments move down-dip towards the center of the target and provide some variation in coupling characteristics with the sensor system. This form of sub-surface imaging or current-tracking can be greatly improved using the new generation of receiver systems (e.g. terraTEM) which provide for greater dynamic range using multiple time-windows with a high-speed sample interval.

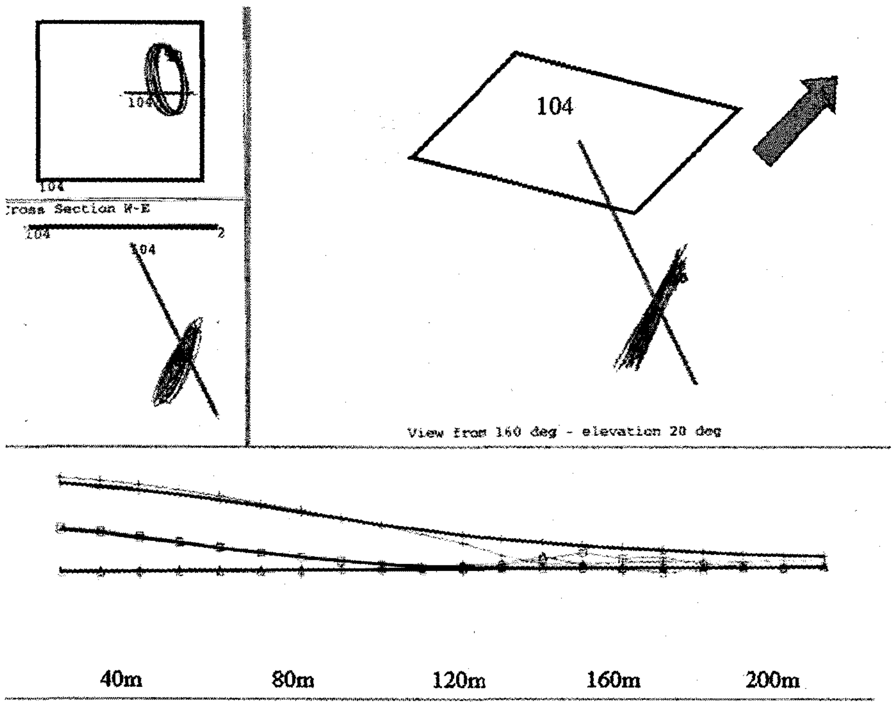

Fig. 5. Sub-surface imaging and vector migration using filament solutions obtained by inversion of DHTEM data from multiple decay-time windows.

5. Conclusions

Crosshole DHTEM data are normally subject to higher levels of noise than data obtained with conventional axial probes. Apart from higher levels of external sferics or telluric noise in the horizontal plane (e.g. McCracken *et al.*, 1984), there are significant differences in the construction of crosshole sensors compared to axial sensors. In particular core materials are relatively ineffective for crosshole sensors and the effective physical area depends primarily on the number of turns used for coil construction. However there is a limit to the total length of wire employed in this process since a second noise floor is imposed by the amplifier and ancilliary components in the probe circuit. In addition the angle of rotation must be determined prior to any vector reconstruction. As a consequence noise levels in the crosshole sensors are significantly higher than for standard axial sensors.

For simple targets a combination of spatial and temporal averaging can be used to improve the quality of DHTEM data prior to interpretation. However more complex targets may require multiple filaments for adequate definition. In these circumstances the corresponding decay curves may be highly specific and each of the orthogonal components must be treated in isolation in order to obtain a consistent solution. New high definition receiver systems with multiple windows may be required to resolve secondary filaments associated with minor conductors previously identified with noise.

The nature and stability of a 3D vector solution may be more fully explored using multiple filament solutions. In particular most viable targets generate local fields of high curvature and a scaled simultaneous response can be anticipated in each of the orthogonal components. Consequently a cross correlation can be anticipated in the resulting signals providing some opportunity for noise reduction. Spies (1988) has demonstrated the potential for noise reduction in TEM data using correlations between noise records for orthogonal components in surface soundings. However these methods are designed to reduce the effect of random external factors and are not strictly applicable to variations relating to internal sensor design.

REFERENCES

Amann, W. J., and Pietila, R., 1998, Geophysical response of the Silver Swan nickel sulphide deposit Western Australia, *Exploration Geophysics*, **29**, 273-279.

Barnett, C. T., 1984, Simple inversion of TDEM data, *Geophysics*, **49**, 925-933.

Cull, J. P., 1993, Downhole three-component TEM probes, *Exploration Geophysics*, **24**, 437-442.

Cull, J. P., 1996a, Rotation and resolution of three-component DHEM data, *Exploration Geophysics*, **27**, 155-159.

Cull, J. P., 1996b, Sensor response and resolution in downhole TEM data, *Exploration Geophysics*, **27**, 167-169.

Dass, G. R., Varaprasada Rao, S. M., and Mohan, N. L., 1986, Application of the Hilbert transform in resolution of magnetic signals: a new technique, *Exploration geophysics*, **17**, 97-104.

Duncan, A. C., 1987, Interpretation of down-hole transient EM data using current Filaments, *Exploration Geophysics*, **18**, 36-39.

Duncan, A. C., and Cull, J. P., 1988, Three-component downhole TEM surveys, *Exploration Geophysics*, **19**, 51-53.

Duncan, A. C., Amann, B., O'Keeffe, K., Williams, P., Tully, T., Wellington, A., and Turner, G., 1998, Examples from a new EM and electrical methods receiver system, *Exploration geophysics*, **29**, 347-354.

Hoschke, T., 1985, A new drill hole magnetometer: preliminary results from the Tennant Creek area, *Exploration Geophysics*, **16**, 365-374.

McCracken, K. G., Pik, J. P., and Harris, R. W., 1984, Noise in EM exploration systems, *Exploration Geophysics*, **15**, 169-174.

Purss, M. B. J., Cull, J. P., and Asten, M. W., 2003, Simultaneous modelling of the phase and amplitude components of downhole magnetometric resistivity (DHMMR) surveys, *Journal of Applied Geophysics*, **54**, 1-14.

Spies, B. R., 1988, Local noise prediction filtering for central induction transient electromagnetic sounding, *Geophysics*, **53**, 1068-1079.

Stolz, E. M., and Macnae, J., 1998, Evaluating EM waveforms by singular-value decomposition of exponential basis functions, *Geophysics*, **63**, 64-74.