A normal mode back-propagation approach for broadband sound source localization and the effects of water column variability

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Outline

• An acoustic normal mode back-propagation approach for low-frequency broadband sound source localization in a shallow-water ocean

• Application to the New Jersey Shallow Water 2006 (SW06) experiment data

• Effects of water-column variability on source range estimates
I. Introduction - Acoustic normal mode theory

- Acoustic normal modes are orthogonal bases to decompose a sound pressure field, and can describe the spatial field coherence.

Shallow-water low-frequency broadband sound propagation simulation

Sound pulse propagation in a shallow-water mixed-layer waveguide model
Source at 25m depth ($f_c = 50\text{Hz}$, $BW = 50\text{Hz}$)
I. Introduction - Acoustic normal mode theory

- Acoustic normal modes are orthogonal bases to decompose a sound pressure field, and can describe the spatial field coherence.

**Shallow-water low-frequency broadband sound propagation simulation**

*Modes are frequency-dependent!!*

![Diagram of sound speed and depth](image)
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Shallow-water low-frequency broadband sound propagation simulation

**Modes are dispersive!!**

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II. Low-frequency broadband source localization by back-propagating acoustic normal modes

- This method is theoretically straightforward — utilizing modal dispersion to localize a sound source.

- The first step is to implement a **vertical mode filter** to obtain individual modal arrivals. Then, back propagate the modal arrivals with their own speeds, which are derived from the **waveguide parameters**. The **source range estimate** is where the back-propagated modes line up with each other.

![received signal](image)
III. Application to the New Jersey Shallow Water 2006 (SW06) experiment data

- Vertical line array (VLA): 64-m long, 16-element array covering the water column from 13 m depth to the bottom (79 m)
- Horizontal line array (HLA): 465-m long, 32-element array

Diagram showing oceanographic moorings, acoustic source, hydrophone array, and other moorings.
III. Application to the New Jersey Shallow Water 2006 (SW06) experiment data — U. Miami sound source (MSM) localization

- MSM source was **19.74 km** northeast (25.73° due north) away from the WHOI VLA.
- M-sequence phase encoded source signals. 5 different frequency bands.
- **100 Hz signal (25 Hz bandwidth) is considered here.** Every ½ hour, a 1.5-min long transmission, which contained 36 identical M-sequence phase encoded signals, is emitted. Complex pulses are obtained from matched filter (pulse compression).
III. Application to the New Jersey Shallow Water 2006 (SW06) experiment data — U. Miami sound source (MSM) localization

- **Least squares mode filtering the VLA data**
- Mode functions are derived *full water-column sound speed profile* (SSP) measurements\(^1\) and a bottom geoacoustic model from a previous study\(^2\).

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III. Application to the New Jersey Shallow Water 2006 (SW06) experiment data — U. Miami sound source (MSM) localization

- **Normal mode back-propagation**
  - Assumptions: 2-D in-plane propagation and no mode-coupling.
  - Environmental reconstruction: 3 range-independent water-column SSP patches, accurate bathymetry and tidal data.
  - Normal modes are calculated every 150 m and back-propagated in a 25-m interval.
III. Application to the New Jersey Shallow Water 2006 (SW06) experiment data — U. Miami sound source (MSM) localization

- An example of normal mode back-propagation
III. Application to the New Jersey Shallow Water 2006 (SW06) experiment data — U. Miami sound source (MSM) localization

- **Source localization results**

  - 8 days data are processed. Every ½ hour, 35 M-sequence pulses are analyzed and 35 range estimates are obtained. The average value and standard deviation (STD) of these estimates are plotted.

  - The total mean range estimate is **19.74 km**, the same as the true distance, along with STD **570 m**.

  - Bottom geoacoustic model: homogeneous bottom with sound speed **1,700 m/s** and density **1.8 g/cm³**.
IV. Effects of water-column variability

— U. Miami sound source (MSM) localization

• Nonlinear internal waves

— The peaks of the standard deviations correlate with nonlinear internal wave events exactly.
IV. Effects of water-column variability
—U. Miami sound source (MSM) localization

• Nonlinear internal waves distort the coherent structure of the sound field due to mode coupling and 3-D sound propagation effects\textsuperscript{1,2} (acoustic ducting, radiation, refraction and shadowing).

\textsuperscript{2pAO8 (3:05)} Acoustic ducting, refracting, and shadowing by curved nonlinear internal waves in shallow water, J.F. Lynch, Y.-T. Lin, T.F. Duda, A.E. Newhall and G. Gawarkiewicz


\textsuperscript{2} Y.-T. Lin, T.F. Duda and J.F. Lynch, “Acoustic mode radiation from the termination of a truncated nonlinear internal gravity wave duct in a shallow ocean area,” submitted to JASA (2009)
IV. Effects of water-column variability

— U. Miami sound source (MSM) localization

• Mesoscale variability
  — SSP measurements separated by ~10 km from each other.
  — Spatial Nyquist sampling rate of the SSP measurements is 20 km.
  — The SSP measurements can not resolve water-column variability that has wavelength less than 20 km.
IV. Effects of water-column variability
— U. Miami sound source (MSM) localization

- MIT-MSEAS\(^1\) (HOPS) data assimilation ocean model
  (water temperature at 30 m depth)

Large domain simulation  small domain nested simulation

IV. Effects of water-column variability
— U. Miami sound source (MSM) localization

• Low-pass filtering source range estimates (cutoff frequency: 4 cycles per day)
  — A large portion of range estimate deviations contains in the frequency band less than 4 cycle per day.
• Sei whale calls have a frequency bandwidth from 40 to 120 Hz.

Conclusions and future work

- A normal mode back-propagation approach for low-frequency broadband sound source localization in a shallow-water ocean is applied to the SW06 data.
- Nonlinear internal waves is responsible for the range estimate deviations in small time-scale (< 2 min).
- Insufficient mesoscale structure measurement (in terms of sound speeds) also cause range estimate deviation in a larger time-scale (hours).
- The normal mode back-propagation approach has been applied for localizing Sei whales presented in the SW06 experiment.
- Future work: careful examination of meso-scale oceanographic variability and connection to acoustics. Comparison of different source localization approaches. Reduction of estimation uncertainty.