New Technology to Acquire, Process, and Interpret Transient EM Data

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Summary

We describe the multi-transient electromagnetic method and focus on new technology for real-time quality control and rapid interpretation of subsurface resistivities for both land and marine environments. The amplitude of the transient EM impulse response decays with offset r as $1/r^5$ and the corresponding step response decays as $1/r^3$. Parameters that must be optimized to maximize the signal include: input current; source bi-pole length; order of the pseudo-random binary sequence (PRBS) source time function; and source bit rate. By exploiting the symmetry of the bi-pole field of the source we are able to measure noise essentially uncontaminated by the signal and use this measurement to reduce the noise in the transient EM measurements. The variation of the arrival time of the peak of the earth impulse response with offset can be mapped to an apparent interval resistivity, creating a pseudo-resistivity section beneath the line. 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.

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.

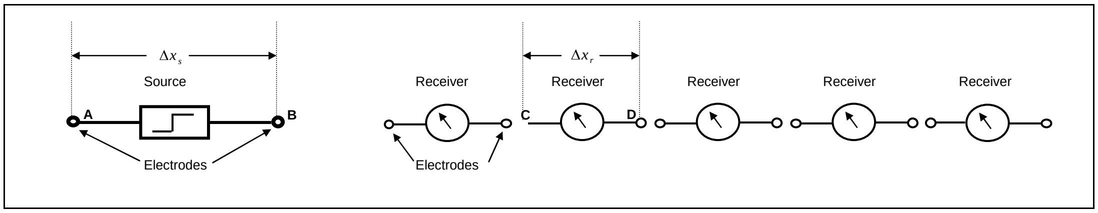


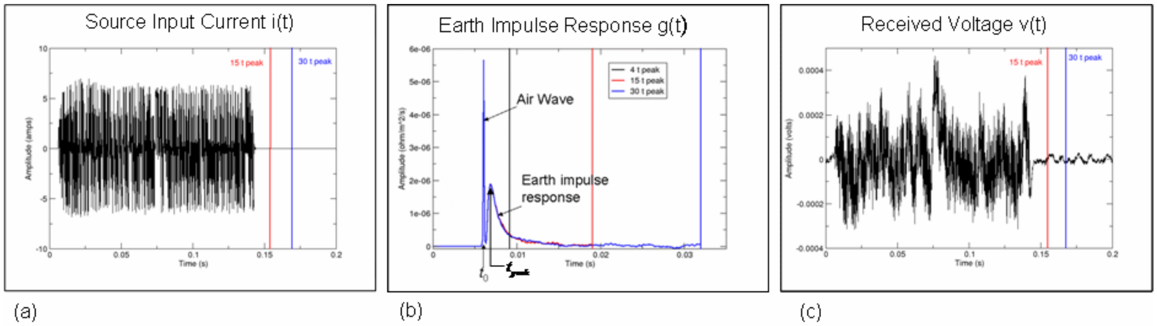
Figure 1. Plan view of a typical MTEM source-receiver configuration, with a current bi-pole source and its two electrodes A and B, and a line of receivers in line with the source, measuring the potential between pairs of receiver electrodes, for instance C and D.

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

$$v_{CD}(t) = \Delta x_s \Delta x_r i_{AB}(t) * g_{CD;AB}(t) + n_{CD}(t)\,, \qquad (1)$$

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. Δx_s and Δx_r are the in-line lengths of the source and receiver bi-poles, respectively.

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.



(a) (b) (c)

Figure 2. (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.

Maximising Signal-to-Noise Ratio

From experience we know we need source-receiver offsets in the range $2d \le r \le 4d$ 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

$$r \ge 4\Delta x_s \, . \tag{2}$$

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

Consider equation (1) with

$$i_{AB}(t) = I\Delta t \tag{3}$$

in which Δt is very small compared with any time interval of interest in $g_{CD;AB}(t)$. The result is

$$v_{CD}(t) = I\Delta x_s \Delta x_r \Delta t g_{CD;AB}(t) + n_{CD}(t) \, , \tag{4}$$

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

$$\frac{\left| I\Delta x_s \Delta x_r \Delta t g_{CD;AB}(t) \right|}{\left| n_{CD}(t) \right|} \, . \tag{5}$$

It is obvious that we must maximize I, Δx_s, Δx_r, and Δt. A key feature of our approach is to use a pseudo-random binary sequence (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 Δt. The PRBS has a frequency spectrum that is flat in the range $1/N\Delta t \le f \le 1/2\Delta t$. It can be shown that the source bit rate $1/\Delta t$ should decrease with offset as $1/r^2$; this maximizes Δt. The deconvolution process compresses the PRBS into a single pulse of amplitude NI.

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 3.

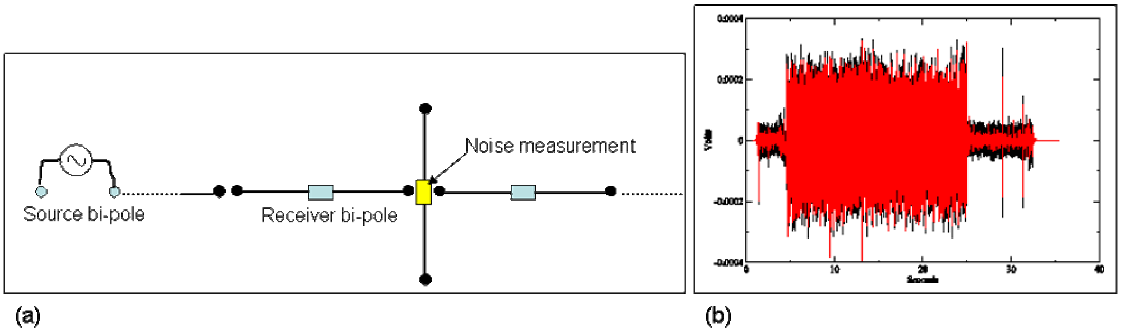


Figure 3. (a) configuration of the cross-line noise measurement in relation to the in-line transient EM measurements. The cross-line noise is correlated with the in-line noise so there is a filter that predicts the correlated in-line noise component from the cross-line measurement. (b) result of applying 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.

Rapid Mapping of Apparent Resistivity

Figure 2(b) shows an impulse response obtained from real data. It consists of an impulsive air wave followed by the impulse response of the earth. The peak of the earth impulse response occurs at time t_{peak}. For a half space of resistivity ρ ohm-m the time of the peak at offset *r* m is

$$t_{peak} = \frac{\mu r^2}{10\rho}, \tag{6}$$

where the magnetic permeability $\mu = 4\pi.10^{-7}$ henry/m. Taking the derivative of (6) and rearranging, yields

$$\rho = \frac{\mu r}{5}\left(\frac{dt_{peak}}{dr}\right)^{-1}. \tag{7}$$

We use this to obtain a pseudo-resistivity section, for instance, as shown in Figure 4. Features include a conductive layer in the near surface that ends abruptly at about CMP 1300 (labelled 1) and two resistive features, labelled (2) and (3), resolvable above a much more highly resistive basement, labelled 4.

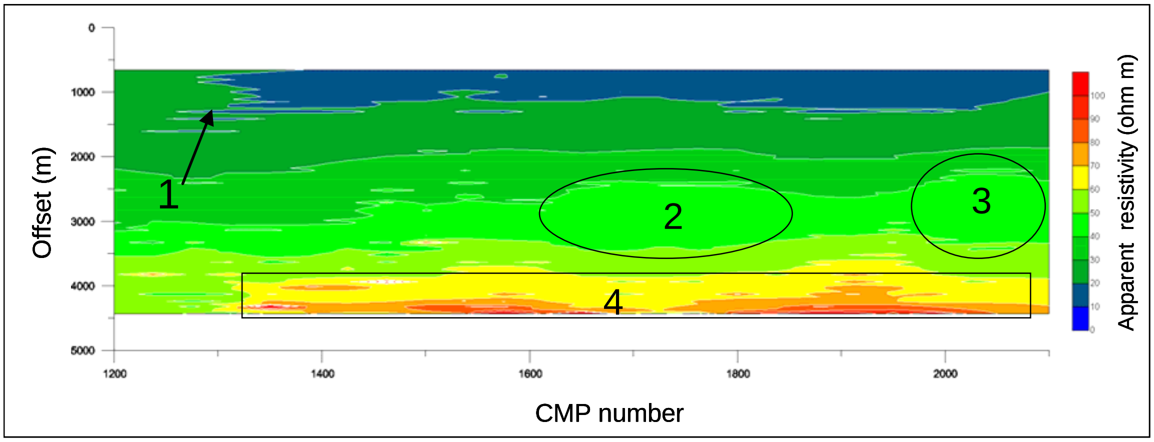


Figure 4. Apparent resistivity obtained using equation (7) and fitting an 8th order polynomial through the travel time data. Horizontal coordinate is source-receiver mid-point; vertical coordinate is source-receiver offset.

Conclusions

Real-time quality control of transient EM data allows the signal-to-noise ratio of the data and recovered impulse responses to be maximized by adjusting the data acquisition parameters. Mapping of the gradient of the peak of the earth impulse response to apparent interval resistivity yields a resistivity pseudo-section. Approximate depth may be obtained using skin-depth calculations.

References

Levinson, N., 1947, The Wiener RMS (root mean square) error criterion in filter design and prediction: Journal of Mathematics and Physics, **25**, 261-278.

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