Understanding the effect of diffusive propagation requires tools that are very different from those that are useful for understanding wave propagation. A convenient starting point is the analytical function that describes the impulse response of an earth half-space as a function of the in-line distance from the dipole source and the earth resistivity. This function has a form that is very similar to the measured earth impulse response and can be manipulated to allow us to optimize the data acquisition parameters. For the MTEM system, the input source time function must have a bandwidth that is approximately two decades, but which shifts inversely as the square of the source-receiver separation. Application of these principles to transient EM data recovers impulse responses from which the air wave can readily be separated.

The flow of electric current in the earth is determined by the bulk resistivities of the rocks, which are affected by the saturating fluids. For instance, hydrocarbon-saturated porous rocks are orders of magnitude more resistive than the same rocks saturated with brine. Hence, the exploration objective is to determine whether hydrocarbons are present by measuring the resistivity of geological formations. This paper reports on some recent developments in the application of the transient electromagnetic method for hydrocarbon exploration and production.

The transient electromagnetic (EM) method has been in use for many years for mineral exploration, but has not yet become a standard tool for hydrocarbon exploration and production. A standard work on the theory of transient EM was written by Kaufman and Keller (1983) who summarized 20 years of work done in Russia and North America. Strack’s 1992 book presented the state of the art of Long Offset Transient EM (LOTEM) surveying for land applications. Strack’s approach has been extended, particularly by the University of Cologne (e.g. Helwig, 2000). The application of transient EM for the marine environment was pioneered by the Physics Department at the University of Toronto (e.g. Chave et al., 1991), especially as applied to the search for shallow gas hydrate deposits in deep water (e.g. Schwalenberg et al.)

Anton Ziolkowski describes how his interest in the use of transient EM for hydrocarbon exploration and production developed initially through research and more recently with the formation of a company to commercialize the method.

The University of Edinburgh led a research project entitled Delineation and Monitoring of Oil Reservoirs using Seismic and Electromagnetic Methods, partially funded by the European Commission under the THERMIE programme, and also sponsored by Elf Enterprise Caledonia. Bruce Hobbs, with many years of experience in electromagnetic induction and magnetotellurics, was my colleague at Edinburgh. The university’s partners were Deutsche Montan Technologie, the University of Cologne, and Compagnie Générale de Géophysique. The six-year project finished in 1998, having collected two data sets over an underground gas storage reservoir in France, but without having achieved any significant results. The stacked responses we measured looked meaningless to Bruce and myself.

After the THERMIE project was finished, Bruce and I started a fresh project to analyze the data with our PhD student David Wright. We discovered timing errors of the order of 1 ms. Once these errors were eliminated, (Wright et al., 2002; Wright, 2003) approximate estimates of the earth impulse responses could be obtained. The data at last made sense to us. We formulated an improved acquisition and processing method which resulted in patents (e.g. US 6,914,433). The company MTEM company was formed as a spin-out of the University of Edinburgh in November 2004 to commercialize the technology.

Multi-transient electromagnetic 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 earth impulse response is recovered from these two measurements by deconvolution.

A plan view of the setup is shown in Figure 1(a). 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 is measured and recorded. The time-varying voltage response between each pair of receiver electrodes, for instance C and D, is also 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

Figure 1 (a) Plan view of a typical land MTEM source-receiver configuration, with a current bipole 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. (b) Sectional view of land MTEM setup showing bipole source and line of bipole receivers on the land surface, synchronized with GPS, and with real-time quality control; typical bipole source and receiver lengths are 100 m. (c) Sectional view of one possible marine MTEM setup showing bipole source on the sea floor and separate receiver cable with bipole receivers, synchronized with GPS, and with real-time quality control; typical bipole source and receiver lengths are 200 m.
in which \( v(x_C, x_D; x_A, x_B, t) \) is the measured voltage response, \( i(x_C, x_D; x_A, x_B, t) \) is the measured input current, the asterisk * denotes convolution, \( g(x_C, x_D; x_A, x_B, t) \) is the unknown earth impulse response, and \( n(x_C, x_D, t) \) is uncorrelated noise; \( x_A \) and \( x_B \) are the source electrode positions, \( x_C \) and \( x_D \) are the receiver electrode positions, \( \Delta x \) is the source bipole (a dipole with finite electrode separation) length, \( \Delta x \) is the receiver bipole length, and \( t \) is time. Note that the convolution is an integral over time, so the impulse response \( g(x_C, x_D; x_A, x_B, t) \) has SI units of ohms/m²/s. The source current and received voltage are recorded with identical devices, whose effects cancel in the subsequent deconvolution.

The total circuit impedance is in general complex and therefore the source current is in general out of phase with the applied voltage. The response in equation (1) depends on the injected current, and that is what we measure: the complex impedance effects are automatically taken into account.

For the land case a schematic cross-section of the setup is shown in Figure 1(b) and for the marine case one possible configuration is shown in Figure 1(c). In both cases the source and receiver electrodes are in a straight line. Onshore the electrode positions, or pegs, are known from surveying. Offshore acoustic transponders are attached to the cable at the electrode positions and are positioned using a commercial underwater acoustic positioning system. The whole setup can be moved along to continue the line, very similar to the 2D seismic reflection method. It is necessary to have offsets up to four times the depth of the target in order to resolve both its top and bottom. Normally we use about 40 receiver channels of equal spacing. This choice is somewhat arbitrary, but it has been found to give good lateral resolution equal to about half the receiver spacing. For a target at 1 km depth, the receiver bipole length would be 100 m and the receiver spread would be 4 km long. Onshore a roll-along system similar to the seismic reflection method is used.

Two special features of the method are precise timing and real-time quality control. The source and receivers are continuously synchronised with GPS, which permits very precise timing, thus avoiding the synchronization problems of the equipment used in the THERMIE project. The data from the source measurement and from all the receivers are transmitted to the recording truck (onshore) or to the receiver vessel (offshore) for real-time analysis. Thus the signal-to-noise ratio of

Figure 2 Screen grab of a typical marine record: source-receiver offset increases from bottom of the screen to the top. Only 16 of the 30 receivers are in the water; the rest of the cable is on the vessel.

© 2007 EAGE
The data can be checked in real time. Figure 2 shows a screen grab of marine data showing good signal-to-noise ratio. The convolution in equation (1) applies because the earth system is linear; that is, Maxwell’s equations are linear. In the frequency domain the convolution becomes a multiplication, so deconvolution becomes a division. A typical land data example of the measured current input, measured voltage output at one receiver, and the result of deconvolution to obtain the earth impulse response for the source-receiver pair, are shown in Figure 3, parts (a), (b), and (c), respectively. In the impulse response there is an initial impulse at the time break which is commonly called the ‘air wave’: this is a pure inductive effect, caused by the magnetic field generated by the current at the electric dipole source, and is seen instantaneously on all receivers. This is followed by the earth impulse response.

The noise consists of random noise plus non-random cultural noise from power lines and railways that is normally orders of magnitude greater than the random component. The noise can be reduced by a variety of processes, including stacking. The fundamental frequency and harmonics of the cultural noise are often not constant and the phase of each of these frequencies also varies in an apparently random way.

Pseudo-random binary sequences (PRBSs) have been used by electrical engineers since at least the 1950s (e.g. Zierler, 1959) and were well established by the 1960s (e.g. Golomb, 1967). A PRBS is a sequence that switches between two levels, say +1 and -1, at a pseudo-random integer multiple of a chosen time interval \( t \). (At each time step it can be considered that a coin is tossed with, for example, heads meaning +1 and tails meaning -1). Conventionally the sequence consists of continuous series of identical cycles each of length \( N = 2^n - 1 \) samples where \( n \) is an integer known as the order of the PRBS. Duncan et al. (1980) proposed using a PRBS as the input signal in EM. The autocorrelation function of the sequence consists of a series of peaks separated by the cycle period \( Nt \). Duncan et al. transmitted their PRBS sequence continuously and cross-correlated the received signals with the known PRBS sequence. Helwig (2000) used a sequence of a few cycles and also correlated the data with the known PRBS.

As discussed by Wright et al. (2006), we use a single cycle and deconvolve with the measured input current. A single cycle has a flat spectrum in the frequency range

\[
\frac{1}{N\Delta t} \leq f \leq \frac{1}{2\Delta t}.
\]

By choosing \( \Delta t \) and \( n \) the spectrum of the input can be flat in any desired frequency range. The PRBS in transient EM serves the same purpose as the Vibroseis sweep in
seismic reflection. The PRBS is convenient for use in EM because the power delivered is constant for the duration of the sequence and the switching time of the current is of the order of a microsecond - much shorter than the time intervals of interest.

**Maximising signal**

For the purposes of this discussion it is convenient to simplify equation (1) to the following:

\[ v(t) = \Delta x, \Delta t, j(t) * g(t) + n(t), \]

(3)

From which we recognize that the signal-to-noise ratio is

\[ \frac{[\text{Signal}]}{[\text{Noise}]} = \frac{\Delta x, \Delta t, j(t) * g(t)}{|n(t)|}. \]

Equation (4) states that the peak of the earth impulse response arrives at a time proportional to \( r^2 \). Therefore \( \Delta t \) should be proportional to \( r^2 \). If \( \Delta x, \) and \( \Delta t \) are scaled in proportion to \( r \), the signal amplitude decays approximately as \( 1/r \), which is not so bad.

The other basic ingredient required for good signal-to-noise ratio is time. From equation (6) it can be seen that the impulse response of the earth is infinitely long: it never decays to zero. Equally, the step response never reaches a steady-state value. However, in reality there comes a time when the impulse response is too small to measure and we can see this in Figure 3(c), where the late signal amplitude is too small to see beneath the noise. For all practical purposes, therefore, the impulse response is of finite duration. From Figure 4, it can be seen that the bulk of the dimensionless response is over by \( \tau = 10 \), or by a true time of 10\( t_{\text{peak}} \). Given the sampling interval defined by equation (9), it is clear that 100 samples are adequate to describe the response at any offset and that the duration of the full response is proportional to \( r^3 \). Figure 5 shows how the duration of the impulse response varies with offset.

**The earth impulse response**

Consider the response of a half-space. The step response of a half-space of resistivity \( \rho \) ohm-m was derived by Weir (1980). Wilson (1997) differentiated it to obtain the impulse response

\[ g(\rho, r, t) = \frac{\rho}{8\pi\sqrt{\pi}} \exp \left( -\frac{r^2}{4\pi t} \right) \frac{r^2}{2} \text{ ohms/m}^2/\text{s}, \]

(6)

in which \( r \) is source-receiver offset in metres, \( c^2 = \rho/\mu \), with magnetic permeability \( \mu = 4\pi \times 10^{-7} \) henry/m and \( t \) is time. This function has a peak at time

\[ t_{\text{peak}} = \frac{\mu r^2}{10\rho} \text{ s}. \]

Substituting \( \tau = t/t_{\text{peak}} \) into the expression in equation (6) gives the result

\[ g(\rho, r, \tau) = 5.65 \times 10^6 \frac{\mu r^2}{r^5} \exp \left( -\frac{r^2}{2\tau} \right) \frac{r^2}{2}. \]

(8)

This function is shown in Figure 4 without the scale factor before the exponential. It is very similar in shape to the real earth impulse response of Figure 3(c) and thus gives an analytical approximation to the real data.

To separate the earth impulse response from the air wave - see Figure 3(c) - about 10 samples are required. That is, we can define the sample interval to be

\[ \Delta t = \frac{t_{\text{peak}}}{10}. \]

(9)

Equation (7) states that the peak of the earth impulse response arrives at a time proportional to \( r^2 \). Therefore \( \Delta t \) should be proportional to \( r^2 \). If \( \Delta x, \) and \( \Delta t \) are scaled in proportion to \( r \), the signal amplitude decays approximately as \( 1/r \), which is not so bad.

**Signal-to-noise ratio and processing gain**

One way to increase the signal-to-noise ratio is to repeat the experiment, say \( m \) times, and to stack the recovered impulse responses. If the noise is random, as it appears to be in Figure 3(c), the increase in signal-to-noise ratio is \( \sqrt{m} \). Another approach is to increase the length of the PRBS: this is better than stacking because it adds less noise to the result for the same increase in signal. The time to acquire the data is PRBS time plus the time to record the full impulse response - the ‘listening time’ in the Vibroseis analogy. For short PRBSs the processing gain is almost equal to \( N \), the number of samples in the PRBS. As the PRBS gets longer, more noise is added to the measurement for the same ‘listening time’ and the signal-to-noise ratio increases less rapidly, tending to \( \sqrt{N} \) for very large \( N \).

For each source-receiver pair an impulse response is recovered. This can be integrated to yield the step response.
Full waveform inversion can be applied to either the impulse responses or the step responses to recover subsurface resistivities (Ziolkowski et al., 2007).

**MTEM and conventional CSEM**

In recent years many conventional Controlled-Source Electromagnetic (CSEM) surveys have been conducted offshore, particularly in deep water, with the objective of minimizing the risk of drilling dry wells (e.g. Smit et al., 2006). In late 2005 the MTEM method was tested in shallow water in the Firth of Forth (Ziolkowski et al., 2006). The test was successful and led to the development of equipment for deployment on the continental shelf. Conventional CSEM uses remote independent receiver units on the sea floor, which are powered by batteries and have clocks to keep track of time. The clocks are synchronized with GPS before the units are sent to the sea floor. The receivers normally measure the magnetic field, two horizontal components of the electric field, and sometimes the vertical component of the electric field. Mostly the in-line electric field is used in the analysis: this has to be constructed from the two horizontal components. Srnka et al. (2006) give an excellent description of the method, allowing the data acquisition parameters to be deduced. The source is towed approximately 50 m above the sea floor at a speed of about 1.5 knots, or about 46 m per minute. The source signal is traditionally a continuous square wave, although novel improvements have been made in recent years. That is, the receivers essentially measure the steady-state response to a continuous periodic signal. The period of the traditional square wave is normally 1–4 s. The continuous movement of the source prevents the response from being exactly steady-state and there is a Doppler effect, which is normally considered to be negligible. Currently

**Figure 4** Impulse response of a half-space plotted as a function of dimensionless time $\tau = t/t_{peak}$. This function is very similar in shape to the earth impulse response measured in real data: see Figure 2(c). To obtain the correct function for a particular combination of resistivity $\rho$ ohm-m and source-receiver offset $r$ m, the amplitude scale is multiplied by $5.65 \times 10^6 \rho^2/r$ and the time scale by $4\pi10^4 t_{peak}/\rho$; the result is the impulse response in ohms/m$^2$/s.

**Figure 5** Duration of impulse response as a function of offset for a 1 ohm-m half-space. The blue curve shows the time to $t_{peak}$ and the red curve shows the time to $10t_{peak}$, when the bulk of the response is over. Ideally, $t_{peak} = 10\Delta t$; therefore the source bit rate $1/\Delta t = 10/t_{peak}$ should be adjusted for offset to maximize the voltage response at the receiver.

<table>
<thead>
<tr>
<th>MTEM</th>
<th>Conventional CSEM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time – transient input</td>
<td>Time – continuous input</td>
</tr>
<tr>
<td><img src="image1" alt="MTEM time-transient input" /></td>
<td><img src="image2" alt="Conventional CSEM time-continuous input" /></td>
</tr>
</tbody>
</table>

**Figure 6** MTEM and conventional CSEM input signals in the time domain and in the frequency domain. The MTEM system typically uses a PRBS of order $n = 12$ and has $N = 2^n - 1 = 4095$ samples; its frequency bandwidth is flat between $f_1 = 1/\Delta t$ and $f_2 = 1/2\Delta t$. The actual values of these frequencies depend on the value of $\Delta t$, which is offset-dependent, as illustrated in Figure 5. The ratio of highest to lowest frequency is $f_2/f_1$ more than two decades for a PRBS of order 11 or greater.
there is no real-time quality control. Data quality is unknown until the receiver units are brought back to the sea surface and the data unloaded. The received data are chopped up into windows approximately 1-2 minutes in length. For a 4 s square-wave period this yields the response to 15-30 cycles of source input signal. By comparison, MTEM data can be seen in real time, and the time required to acquire impulse responses with good signal-to-noise ratio can be adjusted to the circumstances.

Table 1 compares marine MTEM and conventional CSEM data acquisition parameters. Figure 6 compares the MTEM and conventional CSEM signals in the time domain and the frequency domain. The bandwidth of the MTEM signal is adjusted to match the bandwidth of the impulse response, as discussed above. The conventional CSEM signal has a fundamental frequency plus odd harmonics. The frequency domain comparison is perhaps more easily appreciated by considering the keyboard illustration of Figure 7. Since the spectrum of conventional CSEM data is incomplete, it is impossible to construct the impulse response from the data.

Marine air wave
A few words should be said about the marine air wave, which is a known problem in conventional CSEM: the continuous received signal from the earth is continuously contaminated by the signal arriving through the water, including the pure inductive effect in air. If the water is deep enough, the contaminating signal or ‘air wave’ can be ignored, because of the attenuation in the water. In shallow water the air wave problem for conventional CSEM is a challenge and considerable effort has been devoted to the development of methods to tackle it, including up/down wavefield separation (e.g. Amundsen, 2003).

For transient EM in shallow water the impulse response can be decomposed into two major components: the air wave and the earth impulse response. The characteristics of these two components are different and the differences may be exploited to separate the earth impulse response from the total response. The concept is illustrated in Figure 8, where a simple layer over a half-space model is shown. The decomposition is model-dependent and not every case is as clear as this example.

Conclusions
The use of transient EM for hydrocarbon exploration and production is in its infancy. Understanding the effect of diffusive propagation requires tools that are very different.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Conventional CSEM</th>
<th>Marine MTEM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Source bipole length</td>
<td>200-300 m</td>
<td>200-300 m</td>
</tr>
<tr>
<td>Source bipole interval</td>
<td>~100 m</td>
<td>200 m</td>
</tr>
<tr>
<td>Receiver bipole length</td>
<td>~8 m</td>
<td>200 m</td>
</tr>
<tr>
<td>Receiver interval</td>
<td>~1 km</td>
<td>200 m</td>
</tr>
<tr>
<td>Source current amplitude</td>
<td>~1,000 A</td>
<td>~1,000 A</td>
</tr>
</tbody>
</table>

Table 1 Comparison of data acquisition parameters of conventional CSEM and marine MTEM methods.
from those useful for understanding wave propagation. A convenient starting point is the analytical function that describes the impulse response of an earth half-space as a function of the in-line distance from the dipole source and the earth resistivity. This function has a form very similar to the measured earth impulse response and can be manipulated to allow us to optimize the data acquisition parameters. For the MTEM system, the input source time function must have a bandwidth of approximately two decades, but which shifts inversely as the square of the source-receiver separation. Application of these principles to transient EM data recovers impulse responses from which the air wave can readily be separated.

Acknowledgements
I thank Andrew McBarnet for inviting me to submit this paper and I thank the anonymous reviewers for their helpful comments, criticisms, and suggestions. I thank Bruce Hobbs, David Wright, and Guy Hall for many interesting discussions. The ideas presented here have been turned into hardware, software, operations, and real data by my colleagues at MTEM. Optimization of acquisition parameters is the subject of a MTEM patent application.

References