Apparent anisotropy derived from transient electromagnetic Earth responses

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Summary

1D Earth electromagnetic responses to a transient source are shown to be greatly dependent on resistivity anisotropy. Isotropic inversion of synthetic data arising from an anisotropic model leads either to misleading results (incorrect target depth and poor accuracy in recovered resistivities for target and background) or to non-convergence. It is shown that when the correct anisotropy is included in inversion schemes the resulting model is well resolved. A practical method for obtaining a starting value of anisotropy through a newly defined apparent anisotropy is proposed.

Introduction

Resistivity anisotropy arises either as an intrinsically anisotropic rock where the minerals are flat and parallel, for example a shale, or as an effective anisotropy where layers of rocks of sub-resolution thickness and different resistivities are interbedded, for example a sand – shale sequence, where the anisotropy can become very pronounced if the sands are hydrocarbon-charged. 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 vertical transverse anisotropy (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 penetrating horizontal beds, 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 1D electromagnetic impulse and step responses and we formulate apparent anisotropy as a useful investigative tool for 1D, 2D and 3D data. The term apparent anisotropy was first introduced by Edwards (1984) in relation to sea-floor measurements using a vertical electric dipole as source.

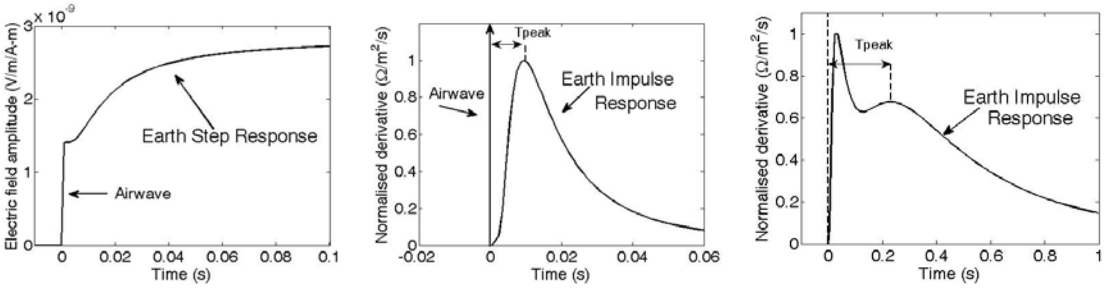
The Multi-Transient Electromagnetic Method

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 r for the simplest case of a uniform, isotropic halfspace. Example impulse responses for land and marine for an offset of 1500 m are shown in Figure 1.

On land 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. In the marine case the Earth response comprises travel through the sea water, through the sea/air interface and through the subsurface. All three parts persist throughout the entire record. The peak value and arrival time of the peak value (Tpeak) depend on the subsurface resistivity.



(a) (b) (c)

Figure 1. (a) Land step response and (b) land impulse response 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} $\Omega m^{-2} s^{-1}$. (c) Marine impulse response calculated at an offset of 1500 m for a uniform halfspace of 1 Ωm overlain by 100 m of sea water of resistivity 0.3125 Ωm. The Earth impulse response has been normalized by its peak value of 1.40 10^{-10} $\Omega m^{-2} s^{-1}$. Note the different timescales.

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_m^c : ρ_m = constant, ρ_h decreases and ρ_v increases with increasing λ

Effects on a uniform halfspace step response, $E(r,t)$ where t is time, for these three cases of varying anisotropy are shown in Figure 2 and effects on land and marine impulse responses will be shown in the full presentation. The effects are dramatic. The airwave (initial step $E(r,0)$) depends only on the horizontal resistivity ρ_h (Fig. 2a), since the airwave is a purely Tranverse Electric mode (Weidelt, 2007) whereas the late time DC value ($E(r,\infty)$) depends only on the geometric mean (Fig. 2c) (Negi and Saraf, 1989). Using results from Wilson (1997) for a uniform isotropic halfspace of resistivity ρ

$$E(r,0) = \frac{\rho}{2\pi r^3} \text{ and hence } = \frac{\rho_h}{2\pi r^3} \quad , \tag{1}$$

$$E(r,\infty) = \frac{\rho}{\pi r^3} \text{ and hence } = \frac{\sqrt{\rho_v \rho_h}}{\pi r^3} \quad . \tag{2}$$

Equations (1) and (2) provide a method of determining the anisotropy of the halfspace as

$$\lambda = \frac{\sqrt{\rho_v \rho_h}}{\rho_h} = \frac{1}{2} \frac{E(r,\infty)}{E(r,0)} \tag{3}$$

and this value holds for all r when the anisotropic halfspace is uniform.

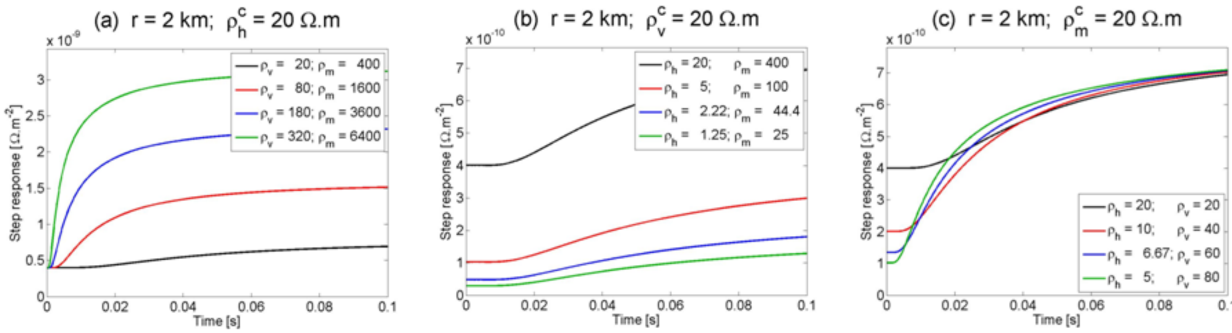


Figure 2. Effects of anisotropy on step responses at an offset of 2 km for a uniform halfspace. λ =1 (black), λ =2 (red), λ =3 (blue) and λ =4 (green). The isotropic case (solid black) is the same in all three cases.

When the anisotropic halfspace is not uniform, Equation (3) may be used to define an apparent anisotropy value dependent on the offset r :

$$\lambda_{app}(r) = \frac{1}{2}\frac{E(r,\infty)}{E(r,0)} \qquad (4)$$

and this is the subject of a patent application. An illustration is afforded by the layered model shown in Figure 3. Early and late time values of the step responses for these two models for a range of offsets yield the apparent anisotropy values shown in Figure 4.

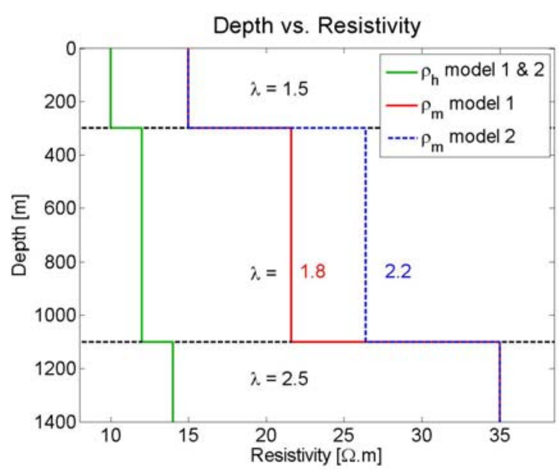


Figure 3. Two anisotropic 3-layer resistivity models. The horizontal resistivity is shown in green. The first and third layers are the same for the two models – the middle layer has an isotropy ratio of either 1.8 (red) or 2.2 (dotted blue).

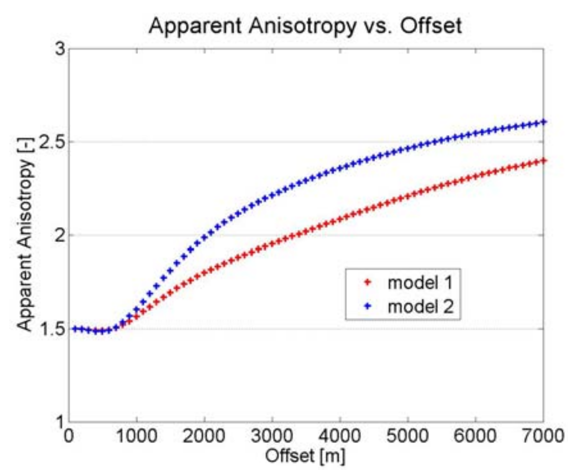
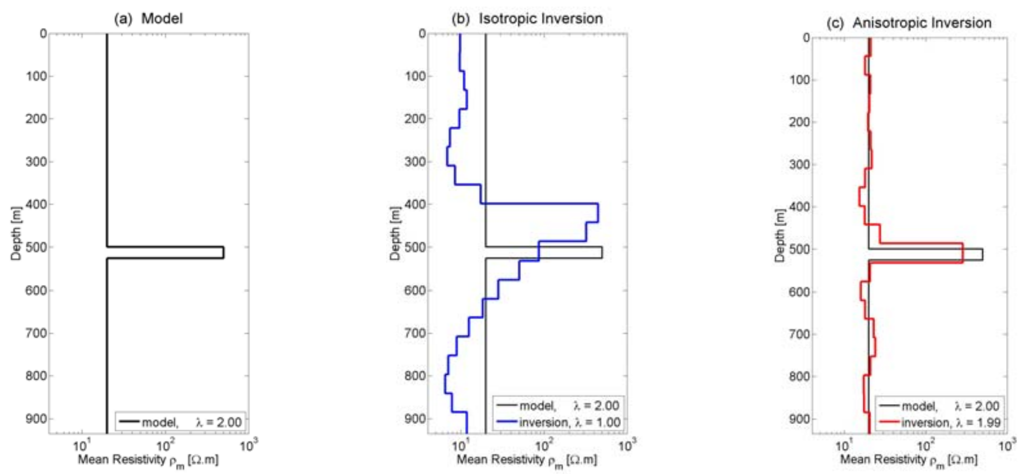


Figure 4. The apparent anisotropy defined by Equation (4) as a function of offset for the two models shown in Figure 3.

Apparent anisotropy calculations on real data will detect changes in both lateral and vertical resistivity that cause the variations in anisotropy and will provide starting values of the average anisotropy in inversion studies.

Implications for the inversion of MTEM data

We now seek to determine the implications of inverting MTEM data acquired over an anisotropic subsurface with an isotropic inversion routine. Anisotropic data were generated from a model comprising a background geometric mean resistivity of 20 Ωm with an embedded target layer 25 m thick with geometric mean resistivity 500 Ωm with the top located at a depth of 500 m (Figure 5a). An anisotropy value $\lambda = 2$ was used for all layers. Step responses were generated for the three offsets 2.5 km, 3.0 km and 3.5 km. A multi-trace isotropic Occam inversion was made using these three offsets simultaneously and the result is shown in Figure 5b. In the inversion-derived model the target is placed too shallow, the transverse resistance (target resistance times layer thickness) is too high and the background resistivity is too low.



(a) (b) (c)

Figure 5. (a) Background resistivity model with parameters described in the text, (b) resulting resistivity model using multi-trace isotropic inversion, and (c) resulting resistivity model using multi-trace anisotropic inversion with a fixed value of anisotropy.

Application of Equation (4) to the three offsets determines an apparent anisotropy value $\lambda = 1.99$. This value of anisotropy was then fixed in the forward modeler and multi-trace Occam inversion again applied to the same three-offset data set. The resulting inversion model is shown in Figure 5c. With the appropriate value of anisotropy included all the deficiencies of isotropic inversion are overcome – i.e. the target depth and background resistivity are correct and the transverse resistance value in the inversion model, 12,700 Ωm^2, is close to the original model transverse resistance of 12,500 Ωm^2. The next stage in the inversion process is the inclusion of anisotropy as a free parameter with a starting values provided by equation (4). It should be remembered that in general much longer offsets need to be used when anisotropy is present since the penetration depth behaves like $offset/(2\lambda)$.

Conclusions

Earth electromagnetic responses are greatly influenced by resistivity anisotropy. Isotropic inversion of anisotropic data gives misleading results concerning target depths and resistivity values both for the target and background. Thus proper interpretation requires anisotropy to be included as part of any inversion scheme. A new definition of apparent anisotropy is proposed and its values can be calculated directly from step response data. The benefits of this approach have been demonstrated on a 1D synthetic example where the method has improved the resolution enormously. This approach should also be useful in assessing anisotropy variations in 2D and 3D data and in providing starting values for 2D and 3D anisotropic inversion routines.

Acknowledgments

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EDITED REFERENCES

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