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

MR23-3971

Brian T. Hefner

Applied Physics Laboratory-UW

In-Progress Review Meeting

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Project Team

Todd
Hefner
APL-UW

Guangyu
Xu
APL-UW

Darrell
Jackson
APL-UW

Anatoliy
Ivakin
APL-UW

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Bottom Line Up Front

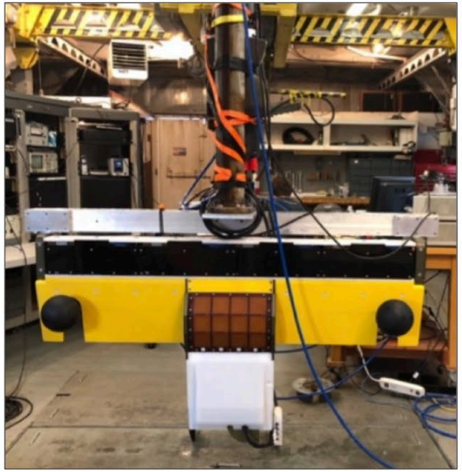
- The goal of this SEED project is to determine whether the multibeam echosounder inversion algorithm can be applied to data collected using volumetric imaging sonars (eBOSS, Skyfish, SVSS) and what would be required to evaluate the performance of the algorithm.
- After discussion and analysis, we believe that the inversion requires minimal modification to invert eBOSS, Skyfish, and SVSS data if the sonar data is collected at high altitudes.
- The process of getting the high-altitude data and calibration measurements for the eBOSS has been slow and this has led to significant delays in the project.
- Pending tests with eBOSS data, and potentially Skyfish data, it should be straightforward to provide a user-friendly version of the inversion for use with these sonars.

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).

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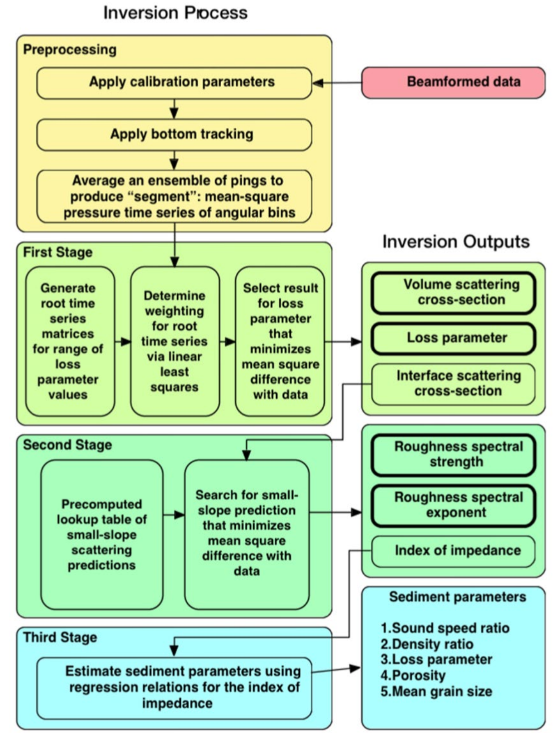
The Multibeam Echosounder Inversion Algorithm



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:

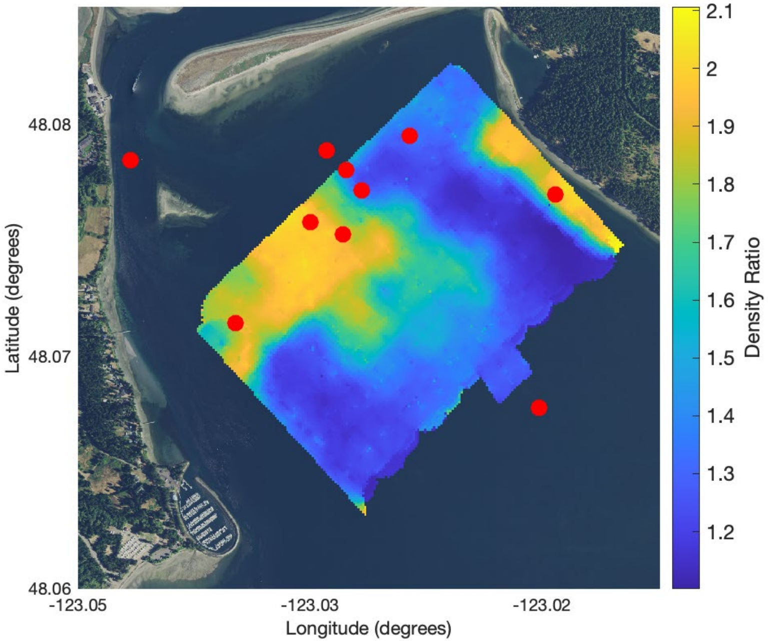
- Sequim Bay, WA (2019)
- Sequim Bay, WA (2021)

Physics-based inversion:

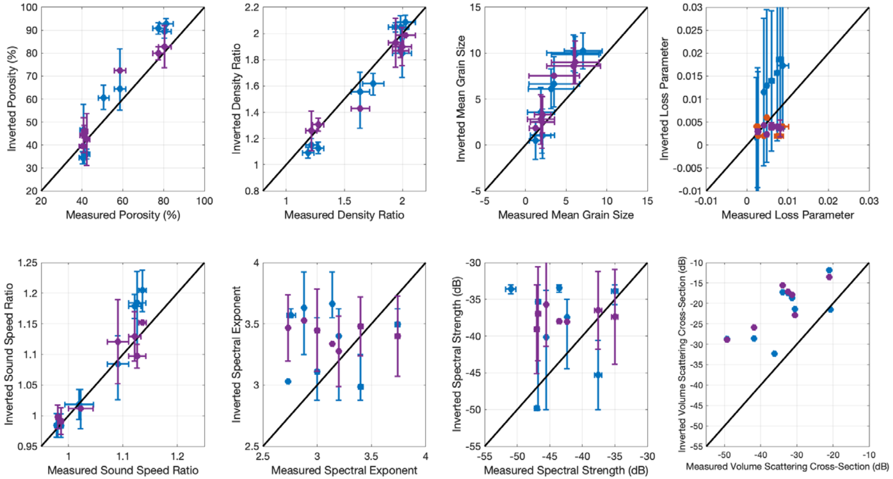
1. Collect multibeam echosounder (MBES) time series at multiple frequencies (or single frequency) and angles.
2. Fit MBES time series from each beam with separate surface and volume scattered components.
3. Best fit of acoustic scattering models to the surface scattering component as a function of grazing 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," Accepted to IEEE J. Ocean. Eng., 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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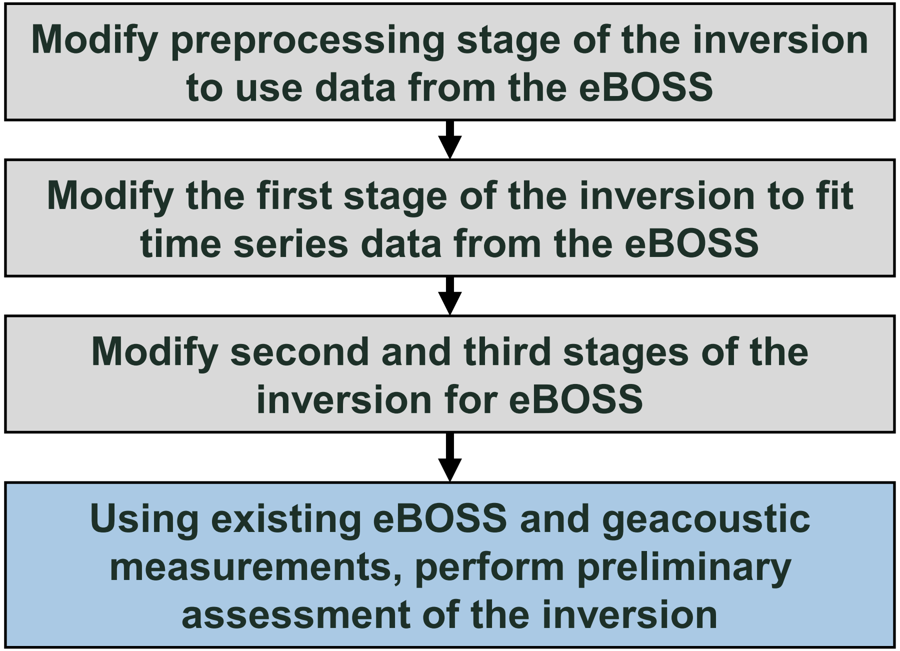
Technical Approach

Approach originally proposed for this project to address differences in sonars:

- eBOSS has a lower and broader frequency range.
- eBOSS beam-forming performed in the near-field of the sonar.

Over the course of project, we have diverged from this approach.



Addressing eBOSS Frequency and Bandwidth

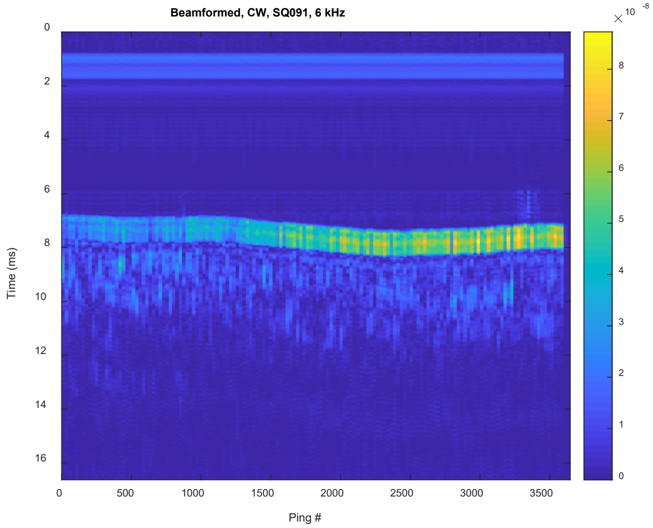
Differences in the sonar operating frequencies and bands:

- 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



Filtered, near-field beamformed example using data collected in Sequim Bay.

- Using eBOSS data, we have been able to show that we can filter the data to mimic pure-tone CW pulses and beamform those pulses.

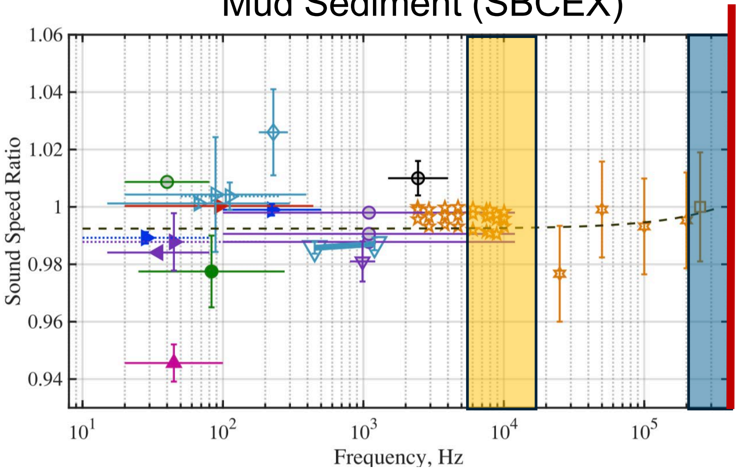
- This does not work well for the highest frequencies, and we feel that we would need to limit the narrowband range to 6-18 kHz.

Using IOI regressions in eBOSS inversion

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

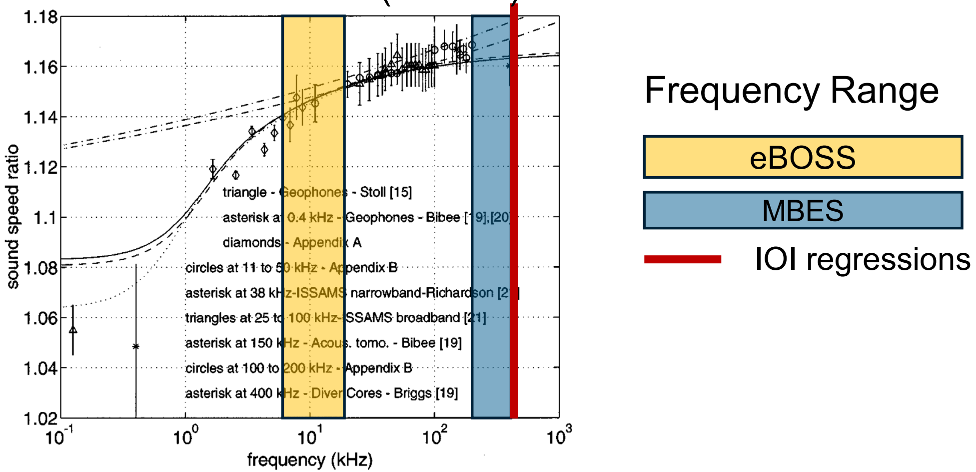
For sand sediments, there is significant dispersion between 400 kHz and the band of the eBOSS frequencies.

Mud Sediment (SBCEX)



From Wilson, et al., JOE, 2020

Sand Sediment (SAX99)



From Williams, et al., JOE, 2002

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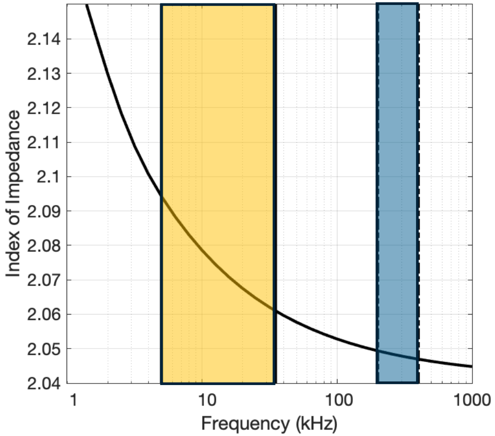
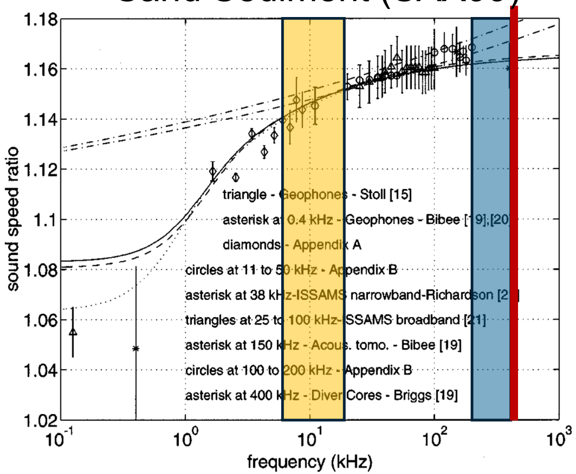
Using IOI regressions in eBOSS inversion

- For the multibeam inversion we use a correction factor to the IOI which takes into account that the acoustically measured density is different from the true density for sand sediments.
- We believe that we can apply an additional correction factor based on the poroelastic theory (EDFM), to adjust the IOI for sand sediments.



IOI calculated using the Effective Density Fluid Model (EDFM)

Sand Sediment (SAX99)



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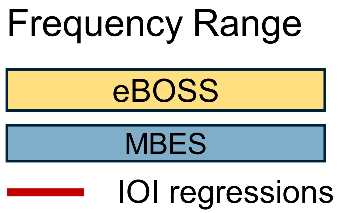

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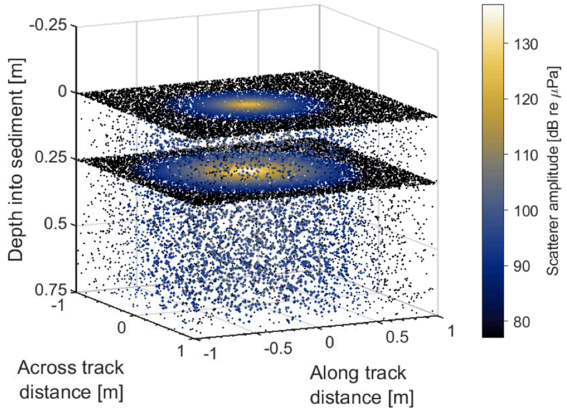
Addressing the Problem of Near-field Beam-forming

- 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)

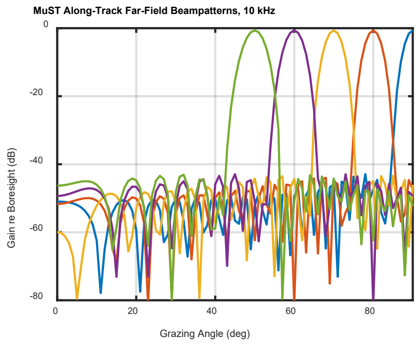
Addressing the Problem of Near-field Beamforming

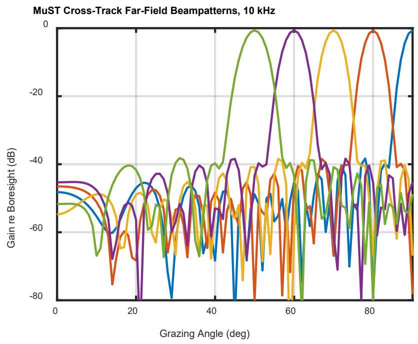
- A more direct approach to applying the inversion is to use data collected in the far-field of the sonar (>8 m above the seafloor).
- This allows us to form beams that have a well-defined incidence angle and which we can simulate using the existing inversion code.

- 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.

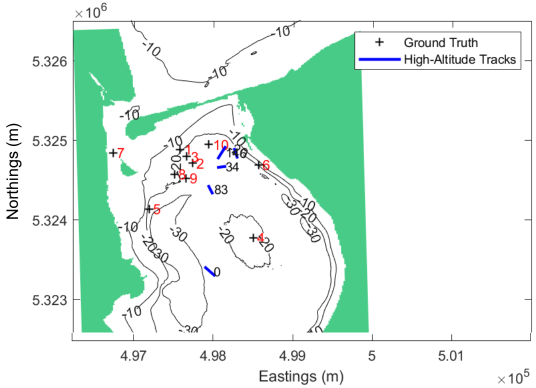




- 48 pings are required to match along-track and cross-track beampatterns
- Effective array is 3 x 3 m
- At 10 m altitude, swath width is 7 m using beams out to 20 degree from nadir.
- Along-track width will depend on averaging.

Identification of High Altitude eBOSS Data and Calibration Information

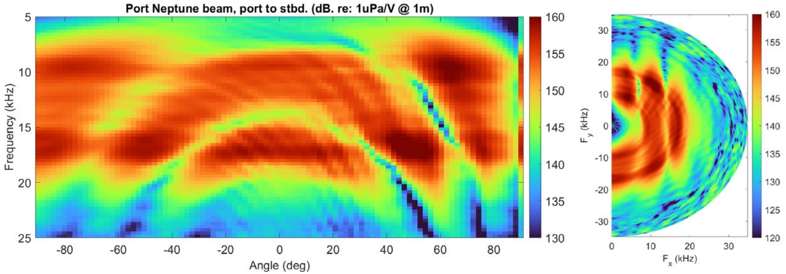
- Working with Tim Marston, initial, high-altitude data has been obtained.
- Data collected in Sequim Bay, so we can compare results against MBES inversion and ground truth.



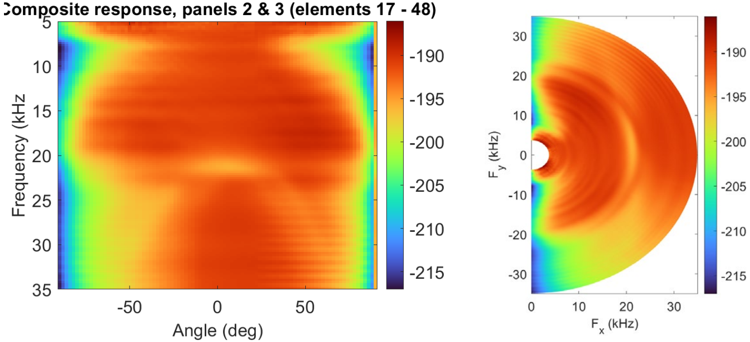
- Also obtained some of the calibration data for the eBOSS.

- **After some delay, we are starting the process of inverting the data now.**

Source Beampattern



Mean Receiver Element Beampattern



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On-going Work and Next Steps

- Work is underway to apply inversion to the high-altitude data.
- Expect results by the end of January.
- Final report submission expected at the end of February.

Future Research

- Remains a need to determine the accuracy of the inversion for the eBOSS.

- There are aspects of the sonar that may impact the inversion in ways we don't yet understand:
    - Lower frequencies
    - Wider beams
    - Deeper penetration into the sediment

- While the first two aspects can be evaluated using Sequim Bay data and ground truth, the last would need additional environmental characterization.

From interim report for **SERDP Project MR18-1051**

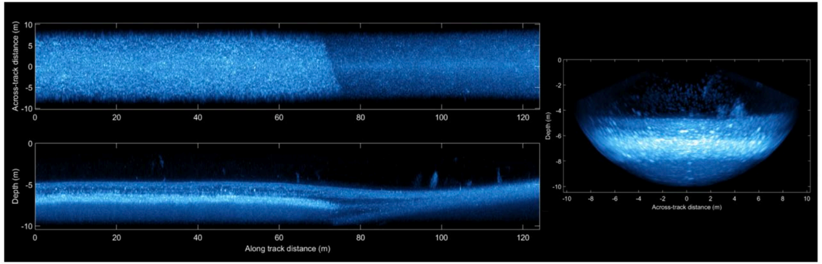

Figure 44: 3-direction orthogonal MIP views for a SAS volume generated using the 2-stage FFBP algorithm described in the technical approach. The region shown here is east of the target field and bridges a very distinct layer transition several meters below the surface layer. Several clouds of fish can also be seen floating above the sediment.

- While the inversion can work in stratified sediments, this aspect of the algorithm has not been well-tested.

Might be possible to leverage existing and planned environmental characterization for upcoming live site evaluations.

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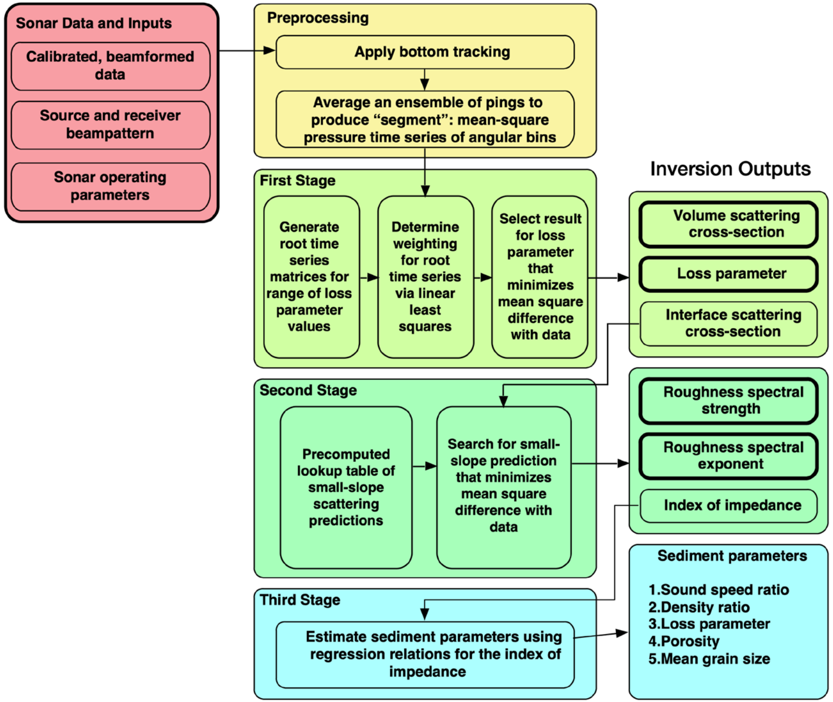
Generalization of the Inversion Algorithm

The MUST and Skyfish teams are ideal beta testers of the generalized code:

1. The sonars are calibrated.
2. Both teams use MATLAB.
3. Both teams will be taking data in multiple environments over the next few years that can be used to exercise the inversion.
4. The MUST also has a T50 sonar, so the generalized inversion can he tested (sanity-check) on a high-frequency MBES.



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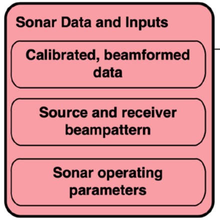
Wider application within the DOD

Once the code is generalized, the next step would be to migrate the inversion to an application that can be run without need for MATLAB license or experience.

Need to estimate the cost of this migration.

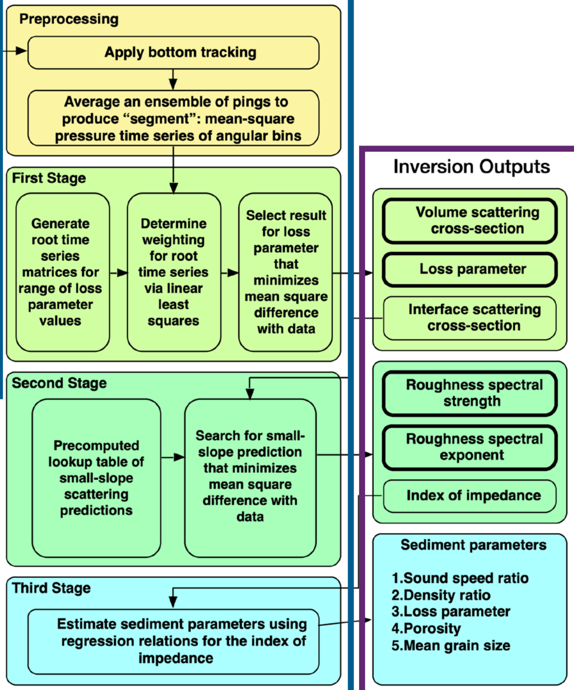
Standardize format for this information.



Flexible tools to put data into this format (Python, MATLAB, etc.)

Migrate the inversion from MATLAB into an application.

C++ or other compiled code such that it can be run on any PC without need for MATLAB.



Use standard formats for geolocated output.

For input to mapping software (CARIS, Esri, etc.)

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 volumetric imaging sonars.*

Research Objectives

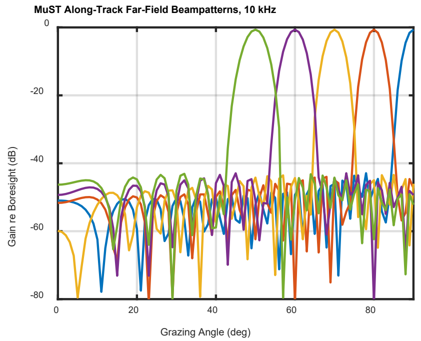
- *Given the differences in design and operation between high-frequency multibeam echosounders and low-frequency volumetric sonars, determine how best to modify the existing, well-tested echosounder inversion technique to work with volumetric sonars.*

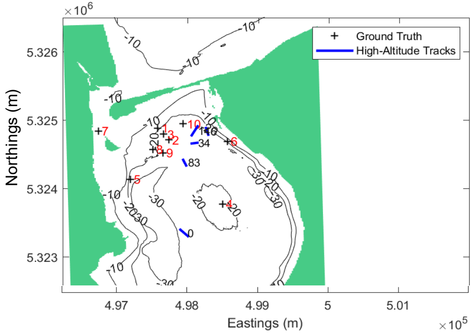
Project Progress and Results

- *Determined that the inversion can be applied as is to high-altitude MUST data*
- *Obtained high-altitude eBOSS data and calibration to test the inversion.*
- *Established an approach to work with Skyfish team to test inversion for their sonar.*

Technology Transition

- *Straightforward approach to generalizing existing inversion code for use by MUST and Skyfish teams.*





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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.

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,” *Accepted to IEEE J. Ocean. Eng.,* 2025.
- Wilson, P. S., Knobles, D. P. & Neilsen, T. B., “Guest Editorial An Overview of the Seabed Characterization Experiment,” *IEEE J. Ocean. Eng.* 45, 1–13 (2020).
- Williams, K. L., Jackson, D. R., Thorsos, E. I., Tang, D. & Schock, S. G., “Comparison of sound speed and attenuation measured in a sandy sediment to predictions based on the Biot theory of porous media,” *IEEE J. Oceanic Eng.,* 27, 413–428 (2002).