Extracting subtle IP responses from airborne time domain electromagnetic data

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Summary

Induced polarization (IP) effects observed in airborne time domain electromagnetic (TEM) survey data offer information on the chargeability of the subsurface in addition to conductivity derived from TEM data. However the IP effect is generally weak and obscured in the total TEM response. As a result, the typical inverse transient associated with IP effect does not always manifest itself in the EM response. This causes difficulty for algorithms that rely on the inverse transient to estimate the chargeability of the subsurface. We have developed a robust method that decomposes the total electromagnetic response into a fundamental (inductive) and a polarization component and we estimate apparent chargeability from the polarization component. In this paper, we discuss the method and illustrate its effectiveness with examples.

Introduction

While IP in time domain electromagnetic measurements has been viewed as impractical as an exploration tool (Hohmann et al, 1970), or as a nuisance to be removed (Elliott, 1991), numerous authors have continued to work on understanding this phenomenon (Lee, 1981; Weidelt, 1982; Raiche, 1983; Smith and West, 1988 and Hohmann and Newman, 1990). IP in airborne TEM has also gained attention. Smith and Klein (1996) examined the IP effect observed in fixed wing TEM data and Walker (2008) showed examples of the negative transient in helicopter TEM data.

With improved understanding and routine detection of IP effect, researchers have been searching ways of deriving chargeability from airborne TEM data. Kratzer and Macnae (2012) used decay curve fitting to extract polarization information. Kang et al (2014) proposed a two stage inversion approach in extracting Cole-Cole parameters from airborne TEM data.

In this paper, we present an algorithm to extract IP responses and derive apparent chargeability from airborne TEM data.

Forward problem: TEM IP through convolution

Polarization impulse response

Smith et al. (1988) showed that the total current induced in a polarizable body can be expressed as a combination of a fundamental and a polarization component. The fundamental current is defined as the current induced in a non-polarizable body, identical to the polarizable body, except with a non-frequency dependent conductivity which equals that of the high frequency asymptote of the polarizable body. The polarization response can be approximated by the convolution of the fundamental response and the polarization impulse response of the polarizable body, ignoring the effect associated with the EM interaction of the polarization current with itself and the fundamental current.

From the Cole-Cole dispersion model (Pelton et al, 1978), the Laplace transform of the polarization impulse response is expressed as:

$$H(s) = \frac{-m}{1+(1-m)(s\tau')^c}, \tag{1}$$

where $s = i\omega$ is the Laplace transform variable, m is chargeability, c the frequency dependence factor and τ' the Cole-Cole polarization time constant. Since the chargeability is positive, equation (1) shows that the polarization response is always opposing the fundamental response and as a result, the total response of a polarizable body is always less than the fundamental response associated with a non-polarizable body. This conclusion is different from Flis et al (1989) whose models show that the polarization current flows in the same direction as the charging current at early times.

The inverse Laplace transform of equation (1) gives the impulse response of a polarizable body. An analytical form can only be obtained when $c = 1$ (Debye model) or $c = 1/2$ (Warburg model). While the Debye model describes a simple RC circuit, the Warburg model effectively describes the overvoltage phenomenon of mineral grains (Wong, 1979). Setting $c = 1/2$ in equation (1) and taking the inverse Laplace transform, we obtain the polarization impulse response of a polarizable body described by a Warburg model as:

$$h(t) = -mb\left(\frac{1}{\sqrt{\pi t}} - be^{b^2 t}\text{erfc}\left(b\sqrt{t}\right)\right)u(t), \tag{2}$$

where $b = 1/((1-m)\sqrt{\tau'})$, m and τ' are the same as in equation (1), $u(t)$ is the unit step function and erfc is the complementary error function.

Convolution

We can obtain the electromagnetic response of a polarizable body through two convolution processes: 1) the convolution of the emf induced in the body with the fundamental impulse response, which gives fundamental current; 2) the convolution of the fundamental current with the polarization impulse response, which gives the polarization current.

The total response is simply the addition of the two convolution results.

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Wireloop example

A confined conductor can be simulated by a wireloop (Grant and West, 1965) and the current response of a wire loop due to an impulse emf input is:

$$I(t) = \frac{1}{L} e^{-\frac{t}{\tau}} u(t), \tag{3}$$

where L is the self-inductance of the wireloop and τ is the time constant. Equation (3) is the inductive impulse response of a wireloop.

We can calculate the electromagnetic response of a confined polarizable conductor with its fundamental impulse response described by equation (3) and its polarization impulse response described by equation (2). Figure 1 shows the current and voltage responses of a polarizable wireloop due to a halfsine current waveform. The wireloop is 100 m in diameter, with fundamental time constant $\tau = 1\ ms$ and resistance $\rho = 10\ \Omega$. The chargeability is set as m = 0.5 and the Cole-Cole polarization time constant $\tau' = 1.5\ ms$. The wireloop is 35 m directly below the transmitter loop. The HELITEM geometry is used: receiver is 12.9 m ahead and 26.67 m above the center of the transmitter loop.
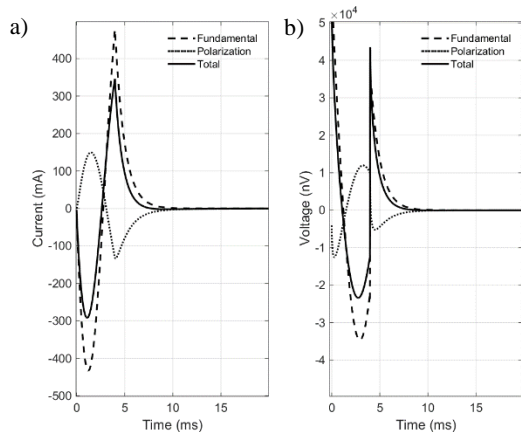

Figure 1: The responses of a polarizable wireloop excited by a halfsine transmitter current with a peak current of 1000 A, a pulse width of 4 ms, and a base frequency of 25 Hz. (a) current response and (b) voltage response.

The current responses in Figure 1 shows that the polarization response always opposes the fundamental response, resulting in a total response less than the fundamental response. The voltage response is proportional to the time derivative of the current response. At very early offtime, the total current decays faster than the fundamental current, therefore, the total voltage response exceeds the fundamental voltage response.

The approximate convolution process proposed by Smith et al. (1988) not only provides a way of calculating the polarization response of a polarizable body, but also illustrates the physics of the polarization process. The polarization current is a result of the fundamental current

flowing in the polarizable body, no matter how the fundamental current is introduced to the body, whether through grounded electrodes or inductive processes.

This forward computation of the TEM response of a polarizable body is the basis for our method in decomposing the measured EM response into fundamental and polarization components.

Inverse problem: decomposing TEM data

The approximate convolution process provides a convenient way of computing the polarization response of a polarizable body. However, what we wish to accomplish is the inverse process: to extract the fundamental and polarization responses from the measured total EM response. The inverse process is not as straightforward as the forward problem, where the input to the system (the polarizable body) and the impulse response of the system are assumed known and the outputs (the fundamental and polarization responses) are thus easily calculated through the two convolution processes previously described.

For an inverse problem we are given only the measured total EM responses and the waveforms of the TEM system. We need to find a way to estimate the fundamental and the polarization components (if the measured body is polarizable) over a range of weak and strong responses. We decompose the total response in two steps: first, we extract the fundamental response; then from the remaining signal, we extract the polarization response.

Extracting the fundamental response

Stolz and Macnae (1998) described a method of fitting the inductive EM response of an arbitrary transmitter current waveform with a summation of a series of basis functions over a range of time constants. The basis functions are calculated by convolving the transmitter primary waveform sampled at the receiver with pure exponential decays of discrete time constants. A pure exponential decay is just the impulse response of a wireloop, as shown in equation (3). A basis function matrix is formed over a selected range of time constants and the receiever measurement windows.

For a halfsine current waveform and dB/dt EM response, the fundamental basis function of a given time constant looks similar to the fundamental voltage response in Figure 1b. The matrix expression of the process can be written as:

$$\mathbf{A\alpha} = \mathbf{d}, \tag{4}$$

where $\mathbf{A}$ is the basis function matrix, $\mathbf{d}$ contains the windowed total TEM response, and $\mathbf{\alpha}$ is the coefficient vector to be estimated. The size of the matrix $\mathbf{A}$ is determined by the number of time constants (columns of $\mathbf{A}$) and the number of data channels (rows). The number of coefficients in $\mathbf{\alpha}$ is the same as the number of time constants used in

constructing the basis functions and thus equals the number of columns of basis function matrix, **A**.

Our goal is to estimate the fundamental response by solving equation (4) through a least squares process. In addition to regularizing the basis function matrix through an exponential weighting scheme and smoothing the coefficients to stabilize the least squares process, we use a non-negative constraint when estimating the coefficients. The non-negative constraint ensures that the offtime EM responses derived from these estimated coefficients are always positive, as the fundamental responses are expected to be. We obtain the fundamental response from the product of the basis function matrix and the estimated coefficients, i.e.:

$$\mathbf{f} = \mathbf{A}\hat{\boldsymbol{\alpha}}, \tag{5}$$

where **f** is the estimated fundamental response and $\hat{\boldsymbol{\alpha}}$ is the vector of the estimated coefficients.

We express the residual (**r**) from the above fundamental response calculation as:

$$\mathbf{r} = \mathbf{d} - \mathbf{f} \tag{6}$$

where **d** is the measured total EM response, same as in equation (4) and **f** the estimated fundamental response derived in equation (5). If the EM response does not contain IP effect, then **f** and **d** should agree with each other and the residual is just the noise in the measured data and the misfit from the least squares process.

However, if the response contains IP effect, then the residual includes the polarization response plus the noise in the data and the misfit from the least squares process. Our next step is to extract from the residual the polarization response.

<u>Extracting the polarization responses</u>

We proceed to extract the polarization responses from the residuals calculated in equation (6) using the least squares process by fitting the residual with a series of polarization basis functions. The polarization basis functions are formed by convolving the fundamental basis functions as constructed in estimating the fundamental responses previously described, with the impulse response of the Warburg model shown in equation (2). For a given time constant, the polarization basis function for a dB/dt EM response looks similar to the voltage polarization response in Figure 1b. The polarization function matrix is constructed over the same range of fundamental time constants used in estimating the fundamental responses and over a range of chargeabilities and polarization time constants. The matrix expression of the linear equations can be written as:

$$\mathbf{B}\boldsymbol{\beta} = \mathbf{r} \tag{7}$$

where **B** is the polarization basis function matrix, $\boldsymbol{\beta}$ is the coefficient vector to be estimated and **r** is the residual derived in equation (6). We use regularization and smoothing in matrix **B** and a non-negative constrained least

squares process to estimate the coefficients. The estimated polarization response (**p**) is obtained by the product of the basis function matrix and the estimated coefficients ($\hat{\boldsymbol{\beta}}$):

$$\mathbf{p} = \mathbf{B}\hat{\boldsymbol{\beta}}, \tag{8}$$

Apparent Chargeability

We derive a parameter that reflects the chargeability of the earth using a simple and robust method: the summation or area of the polarization response, expressed as:

$$m_{app} = \sum_{i=1}^{n} p_i T_i, \tag{9}$$

where m_{app} is the apparent chargeability, n is the total number of offtime channels, p_i and T_i are the estimated polarization and channel width of channel i, respectively.

Results

Figure 2a shows a HELITEM dB/dt Z profile where both strong and weak IP effects are observed. Figure 2b shows a decay in which no IP is observed from the location indicated by the leftmost arrow in the profile. As expected, Figure 2b shows that the estimated fundamental response almost equals the total EM response and the extracted polarization response is within the system noise level (< 1 nT/s). Figures 2c and 2d shows two cases where IP is evident but with different characteristics as reflected by their total EM responses and the estimated fundamental and polarization responses.

Figure 3a shows the same dB/dt Z profile as depicted in Figure 2a, and Figure 3b the derived apparent chargeability. The numbers mark the locations of the apparent chargeability anomalies. The effectiveness of the above described method in extracting polarization responses is demonstrated by its ability to extract weak IP effects, as at locations 1, 4 and 6 as well as at locations 2 and 3, where stronger IP effects are observed. Question marks show the locations where the cause of the anomalies are less definitive. The decomposition process appears to be able to detect any decay rate variations caused by apparent IP effects, but also more subtle effects of less certain causes.

Conclusions

The decomposition method offers a robust way to extract the polarization responses from airborne TEM data where IP effects are observed. The method seems to be effective in extracting weak IP responses which can be more prevalent in conductive environments. Apparent chargeability derived from the decomposed polarization responses reflects the polarizability of the ground where IP is observed.
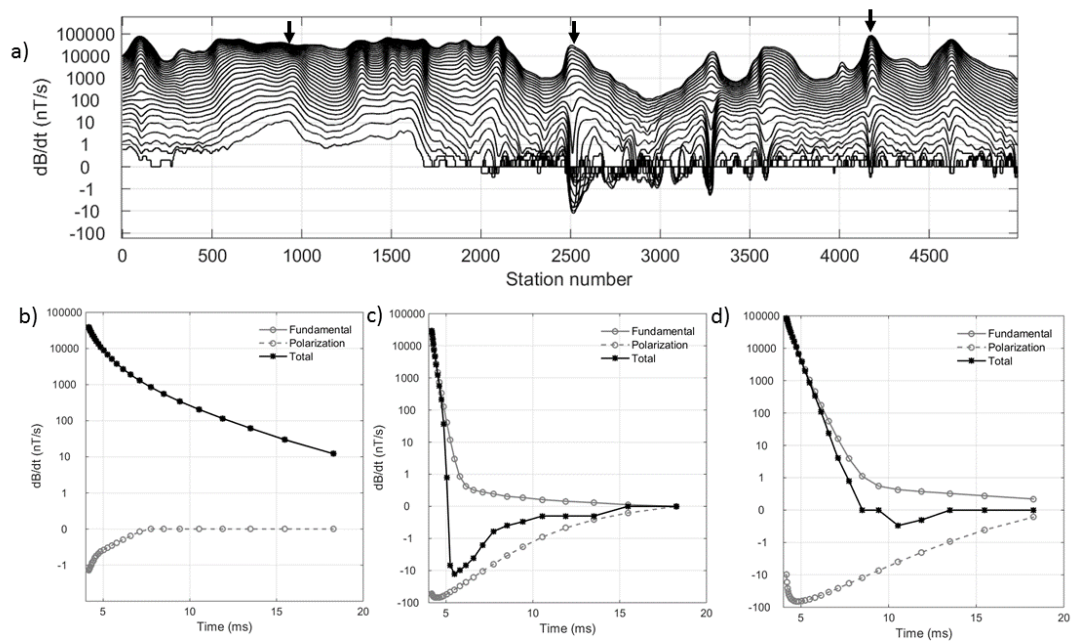
Figure 2: (a) HELITEM dB/dt Z response and (b), (c) and (d) the decomposed fundamental and polarization responses. The black arrows in (a) indicate the locations of these three decay curves.
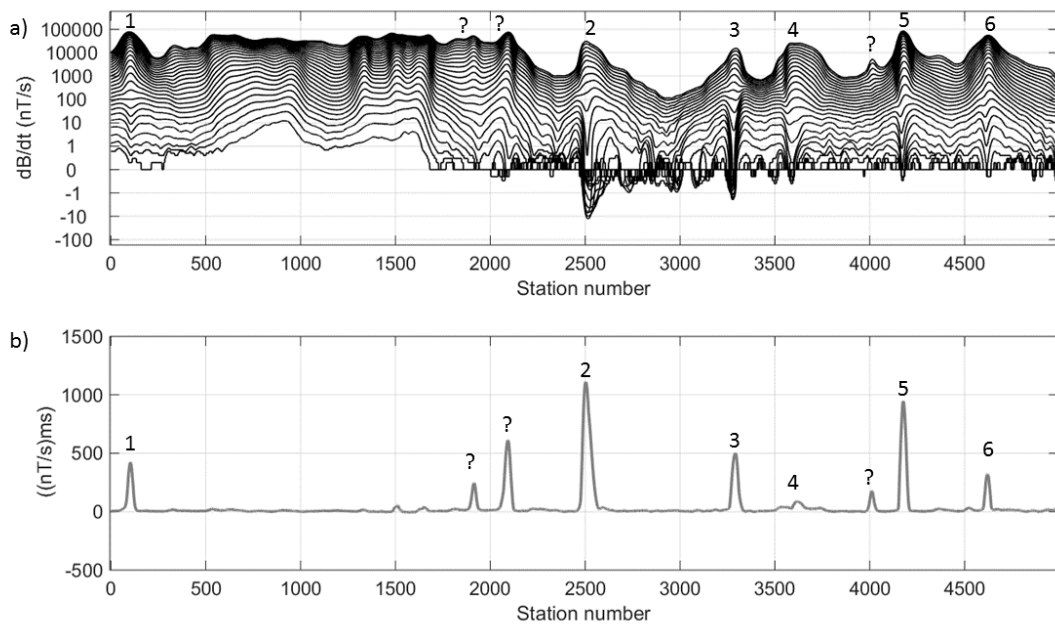

Figure 3: (a) HELITEM dB/dt Z response and (b) derived apparent chargeability. Numbers indicate location of chargeability anomalies, the question marks indicate locations where the nature of the anomalies is less definitive but certainly plausible.

EDITED REFERENCES
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