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De-noising of WA seismic sections by a coherence filter

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Abstract - A new de-noising algorithm was implemented to perform a signal enhancement on high-density wide-angle reflection/refraction seismic sections (WARR). The algorithm was designed such as to attenuate more intensely the signal components that turn out less coherent within given offset intervals. A component is assumed here to be a portion in a short time interval of a single detail of the multi-resolution analysis of a trace. The filtered details are finally synthesised. The algorithm was given the name CDF, which stands for Coherence Detail Filter. The effectiveness of this filter was evaluated through a quantitative comparison between the results achieved from its application to noisy synthetic sections and those obtained with other filters widely used in seismic processing.

1. Introduction

There are a great deal of algorithms in the literature designed for the de-noising of seismic sections using lateral coherence, which is assumed to be a property of the seismic phases to be detected, apart from coherent noise that will have to be removed by other specific procedures.

Generally, these filtering techniques were developed to process near-vertical reflection data, though their adaptation to high-density wide-angle data processing has become necessary in the last years.

The simplest de-noising techniques consist of stacking, normalised or weighted in various ways over seismic traces characterised by different offsets.

Many algorithms are based on the employment of coherence estimators, which may be constituted by cross-correlation functions of two or more traces of different offsets. A particularly suitable algorithm to detect weak arrivals inside larger amplitude signals is C_{PCC} or phase cross-correlation (Schimmel, 1999), an amplitude-unbiased coherence measure based on the signal Hilbert transform.

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Another coherence parameter is semblance (Neidell and Taner, 1971), which denotes the ratio between the total stack energy within a window and the sum of the energies of the single traces.

The MCW algorithm (Chironi et al., 1997) is a stacking technique which operates within a space-time window moving inside the section. It attributes to each signal, shifted so as to maximise lateral coherence, a weight calculated on the basis of its cross-correlation with respect to the central trace in the window.

A coherence filter which is largely used in NVR seismics extracts the coherent energy fraction in a space-time window of a seismic section by decomposing the signal into eigenimages and selecting those corresponding to the highest eigenvalues of the cross-energy matrix (Kramer and Mathews, 1956).

2. The CDF filter

In order to achieve a filter capable of enhancing the coherent signal in a seismic section but producing fewer distortions on it than the filter based on the eigenimage decomposition, an algorithm was designed (Carrozzo et al., 2002), based on the multi-resolution analysis of traces, determination of the space-time distribution of a coherence index, modulation of each detail with a decreasing function of this index, synthesis of the modulated details.

The multi-resolution analysis of seismic signals, in other words their representation, through decomposition, into a wavelet basis, was considered for its high resolving power both in frequency and time domain, and thus for its efficacy in representing non-stationary signals.

The discrete wavelet transform (DWT) of a signal $f(t)$ is expressed by

$$\tilde{w}_{l,k} = \int_{-\infty}^{\infty} f(t)\, \psi_{l,k}(t)\, dt, \tag{1}$$

where $\psi_{l,k}$ is the discrete family of orthonormal wavelets obtained by dilating or contracting the mother function $\psi(t) \equiv \psi_{0,0}(t)$ and $l,k \in Z$ are respectively the scale and the translation parameters.

The inverse wavelet transform is expressed as

$$f(t) = \sum_{l=-\infty}^{+\infty} \sum_{k=-\infty}^{+\infty} \tilde{w}_{l,k}\, \psi_{l,k}(t), \tag{2}$$

where $\tilde{w}_{l,k}$ are the wavelet coefficients.

The DWT enables one to perform a multi-resolution analysis of the signal according to the block diagram in Fig. 1. An example of multi-resolution analysis is shown in Fig. 2.

The Coherence Detail Filter (CDF) is based on the following assumptions:

- the offset interval within which the correlation coefficients between arbitrary pairs of signals exceed a reasonably fixed threshold (coherence interval) is wider for the pure signal than for noise;
- the same assumption of the previous step holds for each detail of multi-resolution analysis, even though the coherence interval generally becomes narrower as its resolution increases;

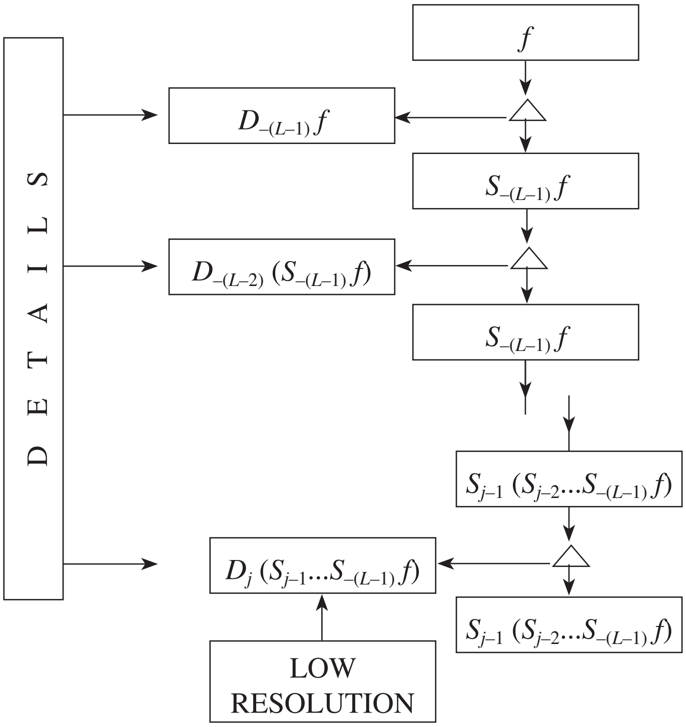

Fig. 1 - Block diagram of the DWT algorithm.

- the signal-to-noise ratio generally has a different time distribution in each detail.

The basic steps of the CDF algorithm are sketched in Fig. 3.

At first a 3D array (detail matrix) is set up containing the details of all traces of the section to be filtered. A window including the details of q consecutive traces (offset window) is made to shift one trace at a time along the offset axis spanning the whole section. Inside this window a second one of size $z \times q \times k$ (analysis window), which spans the time axis at each offset position, is defined.

A vector of coherence attributes having length equal to the number of considered details k is then calculated inside the analysis window and attributed to the z-th time and q-th offset position. The attribute relative to the j-th detail is given by a linear combination over the covered offset range of selected powers of the maximum correlation coefficients between each trace and that lying at the q-th offset, each maximum being chosen by time-shifting the trace with respect to the q-th one within an interval determined by the limiting of apparent velocities expected in that portion of section.

As a whole time path is completed, the coherence vectors will have been collected into a matrix of coherence attributes relative to the q-th trace. The matrix is then transformed into a weight matrix, used to modulate the details of that trace before these are synthesised into a new filtered trace. It has been observed that the introduction of a feedback by replacing the processed trace into the input section increases the filter performance.

To optimise the filter, some input parameters have to be properly fixed, like the size of the moving windows, the scales of multi-resolution analysis and the weighting factors.

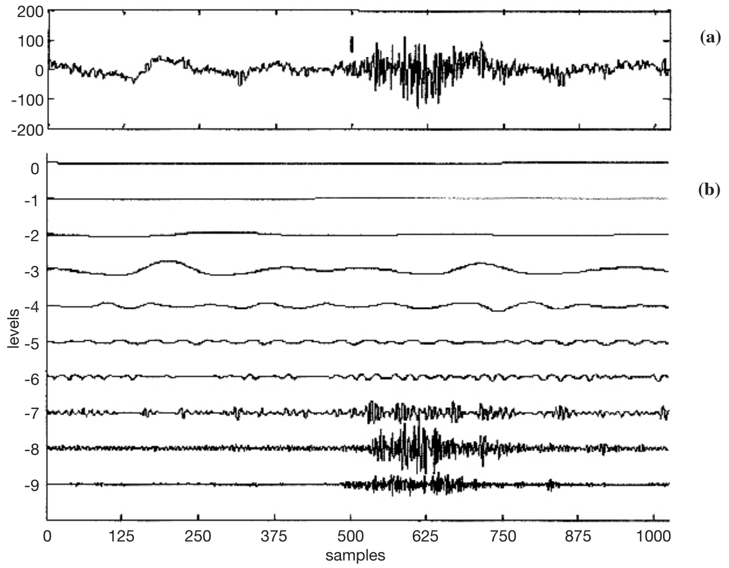

Fig. 2 - Plot of an experimental seismic trace (a) and its multi-resolution analysis (b).

3. Filter performance

The quality of the CDF filter was assessed through a comparative analysis with other filters widely used in seismic processing.

For this purpose, a synthetic section was calculated on the basis of a typical crustal velocity model. It was then perturbed by summing to it a random noise and another with a spectrum typical of natural noise. To test the algorithm in different noise conditions, three sections were generated with signal-to-noise ratio (S/N) equal to 0.2, 0.5 and 1, respectively.

The filters used for the comparative analysis were a Butterworth band-pass filter with cut-off frequencies 2 Hz and 18 Hz (frequency filter: FF), a coherence filter, based on the eigenimage decomposition of a group of consecutive traces and its subsequent reconstruction by the most coherent eigenimages, applied after a band-pass frequency filter and a horizontal stacking (FF + STACK + ED), and finally a soft-thresholding de-nosing algorithm based on single-trace wavelet decomposition and synthesis after a typical kind of thresholding on the wavelet transform coefficients (ST).

Some comparative parameters were defined, capable of evaluating the relative effectiveness of the compared filters in terms of S/N ratio and lateral correlation increase as well as the distortion degree produced.

The first parameter, G_e, is the coherent-energy gain produced by the filter. It is given by

$$G_e = \left[\frac{(E^s_{2c} - E^n_{2c})\, E^t_1}{(E^s_{1c} - E^n_{1c})\, E^t_2} - 1 \right] \cdot 100, \tag{3}$$

where E^s_{2c} and E^n_{2c} are respectively the horizontally correlated energy present in the filtered section and that of the background noise incidentally generated in the same section, E^s_{1c} and

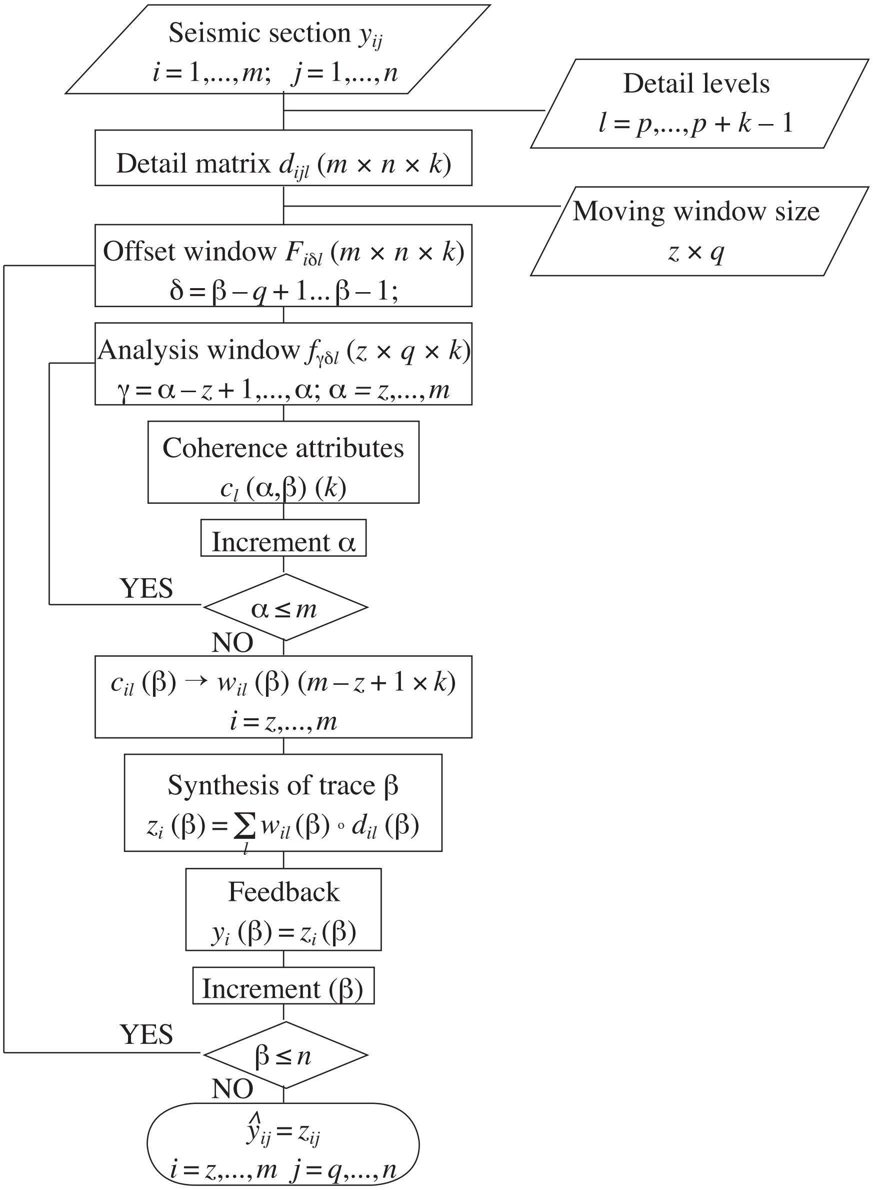

Fig. 3 - Block diagram of the CDF de-noising algorithm.

E^n_{1c} are the corresponding parameters relative to the original section and E^t_2 and E^t_1 are the total energy in the filtered and in the original section respectively.

The correlation extension gain, G_a, defined as

$$G_a = \left[\frac{N^s_{2c} - N^n_{2c}}{N^s_{1c} - N^n_{1c}} - 1\right] \cdot 100, \tag{4}$$

quantifies the increase of coherence in terms of broadening of the area occupied by the coherent signal. The terms N^s_{2c} and N^n_{2c} represent the number of seismic section samples for which there is horizontally correlated energy respectively in the filtered section and in its background noise, N_{1c}^{s} and N_{1c}^{n} are the corresponding number of samples present in the original section.

Other comparative parameters are the fraction of removed energy, ε, defined as

$$\varepsilon = \frac{E_1^t - E_2^t}{E_1^t} \cdot 100, \tag{5}$$

and the correlated energy loss in the residual section, L_c, given by

$$L_c = \frac{(E_{2c}^{s} - E_{2c}^{n})\, E^{rt}}{(E_c^{rs} - E_c^{rn})\, E_2^t}\,, \tag{6}$$

where E_c^{rs} and E_c^{rn} are the correlated energies respectively in the residual section and in its background noise, E^{rt} is the total energy in the residual section.

Table 1 reports the estimates of the comparative parameters resulting from the application of the three filters to sections with different S/N ratios. The values are averages over the results of filtering several sections independently perturbed.

The coherent-energy gain supplied by CDF always turns out greater than the one relative to the other filters. The high G_a obtained with FF + STACK + ED, inconsistent at first sight with the low G_e, is mainly due to an unwanted widening of the signal coherence area near the phase of greatest amplitude (Fig. 4).

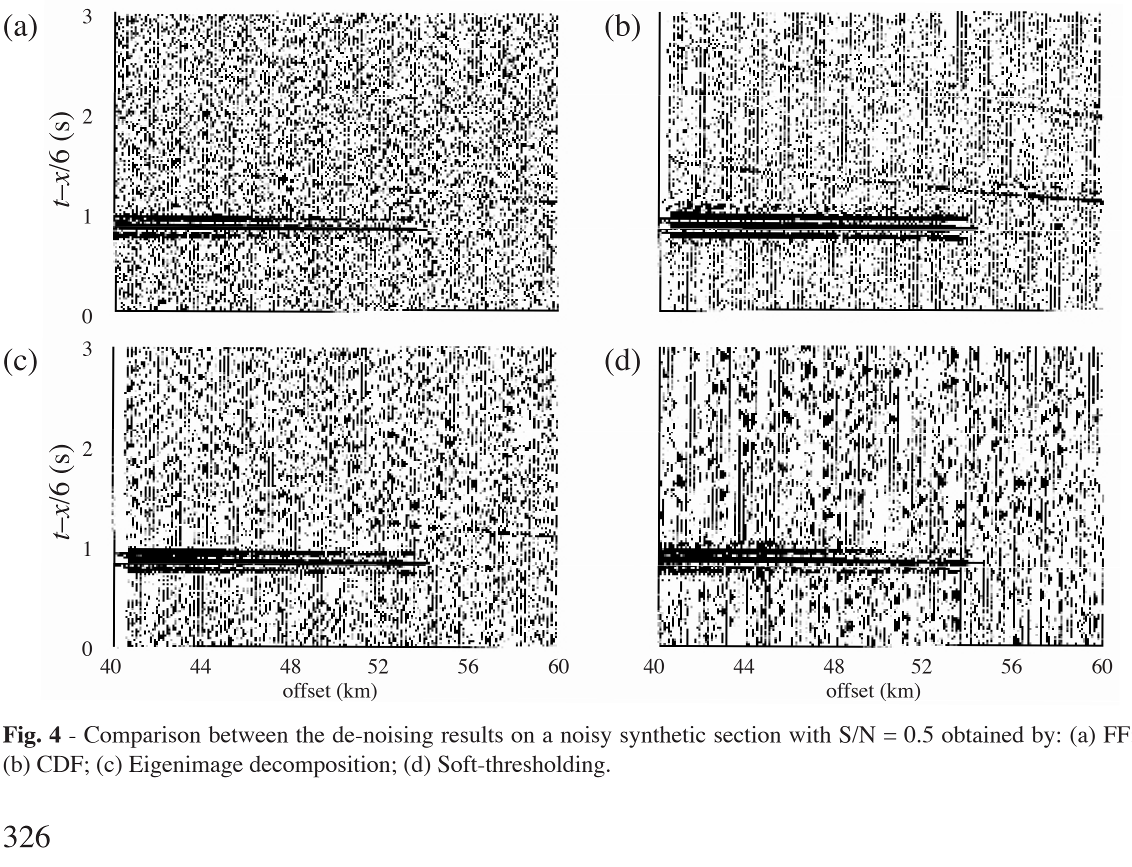

Fig. 4 - Comparison between the de-noising results on a noisy synthetic section with S/N = 0.5 obtained by: (a) FF; (b) CDF; (c) Eigenimage decomposition; (d) Soft-thresholding.

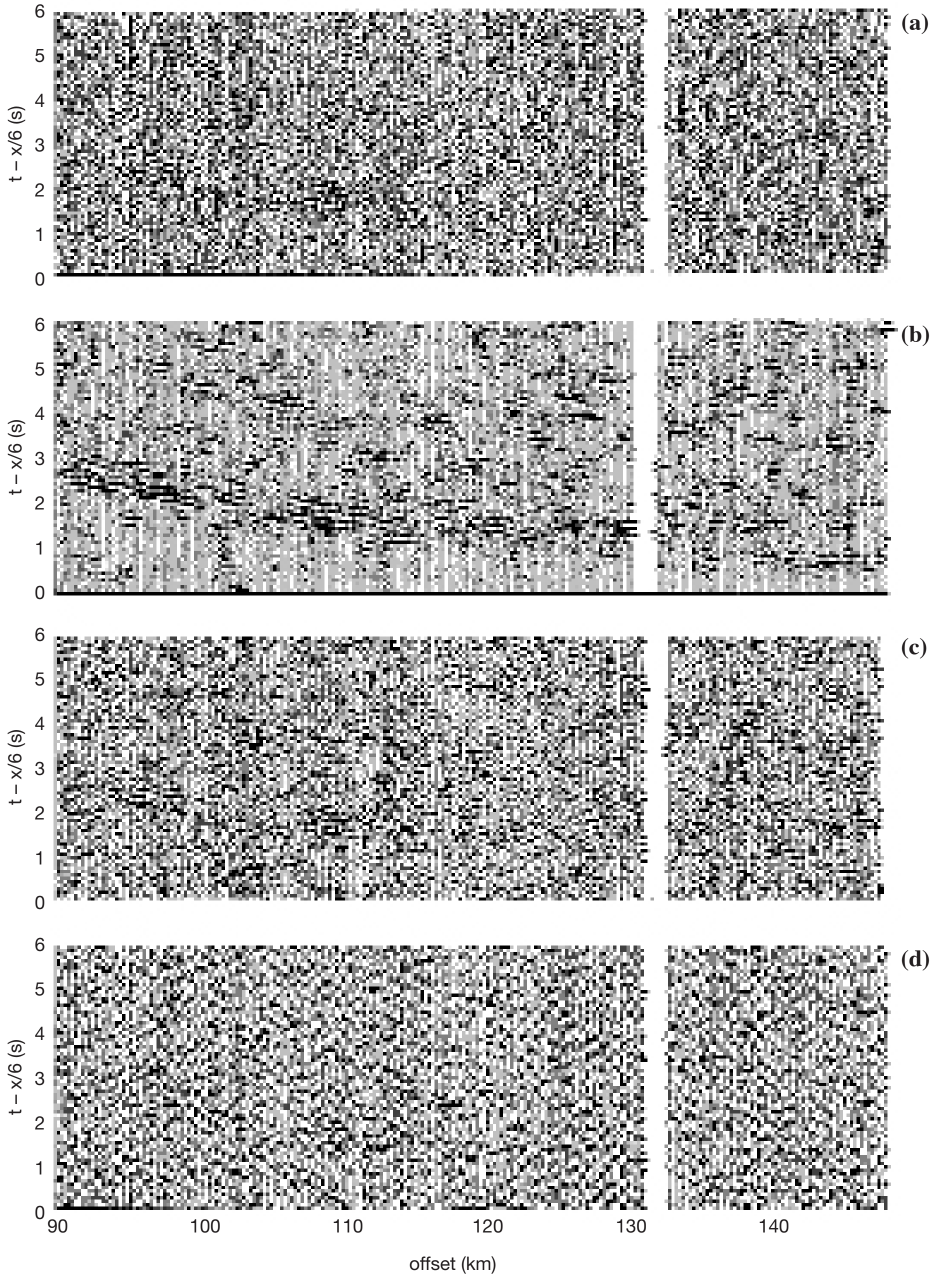

Fig. 5 - Comparison between the de-noising results on the Crop Mare II WARR section M39 (Chironi et al., 2000) obtained by: (a) FF; (b) CDF; (c) Eigenimage decomposition; (d) Soft-thresholding.

The soft-thresholding technique, on the contrary, gives a high coherent-energy gain along with a loss of signal coherence area. This suggests that this filter behaves effectively solely on zones with a high S/N.

The values of ε and L_c indicate that the CDF algorithm removed more energy than the other filters, but its residual section has a lower fraction of coherent energy.

Table 1 - Estimates of comparative parameters obtained with different methods and S/N ratios.

S/N	Method	G_e (%)	G_a (%)	ε (%)	L_c
1	FF (2-18 Hz)	49	7	35	-
	FF + STACK + ED	65	92	40	6.2
	ST (sym8)	73	-43	57	10.9
	CDF (sym8)	90	70	67	13.6
0.5	FF (2-18 Hz)	80	8	47	-
	FF + STACK + ED	123	84	55	10.6
	ST (sym8)	128	-37	70	13.0
	CDF (sym8)	175	67	81	18.2
0.2	FF (2-18 Hz)	126	9	60	-
	FF + STACK + ED	250	99	72	22.2
	ST (sym8)	232	-33	83	15.1
	CDF (sym8)	424	74	94	17.3

4. Conclusions

By using a criterion based on the discrimination of the different coherence characteristics of the signal and noise, a de-noising technique was designed which proved more effective than current widespread filtering methods for wide-angle seismic sections.

The application of a CDF filter to synthetic data perturbed with different noise levels revealed its capability of enhancing the S/N without introducing appreciable distortions on the signal.

The application of a CDF filter to experimental seismic sections even with a high initial S/N always supplied filtered sections with an increased number of correlatable phases (Fig. 5).

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