SERDP

Development of Physics-Based Inversions of BOSS Data for Sediment Properties

MR23-3971

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In-Progress Review Meeting

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Project Team

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Bottom Line Up Front

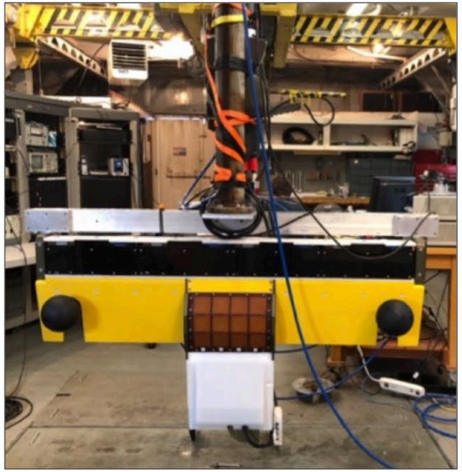
- The goal of this SEED project was to determine whether the multibeam echosounder physics-based inversion algorithm can be applied to data collected using structural acoustics (SA) sonars (eBOSS, Skyfish, SVSS) and what would be required to evaluate the performance of the algorithm.
- We determined that the inversion should work if data collected at high altitudes above the seafloor is used and modifications are made to account for the lower frequencies used in SA sonars.
- The inversion was successfully applied to data collected using the eBOSS in the Dry Tortugas. While the inversion gave reasonable results, we cannot assess the performance due to a lack of additional environmental characterization.
- Uncertainties remain in the calibration of the sonar that would need to be resolved prior to a full implementation.

Technical Objective

Determine if and how the MBES inversion algorithm can be modified to invert data collected with subbottom imaging sonars (eBOSS, Skyfish, etc.)

Teledyne-RESON T-50

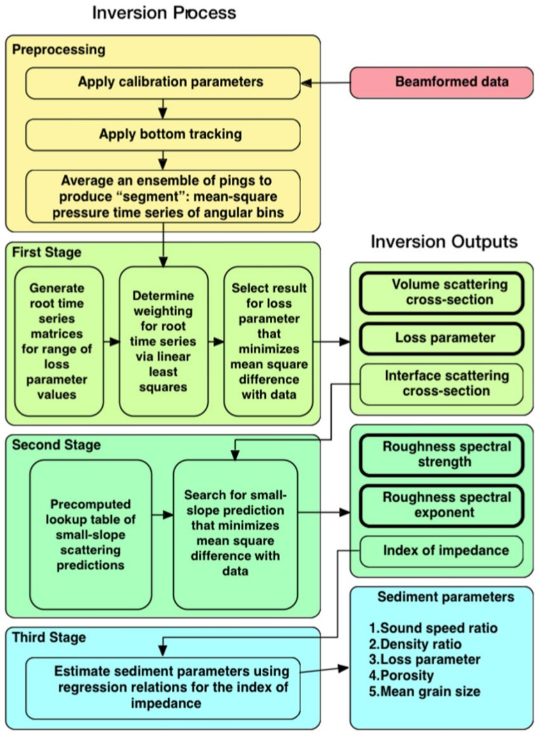
- Frequencies: 200-400 kHz (Typically operates at a single frequency)
- Receive array and source in Mills Cross Configuration
- Beam width: 0.5 degrees, 400 kHz
- Swath Width: 170 degrees
- 256 beams
- Deployed through Moon pool or on pole-mount over side of ship.



EdgeTech Buried Object Scanning Sonar - eBOSS

- Frequencies: 5-35 kHz
- 2 omnidirectional sources
- 64 element linear receive array
- Beams formed via combination of linear and synthetic array processing
- Volume images with 10x10x10 cm^3 voxels
- Deployed on Multi-Sensor Towbody (MuST).

The Multibeam Echosounder Inversion Algorithm



The multibeam echosounder inversion algorithm was developed over the course of two SERDP-funded efforts:

MR-2229:
- GulfEx11 (Gulf of Mexico, 2011)
- TREX13 (Gulf of Mexico, 2013)
- BayEx14 (St. Andrews Bay, 2014)

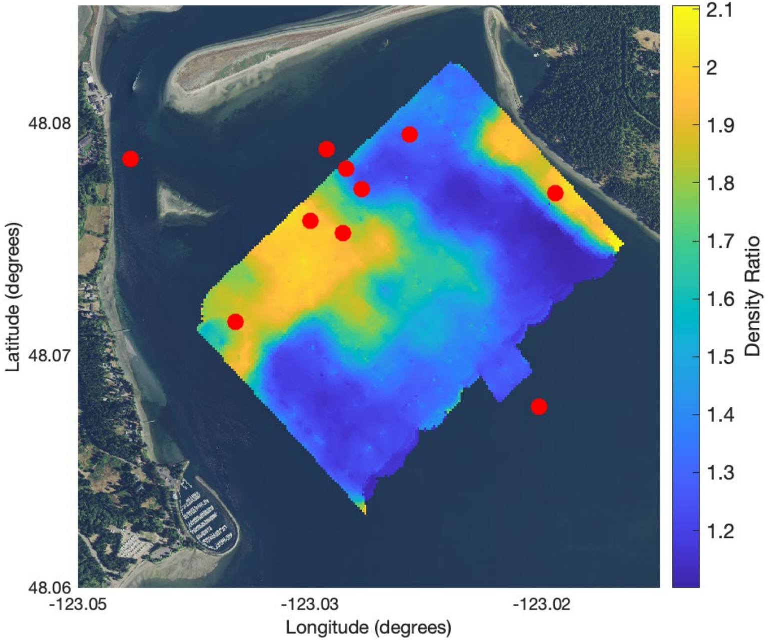
MR18-1406:
- Sequim Bay, WA (2019)
- Sequim Bay, WA (2021)

Physics-based inversion:

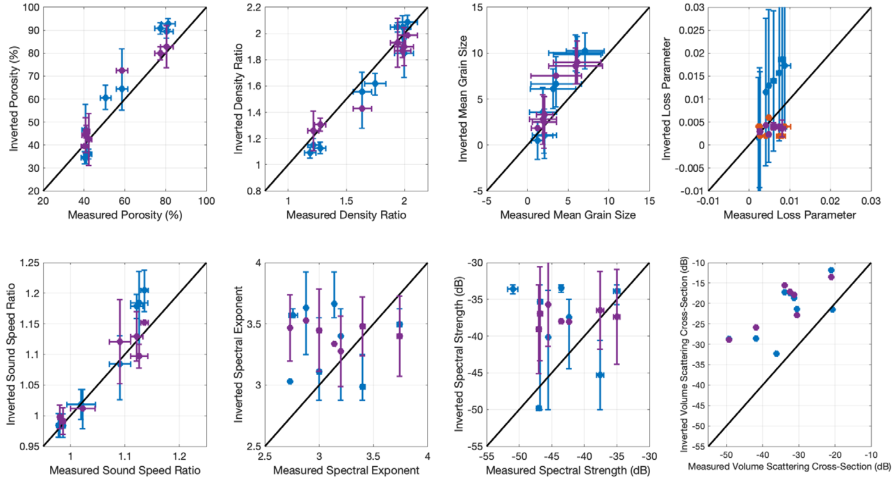
1. Collect multibeam echosounder (MBES) time series at multiple frequencies (or single frequency) and angles.
2. Fit MBES time series from each beam with separate surface and volume scattered components.
3. Best fit of acoustic scattering models to the surface scattering component as a function of grazing angle to determine sediment properties.

G. Xu, B. T. Hefner, D. R. Jackson, A. N. Ivakin, and G. Wendelboe, "A Physics-Based Inversion of Multibeam Sonar Data for Seafloor Characterization," IEEE J. Ocean. Eng. **50**, 1325–1343 (2025).

The Multibeam Echosounder Inversion Algorithm



The 2021 field test demonstrated that the inversion could be applied to survey data to produce maps of geoacoustic properties. Also demonstrated that the inversion results could be replicated using different sonars (although of the same model.)



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Technical Approach

Task 1: Assess Issues in transitioning from MBES to SA Sonar

- Near-field beamforming in the sonar model
- Inverting wide bandwidth and low frequency

Task 2: Modify the inversion code to work with the eBOSS data

Task 3: Invert eBOSS data using the modified inversion code

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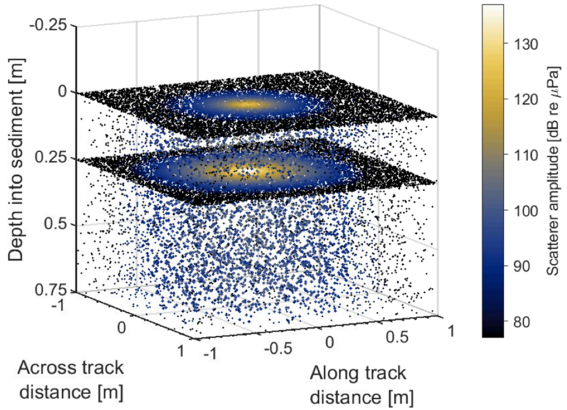
Addressing the Problem of Near-field Beam-forming

- In the MBES inversion, the sonar equation is used to simulate the beamformed data.
- For the eBOSS, near-field beamforming is used to generate high-quality images of the seafloor volume.
- Fitting the beamformed eBOSS data, would require simulating the element-level data.

- **This is both computationally expensive and would require significant changes to the inversion.**



Example of volumetric sonar simulation using POSSM (Dan Brown, MR-2545 final report)

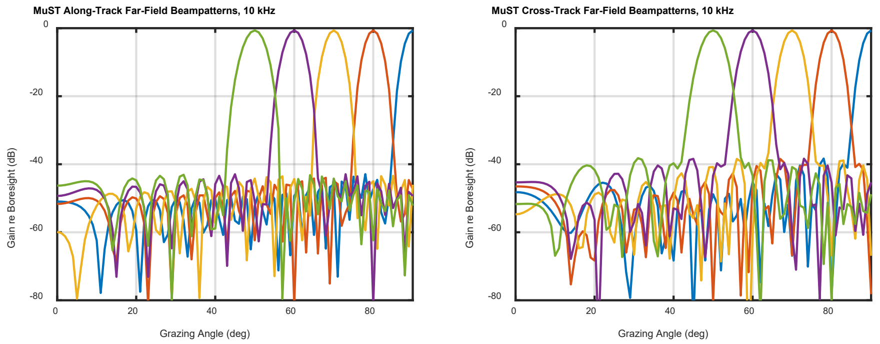
Addressing the Problem of Near-field Beamforming

- A more direct approach to applying the inversion is to use data collected in the far-field of the sonar (>8 m above the seafloor).
- This allows us to form beams that have a well-defined incidence angle and which we can simulate using the existing inversion code.

- Both the MUST and Skyfish teams collect this high-altitude data as part of the survey mission.

In essence, we are operating the eBOSS as a multibeam echosounder.

As a result, the inversion is unchanged.



- 48 pings are required to match along-track and cross-track beampatterns
- Effective array is 3 x 3 m
- At 10 m altitude, swath width is 7 m using beams out to 20 degree from nadir.
- Along-track width will depend on averaging.

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Addressing eBOSS Frequency and Bandwidth

Differences in the sonar operating frequencies and bands:

- MBES typically operate from **150-450 kHz** with narrow pulses with very narrow bandwidths.
- The eBOSS operates from **5-25 kHz** with a single LFM pulse that covers that band.

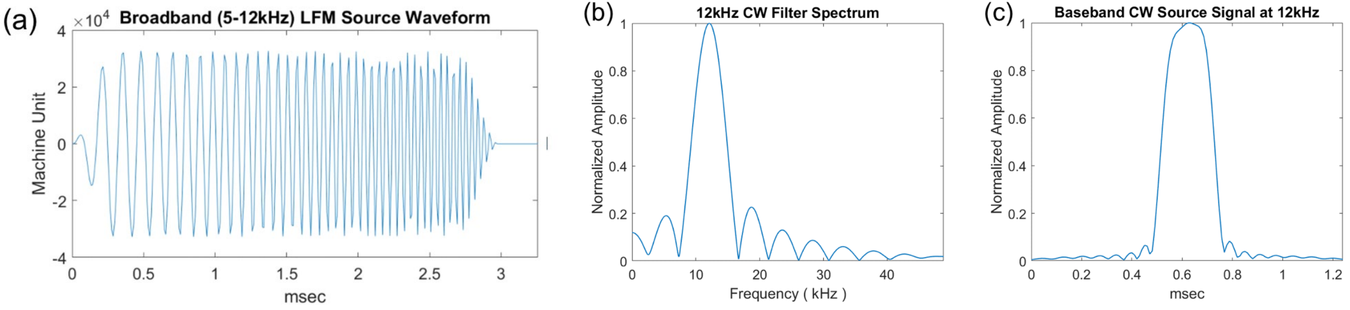
This presents two problems for the inversion:

1. Scattering strength is a quantity defined for a narrowband pulse.
   - Given the low frequencies of the eBOSS, there was concern that filtering the LFM pulse would lead to wide narrowband pulse that could be difficult to beamform and invert.
2. The Index of Impedance (IOI) regressions are based on measurements at 400 kHz.
   - Concern that the regressions would not be applicable to the low frequency IOI fit for the eBOSS.

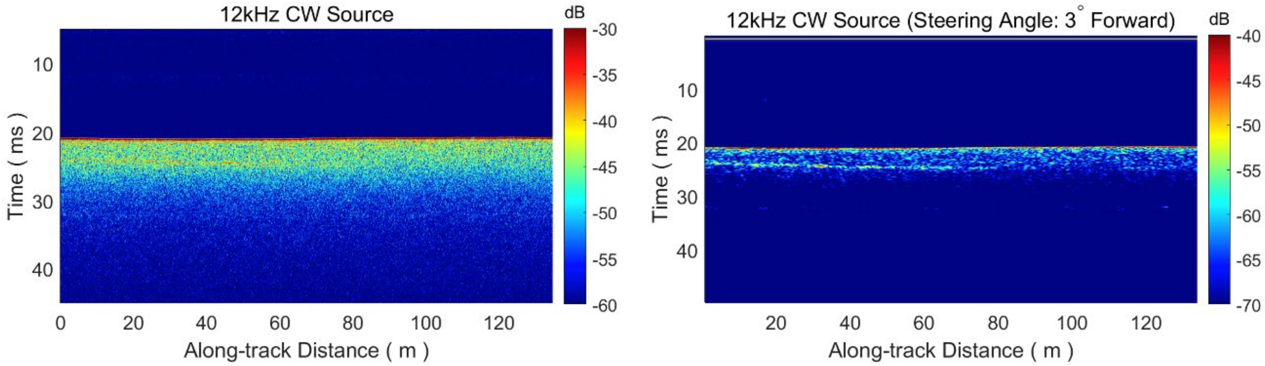
Addressing eBOSS Frequency and Bandwidth

Filtering applied to data to generate waveform that mimics short CW pulse:

$$F_{out}(\omega) = \frac{F_{rec}(\omega)F_{cw}(\omega)}{F_{source}(\omega)}$$



Example from Dry Tortugas data:



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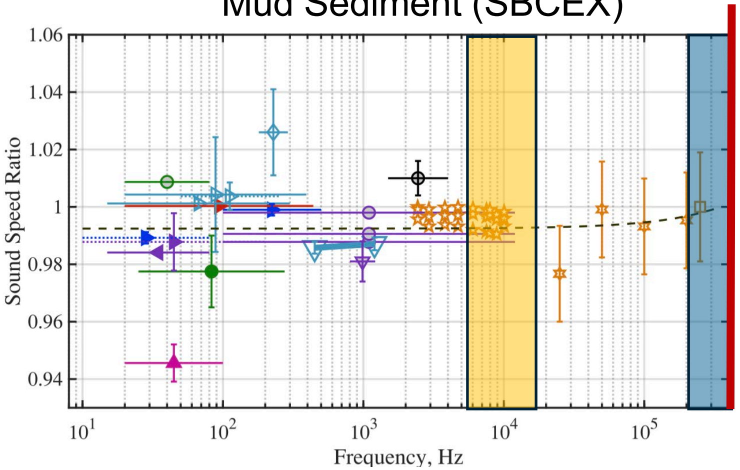
Using IOI regressions in eBOSS inversion

For soft sediments, no significant frequency dependence in geoacoustic parameters has been observed.

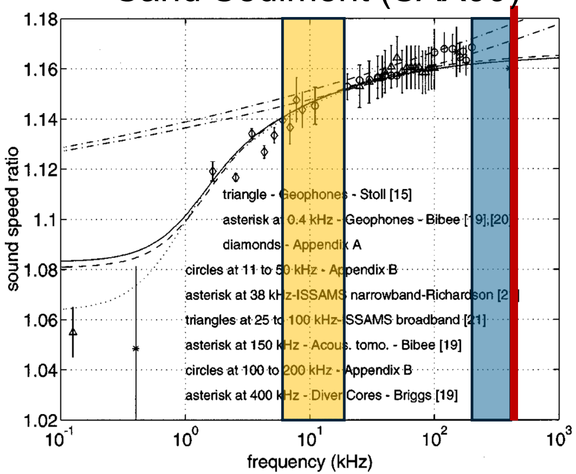
For sand sediments, there is significant dispersion between 400 kHz and the band of the eBOSS frequencies.

Mud Sediment (SBCEX)



From Wilson, et al., JOE, 2020

Sand Sediment (SAX99)



From Williams, et al., JOE, 2002

Frequency Range

- eBOSS
- MBES
- IOI regressions

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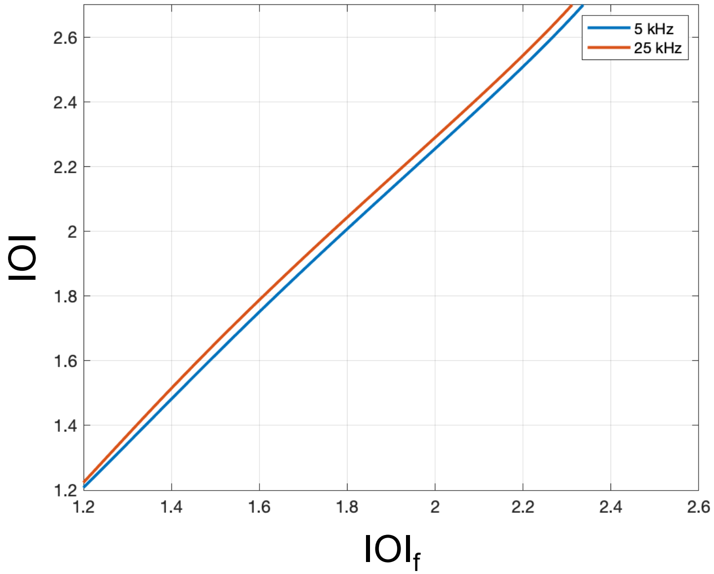
Using IOI regressions in eBOSS inversion

Proposed correction factor to account for poroelastic effects:

1. The regression between porosity and IOI is inverted:

$$IOI = 3.3328(1 - \sqrt{1 - 0.006734(174.6 - \beta)})$$

2. The effective density fluid model [15] is used to obtain the effective density and sound speed ratio as a function of porosity.
3. The product of the effective density and the sound speed ratio is taken to obtain the IOI_f as a function of the *IOI.*
4. Invert to obtain $IOI(IOI_f)$ and use to convert output from stage 2 of the inversion to IOI for use in regressions.



This conversion needs to be tested.

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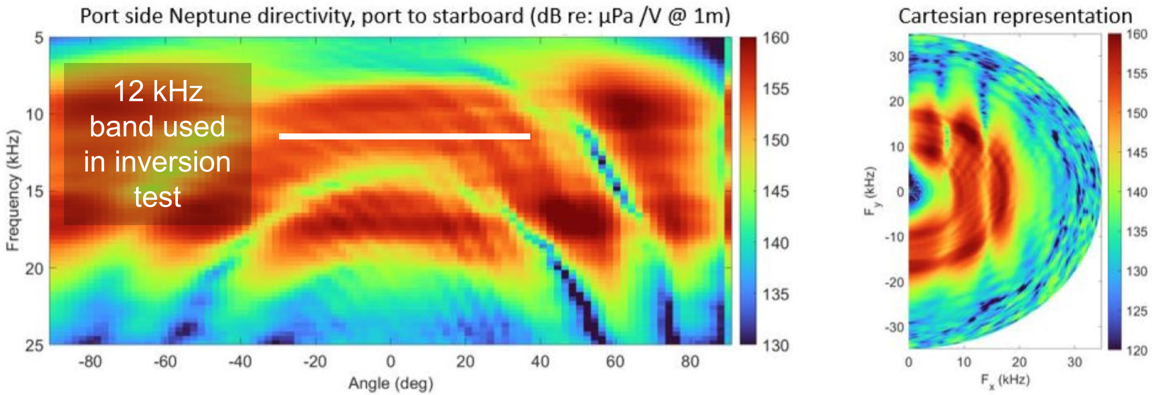
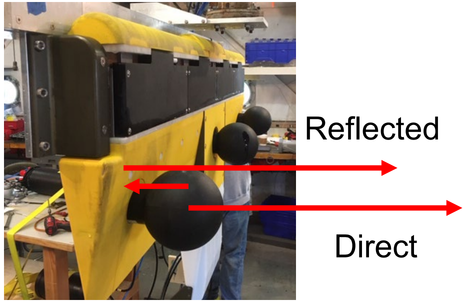
Applying the inversion: Preprocessing

- First step in preprocessing the data is to generate normalized mean-square pressure time series for each receiver element.
- Involves calibration parameters:
  - Voltage response of Neptune transducer
  - Receive sensitivity of elements
- Both measured during 2020 calibration of the eBOSS.

- Also needed is the RMS voltage into the Neptune: Strong frequency dependence, not well-known.

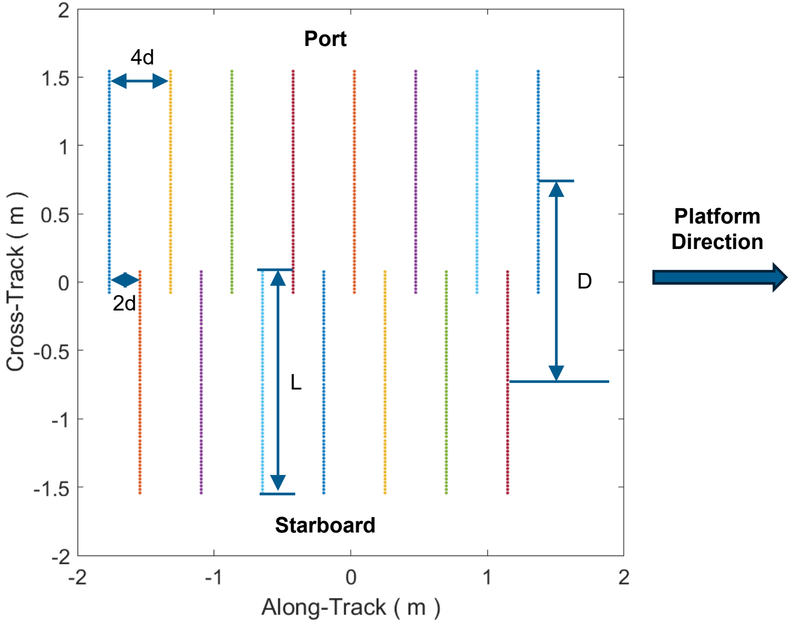




- 2020 calibration found that there is likely signal reflected from wing of eBOSS.
- Delay of 0.13 msec
- Leads to strong frequency dependence in source directivity.

Applying the inversion: Preprocessing

Far-field Synthetic Aperture Beamforming



- Between-ping platform travel distance, d = 0.11 m
- Port-starboard shift distance, D = 1.5 m
- 64-element receive array length, L = 1.6 m

- The port-starboard shift of the receive array between pings reflects the alternating transmissions of the port and starboard sources of the eBOSS system.
- The between-ping along-track spacing of the receive array in the synthetic aperture is twice the platform movement.
- A total of 15 pings are used to construct the synthetic aperture for it to have approximately the same cross-track and along-track lengths.
- Hamming shading is applied in both cross-track and along-track directions for beamforming.

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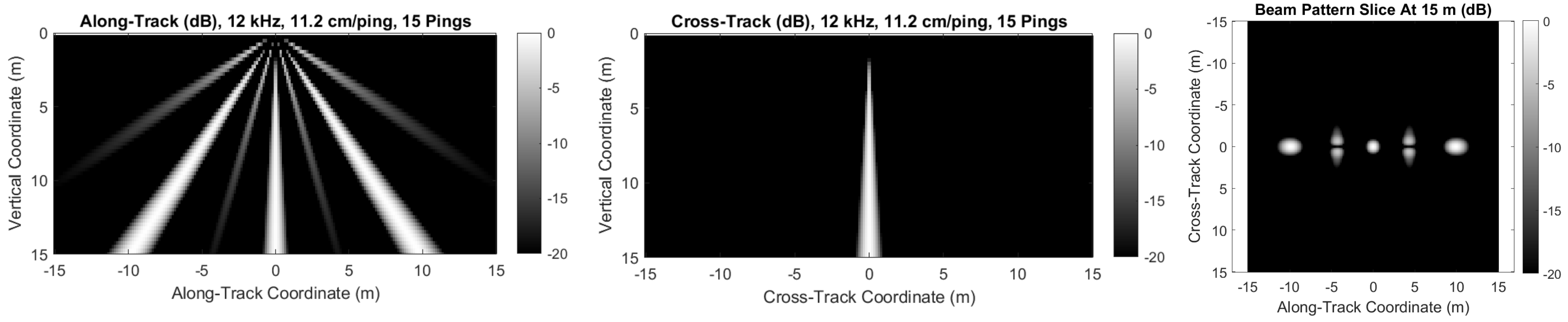
Applying the inversion: Preprocessing

- Beampatterns for the eBOSS at the 15 m altitude used during the Dry Tortugas deployment
- Faster tow speed means larger distance traveled between pings
- This leads to under-sampling in the along-track direction which produces strong grating lobes
- While these are accounted for in the sonar model, the system is operating close to the edge of the far-field and there could be differences between predicted and actual beampatterns.



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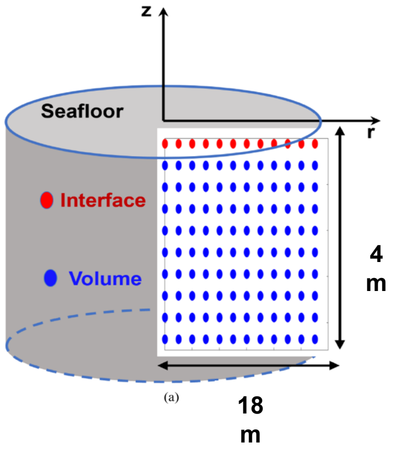
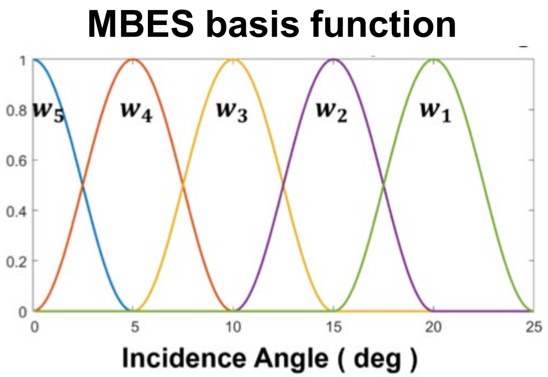
Applying the inversion: First Inversion Stage

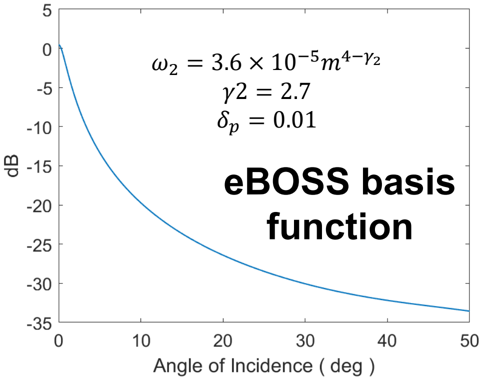


Model domain for eBOSS inversion:

- Horizontal grid spacing (dx):1.6 cm
- Vertical grid spacing (dz): 4.6 cm

- The least-squares-based method described in Xu et al., (2024) is used to determine the best-fit model free parameters.
- MBES inversion used weighted sum of Hann-shaped basis functions for interface scattering cross-section as a function of incidence angle.
- More efficient to use small-slope scattering strength lookup table with roughness spectral strength and spectral slope as free parameters.
    - Efficiency a consequence of low frequencies used in eBOSS





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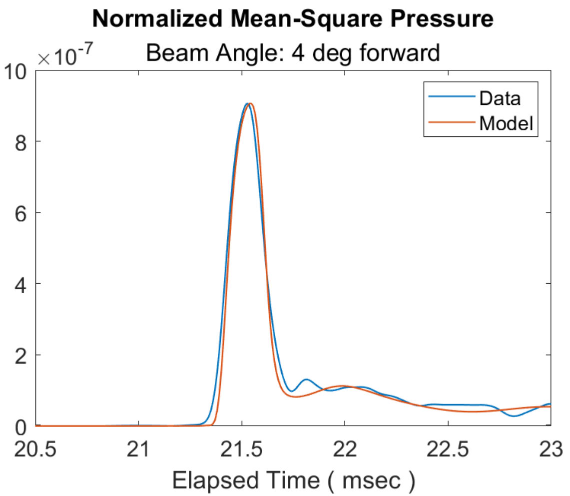
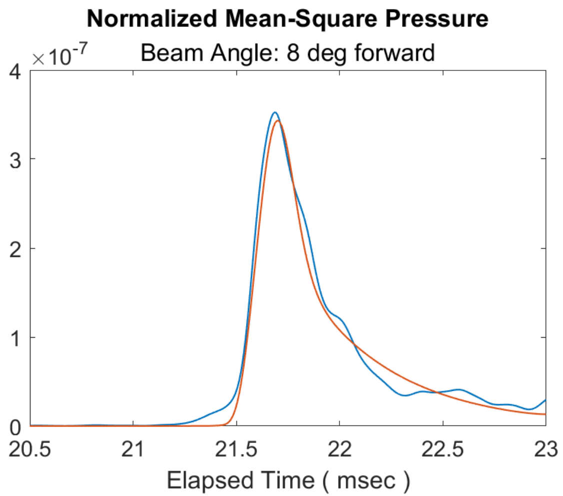
Applying the inversion: First Inversion Stage



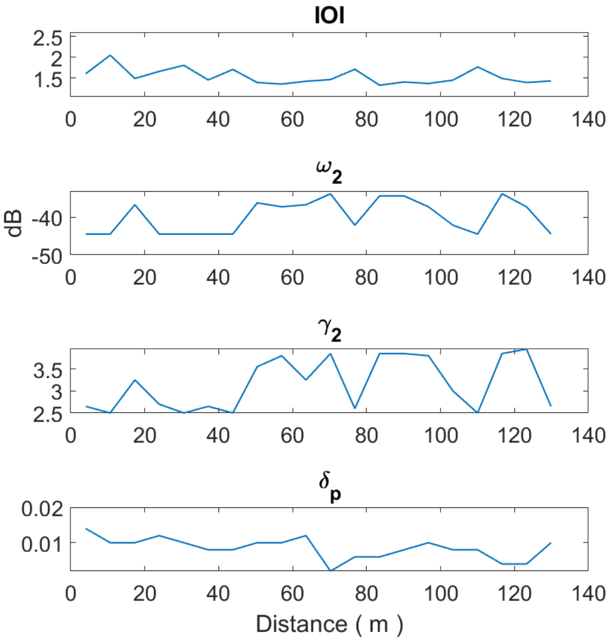


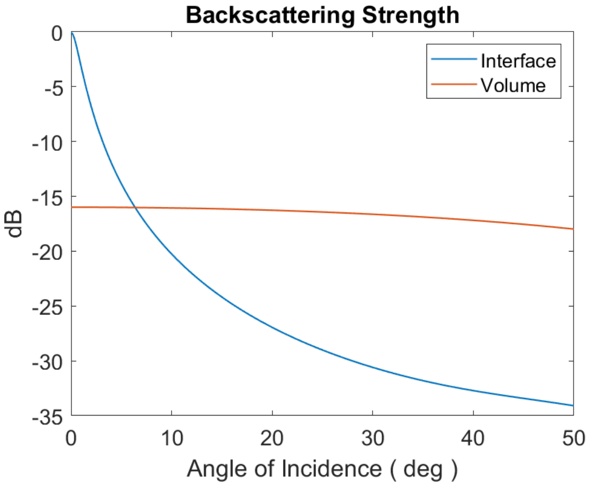
Examples of best fit of the model to the measured normalized mean-square pressure.

Applying the inversion: First Inversion Stage

Output from Stage 1 of the inversion

- Incident beams from 4 to 8 degrees in the along track direction were used with 1 degree separation.
- Adding cross-track beams could reduce variability in the output.
- All parameters are reasonable but there is no environmental data to support assessment of accuracy.





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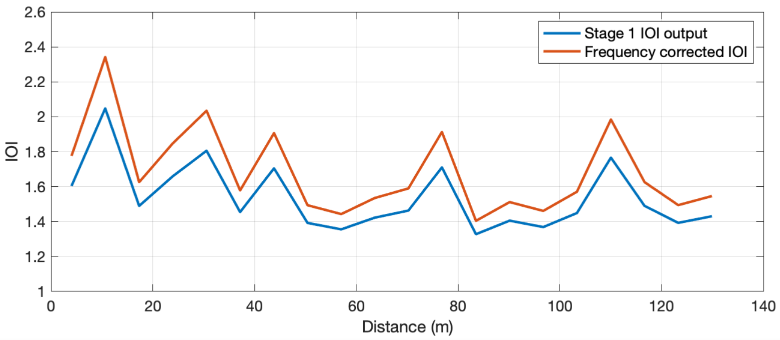
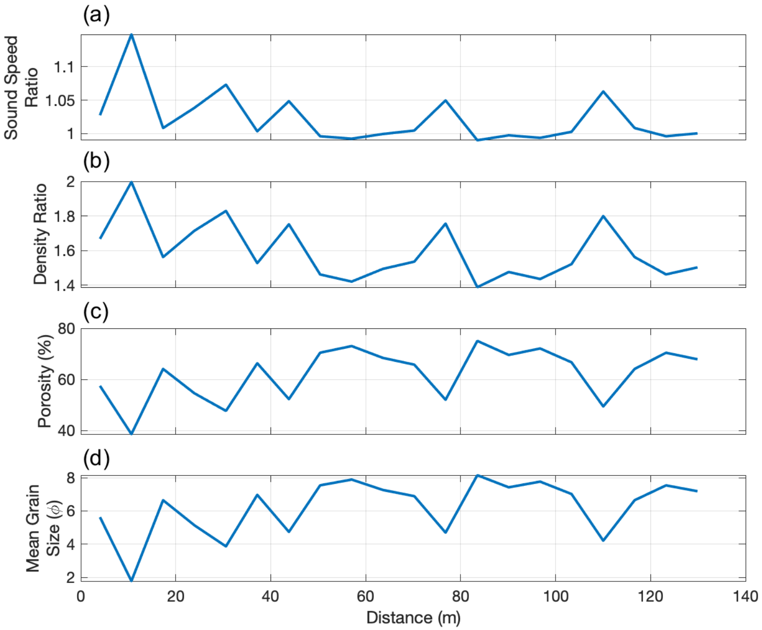
Applying the inversion: Third Inversion Stage

Outputs from the third inversion stage

- Poroelastic correction applied to IOI along the survey track.
- Regression output indicates that the sediment transitions from sand to mud.
- This is unlikely due to the ubiquity of sand sediments in the Dry Tortugas but cannot say for sure.
- Drive voltage to transducer may be lower than expected leading to underestimate of IOI.





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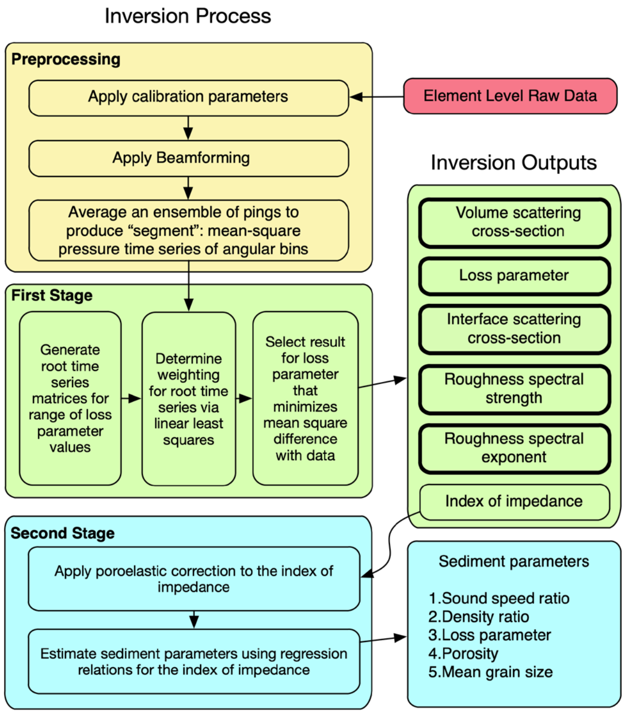
Final implementation of the eBOSS inversion



- The MBES physics-based inversion was modified and applied to high-altitude eBOSS data.
- The modifications were minor and runs efficiently in Matlab.
- Questions that remain to be resolved:

    1. Uncertainties in the calibration parameters.
    2. Impact of signal reflecting from the eBOSS wing.
    3. Evaluation of the poroelastic correction to the IOI.

- It may be possible to resolve issues 1 and 2 with existing eBOSS datasets.
- Algorithm should be able to work with Skyfish and SVSS data provided calibration data is available.

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BACKUP MATERIAL

MR23-3971: Development of Physics-Based Inversions of BOSS Data for Sediment Properties

Performers: *Brian Todd Hefner, Darrell Jackson, Anatoliy Ivakin, and Guangyu Xu*

Technology Focus

- *Develop a path for development of a physics-based sonar inversion technique for use with structural acoustics sonars.*

Research Objectives

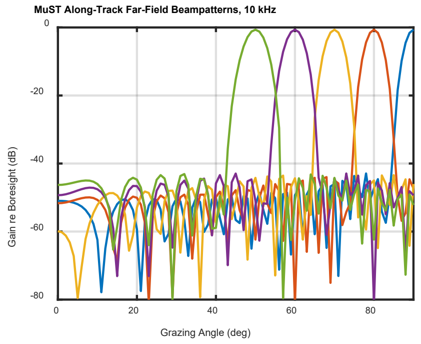
- *Given the differences in design and operation between high-frequency multibeam echosounders and low-frequency volumetric sonars, determine how best to modify the existing, well-tested echosounder inversion technique to work with volumetric sonars.*

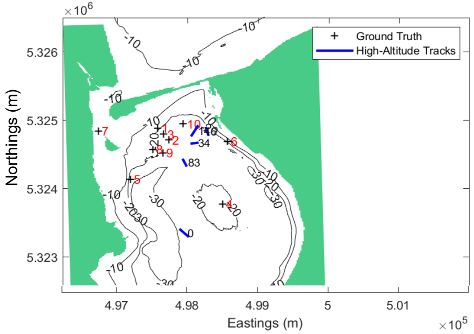
Project Progress and Results

- *Determined that the inversion can be applied as is to high-altitude MUST data*
- *Modified the inversion to work with eBOSS data and demonstrated that the inversion gives reasonable outputs.*

Technology Transition

- *Inversion could be added to the existing set of scripts and codes used with the MuST eBOSS, Skyfish, and the SVSS.*





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Plain Language Summary

- The goal is to augment the capabilities of UXO detecting sonar with tools to collect quantitative information about the seafloor where the UXO are located.
- More information about the seafloor can improve the ability of the sonar to detect and identify UXO.
- This seafloor remote sensing technique was originally developed for use high-frequency bathymetric sonars and the current effort seeks to extend the sensing capability to collect information about the deeper sediments.

Impact to DoD Mission

- Structural acoustics (SA) sonars are seen as solution to the need to detection and classify buried UXO.
- The physics-based inversion has been successfully developed and demonstrated for use with multibeam echosounders.
- This work demonstrates that the physics-based inversion can be applied to SA sonar data as well.
- This has the potential augment the capability of these sonars such that they can provide information about the seafloor properties without additional and costly sediment characterization.
- This information about the seafloor can be used to enhance classification algorithms and aid munitions mobility predictions.

Literature Cited

- G. Xu, B. T. Hefner, D. R. Jackson, A. N. Ivakin, and G. Wendelboe, “A Physics-Based Inversion of Multibeam Sonar Data for Seafloor Characterization,” *IEEE J. Ocean. Eng.* **50**, 1325–1343 (2025).
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