Determination of apparent anisotropy from transient electromagnetic earth responses

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SUMMARY

Earth electromagnetic responses to a transient source are shown to be greatly dependent on resistivity anisotropy. Anisotropy must therefore be included in inversion schemes and a practical method for obtaining a starting value of anisotropy is proposed. This method uses the arrival time of the peak of the Earth's impulse and the late time value of the earth's step response to derive an apparent anisotropy. The effectiveness of the technique is demonstrated through application to a cross-section through a 3D model with varying anisotropy.

Keywords: EM, transient, anisotropy

INTRODUCTION

Resistivity anisotropy arises through a variety of scales from micro (e.g. grain size, pore water connectivity) to macro (e.g. laminated sand-shale sequences). For general anisotropy the physical property under consideration may vary in all three spatial directions. The simplest problems involve transverse anisotropy where resistivity at a point in any direction in a plane differs from the value perpendicular to the plane. We are here concerned solely with transverse anisotropy with a vertical axis of symmetry (VTI) so that resistivity at a point has a constant magnitude in any horizontal direction. Induction logs, laterolog and LWD (logging-while-drilling), at least in vertical wells, may be used to examine VTI in particular and these well log results often differ from indirect determinations of resistivity through DC resistivity and general EM surveying. Much of the earlier EM literature considered resistivity as isotropic but there is now great emphasis on the inclusion of anisotropy in modeling and inversion studies. In this paper we consider the effects of transverse anisotropy (specifically VTI) on the earth's electromagnetic impulse and step responses and we derive a method for determining apparent anisotropy.

The Multi-Transient Electromagnetic Method

In the multi-transient electromagnetic method (Ziolkowski et.al, 2007) current is injected into the ground between two electrodes (the source) and the resulting potential difference is measured between two further electrodes (the receiver). The four electrodes are collinear and the distance between the mid-point of the source electrodes and the mid-point of the receiver electrodes is termed the offset. Transient current injection at the source may take the form of a step change in current, such as a reversal in polarity of a DC current, or a coded, finite-length sequence such as a pseudo-random binary sequence (PRBS). For any form of transient current injection, measurements are made of both the source current and the receiver voltage and deconvolution determines the earth's impulse response. Integration of the impulse response yields the earth's step response.

Earth Step and Impulse Responses

The form of earth response functions may be illustrated by calculating the impulse and step responses at some offset for the simplest (land) case of a uniform, isotropic halfspace. Examples are shown in Figure 1 and further examples may be found in Hobbs(2009).

The impulse response comprises a so-called airwave (which travels along the ground/air interface at a scale comparable to the velocity of light and so arrives at time t=0) followed by a response resulting from diffusion through the resistive subsurface. These two components are immediately separable.

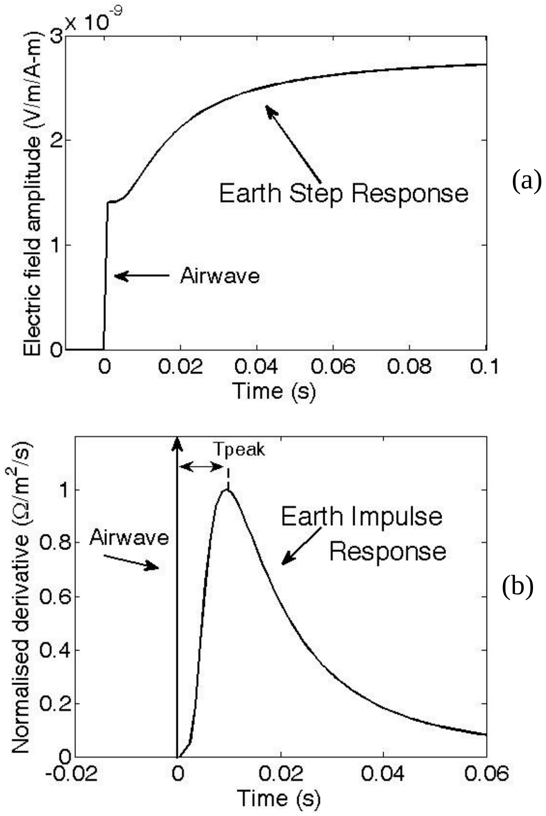

Figure 1. (a) Step and (b) Impulse responses calculated at an offset of 1500 m for a uniform halfspace of resistivity 30 Ωm. The earth impulse response has been normalized by its peak value of 5.49 10^{-8} $\Omega m^{-2} s^{-1}$.

The effects of anisotropy

For the transverse anisotropy under consideration (VTI) the vertical resistivity ρ_v and the horizontal resistivity ρ_h define the anisotropy factor

$$\lambda = \sqrt{\frac{\rho_v}{\rho_h}}$$

with typical values between 1 and 5. The geometric mean resistivity is $\rho_m = \sqrt{\rho_v \rho_h}$. We may now consider three special ways of varying anisotropy – keeping ρ_v, ρ_h or ρ_m constant. We describe these cases as:

ρ_h^c: ρ_h =constant, ρ_v and ρ_m increase with increasing λ

ρ_v^c: ρ_v =constant, ρ_h and ρ_m decrease with increasing λ

ρ_c^2: ρ_m = constant, ρ_h decreases and ρ_v increases with increasing λ

Effects on a uniform halfspace step and impulse responses for two of these three cases of varying anisotropy are shown in Figure 2. The effects are dramatic.

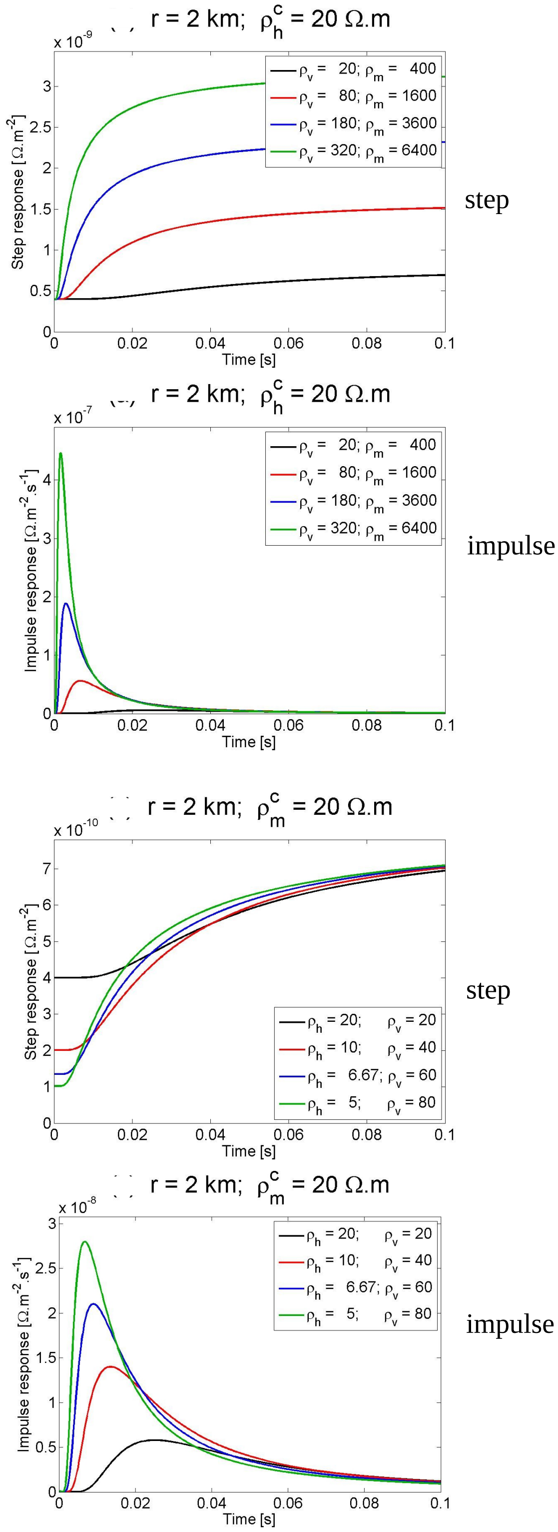

Figure 2. Effects of anisotropy on step and impulse responses at an offset of 2 km for a uniform halfspace

for the two cases of constant ρ_h and constant ρ_m. Anisotropy values are λ=1 (black), λ=2 (red), λ =3 (blue) and λ=4 (green). The isotropic case (solid black) is the same in all three cases.

Analytic solution for an anisotropic halfspace

In keeping with ideas of apparent resistivity, apparent anisotropy can be derived for the general case by appealing to results for a uniform halfspace. Werthmüller and Slob (2010) give the time-domain impulse response of a VTI halfspace as

$$E_x^t(t) = \frac{\rho_h}{2\pi r^3}\sqrt{\frac{\tau}{\pi t^3}}\left\{-\exp\left(-\frac{\tau}{t}\right)+\left(\frac{2\tau}{\lambda^2 t}+1\right)\exp\left(-\frac{\tau}{\lambda^2 t}\right.\right. \quad (1)$$

where $\tau = \frac{\mu_0 r^2}{4\rho_h}$, μ_0 is free space permeability, r is the offset between source and receiver, t is time and we have neglected the air wave. It can be seen from Figure 2 that for a given offset r the peak of the Earth's impulse response varies with anisotropy λ. Differentiating Equation (1) and finding the stationary value yields an equation for T_{peak} as a function of λ.

$$\exp\left\{-\frac{\tau}{T_{peak}}\left(1-\frac{1}{\lambda^2}\right)\right\} = \frac{3\lambda^4 T_{peak}^2 + 8\tau\lambda^2 T_{peak} - \ldots}{\lambda^4 t\left(3T_{peak} - 2\tau\right)} \quad (2)$$

It is also known that the late time value of the Earth's step response is given by

$$E_x^s(\infty) = \frac{\rho_m}{\pi r^3} \quad (3)$$

where $\rho_m = \sqrt{\rho_h \rho_v}$.

Now define a characteristic time:

$\tau_m = \frac{\tau}{\lambda} = \frac{\mu r^2}{4\rho_h \lambda} = \frac{\mu r^2}{4\rho_m}$ and re-write equation (2) in terms of a single unknown λ_{app} :

$$\exp\left\{-\frac{\tau_m}{T_{peak}}\left(\lambda_{app}-\frac{1}{\lambda_{app}}\right)\right\} = \frac{3\lambda_{app}^2 T_{peak}^2 + 8\tau_m \lambda_{app} T \ldots}{\lambda_{app}^2 T_{peak}\left(3T \ldots - 2 \ldots\right.} \quad (4)$$

For measured values of $E_x^s(\infty)$ and T_{peak}, Equation (4) may be solved (numerically) for the apparent resistivity corresponding to this offset r.

An approximate apparent anisotropy determination

However, more simply, a good approximation to the arrival time of the peak has been derived empirically as

$$T_{peak}(r) = \frac{\mu r^2}{9\rho_v + \rho_h} \quad (5)$$

Combining Equations (3) and (5), apparent resistivity satisfies the quadratic equation

$$9\lambda_{app}^2 - \frac{\mu}{\pi\, \mathrm{r}\, \mathrm{E}_\mathrm{x}^\mathrm{s}(\infty) T_{peak}}\lambda_{app} + 1 = 0 \quad (6)$$

The appropriate root is the larger root given by

$$\lambda_{app}(r) = \frac{P}{3}\left\{1+\sqrt{1-\frac{1}{P^2}}\right\} \quad (7)$$

where $P = \frac{\mu_0}{6\pi r E_x^s(\infty) T_{peak}}$

Equation (7) affords a simple method of determining apparent resistivity as a function of offset r and larger offsets correspond to deeper penetration within the Earth.

Illustrative application

We have applied the method to a 3D model where two anomalies of differing anisotropies are embedded in an otherwise uniform halfspace. A cross section through the model is shown schematically in Figure 3.

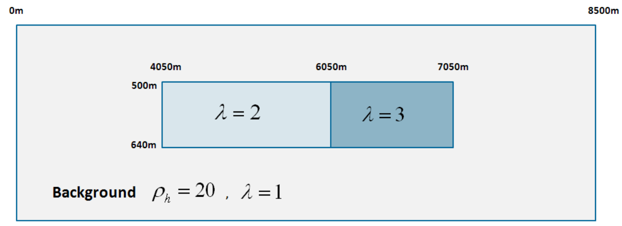

Figure 3. Vertical cross section through a 3D model. Horizontal target dimension is 4 km. Horizontal resistivity is everywhere 20 Ohm m and the target has two anisotropic regions.

Data were generated for 40 source positions from 0 m to 7800 m along the surface. For each source position impulse and step responses were determined for 12 source-receiver offsets from 1000 m to 3200 m.

From the data generated at each source-receiver position, T_{peak} and $E_x^s(\infty)$ were determined and Equation (7) used to find a value for the apparent anisotropy. The results are plotted in terms of source-receiver mid points on the horizontal axis and offset on the vertical axis (a proxy for depth) and displayed in Figure 4.

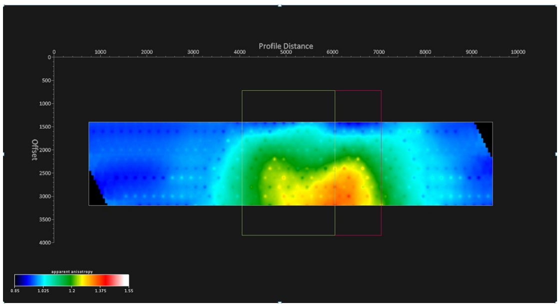

Figure 4. Apparent anisotropy as derived from Equation (7).

As with apparent resistivity determinations, apparent anisotropy values do not reach the true anisotropy values. Nevertheless Figure 4 shows clearly the variation between the background and target anisotropies and also shows the variation within the target zone.

The methods described above are the subject of US Patent Application 12/381,690 filed on 16 March 2009.

CONCLUSIONS

Anisotropy plays an extremely important role in affecting the form of Earth impulse and step responses. It is therefore important to include anisotropy when inverting such EM data. Inversions require good starting models and the apparent anisotropy technique presented here shows how an indication of variations of anisotropy can be deduced directly from simple parameters determined directly from the data. It is suggested that this technique will help the construction of starting models for anisotropic inversion.

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