The Superiority of M-sequence in MTEM Data Processing: a Field Contrast Experiment

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Abstract. The two commonly used sources in the multi-transient electromagnetic (MTEM) method, square-wave and m-sequence, have different anti-noise performance which had been theoretically discussed in previous studies. But the onshore contrast experiment had rarely been conducted. An onshore experiment was performed over the Laizhou gold deposit, China, and the results obtained with two different source signatures were compared and analyzed. The signals had the same amplitude ~40 A and about the same length, so they had approximately equal energy. Two data sets with extremely different signal-to-noise ratio (SNR) were acquired with different source-receiver offsets. The skin-depth of two sources was analyzed; the recovered earth impulse responses indicated that m-sequence can compensate the high-frequency attenuation handsomely and the powerline noise suppression of m-sequence is 22 dB greater than the suppression of the square-wave, which demonstrated the superiority of m-sequence in MTEM data processing.

1. Introduction
The multi-transient electromagnetic (MTEM) is a time-domain electromagnetic method developed by Wright [1], which had been widely used in onshore and offshore exploration [2, 3, 4, 5]. The essence of MTEM 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.

Two sources were used in the MTEM: square-wave and m-sequence [6]. Both sources switch between two levels follow a clock pulse signal with a fixed frequency; the difference is that square-wave switches periodically but m-sequence switches randomly [7, 8]. Compared with the square-wave, the superiorities of m-sequence for noise reduction had been theoretically discussed in previous studies and can be summarized in two viewpoints: (a) m-sequence can stimulate all the modals of the earth system continuously due to its wide frequency spectrum; therefore, the identified earth impulse response consists of rich frequency information [9]; (b) m-sequence has excellent autocorrelation properties and the signal to noise ratio (SNR) of the identified results can be increased by a correlation operation [6]. But field contrast experiments have rarely been conducted.

In order to compare the two sources; we conducted an MTEM experiment in the Laizhou gold deposit with equal energy square-wave and m-sequence sources for the same MTEM survey station. The experimental results showed that the m-sequence achieve better powerline noise reduction.

2. The MTEM method
The earth impulse response is identified by the MTEM method which uses coded current passed via
grounded dipole electrodes to probe the subsurface geology [1]. The earth voltage response is measured simultaneously with multiple sets of dipole receivers which are laid collinear to the current dipole and extends from few hundreds of meters to several kilometers (figure 1). The measured voltage response can be expressed as the convolution:

\[ r(t) = s(t) * g(t) + n(t) \]  

where \( r(t) \) is the voltage response, \( s(t) \) is the source current, \( g(t) \) is the unknown earth impulse response and \( n(t) \) is the introduced noise at receiver, including random noise and cultural noise.

**Figure 1. The MTEM setup.**

Recovering the earth impulse response allows the data to be processed in a manner similar to seismic data processing, called deconvolution. The objective of deconvolution is to replace \( s(t) \) with an impulse.

Transform equation 1 from the time domain to the frequency domain:

\[ R(\omega) = S(\omega)G(\omega) + N(\omega) \]  

and the convolution becomes a multiplication, we multiply by

\[ F(\omega) = \frac{S'(\omega)}{|S(\omega)|^2 + \varepsilon} \approx \frac{1}{S(\omega)} \]  

in which the asterisk denotes complex conjugate. The denominator is real, and the constant \( \varepsilon \) prevents division by zero where \( S(\omega) \) is small.

Multiplying equation 2 by \( F(\omega) \) and \( R(\omega) \) gives

\[ F(\omega)R(\omega) = F(\omega)S(\omega)G(\omega) + F(\omega)N(\omega) \]  

\[ \approx G(\omega) + F(\omega)N(\omega) \]  

Finally, transforming back to the time domain gives

\[ f(t) * r(t) = f(t) * s(t) * g(t) + f(t) * n(t) \]  

\[ \approx g(t) + f(t) * n(t) \]  

Comparing equations 1 and 5, we see that the objective of replacing \( s(t) \) by an impulse has almost been achieved; but clearly, the identified result is not pure due to the noise component \( f(t) * n(t) \). Considering that \( g(t) \) is an objective existence which is invariant, the noise component \( f(t) * n(t) \) should be minimized to get a higher SNR, that is, the identification process need to achieve powerful noise reduction.

The MTEM method was illustrated on a 30 ohm-m half-space model which a 25-m-thick layer is inserted with a resistivity that takes a value of 400 ohm-m if hydrocarbons are present and 30 ohm-m if they are absent, as shown in figure 2.
Figure 2. The half-space model.

Figure 3 shows the corresponding impulse responses obtained by deconvolution for a switch-on step, which shows a rise to a peak at about 4.2 ms (half-space response), followed by an asymptotic decay to zero. The influence of the thin resistive layer on the response is shown as the red curve, which has a significantly higher peak arriving at 3.8 ms — slightly earlier than the peak of the half-space response. Thus, the effect of the resistor can be seen in both the amplitude of the earth impulse response and the arrival time of the peak [2, 6]. Virtually, the earth impulse response contains all the information about the cumulative subsurface resistivity distribution over the earth material between the current and the receiver dipole.

Figure 3. Impulse response of a 30 ohm-m half-space (black curve), with peak at 4.2 ms, and with a 25-m-thick, 400-ohm-m resistive layer at a depth of 500 m (red curve), with peak at 3.8 ms.

3. Contrast experiment
The field experiment was performed in the Laizhou gold deposite, Shandong Province. The field layout is shown in figure 4; the current source electrodes were separated by 300 m with a current amplitude of 40 amperes. The inline component of electric field was recorded by receivers at a polar distance of 100 m. Two offsets were used: the receiver at 500 m offset was placed in an open farmland and the receiver at 2400 m offset was placed near the power line, that is, the two offsets have a distinct difference in the SNR of voltage response, which described later.
The m-sequence and square-wave were transmitted in the same amplitude (40A) and the same time duration (about 0.5 ms), which had approximately equal energy. Compared to square-wave, m-sequence is more like an encoded signal, therefore, we take bit-per-second (bps) as the unit of coding frequency of m-sequence, while Hertz (Hz) for the frequency of square-wave. Additionally, m-sequence has another length parameter – the order, denoted as \( n \). The m-sequence repeats after \( 2^n - 1 \) clock pulses. It should be noted that one cycle of square-wave contains two samples, that is, 1 Hz equivalent to 2 bps. The m-sequence used here was order 10 with coding frequency of 2048 bps, compared with a 1024 Hz square-wave.

Figure 5 shows the partial source-receiver waveforms of 500 m offset. The source signal were clearly distinguishable in the voltage response and reached nearly 5 volts due to the short offset and the long receiver electrode separation. Note that the energy of the m-sequence response is 3.55 dB greater than the energy of the square-wave response; we attribute the difference to the diffusive attenuation of higher frequencies, that is, m-sequence distribute the energy to the entire frequency band, mainly in the low frequency band while the square-wave spectrum has peaks at fundamental frequency and odd harmonics.

At short offset, the air wave and the response through the earth arrives almost simultaneously; the identified earth impulse response approach an sharp peak close to \( t = 0 \), decaying to almost zero amplitude at about 2 ms, as shown in figure 6(a) and (b). The two sources achieved nearly identical
results due to the high SNR data.

Figure 6(c) and (d) show the corresponding spectrums in the semilog coordinate. Note that the maximum noise arise in the coding frequency and its harmonics due to the minimum attenuation at these frequencies, which called sensitive frequencies. The response spectrum of square-wave is relatively cleaner; we attribute the difference in skin depth (figure 7); a high frequency component play a role at the short offset which is a shortage for the m-sequence, that is, the m-sequence is relatively unsuitable for short offset due to the lack of high frequency components.

![Figure 6](image)

**Figure 6.** (a), (b) The identified responses at 500 m offset (time domain). (c), (d) The identified responses at 500 m offset (frequency domain).

![Figure 7](image)

**Figure 7.** Representation of skin depth variation with frequency and resistivity.

The SNR of the voltage response at 2400 m offset was extremely low due to the adjacent power line and the source signal was drowned by strong 50 Hz noise, as shown in figure 8.
Figure 8. The partial waveform (0.0-0.1s) of the source current and voltage response at 2400 m offset.

At long offset, the air wave travels faster and arrives first, manifest as an initial impulse in the identified earth impulse response (Figure 9(a) and (b)). The two sources exhibit extremely different noise reduction in the powerline noise environment; an obvious 50 Hz noise was observed in the response identified with square-wave. The response spectrum (Figure 9(c) and (d)) indicated that the 50 Hz noise suppression of m-sequence is 22 dB greater than the suppression of the square-wave, and the noise frequency concentrated in the sensitive frequencies for m-sequence, as expected. Consequently, the m-sequence can achieve better noise reduction than the square-wave, which is consistent with the previous theoretical analysis.

Figure 9. (a), (b) The identified responses at 2400 m offset (time domain). (c), (d) The identified responses at 2400 m offset (frequency domain).

4. Conclusion
The m-sequence has a distinctly different spectrum which distribute most of the energy to the low frequency band and compensate the high-frequency attenuation handsomely. But the characteristic is also plagued by the skin depth, particularly for the short offset. Two offsets were performed in the experiment, which corresponding to different SNR data. At 500 m offset, the two sources achieved
nearly identical results due to the high SNR data. The receiver at 2400 m offset was severely disturbed by power line; and the two sources exhibit extremely different noise reduction; the identified response of m-sequence suppressed the 50 Hz noise perfectly but contains interferences in sensitive frequencies, as expected. The powerline noise suppression of m-sequence is 22 dB greater than the suppression of the square-wave which demonstrate the superiority of m-sequence in MTEM data processing.

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