

Distorted Transient Electromagnetic data modelling

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SUMMARY

Observed transient electromagnetic (TEM) data are often distorted by IP effects as well as by the subsurface geometry. Therefore, a reliable interpretation needs to incorporate both effects into the data modelling. The objective of this study is to incorporate IP effects in a forward modelling and to be able to recover the IP parameters from distorted TEM data using an efficient inversion algorithm. To achieve this aim, we developed a 1D forward and inversion algorithm to investigate the incorporation of IP effects using different IP parameterizations including Cole-Cole, maximum phase angle (MPA), maximum imaginary conductivity (MIC) and the Jeffrey transform of Cole-Cole parameters. For the 1D inversion of IP-distorted TEM data we used the Levenberg-Marquardt (LM) algorithm. However, the result of the inversion strongly depends on the starting model. The result of 1D forward calculation and inversion of synthetic TEM data revealed that the Cole-Cole parameterization is more robust and reliable than MPA, MIC, and Jeffrey transform. Subsequently, we performed a 3D modelling study to better understand the effect of 3D geometry, which may cause a sign reversal in the TEM data similar to the IP effect. To evaluate the performance of our algorithm, we carried out a 1D inversion of TEM data acquired from a landfill located near Cologne, Germany. To obtain priori information and validate the results of TEM data modelling, we conducted an electrical resistivity tomography (ERT) and time-domain IP (TDIP) survey along the TEM profile. Subsequently, the retrieved Cole-Cole parameters from these data were used as input for TEM data interpretation. By including the IP information, the TEM field data can be explained quantitatively, and a consistent and improved interpretation of the waste body is achieved.

Keywords: Transient Electromagnetic, Induced Polarization, 3D Geometry

INTRODUCTION

Transient electromagnetic (TEM) methods are commonly employed for subsurface conductivity characterization in diverse geoscience fields. The observed electromagnetic data are often associated with IP effects which introduces a sign reversal into the TEM data when in-loop configurations are considered (Weidelt 1982; Seidel and Tezkan 2017, Sharifi and Tezkan 2023). Therefore, a reliable interpretation needs to incorporate IP effect into the modeling of these data. Besides enabling a more reliable interpretation of TEM data, considering IP effects may provide a valuable insight into the electrical features and structure of the subsurface chargeable target. However, as IP effects superimpose the electromagnetic induction, they can pose a significant issue if overlooked and lead to misinterpretation (Sharifi et al. 2020). However, it has been demonstrated that a 3D geometry of the subsurface structures may distort TEM data and result in sign reversal as well (Sudha et al. 2011, Yogeshwar and Tezkan 2017).

In this research, we have developed an inversion algorithm based on Levenberg-Marquardt, for

recovering IP effects from 1D TEM data. For incorporating the IP effect into the TEM data, we have investigated the benefits of using several IP parameterization methods such as Cole-Cole (Pelton et al. 1978), MPA, MIC (Fiandaca et al. 2018) and Jeffrey transform (Ghorbani et al. 2007). Our numerical analysis and inversion of synthetic data show that using MPA, MIC and Jeffrey transform for including the IP effect in the inversion procedure has some drawbacks. However, from the numerical stability point of view, using Cole-Cole parameterization is more efficient (Sharifi et al. 2024, in rev.).

Furthermore, our numerical simulation and field measurement experiments show that the dimensionality of subsurface can introduce a prominent distortion in the TEM data. To distinguish whether the distortion of TEM data is attributed to the IP effect, dimensionality of the subsurface structure or both of these features, a coincident loop configuration (Weidelt, 1982) or ERT-TDIP measurement (Sharifi et al. 2024, in rev.) is recommended.

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METHODS

IP effects incorporated in the electromagnetic simulation, result in a frequency-dependent and complex-valued resistivity of the subsurface. For including the IP effect into the 1D TEM data modelling, the vertical time derivative of magnetic field is given through inverse Fourier transform procedure as follow (Seidel and Tezkan 2017, Börner 2020),

$$\frac{\partial B_z(t)}{\partial t} = \sqrt{\frac{2}{\pi t}} \int_0^{\infty} \text{Re}(B_z(\omega)) \times \sqrt{\frac{2}{\pi \omega t}} \cos(\omega t) \sqrt{\omega} d\omega \quad (1)$$

$$B_z(\omega) = \frac{\mu M}{2} \int_0^{\infty} (e^{-\alpha_0(z+h)} + r_{TE} \cdot e^{\alpha_0(z-h)}) \frac{\lambda^2}{\alpha_0} J_1(\lambda a) d\lambda \quad (2)$$

$$r_{TE} = \frac{\lambda - \beta_1}{\lambda + \beta_1} \quad (3)$$

$$\beta_n = \alpha_n \frac{\beta_{n+1} + \alpha_n \tanh(\alpha_n d_n)}{\alpha_n + \beta_{n+1} \tanh(\alpha_n d_n)} \quad (4)$$

$$\alpha_n = \sqrt{\lambda^2 + \frac{i\omega\mu}{\rho_n(\omega)}} \quad (5)$$

$$\rho_n(\omega) = \rho_{0n} \left(1 - m_n \left(1 - \frac{1}{1 + (i\omega\tau_n)^{c_n}} \right) \right) \quad (6)$$

where B_z is a magnetic flux density, ω is the angular frequency, μ is the magnetic permeability, M is the magnetic dipole moment, a is the transmitter loop radius, λ is the wave number, r_{TE} is the reflection coefficient, J_1 is the Bessel function of order 1 of the first kind, α_n and β_n are the characteristic admittance, $\rho_n(\omega)$ is the complex resistivity, m_n , τ_n , c_n are, respectively, the chargeability, time constant and frequency exponent of chargeable layer, i is the imaginary unit ($i = \sqrt{-1}$) and the subscript n stands for the layer number.

We implemented the LM algorithm to minimize the following cost function:

$$\varphi(\mathbf{m}) = \|\mathbf{d}_{obs} - F(\mathbf{m})\|_2^2 + \frac{\beta}{2} \|\mathbf{W}_m \mathbf{m}\|_2^2 \quad (7)$$

Where \mathbf{m} , \mathbf{d}_{obs} , F , β , and \mathbf{W}_m stand for model parameter vector, observed data, forward operator, regularization parameter, and weighting matrix (identity matrix) of model parameters, respectively.

For 3D simulation of TEM data, the 3D finite difference SLDMEM3t algorithm is used (Druskin and Knizhnerman 1988).

RESULTS AND DISCUSSION

Our forward calculation indicates that including strong IP into the TEM data using MPA leads to an artifact in the simulated data. However, the forward response using all of employed IP parameterization are identical. Hence, we used the 1D inversion algorithm for inversion of central loop TEM data distorted by moderate IP effect (Table 1). For this model, although using MPA improves the recovered values of m and ρ but deteriorates the recovered time constant and frequency exponent values. Using MIC and Jeffrey leads to the premature convergence and an ill-posed problem, respectively (Table 1 and Figure 1).

The result of 3D simulation of TEM data over a 3D model (Figure 2), using SLDMEM3t code, shown in Figure 3. As seen in the figure, the 3D structure may introduce a sign-reversal into the TEM data as well.

CONCLUSIONS

- By incorporating the IP effects into the TEM simulation, the TEM response show either a sign reversal or a rapid decaying
- Cole-Cole parametrization is more robust than MPA, MIC, and Jeffrey transform for recovering IP effect from TEM data using LM
- For the strong IP effect, using MPA transform results in artefacts in the forward response, and for moderate IP, recovered τ and c are, respectively overestimated and underestimated.
- Using MIC, leads to a poor fit and poor recovery of the model parameters
- The result of inversion strongly depends on the starting model.
- Similar to the IP effect, a 3D geometry may distort the TEM data and lead to sign reversal. These effects can be discerned using coincident-loop TEM or TDIP measurements.

ACKNOWLEDGEMENTS

The authors would like to thank the Alexander von Humboldt foundation for funding this project. The TEM field data used in this research were collected in a project funded by the Volkswagen Foundation.

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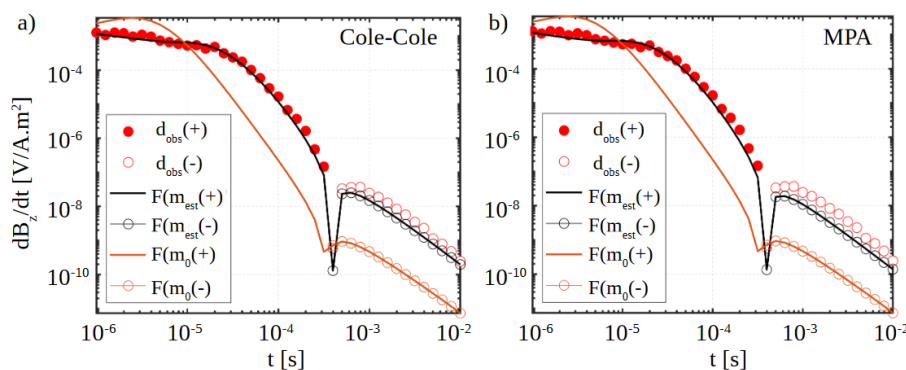
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Table 1. The result of inversion of the IP parameters from central loop TEM data of a 3-layer half space model (second layer is chargeable) using the LM algorithm (MP: model parameters, TM: True model, SM: starting model) (Sharifi et al. 2024, in rev.).

MP	TM	SM	Cole-Cole		MPA		MIC		Jeffrey	
			noise free	10% noise	noise free	10% noise	noise free	10% noise	noise free	10% noise
ρ_1	10	20	16.4	16.5	18.9	17.9	18.5	21.5	10.9	18
ρ_2	5	10	6.2	4.4	5.2	5.1	7.9	8.8	8.3	4.7
ρ_3	300	400	238.4	293.5	327	294.5	326.6	263.4	104.1	332.3
m_2	0.5	0.2	0.44	0.36	0.6	0.42	0.2	0.22	0.55	0.36
τ_2	0.01	0.05	0.038	0.05	0.231	0.09	0.049	0.044	0.021	0.044
c_2	0.5	0.2	0.36	0.32	0.21	0.23	0.21	0.22	0.40	0.36
d_1	5	2	2.6	2.4	2.7	2.5	2.2	2.2	3.6	2.4
d_2	5	2	6.7	4.4	6.3	5.4	3.5	4.3	8.3	4.7
RMS (χ)		14.8	4.6	6	5	5.8	11.6	11.2	1.7	6



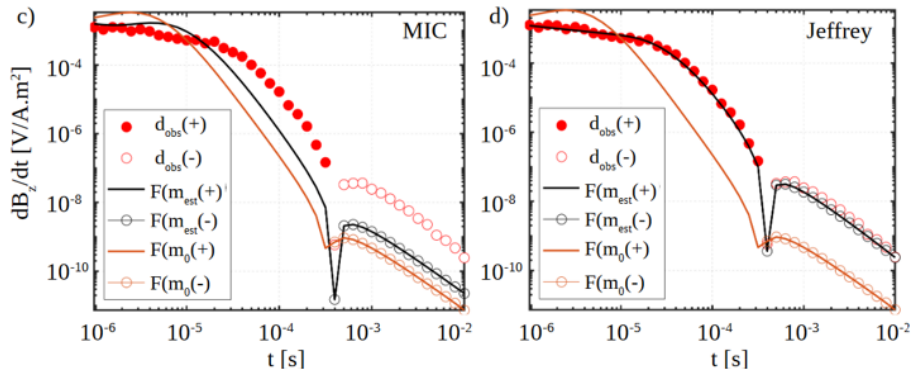


Figure 1. LM Inversion of central loop noisy TEM data (10% random noise) of a 3-layer half space model which second layer is considered chargeable. The IP effect incorporated using a) Cole-Cole, b) MPA, c) MIC, and d) Jeffrey transform. Here, $F(m_0)$ and $F(m_{est})$ are, respectively, the TEM responses of the starting model and the estimated model shown in Table 1 (Sharifi *et al.* 2024, in rev.).

Figure 2. Cross section of a 3D model composed of 4 layers and a conductive cylindrical body with resistivity of $1 \Omega\text{m}$ surrounded by a conductive object embedded in the first layer at the depth of 1.5 m. The section is a xz-slice at $y = 0 \text{ m}$ through the center of transmitter. A transmitter (Tx) loop size of $25 \times 25 \text{ m}^2$, a red color located at $z = 0$, with a current of 1 A is used for the electromagnetic excitation. The model volume is discretized using finite-difference method (Nienhaus, 2020)

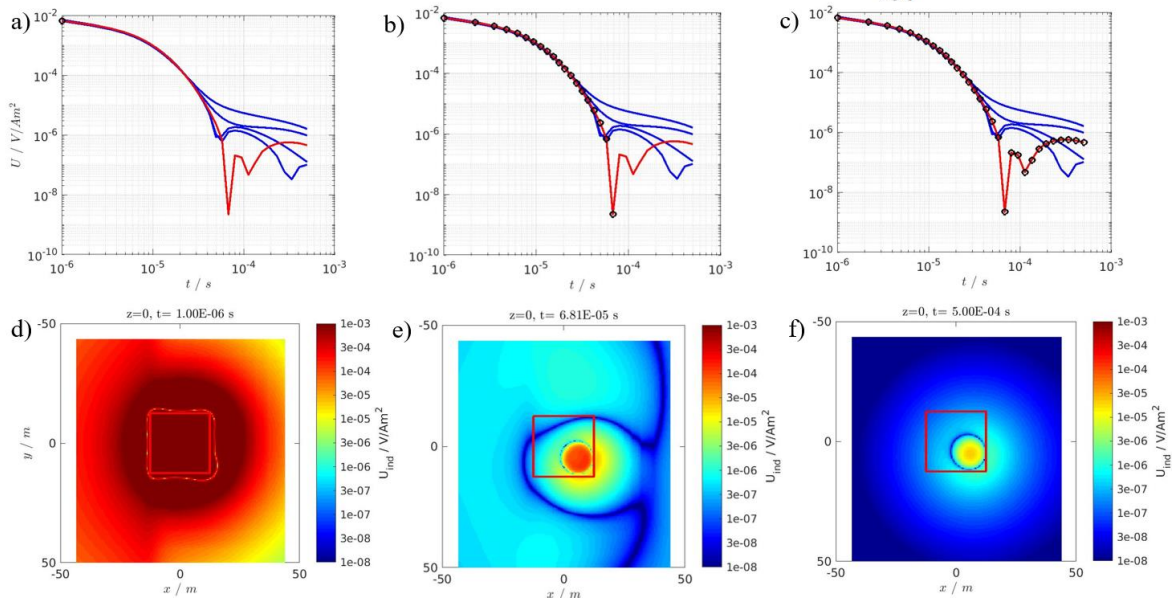
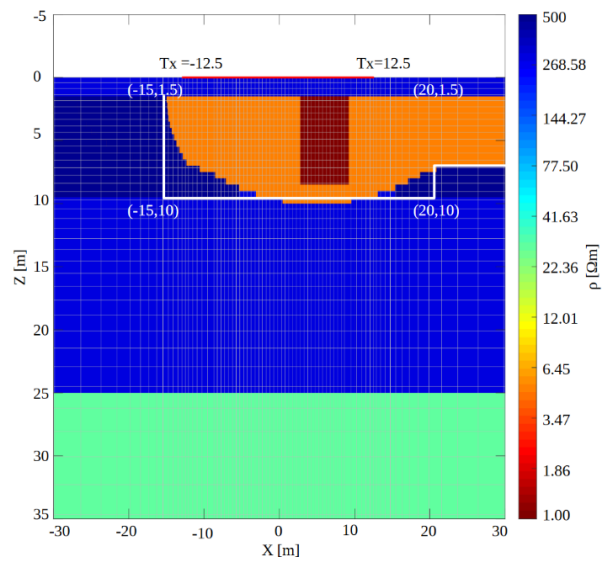


Figure 3. TEM data over a 3D model. Top panel (a, b and c) shows the 1D transient at the center of transmitter loop, and bottom panel depicts the xy-view of simulated TEM data, d) early time, e) middle time, and f) late time.