MTEM: The Next Step in EM Surveying

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Summary

The MTEM (Multi-Transient Electro-Magnetic) technique has been developed over the last decade at the University of Edinburgh in Scotland. The MTEM technique, in common with other surface EM methods, detects resistors at depth below the earth's surface. Sediments saturated with hydrocarbons are relatively resistive compared with those saturated with brine; processing and inversion of the MTEM data delineates the potential reserves.

Introduction

The MTEM technique applied in a land setting is shown in figure 1. A pair of source electrodes is pushed into the earth, typically 100m apart. A line of receiver electrodes is similarly placed at offsets typically between 1 and 5km, with the separation of electrodes being similar to that of the source electrodes. The actual separation of electrodes and the offsets are chosen according to the target.

A transient current, typically a step change in voltage, is input into the earth. This is easily achieved by applying 1000V between the electrodes and instantly flipping the polarity. The induced electric field diffuses through the earth and the earth's response is sampled as voltage differences between the receiver electrodes and the data recorded.

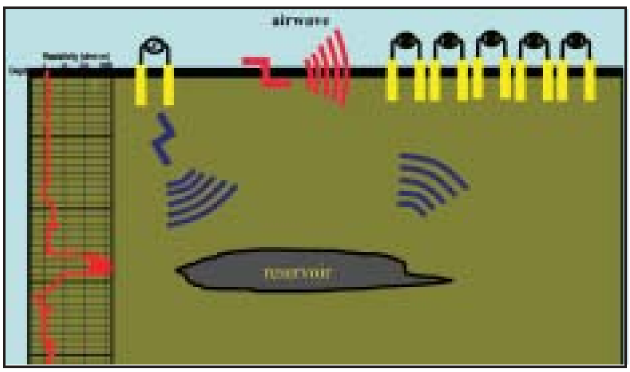

Fig 1 : MTEM applied on land. The well log on the left shows the expected resisitvity profile that will be estimated from the surface using MTEM.

MTEM theory

$$E(X_s,X_r,t) = S(X_s,X_r,t) * G(X_s,X_r,t) + N(X_r,t) \quad (1)$$

Equation 1 is the basis of the MTEM method. The voltage $E(X_s,X_r,t)$ from the electric field received at position X_r from a source at position xs is obtained from the convolution of the system function S(xr, xs, t) with the earth response function G(xr, xs, t), plus the uncorrelated noise N(xr, t). The system function contains the source function and the filter response of the acquisition system, and must be measured for every shot. Deconvolution of the known S from the measured voltage E gives the earth impulse response G.

This equation is the basis of the seismic method, and we use its properties in many similar ways. For example, we can select the source function to be such that sufficient signal to noise is achieved in the data. By taking into consideration the absorption of relatively high frequency energy, we may limit our expectations and put more effort to lower frequencies in the time available to make a shot. The MTEM method includes the use of swept sine waves and pseudo random binary sequences as the source function. The former of these is well known from land seismic and much theory on their application has been developed. The second is familiar from signal transmission technology used where noise is an issue.

In order to understand MTEM data we consider the response of a uniform half-space (of constant resistivity) to instantaneous change from 0 to 1000V between the source-electrodes. Figure 2 shows the modelled response at between one receiver electrode pair at an offset of 1km from the source. The vertical arrival at 0.00 seconds is the energy which travels across the surface of the earth close to the speed of light in air and is known as the airwave. Then the energy which has traveled through the earth arrives, with asymptotes to a value twice that of the airwave.

As stated earlier, a key component of the MTEM method is that the source signature is known to vary from shot to shot and must be measured in the field for every shot, and that variation must be compensated for in processing. In this case, the source function is a perfect

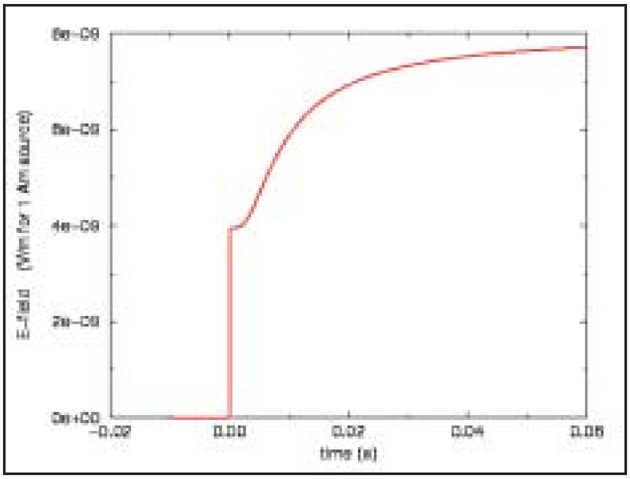

Fig 2 : The modelled MTEM response from the input of instantaneous step from 0 to 1000V.

step and deconvolution of the step is mathematically the same differentiating the received data, and multiplying by a suitable scale factor. Deconvolution of the step from the receiver data gives the impulse response shown in figure 3.

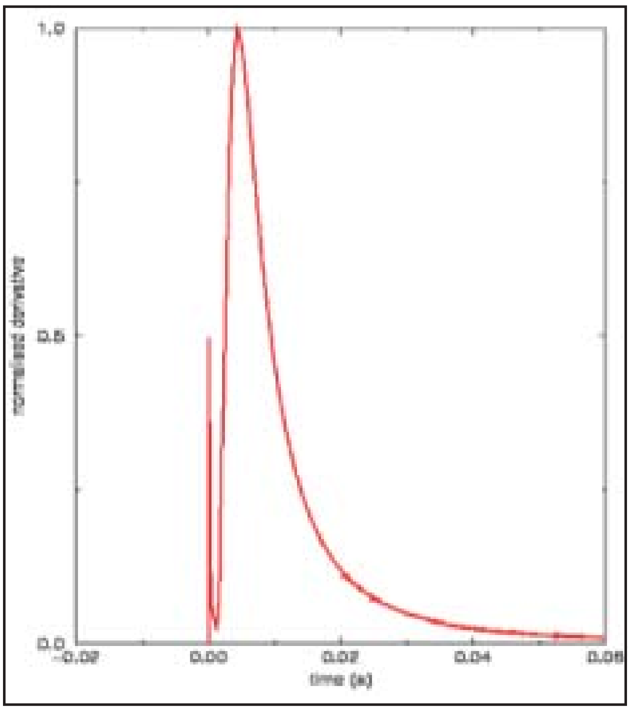

Fig 3 : The deconvolution of the system function from the synthetic data shown in figure 2.

The spike at 0.0 is the airwave whilst the response from the earth below rises to a peak then asymptotes back to 0. The airwave is the arrival which flashes across the surface of the earth at close to the speed of light in the air, whilst the later "bump" is the energy which has diffused through the earth. The height of this second peak and its arrival time are a function of the resistivity of the half space. The more resistive the earth, the higher and earlier the peak will be.

We use this idea to consider whether a target will be responsive to the MTEM method. Figure 4 shows synthetic data which indicates what can be expected for a particular survey. Here the data has been band limited, which is what we will see in practice.

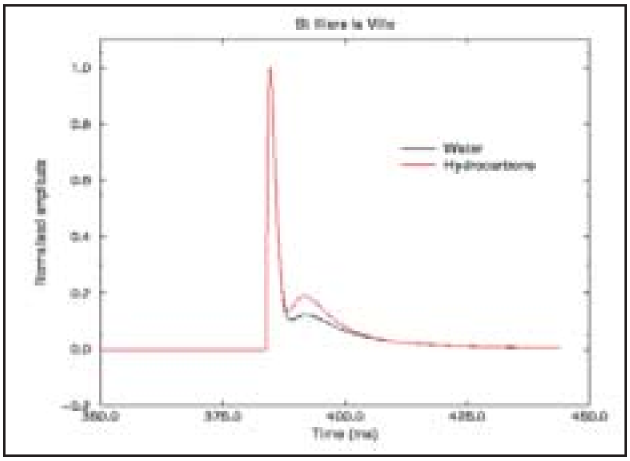

Fig 4 : Synthetic earth responses over a reservoir filled with hydrocarbons and filled with brine.

When the reservoir is relatively highly saturated with hydrocarbon and not brine, the relatively high resistivity has the effect of pushing more energy back to the surface at an earlier time. If the change in height of the second arrival and/or the change in time of arrival are significant then the chance of success is high.

In practice the challenge is to achieve sufficient signal to noise ratio in the data. In the presence of power lines or other sources of electromagnetic noise, vertical stacking must be performed to increase the signal strength. Recent advances include the use of pseudo random binary sequences as a sophisticated form of vertical stacking.

MTEM in practice

As shown in figure 1, MTEM data is acquired in a very similar way to land seismic data, and similar considerations with respect to illumination and signal to noise must be made in order to design the survey. Parameters include the source function, receiver and source electrode separations, listening time, sample rate, number of live channels and minimum and maximum source-receiver offset.

Figure 5 shows the acquisition geometry and

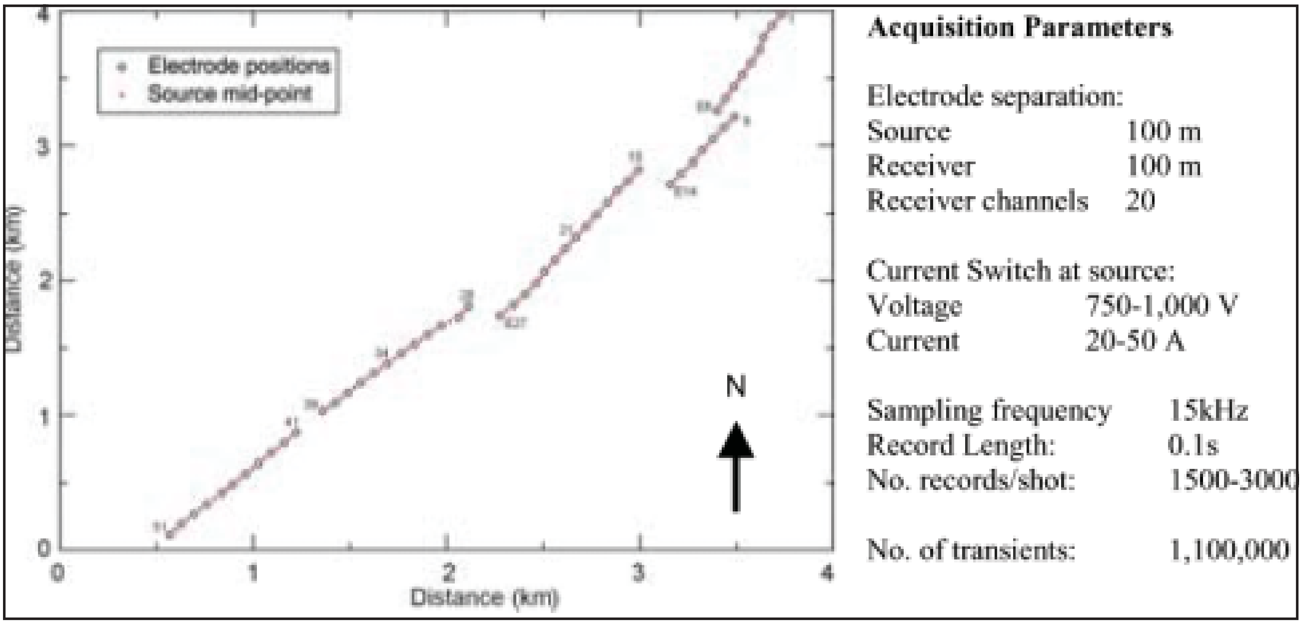

Fig 5 : Acqustion parameters and geometry for an MTEM line.

parameters used for a particular survey. Some compromises have been made with the geometry because of the presence of roads and surface installations. Such compromises must be understood and compensated for in the processing and inversion steps.

Following data acquisition, processing is performed. Figure 6 shows a common offset section, where we plot a set of traces with the same source-receiver separation. The gaps in the data are where access was restricted because of the presence of well-heads or similar equipment. These plots can be used as a quick-look tool for determining the presence or absence of hydrocarbons. The airwave is seen as the first arrival, followed by the energy coming back from the earth. As discussed above, we should expect an earlier arrival with increased amplitude if a resistor is present. We see clearly the increased amplitude in the centre of the section, indicating the presence of a subsurface resistor below these stations.

An additional approach is to analyze the arrival time of the impulse response, in a process similar to that of velocity analysis used in seismic processing. To enable accurate picking of the pick, we plot a shot-record in log-time. This transformation has the effect of removing the dispersion of the earth's impulse response, and dispersing the airwave. An example is shown in figure 7.

The arrival time of the peak of the earth's impulse response for each source-receiver pair in the dataset is then easily determined. In common with the practice in seismic processing we use expressions arrival time and travel-time interchangeably.

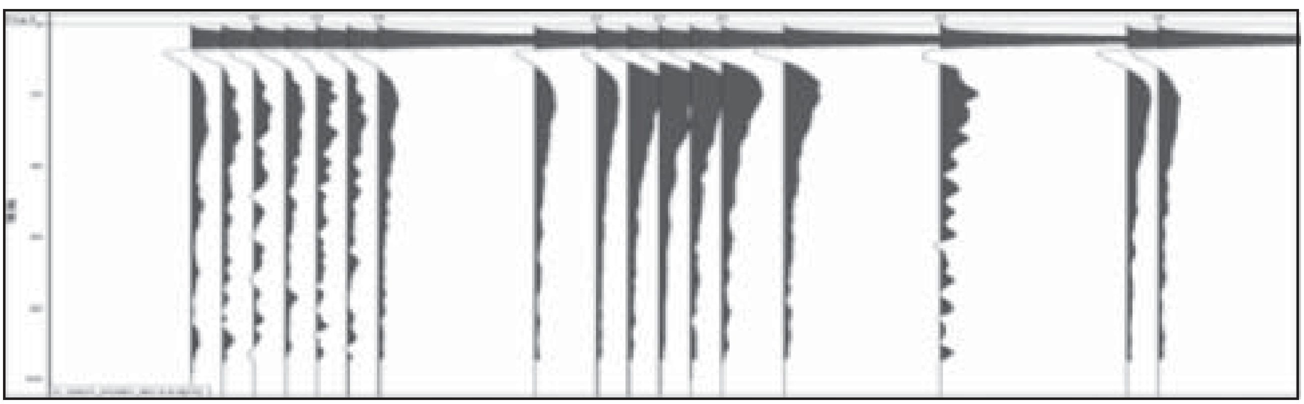

Fig 6 : A common-offset section. The vertical axis is time, and the horizontal is station number.

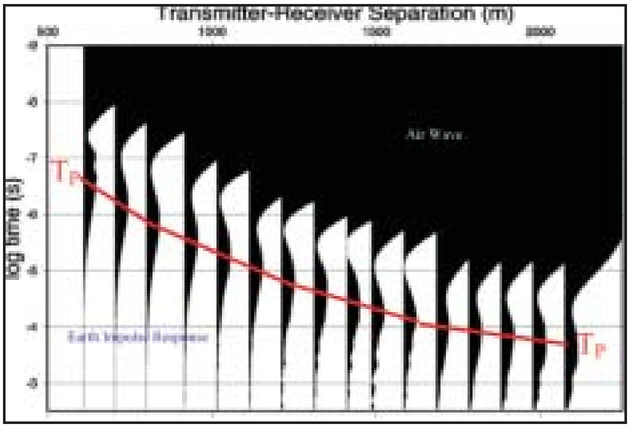

Fig 7 : A shot gather plotted in log-time.

To transform the travel-times to resistivity we consider the passage of an electro-magnetic wave through a half-space with constant resistivity. The travel-time is given by the equation:

$$T_p = kd^2/\rho \qquad (2)$$

where d is the source-receiver separation,ñ is the resistivity and k is a constant. The travel-times for a range of uniform half spaces are plotted in figure 8. It can be seen clearly that arrival time decreases as the resistivity increases and increases with the square of the offset.

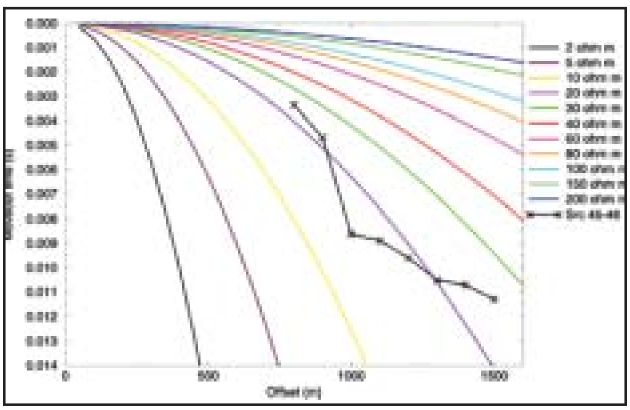

Fig 8 : Travel-time to restivity mapping.

Superimposed on the chart are the arrival times of the first peak for a single source across all the offsets. The equivalent half-space resistivity of each segment is given by the gradient between measured points, so for the first two points the equivalent resistivity is approximately 3 ohm m whereas for the last two points the equivalent resistivity is approx 80 ohm m. i.e. simply pick up the segment and move it to the corresponding curve. On the example shown there is a sudden change in gradient at the third point which indicates the onset of the resistor at an offset of approximately 1000m.

Performing this procedure on the travel-times for all source-receiver pairs gives a set of (ñ , d) pairs for each station. To plot a section of equivalent-resistivity against depth we use a heuristic model that the depth of penetration is approximately the offset divided by 2.5.

Figure 9 shows a plot of equivalent (pseudo) resistivity against (pseudo) depth. Also shown is the top of the gas storage reservoir provided by the client. The mismatch in depth is caused by the error in using the heuristic depth-offset relationship. However, the process to produce such a section is rapid and may be performed in the field. We see below that this pseudo section is similar in character to that from full inversion, and hence is a useful quick look tool.

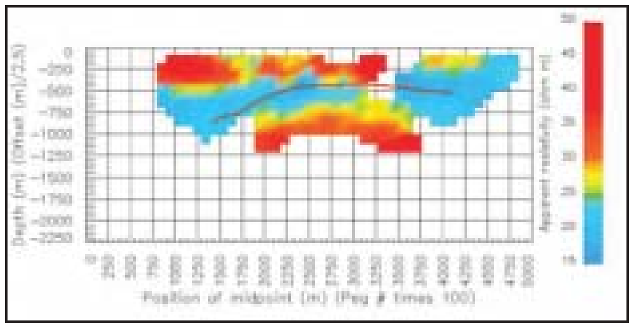

Fig 9 : Pseudo-resistivty against pseudo-depth calculated from travel-times.

The most accurate answer form an MTEM survey is achieved by performing full waveform inversion. Computer modelling is used to generate synthetic data from a synthetic model, and the model adjusted until sufficient match between the real data and the synthetic data is achieved.

Currently, we are using a 1D Occam inversion based on a layered model with fixed boundaries. The parameters for variation are the resistivities of the layers, and we typically use 20 layers over a uniform halfspace. The starting model is a uniform halfspace and convergence occurs in around four to eight iterations. Inversion is performed on a suite of step response traces within a common mid-point gather, and each gather is inverted independently. The individual inversions are plotted side-by-side, to produce a resistivity section. A method for compensating for near-surface anomalies is also included.

Figure 10 shows the inversion of a dataset shot over a gas-storage reservoir in France. The client provided interpretation, which was made using other datasets, matches the inversion closely.

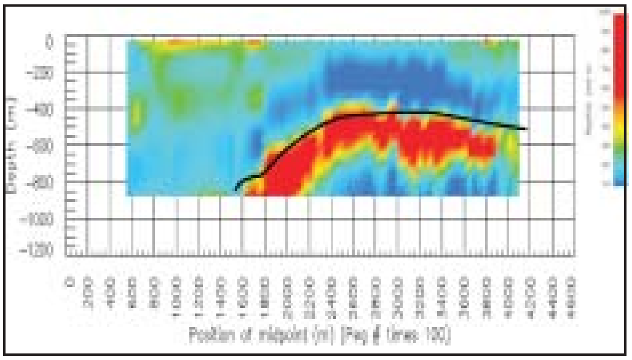

Fig 10 : Full waveform 1D inversion.

Conclusions

The MTEM method has been developed by applying the techniques and knowledge to EM theory. We have used the concept that a linear earth allows us to use a convolution approach where we can design an appropriate source signature to achieve optimal illumination and signal to noise. By measuring and deconvolving the actual input we recover the impulse response of the earth.

We have shown two simple processing techniques which can be used rapidly in the field to determine the presence or absence of resistors at depth. The first is simply to plot the common offset sections. The earth's impulse response will be larger in those traces where a sub-surface resistor is present. The second method is use a mapping of travel time of the impulse response to resistivity of the equivalent halfspace, and a heuristic relationship between depth of penetration and offset.

Finally, full waveform inversion is used to determine the most accurate estimate of the sub-surface resistivity section. In this example a 1D Occam inversion method has been used.

Acknowledgements

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