Surface-consistent matching filter for time-lapse processing

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Summary

We design a suite of surface-consistent matching filters for processing time-lapse seismic data in a surface-consistent manner. The frequency-domain surface-consistent design equations are similar to those for surface-consistent deconvolution except that the data term is the spectral ratio of two surveys. We compute the spectral ratio in the time domain by first designing trace-sequential, least-squares match filters and then Fourier transforming them. A subsequent least-squares solution then factors the trace-sequential match filters into surface-consistent operators.

Introduction

It has become an industry practice to acquire multiple seismic surveys at regular time intervals to monitor subsurface changes due to hydrocarbon production or fluid injection. As exploration seismologists, our main objective is to obtain an image that represents our best estimate of the subsurface changes. This goal is challenged by the fact that seismic acquisition is nonrepeatable, and that diverts our attention from investigating the time-lapse difference to minimizing the nonrepeatability issues of seismic acquisition. There has been significant work published on processing time-lapse seismic, in particular that of Rickett and Lumley (2001) who discuss the details of the cross-equalization process that reduces the nonrepeatable noise caused by differences in vintage of seismic acquisition and processing. Cross-equalization is based on processing two repeated seismic surveys in parallel and taking the difference between them after each step. Generally, this cross-equalization process should show a progressive decrease in nonrepeatable noise and improvement in time-lapse changes (Rickett and Lumely, 2001).

The progressive decrease in nonrepeatable noise can be an exhaustive process. Instead, we propose a method that takes care of much of the nonrepeatable noise at the very beginning of the processing workflow. This method employs two basic concepts that are widely used in geophysical data processing: the surface-consistent model and matching filters. We will present an algorithm that combines both ideas and demonstrate its simplicity and advantage in processing time-lapse dataset.

Theory of surface-consistent matching filter

The surface-consistent model was first introduced by Taner and Koehler (1981) who suggested the recorded seismic trace can be modeled as the convolution of each trace's source effect, receiver effect, offset effect and midpoint effect. This model is similar to the one used for solving the static problem by Taner et al. (1974) and Wiggins et al. (1976). The surface-consistent model has been implemented by many authors to obtain a more accurate and stable deconvolution (Morley and Claerbout, 1983; Levin, 1989; Cambois and Stoffa, 1992; and Cary and Lorentz, 1993), and amplitude adjustment (Yu, 1985).

The time-domain form of the modeled seismic trace (Taner and Koehler, 1981; and Morley and Claerbout, 1983) is:

$$d_{ij}(t) = s_i(t) * r_j(t) * h_k(t) * y_l(t) \tag{1}$$

where $d_{ij}(t)$ is the seismic trace, t represents the time-domain, s_i is the source effect at the i^{th} location, r_j is the receiver effect at the j^{th} location, h_k is the offset effect, $k = |i - j|$, and y_l is the common midpoint effect, $l = \frac{i + j}{2}$. The asterisk ($*$) represents the convolution.

Extending the surface-consistent data model to the case of designing matching filters to equalize two seismic surveys, we write equation 1 as follow:

$$d1_{ij}(t) = s1_i(t) * r1_j(t) * h1_k(t) * y1_l(t) \tag{2}$$

$$d2_{ij}(t) = s2_i(t) * r2_j(t) * h2_k(t) * y2_l(t) \tag{3}$$

where indices 1 and 2 denote two datasets, a baseline survey and a monitoring survey, respectively. Fourier transforming equations 2 and 3 and forming their ratio and taking the logarithm gives

$$\log\left(\frac{d1_{ij}(\omega)}{d2_{ij}(\omega)}\right) = \log\left(\frac{s1_i}{s2_i}\right)(\omega) + \log\left(\frac{r1_j}{r2_j}\right)(\omega) + \log\left(\frac{h1_k}{h2_k}\right)(\omega) + \log\left(\frac{y1_l}{y2_l}\right)(\omega) \tag{4}$$

where ω is frequency, the left-hand side is the data log spectral ratio and the right-hand-side contains its surface consistent components and the "hat" denotes the Fourier transform. However, computing the ratio of two spectra directly is undesirable because there may be division by zero or very small numbers and the resulting time-domain match filter will match both signal and noise.

As a stable alternative, we compute a trace-sequential matching filter, $\underline{m}$, in the time-domain for pair of traces in the two surveys. The design equations for this filter are:

$$\underline{d}_1 = \underline{\underline{D}}_2 \underline{m} \tag{5}$$

where $\underline{d}_1$ and $\underline{d}_2$ represent the same trace from survey 1 and 2, respectively, and $\underline{\underline{D}}_2$ is a convolution matrix formed from $\underline{d}_2$. A Solution for equation 5 can be obtained such that the L_2 norm, $\left\|\underline{d}_1 - \underline{\underline{D}}_2 \underline{m}\right\|_2$, is minimum. Once this trace-by-trace matching filter is computed, the result is transformed into the frequency-domain, giving a stable estimate of the left-hand side of equation (4).

Now that we have obtained the data part of equation 4, we can solve it as a general linear inverse problem such that

$$\underline{d} = \underline{\underline{G}}\underline{x} \tag{6}$$

where $\underline{\underline{G}}$ is a coefficient matrix containing the positions of the sources, receivers, offsets, and common mid-points. The unknowns $\log\left(\frac{s1_i}{s2_i}\right)(\omega)$, $\log\left(\frac{r1_j}{r2_j}\right)(\omega)$, $\log\left(\frac{h1_k}{h2_k}\right)(\omega)$, and $\log\left(\frac{y1_l}{y2_l}\right)(\omega)$ are in the column vector $\underline{x}$. Figure 1 illustrates the general form of equation 6. Solving equation 6 is now straight forward where the aim is to minimize the $\left\|\underline{d} - \underline{\underline{G}}\underline{x}\right\|_2$. The solution for $\underline{x}$ can be decomposed into four-components: source component, receiver component, offset component, and common mid-point component. These components are the matching filters applied to the static section of the monitoring survey in order to match it to the baseline survey.

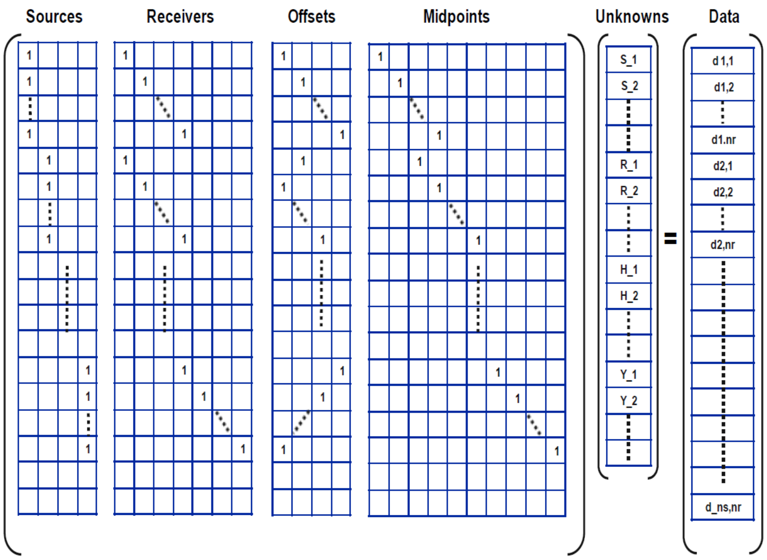


Figure 1: Matrix structure of the system of linear equation described in equation 6.

Example

To examine our new idea, we constructed a simple 2.5*km* wide and 1*km* thick 2D geometry. The model consists of four layers and a reservoir unit, 500*m* wide and 20*m* thick (Figure 2), between layers three and four. The velocity is homogeneous in each layer, except for the near-surface layer where lateral variations were introduced. Using this geometry, we generated two earth models, a baseline model and a monitoring model, with different near-surface and reservoir velocities. We created 51 shots with spacing 50*m* and 101 geophones per shot incremented by 10*m*. The maximum record length is 1*s* with a 4*ms* sampling interval. An acoustic finite-difference modeling algorithm is used to create the shot records. We have also added variations to the shot strengths and the receiver couplings to allow for the nonrepeatability observed in real seismic acquisition.

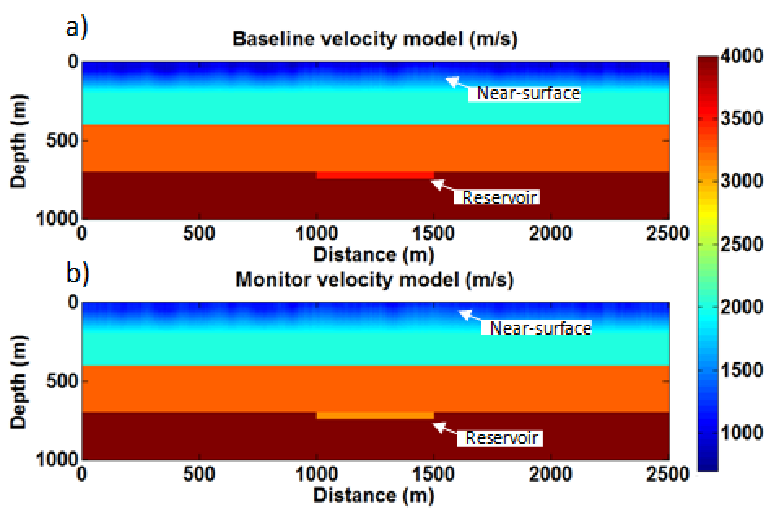


Figure 2: Earth model representing baseline model (a) and monitoring model (b). Both models have different near-surface and reservoir layer velocities.

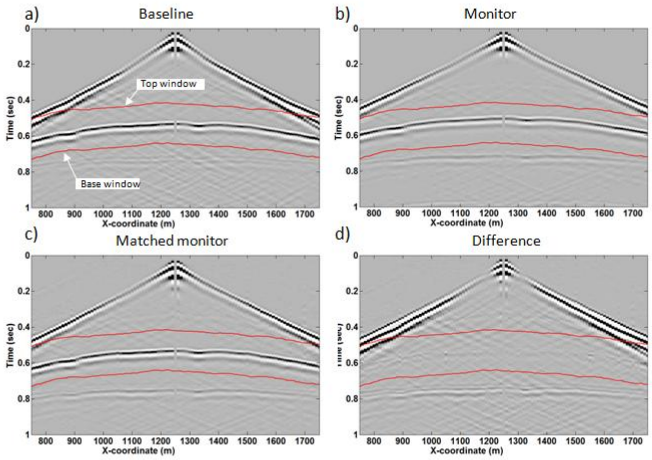
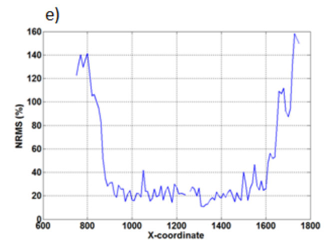


Figure 3: An example of a shot gather at x-coordinate 1250m from baseline survey (a), monitoring survey (b), matched monitoring survey (c) and the difference (d) between the baseline shot and the matched monitoring shot. The NRMS of the difference is shown in (e). The window of analysis is between the two red lines.



In Figure 3 we show an example of a single shot record located at x-coordinate 1250m from both the baseline survey and the monitoring survey. The computed four-component surface-consistent matching filter is applied to the monitoring survey and is shown in Figure 3c. The difference between the baseline survey shot record and the matched monitoring survey shot record is illustrated in Figure 3d and all plots have the same amplitude scaling as the baseline shot record. The difference is very small inside the matching filter window between the two red lines. In addition to this qualitative analysis of the difference, we plotted the NRMS (normalized root mean square) of the difference, only in the window of analysis, where small NRMS values indicate similarities between the traces of the baseline survey and the matched monitoring survey. Preferred values for NRMS are in the 20% range and those values are commonly obtained towards the final stages of processing. Our new technique was able to reduce the difference quite significantly down to about 20% in prestack stage prior to any processing (Figure 3e).

Conclusions

We have developed a method to design surface-consistent matching filters that can be used to match one dataset to another in a time-lapse experiment. Our method is similar to surface-consistent deconvolution except that the data required is the spectral ratio of each pair of traces in the survey. We compute the spectral ratios in a stable fashion as the Fourier transform of a least-squares matching filter for each pair of traces. Then we factor these trace sequential matching filters into surface consistent terms by a second least-squares solution. We have shown that the surface-consistent matching filter can significantly reduce the nonrepeatability often observed in time-lapse datasets.

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