Can We See the Underwater Acoustic Propagation Paths?

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Summary and Objective

An acoustic signal propagates underwater through multiple paths, including direct, surface-reflected, and bottom-reflected arrivals. Each path is characterized by its gain, delay, and angle of arrival. In addition, relative motion causes path delays to vary rapidly over time, while path gains and angles of arrival may also vary, typically more slowly.

The geometry below illustrates a typical shallow-water underwater acoustic channel, where a transmitter (TX) and a receiver array are separated by distance L_{TR}. The main propagation paths are the direct path (D), the surface-reflected path (S), and the bottom-reflected path (B).

Our goal is to answer the following question: **Can we see the underwater acoustic propagation paths?**

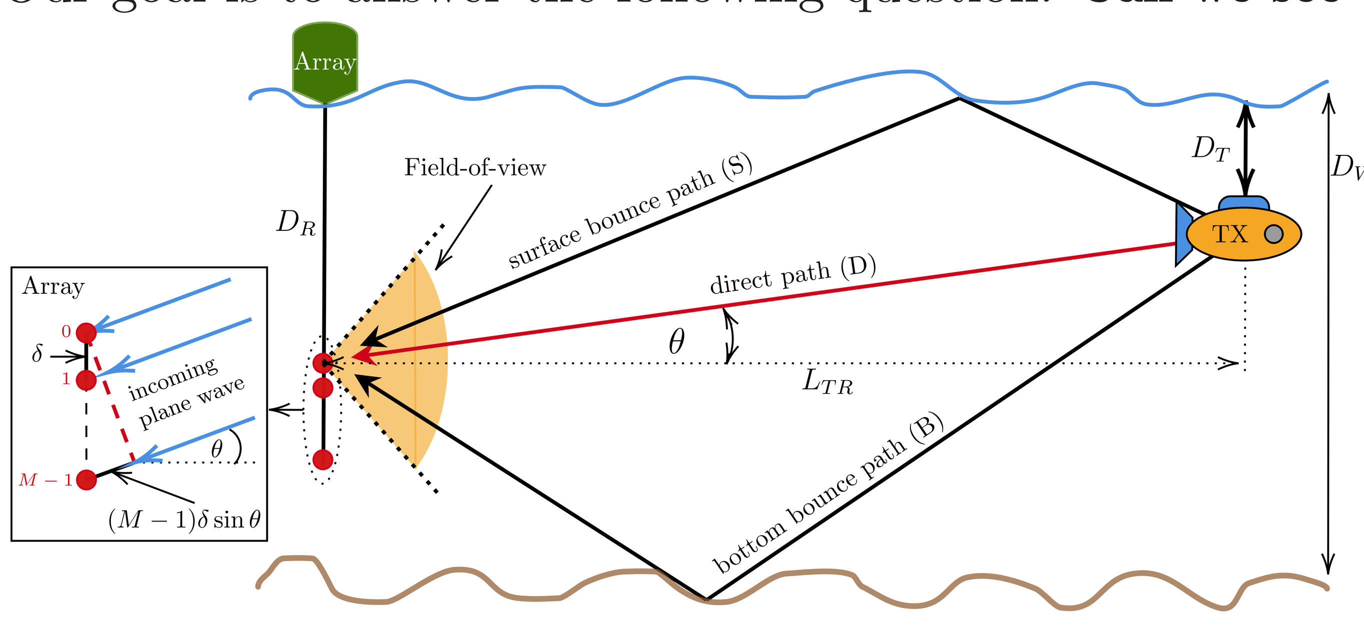


Fig. 1 System Geometry

Parameter Description

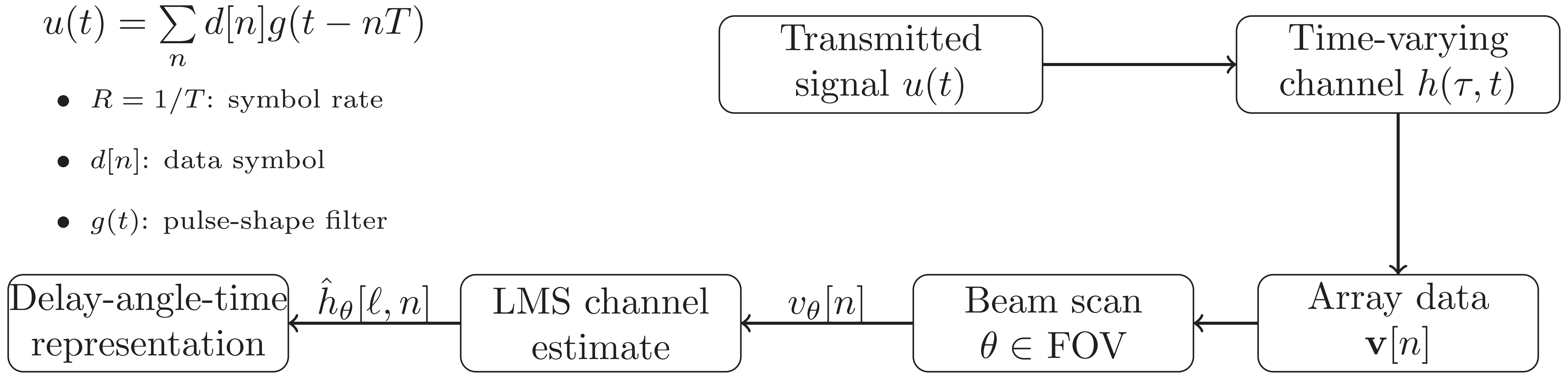
water depth	D_W
TX depth	D_T
Array depth	D_R
TX-to-array distance	L_{TR}
Element spacing	δ
Number array elements	M

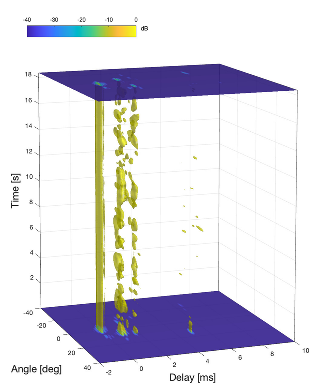
Methodology

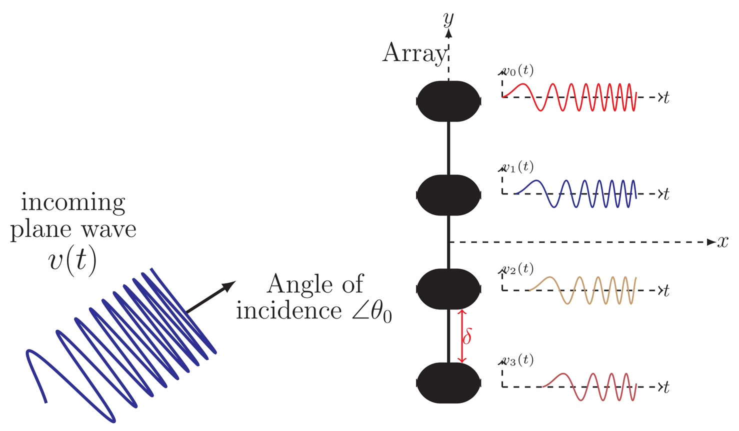
We steer beams across the field of view of the receiver array. For each steering angle, the array outputs are combined into a beamformed signal, and the channel impulse response is estimated using an LMS adaptive filter. Repeating this procedure for all steering angles produces a time-varying channel estimate indexed by angle, delay, and time. The resulting delay-angle-time representation reveals the dominant underwater acoustic propagation paths.

$$u(t) = \sum_n d[n] g(t - nT)$$

- $R = 1/T$: symbol rate
- $d[n]$: data symbol
- $g(t)$: pulse-shape filter







Delay-angle-time power:

$$P(\theta, \ell, w) = \frac{1}{N_w} \sum_{n \in \mathcal{I}_w} \left| \hat{h}_\theta[\ell, n] \right|^2$$

where w indexes the time window, $\mathcal{I}_w$ is the set of samples in that window, and $N_w = |\mathcal{I}_w|$.

Delay-angle average power:

$$P(\theta, \ell) = \frac{1}{N} \sum_{n=1}^{N} \left| \hat{h}_\theta[\ell, n] \right|^2$$

Experimental Results

Experiment description: We process data from SPACE 2008 and MACE 2010, two at-sea experiments in which BPSK-modulated M-sequences were transmitted through shallow-water channels and received on vertical arrays.

SPACE used length-4095 M-sequences on a 24-element array under varying sea-surface conditions. MACE used length-2047 M-sequences on a 12-element array with transmitter motion of approximately 0.5–1.5 m/s.

Experiment Parameters

	SPACE	MACE
band [kHz]	[9.24,15.76]	[10.56,15.44]
R [sym/s]	6510.4	4882.8
δ [m]	0.05	0.12
D_W [m]	15	100
D_T [m]	11	40–60
D_R [m]	11	50
L_{TR} [m]	200	3000–7000

Surface Processes Acoustic Communication Experiment (SPACE)

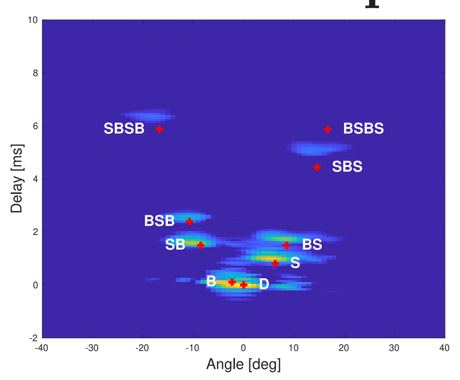


Fig. 2 Delay-angle representation

- D: Direct path
- B: Bottom-reflected path
- S: Surface-reflected path
- BS: Bottom-Surface
- SB: Surface-Bottom

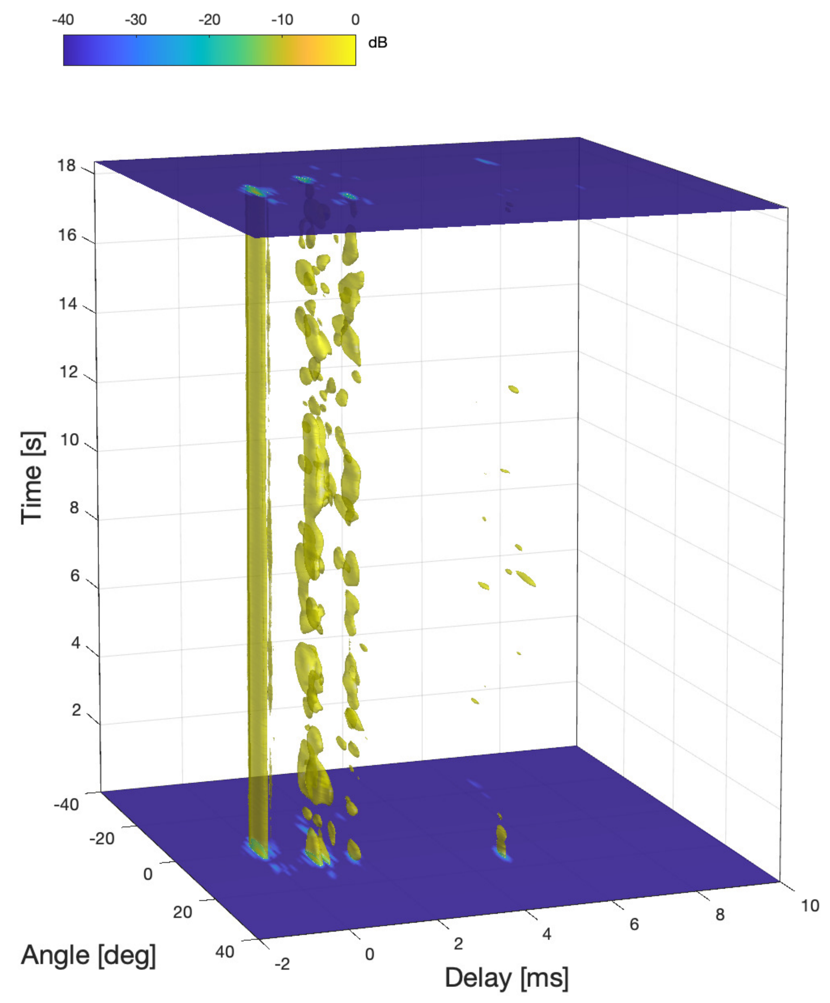


Fig. 3 Delay-angle-time representation

Mobile Acoustic Communication Experiment (MACE)

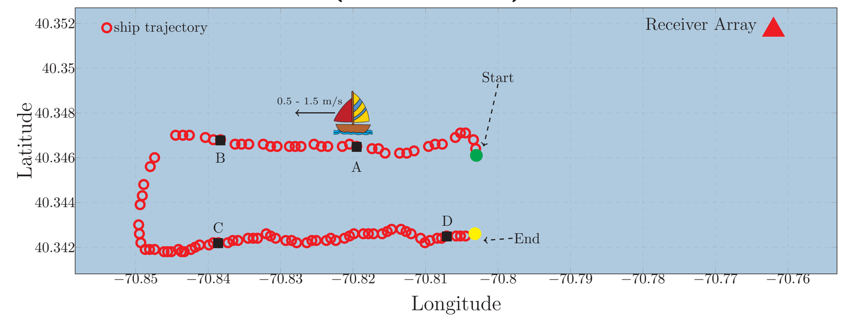


Fig. 4 Ship trajectory during the MACE experiment.

Examples of MACE delay-angle-time plots

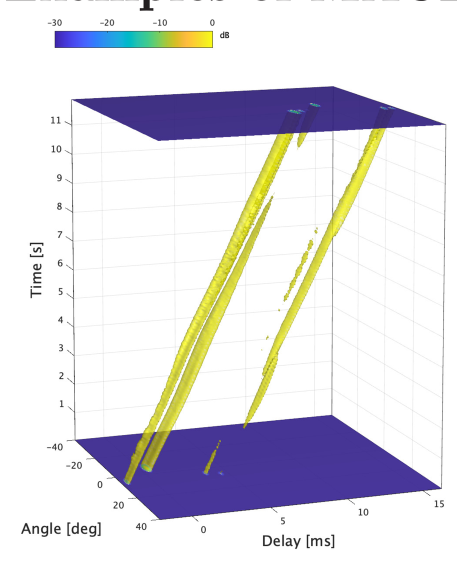


Fig. 5 Measured at **A**

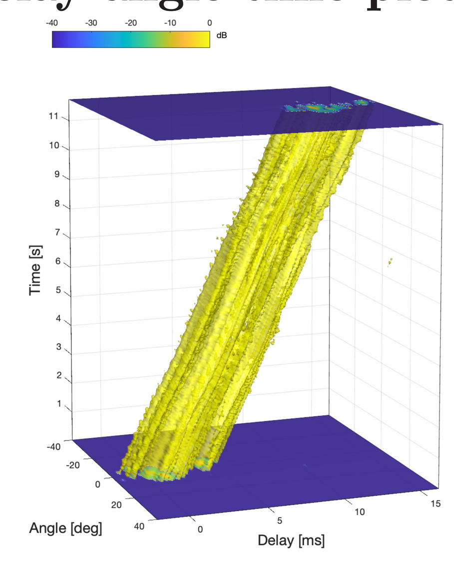


Fig. 6 Measured at **B**

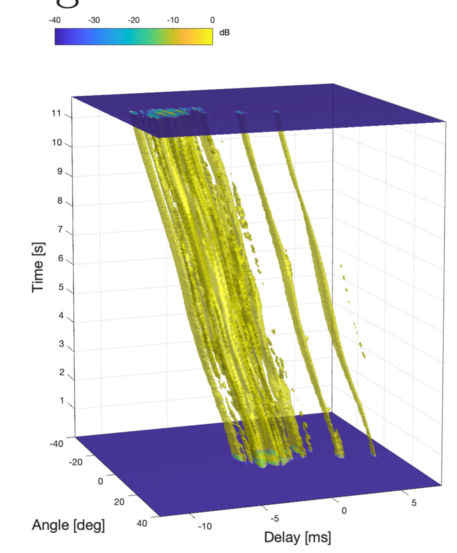


Fig. 7 Measured at **C**

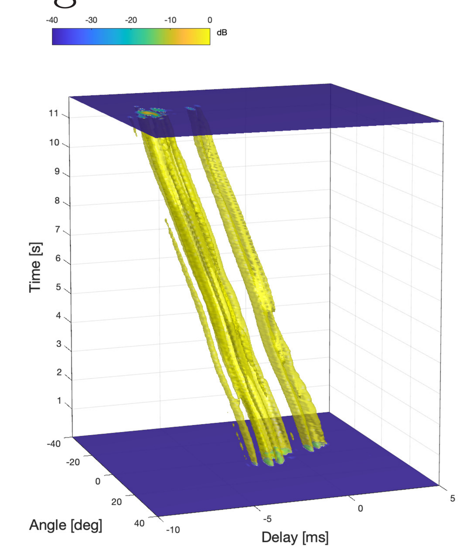


Fig. 8 Measured at **D**

Discussion

For SPACE, Fig. 2 agrees well with ray-tracing predictions, while Fig. 3 shows stable direct (D) and bottom-reflected (B) paths and fluctuating surface-reflected (S) paths.

For MACE, Fig. 5 to Fig. 8 show delay-angle-time measurements at different times and ship speeds. The delay-axis slant reveals motion-induced Doppler drifts.

Future Work

This work provides a visual way to identify stable and time-varying underwater acoustic paths for beamforming, tracking, and communication system design. Future work will address multi-user path tracking for communications and transmit beamforming in time-varying channels.

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