

# The physics of the ground loop

Braam du Plooy<sup>1</sup>, John Bell<sup>2</sup>

1. Spectrem Air Ltd., South Africa, braam@spectrem.co.za
2. Anglogold Ashanti, South Africa, JBell@AngloGoldAshanti.com

## ABSTRACT

A ground loop is often used both as a model to explain the basics of electromagnetic exploration and as a tool in the calibration of AEM systems. A thorough understanding of the underlying physics is essential.

During the calibration procedure of an AEM system, the electrical current in the ground loop was measured and recorded. A mathematical model in the form of a differential equation was stated for the current in the ground loop. The solution of the differential equation was calculated allowing for the particular transmitter current wave shape.

There is good qualitative conformity between the measured current and modelled current. Quantitative agreement of the current amplitude depends on an accurate knowledge of the geometries of the problem.

**Key words:** ground loop current, airborne electromagnetics, calibration.

## INTRODUCTION

During a calibration procedure of an airborne electromagnetic system, the electric current in a ground loop was measured.

The aim of the study was to give an explanation of the perplexing appearance of this loop current.

In order to understand the underlying physics, use was made of a mathematical model of the problem.

It was possible to explain in detail the behaviour of the loop current.

## EXPERIMENT

An insulated copper cable was placed on the ground in the shape of a square with side length 80 metre. A helicopter borne transmitter loop was flown across the loop at different heights between 30 and 60 metre. The transmitter current is depicted in Figure 1.

In order to have a record of the current in the ground loop, the voltage drop across a series resistor was measured and recorded. Figure 2 is a plot of the current during several cycles of the transmitter.

## MODELLING

In order to simulate the current in the ground loop, a mathematical model was needed that describes the electromagnetic interaction between the loops.

The ground loop was modelled as a circuit consisting of a resistor and an inductor in series with a voltage source

that represents the electromagnetic induction from the Tx (transmitter). Given the low frequencies present in the system, all capacitive effects were ignored.

Considering the voltage across each element in the circuit, one obtains the following differential equation that governs the current in the ground loop (Grant and West, 1965, p541)

$$L \frac{di}{dt} + Ri = -M \frac{dI}{dt} \quad (1)$$

where

$i$  is the current in the loop;

$L$  is the self inductance of the loop;

$R$  is the resistance of the loop;

$t$  is time;

$M$  is the mutual inductance between the transmitter loop and the ground loop  
and

$I$  is the transmitter current.

In order to solve Equation 1, several quantities must first be measured or calculated.

The self inductance and resistance of the loop were measured in situ by an RLC meter. The values were  $L = 695$  microhenry and  $R = 1.35$  ohm.

In the modelling, a transmitter is simulated of which the position is changing relative to the ground loop. Consequently one needs to calculate a changing mutual inductance. The following integral expression for the

mutual inductance was numerically evaluated (Reitz *et al.*, 1979):

$$M = \frac{\mu}{4\pi} \oint_{C_2} \oint_{C_1} \frac{dl_1 \cdot dl_2}{|r_2 - r_1|}$$

where  $C_1$  and  $C_2$  refer to the transmitter loop and ground loop respectively.

As is clear from the right hand side of Equation 1, the transmitter current is not explicitly used but rather its time derivative.

When the transmitter current is a step function, Equation 1 has the closed form solution

$$i(t) = \frac{M}{L} e^{-\frac{R}{L}t} \quad (2)$$

When the transmitter current has a more general wave shape like that depicted in Figure 1, one has to resort to a numerical solution. I wrote a program utilizing fourth order Runge-Kutta from Press *et al.* (1992) for the solution of the differential equation.

Figure 3 shows the computed loop current during the first half-cycle of the transmitter. There is good correlation between the computed and measured current (Figure 4). The correspondence can be improved by more accurate control over system geometries e.g. transmitter height.

We are more interested in a physical explanation of the loop current behaviour.

The underlying physics can most easily be explained by dividing the Tx current function into three time intervals (see Figure 1): an up-ramp, a down-ramp and an off-time.

During the up-ramp the Tx current has a constant positive slope. Hence the right hand side of Equation 1 is a constant

$$-V_1 = -M \frac{dI}{dt}$$

with  $V_1 > 0$  .

The circuit equation can be written as

$$L \frac{di}{dt} + Ri = -V_1 \quad (3)$$

with the initial condition  $i(t = 0) = 0$  .

The solution of this problem yields the current:

$$i(t) = \frac{V_1}{R} (e^{-\frac{R}{L}t} - 1) \quad (4)$$

The slope of the current is

$$\frac{di}{dt} = -\frac{V_1}{L} e^{-\frac{R}{L}t}$$

Thus both the current and its slope are negative during this time interval. The time constant  $L/R$  is an intrinsic property of the ground loop, independent of any other parameter of the model.

The current is plotted in Figure 5. The plot matches the first (decaying) part of the loop current in Figures 3 and 4. If the transmitter current was an infinitely long ramp, the loop current is in the limit equal to  $-V_1/R$  which is just the galvanic current after all decaying behaviour has disappeared.

Before the loop current approaches this asymptote, the slope of the Tx current changes abruptly (see Figure 1).

This is equivalent to changing the applied voltage in the circuit equation (3) suddenly to a positive constant (say  $V_2$ ). The differential equation becomes

$$L \frac{di}{dt} + Ri = V_2 \quad (5)$$

The inductor prevents the loop current from changing discontinuously, but the slope of the current is suddenly positive, as is clearly seen from Equation 5 (recall that the loop current was negative at the start of the down-ramp):

$$L \frac{di}{dt} = V_2 - Ri > 0$$

The current has a similar shape as expressed in Equation 4 (with identical time constant), except the starting value is negative, the slope is positive and the asymptote is  $V_2/R$  .

The continual application of the constant voltage eventually causes the current to go through zero (Figure 3). Long before the current reaches its asymptote, the Tx current is switched off. There is no voltage source that drives the current and it decays in a natural way similarly to the expression in Equation 2.

During the second half-cycle of the Tx current, the process described above is repeated exactly, with the difference that the Tx current now has the opposite sign. The resulting loop current is seen in Figure 2.

That concludes the explanation of the physics of the ground loop current.

For the sake of completeness, I shortly discuss the signal one would expect to measure at a typical receiver of an AEM system.

The receiver unit in the experimental system comprised of a set of three induction coils orientated perpendicularly.

For geophysical purposes, it is not the field of the transmitter, but the signal from the target that is of interest. It is usually referred to as the *secondary field*. In the case of the ground loop experiment, only the loop current contributes to this secondary field.

Since the receivers are induction coils, they effectively measure the change of the magnetic field associated with the ground loop current. That means that the received signal is at all times proportional to the slope of the current in the ground loop.

Figure 6 shows the time derivative of the loop current which was calculated during the solution of the differential equation (Equation 1).

## **CONCLUSIONS**

The measured current in the ground loop can be completely explained in terms of known electromagnetic principles.

Perfect agreement between measured and modelled results depends on an accurate knowledge of system geometries.

The loop current is modelled by a simple circuit equation, but it offers insight into the much more complicated physics of the three-dimensional problem.

## **ACKNOWLEDGMENTS**

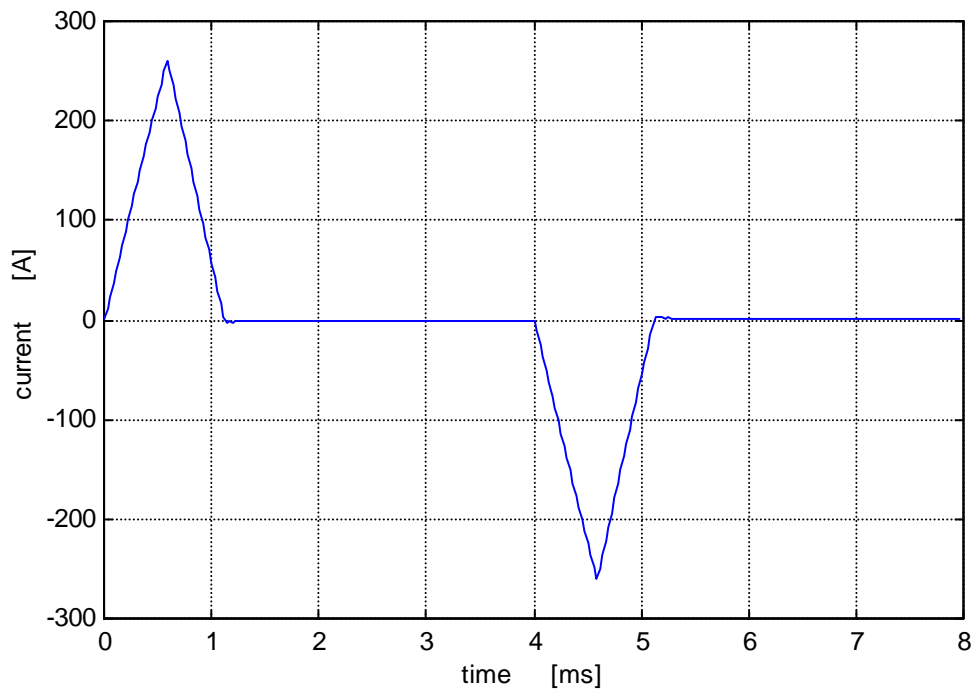
Spectrem Air Ltd. is thanked for the opportunity to present these results.

## **REFERENCES**

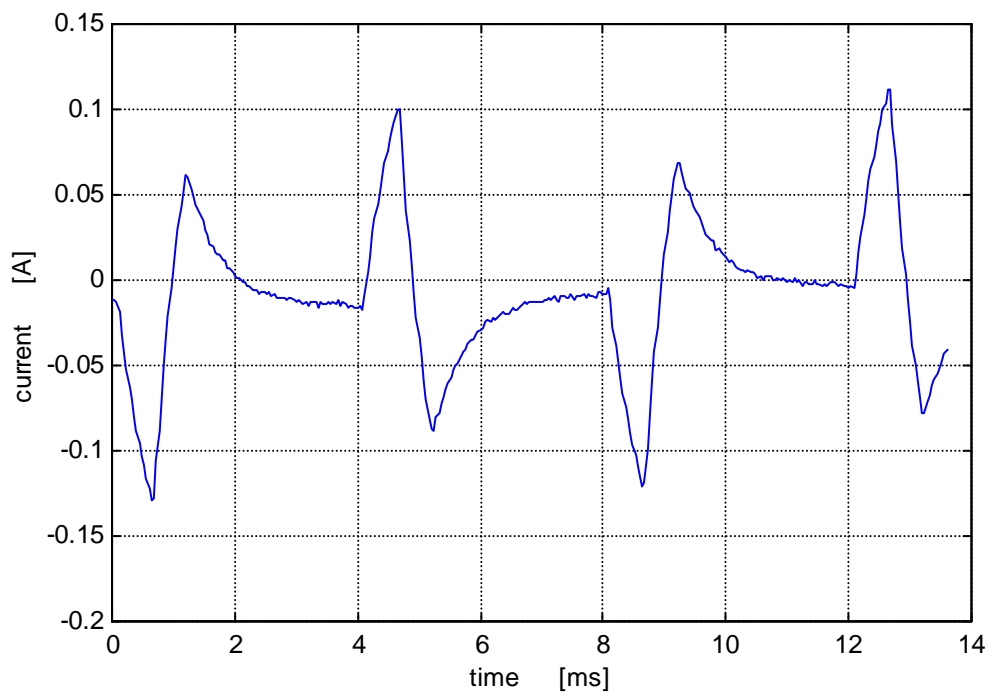
Grant, F.S. and West, G.F., 1965, Interpretation theory in applied geophysics: McGraw-Hill Book Company.

Press, W.H., Flannery, B.P., Teukolski, S.A., and Vetterling, W.T., 1992, Numerical recipes in Fortran77 2nd edition - The art of scientific computing: Cambridge University Press.

Reitz, J.R., Milford, F.J. and Christy, R.W., 1979, Foundations of electromagnetic theory, third edition: Addison-Wesley Publishing Company.



**Figure 1. One cycle of the recorded transmitter current. The frequency is 125 Hz.**



**Figure 2. The current in the ground loop, recorded while the transmitter crossed overhead.**

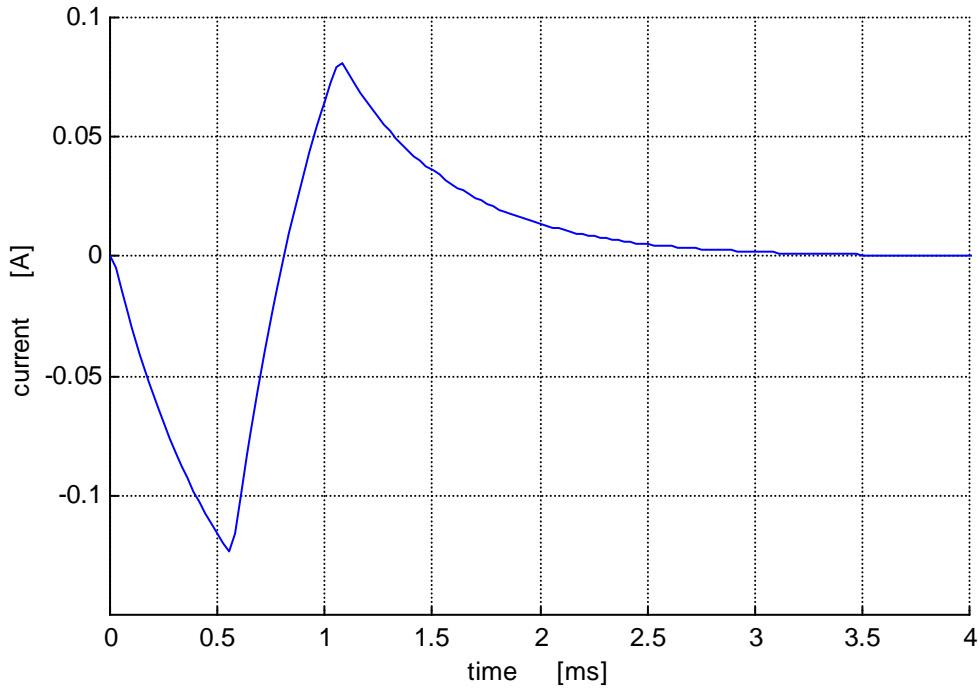


Figure 3. The calculated loop current for a half-cycle of the transmitter.

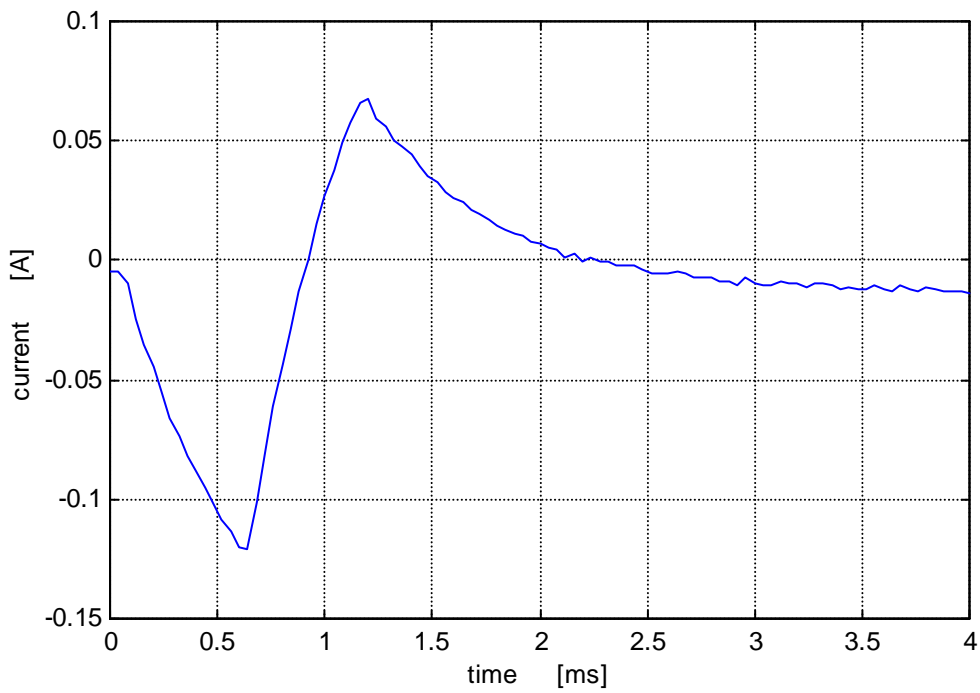


Figure 4. The recorded loop current during a half cycle of the transmitter.

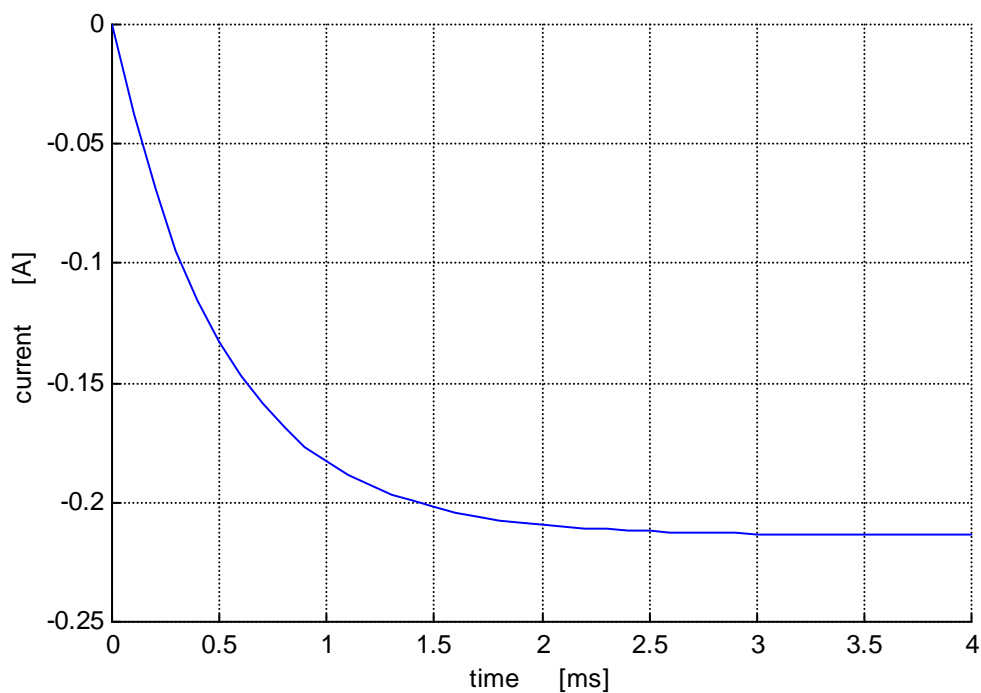


Figure 5. The loop current during the up-ramp part of the transmitter current (Equation 4).

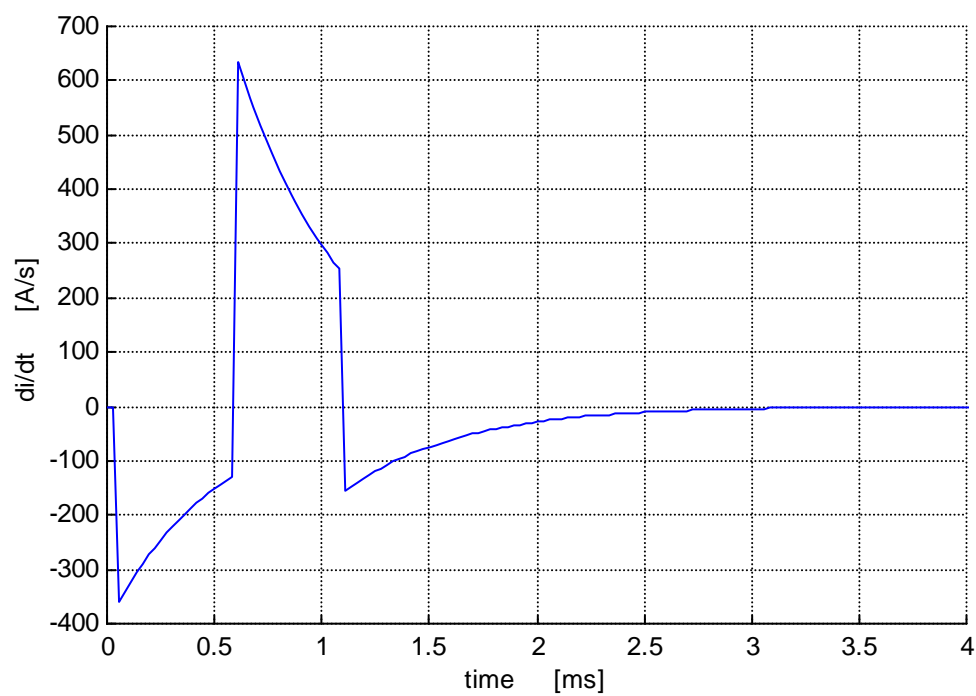


Figure 6. The time derivative of the ground loop current calculated during a half-cycle of the transmitter. This is directly proportional to the secondary signal in a receiver coil.