Surface-consistent Matching Filters for Time-lapse Processing - Application to the Violet Grove Data Set

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Summary

A new algorithm for processing time-lapse seismic data is applied to the Violet Grove pilot data in central Alberta. Detecting time-lapse difference on this data has proved to be difficult due to the small impedance contrast at the Cardium reservoir where CO2 is injected and the low injection volume. However, we consider this data to examine the surface-consistent matching filters algorithm in order to minimize differences observed above the reservoir interval. These matching filters compensate for differences in amplitude, time, and phase at prestack level. After applying the surface-consistent matching filters to the monitor survey, we reduce most of the mismatch caused by acquisition differences and near surface variations. Differences caused by nonrepeatable noise in the data are difficult to remove since they are often nonstationary. The shallow window above the reservoir is dominated by the near-surface noise. Despite this issue, we notice an improvement in the prestack and the poststack difference image after applying the surface-consistent matching filters.
Introduction

CO₂ sequestration, also known as carbon capture and storage (CCS) in deep geological formations, is a multidisciplinary technology that involves capturing, transporting, and storing CO₂ gas. The geophysicist’s role in this technology includes evaluating the earth’s subsurface seismic response to the injected CO₂ gas. The earth’s subsurface variations include, but not limited to, P-wave and S-wave speeds decrease (e.g. Wang et al., 1998), density decrease (e.g. Avseth et al., 2005), increase in seismic wave attenuation (e.g. Hilterman, 2001), and other important seismic property changes reported in many geophysical papers. To monitor these effects, we acquire seismic data at different calendar times hoping to capture the subsurface change in the time-lapse seismic image.

Almutlaq and Margrave (2012) presented a prestack surface-consistent matching filters algorithm that minimizes the difference observed when processing time-lapse data, which is not related to reservoir changes, and reduce nonrepeatable noise. The algorithm was presented with modeled time-lapse data and in this paper we are applying it to a real data example from the Violet Grove CO₂-EOR site in Alberta, Canada (Alshuhail et al., 2011).

The surface-consistent matching filters

Almutlaq and Margrave (2012) showed that the surface-consistent data model can be extended to the case of designing matching filters to equalize two seismic surveys. This matching filter algorithm is based on Taner and Koehler (1981) surface-consistent model where a seismic trace is represented as the convolution of four terms expressed by:

\[ d_i(t) = s_i(t) * r_j(t) * h_k(t) * y_l(t) \]  

where \( * \) denotes convolution in the time domain, \( d_i(t) \) is the seismic trace resulting from the \( i^{th} \) source recorded into the \( j^{th} \) receiver, \( s_i(t) \) is source response, \( r_j(t) \) is receiver response, \( h_k(t) \) is offset response at offset location \( k \), and finally \( y_l(t) \) is midpoint response below surface location \( l \) (Indices \( k \) and \( l \) depend on \( i \) and \( j \) through the acquisition geometry).

Extending this model such that the data term represents two data sets, we can rewrite Eq. (1) with two subscripts: 1 for a baseline survey and 2 for a monitor survey. Now that we have expressed both surveys with their surface-consistent models, we can derive a set of matching filters that equalizes the monitor to the baseline (or vice versa) designed over a temporal window where changes are not expected. After extending the model, we Fourier transform the equations, form their ratio, and then express this spectral ratio in the log-Fourier domain as follows:

\[ \log \left( \frac{\hat{d}_{2i}(\omega)}{\hat{d}_{1i}(\omega)} \right) = \log \left( \frac{\hat{s}_{2i}(\omega)}{\hat{s}_{1i}(\omega)} \right) + \log \left( \frac{\hat{r}_{2j}(\omega)}{\hat{r}_{1j}(\omega)} \right) + \log \left( \frac{\hat{h}_{2k}(\omega)}{\hat{h}_{1k}(\omega)} \right) + \log \left( \frac{\hat{y}_{2l}(\omega)}{\hat{y}_{1l}(\omega)} \right), \]  

where \( \omega \) is frequency and the hat symbol denotes the Fourier transform. Eq. (1) describes how the data log spectral ratio on the left-hand side of Eq. (2) can be decomposed into its four surface-consistent terms (right-hand side of Eq. (2)). For each frequency, Eq. (2) can be written for each corresponding pair of traces in the two surveys and these equations form a linear system

\[ \mathbf{G} \mathbf{m} = \mathbf{d}, \]  

where \( \mathbf{G} \) represents the seismic geometry matrix, \( \mathbf{m} \) is the four surface-consistent terms vector, and \( \mathbf{d} \) is the log-spectral ratios vector. Direct construction of the data term in Eq. (2) is unstable due to the spectral division. Fortunately, there is a stable alternative. The “term matching” filter is defined by Claerbout (1976) as a convolutional filter that minimizes the sum-squared difference between two traces. The form is

\[ m(t) * d_2(t) = d_1(t), \]  

where \( m(t) \) is the time-domain matching filter that minimizes the difference between two traces, \( d_1 \) and \( d_2 \). In the frequency domain, Eq. (4) has an exact solution as a spectral ratio

\[ \frac{\hat{m}(\omega)}{\hat{d}_2(\omega)} = \frac{\hat{d}_1(\omega)}{\hat{d}_2(\omega)}. \]
\[ \hat{m}(\omega) = \frac{\hat{d}_1(\omega)}{\hat{d}_2(\omega)}. \]  

(5)

Thus the computation of the data spectral ratio by direct division in the frequency domain can be avoided by solving the time-domain least squares problem \( (\sum_{i}(m(i)\cdot d_2(i) - d_1(i))^2 = \min) \), then transforming the solution to the frequency domain to obtain a stable spectral ratio estimate. The following steps highlight Almutlaq and Margrave (2012) approach to the surface-consistent matching filters:

- in the time-domain, compute a least-squares trace-by-trace matching filter for each pair of traces from baseline and monitor surveys over a temporal window above the target level.
- FFT the above result and take the logarithm, then
- for every frequency, solve Eq. (3) using least-squares method,
- accumulate the solution frequency-by-frequency
- IFFT the result to obtain surface-consistent matching filters,
- and finally, apply these filters to the monitor survey.

Thus our algorithm takes trace-by-trace matching filters and decomposes them into surface-consistent factors.

**Field example**

In this study, we only consider the vertical component of multicomponent data from Phase I (March 2005) and III (March 2007) since these surveys were recorded at the beginning and at the end of the monitoring project and are expected to have the largest time-lapse differences (Alshuhail et al., 2011). During this period, approximately 60,000 tonnes of CO\(_2\) were injected in the Cardium Reservoir which has a maximum cumulative thickness of about 20 m at a depth of about 1600 m. A time-lapse seismic data set, consisted of 2D surface seismic, a small sparse 3D survey, and 2D vertical seismic profile (2D VSP), was designed and acquired as part of the monitoring program. The main objective of the seismic program is to verify the CO\(_2\) plume, and to evaluate the integrity of the storage. The data quality is excellent and the main reflections were easy to pick starting from the shallow top Ardley Coal Zone to the Viking Formation which is sandstone dominated. The Cardium Formation (sand overlain by shale) is a low impedance unit on the baseline seismic, and even after injecting the CO\(_2\) gas, it shows as low amplitude on the monitor survey.

Table 1 summarizes the parallel processing steps of both baseline and monitoring surveys. For this data set, we compute and apply all four terms of the surface-consistent matching filters. The monitoring survey contains more noise compared to the baseline (due to increasing field activities) and even after attenuating most of the coherent noise, some noise level is still observed (Figure 1) particularly in near offsets.

<table>
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<th>Baseline</th>
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We computed the surface-consistent matching filters for a shallow window above the reservoir (top panel of Figure 1) centered on the Ardley Coal which is a relatively good reflector and the only one visible above the Cardium reservoir on prestack data. The difference between the baseline survey and the monitor survey is quite large at this level and dominated by noise. After applying the four term surface-consistent matching filters, the difference reduced considerably. Because of the low fold and high random noise in the shallow window, we designed another gate below the reservoir where good quality reflectors are present. It is not common in time-lapse processing to start by matching a gate below the reservoir but we are attempting this in order to examine the performance of the surface-consistent matching filters on a relatively high signal to noise event. We also feel that the surface consistent algorithm should isolate reservoir changes into the midpoint and perhaps the offset terms. The result is shown in the bottom panel of Figure 1. The difference after applying the matching filter is significantly small and displays a much better result compared to the shallow window.

Figure 2 illustrates the migrated stack of baseline, monitor and their difference. Amplitude and phase difference is obvious throughout the section. After applying the surface-consistent matching filters computed from the shallow window, the difference reduced significantly compared to the prestack example. This result is encouraging and illustrates the progressive decrease of the error after applying the surface-consistent matching filters. With this algorithm, variations in amplitude, time, and phase between both surveys have been corrected and reduced significantly. Figure 3 shows the amplitude spectrum of baseline, monitor, and matched monitor survey. The large difference in amplitude between the base and the monitor is obvious but after applying the matching filters, these differences are now small.

Conclusions

We successfully applied the surface-consistent matching filters to a time-lapse data set from Violet Grove area in central Alberta. Differences in the non-reservoir section of the data are present. They are a combination of amplitude, time, and phase variations between both surveys. We evaluate two zones: a shallow one above the reservoir centered on the Ardley Coal Zone, and a deeper one below the reservoir. Noise dominate the shallow zone but the matching filters seem to reduce the difference between both surveys. The deeper window has events with higher signal to noise ratio. The result of the deeper window is better than that of the shallow one and progressive decrease in amplitude, time, and phase differences between baseline and monitor survey is illustrated.

**Figure 1** A prestack shot record near the injection well. In top panel is a baseline, a monitor, their difference, the matched monitor and difference after applying matching filters based on shallow
window above reservoir. Note there is a slight improvement after applying the matching filters but it is not as good as computing the matching filters from a deeper window (i.e. bottom panel). This is due to higher signal to noise ratio and higher fold in deeper window.

Figure 2 A poststack comparison of baseline, monitor, difference, matched monitor and difference between the baseline and the matched monitor. The matching filters computed here is from a window above the reservoir as indicated between the two red lines. This is a short segment of the 2D line with the well in the middle.

Figure 3 Amplitude spectrum of baseline (blue), monitor (green), and matched monitor (red). Note the large amplitude difference between the base and the monitor is reduced after applying the surface-consistent matching filters.

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