Match filtering a time-lapse data set utilizing the surface-consistent method

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CREWES Technical talk
Outline

• Surface-consistent hypothesis
• What’s a surface-consistent matching filter?
• Examples
• Conclusions & FW
• Acknowledgements
Surface-consistent hypothesis

The surface-consistent model:
the seismic trace can be modeled as

\[ d_{ij}(t) \approx s_i(t) * r_j(t) * h_k(t) * y_l(t) \]  \hspace{1cm} (1)

where
- \( d_{ij} \): seismic trace
- \( s_i \): source response at location \( i \)
- \( r_j \): receiver response at location \( j \)
- \( h_k \): offset response at location \( k; k=|i-j| \)
- \( y_l \): subsurface response at \( l; l=(i+j)/2 \)

**FACT**: the model is reasonable approximation of the seismic trace that is easy to compute.
Forward modeling

\[ \tilde{S}_i(t) \ast r_j(t) \ast h_k(t) \ast y_l(t) \approx d_{ij}(t) \]

Forward model
Inverse modeling

**Predicted model (4-components)**

**Data**

\[
Gx = d \\
x = \begin{bmatrix} s_i & r_j & h_k & y_l \end{bmatrix}^T \\
x = (G^T G)^{-1} G^T d
\]

**FACT:** Seismic data geometry matrix has **no unique inverse** due to singularity of the square matrix \( G^T G \), where \( G \) contains the positions of four-components above.

\[
s_i(t) * r_j(t) * h_k(t) * y_l(t) \approx d_{ij}(t)
\]
Difference

Seismic traces

Input traces

Difference

Predicted traces

NRMS = 200 \left[ \frac{\text{rms}(\text{base} - \text{monitor})}{\text{rms}(\text{base}) + \text{rms}(\text{monitor})} \right]
NRMS vs. Time shift

\[ D_1(t) = a \sin(2\pi ft) \]
\[ D_2(t) = a \sin(2\pi f(t + \delta t)) \]
\[ \delta D(t) = D_1(t) - D_2(t) = a(2\pi f \delta t) \cos(2\pi ft) \]

\[ NRMS = 200 \left[ \frac{a(2\pi f \delta t)RMS[\cos(2\pi ft)]}{a.RMS[\sin(2\pi ft)] + a.RMS[\sin(2\pi f(t + \delta t))]} \right] \]

\[ NRMS(\%) = 100 \left[ 2\pi f \delta t \right] \]

<table>
<thead>
<tr>
<th>F (Hz)</th>
<th>Time shift ( \delta t ) (ms)</th>
<th>NRMS (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>50</td>
<td>0.001</td>
<td>31.4</td>
</tr>
<tr>
<td>50</td>
<td>0.002</td>
<td>62.8</td>
</tr>
</tbody>
</table>
NRMS vs. Amplitude

\[ D_1(t) = \sin(2\pi ft) \]
\[ D_2(t) = (1 + b) \sin(2\pi ft) \]
\[ \delta D(t) = D_1(t) - D_2(t) = b \sin(2\pi ft) \]

\[ NRMS(\%) \approx 100 \times b \]

Assuming amplitude change is small

<table>
<thead>
<tr>
<th>a</th>
<th>b</th>
<th>NRMS (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0</td>
<td>0.1</td>
<td>9.5</td>
</tr>
<tr>
<td>1.0</td>
<td>0.6</td>
<td>46</td>
</tr>
</tbody>
</table>

Small amplitude difference
Large amplitude difference
Surface-consistent matching filters (SCMF)

For two repeated data sets, their surface-consistent model is:

\[ d_{ij}(t) \approx s_{i}(t) * r_{j}(t) * h_{k}(t) * y_{l}(t) \]  

\[ d_{ij}(t) \approx s_{i}(t) * r_{j}(t) * h_{k}(t) * y_{l}(t) \]  

Q. Can we design a matching filter for these two data sets?

Matching filter concept:

\[ m * s_{1} = s_{2} \]  

\[ M(\omega) = \frac{S_{2}(\omega)}{S_{1}(\omega)} \]  

Spectral ratio is an exact matching filter, but it is unstable in presence of noise.

**Alternatively:** solve the time-domain in LSQ & FT the solution which is a good approx to the spectral ratio.
Surface-consistent matching filters (cont’)

1. Define filter length
2. Compute LSQ match filter in time for each trace
3. Take the Fourier transform
4. Spectral decomposition
5. Apply filters to monitor trace and difference from base trace.
6. If NRMS value is within your spec. range (0 to 0.2) then stop.
7. Else, use your matched traces and iterate until goal is reached.

- YES
- NO
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Two earth models
Other non-repeatable parameters

- Attenuation Q vs. Distance (m)
- Shot strength vs. Shot
- Receiver coupling vs. Receiver
Raw shot: before match filtering

Difference = Baseline – monitor (before match filtering)

Avg NRMS = 41%
Raw shot: after match filtering

Difference = Baseline – monitor (after match filtering)
Raw stack: before match filtering

Baseline: Raw stack

Monitor: Raw stack bulk shifted

Difference

Mean NRMS = 70%
Stack: after match filtering

Mean NRMS = 28%
Stack: After match filtering & statics

Not: 3rd iteration of statics was not necessary. Match filtering was iterated 2 times.
NRMS values: GOM vs. MGM

(modified plot from Helgerud et al., TLE 2011)
Conclusions

- Surface-consistent matching filter is analogous to other surface-consistent methods (decon, statics, ...), except the data term is spectral ratio of 2 surveys.
- We compute MF in time in LSQ & FT the result which is an approx to spectral ratio.
- Spectral decomposition of trace-by-trace MF into surface-consistent operators; and
- small NRMS values $\rightarrow$ balanced amplitude, equalized phase & bandwidth, and small or no time-shifts
- $\rightarrow$ we have a SCMF that can significantly reduce the non-repeatability observed in TL data sets.
Future work

Violet Grove

Walkway PP VSP data from the observation well (Alshuhail, et al., 2008)
Acknowledgements

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