Range estimation of bowhead whales in shallow Arctic waters using a single hydrophone

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Outline

1. Introduction
2. Ranging methodology
3. Application to bowhead data
4. Conclusion
Context

- Bowhead whale vocalization (0-400Hz) in the Beaufort Sea
- Shallow water ($\sim 50$ m) $\Rightarrow$ modal propagation ($N_{\text{modes}} \lesssim 5$)
- Modes contain information about propagation: environment, source
- Objective: range (and depth) estimation using a single hydrophone
Modal propagation

- Low frequency propagation in shallow water is described by normal mode theory

\[
Y(f) = |S(f)| e^{i \phi_s(f)} \sum_{m=1}^{N} \frac{\Psi_m(z_s, f) \Psi_m(z, f) e^{ir k_{rm}(f)}}{\sqrt{r k_{rm}(f)}}
\]

- Modal phase = \( r k_{rm}(f) \)
  - defines travel time
  - position in the spectrogram
  - allows range \( r \) estimation

- Modal amplitude \( \propto \Psi_m(z_s, f) \)
  - energy (color) in the spectrogram
  - allows depth \( z_s \) estimation

Example: airgun signal
1 Introduction

2 Ranging methodology
   • Passive localization scheme
   • Modal filtering
   • Detailed example

3 Application to bowhead data

4 Conclusion
Passive localization scheme

- Localization scheme
  1. Modal filtering using warping
  2. Range inversion using filtered modes

- Modal filtering using warping
  - idea: transform the signal so that modes become separated
  - aim: warped modes = cw tones (horizontal lines in the spectrogram)
  - how: non-linear resampling

- Range inversion: classical backpropagation methodology (phase only)
  - source IF is obtained as a by-product

- Range/depth inversion: Matched Mode processing

- Geoacoustic inversion is required for each call
  - environment is modeled as a Pekeris waveguide with unknown seabed
  - inversion is performed over range \( r \) and seabed soundspeed \( c_b \)
Passive localization scheme

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Warping?

- What warping sounds like
  - Recorded off Australia  
  - After warping

- How it is done

Warping requires a physical model to adjust the non-linear sampling
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Modal filtering using warping

Deconvolution and warping parametrization only need to be accurate enough to allow mode filtering. Inverse steps allow full signal recovery.
Example with real data

(a) Received signal

(b) Signal after source deconvolution

(c) Warped signal

(d) Estimated source IF

Ranging methodology  Detailed example
1 Introduction

2 Ranging methodology

3 Application to bowhead data
   - Dataset
   - Results
   - Depth estimation

4 Conclusion
Dataset

Analysis of 12 calls with various bandwidths, durations, structure (fast/slow up/down sweeps), SNR, and modal resolution
Localization results

- Call 1
- Call 2
- Call 3
- Call 4
- Call 5
- Call 6
- Call 7
- Call 8
- Call 9
- Call 10
- Call 11
- Call 12

Easting (km) vs. Northing (km) for each call.
### Detailed results

<table>
<thead>
<tr>
<th>n°</th>
<th>time</th>
<th>SNR (dB)</th>
<th>ΔF (Hz)</th>
<th>modes</th>
<th>$\hat{r}$ (km)</th>
<th>$c_b$ (m/s)</th>
<th>DASARs</th>
<th>$\hat{r}$ (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>14:48:21</td>
<td>15</td>
<td>85-120</td>
<td>1-2-3</td>
<td>9.4 ± 1.8</td>
<td>1870</td>
<td>b-c-e</td>
<td>8.3 ± 1.3</td>
</tr>
<tr>
<td>2</td>
<td>14:58:10</td>
<td>12</td>
<td>85-115</td>
<td>1-2-3</td>
<td>9.8 ± 1.0</td>
<td>1830</td>
<td>a-b-c-d-e-g</td>
<td>8.5 ± 0.5</td>
</tr>
<tr>
<td>3</td>
<td>02:08:16</td>
<td>23</td>
<td>75-90</td>
<td>1-2-3</td>
<td>8.7 ± 1.3</td>
<td>1950</td>
<td>a-b-c-d-e-g</td>
<td>8.7 ± 0.2</td>
</tr>
<tr>
<td>4</td>
<td>14:40:28</td>
<td>18</td>
<td>110-130</td>
<td>1-2-3</td>
<td>11.7 ± 1.0</td>
<td>1710</td>
<td>a-b-c-d-e-g</td>
<td>10.7 ± 0.9</td>
</tr>
<tr>
<td>5</td>
<td>01:46:22</td>
<td>6</td>
<td>65-115</td>
<td>1-2-3</td>
<td>13.5 ± 2.0</td>
<td>1580</td>
<td>a-b-c-d-e-g</td>
<td>11.9 ± 0.6</td>
</tr>
<tr>
<td>6</td>
<td>15:14:21</td>
<td>9</td>
<td>85-105</td>
<td>1-2-3</td>
<td>14.6 ± 0.9</td>
<td>1820</td>
<td>a-b-c-d-e-g</td>
<td>14.1 ± 1.8</td>
</tr>
<tr>
<td>7</td>
<td>10:50:14</td>
<td>8</td>
<td>85-100</td>
<td>1-2-3</td>
<td>17.6 ± 1.7</td>
<td>1830</td>
<td>a-b-c-d-e-g</td>
<td>16.5 ± 3.0</td>
</tr>
<tr>
<td>8</td>
<td>15:14:15</td>
<td>15</td>
<td>150-175</td>
<td>1-3</td>
<td>23.7 ± 1.2</td>
<td>1550</td>
<td>a-b-c-d-e-g</td>
<td>22.2 ± 2.4</td>
</tr>
<tr>
<td>9</td>
<td>09:50:37</td>
<td>15</td>
<td>110-130</td>
<td>1-2-3</td>
<td>22.1 ± 1.8</td>
<td>1840</td>
<td>a-b-c-d-e-g</td>
<td>23.8 ± 6.6</td>
</tr>
<tr>
<td>10</td>
<td>02:27:31</td>
<td>7</td>
<td>40-140</td>
<td>1-2</td>
<td>27.3 ± 2.2</td>
<td>1940</td>
<td>a-b-c-d</td>
<td>25.7 ± 1.5</td>
</tr>
<tr>
<td>11</td>
<td>09:51:02</td>
<td>13</td>
<td>120-130</td>
<td>1-2-3</td>
<td>25.0 ± 1.6</td>
<td>1880</td>
<td>a-b-c-d-e</td>
<td>27.8 ± 5.7</td>
</tr>
<tr>
<td>12</td>
<td>10:57:48</td>
<td>7</td>
<td>120-145</td>
<td>1-2</td>
<td>34.1 ± 0.7</td>
<td>1570</td>
<td>a-b-c-e</td>
<td>34.5 ± 5.0</td>
</tr>
</tbody>
</table>

- single receiver range estimates are consistent with DASAR estimates
- no direct link between range and SNR
- no physical meaning to the seabed sound speed estimates
- estimated source IFs different from received signals
Depth estimation: preliminary results

- Modal filtering ⇒ matched mode processing (MMP)
  ⇒ range and depth estimation

- Warping ⇒ opportunity for single receiver MMP

- Example on an "easy" call

Results ($\hat{r} = 7.7$ km, $\hat{z}_s = 33$ m) consistent with MFP estimation using a VLA (15 hydrophones)
Conclusion

- **Bowhead whale ranging using a single receiver**
- **Modal filtering using warping**
  - robust to uncertain knowledge of waveguide environment, experimental geometry and source signal
  - allows modal filtering at "short" range
  - allows source ranging and estimation of the source IF

- **Existing dataset can be revisited. However**
  - several manual iterations
  - source = monotonic FM sweep
  - at least two propagating modes

- **Continuing work**
  - automation
  - source depth and source level estimation
  - depth discrimination ⇒ **discrimination between Right whales and Humpback whales**
Thanks !!! Any questions ???