CSEM data in shallow water

Summary

This paper considers the simple case of a water layer overlying a 1 ohm-m half space to study the signal properties of a horizontal current dipole source in controlled source electromagnetic surveying. Although a conventional CSEM source has much more energy at certain frequencies than a transient PRBS signal with the same strength, processing of the PRBS data provides tremendous gain in signal-to-noise ratio. Deconvolution alone gives two orders of magnitude increase in signal-to-noise ratio; correlated noise, including magnetotelluric noise, can be reduced by a further order of magnitude; and the air wave becomes separable from the earth response.

Introduction

This paper considers the problem of obtaining electromagnetic data in shallow water (<300 m) with a horizontal electric bipole source and asks the question: Given a finite amount of signal energy, is it better to concentrate it in a few frequencies, or to spread it over a broad bandwidth?

Conventional controlled-source electromagnetic (CSEM) surveying uses a horizontal current bipole source emitting a continuous signal, often a square wave, which has energy concentrated at discrete frequencies (Ellingsrud et al., 2002; Johansen, et al., 2005). Between these frequencies the energy in the source signal is effectively zero. In transient EM the current bipole source is essentially the same (and also controlled, so it is also CSEM), but the signal has a beginning and an end and has a generally smooth frequency spectrum over a limited bandwidth. Because it is easy to switch the polarity of electric current very fast, it is particularly easy to choose the frequency bandwidth of the signal using a pseudo-random binary sequence, or PRBS (Duncan et al., 1980).

This paper considers the effect of three kinds of noise on the data: random noise, correlated noise such as magnetotelluric noise, and the air wave. It shows that discrimination between signal and noise is much better with a broad bandwidth transient signal than with a continuous signal containing a few discrete frequencies. Specifically, a PRBS is much better at discriminating between signal and noise than a square wave.

Methodology

The argument is general, but is illustrated by considering a specific problem. We consider the problem of a 100 m water layer overlying a 1 ohm-m halfspace. The dipole current source and dipole electric receiver are on, or close to, the sea floor and the source-receiver separation is 3,000 m.

The response we are interested in is the response of the earth below the sea floor. Figure 1(a) shows the analytical impulse response for a 1 ohm-m halfspace (Weir, 1980; Wilson, 1997). Figure 1(b) shows its amplitude spectrum. It is clear from Figure 1(a) that frequencies no higher than 2 Hz are required, but the lowest required frequency is 0 Hz. This low frequency requirement enables the tail of the impulse response to be extended to infinite time. It can be seen from Figure 1(a) that the amplitude of the response is very small after 15 seconds, so the lowest required frequency is $1/15 = 0.067$ Hz.
Figure 1  
(a) Impulse response of 1 ohm-m halfspace at 3,000 m offset. (b) Amplitude spectrum of (a)

Figure 2  
(a) 100 s window of 0.25 Hz square wave. (b) Amplitude spectrum of (a)

Figure 3  
(a) Order 9 PRBS, 0.2 s sampling. (b) Amplitude spectrum of (a)
We now compare the square wave and the PRBS. A 0.25 Hz square wave is commonly used in conventional CSEM and it is common to divide the recorded data in 100 s windows for processing. Figure 2(a) shows 100 s of a 0.25 Hz square wave with 0.2 s sampling. Figure 2(b) shows its amplitude spectrum. Figure 3 shows the PRBS at 0.2 s sampling and its amplitude spectrum.

The PRBS is of order 9 and has $2^9 - 1 = 511$ samples at 0.2 s sample intervals. Its amplitude is flat between 0.0097 Hz and 2.5 Hz, whereas the square wave has energy only at discrete frequencies, but at much larger amplitudes; at 0.25 Hz, the amplitude is about 14 times greater. Note that the PRBS is flat over the frequency bandwidth of the earth response.

The response at the receiver is the convolution of the earth response with the input signal – 2(a) in the case of the square wave, and 3(a) in the case of the PRBS – plus noise. The real power of the transient PRBS is in how it handles the noise.

**Deconvolution**

Deconvolution of the measured response for the input is possible for the PRBS because the convolution is complete and the PRBS has all the frequencies of the earth response. Deconvolution is impossible for the square wave because the convolution is incomplete – the input signal is continuous – and the bandwidth of the input signal is incomplete. Deconvolution of the PRBS signal effectively compresses all the energy of the 511 PRBS samples into one sample. The gain in signal-to-random noise of this process is

$$G = N\sqrt{\frac{M}{N + M - 1}}$$  \hspace{1cm} (1)

where $M$ is the number of samples in the impulse response and $N$ is the number of samples in the PRBS. For 0.2 s sample intervals, the response in Figure 1(a) can be defined by 75 samples; thus $M = 75$, and for this PRBS, $N = 511$. From these values equation (1) gives a gain of 122, or 42 dB. This is an extremely powerful process for enhancing the signal-noise ratio that is not available to conventional CSEM data.

**Removal of the air wave**

Figure 4 Total impulse response at 3000 m: the sum of the earth impulse response and the air wave.
After deconvolution the impulse response is recovered from the data. For the problem under consideration it is shown in Figure 4, in which a half-Nyquist zero-phase Gaussian filter has been applied to the synthetic data, making the response appear slightly non-causal. The total response, shown in black is the sum of two components: the earth impulse response, shown in green – this is the same as the response shown in Figure 1(a) – and the air wave, shown in red. For the purposes of this example the air wave is defined as the total response minus the earth impulse response.

It is clear that the initial peak of the air wave arrives at the receiver before the earth impulse response. It follows from the principle of causality that the shape of the peak is affected by the earth parameters only very weakly. We must conclude that the air wave is determined predominantly by the water layer parameters. Ziolkowski and Wright (2009) used this principle for estimating the air wave from deconvolved marine transient EM data enabling the air wave to be subtracted from the total response to recover the earth impulse response.

We note that this separation can only be done on the recovered total impulse response. Therefore it is not possible to apply this method to conventional CSEM data. Removal of the air wave from conventional CSEM data remains a problem.

Correlated and magnetotelluric noise

Ziolkowski et al. (2009) demonstrated on real North Sea transient EM data that a method developed by Ziolkowski et al. (2009) was able to suppress correlated noise and increase the signal-to-noise ratio by 20 dB (a factor of 10). This was possible only because of the signal compression provided by the deconvolution.

Conclusions

Although a conventional CSEM source has more energy at certain individual frequencies than a transient PRBS signal with the same strength, the PRBS signal has tremendous advantages in discriminating between signal and noise. Deconvolution alone gives two orders of magnitude increase in signal-to-noise ratio; correlated noise, including magnetotelluric noise, can be reduced by a further order of magnitude; and the air wave becomes separable from the earth response.

References


