Geoacoustic inversion performed from two source-receive arrays in shallow water

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Outline

• Introduction

• Experiments

• Double Beamforming* (DBF) between two transducer arrays

• Bottom parameters retrieval via DBF

• Experimental results: Tank experiment

• Experimental results: At-sea experiment

• Conclusions

* Roux et al., JASA 124, 3430 (2008)
Shallow-Water Waveguides

GEOMETRY
Length \( L \gg \text{Depth } d \)
Source depth \( z_e \)
Receiver depth \( z_r \)

When \( \lambda \ll d \), \( L \Rightarrow \text{Ray-picture} \)

Each source-receiver combination \( \Leftrightarrow \) Set of Eigenrays

Characterize eigenrays by:
- EMISSION ANGLE \( \theta_e \)
- RECEPTION ANGLE \( \theta_r \)
- TRAVEL TIME \( t \)
Experiments: Geometry

AT-SEA EXPERIMENT (Mediterranean Sea, near Elba Island)

Acoustic waveguide: $L \sim 1.2$ km, $d \sim 110$ m, $\lambda \sim 0.4$ m at $f = 3.5$ kHz

![Diagram of AT-SEA experiment setup and water sound speed profile](image)

TANK EXPERIMENT

Ultrasonic waveguide: $L = 150$ cm, $d = 5$ cm, $\lambda \sim 1$ mm at $f = 1$ MHz

![Diagram of TANK experiment setup](image)
Experiments: Data Acquisition

• Each source fired one by one
• Each recorded signal characterized by \((z_e, z_r)\)
• Original data exist in \((t, z_e, z_r)\) - domain

TANK DATA
Experiments: Data Acquisition

- Each source fired one by one
- Each recorded signal characterized by \((z_e, z_r)\)
- Original data exist in \((t, z_e, z_r)\) - domain

AT-SEA DATA
Double Beamforming: Source Array

Beamforming on the **source array**: Time-delay according to an emission angle $\theta_e$

**Source array**

![Source array diagram]

**Time-delay:**

$$\tau(\theta_e, z_{ei}) = \frac{(z_{ei} - z_{e0}) \sin \theta_e}{c}$$

where

- $z_{e0}$ – position of the reference source,
- $c$ – speed of sound

Each source-dependent pattern is time-shifted by its own $\tau(\theta_e, z_{ei})$ ⇒ Coherent summation of time-shifted waveforms for the **same** receiver $z_{rj}$

$$p'(t, \theta_e, z_{rj}) = \frac{1}{N_e} \sum_{i=1}^{N_e} p(t + \tau(\theta_e, z_{ei}), z_{ei}, z_{rj})$$

**Transformation:** $(t, z_e, z_r) \Rightarrow (t, \theta_e, z_r)$
Double Beamforming: Source Array

AT-SEA EXPERIMENT

\((t, z_e, z_r) - \text{domain}\)

\(z_r (\text{m})\)

\(z_e0\)

\(\theta_e = 8.4^\circ\)

\(\theta_e = -12^\circ\)

Time (s)

TANK EXPERIMENT

\((t, \theta_e, z_r) - \text{domain}\)

\(z_r (\text{mm})\)

\(z_e0\)

\(\theta_e = -8.5^\circ\)

\(\theta_e = -12.5^\circ\)

Time (ms)
Double Beamforming: Receive Array

Beamforming on the **receive array**: Time-delay according to a reception angle \( \theta_r \).

**Receive array**

Time-delay:

\[
\tau(\theta_r, z_{rj}) = \frac{(z_{rj} - z_{r0}) \sin \theta_r}{c}
\]

where

- \( z_{r0} \) – position of reference receiver,
- \( c \) – speed of sound

At given \( \theta_e = \text{const} \), each waveform is time-shifted by its own \( \tau(\theta_r, z_{rj}) \)

\[\Rightarrow\]

Coherent summation of time-shifted waveforms for a given \( \theta_r \)

**TRANSFORMATION**: \((t, \theta_e, z_r)\)-domain \(\Rightarrow\) \((t, \theta_e, \theta_r)\)-domain
Double Beamforming: Eigenray Identification

TANK EXPERIMENT

\((t, \theta_e, z_r)\) – domain

\[ \theta_e = -8.5^\circ \]

\[ \theta_e = -12.5^\circ \]

\(z_r\) (mm)

\begin{align*}
1010 & \quad 1020 & \quad 1030 & \quad 1040 & \quad 1050 \\
\end{align*}

time (ms)

\(\theta_e\) (deg)

\[ \theta_e = -8.5^\circ \]

\[ \theta_e = -12.5^\circ \]

\(\theta_r\) (deg)

\begin{align*}
-15 & \quad -10 & \quad -5 & \quad 0 & \quad 5 & \quad 10 & \quad 15 \\
\end{align*}

time (ms)

\begin{align*}
1010 & \quad 1020 & \quad 1030 & \quad 1040 & \quad 1050 \\
\end{align*}

\(\theta_e\) (deg)

\begin{align*}
-15 & \quad -10 & \quad -5 & \quad 0 & \quad 5 & \quad 10 & \quad 15 \\
\end{align*}

time (ms)

\(\theta_r\) (deg)

\begin{align*}
-15 & \quad -10 & \quad -5 & \quad 0 & \quad 5 & \quad 10 & \quad 15 \\
\end{align*}

time=1.028 ms

\[ \theta_e = -12.5^\circ \]

\[ \theta_e = -8.5^\circ \]

\(\theta_r\) (deg)

\begin{align*}
-15 & \quad -10 & \quad -5 & \quad 0 & \quad 5 & \quad 10 & \quad 15 \\
\end{align*}

time=1.042 ms
Double Beamforming: Eigenray Identification

AT-SEA EXPERIMENT

$(t, \theta_e, z_r) – \text{domain}$

Use eigenray **amplitudes** to get information on waveguide bottom
**Bottom Parameters Retrieval**

Waveguide with constant depth $d$

Intensity of an eigenray with $n$ bottom reflections

$$I_n(\theta) = I_0 |R(\theta)|^{2n} \Rightarrow$$

Reflection coefficient

$$|R(\theta)|^2 = \left(\frac{I_n(\theta)}{I_0}\right)^{1/n}$$

Fit experimental $|R(\theta)|$ with the one predicted theoretically

$$\Rightarrow$$

Acoustic parameters of the waveguide bottom
Results: Tank Experiment

\[ |R(\theta)|^2 = \left( \frac{I_n(\theta)}{I_0} \right)^{1/n} \]

MODEL

Plane wave incident on interface between infinite liquid and elastic media

Longitudinal: \( \nu_l > \nu_w \)
Shear: \( \nu_s < \nu_w \)

CRITICAL ANGLES:
longitudinal waves: 54º
shear waves: none

FROM FIT

\[ \nu_s = 1380 \text{ m/s} \]
\[ ab_s = 0.8 \text{ dB/\lambda} \]
**Results: At-Sea Experiment**

**THEORETICAL MODEL**
System of 5 liquid layers (no shear waves)

**FITTING PARAMETERS**
Layer thicknesses, sound speeds, absorption coefficients

**FITTING PROCEDURE**
Improved Neighbourhood Algorithm*
500,000 generated models ⇒
Select models with 1.5% deviation from the best model ⇒
Average depth-dependent bottom acoustic parameters

### AVERAGE DEPTH-DEPENDENT PROFILES

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<th>DEPTH (m)</th>
<th>MEAN</th>
<th>STD</th>
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<td>1450</td>
<td>1500</td>
</tr>
<tr>
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<td>0.1</td>
</tr>
<tr>
<td>5</td>
<td>0</td>
<td>0.2</td>
</tr>
</tbody>
</table>

### KEY OBSERVATIONS
- shallow top layer with speed of sound < speed of sound in water
- strong sound speed gradient between first and second layers
- deeper layer (2 – 3.5 m) with highest sound speed
Comparison with Other Techniques

- Similar geographic location
- Joint time- and frequency-domain technique*:  
  • single source towed along sea surface  
  • single receiver moored close to the seafloor  
  • one bottom reflection

* Holland and Osler,  *JASA* 107, 1263 (2000)
Conclusions

• DBF allows extraction of eigenrays according to arrival time $t$, emission angle $\theta_e$ and reception angle $\theta_r$.

• New scheme developed, permitting extraction of bottom acoustic parameters from eigenray intensities.

• Proposed scheme used to perform geoacoustic inversion on the data collected in at-sea experiment.

• Retrieved sea bottom parameters are in good qualitative agreement with those determined from a different geoacoustic inversion scheme.*

* Holland and Osler, JASA 107, 1263 (2000)