Overcoming Airborne IP in Frequency Domain: Hopes and Disappointments

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BIOGRAPHY

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SUMMARY

We analyse responses in frequency domain and time domain. They significantly differ. Moreover, quadrature and inphase components in frequency domain behave differently in case of airborne IP. We propose resistance calculation which has to be poorly influenced by airborne IP. Also we offered a method for resistivity calculation. We made a comparison of such resistivity and apparent resistivity calculated by the quadrature component. These resistivity data are rather similar. We hope that quadrature component is less affected by AIP. Further researches are required to receive estimates of resistance and capacity for more general case.

Key words: airborne electromagnetics, frequency domain, time domain, airborne induced polarisation, EQUATOR.

INTRODUCTION

Since the sensitivity of airborne electromagnetic (EM) systems significantly increased in the last decade, more and more authors pay careful attention to the effect of induced polarisation (IP) sometimes causing negative transients in time domain EM (TDEM) data (Chen et al., 2015; Kaminskiy and Viezzoli, 2017; Kwan et al., 2018). The most common approach to describe the airborne IP effect is to use Cole-Cole model, which appeared as an empirical method to analyse the IP in galvanic ground measurements (Cole and Cole, 1941). In many cases it allows to exclude the IP effect or even to evaluate the apparent chargeability. For example, Kaminskiy and Viezzoli (2017) reported quite successful chargeability estimation in comparison to borehole data.

At the same time, Macnae and Hine (2016) comparing conventional ground and apparent airborne IP show no useful correspondence between the locations of airborne IP (AIP) and gradient array ground IP anomalies. It is likely that all the considered ground IP targets would have time constants outside the detectable range of modern AEM systems. Also they note that modelling using the established Cole-Cole physical property values for sulphides predicts that an inductive airborne system is insensitive to many conventional IP targets, unless the mineral grain size is substantially less than 1 mm.

Thus, it is difficult to consider airborne IP problem solved. Moreover, sometimes we can’t be sure that the Cole-Cole parameters reflect true physical properties. By this reason a new approach to IP analysis may be of interest.

In this paper we suggest to analyse airborne IP in frequency domain (FD). On the one hand, FD signals are obviously affected by IP in case it is presented. On the other hand, they can provide information on IP in a more convenient form. The idea comes from using helicopter-borne TDEM system EQUATOR (Moilanen et al., 2013), the only system that provides data both in time domain and frequency domain. Karshakov (2017) has shown how effective joint FD and TD measurements could be in resistivity analysis. So possibly, it can give a new clue to the IP problem solution. A spoiler: it can, although it doesn’t solve it fully.

We do not offer a strict theory for IP affected data processing. We rather try to rethink the essence of the phenomenon on some trivial models, hoping to get a qualitatively new solution. We’ve applied the developed approach to airborne EM data we have.

The EQUATOR is a helicopter TDEM system with towed transmitter. The receiver is attached to the tow cable at 40 m distance apart from transmitter. As a result, full waveform measurements are performed, which allow to apply Fast Fourier Transform (FFT) to get FD data. Frequencies are several odd harmonics of the base frequency: $f_n = (2n - 1)\cdot 77$ Hz, n = 1, 2, 3… This system was used for several objects in Russia in the areas, where the airborne IP is widely presented. The area of Amakinskaya kimbrelite pipe considered by

Viezzoli and Kaminski (2016) is among them. All the presented field examples are from that region.

METHOD AND RESULTS

Starting from the very beginning, let's consider the first of Maxwell's equations for EM-field in homogeneous medium for some specific frequency ω (Collett, 1959):

$$\nabla \times \mathbf{H} = (\sigma - i\omega\varepsilon)\mathbf{E}, \qquad (1)$$

where in the left is the curl of the complex amplitude vector of magnetic field **H**, σ – conductivity and ε – absolute permittivity of the medium, *i* – imaginary unit, **E** – the complex amplitude vector of electric field. In Equation (1) ε is the only value that can force negative respond. More precisely, $-i\omega\varepsilon$ is the only difference from quasi-stationary form, which doesn't fit the case of IP effect.

From the presented EQUATOR data (Figure 1) follows that maximal IP effect in frequency domain is presented at frequency ($2.7\ \text{kHz} \sim 1.7{\cdot}10^4\ \text{s}^{-1}$) or lower. The background apparent conductivity there is about $3{\cdot}10^{-3}$ S/m. To affect significantly measured signals absolute permittivity should be of the order $\sigma/\omega \sim 1.7{\cdot}10^{-7}$ F/m at least. But for a reasonable medium it hardly can exceed 10^{-9} F/m. For instance, clays have maximum permittivity $40{\cdot}\varepsilon_0 = 0.35{\cdot}10^{-9}$ F/m (Hubbard, 1997), i.e. two orders smaller at least. Here $\varepsilon_0 = 8.85{\cdot}10^{-12}$ F/m is permittivity of vacuum.

Thus, there is no reason to consider IP effect as a consequence of the homogeneous medium permittivity. Obviously, the source of IP is most likely heterogeneity of the medium. There can be capacitors formed by local faults with air as dielectric, without any valuable permittivity.

Suppose there are no capacitors. In this case electromotive force and currents will be distributed as presented in Figure 2, transmitter altitude here is 40 m. It is clearly seen, that the currents basically runs at distance from 20 to 30 m from the dipole axis. This case can be represented by a simple circuit diagram containing voltage source with electromotive force *E*, inductor with inductance *L*, which is directly related to the flight altitude, and resistor with resistance *R*, which depends on both flight altitude and conductivity (Figure 3a).

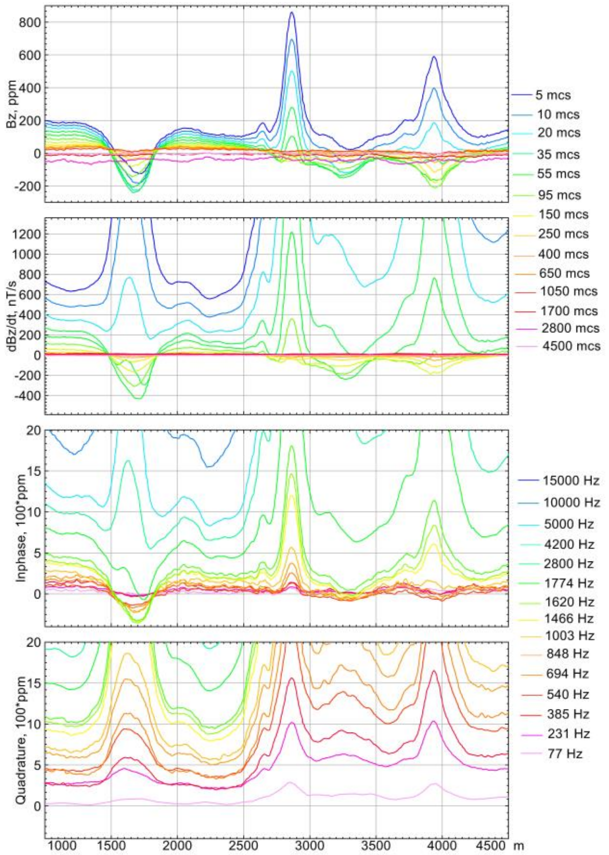

Figure 1. IP affected signals: a) TD *dB/dt*, b) FD inphase components, c) FD quadrature component.

As Cole and Cole (1941) did, let's add a capacitor with capacitance *C*. We've figured out two fundamentally different ways to do it: Figure 3b and Figure 3c. Of course, there are more, but we will focus on these two to illustrate the main issues. Ohm's law for connection in series gives

$$E = I\left(R + i\omega L - \frac{i}{\omega C}\right), \qquad (2)$$

where *I* is the amplitude of the current. In case of connection in parallel we have

$$E = I\left(R + i\omega L - \frac{iR_C}{\omega R_C C - i}\right), \qquad (3)$$

where R_C is resistance parallel to capacitor. There are two extreme cases in Equation (3): $\omega R_C C << 1$ and $\omega R_C C >> 1$. The first case allows to neglect the capacity, so there are no IP. The second one just gives Equation (2).

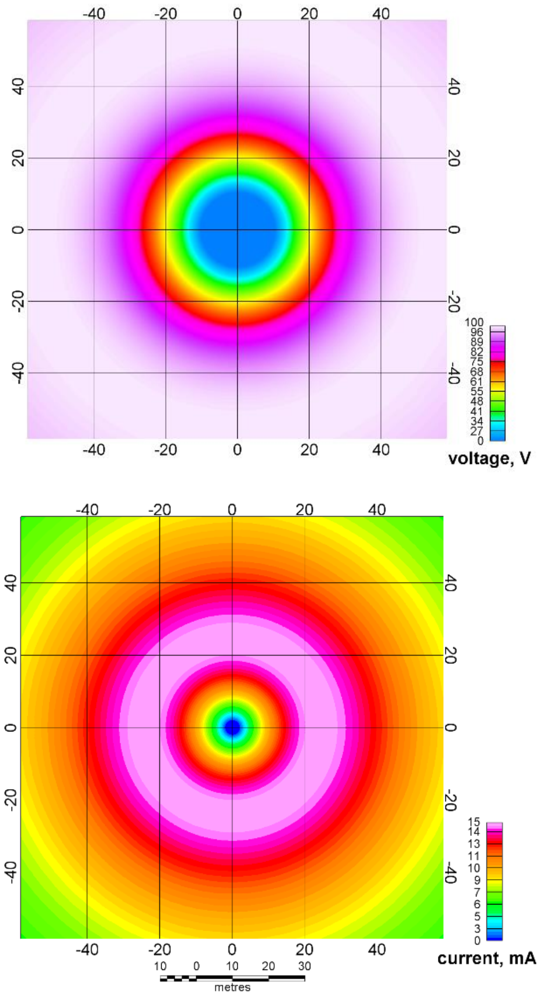

Figure 2. Electromotive force (up) and current (bottom) distribution for vertical dipole 40 m above the surface, (0, 0) is the axis of dipole.

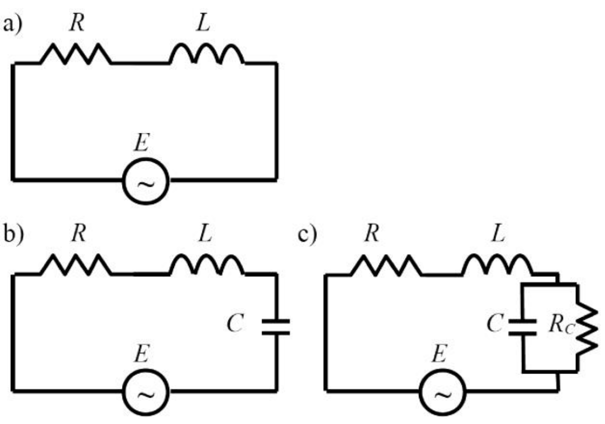

Figure 3. Circuit diagrams for the currents in the medium at certain frequency without (a) and with capacitor in series (b) and in parallel (c).

The main feature of Equation (2) is the fact that both capacitance and inductance give only imaginary part of impedance, while resistance gives pure real part. Let's rewrite (2) as

$$\frac{E\bar{I}}{I^2} = \left(R + i\omega L - \frac{i}{\omega C}\right), \qquad (4)$$

where $\bar{I}$ is the complex conjugate of I, Im $\bar{I} = -$ Im I. According to the Faraday's law, electromotive force E has phase equal to 90° with respect to the primary field, so if the primary field B_p is real, Im $B_p = 0$, then Re $E = 0$, Im $E \sim \omega B_p$.

According to Ampere's law, the secondary field B_s has the same phase with the current. After all,

$$\frac{k\omega B_p}{B_s^2}(i\mathrm{Re}B_s + \mathrm{Im}B_s) = \left(R + i\omega L - \frac{i}{\omega C}\right), \qquad (5)$$

where k is a real number, which depends on the position of the transmitter and the receiver with respect to the ground.

The resistance R can be calculated from the real part of Equation (5):

$$R = \frac{k\omega B_p}{B_s^2}\mathrm{Im}B_s. \qquad (6)$$

We can calculate the resistivity directly from R if we know the radius of the current path and can suggest the area of section. It promises to be free of IP effect! Moreover, if we can calculate the correspondent L and evaluate the capacitance as a frequency dependent parameter.

According to Figure 2 we have tried to estimate L. First, we have got apparent resistivity for the current frequency from Equation (6). Next, we suppose the currents to be mostly represented in the upper 5–10% of the skin depth for the correspondent frequency and resistivity. After we have calculated L from the loop dimensions, we can find C from the imaginary part of Equation (5):

$$\frac{1}{\omega C} = \omega L - \frac{k\omega B_p}{B_s^2}\mathrm{Re}B_s. \qquad (7)$$

The final result for the frequency 848 Hz is presented in Figure 4. Calculated resistivity as well as apparent resistivity based on quadrature component both are not affected by flight altitude. At the same time apparent resistivity looks the same to calculated one. It seems quadrature component is less affected by AIP than inphase secondary field. The capacitor impedance (middle graph) marks the area of AIP influence.

Nevertheless, for more common Equation (3) the capacitance related part of the impedance can be of any phase from 0º to –90º. So, this is the main disappointment – we need more than one frequency to exclude IP. In this case the suggested approach is not fully adequate, because the currents at different frequencies can run different paths. But still, in case we managed to calculate the capacitance as it was described above, we can hope that the calculated from Equation (6) value is less affected by airborne IP.

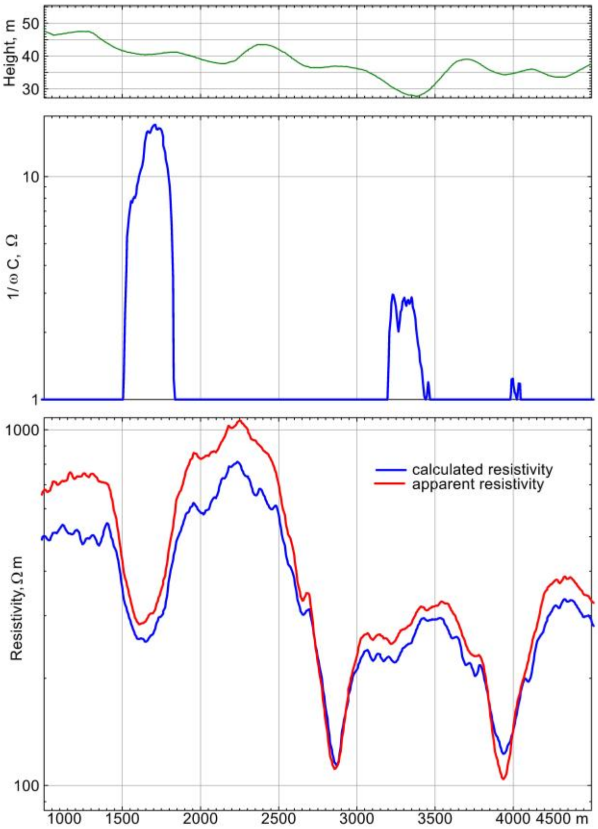

Figure 4. Calculated resistivity versus apparent resistivity for 848 Hz (bottom graphs), calculated capacitor impedance (middle graph) and transmitter's height (upper graph).

CONCLUSIONS

For the current progress we acquired following conclusions:

1. The analysis of responses in frequency domain significantly differs from time domain ones.
2. Quadrature and inphase components behave differently to AIP.
3. It was succeeded to receive value of resistance which has to be poorly subject to influence of AIP for the simplified model of consecutive connection of capacity, inductance and resistance (Fig. 3b).
4. We offered a method for resistivity calculation. We made a comparison of such resistivity and apparent resistivity calculated by the quadrature component. These resistivity data are rather similar. We hope that quadrature component is less affected by AIP.
5. Further researches are required to receive estimates of resistance and capacity for more general case (Fig. 3c).

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REFERENCES

Chen, T., Smiarowski, A., and Hodges, G., 2015, Understanding airborne IP: First European Airborne Electromagnetic Conference, EAGE, Extended Abstracts.

Cole, K.S., and Cole, R.H., 1941, Dispersion and absorption in dielectrics. I. Alternating current characteristics: Journal of Chemical Physics, 9, 341-351.

Collett, L.S., 1959, Laboratory investigation of overvoltage, in Overvoltage research and Geophysical applications: J. R. Wait, Ed., New York, Pergamon Press.

Hubbard, S.S., Peterson, J.E., Majer, E.L., Zawislanski, P.T., Williams, K.H., Roberts, J., and Wobber, F., 1997, Estimation of permeable pathways and water content using tomographic radar data: The Leading Edge, 16(11), 1623-1628.

Kaminskiy, V. and Viezzoli, A., 2017, Modelling induced polarisation effects in helicopter time-domain electromagnetic data: Field case studies: Geophysics, 82(2), 1-13.

Karshakov, E., Podmogov, Y., Kertsman, V. and Moilanen, J., 2017, Combined frequency domain and time domain airborne data for environmental and engineering challenges: Journal of Environmental & Engineering Geophysics, 22(1), 1-11.

Kwan, K., Legault, J., Johnson, I., Prikhodko, A., and Plastow, G., 2018, Interpretation of Cole-Cole parameters derived from helicopter TDEM data – Case studies: SEG Annual Meeting and Exhibition, Anaheim, Extended Abstracts, 1-6.

Macnae, J., and Hine, K., 2016, Comparing induced polarisation responses from airborne inductive and galvanic ground systems: Tasmania: Geophysics, 81(6), E471-E479.

Moilanen, J., Karshakov., E. and Volkovitsky, A., 2013, Time domain helicopter EM system "Equator": resolution, sensitivity, universality: 13th SAGA Biennial @ 6th International AEM Conference, Extended Abstracts, 1-4.

Viezzoli, A., and Kaminski, V., 2016, Airborne IP: examples from the Mount Milligan deposit, Canada, and the Amakinskaya kimbrelite pipe, Russia: Exploration Geophysics, 47(4), 269-278.