Journal of Applied Geophysics 121 (2015) 116–127

Contents lists available at ScienceDirect

Journal of Applied Geophysics

journal homepage: www.elsevier.com/locate/jappgeo

The Total Component (or vector magnitude) and the Energy Envelope as tools to interpret airborne electromagnetic data: A comparative study

Jacques K. Desmarais [a,*], Richard S. Smith [b]

[a] Earth Sciences, University of Saskatchewan, 114 Science Place, Saskatoon, Saskatchewan S7N 5E2, Canada
[b] Department of Earth Sciences, Laurentian University, 935 Ramsey Lake Road, Sudbury, Ontario P3E 2C6, Canada

ARTICLE INFO

Article history:
Received 17 February 2015
Received in revised form 20 July 2015
Accepted 23 July 2015
Available online 30 July 2015

Keywords:
Airborne electromagnetic
Dipole
Conductor
Energy Envelope
Total Component

ABSTRACT

This paper is a comparative study of the Energy Envelope and the *T*-component response for interpreting airborne electromagnetic (AEM) data. The Energy Envelope is the square root of the sum of squares of three component AEM data along with their Hilbert transforms, while the *T*-component response is a similar quantity, except without the Hilbert transform terms. These quantities can be used to determine approximate geometrical parameters of compact anomalous targets. The approximate parameters are useful for constraining automatic interpretation algorithms.

Synthetic examples are generated using a dipole conductor model. The synthetic models show that the Hilbert transform terms included in the Energy Envelope yield no additional benefits with regard to AEM data interpretation. Hence, the *T*-component response is a more efficient quantity for AEM modeling.

The position of the peak of the *T*-component response can be used to estimate the position of a compact target that is consistent with the measured response. In particular for a MEGATEM configuration and when the target lies directly below the flight line and the line spacing of the survey is 200 m, the error in predicting the position of the target is under 200 m. This error is improved in situations where the conductor is at an offset to the flight line, or when the line spacing is decreased. The strike of the conductor can also be estimated, as a series of peaks will align along the strike direction.

Once the position and strike of the conductor is known, look-up-tables are generated for these specific parameters. The look-up-tables can be used to determine the depth and dip of the target. The depth can be estimated from the full width at half magnitude of the *T*-component response. The dip can be estimated from the asymmetry of the *T*-component response.

Tests over the Chibougamau field site yield results in reasonable agreement with previous work of the same authors.

1. Introduction

Airborne electromagnetic (AEM) methods are an important tool in the exploration for mineral deposits (Vallée et al., 2011). Recent case history examples that focus on AEM methods are given by (Guo et al., in press; Legault, in press; Lymburner and Smith, 2015; Sattel, 2005; Yang et al., 2014). Methods to interpret and invert the data have recently been reviewed by Yin et al. (2015). Important models for interpretation of these data are the plate and the sphere models (Macnae et al., 1998; Schaa, 2010; Smith and Wasylechko, 2012; Vallée, 2015; Fullagar et al., in press).

AEM data is challenging to interpret as a result of the dependence on complex system geometry. This issue was addressed by Desmarais and Smith (accepted for publication-a), who devised an automatic interpretation algorithm capable of determining the geometrical parameters of a dipole conductor. However, the Desmarais and Smith (accepted for publication-a) algorithm can take several hours to run on the average personal computer, when sampling a large region of parameter space, if applied to large datasets. A more effective approach would consist of initially determining approximate parameters through forward modeling, prior to applying automatic interpretation algorithms. In this manner, a smaller region of parameter space would be investigated and computational resources could be greatly reduced.

Authors have suggested using the Hilbert (or Kramers–Kronig) transform for interpretation of potential field data acquired using the self-potential method (Akgün, 2001; Debeglia and Corpel, 1997) and the magnetic method (Bournas and Baker, 2001; Cooper, 2009; Nabighian, 1972, 1974, 1984). The Hilbert transform is a relation between the real and imaginary parts of a complex function known as the analytic signal. The real part of the analytic signal is the original data, the imaginary part is the Hilbert transform of the original data. The Hilbert transform follows directly from the properties of analytical

* Corresponding author at: Formerly Laurentian University.
E-mail addresses: jkd788@mail.usask.ca (J.K. Desmarais), RSSmith@laurentian.ca (R.S. Smith).

http://dx.doi.org/10.1016/j.jappgeo.2015.07.015
0926-9851/

functions (namely, the Cauchy–Riemann conditions and the Cauchy integral theorem), applied to the Fourier transform (Oppenheim et al., 1998).

Smith and Keating (1996) suggested interpreting electromagnetic data using an empirical quantity calculated the same way as the absolute amplitude of the analytic signal. They formed a quantity known as the Energy Envelope (EE). The EE is the square root of the sum of the squares of the three components and their three Hilbert transforms. This quantity is useful as it gives a single peak over a vertical conductor when calculated on the data acquired with an airborne EM system. The EE also shows some asymmetry for fixed-wing systems. This asymmetry is a consequence of the manner in which the asymmetric transmitter receiver system couples to the conductor. Normalizing the individual components by the EE can remove some of this asymmetry.

Mercer (2012) has proposed using the EE for generating maps of ground EM data. He argues that it generates a single peak anomaly over an anomalous body; whereas the individual components (in the *x*, *y* or *z* directions) show crossover anomalies or more complex features involving lows and highs. He also argued that the EE gave a sharper or narrower anomaly than the individual components or the *T*-component (The square root of the sum of the squared of the three individual components; i.e. the EE without the Hilbert transforms terms included).

Following the work of Mercer (2012), Desmarais and Smith, 2015b generated maps of the EE, the *T*-component response, as well as the *T*-component Hilbert transform response (the EE without the untransformed quantities), for the case of ground EM data. They showed that the *T*-component response and the EE generate peaks over a dipolar body, regardless of the orientation of this body. Thus, the position of the peak of the EE or the *T*-component response can be used to infer the position of the conductor. Once the position has been determined, other geometrical parameters such as the strike, dip and depth of the body can be extracted by combining the *T*-component and *T*-component Hilbert transform of the secondary magnetic field response (Desmarais and Smith, 2015b). In addition, Desmarais and Smith, 2015b showed that the *T*-component response is sharper in plan format than the EE for the majority of possible target orientations and is thus most useful to plot in plan format for locating the conductor.

Macnae (1984) showed that the response of a conductor excited by a fixed transmitter source is a potential field, in the quasi-static approximation. Thus, measurements obtained from ground EM systems are potential fields. In the case of potential fields, the EE is equivalent to the absolute amplitude of the analytic signal. In contrast, for the case of AEM systems where the transmitter is mobile, a profile of measurements is not a potential field, but rather a series of potential fields each generated from locally fixed transmitters. Consequently, it is expected that the manner in which the EE and *T*-component responses vary as a function of target geometry may differ from the findings of Mercer (2012) and Desmarais and Smith, 2015b, for the case of AEM systems.

In what follows, we generate examples to compare the EE and the *T*-component responses, and use these quantities to determine approximate geometrical parameters of compact anomalous targets for AEM surveys. We hope that this modeling approach will aid geophysical practitioners to determine approximate parameters in order to constrain automatic interpretation algorithms and regularize inversion algorithms.

2. Methodology

The synthetic models investigated in this study are generated using the dipole conductor formula of Desmarais and Smith (accepted for publication-a). A dipole is a good approximation to an inductively thin plate, which may be considered small relative to the distance between the body and the transmitter–receiver system (Desmarais and Smith, accepted for publication-a). Extension to more complex models including the effects of galvanic interactions, plate-like conductors of finite extent or higher order poles are not considered in this paper. We restrict our study to the case of a dipole–conductor model, as we seek to find a fully time-independent method for extracting the geometrical parameters of the conductor. Indeed, within the dipole approximation, the shape and relative amplitudes of the spatial components of the secondary-magnetic fields are not a function of time (Desmarais and Smith, accepted for publication-a). Only the absolute amplitudes of the spatial components change as a function of time. The manner in which the absolute amplitudes vary as a function of time depends on the body dimensions and its conductivity (Smith and Lee, 2001). As such, using a dipole conductor model, the geometrical parameters of the conductor may be extracted through modeling the response acquired along one channel and the effects of body dimensions and conductivity may be separated from those of the geometrical parameters. In this manner, we show that the geometrical parameters of the conductor can be extracted using the *T*-component response or the EE.

Consider now a physical model consisting of a compact plate-like conductor in free space (Fig. 1). The transmitter consists of an elevated vertical magnetic dipole. The free space dipolar field of the transmitter at the location of the target $\boldsymbol{F_{tot}}$ can be expressed as:

$$\boldsymbol{F_{tot}} = \frac{1}{4\pi r_{trtx}}\left[\frac{3\boldsymbol{m_{tx}}\cdot\boldsymbol{r_{trtx}}}{r_{trtx}^2}\boldsymbol{r_{trtx}} - \boldsymbol{m_{tx}}\right] \quad (1)$$

$$\boldsymbol{F_{tot}} = \left[F_x, F_y, F_z\right] \quad (2)$$

where $\boldsymbol{m_{tx}}$ is the magnetic moment of the transmitter vector, $\boldsymbol{r_{trtx}}$ is the vector offset from the target to the transmitter, r_{trtx} is the magnitude of $\boldsymbol{r_{trtx}}$, and · is the dot product operator. This formula is defined in a Cartesian coordinate system with its origin at the target (Fig. 1).

Then, the time-independent magnetic field response of the target measured at the location of the receiver $\boldsymbol{H}$ can be expressed as (Desmarais and Smith, accepted for publication-a):

$$\begin{aligned}\boldsymbol{H} = {} & \boldsymbol{R_x}F_x sin^2\theta sin^2\phi + (\boldsymbol{R_x}F_y + \boldsymbol{R_y}F_x)sin^2\theta sin\phi cos\phi \\ & + (\boldsymbol{R_x}F_z + \boldsymbol{R_z}F_x)sin\theta cos\theta sin\phi + \boldsymbol{R_y}F_y sin^2\theta cos^2\phi \\ & + (\boldsymbol{R_y}F_z + \boldsymbol{R_z}F_y)sin\theta cos\theta cos\phi + \boldsymbol{R_z}F_z cos^2\theta,\end{aligned} \quad (3)$$

where θ is the dip of the target and ϕ is the strike of the target. The dip is expressed in degrees below the horizontal over the interval $\theta \in (0, 90)$, and the strike is expressed in degrees from the traverse line in the clockwise direction over the interval $\phi \in (0, 180)$. The terms $\boldsymbol{R_i}$ are the fields

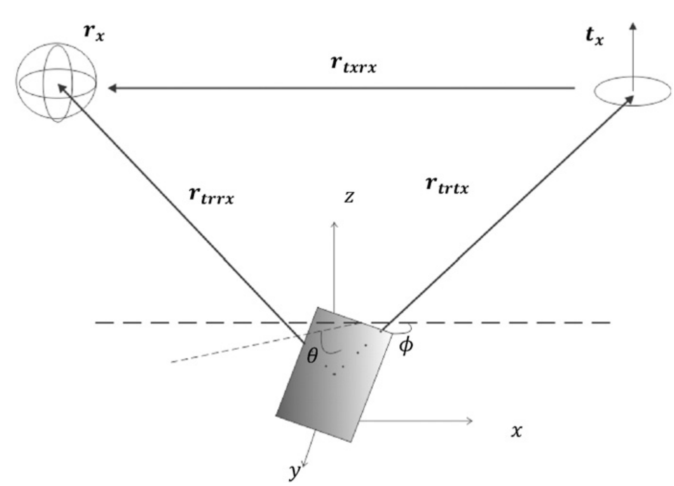

Fig. 1. Perspective diagram of the physical model of interest. The problem is defined in a Cartesian coordinate system with its origin at the center of the plate. The plate is oriented at a strike ϕ and a dip θ. The transmitter $\boldsymbol{t_x}$ is at a distance $\boldsymbol{r_{trtx}}$ from the plate, and is approximated as a vertical magnetic dipole. The three component receiver $\boldsymbol{r_x}$ is at a distance $\boldsymbol{r_{trrx}}$ from the target, and a distance $\boldsymbol{r_{rxtx}}$ from the transmitter.