E048

Maximising Signal-To-Noise Ratio in Transient EM Data

A.M. Ziolkowski* (MTEM Ltd) & R. Carson (MTEM Ltd)

SUMMARY

We describe the multi-transient electromagnetic method and focus on new technology to maximise the signal-to-noise ratio. The amplitude of the transient EM impulse response decays with offset \( r \) as \( 1/r^5 \). We employ a variety of techniques to maximize the signal: maximizing the input current; increasing the source bi-pole length proportional to offset \( r \), but satisfying the constraint that the length must be less than a quarter of the offset; choosing the order of the PRBS source time function to be large enough; and choosing the source bit rate to be proportional to \( r \). Our equipment is designed such that the land source is controlled from the recording truck. In land surveys suppression of noise is also a key requirement. By exploiting the symmetry of the bi-pole field of the source we are able to measure noise uncontaminated by the signal and use this measurement to reduce the noise in the transient EM measurements. We plan to illustrate the concepts presented here with both land and marine data.
Introduction

The multi-transient electromagnetic (MTEM) method was first presented by Wright et al. (2002). Robust field data acquisition systems, meeting oilfield industry standards, have now been developed to acquire MTEM data both onshore and offshore. The acquired digital data are monitored in real time enabling the acquisition parameters to be modified to maintain data quality and to minimise the time taken to acquire data of adequate quality. We describe the method and focus on new technology to maximise the signal-to-noise ratio.

Method

The essence of the Multi-Transient ElectroMagnetic (MTEM) method is that both the received voltage and the input current are measured simultaneously and the impulse response of the earth is recovered from these two measurements by deconvolution. A plan view of the common-source setup, for both the land and the marine cases is shown in Figure 1.

![Figure 1. Plan view of a typical MTEM source-receiver configuration, with a current bi-pole source and its two electrodes A and B, and a line of receivers in line with the source, measuring the potential between pairs of receiver electrodes, for instance C and D.](image)

A change in current, typically a step function or a finite-length signal such as a pseudo-random binary sequence (PRBS), is injected between the two source electrodes A and B and the time-varying voltage response between each pair of receiver electrodes, for instance C and D, is measured simultaneously. If the response reaches steady state before the next change in current is applied at the source, the full response has been measured and is the convolution

\[
v_{CD}(t) = \Delta x_s \Delta x_r i_{AB}(t) * g_{CD,AB}(t) + n_{CD}(t),
\]

where \(v_{CD}(t)\) is the voltage at the receiver, \(i_{AB}(t)\) is the current at the source, \(g_{CD,AB}(t)\) is the impulse response of the earth, the asterisk * denotes convolution, and \(n_{CD}(t)\) is the noise at the receiver. \(\Delta x_s\) and \(\Delta x_r\) are the in-line lengths of the source and receiver bi-poles, respectively.

![Figure 2](image)

(a) Measured source input current \(i_{AB}(t)\); (b) recovered earth impulse response, including the air wave \(g_{CD,AB}(t)\); (c) received voltage \(v_{CD}(t)\). The impulse response (b) is obtained from the measurements (a) and (c) by deconvolution. The time scale for (a) and (c) is 0 - 0.2 s, and for (b) is 0 – 0.03 s.
Figure 2 shows a typical measurement of the input current, the corresponding measured voltage at one receiver, and the impulse response obtained by deconvolving the received signal for the measured input signal. One impulse response is recovered for each source-receiver pair and its quality is controlled as the data are acquired. The complete set of impulse responses may be inverted for the subsurface resistivity.

**Maximising the Signal**

From experience we know that we need source-receiver offsets in the range \(2d \leq r \leq 4d\) to resolve a target at depth \(d\). It is also important to determine the resistivities above the target; that is, the earth model should be built from the top down. Therefore a range of offsets should be used out to 4 times the target depth. The in-line field of a bi-pole source approximates that of an equivalent dipole at offsets

\[
r \geq 4\Delta x_y .
\]  

(2)

We use a receiver spread of, typically, about 40 live channels, with all receiver bi-pole lengths \(\Delta x_y\) the same and laid end-to-end to give continuous coverage. For the land case the peg interval equals the receiver interval equals \(\Delta x_y\). We use the roll-along principle of the 2-D seismic reflection method to move the source and receivers along the line.

To understand the relationship between the data acquisition parameters and the earth impulse response, consider equation (1) with

\[
i_{AB}(t) = I\Delta t
\]  

(3)

in which \(\Delta t\) is very small compared with any time interval of interest in \(g_{CD,AB}(t)\). The result is

\[
v_{CD}(t) = I\Delta x_y \Delta x_y \Delta t g_{CD,AB}(t) + n_{CD}(t),
\]  

(4)

from which we see that the instantaneous signal-to-noise ratio is

\[
\frac{|I\Delta x_y \Delta x_y \Delta t g_{CD,AB}(t)|}{|n_{CD}(t)|}.
\]  

(5)

It is obvious that we must maximize \(I\), \(\Delta x_y\), \(\Delta x_y\), and \(\Delta t\). The product \(I\Delta x_y\) is known as the dipole moment. There are several ways to maximize the current, including (on land) the use of multiple stakes in parallel to reduce the source electrode contact resistance, using more powerful transmitters, and using transmitters in parallel. On land we use the maximum source bi-pole length possible consistent with the inequality (2), keeping the centre of the source the same for all common-source measurements, and putting the electrodes at peg positions.

We have considered making \(\Delta x_y\) a variable within a common source gather, but the roll-along principle is too valuable: it means all receivers are the same and both operations and maintenance are simple. We can always sum adjacent traces together in processing: this can increase the signal-to-noise ratio at the expense of lateral smearing, just as in seismic data processing.

The choice of \(\Delta t\) is not so simple. We note that we need to be able to separate the air wave – the initial peak in Figure 2(b) - from the earth impulse response. To do this we need about 10
samples between the arrival of the air wave and the arrival of the peak of the earth impulse response. The function $g_{CD:AB}(t)$ is unknown: it is what we are trying to find. We can find an approximation to it by considering the in-line impulse response at an offset $r$ to an impulsive dipole source at the surface of a half space,

$$g(\rho, r, \tau) = 5.65 \times 10^6 \frac{\rho^2}{r^5} \exp\left(-\frac{5}{2r}\right) r^{-\frac{5}{2}}, \quad (6)$$

in which $\rho$ is resistivity (ohm-m), $\tau = t/t_{\text{peak}}$ is dimensionless time, with $t_{\text{peak}}$ the time to the peak. Note the factor of $r^5$ in the dominator. It is clearly imperative to do everything to maximize signal strength with offset. This function is plotted in Figure 3 without the scaling factor before the exponential. This function is very similar to the earth impulse response of Figure 2(b). In Figure 3, the peak occurs at $\tau = 1$. In true time the peak occurs at

$$t_{\text{peak}} = \frac{\mu r^2}{10\rho}, \quad (7)$$

where the magnetic permeability $\mu = 4\pi \times 10^{-7}$ henry/m.

The shape of this function is invariant with both the resistivity $\rho$ and the offset $r$. These two parameters contribute only to the scaling factor in equation (3). Since $t_{\text{peak}}$ increases as $r^2$, it follows that the time scale of the function increases as $r^2$. Therefore, $\Delta t$ must increase as $r^2$.

We employ a PRBS as the source time function. A PRBS of order $n$ is a sequence of $N = 2^n - 1$ samples that switches between two levels, say $+I$ and $-I$, at pseudo-random integer multiples of a fixed time $\Delta t$. The PRBS has a frequency spectrum that is flat in the range $1/N\Delta t \leq f \leq 1/2\Delta t$. The deconvolution process compresses the PRBS into a single pulse of amplitude $NI$. Because of the presence of noise, the processing gain $G$ of the deconvolution process is less than $N$, but it is better than $\sqrt{N}$. That is, $\sqrt{N} < G < N$. The signal-to-noise ratio of the deconvolved impulse response increases by the factor $G$ as the order of the PRBS is increased. It is also possible to stack impulse responses. If the noise is random, the signal-
to-noise ratio improvement by stacking is $\sqrt{N}$. Increasing the order of the PRBS is more efficient than stacking.

**Reduction of the Noise**

We have developed a method to reduce the noise, the denominator in the expression (5). The dipole field of the source bi-pole is symmetric about its axis (over a 1-D earth): two points on a line perpendicular to the axis and on opposite sides and equidistant from the axis have the same potential. The potential difference between these two points in the source field is therefore zero. Any voltage between two such points must be pure noise; in a 3-D earth there may be a small component from the source. The cross-line noise measurement can be used to predict the correlated part of the noise on the in-line measurement, using the Wiener-Levinson method (Levinson, 1947). The predicted part can be subtracted from the measurement to improve the signal-to-noise ratio. The process is summarised in Figure 4.

![Figure 4](image)

Figure 4. (a) configuration of the cross-line noise measurement in relation to the in-line transient EM measurements. The cross-line noise is correlated with the in-line noise so there is a filter that predicts the correlated in-line noise component from the cross-line measurement. (b) result of applying this to a nearby in-line measurement: the black curve is the measurement and the red curve is the result of removing the predicted noise: the noise level is reduced by about a factor of 2.

**Conclusions**

The amplitude of the transient EM impulse response decays with offset $r$ as $1/r^5$. It is imperative to optimize the data acquisition parameters to maximize the signal. We employ a variety of techniques to do this: maximizing the input current $I$; increasing the source bi-pole length $\Delta x$, proportional to offset $r$ but satisfying the constraint (2); choosing the order of the PRBS source time function to be large enough; and choosing the source bit rate $1/\Delta t$ to be proportional to $1/r^2$. Our equipment is designed such that the land source is controlled from the recording truck. In land surveys suppression of noise is also a key requirement. By exploiting the symmetry of the bi-pole field of the source we are able to measure noise independent of the signal and use this measurement to reduce the noise in the transient EM measurements.

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**References**
