Early time data processing in shallow AEM exploration

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Abstract. For shallow exploration, high-frequency pseudo-random binary sequence is used in the time-domain airborne electromagnetic system. This system is working in the on-time and the earth response could be derived from system identification, which is different from the previous time-domain electromagnetic systems. The early time data is crucial for obtaining a detailed resolution. It could be severely disturbed by the primary field, the receiver response and noise. Here we present an approach for removing the primary field by matching subtraction in transformation of correlation calculation. The noise is suppressed as not correlated with the pseudo-random binary sequence. This approach is proved efficient by applying to simulation data based on forward modeling. The receiver influence is analyzed through the response of the equivalent electronic circuit. The 1D inversion results indicate that critical damping state and high cut-off frequency could reduce the adverse effect on the resolution of shallow exploration.

1. Introduction
The shallow surface supports the needs of human survival and development. People live on it and drill and excavate in it. High-resolution detection of shallow geological bodies has attracted more and more attention. It is an effective way by using high-frequency pseudo-random binary sequence (PRBS) as a field source in the airborne electromagnetic (AEM) system. At present, the AEM system is widely used in the fields of rapid geological mapping, general survey of good conductive metal ore, groundwater, etc., with the advantages of high speed, low cost and good traffic-ability [4]. The geological exploration using PRBS source has been applied to the multi-channel transient electromagnetic (MTEM) system [1], and proved that PRBS has higher resolution than square waves [5].

The high-resolution shallow exploration in the AEM system needs to obtain early time data of the earth response, which is the fundamental purpose of this paper. Based on the time-domain AEM system using high-frequency PRBS source, we simulated the transmitting and receiving signal by forward modeling and the characteristics of hardware structure. The correlation identification method was used to process the early time data for suppressing noise and the method was found to remove the primary field during the process. Due to the great influence of the receiver [2], we analyzed the role of the main parameters.

2. Forward modeling
A PRBS is defined by two parameters, known as the clock frequency and the sequence order. It is generated by linear feedback shift register through a given initial value. Figure 1(a) shows the theoretical PRBS waveform. The waveform includes both rising edge and falling edge which are often different in practice. For example, a transmitter circuit with full-bridge structure was used, the rising edge of the
generated current waveform was approximately exponential and the falling edge was linear. According to the structure of circuit, the simulated PRBS waveform is shown in Figure 1(b).

![Figure 1. PRBS waveform of sequence order 4](image)

(a) theoretical PRBS waveform; (b) simulated PRBS waveform.

On the basis of the Biot-Savart law, which gives the induction field generated by a current I(t) going through a wire as follows:

$$B_1(t) = P \cdot I(t), \quad P = \frac{\mu_0}{4\pi} \int \frac{dl \times r}{|r|}$$

where $B_1(t)$ is the primary field, $P$ is a coefficient of the primary field calculated by the wire with the contour $C$, $dl$ the infinitesimal vector belonging to the wire and $r$ the vector from the position of the infinitesimal wire to the point of observation.

According to the full-time forward modeling method (Yin et al., 2013), the earth response for the current $I(t)$ is calculated by convolution as follows:

$$B_2(t) = I(t) \ast B_1(t)$$

where $B_2(t)$ is the secondary field represents the earth response, $B_1(t)$ is the impulse response of the earth calculated by AarhusInv program in this paper.

3. Data processing

According to skin effect, the penetration depth and resolution of electromagnetic exploration are mainly affected by the earth resistivity, electromagnetic wave frequency and sampling density of frequency points. The advantages of the PRBS signal are broad bandwidth and high spectral density which refer to system identification method. Using PRBS as field source in shallow AEM exploration is feasible to detect shallow geological bodies with high-resolution.

One of the key points to achieve the goal is the early time data processing of the observed response. From equation (3), except for the secondary field, the observed response includes the primary field, the receiver response and the noise, which are the main influencing factors.

$$\frac{dB(t)}{dt} = \left[ \frac{dB_1(t)}{dt} + \frac{dB_2(t)}{dt} \right] \ast R(t) + n(t)$$

where $B(t)$ is the observed response, $R(t)$ is the receiver response, and $n(t)$ is the noise.

3.1. Identification method

For a linear time-invariant system, $y(t) = x(t) \ast h(t) + n(t)$, where $y(t)$ is the output signal, $x(t)$ is the input signal, $h(t)$ is the system impulse response, $n(t)$ is the noise.

When $x(t)$, $y(t)$, $n(t)$ are stationary ergodic Gaussian random processes, the correlation function is $R_{xy}(\tau) = E[x(t), y(t+\tau)]$, $R_{xn}(\tau) = E[x(t), n(t+\tau)]$, $R_{x}(\tau) = E[x(t)2]$.

According to Wiener-Hoff equation, it is derived as follows:

$$R_{xy}(\tau) = R_{x}(\tau) \ast h(\tau) + R_{xn}(\tau)$$

(4)
Let $B = R_{xy}(\tau)$, $A = R_x(\tau)$, $G = h(t)$, $C = R_{xn}(\tau)$. In the discrete case, transform autocorrelation function $A$ to autocorrelation matrix, then the equation is obtained as follows:

$$B = AG+C.$$  

(5)

If the noise is not correlated with the input signal, the correlation between input signal and noise will be much smaller than that between input signal and output signal. Thus the noise is suppressed and the equation can be expressed as follows:

$$
\begin{bmatrix}
  b(n_m) \\
  b(n_m + 1) \\
  \vdots \\
  b(n_m + N_k - 1)
\end{bmatrix}
\begin{bmatrix}
  a(n_m) & a(n_m - 1) & \cdots & a(n_m - N_k + 1) \\
  a(n_m + 1) & a(n_m) & \cdots & a(n_m - N_k + 2) \\
  \vdots & \vdots & \ddots & \vdots \\
  a(n_m + N_k - 1) & a(n_m + N_k - 2) & \cdots & a(n_m)
\end{bmatrix}
\times
\begin{bmatrix}
  g(1) \\
  g(2) \\
  \vdots \\
  g(N_k)
\end{bmatrix}
$$

(6)

Conjugate gradient method (CGM) is one of the effective methods to solve this equation and the system response $G$ will be obtained.

3.2. The primary field removal and noise suppressing

In shallow AEM exploration, the earth is considered as a linear time-invariant system. And the current is input signal, the observed response is output signal. According to equation (1)(2)(3):

$$\frac{dB(t)}{dt} = [P \cdot \frac{dl(t)}{dt} + \frac{dl(t)}{dt} * B_c(t)] * R(t) + n(t)$$

(7)

Let $x(t) = I(t), y(t) = \frac{dB(t)}{dt}$, and $x(t), y(t), n(t)$ are stationary ergodic Gaussian random processes.

According to the identification method, we could obtain the equation expressed as follows:

$$R_{xy}(\tau) * P \cdot \frac{dR_x(\tau)}{d\tau} * R(\tau) = R_{xn}(\tau) * \frac{dB(t)}{dt} * R(t) + R_{xn}(\tau)$$

(8)

From the equation, the primary field and receiver response are both affecting the identification result, which means affecting the early time data observed. The influence of the primary field is considered first.

Let $B = R_{xy}(\tau) * P \cdot \frac{dR_x(\tau)}{d\tau}$, the primary field is transformed into the product of the coefficient $P$ and the derivative of the current autocorrelation function. From this transformation, it is found that matching subtraction by peak is an accurate way to remove the primary field. In practice, another advantage is that the noise in current is suppressed, which avoids the large error caused by directly subtracting the primary field through calculation.

As the noise is not correlated with the current of PRBS, it is suppressed. Let $G = \frac{dB(t)}{dt}$, use equation (6) and solve it by CGM. The integration of $G$ is the final identification result without primary field which is the earth impulse response

3.3. Analysis of receiver response

The electromagnetic signal calculated theoretically is not same as the observed response, which is caused by the performance characteristics of the receiver [3]. Figure 2 shows the equivalent electronic circuit. In the Figure, $v_i(t)$ is the induced electromotive force, $L$ the total inductance, $r$ the internal resistance, $R$ the damping resistance, $C$ the total capacitance, and $v_o(t)$ is the voltage observed by the preamplifier.
Figure 2. Equivalent circuit diagram of receiver

The system transfer function of the receiver is as follows:

\[ R(s) = \frac{1}{LC(s^2 + 2\zeta \omega_n s + \omega_n^2)} \]  

(9)

The damping coefficient is \( \zeta = \frac{Rr + L}{2\sqrt{LC(r + R)}} \), coil resonance frequency is \( \omega_n = \sqrt{\frac{1}{LC} \left( \frac{r}{R} + 1 \right)} \), cut-off frequency is \( f_c = \frac{\omega_n}{2\pi} \sqrt{1 - (2\zeta^2 + \sqrt{4\zeta^4 - 4\zeta^2 + 2}}} \).

In the case of over damping, the response is in small amplitude and large attenuation. The sensitivity is low. In the case of under damping, the response is in large amplitude and small attenuation. The sensitivity is high but the response curve vibrates. The ideal working state is the critical damping state.

4. Examples

According to the skin depth equation, we calculated a set of parameters of PRBS source to achieve the resolution of 10m in the depth interval 20m-100m. The sequence order was 8 and the clock frequency was 200 kHz. The sampling rate was set to 1MHz. 1D modeling was performed over three-layer space with resistivity value of 200 Ωm, 5 Ωm, 200 Ωm and thickness value of 20 m and 10 m. A circular loop with a radius of 3 m was placed at a height of 30m and the observation location was at the loop center. The coefficient of the primary field was \( \mu_0/6 \). The earth response was calculated by AarhusInv program as shown in Figure 3(a). The receiver response was calculated by cut-off frequency and damping coefficient as shown in Figure 3(b). Figure 3(c) shows the simulated current as a combination of the PRBS and 3% noise. Figure 3(d) shows the observed response as a combination of the primary field, secondary field, and 5% noise which is picked up by a receiver.
Figure 3. Simulated signal: (a) the earth response; (b) receiver response; (c) current; (d) observed response.

From the simulated signal, the earth response was identified. Figure 4(a) shows the results that the cut-off frequency is 150 kHz and damping coefficient is 0.707, 1.0 and 1.414. Figure 4(b) shows the results that the damping coefficient is 1.0 and cut-off frequency is 100 kHz, 150 kHz and 250 kHz. It can be seen that the primary field is removed and the curves vary in shapes with different cut-off frequencies and damping coefficients mainly in the initial segment.

Figure 4. The identification results: (a) the cut-off frequency is 150 kHz and damping coefficient is 0.707, 1.0 and 1.414; (b) the damping coefficient is 1.0 and cut-off frequency is 100 kHz, 150 kHz and 250 kHz.

In the initial segment, the signal frequency is high and the noise is suppressed definitely by correlation, thus the error of identification is mainly affected by the receiver which filers the high-frequency signal. From the initial segment to the final, the signal frequency gradually decreases, the impact of receiver also gradually decreases, the effect of suppressing noise is getting worse and the error of identification is mainly affected by the noise.

1D inversion was performed over the five identification results by AarhusInv program as shown in Figure 5. Compared to Figure 5(a), Figure 5(b) and Figure 5(c), with the same cut-off frequency of 150 kHz, it is shown that the inversion result is more accurate when the receiver works in the critical damping state (damping coefficient is 1.0). Compared to Figure 5(b), Figure 5(d) and Figure 5(e), with the same damping coefficient of 1.0, it is shown that the inversion result is more accurate when the cut-off frequency is higher. The best case is that the cut-off frequency is high enough and the receiver works in the critical damping state.
5. Conclusions

The early time data processing is essential to achieve shallow high-resolution exploration. In this paper, the identification method was used and the noise was suppressed as not correlated with PRBS. The primary field was transformed in the correlation calculation and removed by matching subtraction. The receiver response was analyzed through the cut-off frequency and damping coefficient. It was found that working in the critical damping state with high cut-off frequency could reduce the adverse effect.

However, the critical damping state is an ideal situation which is difficult for the hardware. The under damping state close to the critical damping state will be a compromise choice. As the cut-off frequency is impossible to be high enough in practice, the influence of receiver still needs to be eliminated in shallow AEM exploration which requires further research.

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