CANADIAN JOURNAL OF EXPLORATION GEOPHYSICS
VOL 30, NO 2 (DECEMBER 1994), P. 115-119

A METHOD FOR DERIVING A PSEUDO DEPTH SECTION FROM THE RESPONSE OF A TWO–COIL HORIZONTAL COPLANAR COIL SLINGRAM ELECTROMAGNETIC EXPLORATION SYSTEM

K. DUCKWORTH[1] AND E.S. KREBES[1]

ABSTRACT

A procedure by which horizontal coplanar coil Slingram electromagnetic profiles can be converted to apparent or pseudo depth sections is demonstrated by means of theoretical and field examples. It is shown that the procedure produces a contoured depth section which focuses on the conductive target if that target is thin and located in a resistive host. In these circumstances the method would provide reliable drilling targets. If the target conductor is wide with respect to the coil separation used in the original survey the procedure indicates depth which is greater than the true depth of the target. The depth information provided by this concept is derived entirely from the geometry of the recorded profile as opposed to being derived from the magnitude of the profile, as in the conventional means of deriving depth information from horizontal coplanar coil electromagnetic surveys. A notable feature of this new method is that the depth and direction of dip of the target are indicated directly and simultaneously by the distribution of the contours around the location of the target.

INTRODUCTION

The concept of an apparent or pseudo current density depth section introduced by Karous and Hjelt (1983) provides a convenient visualization of the lateral and vertical location of a conductive target as detected by means of VLF surveys. The technique described by Karous and Hjelt (1983) and tested against theoretical models by Ogilvy and Lee (1991) is based upon spatial filtering of the VLF profile over a target and plotting the output of the filter in the form of a depth section where the vertical coordinate is the expanding interval between the points at which the original profile is sampled by the expanding filter operator.

The creation of an apparent depth section by spatial filtering depends upon the lateral geometry of the original profile being directly dependent upon the depth of the target. Thus, this concept would not normally be applicable to data acquired by a horizontal coplanar coil Slingram electromagnetic system because the width of an anomaly generated by such a system is controlled by the separation of the coils. However, the output from a Slingram system can be converted to a form which is free of the effects of coil separation as described by Duckworth et al. (1991) so that the geometry of these converted profiles is related to target depth and therefore is potentially capable of being converted into an apparent depth section by filtering.

The purpose of the discussion presented here is to demonstrate a method for the conversion of Slingram responses to apparent or pseudo depth sections. The process employed in the conversion differs from that described by Karous and Hjelt (1983) and it is not intended that this be viewed as a conversion to a current density depth section.

THEORY

The response of a horizontal coplanar coil Slingram type of electromagnetic system to a localized target is the product of the separate coupling functions of the transmitter and receiver coils with respect to the target. Thus:

$$S = k_{TxC} . k_{CRx} . \qquad (1)$$

This response is usually normalized with respect to the primary coupling so that the expression becomes:

$$S_n = \frac{k_{TxC} k_{CRx}}{k_{TxRx}} . \qquad (2)$$

In the case of horizontal coplanar coils of identical dimensions, the spatial character of the two single-coil functions k_{TxC} and k_{CRx} is identical so that the two-coil response S can be viewed as being derived from one common single-coil function k and if the two-coil Slingram type of function is converted back to the single-coil form it will be free of the influence of coil separation and will display a lateral geometry which depends strongly on the depth of the target, as is evident in the single-coil function displayed in Figure 1 for the response of a horizontal line type of target.

Conversion of Slingram profiles to the true single-coil form k requires that separate Slingram profiles with different coil separations be obtained over the target (Duckworth et al., 1991). However, a simplified conversion which will be

---

Manuscript received by the Editor June 15, 1994; revised manuscript received February 23, 1995.

[1] Department of Geology and Geophysics, The University of Calgary, Calgary, Alberta T2N 1N4

We are indebted to Geonics Ltd. of Mississauga for the loan of equipment used in acquiring some of the field results presented here and to John Juigalli and Carl Gunhold for their enthusiastic efforts in acquiring that data.

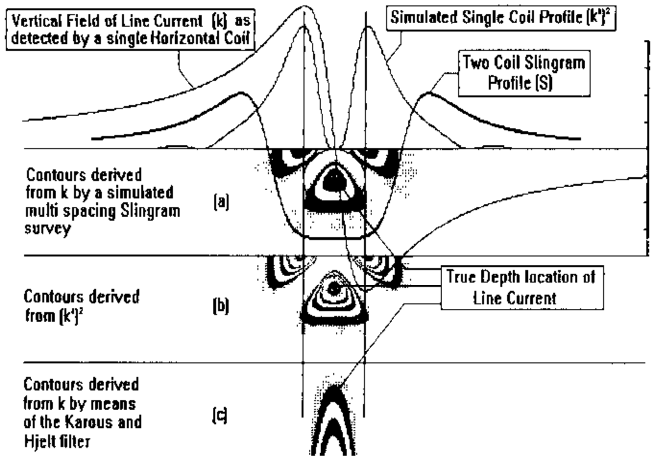

Fig. 1. The coupling function *k* for a single horizontal search coil when traversed over a horizontal line target, the corresponding two-coil Slingram function *S* which can be derived from *k* for a simulated coil separation equal to four times the target depth and the approximate single-coil function (squared) which can be derived from *S*. (a) shows contours derived from *k* by a simulated Slingram survey for a wide range of coil separations. (b) shows contours derived from *S* and $(k')^2$. (c) shows the result of applying the Karous and Hjelt filter to the original function *k*.

denoted k' can be achieved by taking the products of pairs of values sampled from a single Slingram profile with the interval between the samples being equal to the separation of the coils used in acquiring the Slingram profile (Duckworth et al., 1991). Thus:

$$k' = S_{x-a/2} \cdot S_{x+a/2}\ , \qquad (3)$$

where a is the coil separation.

This simplified process produces only an approximate transformation of the two-coil Slingram function to the single-coil function but it has the merit of requiring only a single pass over the target with the field equipment, using any arbitrary coil separation, but the function that results retains the necessary geometric dependence on target depth. The production of a smooth profile is necessary to the effectiveness of this process but this may be achieved by interpolation of additional data between the recorded data points as described later. The use of interpolation allows the process to be applied to data acquired with any coil separation at any station spacing although these parameters must be such as to permit the system to produce a reasonable sampling of the anomaly.

The horizontal line target provides the most immediate means of appreciating the behaviour of the conversion of a Slingram profile to a depth section. A profile (k) of the coupling between a single horizontal search coil and a horizontal line target is shown in Figure 1 along with the Slingram profile (S) that would be observed over that target for a simulated coil separation equal to four times the target depth. This profile was derived from the single-coil profile by means of expression (1). The function (k') which results from the simplified conversion of this Slingram profile back to the single-coil function by means of expression (3) is also shown. In fact, the function shown is the square of k' as this provides a clearer separation of the contours in the apparent depth section. The approximate single coil function k' [or $(k')^2$] is a double-peaked even function in which the lateral separation of the peaks is directly related to the depth of the target just as is the separation of the positive and negative maxima on the original single-coil function. The theoretical single-coil coupling function k is an odd function but the even function k' can not be converted into an odd function nor is this necessary for the purposes of obtaining depth estimates.

A filtering process which converts the single-coil coupling function into a pseudo depth section would ideally produce a contour pattern which would focus on the location of the target conductor both laterally and in depth. In this context the two-coil horizontal coplanar Slingram device itself provides a type of focused response which comes close to this ideal, as can be seen in the contours presented in Figure 1a which were generated by computing Slingram response profiles from the single-coil profile (k) for a range of simulated coil separations using expression (1). In order for the contours to display this focused form, the computed two-coil response must be presented in the absolute form rather than being normalized with respect to the primary coupling. The central negative on the Slingram anomaly reaches its maximum absolute value when the simulated coil separation is equal to the depth of the line target, this being the separation at which the transmitter and receiver coils simultaneously achieve maximum coupling with the target (Duckworth et al., 1993). Thus, the contours of the central negative anomaly naturally focus on the true depth of the line current. By comparison, the Karous and Hjelt filter when applied to the original single-coil coupling function k as shown in Figure 1c provides for good lateral location of the contours with respect to the line current target and a notable freedom from the flanking peaks, but it does not focus on the true depth location of the line current which suggests that the description of this filter as a current density filter can be misleading. In that the Karous and Hjelt filter is designed for application to odd functions it can not be applied to even functions such as k', so that it could not be adapted to generating depth sections from the approximate single-coil type of function.

Thus, as a contour distribution which focuses on the target can be derived from the single-coil function k then a similar contour distribution can be derived from the approximate single-coil function k' [or from $(k')^2$], again by means of expression (1) but with k' [or $(k')^2$] substituted for k. The result of converting $(k')^2$ to a depth section by this means is shown in Figure 1b. The depth section which results shows the same focus on the true depth location of the line current and the same associated flanking peaks that the section derived directly from the single-coil function k displays. These flanking peaks clearly have no relationship to the spatial position of any current but their separation is very immediately related to the depth of the target. Thus, given a single Slingram profile, the use of expression (2) allows an approximation to the single-coil function to be generated which then permits an apparent depth section to be generated which has the desirable ability to focus on the true depth of the target. In effect, this process approximately converts a single Slingram traverse into a range of traverses at different separations but presents them as a map.

This appears to be a desirable achievement as it is not uncommon that surveys are repeated at different coil separations to provide the interpreter with additional views of the response of a target to aid the interpretation. As this process provides an almost unlimited range of these alternative views using only data already acquired without the need to repeat the traverse over the conductor, it appears that this could result in savings in survey costs. The presentation of the results in depth map or pseudo section form is a necessity as the large number of profiles represented by one of these sections would be incomprehensible if actually presented in profile form. It can also be appreciated that if the results of the process were presented in profile form, they would not automatically indicate the location of the target as does the pseudo section.

The perfectly conductive semiinfinite half-plane model provided by Wesley (1958) permits the application of this method of deriving an apparent depth section to a more meaningful target. The response of such a target may be readily computed for any depth dip or coil separation as described by Duckworth and Krebes (1994). The result of converting a single Slingram profile over such a target into a simulation of the single-coil coupling function and then converting the single-coil function into a depth section is shown in Figure 2 for a target dipping at 70° at a depth equal to 0.15 of the coil separation. The focus of the resulting contours is located on the actual target but somewhat below the top of the target. In that this is a perfectly conductive target it might be expected that current would concentrate at the top edge of the conductor and that the contours would focus on that location. This deviation from what might be expected lies in the approximate nature of the conversion embodied by expression (3). It is notable that, as shown in Figure 2, a circle centred on the focus of the contours and tangent to the ground surface is also tangent to the lines which locate the peaks on the simulated single-coil profile. This geometry would be characteristic of the vertical component of a horizontal line of current located at the focus of the contours except that such a line could not create a field with the disparity of magnitudes in the two peaks that results from the dip of the target. From the practical point of view, the focus of the contours would clearly provide a reliable drilling target and the direction of dip would be clear both from the distribution of the contours around the focus and in the relative magnitudes of the flanking peaks.

It must be stressed that the simplified conversion to the single-coil profile *k'* is only approximate and that the approximation becomes worse as the ratio of the coil separation to target depth in the original Slingram profile becomes smaller so that its application to responses obtained over deep targets would be inappropriate.

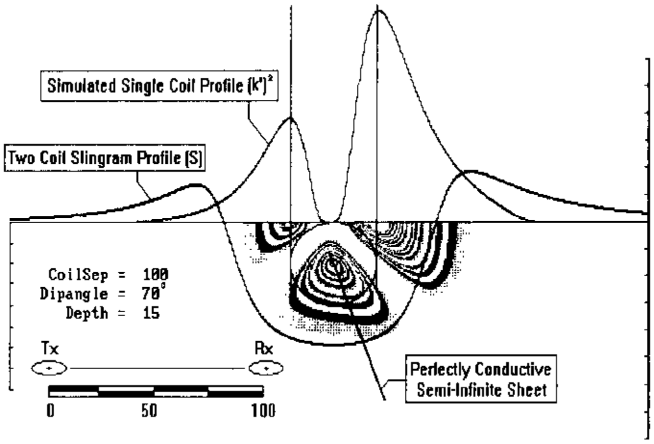

Fig. 2. The two-coil Slingram response *S* of a perfectly conducting semiinfinite half-plane dipping at 70° and the contours which result from the conversion of *S* to the approximate single-coil function *k'* (squared) and then to the depth section. The focus of the contours would clearly provide a good drilling target.

FIELD EXAMPLES

An example of the application of this process to the inphase data provided by a Geonics EM-31 system operated over an environmental test range in which two steel drums had been buried at a depth of 1 m is shown in Figure 3. The original observations were acquired at a one-metre station spacing and are displayed as the emphasized data points. The smoothed profile was generated by sinc interpolation. In sinc interpolation the value of a function *F(x)* which has been sampled at a regular interval Δx may be derived from the sampled data for any value of *x* by means of the sampling theorem (Bath, 1974):

$$F(x) = \sum_{n=-\infty}^{+\infty} F(x_o + n\Delta x)\left\{\frac{\sin\left[\pi(x - x_o - n\Delta x)/\Delta x\right]}{\pi(x - x_o - n\Delta x)/\Delta x}\right\}$$

where $F(x_o + n\Delta x)$ represents the sampled data and

$$\left\{\frac{\sin\left[\pi(x - x_o - n\Delta x)/\Delta x\right]}{\pi(x - x_o - n\Delta x)/\Delta x}\right\}$$

is the sinc function. The use of this interpolation procedure requires care in the avoidance of high-frequency effects due to step terminations of the data set but is otherwise well behaved. Interpolation of additional data between the data values observed in the field is necessary if reasonably smooth-contoured sections are to be achieved from field data. The contoured depth section suggests that the second drum was located at a slightly greater depth than the first. However, the indication of greater depth for the second drum may be due to the fact that that drum was laid horizontally and oriented along the traverse while the first drum was upright. This probably caused the anomaly due to the second drum to be slightly wider than that due to the first drum, thereby resulting in an anomaly which appeared to originate from a slightly deeper source.

Conversion of a Slingram real component profile recorded over a graphitic shale conductor located in the Northern Territory of Australia (Duckworth, 1968) to an apparent

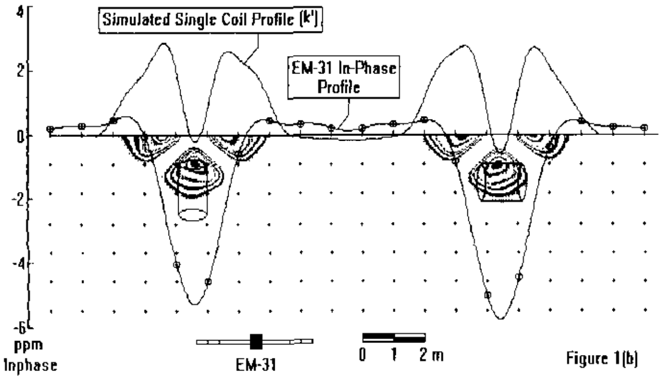

Fig. 3. An example of the application of the method to data acquired over two steel drums buried in an environmental test range.

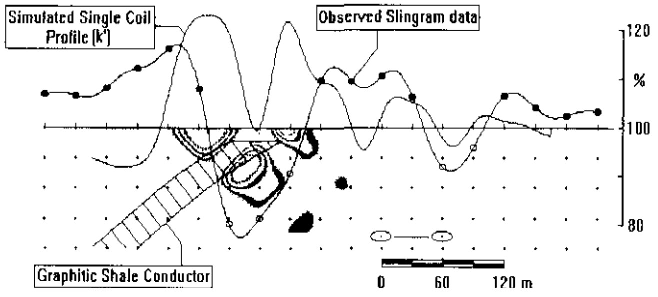

Fig. 4. Application of the method to data acquired over a highly conductive graphitic shale shows contours which focus below the target due to the target being of appreciable width with respect to the original coil separation of 60 m.

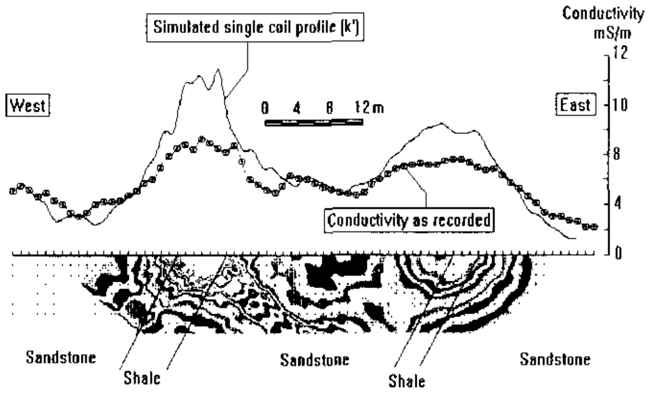

Fig. 5. An example of an inappropriate application of the method where it produces a depth section which is very poorly related to the actual structure.

depth section is shown in Figure 4. The imaginary component response of this conductor (not shown) was so weak that the conductor responded in a manner very close to that of a perfect conductor (Duckworth, 1970, 1977). For this target, the depth contours focused below its true depth position but the indication of the direction of dip provided by the contours is in agreement with the known dip of the structure. The probable cause of this location of the focus of the contours below the actual conductor was the considerable width of the conductor with respect to the coil separation. As shown by Duckworth et al. (1991), the depth of this conductor as indicated by the anomaly was too great unless a correction was applied for the width of the target. It is possible for a correction to be applied for conductor width in applying the procedure which generates the pseudosection but it was decided that this example should be presented without any correction in order to demonstrate at least one possible problem with the concept.

The conversion of a data profile to a depth section by means of spatial filtering of any kind must be applied with caution. An example of a clearly inappropriate application of the methods described here is presented in Figure 5. This data is a profile of the quadrature or conductivity readout of a Geonics EM-31 traversed over an outcrop of the Lower Brazeau Formation located in the Rocky Mountain Foothills Belt of southern Alberta. The outcrop consists of interbedded sandstones and shales all of which dip to the west at approximately 60°. The depth section that results from this data is clearly not well related to the structure of the outcrop.

CONCLUSIONS

Pseudosections are a familiar device in the presentation of Induced Polarization data, yet are well known to produce results which can be misleading as to the actual polarizeability structure of the subsurface. Despite this, the pseudosection is a well accepted tool in IP surveys. In VLF surveys the so-called current density pseudosection is now in widespread use and is currently incorporated into the software of some of the latest VLF receivers, yet it is clear that this too can be very misleading as to the true structure of the subsurface. The procedure described here has the merit that the pseudosection it produces inherently locates the target both laterally and in depth quite accurately while also suggesting the dip direction of the target, assuming the restrictions of this concept are appreciated. The flanking peaks that this process produces might possibly be misleading to a nonspecialist but similar difficulties are inherent in the use of pseudosections in IP surveys. The simplicity of the process is such that it could readily be programmed into the receiver of a two-coil horizontal coplanar system and provide the operator with an immediate display of the results as is already being done in some VLF receivers.

The principal restriction which must be stressed in using the process described here is that it should not be applied without consideration for the type of target that is being sought. The concept works best for responses obtained from thin steeply dipping conductors located in resistive host rocks. Its use with responses obtained over wide conductors will result in depth estimates which are too large and its application to responses obtained over deep targets will be inaccurate due to the approximate nature of the transformation to the single-coil type of profile. If groups of closely spaced parallel conductors are detected then the apparent depth section that will result from this process will probably have little value.

In that the process described here is essentially one which converts a single profile obtained with a single-coil separation into a range of profiles which simulate the responses that would have been obtained with a range of coil separations without having to actually acquire those profiles in the field, the process appears to offer a bargain in reduced field survey costs. When, additionally, the result is presented in a map or section form which automatically (and reasonably accurately) locates the target while simultaneously indicating its dip based solely on the geometry of the original profile, it appears that the bargain is even more notable. By comparison, conventional interpretation which is based on anomaly magnitude (Nair et al., 1968) depends upon a prior determination of dip and selection of the appropriate vector phase diagram corresponding to that dip from a suite of such diagrams. In that anomaly magnitude is subject to a wide range of influences other than the depth of the target, the conventional process is subject to error (Parasnis 1971), particularly if the wrong dip for the target is selected. Thus, the interpreter may find that this new method provides a useful complement to the conventional depth and dip determination methods and may find that the presentation of the result in the form of a pseudo depth section proves more readily acceptable to nonspecialists who must use the results in making exploration decisions.

REFERENCES

Bath, M., 1974, Spectral analysis in geophysics: Elsevier.

Duckworth, K., 1968, Mount Minza experimental geophysical surveys, Northern Territory 1966 and 1967: Bur. Min. Res. Austral., Rec. no. 1968.107.

_______, 1970, Electromagnetic depth sounding applied to mining problems: Geophysics **35**, 1086-1098.

_______, 1977, Field tests of a new electromagnetic depth sounding technique: Bur. Min. Res. J. Austral. Geol. Geophys. **2**, 155-163.

and Krebes, E.S., 1995, A QuickBasic program for the computation of the response of a thin tabular perfect conductor to a two coil horizontal coplanar electromagnetic prospecting system: Computers and Geosciences **21**, 333-343.

, Calvert, H.T. and Juigalli, J., 1991, A method for obtaining depth estimates from the geometry of Slingram profiles: Geophysics **56**, 1543-1552.

_______, Krebes, E.S., Juigalli, J., Rogozinski, A. and Calvert, H.T., 1993, A coincident coil frequency-domain electromagnetic prospecting system: Can. J. Expl. Geophys. **29**, 411-418.

Karous, M. and Hjelt, S.E., 1983, Linear filtering of VLF dip-angle measurements: Geophys. Prosp. **31**, 782-794.

Nair, M.R., Biswas, S.K. and Mazumdar, 1968, Experimental studies of the electromagnetic response of tilted conducting half-planes to a horizontal-loop prospecting system: Geoexplor. **6**, 207-244.

Ogilvy, R.D. and Lee, A.C., 1991, Interpretation of VLF-EM in-phase data using current density pseudosections: Geophys. Prosp. **39**, 567-580.

Parasnis, D.S., 1971, Analysis of some multi-frequency multi-separation electromagnetic surveys: Geophys. Prosp. **19**, 163-179.

Wesley, J., 1958, Response of a dyke to an oscillating dipole: Geophysics **23**, 128-133.