Joint Inversions of AEM modelling AIP effects: Helicopter-borne, Ground IP and Fixed-Wing systems

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SUMMARY

It is nowadays widely accepted that Induced Polarization (IP) effects can affect Airborne Electromagnetic (AEM) measurements. Modelling the AEM data with a dispersive-resistivity allow to properly retrieve the halfspace parameters avoiding high inversion misfits and wrong structures. Even if the Airborne IP (AIP) modelling it is a known and controlled practice, there are still some open questions regarding the complexities of this modelling approach. Most of this lie into the AIP sensitivity to geological targets, others in its capability in integrate with the ground IP and other more about the parametrical management during the inversion process. To contribute on the AEM-IP modelling field of research, with this work we performed two joint inversions on real data modelling AIP effects. For the first experiment we jointly inverted AEM-IP fixed-wing data with helicopter-borne data. For the other experiment, we jointly modelled ground DCIP and helicopter-borne AEM data, modelling AIP parameters. With these experiments we retrieved that inductive airborne IP can contribute, in term of sensitivity, to the ground IP modelling procedure and that fixed-wing airborne data have a good sensitivity to chargeable geological targets as well as helicopter-borne platforms. More in general, it has been seen that inductive IP contains complementary information for modelling IP effects.

Key words: Airborne Electromagnetics, Airborne IP, Fixed-Wing measurements, Ground IP measurements.

INTRODUCTION

Airborne Electromagnetic methodologies represent nowadays one of the most common and effective techniques for large scale resistivity mapping in mineral exploration and environmental issues (Flis et al., 1989; Smith, 1989; Smith and Klein, 1996; Kratzer and Macnae, 2012; Viezzoli et al., 2013). At the same time, it is recognized and subject of a growing interest, that AEM measurements are sensitive to Induced Polarization (IP) effects when acquired over a polarizable halfspace (Kratzer and Macnae, 2012; Viezzoli et al., 2013). These effects are given by the physics of polarizable materials that are able to complete a full charge and discharge cycle in a finite time interval when subject to an external electric field. The polarization ion-movement generates a polarization current that is is add, under the quasi-static approximation, to the pure EM currents induced in the ground by the AEM system. This currents interaction will inevitably manifest itself into the secondary magnetic field generated with their flow and that is recorded by the system's receiver (Flis, 1989). The IP effects are thus detectable with a typical signature in EM data: a fast decay that can culminate, if the polarization currents dominate the EM currents (opposite sign during discharging phase), to a change of sign of the EM signal. Under these conditions, the general relationships between the measured voltages versus time and depth (from which derive the correlation between the conductance and the data sensitivity) are compromised if the capacitive behaviour of the ground is not considered (Viezzoli 2017, Smith and Klein, 1996). It follows that modelling the AIP effects when they affect the AEM data is crucial to recover a correct parametrization of the investigated halfspace and to properly fit the data. The illustrated physics behaviour is model with the well-known dispersive resistivity models (such as Cole&Cole, Maximum Phase Angle, Constant Phase Angle…) typically used for galvanic DCIP data and that make the AEM data modelling effective but more complex at the same time. The modelling effectiveness is demonstrated by ground proven correct structures recovery such as cover thicknesses, conductive bodies top and bottoms, chargeable anomalies, and more (Viezzoli et al., 2017). Moreover, with a recent study (Dauti et al., 2023), it has been shown how AIP can provide significative information for exploration purposes providing airborne chargeable anomalies confirmed subsequently by ground DCIP acquisitions.

All these contributions and confirmations made the AIP interest increase in industry and in academia in the last decades.

With this work we will thus focus on AEM data modelling considering IP effects, illustrating two attempts of AEM-IP joint real data modelling. The joint inversions are carried between:

- AEM helicopter borne and galvanic DCIP data
- AEM helicopter borne and AEM fixed-wing data

Both the experiments aim to use the AEM-IP data sensitivity to increase the spectral content modelling of the acquired inductive (or galvanic) data.

For the first joint inversion, between airborne and ground IP, we wanted to verify if and how AEM-IP data are able to integrate the ground DCIP sensitivity to recover the dispersive-resistivity of the ground. As well known, the two methodologies work at different base frequencies and are considered, at this state of the art, spectrally sensitive to different and not compatible geological features (Macnae 2016). At this regard, given its spectral range, the airborne IP measurements are considered sensitive only to low time constants (quick polarization) and high chargeabilities only that, geologically speaking, is translatable to fine grained materials like clay, alterations or non-economic minerals.

Regarding the second experiment, between helicopter-borne and fixed-wing systems, we wanted to verify if the fixed-wing systems are sensitive to the same geological features of helicopter-borne platforms and are able to contribute to the model resolution. The fixed-wing systems were historically considered not able to detect IP effects, given their in-offset geometry that does not allow to uniquely relate negative voltages to IP effects (contrary to concentric loop helicopter-borne platforms), and to their bigger system footprint (lower shallow resolution). Anyway, recent studies (Viezzoli et al. 2021, Dauti et al., 2022), showed that it is possible to theoretically detect IP effects for fixed wing data and that it is satisfying model them.

With this work we thus want to contribute to the understanding of the sensitivity of the AIP spectral content in AEM data modelling.

METHOD AND RESULTS

The experiment set up and their results will be separately treated and illustrated in detail in the sections below.

Helicopter-Borne and Ground DCIP joint Inversion modelling AIP

The Airborne EM data have been acquired the last spring with the NRG XCite Time Domain 25Hz base frequency system, illustrated in black lines in figure 3. As introduced, for the same area 18 SyscalPro lines (0.125Hz of base frequency, 50% duty cycle) of ground Time Domain DCIP have been acquired.

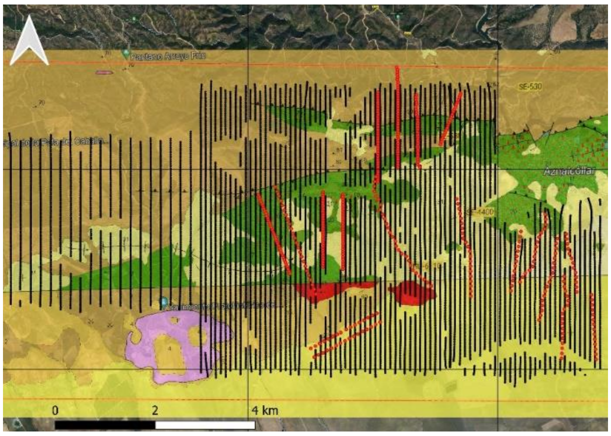

Figure 1. Survey location. In black the Airborne EM lines are displayed, in red the DCIP.

The datasets have been modelled with a consistent modelling procedure, with a 2D forward response formulation for the DCIP data (Fiandaca 2013) and 1D for the TDEM (Fiandaca 2012). The modelling approach proposed by Fiandaca allows to model the full-voltage decay (instead of the integral chargeability), the transmitter waveform and the receiver transfer function, increasing the procedure accuracy in recovering the spectral parameters. These features have been modelled both for the Airborne EM than for the Ground DCIP. Regarding the model-space parametrisation, we used the Maximum Phase Angle (MPA) Cole-Cole re-parametrisation (Fiandaca et al., 2018; Madsen et al., 2018) instead of the classical Cole-Cole model re-arranged by Pelton (1978). The MPA Cole-Cole model is a re-parametrized form of the classic Cole-Cole, where instead of m_0 and τ_ρ we used the maximum phase φ_{max} and the phase relaxation time τ_φ. The phase of the complex conductivity can be defined in terms of both *equations 1* and *2* as:

$$\varphi(\omega) = atan\left(\frac{\sigma''(\omega)}{\sigma'(\omega)}\right) = atan\left(\frac{\rho''(\omega)}{\rho'(\omega)}\right) \qquad \text{(eq. 1)}$$

The phase reaches his maximum φ_{max} at an angular frequency $\omega_\varphi \equiv 1/\tau_\varphi$ as:

$$\varphi_{max} = atan\left(\frac{\sigma''(1/\tau_\varphi)}{\sigma'(1/\tau_\varphi)}\right) = atan\left(\frac{\rho''(1/\tau_\varphi)}{\rho'(1/\tau_\varphi)}\right) \qquad \text{(eq. 2)}$$

Furthermore, the model space of the MPA Cole-Cole model can be written as:

$$m_{MPA\ Cole-Cole} = \{\rho_0,\ \varphi_{max},\ \tau_\varphi,\ C\}$$

The MPA parametrisation allows to minimize the correlations between the Cole-Cole m_0 and C using the poorly correlated φ_{max} and C, and to improve the resolution retrieved from inversion IP data of the classical Cole-Cole model.

The inversions have been performed with the inversion scheme proposed by Fiandaca et al., 2023 that uses voxel model mesh to map the solved parameters via an interpolation of the forward mesh solutions. The decoupling of the model mesh and the forward mesh allows to work with more flexible and manageable spaces (forward and model) to perform joint inversions and time laps inversions. In our inversion procedure, in order to increase the parametrical resolution and the phase sensitivity in depth, we parametrized the spectral parameters (τ_φ, C) on an independent mesh respect to resistivity and phase, with different lateral constraints and vertically fixed (as proposed by Viezzoli and Fiandaca in 2021).

The inversion results for the lines on which we performed the joint modelling are presented in Figure 2. In the figure we compared the results for AEM chargeability section only, the modelled DCIP chargeability, and the joint inversion model of the two. In terms of inversion misfit, we obtained: AEM only: 1.10, DC only: 4.2, IP only: 1.2 and, for the joint inversion, AEM joint: 1.18, DC joint: 4.9, IP joint: 1.20. The misfits are thus comparable and satisfying considering the standard deviations of each dataset. As visible from the results, the joint inversion model merges the sensitivities of the two methodologies and add the information of the ground DCIP to the chargeable bodies. It is also visible how the AIP modelling add information to the joint inversion and, at the same time, accept the ground DCIP sensitivity.

Helicopter-Borne and Fixed-Wing joint Inversion modelling AIP

For our experiments we used data from a $\text{GEOTEM}_{\text{DEEP}}$ fixed-wing system (Annan, 1990) acquired in Northern Territories, Australia, in 2010 and some overlapping (Figure 3) government VTEM helicopter-borne data acquired in 2009. Geologically, the investigated area is a classical Australian environment with a conductive cover over a resistive bedrock; the aim of the investigation was the estimation of the cover thickness for exploration purposes.

From a geophysical point of view, the differences between the two systems are many and are reflected in the acquired data. The dipole moment for the fixed wing GEOTEM system is almost the double of the VTEM one and, geometrically, the offset configuration (and a 15-year-old technology) does not allow to properly monitor and measure the receiver bird position producing strong modelling complexities. For our modelling procedure we used the theoretical bird position, with a receiver horizontal offset of 70 m and a vertical offset of 50 m respect the craft.

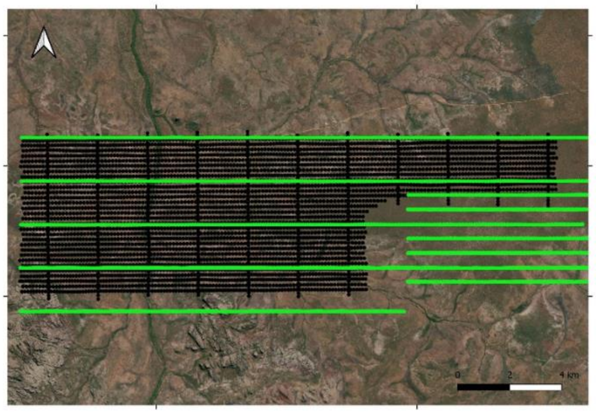

Figure 3. In black: GEOTEM's lines; in green: VTEM's lines.

As workflow, we firstly manually processed the EM data to assess the noise level for the two systems, to improve the S/N and to delete artifacts. Then we proceed with the joint inversion of the overlapping lines using, as before, the approach proposed by Fiandaca et al., 2023 and using the MPA parametrization as presented in Equations 1 and 2. In Figure 4 an example of a jointly modelled couple of lines is presented. The presented models are cropped with the depth of investigation (DOI). This is calculated as Fiandaca et al., 2015, based on an approximated covariance analysis applied to the model output from the inversion while considering the data standard deviations.

In the figure is interesting to see how the chargeability has a good resolution and follows, also in depth, the conductive shallow layer modelled in the resistivity model as expected from the geological information of the area.

CONCLUSIONS

With this contribution we shown that the AIP spectral content can significatively contribute to the dispersive-resistivity modelling when jointly modelled with other techniques (galvanic Induced Polarization) and between different airborne systems (fixed wing and helicopter borne platforms).

First, it has been demonstrated that is successfully possible to jointly model Airborne and Ground IP. In particular, it has been shown how the airborne IP contributes to the sensitivity of the modelling procedure and accepts the ground sensitivity in the inversion procedure. Important is to underly how the recovered structure not only changes (if comparing galvanic-only or inductive-only inversions) in terms of resistivity modelling but also in terms of chargeability. This importantly evidence that the spectral content of airborne data is complementary and can add information to the ground DCIP.

Regarding the airborne inversions, it is possible to jointly model helicopter borne and fixed-wing AEM data considering IP effects. The inversion process, as expected, converged to the resultant model using the different sensitivities of the two systems fitting the data. The different sensitivities are given by the different system's features (such as footprint, geometry, height of flight, dipole moment…) and the obtained results merge the features of both.

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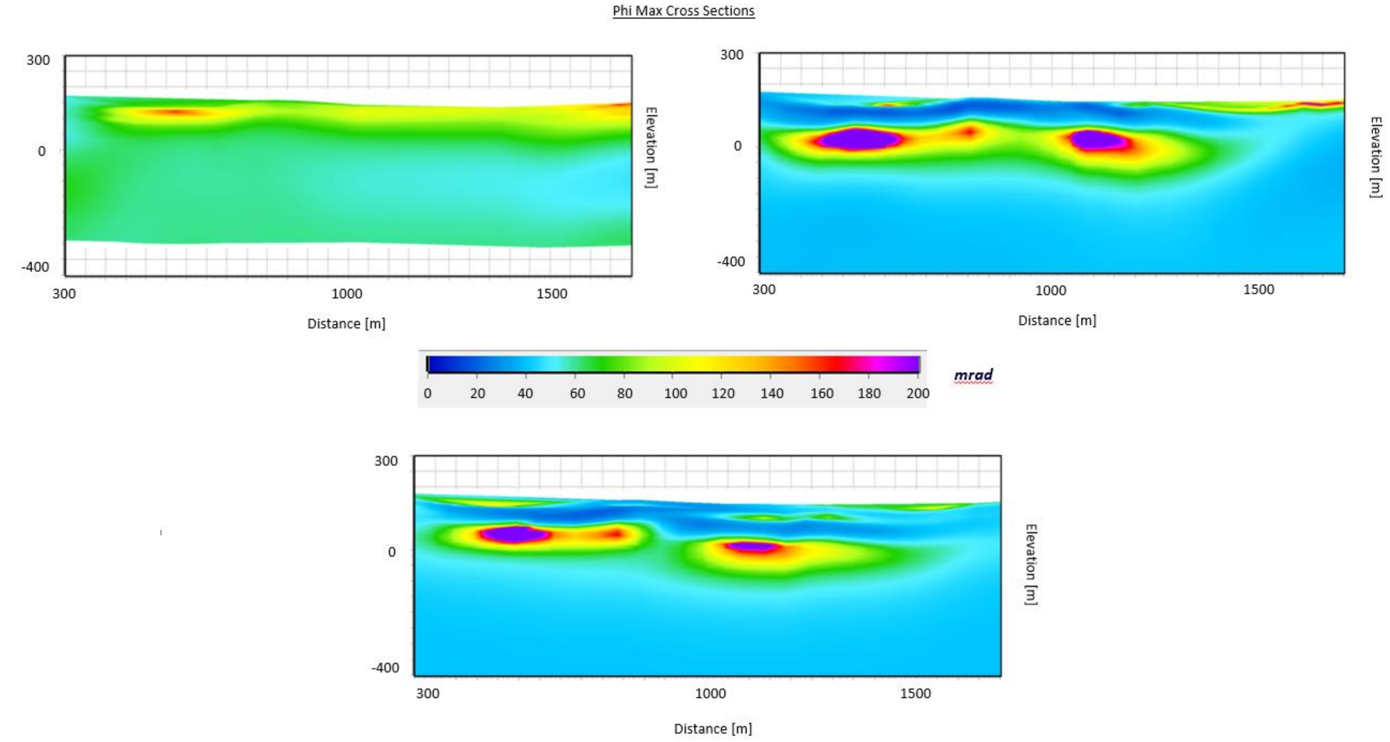

Figure 2. Top left: DCIP chargeability only. Top right: AEM chargeability model for the selected line only. Bottom: Joint inversion chargeability model of DCIP and AEM for the selected line.

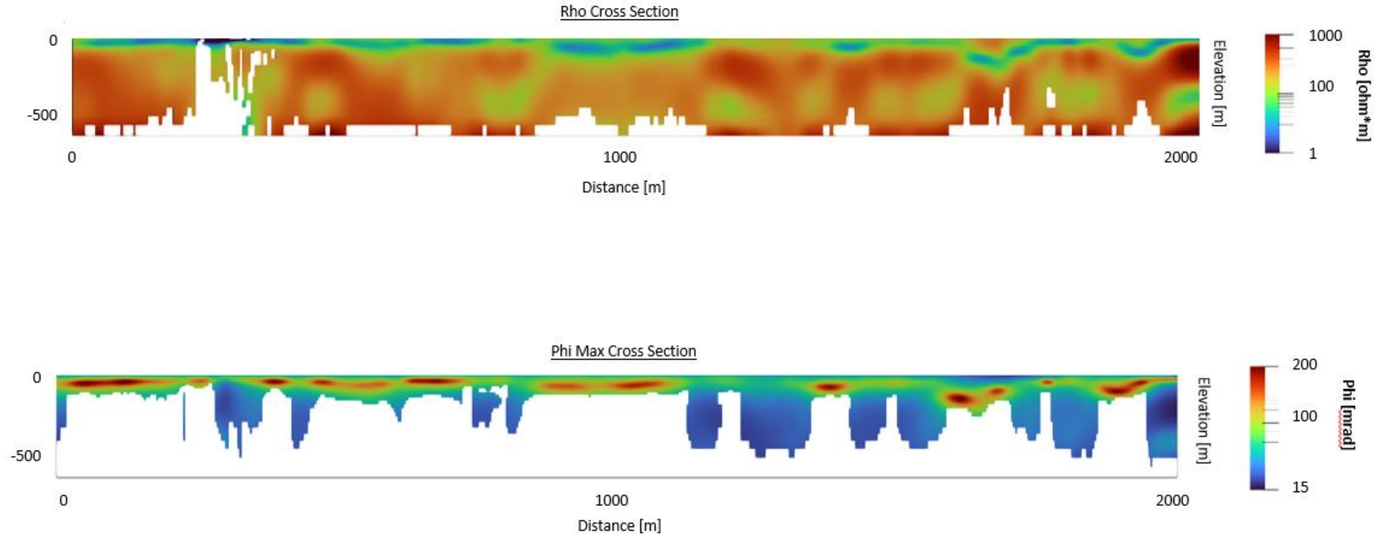

Figure 4. Top: jointly modelled resistivity cross section of two overlapping VTEM and GEOTEM lines. Bottom: jointly modelled chargeability cross section of same selected lines. Both the lines are cropped with the DOI.