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Deconvolution of correlation noise in coded-impact seismic systems

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SUMMARY

Coded-impact seismic sources, including Mini-SOSIE and SIST, deliver a sequence of impacts in a controlled pattern. These sources generate seismic data with acceptable bandwidth and signal-to-noise, but also introduce correlation noise proportional to the rate of production.

We examine a method for correlation-noise attenuation utilising a Weiner filter designed on the known impact sequence. Numerical models demonstrate that the algorithm can achieve very significant attenuation of correlation noise in both Mini-SOSIE and SIST records. The practical viability of the approach is examined with reference to real-data examples.

This procedure has the potential to provide records of acceptable quality from rapid impact sequences, yielding significant productivity benefits over current Mini-SOSIE and SIST approaches.

Key words: Mini-SOSIE, SIST, correlation noise, deconvolution, filtering.

INTRODUCTION

Vibroseis is the most commonly used land-seismic source. In situations where Vibroseis is not viable for logistical or environmental reasons, coded-impact systems such as Mini-SOSIE or SIST (Swept Impact Seismic Technique) can provide a viable alternative. These use a smaller, impulsive source (e.g. road compactor, jackhammer) to deliver a sequence of low-energy impacts in a controlled pattern referred to as an impact series. Stacking yields a signal with good bandwidth and acceptable signal-to-noise ratio. The main disadvantage is much slower production compared to Vibroseis. Improved productivity could be achieved by using a more rapid impact sequence, or multiple simultaneous sources. However, this has the undesirable side effect of degraded record quality, due to increased correlation noise (also known as stacking noise).

Correlation noise is a function of the impact sequence, and can be calculated directly if the impact sequence is known. This allows investigation of the correlation noise associated with different Mini-SOSIE and SIST sequences. It also suggests the possibility of using post-processing techniques such as Weiner filtering to reduce the amount of correlation noise in the final record.

Mini-SOSIE Method

The Mini-SOSIE method (Barbier, 1979) uses a conventional dirt tamper to create the impact series. The operator varies the throttle in an attempt to randomise the impact sequence. The impact sequence needs to be randomised in order to minimise the correlation noise. Other factors which influence the correlation noise are the average rate of impact and the sample rate of the recording system. The average rate of impact defines the amount of correlation noise in the recording which is then distributed across a number of samples – the greater the number of samples the lower the average amount of correlation noise.

Thus in general, slower, more random impact sequences will have reduced amounts of correlation noise in the associated shot record. As the impact sequence becomes less random spurious events start to appear in the decoded data which interfere with the true events (Strong and Hearn, 2004).

Swept Impact Seismic Technique (SIST)

SIST uses an electric jackhammer or similar source to generate a sweep of impacts. SIST sweeps have a programmed starting frequency, stopping frequency and duration. Because correlation noise is dependent upon the impact series, the correlation noise for a SIST sweep can be determined prior to acquisition from these sweep parameters. In contrast, the Mini-SOSIE impact series is operator dependent and varies from shot to shot. Park (1996) examined optimisation of sweep parameters in order to minimise correlation noise.

As with the Mini-SOSIE method, the faster the impact series the greater the total amount of correlation noise in the associated shot record. The total number of impacts required is influenced by the recording environment and thus the design of a SIST sweep is generally a trade off between productivity and correlation noise.

One property of a SIST sweep is that it effectively incorporates a low cut filter. When the frequency spectrum of the autocorrelation of a SIST impact sequence is examined a zone of zero amplitude can be seen. The cut off frequency of this zone is dependent upon the low-frequency end of the sweep. The autocorrelation is convolved with the recording and thus the data are band limited. The cut-off frequency can be tuned by modifying the sweep parameters. This has the potential to attenuate unwanted low-frequency signals such as ground roll. The disadvantage is that by increasing the low-frequency end of the sweep the average impact rate is faster and the amount of correlation noise in the recording is increased.

METHOD

A generalised seismic trace consists of a range of repeatable source-generated coherent signals plus some non-repeatable noise. These signals will include primary reflections, multiples and surface waves. Thus, using Z-transform notation, a seismic trace X(z) can be described by

$$X(z) = Y(z) + N_a(z)$$

where $Y(z)$ is the repeatable, source generated signal and $N_a(z)$ is the non-repeatable noise. In the coded-impact seismic technique the source operates multiple times in a single recording. Assuming the source wavelet does not vary then the coded-impact recording can be written as

$$X_C(z) = Y(z)z^{n1} + Y(z)z^{n2} + ... + Y(z)z^{nk} + N_a(z)$$

where nk is the z-shift of the kth impact. These terms can be collected such that

$$X_C(z) = [z^{n1} + z^{n2} + ... + z^{nk}]\ Y(z) + N_a(z)$$

We will refer to the impact series $[z^{n1} + z^{n2} + \ldots + z^{nk}]$ as $I(z)$, a time series consisting of unit-amplitude spikes. Thus the coded-impact recording $X_C(z)$ can be written as

$$X_C(z) = I(z)Y(z) + N_a(z)$$

The stacking algorithm used to decode the recording is equivalent to correlation, thus the stacked record $X_d(z)$ can be written as the correlation of the record with the impact series,

$$\begin{aligned} X_d(z) &= [I(z)\ Y(z) + N_a(z)]I(z^{-1}) \\ &= R_{II}\ (z)\ Y(z) + R_{NI}(z) \qquad (1) \end{aligned}$$

Here $R_{II}(z) = I(z)I(z^{-1})$ is the autocorrelation of the impact series and $R_{NI}(z) = N_a(z)I(z^{-1})$ is the cross correlation of the ambient noise and the impact series.

It would be desirable if $R_{II}(z)$ were be a scalar term at lag zero, in which case the convolution $R_{II}(z)Y(z)$ would thus be a scaled version of $Y(z)$. In reality $I(z)$ is a time series of unit impulses and as seen in Figure 1 the autocorrelation is more complex.

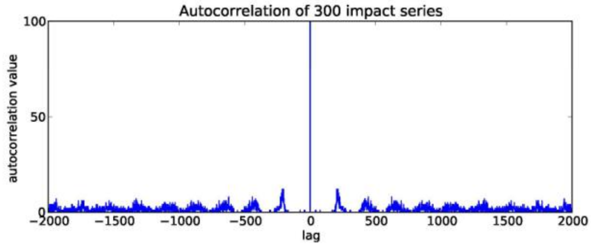

Figure 1. Autocorrelation of 300 impact spike series taken from a field dataset. Record length was 40 seconds with sample interval of 0.5 ms and a stacking window of 1 sec. Note the amplitude of the zero-lag spike is 300, and has been truncated for plotting purposes.

The autocorrelation of the impact series consists of a scalar term at zero lag whose amplitude is equal to the number of impacts k. The remainder of the autocorrelation is unwanted and is referred to as correlation noise. Thus the autocorrelation can be described as

$$R_{II}(z) = k + N_C(z)$$

where k is the zero-lag autocorrelation and $N_C(z)$ is the correlation noise, comprising the remainder of the autocorrelation. When substituted into Equation (1) the stacked coded-impact trace can be described as

$$X_d(z) = k\ Y(z) + N_C(z)\ Y(z) + R_{NI}(z) \qquad (2)$$

Correlation-Noise Filtering

If the impact series $I(z)$ is known, the autocorrelation of the impact series R_{II} is also known and the correlation noise $N_c(z)$ can be determined exactly. Because the correlation noise is known exactly it can, in theory, be removed by using signature deconvolution (Robinson and Treitel, 2000). A Weiner (least squares) filter $F(z)$, is designed which removes autocorrelation terms at non-zero lags. That is

$$F(z)R_{II}(z) = F(z)\ [k + N_C(z)] = k$$

Because convolution is commutative, associative and distributive (Weisstein, 2003) application of the filter to the stacked record will remove the correlation noise from the record. That is, application of the filter to equation 3 gives

$$F(z)X_d(z) = kY(z) + F(z)R_{NI}(z) \qquad (3)$$

Note the correlation-noise term Equation (2) has been removed. The term $F(z)R_{NI}(z)$ is the convolution of the filter $F(z)$ with $R_{NI}(z)$, the cross correlation of the impact series with the ambient noise. The response of this term is complicated but modelling has shown its impact to be minimal.

Figure 2 gives a synthetic example which validates the theory behind the concept of correlation noise filtering.

Filter Performance

Ideally the correlation noise would be removed entirely. This would require a perfect inverse filter. In reality the filter performance can vary depending upon the filter design and the character of the trace to be filtered.

Firstly, the effectiveness of the correlation noise filter depends on whether we apply a so-called "single sided" or "double sided" correlation noise filter. As seen in Figure 1 the correlation-noise function $N_c(z)$ is symmetric about zero lag. Hence when this noise function is convolved with each event in the signal $Y(z)$ (Equation 2) it introduces correlation noise symmetrically before and after that event.

Assume that the output trace has a length of N samples. An event at sample 1 will have associated correlation noise extending to sample N. An event at sample N will have associated correlation noise extending back to sample 1. Intuitively, to achieve optimum noise rejection we would need to use a symmetric, double-sided filter of length 2N. Figure 2 gives a synthetic example of the benefit of using double sided filters.

One complication is that when a filter is applied to a truncated version of the signal it was designed on, artefacts are introduced. To explain this consider a filter $F(z)$ designed on some signal $S(z) = A(z) + B(z)$ such that $F(z)S(z) = 1$. If the same filter is applied to $A(z)$ only it can be shown that

$$F(z)A(z) = 1 - F(z)B(z)$$

Where *F(z)B(z)* represents the unwanted artefacts. In general standard recording systems only output records with positive times. Note that an improved result would be achieved if the recording system were modified to output a stack length of 2*N* samples symmetric around lag zero. In this case a double sided filter could be used without introduction of artefacts.

A separate issue is that coded-impact systems often record only the times of impacts. In reality source impacts will vary in amplitude. This means that the noise filter is designed on a unit-impulse series which does not match the actual recorded impact series. This will limit the effectiveness of the filter. Improved performance would be expected if impact amplitudes were also recorded.

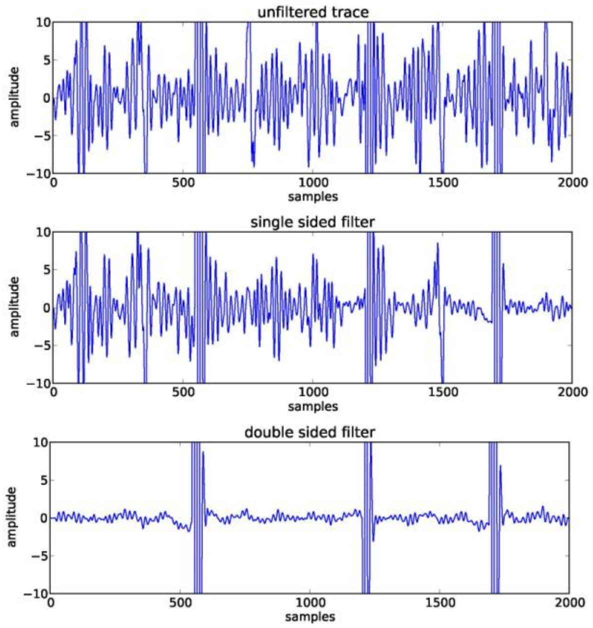

Figure 2. A synthetic trace with correlation noise (top) filtered based on known impulse series. Both a single-sided filter (middle) and double-sided filter (bottom) are demonstrated. The expected output consists of three events, as detected by the double-sided filter.

A related effect occurs when the recorded impact times do not match the actual impact times. This can occur when a threshold style trigger is used to generate the timings. A threshold trigger detects a rising edge from a sensor and returns a spike to the recording-system electronics. If the sensor waveform rises at a different rate for different amplitude impacts it can trigger at different times relative to the start of the source wavelet. This error can combine with the amplitude errors above. The resulting impact series will have both amplitude and timing errors. The impact sequence used to design the filter will not perfectly match the true impact sequence and performance will be degraded.

Real-Data Example

Figure 3 shows a standard production Mini-SOSIE shot record before and after correlation noise filtering. This raw record has a very high level of correlation noise, due to poor impact randomisation. The improvement following filtering is dramatic. Figure 4 shows the corresponding field stack before and after singled-sided correlation-noise filtering. The improvement is much more subtle. Fortunately, most shot records have much lower correlation noise than the example in Figure 3. Additionally, CMP stacking is very effective at removing correlation noise. Because the impact series for each source-receiver pair in a CMP has a different impact series the correlation noise tends to be stacked out. (Note this is not true of SIST sources.) Thus, when Mini-SOSIE is recorded using the conventional approach (i.e. single source, good operator randomisation), noise filtering will provide significant improvement to occasional shot records but only subtle improvement to stacked data.

However, the performance demonstrated on Figure 3 suggests that if a coded-impact source were applied less conservatively (e.g. multiple sources, more rapid impact sequences) the resultant more severe correlation noise could be rectified using the Wiener filtering technique.

CONCLUSIONS

Where coded-impact systems are applied using conventional best-practice approaches (single sources, slow impact series) correlation noise is manageable, except on occasional shot records. In these circumstances, correlation filtering will provide only subtle improvements to stacked images. However, if coded-impact techniques are pushed to their limits (faster impact series, faster SIST sweeps, multiple sources) correlation noise will become a significant factor. The filtering technique introduced here has potential to attenuate such noise. This provides promise for significant increases in the productivity of coded-impact seismic techniques.

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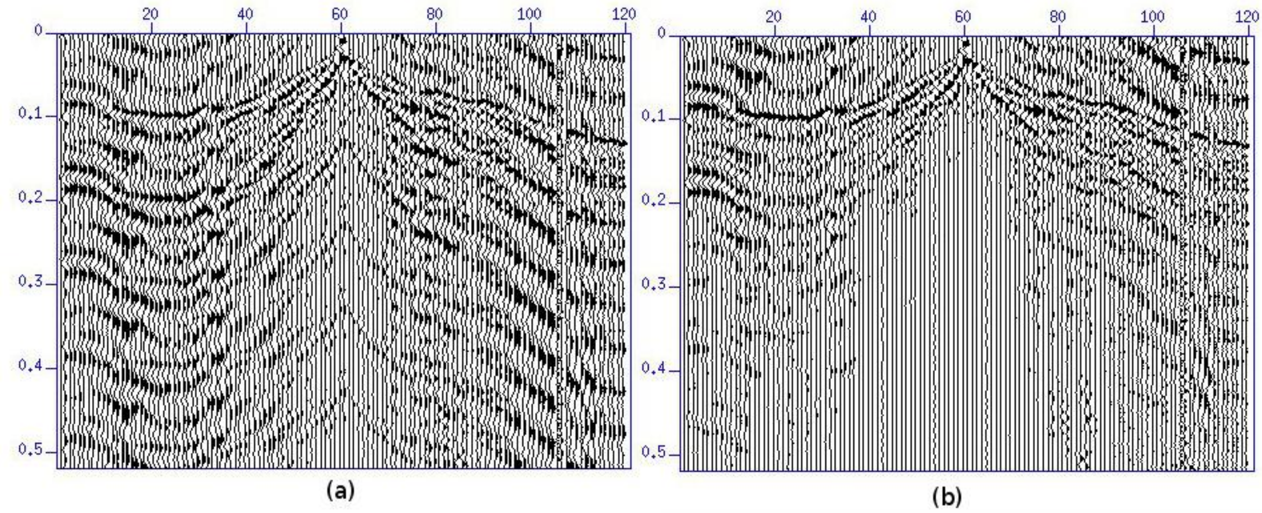

Figure 3. (a) Raw Mini-SOSIE shot record exhibiting severe correlation noise.
(b) Record from (a) after single-sided correlation-noise filter has been applied.

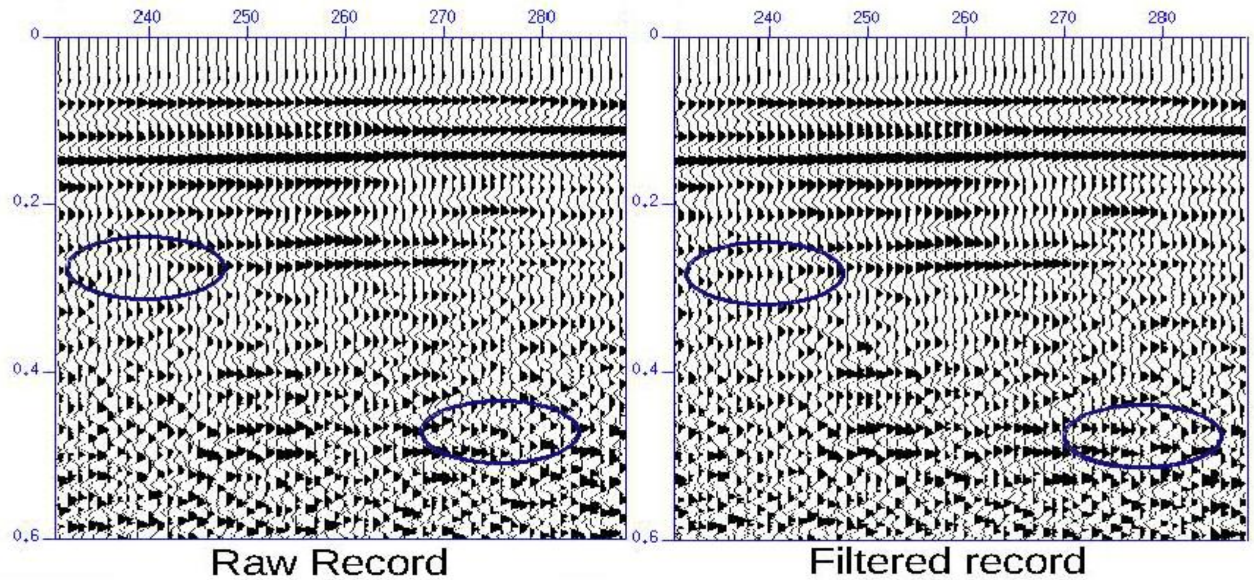

Figure 4. Mini-SOSIE field stack built from (a) raw traces
(b) single-sided correlation-noise filtered traces