EAGE-99: 1-10

MSvE - a novel approach to statistical estimation of primaries superimposed on incoherent multiples

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Introduction

The problem of attenuation of multiples is of permanent interest for theoreticians as well as for practical geophysicists (e.g. [1]). Classical approaches to suppression of multiples exploit a well-seen self-repetition of wave-forms, resulting in a rather high correlation of primaries and respective multiples (*coherent*-, or wave-form preserved-, reverberations). In a routine processing of marine data it gives a good result, when the multiples are associated mainly with the water-layer reverberations in a locally 1D-environment, with a fairly simple layering of a sea-bed. Multiple Suppression via Envelopes (let us call it **MSvE**), exposed here, aims to deal with elimination of multiples which are *incoherent,* albeit well-seen, with primaries. Losses of coherency can be of different physical grounds, while the relevant statistical aspects are general for the transition: wave/transfer phenomena. The coherency losses can be associated, e.g., with dispersion, absorption, with thin-layer slabs forming a sea-floor, lateral variation of layering or inhomogeneities, traps and so forth, i.e. these effects are highly expectable at the most of geological regions of interest. We utilize the fact that despite the phase portrait of multiples can be drastically destroyed, they can be still well-seen as a self-repetition of envelope-forms. Statistical estimation/extraction of primaries is based therefore upon low-frequency components of envelopes induced by multiples. Because of the non-stationarity of the time series/records the relevant mask-filter is constructed directly in the τ-domain. The strategy of *MSvE* is analogous to that one of predictive deconvolution: " find self-repetitions of records", but utilizes properly evaluated low-frequency envelope-forms of the time series, not the wave-forms themselves, besides the relevant prediction-error filter is of non-Wiener design, which we elaborated earlier for elimination of coherent multiples [5]. In its turn the envelopes are the result of a few-parameter transform based on statistical interpretation of a pulse propagation in a deterministic media of an intricate layered structure. *MSvE* yields a fast and robust way to detect self-repetitions for the records of strong interference and thus to attenuate multiples: eliminating from an envelope such energetic wavelets which rehashes the envelope itself, we get a relative mask-filter in a $\tau-$domain.

Multiple Suppression via Envelopes (*MSvE*)

To clarify the strategy of elimination of multiples via envelopes, let a τ-record $D = D(\tau)$ in a chosen window $[\tau - \Delta/2, \tau + \Delta/2]$ contain primaries of interest (*signal* S) and noise of multiples N. The latter is supposed to be a linear combination of foregoing primaries $\overleftarrow{P}$: $N(\tau) = r_{\tau\tau'}\ \overleftarrow{P(\tau')}$, where $r_{\tau\tau'}$ stands for the reflection coefficients and respective τ-shifts.
Then

$$D^2 = (S + N)^2 = (S + r\ \overleftarrow{P})^2$$

Let us now take en *envelope* $\widetilde{D^2}\ (\tau)$ instead of $D^2(\tau)$ (Fig.1, **B**), averaging the latter over the moving τ-window of the width $\Delta \gg \Delta_0$, (Δ_0 is a characteristic length of the source wavelet) and centered at τ (see comments on the design of the weighting function):

$$\widetilde{D^2} = \langle D^2 \rangle_\Delta = \langle (S + r\ \overleftarrow{P})^2 \rangle_\Delta = \langle S^2 + r^2\ \overleftarrow{P^2} + 2Sr\ \overleftarrow{P} \rangle_\Delta \tag{1}$$

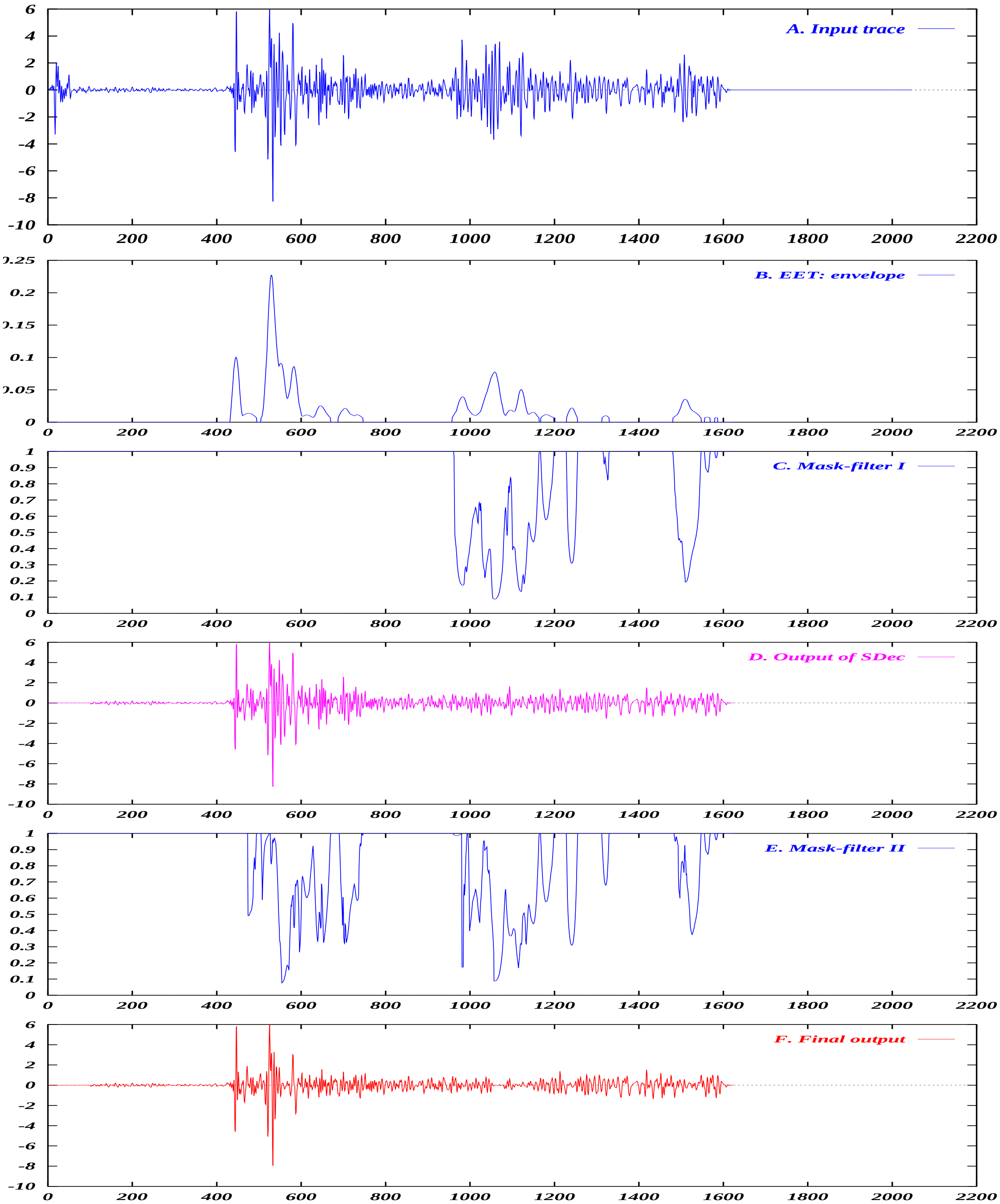

Figure 1: Example of **MSvE**-run: one of p-τ traces of real data corrupted with incoherent multiples. Besides a sea-surface two main horizons generate multiples: a thin-layer slab forming a sea-floor and basalt beneath. • **A. Input trace;** • **B. EET output: Envelope;** • **C. Mask-filter I**, responsible for removal of all of a free-surface related multiples; • **D. Respective output I;** • **E. Mask-filter II**, responsible for removal of intrabed reverberations sea-floor - basalt; • **F. Final output of MSvE**. Unfortunately, the fragment we got did not contain primaries.

Taking into account that in general primaries S and multiples $r\,\overleftarrow{P}$ are out of phase, the result of a proper chosen averaging is expected to be negligible: $\langle\, r\,\overleftarrow{P}\,S\,\rangle_\Delta \;\approx\; 0,$, and hence

$$\widetilde{D}^2 \approx \langle\, S^2 \,+\, r^2\;\overleftarrow{P}^2\,\rangle_\Delta \tag{2}$$

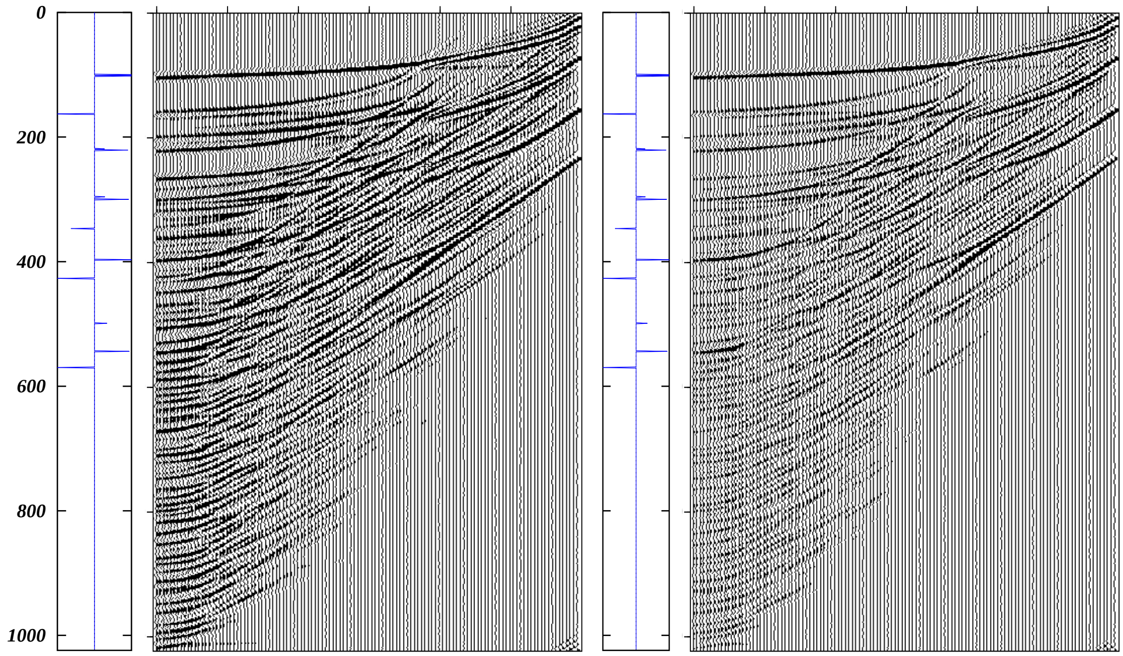

Figure 2: Trial run of **MSvE** with synthetic 1.5 D marine data: just to illustrate the capability of **MSvE** to save primaries superimposed on multiples, being even precisely coherent. Two Common Source Gathers in $p-\tau$ domain: • **Left:** Input of MSvE; • **Right: Output.** `Two narrow columns in between represent a theoretical impulse trace of primaries: normal incidence`

Let the result of elimination of multiples from the envelope $\widetilde{D}^2\,(\tau)$ be notated as $\overline{\widetilde{D}^2}(\tau)$. In terms of envelopes the latter can be written as follows:

$$\overline{\widetilde{D}^2}(\tau) = \widetilde{D}^2\,(\tau) - \widehat{r^2_{\tau\tau'}}\;\widetilde{P}^2\,(\tau') = \langle\, S^2 + r^2\;\overleftarrow{P}^2\,\rangle_\Delta - \widehat{r^2}\langle\,\overleftarrow{P}^2\,\rangle_\Delta = \langle\, S^2 + (r^2 - \widehat{r^2})\;\overleftarrow{P}^2\,\rangle_\Delta \tag{3}$$

where $\widehat{r^2}$ is an estimate of (positive) prediction-error-filter coefficients. To return to the τ-record $D(\tau)$ we introduce a mask-filter $\mathcal{M}(\tau)$ (see Fig.1, **C** and **E**):

$$\mathcal{M}(\tau) = \frac{\overline{\widetilde{D}^2}}{\widetilde{D}^2}(\tau) = \frac{\langle\, S^2 + (r^2 - \widehat{r^2})\;\overleftarrow{P}^2\,\rangle_\Delta}{\langle\, S^2 + r^2\;\overleftarrow{P}^2\,\rangle_\Delta} = \frac{\langle\, S^2 + \delta N^2\,\rangle_\Delta}{\langle\, S^2 + N^2\,\rangle_\Delta} \tag{4}$$

where $\delta = (r^2 - \widehat{r^2})/r^2$ tends to 0 when the estimate $\widehat{r^2}$ is fairly good. To some extent the mask-filter is analogous to a mask of band-pass filters, but acts in a τ-domain. Finally, to get the desired estimate of the primaries $\widehat{S(\tau)}$ we undergo the record $D(\tau)$ to filtering with the mask $\mathcal{M}(\tau)$:

$$\widehat{S(\tau)} = \mathcal{M}(\tau)\,D(\tau) \tag{5}$$

Analysis of Eqs.4 and 5 shows, that the approach results in eliminating of multiples and keeping in an existing state of primaries, provided: **a** in a chosen time-window the energy of primaries is higher than the energy of primaries, and **b** the estimate of $\mathcal{M}(\tau)$, i.e. coefficients $\widehat{r^2}$, should be reasonably reliable. To afford the **b**-condition we put into operation the Sharp Deconvolution [5].

A few comments, conclusion, discussion

• The elaborated algorithm of *MSvE* is of very low computational costs (a few seconds per 100 traces on a HP PC), acts in a fully automatic mode (all of parameters involved are self-adaptive), robust (see, e.g., Fig. 2: despite every trace was processed quite independently, there is no continuity loss in the p-direction Fig. 2, **Right**), and, hopefully, it is feasible for development and implementation into processing practice. • We introduced the **e**nergetic **e**nvelope **t**ransform (EET) in [3] to avoid, say so, the very sophisticated problem of a "ray-path" interpretation of coda in seismological records, under uncertainties in a lithosphere model. Due to autoscaling of wave phenomena there are lots of similarities in the seismic exploration. The design of EET is based on a so called *diffusion regularization,* which we introduced in [4]. Diffusion regularization admits to interpret a time series as a random realization of a relevant diffusion process. In this abstract we omit details of EET-operator $\mathcal{E}$ design and give just the relevant criterion:

$$\mathrm{Tr}\,[(I-\mathcal{E})\mathrm{e}^{\alpha\nabla_\tau^2}(I-\mathcal{E})^\dagger \;+\; \beta\mathcal{E}\mathcal{E}^\dagger] \;=\; \mathrm{Tr}\,[(I-\mathcal{E})^2\mathrm{e}^{\alpha\nabla_\tau^2} \;+\; \beta\mathcal{E}^2] \;=\; \min_{\mathcal{E}} \tag{6}$$

where ∇_τ stands for the derivative with respect to τ, the exponential operator $\mathrm{e}^{\alpha\nabla_\tau^2}$ itself represents the convolution with a Gaussian curve, and α is a "parameter of diffusion": the less is a coherence the larger should be α. The operator $\mathcal{E}$ is a Toeplitz one, thus EET is reduced to a convolution, and the Eq.1 can be rewritten in a form:

$$\tilde{D^2} \;=\; \mathcal{E}D^2 \;=\; e * D^2,$$

where $*$ is a convolution, and e defines the relevant weighting function used for averaging in Eq. 1.

• Criterion on Sharp Deconvolution (SDec) design [5]:

$$||(I+r)\varphi||^2 \;+\; \gamma||\mathcal{S}r||^2 \;=\; \min_{r} \tag{7}$$

where $\mathcal{S} \;=<\varphi_\tau\varphi_{\tau'}>^{-1/2}$, while $<\varphi_\tau\varphi_{\tau'}>$ denotes an autocorrelator of $\varphi \;=\; D$ in the "conventional **SDec**" (it allows us to remove successfully all *coherent* multiples) and $\varphi = \tilde{D^2}$ in the **MSvE**. Note, that the 2nd functional (*regularizer*) in the criterion 7 results in non-Wiener filter design, yielding much more robust algorithms [5].

• The 2nd order operator in the Sharp Deconvolution, responsible for the removal of intrabed multiples:

$$||(I+\tilde{r})T_\tau\tilde{w}^\star||^2 \;+\; \gamma||\mathcal{S}\tilde{r}||^2 \;=\; \min_{\tilde{r}} \tag{8}$$

where $\tilde{w}^\star$ is an output of the 1st step, and T_τ stands for the shift of $\tau \;=\; 0:$ "reduction to the sea-floor". The 2nd order operator allows us to eliminate intrabed multiples (example is given with Fig.1, $\mathbf{D} \rightarrow \mathbf{F}$.).

• The strategy of Multiple Suppression via Envelope does not assume that a seismic trace can be always represented as a result of interference of a few time/τ - shifted given wave-forms: even when it is true, it is hard to detect the necessary parameters under uncertainties in a medium models. Sure, it is possible to estimate the parameters when the model is given, but then the goal of the multiple suppression problem becomes rather questionable, does not it?

Acknowledgements

The research was stimulated by a short-term project, having stipulated an evolvement of the industrial package *Remul* (Norsk Hydro Research Centre, D.Lokshtanov and A.Sagehaug [2]). We are grateful to D.Lokshtanov, who has been providing us with *blind* synthetic/real data and severe critic on the MSvE. We are also thankful to Prof.Dirk Gajewski (University of Hamburg) who supplied us with reflectivity codes: all preliminary numerical experiments have been carried out with those ones. The relevant files were displayed with SeismicUnix package: thanks to The Center for Wave Phenomena, to John Stockwell in particular. We would like to express our gratitude to colleagues from the Institute of Physics, to Prof. Jakob J.Stamnes especially.

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