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The application of tilt derivatives to EM conductivity data

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SUMMARY

In the processing of geophysical potential fields, a wide range of spatial derivatives are available to enhance the information contained in the basic data. Here the ability of the tilt and tilt derivatives to provide enhanced mapping of conductivity data is considered. Tilt and its associated functions are formed by taking combinations of vertical and horizontal derivatives of the data set. A theoretical forward modelling study is carried out to assess the performance of tilt derivatives in relation to the detection and definition of concealed conductivity structure. Case studies of the practical application of the procedures to survey data are performed. The case studies derive from large scale airborne EM data sets but the methods have a general applicability to a wide range of geophysical conductivity and resistivity data. The tilt functions embody Automatic Gain Control that normalise the detection and definition of both weak and strong conductivity gradients across an appropriate subsurface depth range. The use of high order spatial derivatives inevitably results in a degree of noise amplification that is survey and technique specific. Filtering methods for the reduction of undesired, usually high wavenumber, artefacts are available and are shown to be effective.

Introduction

Magnetic and gravity derivatives have a well-established role in the interpretation of potential fields from both ground-based and airborne surveys. There exist a range of processing procedures and filters, largely relating to vertical and horizontal derivatives and their combinations, (e.g. Cooper and Cowan, 2006) that perform as enhanced mapping functions when applied to the basic data sets. In the case of fields obeying Laplace's equation, filtering procedures, such as Euler deconvolution, can be extended to provide information on the position and depths of sources. The ability of the tilt and tilt derivatives to provide enhanced mapping of electromagnetic (EM)/conductivity structure is considered here. Although the study considers airborne EM survey data, the concept can equally be applied to ground-based conductivity/resistivity data sets.

The field interactions involved in EM induction within a 3D conductivity contrast are profoundly more complex than those occurring in the corresponding magnetic susceptibility/density case. Although it is known that in the limit of low frequency and very high contrast targets, the EM wave equation may approximate Laplace's equation, the general case is considered here. Equally, although basic airborne EM data comprises in phase and quadrature coupling ratios, we consider the enhanced mapping of the conductivity data derived from these data. The conductivity data essentially have had the height dependence of the basic data removed. The present study, based on conductivity map information, has a general validity, although it should be acknowledged that different airborne systems (including frequency and time domain systems together with their specific bandwidths) will provide different EM interactions with specific 3D targets.

The tilt derivative method

The tilt angle (T) is defined by Millar and Singh (1994) as the ratio of a vertical to a combined horizontal derivative:

$$T = \tan^{-1}\left(\frac{\partial f / \partial z}{\sqrt{(\partial f / \partial x)^2 + (\partial f / \partial y)^2}} \right)$$

Where f is the magnetic or gravity field. More recently, Verduzco et al. (2004) suggested using the total horizontal derivative (THDR) of the tilt angle, as an improved edge detector:

$$THDR = \sqrt{(\partial T / \partial x)^2 + (\partial T / \partial y)^2}$$

The amplitude range of the dimensionless ratio is restricted to the range π/2 to - π/2 (or 90° to -90°) by virtue of the arctan function. Both T and THDR act as an Automatic Gain Control (AGC) filter when applied to the field observations. This is an important feature when considering its application to larger scale data sets with a wide dynamic range. It is possible to consider additional functions that may be derived from tilt using higher order derivatives such as the total horizontal derivative of the THDR. As noted by Cooper and Cowan (2006), as the order of the derivative function increases, in the search for higher resolution, the degree of noise amplification also increases. The signal/noise content of the data considered is thus an important aspect in relation to the practical application of the procedures. Summaries of the behaviour of tilt derivatives in the case of potential field data are provided by Fairhead et al. (2004) and Cooper and Cowan (2006).

A synthetic modelling study

In order to evaluate the performance of tilt derivatives in relation to EM conductivity data we consider the AEM-05 airborne EM system described by Leväniemi et al. (2008). The 4 frequency system comprises a vertical coplanar coil set, mounted across the wing-tips of a DHC Twin-Otter. The 4 frequencies provide different depth ranges of investigation. The lowest frequency is 912 Hz and this provides the greatest depth of penetration. 3D EM modelling of thin-plate conductivity structures offers the simplest and, typically, the most stable set of solutions for the forward modelling case. Here the thin-plate modelling algorithm LeroiAir developed by the CSIRO Electromagnetic Modelling Group is used for the computations. A single horizontal thin-plate with a width of 50 m and a length of 1 km was embedded in a uniform host of 5 mS/m. The conductance of the plate was 10 S.m and the survey height was 50 m. By using a large plate length, it is possible to generate profiles and grids over the central area of the model (e.g. 200 x 200 m) free from the 3D edge effects of a more compact body. Computations were performed with the depth of the plate increasing from the near-surface to a depth of 150 m. The coupling ratios calculated from the forward modelling at 912 Hz were converted to half-space apparent conductivities in the standard manner. Figure 1a shows the results obtained across a profile through the centre of the model with the edges of the 50 m wide body indicated by dash lines. The detection amplitudes of the plate decrease with increasing depth and range from 8 mS/m for the shallowest depth to 1 mS/m with the plate at a depth of 150 m.

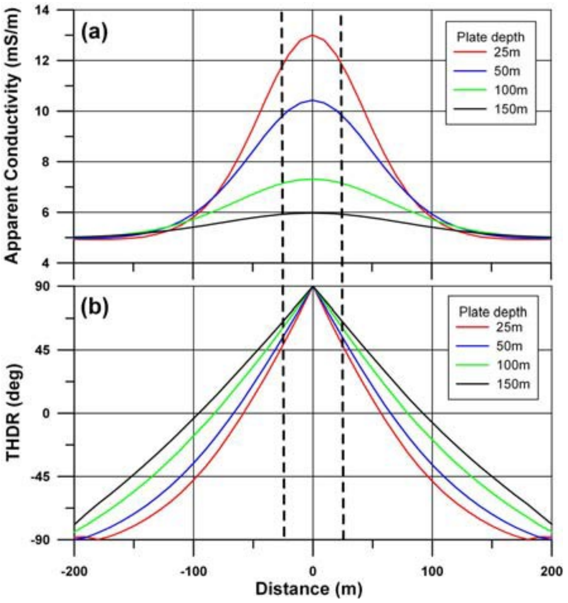

Figure 1. Results obtained from thin-sheet modelling study described in the text. The width of the thin-plate is shown by dash lines. (a) Apparent conductivity. (b) Total Horizontal Derivative (THDR).

The THDR calculated for these data is shown in Figure 1b. The responses display the expected uniform gain at all plate depths, with a value of +90°achieved over the centre. If a reference value of +45° is chosen as a reference THDR level then the 50 m width of the plate is well defined for plates at shallow depths (e.g. 25 m). As the plate increases in depth to 150 m, the assessment of the target width, at the +45° reference level, increases towards 100 m.

Survey data example

A selected example of the application of the THDR method to conductivity mapping uses half-space conductivity data from the Tellus airborne geophysical survey of Northern Ireland (Beamish and Leväniemi, 2006). The example is a 5 x 5 km area taken from the Southern-Upland-Longford-Down Paleozoic terrain and is centred on the town of Newtonhamilton. The survey detected a swathe of conductive structures traversing the terrain. Modelling of the conductive features indicates that they are all concealed and they appear to be vertical, or near-vertical structures with upper surfaces at a variety of depths in the upper 100 m. The different depths give rise to a variety of amplitudes in the half-space conductivity maps. In a number of cases, the depth of the conductive feature is sufficiently great to make detection marginal. Figure 2a shows the apparent conductivity data obtained at a frequency of 3 kHz across the 5 x 5 km area. The colour scale is linear and ranges from 1 (black) to 200 (pink) mS/m. Sun shading from the NW has been applied to emphasise the conductivity gradients. The break in structure in the centre of the plot is due to a regulatory high-fly condition above the town of Newtonhamilton. Four quasi-linear conductive features are observed to cross the area. Figure 2a shows the THDR calculated from the data with only positive values displayed. Blue corresponds to the THDR range 0°to 45° and red corresponds to the range 45° to 90°. Using Figure 1 as a reference, it is this latter region that would provide the most appropriate conductive feature mapping.

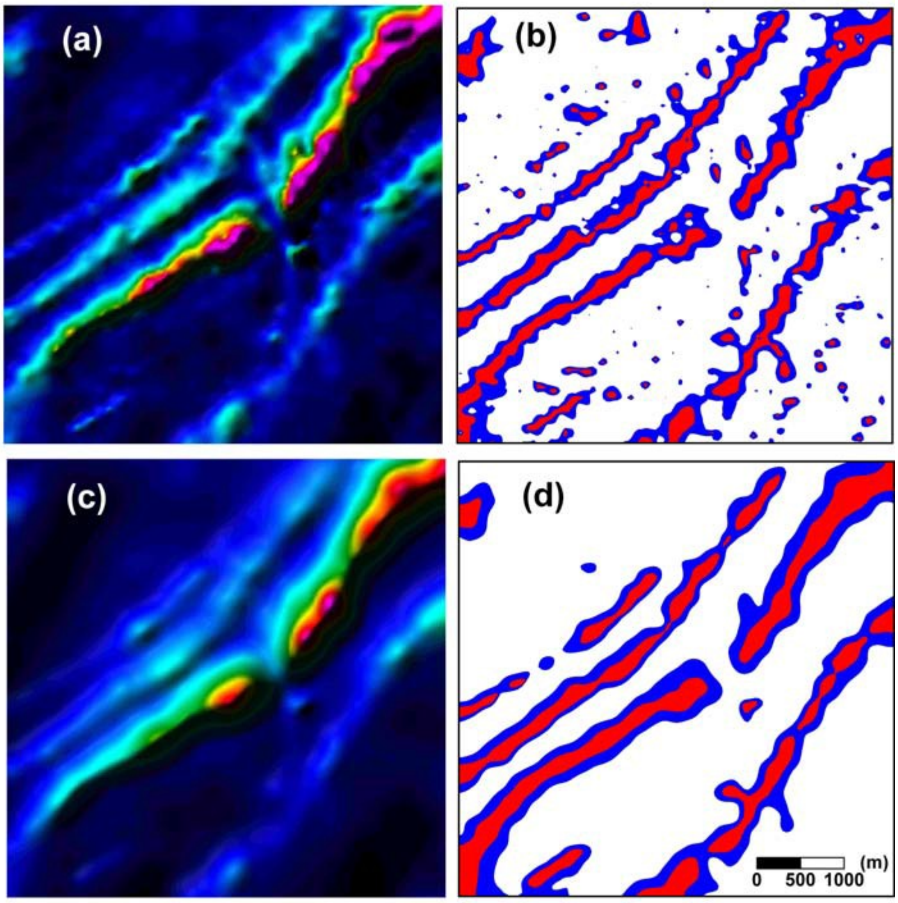

Figure 2. Results from the 5 x 5 km study area. (a) Half-space conductivity at 3 kHz. (b) THDR of data in (a). (c) Conductivity data in (a) upward-continued to a height of 100 m. (d) THDR of data in (c). All colour ranges are linear (see text).

The results also demonstrate the noise amplification inherent in the procedure. A large number of high-wavenumber features are clearly present in the THDR map. When applied to other data sets from the UK, the sensitivity of the procedure to small scale conductivity gradients such as those associated with roads is well demonstrated. Although some of these features may be of interest in relation to local-scale environmental investigations, it is worth demonstrating the application of another form of filtering procedure, common in potential field processing, to the removal of the high wave-number content. Although a number of potential low-pass filters could be applied to the conductivity data, the method of upward-continuation is demonstrated in Figure 2c. It should be noted that, in contrast to the basic coupling ratios which were acquired, in this case, at a nominal survey height of 56 m (but with flight elevation variations), the conductivity data is essentially a subsurface description of the conductivity distribution. Although the optimum height for upward-continuation is a matter of experimentation, Figure 2c shows the conductivity data of Figure 2a, upward continued to a height of 100 m. Figure 2d then shows the resulting THDR map calculated from the data and shown using the same colour ranges as previously. The results indicate the ability of the procedure to detect and outline significant conductive features throughout the subsurface.

Conclusions

This study has considered the application of the total horizontal derivative of the tilt angle to enhance half-space conductivity mapping. In the airborne case, the lowest frequency (or latest time) offers the greatest potential for summarising the outlines of conductive domains across the largest range of depths. The inherent AGC of the technique normalises the detection and definition of both strong and weak subsurface conductive features. An equivalent procedure to map resistive features could equally be applied to any geophysical data sets mapped in terms of their resistivity.

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