Geoacoustic inversion using simple hand-deployable acoustic systems

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CONTEXT

- Geoacoustic inversion = estimation of seafloor parameters
  - required to simulate in-water acoustic propagation
  - needed to assess sonar performance, localize sources, etc.
  - needed to understand/forecast noise pollution
- Inversion usually requires complex acoustic assets
  - receiver: vertical or horizontal arrays
  - source: powerful towed loudspeaker, explosives, etc.

THIS TALK

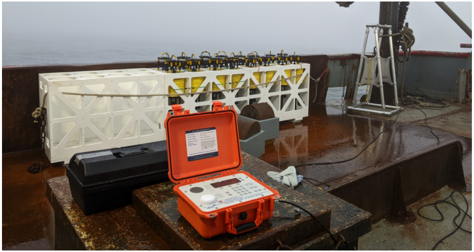
- Simple experimental assets to collect at-sea data
  - TOSSIT (single hydrophone) and RIUSS (mechanical source)
- Processing, inversion & uncertainty evaluation
  - warping to estimate modal dispersion
  - trans-dimensional (trans-D) Bayesian inversion
- Quantitative experimental validation
  - New England Mud Patch

TOSSIT

- TOSSIT = simple PAM mooring
  - designed at WHOI
  - single hydrophone
  - depth rated to 500 m
  - low cost < \$10k
- A ropeless design based on commercially available instruments
  - acoustic recorder: SoundTraps
  - acoustic release: Vemco Ascent AR
  - thermoplastic frame & synthetic foam
- Deployment and recovery by hand from small/big boats
  - heigth $\simeq 1$ m
  - weigth < 20 kg including anchor

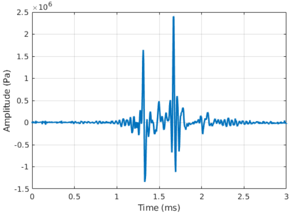
D. Zitterbart, A. Bocconcelli, M. Ochs, and J. Bonnel. Tossit: A low-cost, hand deployable, rope-less and acoustically silent mooring for underwater passive acoustic monitoring. HardwareX, page e00304, 2022

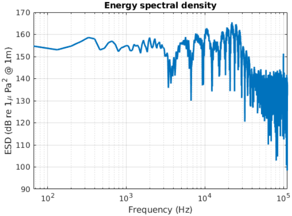
TOSSIT: deployment and recovery



RIUSS: Rupture Induced, Underwater Sound Source

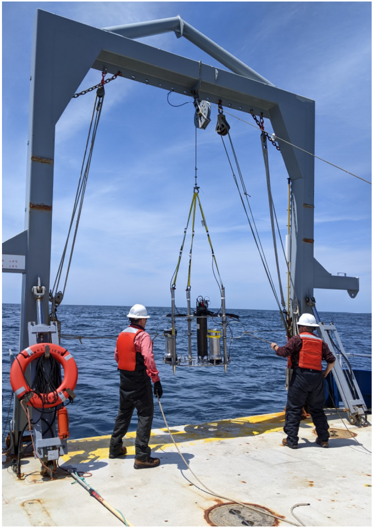
- RIUSS = simple impulsive source
  - designed at ARL-UT
  - depth rated to 155 m (graphite disc)
  - low cost (expendable RIUSS ≃ $250)
- A simple design based on a vacuum chamber and a rupture disc
  - disc ruptures at specified pressure differential between the two faces
    - ★ similar to lightbulb implosion
  - disc spec → source depth
  - SL ← rupture depth & chamber size
- Several deployment systems
  - frame with multiple chambers (need A-frame + winch)
  - **single expendable chamber**





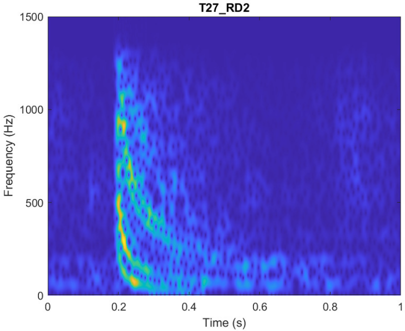
A. McNeese, K. Lee, J. Sagers, M. Lee, P. Wilson. Experimental observations of a rupture induced underwater sound source. JASA, 148(4), EL370-EL374, 2020 → VIDEO

RIUSS: deployment



Modal propagation and dispersion data

- Low-frequency & shallow water → modal propagation
  - received signal $Y(f) = |S(f)|e^{j\phi_s(f)} \sum_{m=1}^{N} \psi_m(z_s, f)\psi_m(z, f) \frac{e^{jrk_m(f)}}{\sqrt{rk_m(f)}}$
- Single hydrophone → time-frequency analysis
- Modal phase $= rk_m(f)$
  - defines travel time
  - position in the spectrogram
    - ★ **"modal dispersion data"**
- Modal dispersion data
  - $\tau_m(f) = t_s + \frac{r}{v_m(f)}$
  - estimated with warping
  - used as input for geoacoustic inversion



TOSSIT/RIUSS signal from SBCEX22

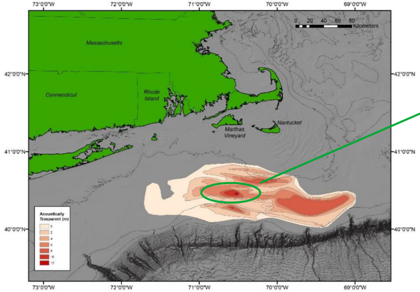
J. Bonnel, A. Thode, D. Wright, and R. Chapman. Nonlinear time-warping made simple: A step-by-step tutorial on underwater acoustic modal separation with a single hydrophone. JASA, 147(3):1897-1926, 2020.

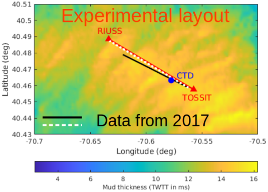
Trans-D Bayesian inversion: theory

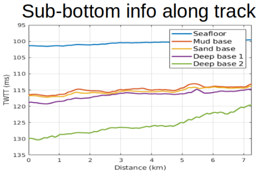
- Bayesian inversion of seafloor parameters x given dispersion data d
  - $P(\mathrm{x}|\mathrm{d}) \propto P(\mathrm{x})\, L(\mathrm{x})$
- Trans-D inversion: x contains many models (model selection)
  - $P(k, \mathrm{x}_k|\mathrm{d}) \propto P(k)\, P(\mathrm{x}_k|k)\, L(k, \mathrm{x}_k)$
  - k unknown number of seabed layers
  - x_k model parameters (e.g. c, ρ, h) for k layers
- Proper definition of the likelihood L requires knowledge/assumption about data error statistics:
  - assumed to be unbiased, Gaussian distributed and independent between modes → trans-D inversion for AR coeff. and var. for each mode
- Water column SSP parameters can be
  - known (e.g. CTD data) and included as prior information
  - unknown and estimated as part of the inversion
    - ★ number of SSP nodes estimated using Bayesian Information Criterion

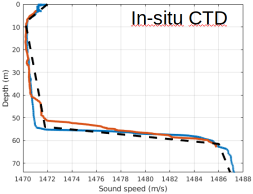
J. Dettmer, S. Dosso, C. Holland. Trans-dimensional geoacoustic inversion. JASA, 128(6), 3393-3405, 2010.

At-sea experiment: New England Mud Patch, May 2021

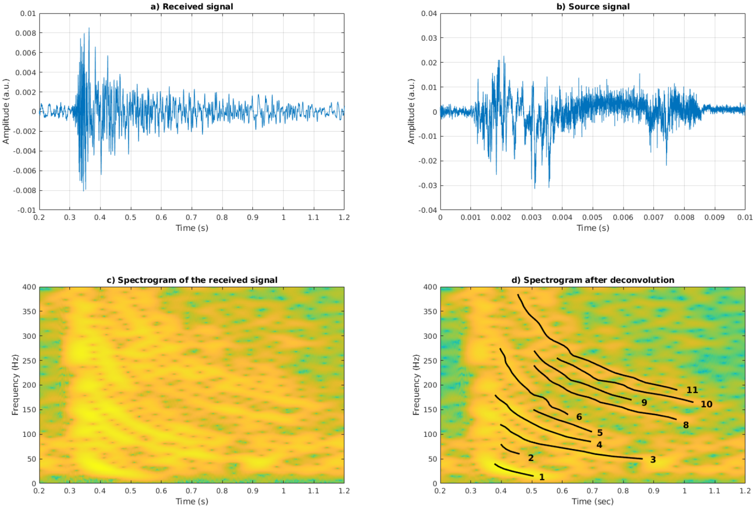




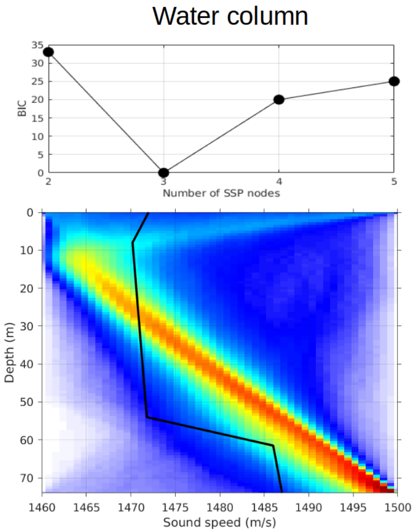


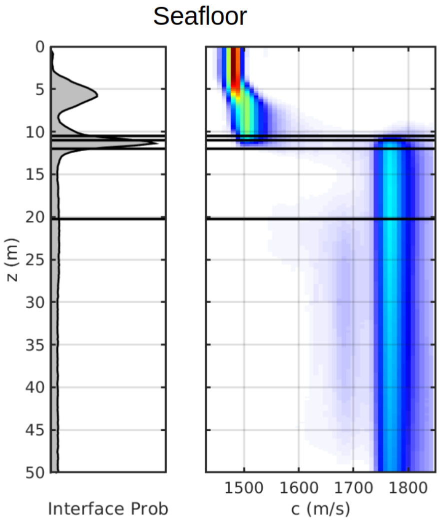


Acoustic data

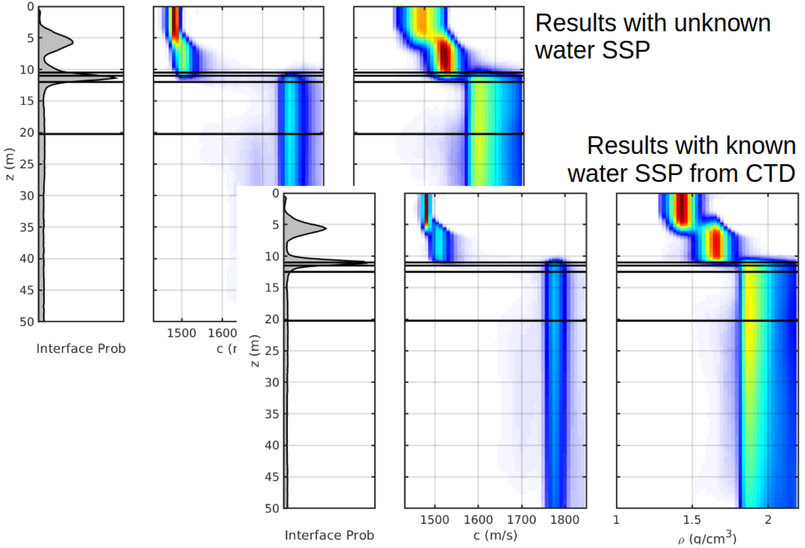


Inversion results with unknown water SSP

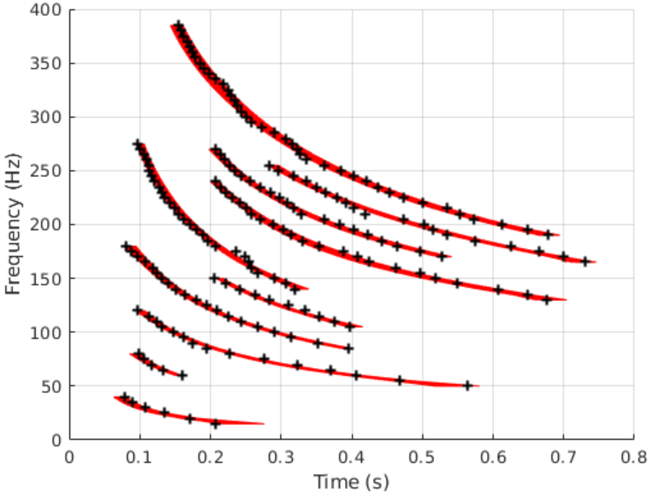




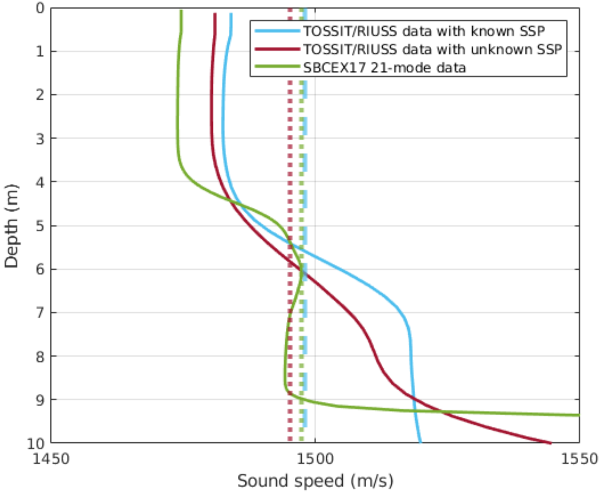
Inversion results with/without water SSP information



Data (black) / prediction (red) comparison



Comparison with SBCEX17: posterior mean of the mud SSP



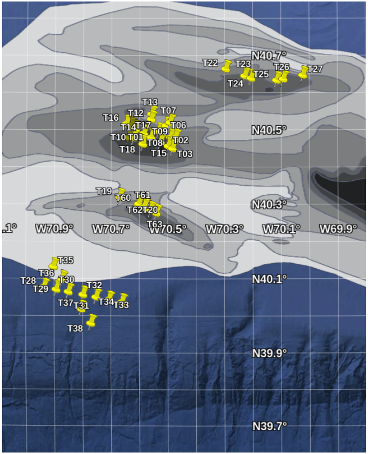
21-mode inversion result from J. Bonnel, S. Dosso, D. Knobles, and S. Wilson. Trans-dimensional inversion on the New England Mudpatch using high-order modes. IEEE JOE, 2021. Published Online (DOI: 10.1109/JOE.2021.3075824)

Conclusion

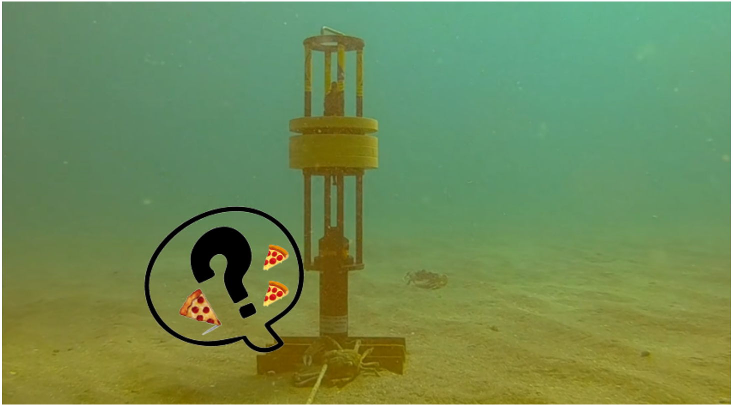
- RIUSS/TOSSIT make experimental inversion easy
- demonstration of inversion during frontal intrusion without CTD
  $\rightarrow$ **replace experimental cost with computational cost**
- SBCEX17 area revisited

Ongoing/Future Work

- TOSSIT/RIUSS combination allows large area coverage $\rightarrow$ SBCEX22
  - $\simeq$ 2 weeks at sea
  - New England mud patches and New England shelf break
  - 20 TOSSITs deployed 60 times (1 lost)
  - $\simeq$ 75 RIUSS deployed ($<$ 5 disc failures)



Questions ... ?



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Trans-D Bayesian inversion: in practice

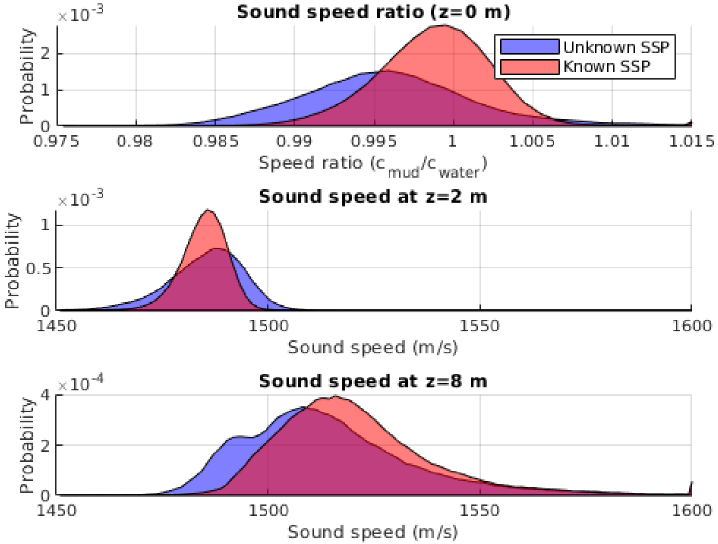
- Parameter list and prior

Parameter	Units	Prior bounds	Method
Seafloor: number of interfaces k	-	$[1, 10]$	fixed-D
Basement: sound speed c_b	m/s	[1515, 2500]	fixed-D
Basement: density ρ_b	g/cm^3	[1.3, 2.4]	fixed-D
Source: range r	km	[6.3, 8.3]	fixed-D
Source: emission time t_s	s	$[-6.5, -3.2]$	fixed-D
Error model: standard deviation σ_i	s	$(0, +\infty)$	fixed-D
Error model: AR coefficient a_m	-	$[-0.5, 0.99]$	trans-D
Seafloor: interface depths z_i	m*	[0.5, 50]	trans-D
Seafloor: layer sound speeds c_i	m/s	[1450, 2500]	trans-D
Seafloor: layer density ρ_i	g/cm^3	[1.3, 2.4]	trans-D
Water: number of SSP nodes q	-	$[2, 5]$	BIC
Water: depth of SSP nodes z_j	m	[2, 72]	fixed-D
Water: speed of SSP nodes c_j	m/s	[1460, 1500]	fixed-D

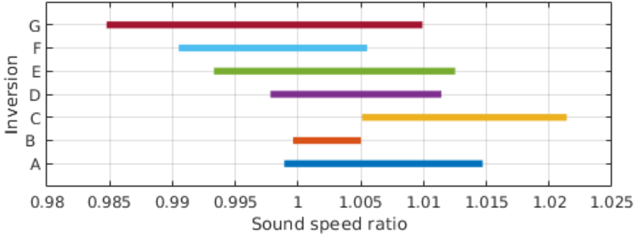
* in meters below seafloor

- Total number of parameters : 18-64
  - trans-D sampling using rjMCMC with parallel tempering (8 chains)
- Results: 400k samples from $T_1 = 1$ chain after burn-in

Inversion results: known vs unknown water SSP



Comparison with SBCEX17: mud/water sound speed ratio



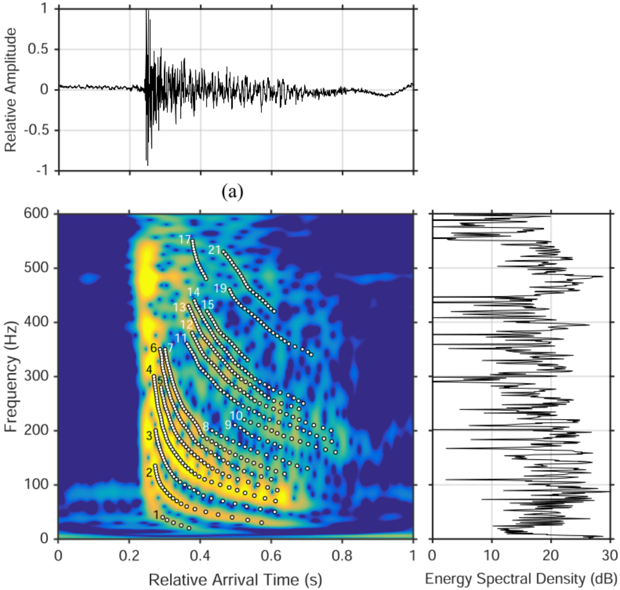
- SBCEX17 data on the same track: trans-D inversion based on modal dispersion
  - A J15 source ($r \simeq 7$ km, 6 modes with $52 < f < 248$ Hz)
  - B CSS source ($r \simeq 7$ km, 7 modes with $15 < f < 300$ Hz)
  - C CSS source ($r \simeq 5$ km, 7 modes with $20 < f < 350$ Hz)
  - D CSS source ($r \simeq 5$ km, 15 modes with $20 < f < 440$ Hz)
  - E CSS source ($r \simeq 5$ km, 21 modes with $20 < f < 550$ Hz)
- This study
  - F RIUSS ($r \simeq 7$ km, 11 modes with $15 < f < 385$ Hz)
  - G RIUSS ($r \simeq 7$ km, 11 modes with $15 < f < 385$ Hz)
- References

A, B : J. Bonnel, S. Dosso, D. Eleftherakis, and R. Chapman. Trans-dimensional inversion of modal dispersion data on the New England Mud Patch. IEEE JOE, 45(1):116-130, 2019.

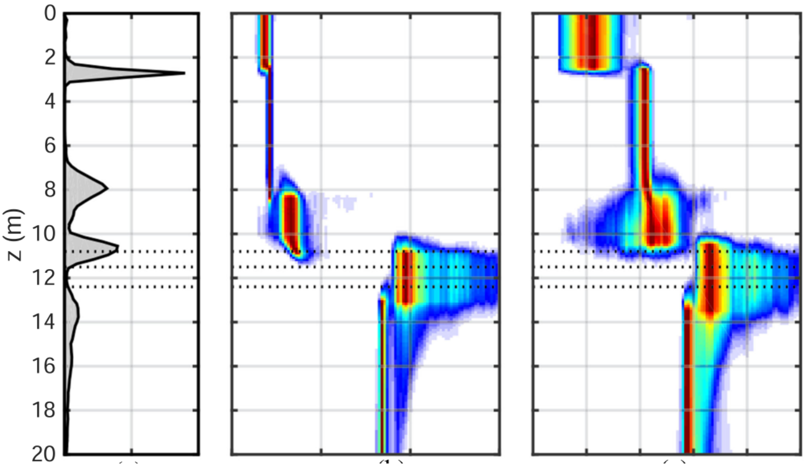
C, D, E : J. Bonnel, S. Dosso, D. Knobles, and S. Wilson. Trans-dimensional inversion on the New England Mudpatch using high-order modes. IEEE JOE, 2021. Published Online (DOI: 10.1109/JOE.2021.3075824)

SBCEX17: 21-mode dataset

21-mode dataset: dispersion data

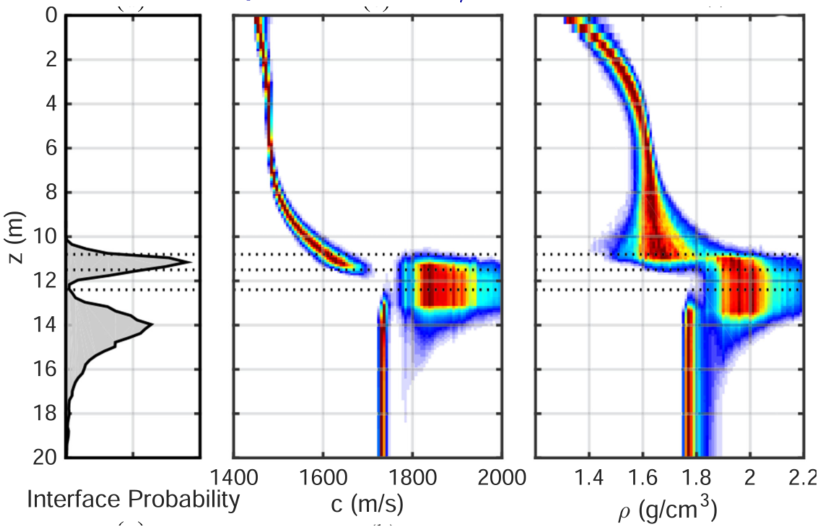


21-mode dataset: trans-D



J. Bonnel, S. Dosso, D. Knobles, and S. Wilson. Trans-dimensional inversion on the New England Mudpatch using high-order modes. IEEE JOE, 2021. Published Online (DOI: 10.1109/JOE.2021.3075824).

21-mode dataset: hybrid trans-D / BP



S. Dosso and J. Bonnel. Hybrid seabed parameterization to investigate geoacoustic gradients at the new england mud patch. IEEE JOE, 2022. Published Online (DOI: 10.1109/JOE.2022.3159315).