Very low frequency marine seismic noise

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SUMMARY

Some ocean bottom seismic records from Western Australia show very low frequency noise amplitudes that are larger than peak-to-peak amplitudes of seismic reflections on hydrophone records. The noise period is longer than a 5000 ms record length. As a result, it is hard to suppress this noise using traditional seismic processing filters without generating large truncation edge effects.

Spectra from 100 trace windows were computed using a Burg multiple segment algorithm. Low frequency peaks near 0.12 Hz dominate the spectra from either hydrophone or vertical accelerometer sensors with or without air gun array shots. The low frequency peaks correspond with wavelength peaks near 500 m. Therefore, the apparent speed of propagation of this low frequency noise is about 60 m/s. This is close to the speed of gravity water waves for the OBC sensor depths.

Since this marine seismic noise is at a very low frequency and not generated by the seismic source, a best practice would be additional, analogue, low cut, filtering in the field to suppress its effects on seismic records and processing. Alternatively, digital recursive filters can be designed to be applied with initial condition constraints derived for each seismic trace. The very low frequency noise can then be suppressed in the computer without truncation edge effects.

Key words: OBC, noise, filtering, acquisition, processing

INTRODUCTION

Very low frequency seismic noise is an unintended consequence of the improved low frequency sensitivity of modern ocean bottom sensors and recording instruments. Older seismic recording systems typically used geophones and (transformer coupled) hydrophones that have a critically damped 10 Hz @ 12 dB/octave transduction-sensitivity. In such legacy systems, very low frequency noise is suppressed by at least 40 dB below 1 Hz.

An example marine seismic trace from the western coast of Australia is shown as a blue dotted line in Figure 1. It was recorded by a Sercel SeaRay® hydrophone that has a 2 Hz @ 6 dB/octave transduction-sensitivity. The peak-to-peak voltage of the very low frequency noise (>1.2 mV) is almost as large as the largest peak-to-peak seismic voltages (>2 mV) in this trace #50 from a collection of 100 traces within a shot record. Because the noise period appears longer than the 5000 ms record length, the dominant noise frequency is expected to be below 0.2 Hz.

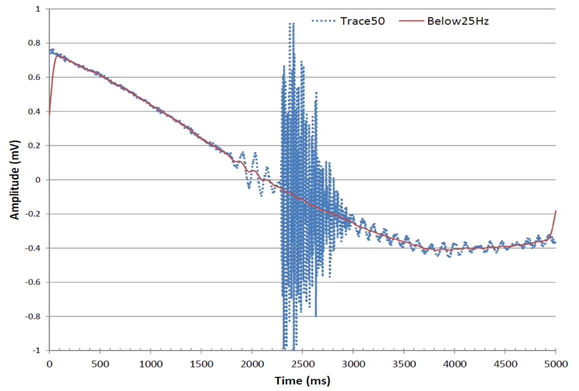

Figure 1: Trace 50 from 100 trace shot ensemble. Blue dotted line is raw input. Solid red line is below 25 Hz.

Although these examples are all from Australia, observations of very low frequency noise are ubiquitous. The noise frequency is much below those expected for seismic signals so this noise is commonly ignored or casually suppressed with convolutional low-cut filters. However, the noise amplitude is so large that there may be serious consequences for analysis, processing, or interpretation if the noise is simply ignored or only partially suppressed.

A best practice would have been suppression of this noise before it was recorded. Conventional digital convolution filters generally have significant truncation edge effects at the beginning or end of a seismic record, like those visible on the solid red line in Figure 1. However, by estimating initial conditions, recursive digital filters can be applied without significant edge effects.

OBSERVATIONS AND ANALYSIS

The single trace shown in Figure 1 is not long enough to fully characterize the spectrum of a fragment of very low frequency noise. Nevertheless, the autocorrelation of this trace can be summed with autocorrelations from another 99 traces in the shot record collection to form a robust estimate shown by the solid red line in Figure 2. The dotted blue line is the sum of 100 autocorrelations from a record at the same physical location but without an air gun shot. Both curves show a large negative trough near 3200 ms suggesting low frequency noise peaks at or below 0.15 Hz.

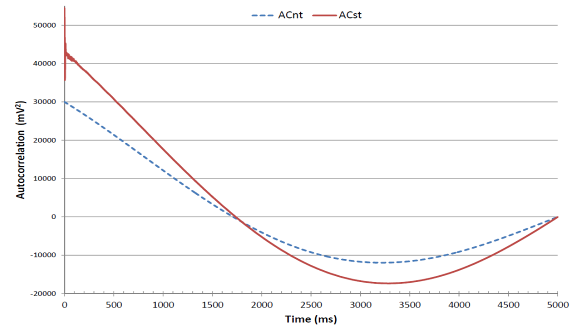

Figure 2: Temporal autocorrelations from 100 trace ensembles with and without air gun shot.

Fourier Spectra

Fourier transforms of the autocorrelations from Figure 2 show strong noise peaks at 0.2 Hz. However, the temporal boxcar spectral resolution side lobes are so large and decay so slowly that the higher frequency, signal-like, parts of the spectrum are difficult to interpret because they are obscured by the noise side lobes. A full 2501 sample Hanning taper was applied to the traces before calculating the FFT spectra shown in Figure 3. There are very large and very low frequency noise peaks on both spectra below 4 Hz. Nevertheless, above 6 Hz the average shot generated spectrum exceeds the average noise spectrum by more than 20 dB well beyond the recording instrument's 200 Hz antialias filter. Integrating the spectral densities into spectral distributions between 0 and 250 Hz reveals that 49% of the shot record spectral distribution is below 0.5 Hz. On the spectral distribution without a shot, more than 99% of the spectrum is below 0.5 Hz.

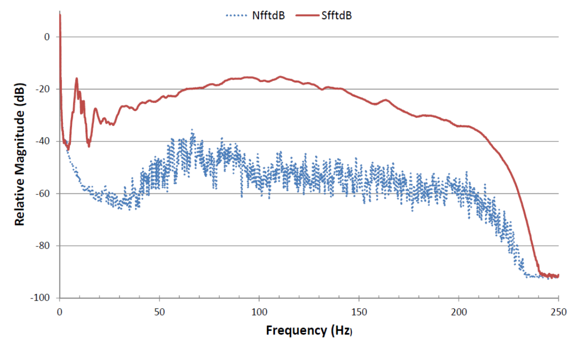

Figure 3: FFT spectra from Hanning tapered 100 trace ensembles with and without air gun shot.

The lowest 4 Hz intervals of these spectra have been expanded into the display in Figure 4. The noise peaks near 0.2 Hz have spectral densities nearly 50 dB stronger than the average noise and average shot generated spectral densities near 4 Hz. The rapidly increasing noise spectral densities below 2 Hz must be suppressed before the signal-like features between 2 Hz and 6 Hz can be enhanced reliably.

Burg Spectra

It was not convenient to try to compute a Burg (1975) prediction filter for 2500 lags for each 100 trace seismic record. However, because the signal-like shot generated spectral density is much less than the noise spectral density, only a mild antialias filter is needed before resampling each trace from 2 ms to a 20 ms sampling interval. A 200 ms, 100 samples, zero phase, Hanning smoothing filter was convolved with each trace. Its effect on Trace #50 is shown by the smooth red curve in Figure 1. Note the truncation edge effects that contaminate the filtered values during the first and last 100 ms of the red curve. The remaining 4800 ms interval was resampled into 241 samples spaced 20 ms apart. Ensemble Burg spectral estimation (230 lags, 4600 ms) yielded the two additional curves shown in Figure 4. The Burg spectral noise peaks now appear near 0.10 to 0.12 Hz with a modestly improved spectral resolution. Above 0.5 Hz, the Burg spectral estimates do not appear significantly different from the Fourier spectral estimates.

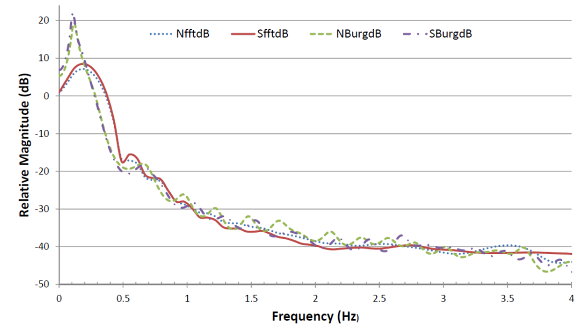

Figure 4: FFT spectra, 0 to 4 Hz, from Hanning tapered 100 trace ensembles with and without air gun shot compared with equivalent Burg spectra.

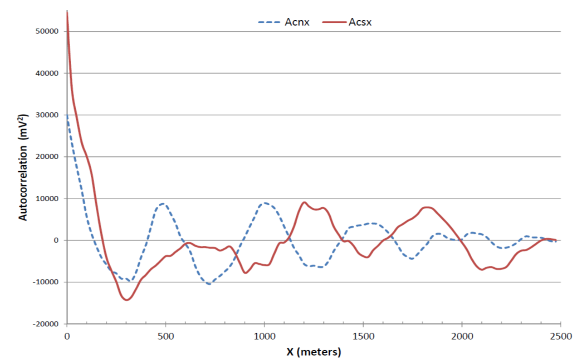

Figure 5: Spatial autocorrelations from 100 trace ensembles with and without air gun shot.

Noise Wavelengths

Because the very low frequency noise dominates a very narrow frequency band, the average spatial autocorrelation reveals some interesting features. The curves in Figure 5 show the values of the 100 spatial correlation lags when summed across the 2501 time samples within each seismic record. As a result of summing the squares of the same 250100 sample values in each ensemble, the peak, zero-shift, values of these two curves are identical to the zero shift values of the two temporal autocorrelation curves in Figure 2. The average spatial correlation behavior is striking with or without an air gun shot. The nearest 300 meters of each curve seems to be controlled by a different mechanism than the lags beyond 500 or 800 meters. Moreover, the dominant wavelength differs between these two ensembles even though they are at the same location and separated in time by less than a minute. A 500 meter periodicity persists out to 2000 meters without an air gun shot. The air gun shot puts considerably more energy into lags that are less than 500 to 1000 meters. Between lags of 1000 meters to 2500 meters, the air gun record seems to be periodic with a wavelength near 600 meters.

NOTE: The respective products of the apparent frequencies (0.12 or 0.10 Hz) and wavelengths (500 or 600 meters) yields an apparent speed of noise propagation near 60 m/s that is slightly faster than the speed of ocean swell (gravity waves) expected in the 40 to 50 m water depths of these ocean bottom sensors.

DIGITAL FILTERING RESULTS

Since the very low frequency noises, which are mostly below 0.2 Hz, are well separated from the shot generated signals, which are mostly above 2 Hz, the simple engineering solution is to devise a temporal filter to suppress the noise relative to the signal. The hydrophone sensor has already provided 6 dB/octave (20 dB/decade) suppression. Implementing an additional 2 Hz @ 12 dB/octave filter in the recording instrument could have provided another 52 dB of suppression at 0.1 Hz without any temporal edge effects. Such a filter would have been just enough to whiten the low frequency noise into insignificance.

Unfortunately, this seismic data set has already been recorded so it is necessary to devise a temporal filter in the computer that does not exhibit the large, finite impulse response (FIR), convolution, edge effects like those visible in Figure 1. The trace to trace, variable, transients at the beginning of the filtered record can make the shallow data "flutter" spatially. The varying transients at the end of each filtered record can sweep up into "migration smiles" visible at any level within a final section. Applying a causal or anti-causal FIR filter can alleviate either the initial or final transient but not both.

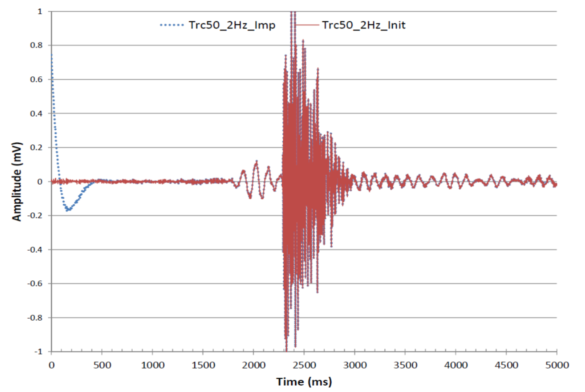

Figure 6: Trace 50 from 100 trace shot ensemble after 2 Hz @ 12 dB/octave digital Butterworth filter. Blue dotted line is causal convolution. Solid red line is same filter with initial conditions.

Recursive infinite impulse response (IIR) filters have several advantages over FIR filters. An IIR filter needs only a few coefficients to represent long impulse responses that are needed to suppress low frequency noises. Both IIR and FIR filters are linear and an output can be expressed as a linear superposition of separate input sequences before or after the start or end of a trace. Finally, the effects of all past values on all future output values can be expressed by only one real number for each order of a recursive filter.

As shown by the dotted blue curve in Figure 6, the impulse response of a causal, 2nd order, 2 Hz @ 12 dB/octave digital Butterworth filter has an initial edge effect that persists for about 500 ms but does not have any edge effect at the end of the record. The solid red curve in Figure 6 has neither an initial nor a final edge effect. It is the result of applying the identical Butterworth filter after estimating initial conditions appropriate for an infinite past history of that trace.

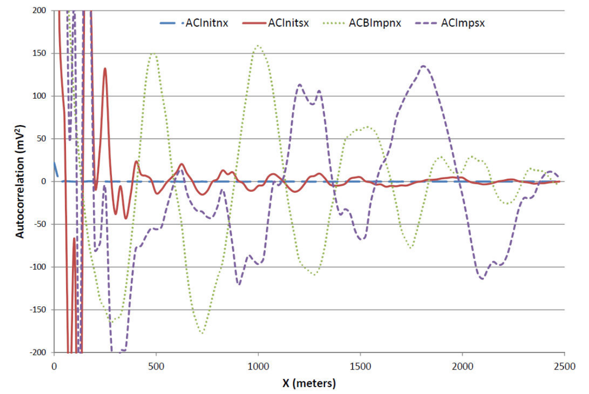

Figure 7: Spatial autocorrelations from 100 trace ensembles with and without air gun shot after2 Hz @ 12 dB/octave digital Butterworth filter.

A 2nd order Butterworth filter needs only two real numbers to represent the effects of an infinite number of past values. The appropriate two initialization values can be estimated for each trace in an ensemble in order to minimize the effects due to the initial edge, as demonstrated by the red curve in Figure 6. Improved spatial autocorrelations are shown in Figure 7. The two dotted curves show that long wavelength periodicities persist when the IIR impulse is convolved with the ensemble but the initial edge effects are not removed. The dashed blue curve shows that the noise ensemble has no visible periodicities at any wavelength when the IIR filter is initialized for an infinite number of past values. The solid red curve shows that an ensemble with an air gun shot is strongly correlated within the first few hundred meters. The smaller correlations at larger lags are presumed to be due to shot generated reflections or any of the multiple paths between the sources and receivers.

	Signal:SQ	*Noise:SQ*	*S/N:dB*
Input	54505	30024	2.6
Filtered:Imp	12110	486	14
Filtered:Init	11501	22	27

Table 1: Sum of squared values for 100 trace ensembles with and without air gun shot. First row: raw input. Second row: 2 Hz @ 12 dB/octave digital Butterworth filter. Third row: same filter with initial conditions

Table 1 shows a simple estimate of the average signal-to-noise ratio that is based upon sums of the squared values for all of the sample values within ensembles with and without an air gun shot. The first row shows the peak values of the temporal or spatial autocorrelations of the input ensembles as displayed in Figures 2 and 5. The average signal-to-noise ratio of the input is only 2.6 dB by this measure. After applying the 2nd order Butterworth filter as a convolutional impulse, peak autocorrelation values of both ensembles are reduced, as shown in the second row. The S/N ratio has been improved to 14 dB. This is a significant, 11 dB improvement, but the initial edge effect can still contaminate the early parts of the traces. After initialization, the 2nd order Butterworth filter changes the signal-like peak autocorrelation value in the third row by only a small amount, but the noise-like peak value drops dramatically. Correctly initializing the temporal filter improves the spatial autocorrelation estimate of the S/N ratio to 27 dB, an improvement of 24 dB.

CONCLUSIONS

Very low frequency seismic noise is an unintended consequence of the improved low frequency sensitivity of modern ocean bottom sensors and recording instruments. Observations of very low frequency noise are ubiquitous. For a hydrophone sensor example from the western coast of Australia, the noise ensemble peak frequency is near 0.12 Hz with wavelength periodicities near 500 meters. Without an air gun shot, more than 99% of the spectral distribution is below 0.5 Hz. The ensemble with an air gun shot has a peak frequency near 0.10 Hz with wavelength periodicities near 600 meters. This very low frequency noise is not shot generated because its amplitude remains very large with or without an air gun shot and its apparent speed of propagation (~60 m/s) is very small.

The noise frequency is much below those expected for seismic signals so this noise is commonly ignored or casually suppressed with convolutional low-cut filters. However, the noise amplitude is so large that there may be serious consequences for analysis, processing, or interpretation if the noise is only partially suppressed or any filter edge effects are ignored. A best practice would have been suppression of this noise before it was recorded.

Conventional digital convolution filters generally have significant truncation edge effects at the beginning or end of a seismic record. However, recursive digital filters can be applied without significant edge effects because the contribution from all past values to all future output values can be expressed by only one real number for each order of a recursive filter. For this example from Australia, correctly initializing a causal, 2nd order, 2 Hz @ 12 dB/octave digital Butterworth filter improves an S/N ratio estimate by 24 dB.

REFERENCES

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