PHYSICS-BASED FEATURES AND CLASSIFICATION ARCHITECTURE FOR UNDERWATER BURIED TARGETS

MR20-1443

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In-Progress Review Meeting

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Bottom Line Up Front

- Technology/methodology:
  - Incorporating physics knowledge into sonar-based DCL
- What's going well?
  - Development of an elastic cylindrical shell detector and its initial application to MuST data
- What's not working?
  - Known deficiencies in the detector related to high scattering areas of the acoustic color (broadside & ends)
  - Combining detector results from different resonance types in a physics-based way
- What support do you need?
  - The detector shows promise, but it would take additional investment to thoroughly test and mitigate known deficiencies

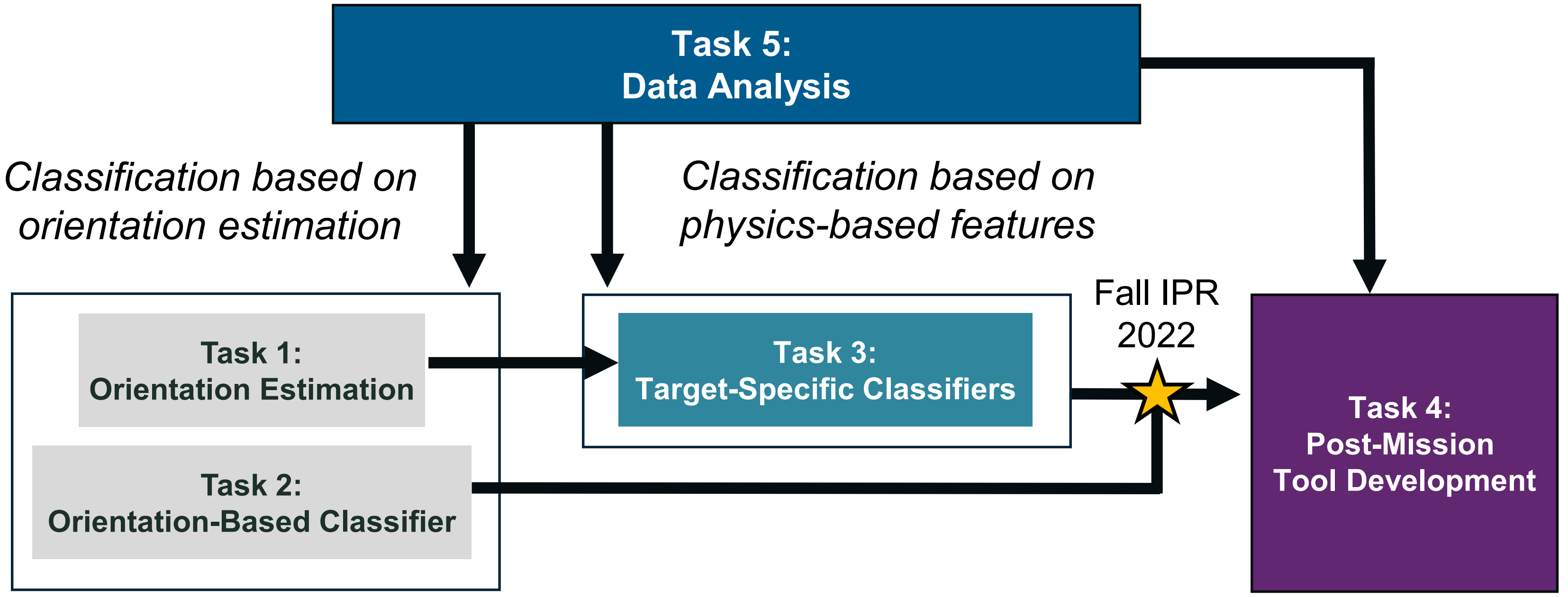
Technical Objective

Overall Objective: Improve the detection, both real-time and in post-mission analysis, for UXO-identification systems incorporating sonar. Initial transition target: APL-UW Multi-sensor Towbody (MuST) down-looking sonar system

- Incorporate orientation estimation into detection architecture
- Develop detection based on unique physics of specific target classes rather than their differences from (limited) known clutter examples
- Provide specific post-mission analysis tools to give users relevant information to improve system performance with low workload

Technical Approach

Technology Focus: MuST System



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Technical Approach

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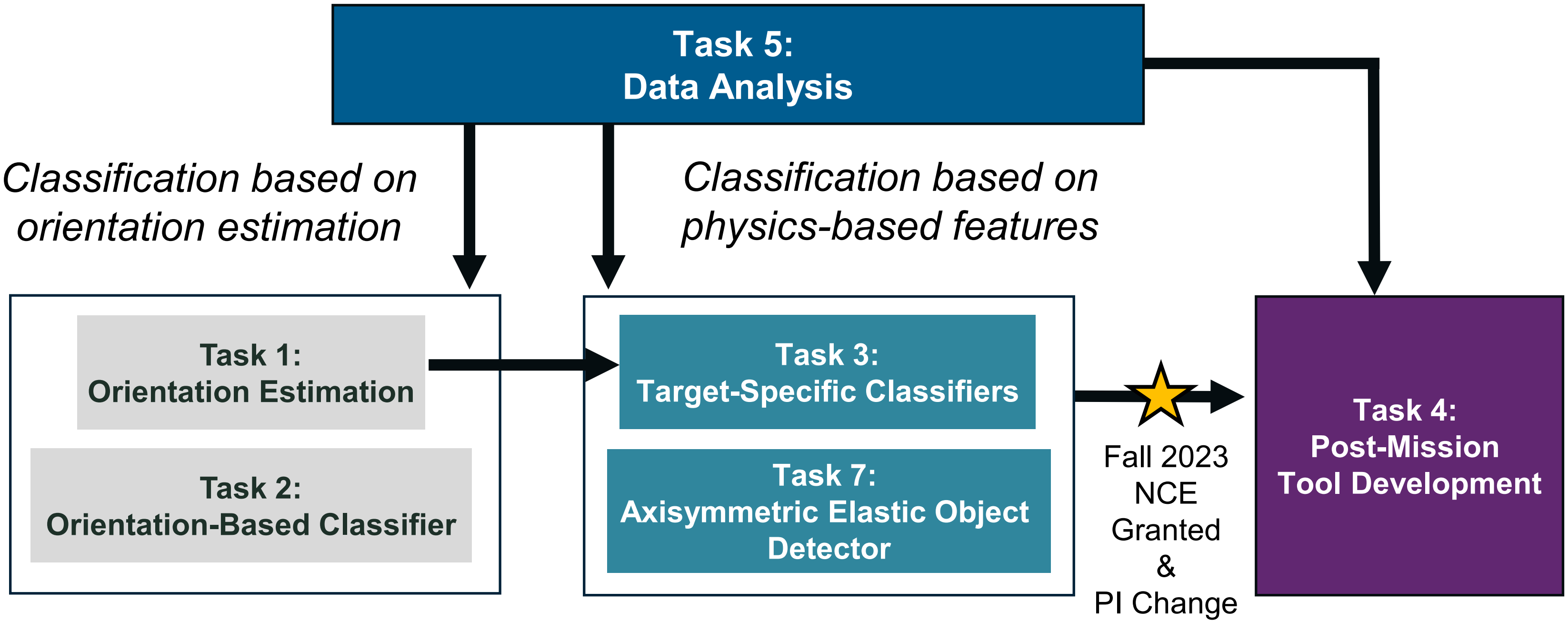


Results – Overview/Outline

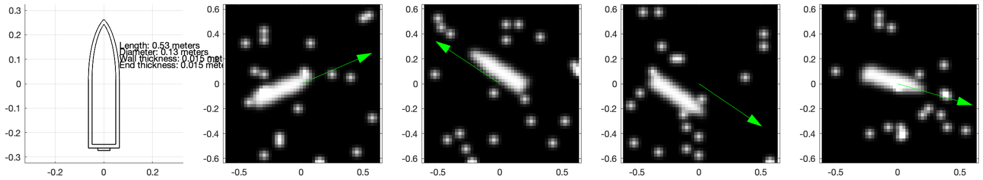
- Brief review:
  - Task 1: Orientation Estimation
    - Image-based techniques
    - Matched filter technique
  - Task 2: Orientation-based classifier
  - Task 3: Target-specific classifiers
    - Simple shapes
    - Physics theory based on cylindrical shells
- Recent progress:
  - Axisymmetric elastic cylindrical shell detector (Task 7)
  - MuST data survey and tools (Task 5)
  - Development of post-mission analysis tools (Task 4)

Results – Orientation Estimation

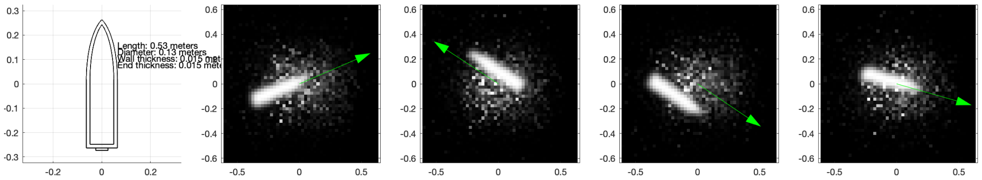
- Physics features being leveraged are a function of target angle, so a rough estimate of target orientation reduces search space and improves roughness and confidence measures.
- Image-Based Estimation: Using image processing and/or machine learning techniques to extract target orientation information from the image data product
  - Advantage:
    - Many target types allow for good visual orientation estimation by non-experts based on general knowledge, suggesting estimation systems could be trained with generic image datasets and not require large field collections
  - Challenges:
    - Imaging capabilities degrade with burial depth
    - For some targets and angles, the low frequency images are less intuitive from a physical shape perspective

Results – Orientation Estimation

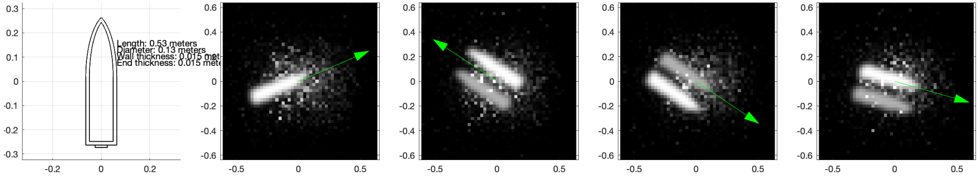
Baseline training simulations



Backgrounds derived from Sequim MuST images



“Crude” addition of elastic response effects



Results – Orientation Estimation

- Both simulation modifications provided notable improvement to orientation estimation accuracy
- CNN based orientation estimation
- Baseline neural network adapted from MR18-B4-5004 CNN classifier [1]
  - Recast problem as regression rather than classification
- **Result: improvement from 13.7 degrees mean error to 10.2**

Image-Based Orientation Estimation Results Summary

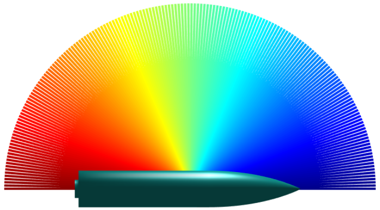
Method Parameters					Error	Error
Method index	Bin width (degrees)	Sequim BG added	Images w/Echoes	Echo Strength	(deg rel to bin center)	(absolute degrees)
1	20	No	0.0	-	21.4	22.0
2	10	No	0.0	-	19.4	19.8
3	20	Yes	0.0	-	22.9	24.7
4	10	Yes	0.0	-	21.6	22.2
5	20	Yes	0.5	0.7	18.8	19.9
6	10	Yes	0.5	0.7	13.5	13.7
7	20	Yes	1.0	0.7	19.2	19.9
8	10	Yes	1.0	0.7	23.5	23.7
9	5	Yes	0.5	0.7	33.8	33.7
10	10	No	0.5	0.7	23.5	24.2
11	10	Yes	0.5	0.4	17.2	17.6
12	10	Yes	0.5	0.9	15.9	16.2

Results – Orientation Estimation

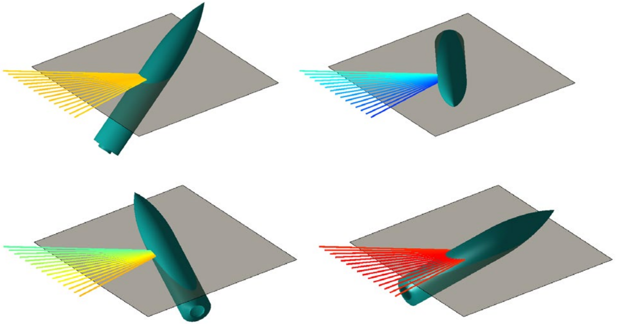
Matched-filter-based orientation estimation

- Basic concept:
  - Model a target-type's scattered impulse response as a function of ping incident angle (and possibly grazing angle and/or burial state)
  - For a particular object interrogation, hypothesize a range of orientations, pitches, and burial states; use model to build a predicted return for each such hypothesis
- Advantages:
  - Many physics cues are available in acoustic color for burial states where imaging capabilities are degraded
  - Results may provide classification information as a by-product
- Challenges:
  - The optimality conditions for matched filtering are violated by multi-path returns and returns from nearby objects
  - Modeled responses may differ from collected data in ways that degrade performance or cause results that are sensitive to small target variations

Model



Predicted returns (4 example hypothesized target configurations)



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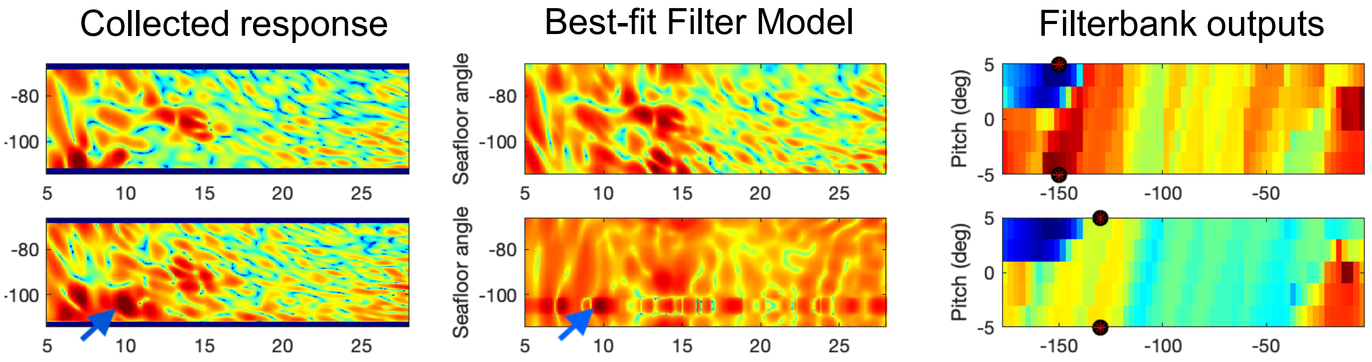
Results – Orientation Estimation

- The broadside response is the major contributor to the orientation estimate
- Orientation estimation errors occur when spectral peaks in interrogated object response match resonances in filterbank model

Good estimate example

Bad estimate example



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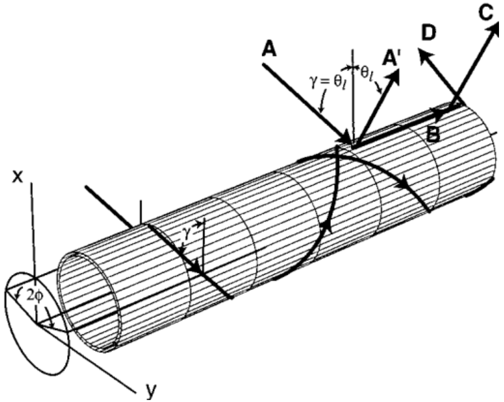
Results: Physics-Based Features

- Any understanding of the physics that can be leveraged to reduce the complexity of the input space can make the machine-learning system more accurate and robust.
- Cylindrical body is a dominant characteristic of many UXO
- Surface guided elastic waves can produce significant enhancements to acoustic scattering [2-7].
- Key thing you have to calculate is the velocity of these waves
  - Dependent variables: shell thickness & phase velocity of material



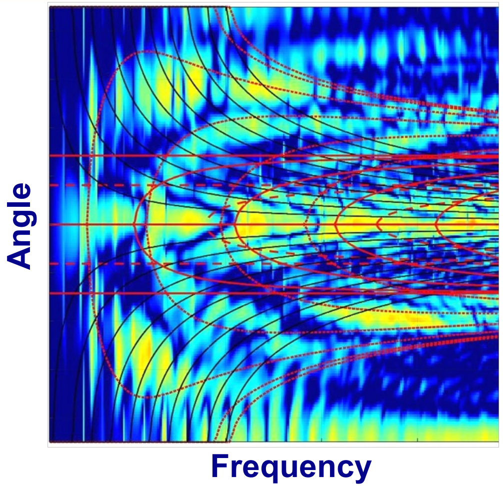
[2] Morse and Marston, IEEE JOE (2001)

$$\frac{tanh\{(hk_l/2)[1-(c_l/c_s)^2]^{1/2}\}}{tanh\{(hk_l/2)[1-(c_l/c_L)^2]^{1/2}\}} = \frac{[2-(c_l/c_s)^2]^2}{4\{[1-(c_l/c_L)^2][1-(c_l/c_s)^2]\}^{1/2}}$$

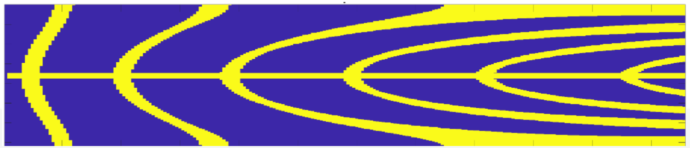
TASK 3

Results: Coupling Curve Masks

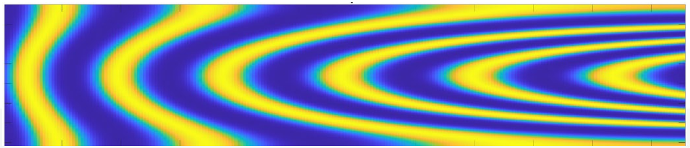
- The guided wave velocities can be used to derive a set of “coupling curves”
- Coupling curves predict where sound can couple into specific resonance wave types in the frequency-angle domain



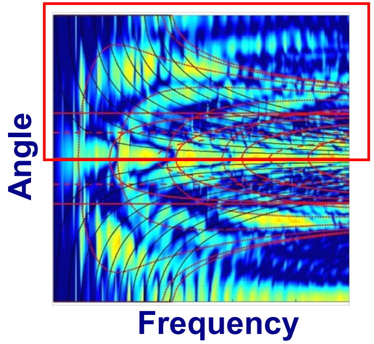
Baseline Detector
Integrate energy in a binary mask



Updated Detector
Continuous measure of degree of fit to predicted resonance location



Results: Coupling Curve Masks



Zoom In

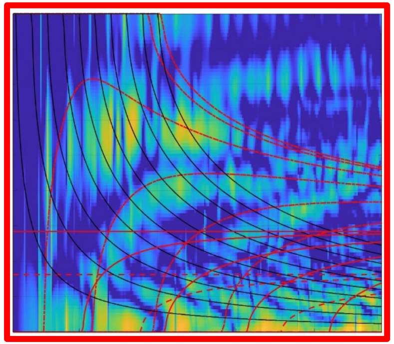
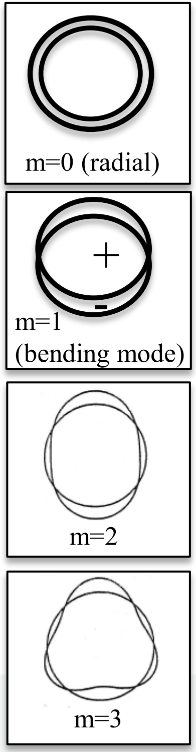


Illustration of the first couple of mode shapes [8]

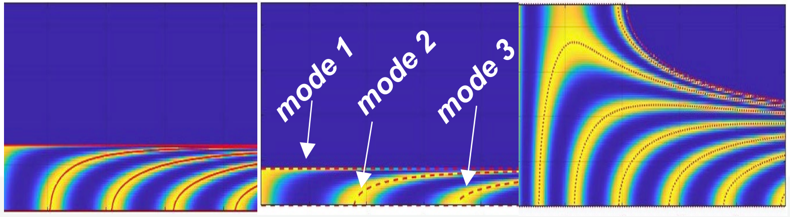


Detectors for 3 wave types

Shear

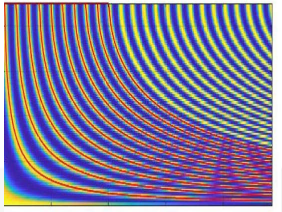
Compressional

Antisymmetric lamb waves



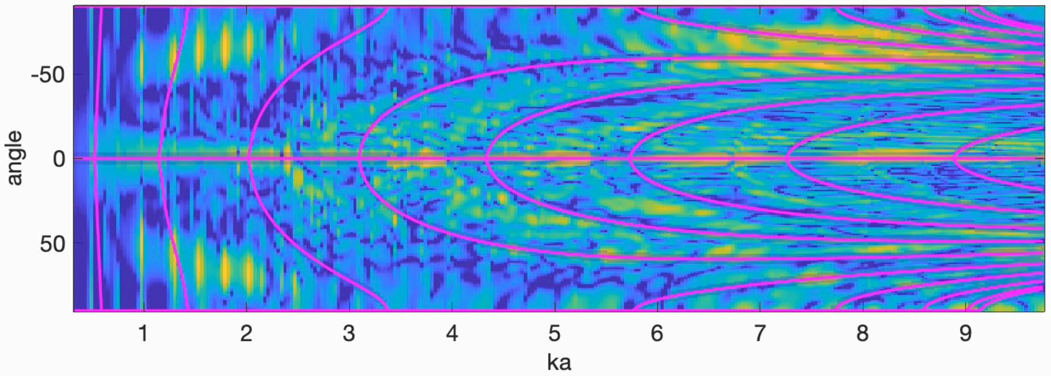
"Matching condition" for the axial projection of incident sound

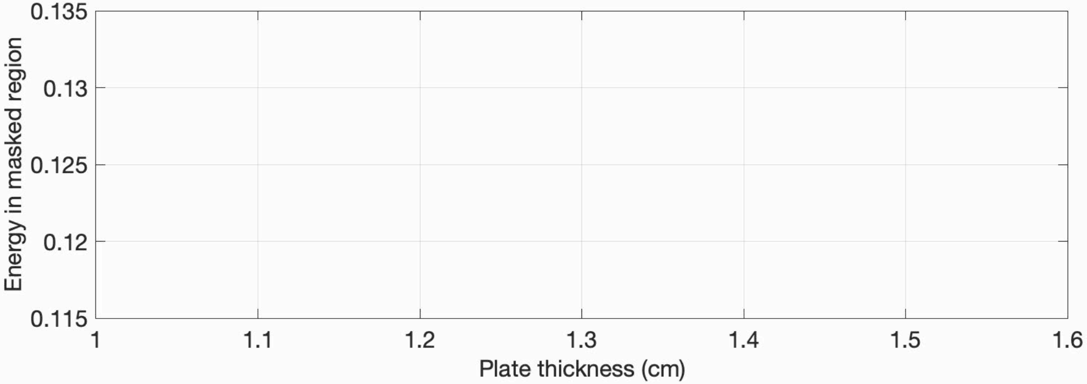
Axial



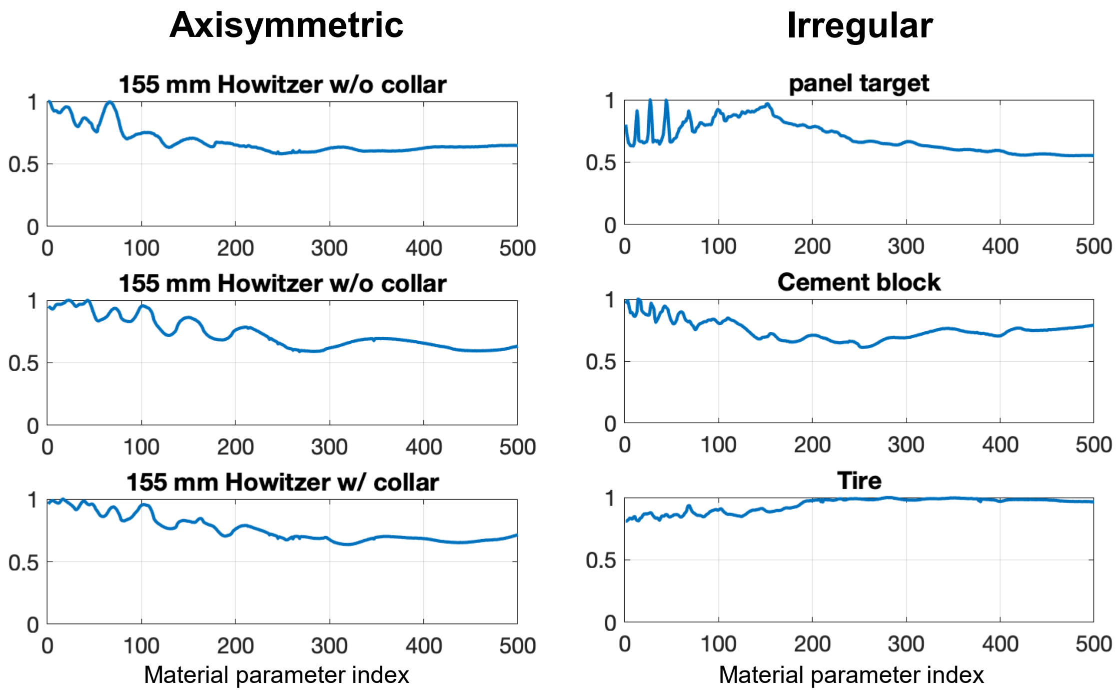
Results

- Detector built off of free field models where all parameters are known
- During demonstrations and live exercises, you don't know anything about the object nor its orientation
- Algorithm is fast enough to sweep through parameters
- **Example: Sweeping over shell thickness (Antisymmetric Lamb Waves)**





Results: Axisymmetric vs. Irregular Objects



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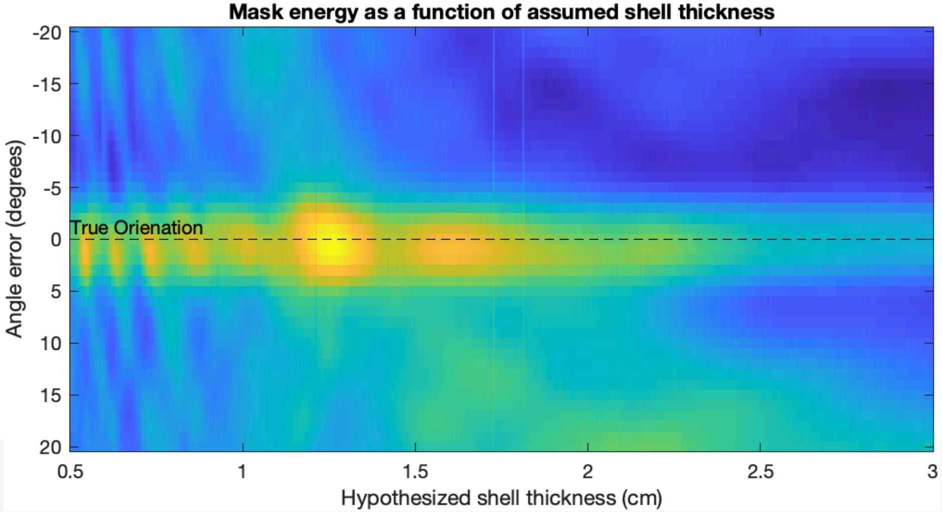
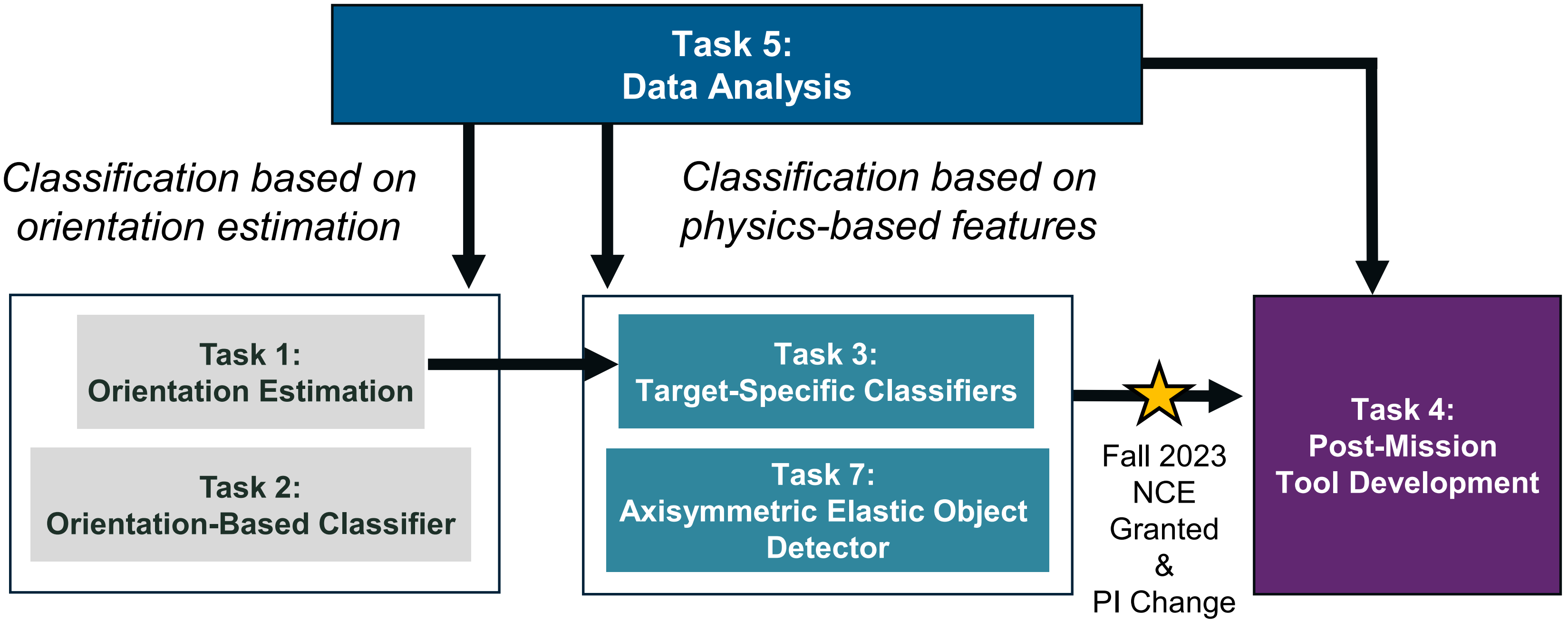
Results: Sweeping Through Two Object Parameters

- Example below is a two parameter sweep
- Introduce error into the orientation of the object and repeat the process on the previous slide
- An approximate orientation estimate of up to 20 deg error could be used as the basis for a search window to obtain the same result as the ideal estimate



Technical Approach

Technology Focus: MuST System



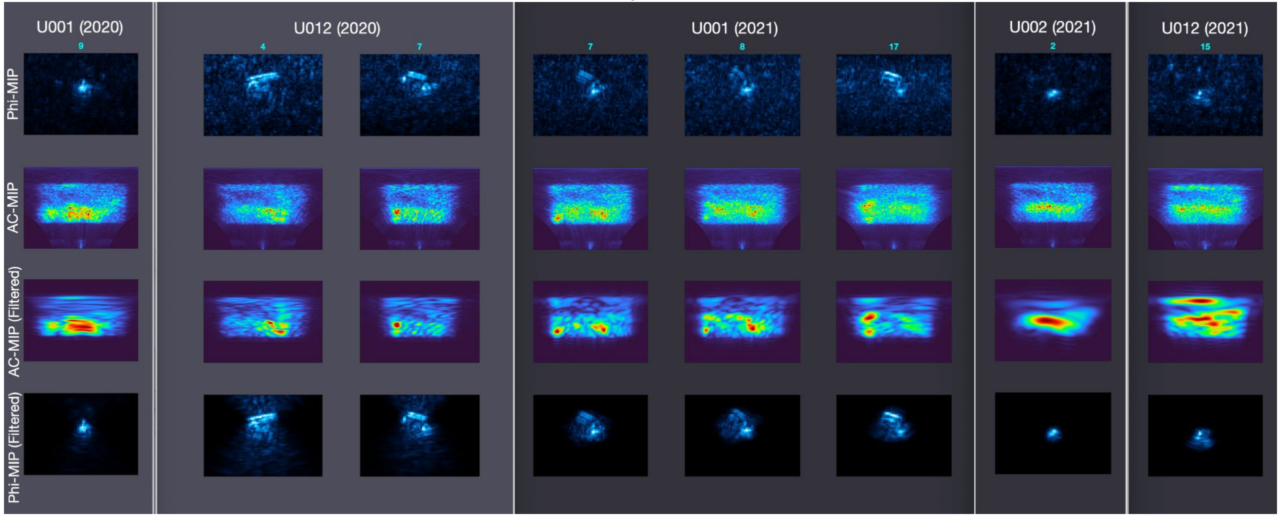
Results: MuST Data Analysis

- Goal is to apply this to MuST data
- Are these types of resonant behavior even visible in MuST data?
- If so, to what degree are they affected by seafloor reverberation and burial depth?
- This motivated the need to dig into MuST data and develop additional post-processing tools that would aid the interpretation

Results: MuST Data Analysis

- MuST data collected at Sequim Bay Test Bed in 2020 and 2021 [9]
- Three different 155 mm Howitzers
- Different burial states and orientations relative to MuST path (incident angle)

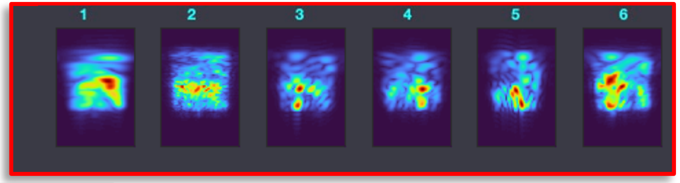
PROUD NOSE SLIGHTLY BURIED ½-BURIED ½-BURIED DEEPLY BURIED

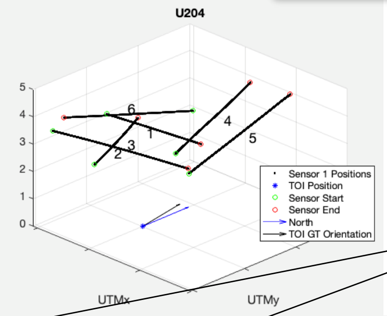


Results: MuST Data Tool Development

- Additional "researchy" tools have been generated to ease comparison to models
- Utilizes ground truth of target orientation and burial depth
- Transforms cartesian sensor position into a target-centered angle domain
- Knowing the angles allows for comparison to model results
- You really have to be a subject matter expert to find utility in the information

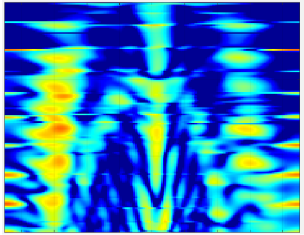
MUST DATA

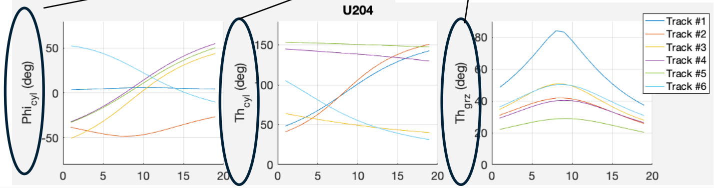




These angles are needed in order to make comparisons to model

MODEL RESULTS





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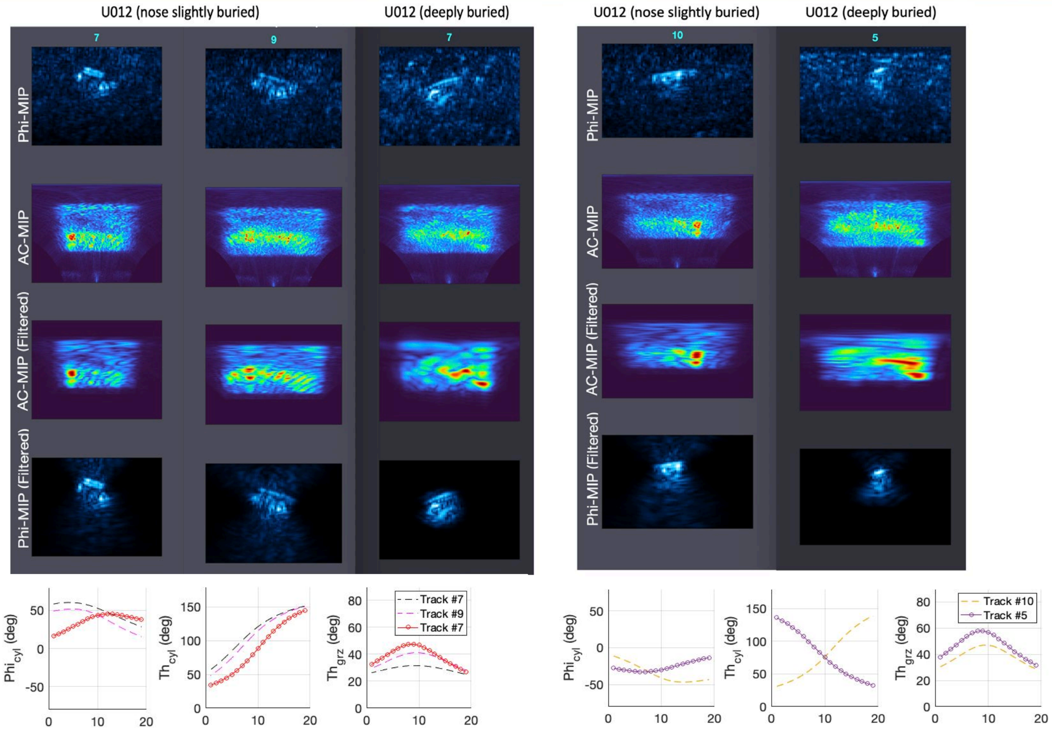
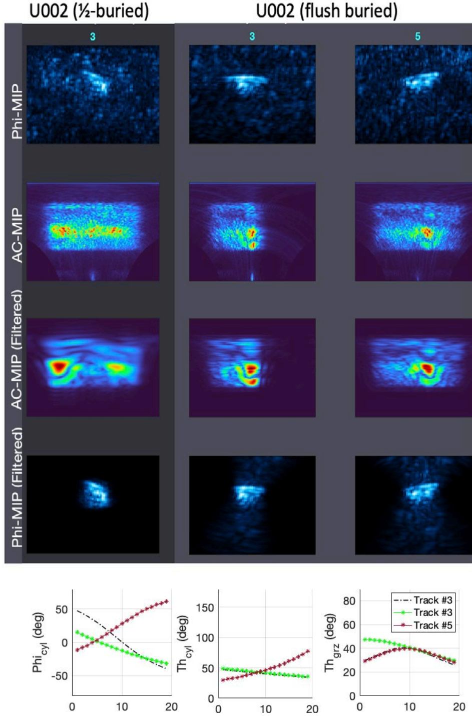
TASK 5

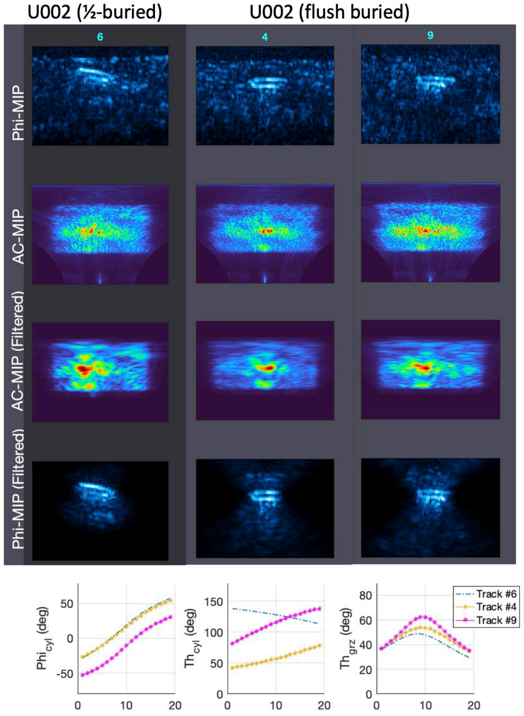
Results: MuST Data Analysis w/ Tools



TASK 5

Results: MuST Data Analysis w/ Tools





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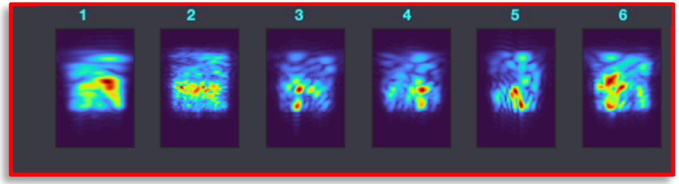
Results: Development of Post-Mission Operator Assist Tool

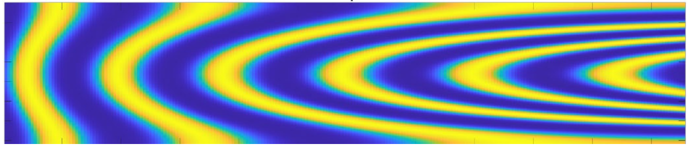
- Leveraging progress from MR23-3978 (Final Outbrief subject of next presentation)
- 20 inert UXO were characterized and modeled
    - These inert UXO were the same items that were deployed during tests of the MuST system at Sequim Bay
    - The free field response for these objects was incorporated into the detector, specifically calculating the coupling curves and corresponding resonant masks
- Post-processing wavenumber “k-space” widget was developed to facilitate visualization and comparisons of MuST data and TIER simulations.
- Most recently, TIER simulations (time domain) were created mimicking the exact MuST data that had been surveyed in this project
- The simulated data was processed with the identical MuST post-processing tools to create data products for classification experiments using the MuST CNN classifier

TASK 4

Results: Development of Post-Mission Operator Assist Tool

- Two key pieces of this:
  - Need to compute the coupling curves and corresponding masks for inert UXO that were deployed at Sequim Bay
  - Need to create data products (AC template) for MuST and TIER simulations [10] that allow you to apply the coupling curve masks





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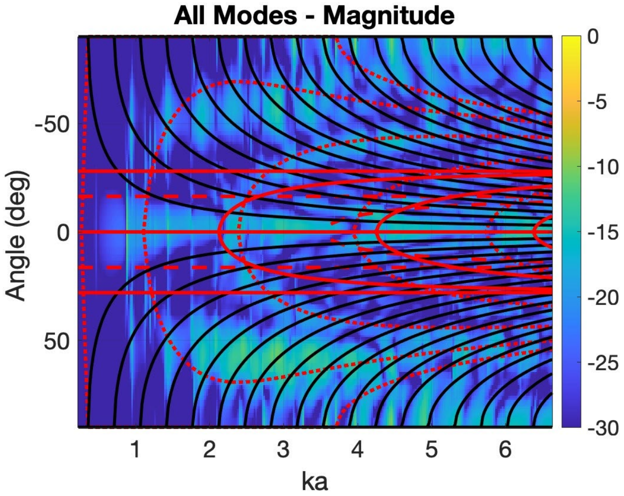
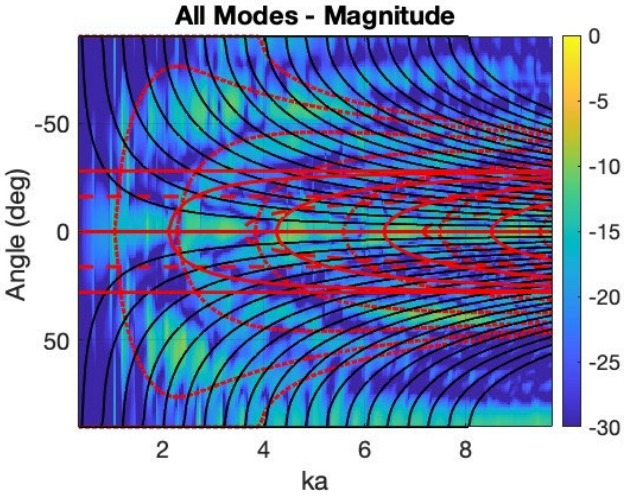
Results: Coupling curve maps for inert UXO

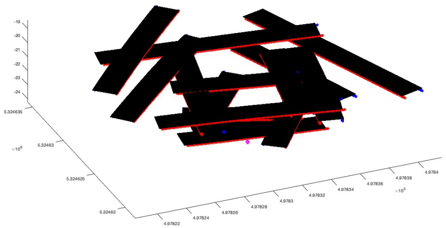


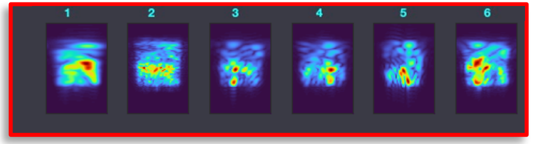


TASK 4

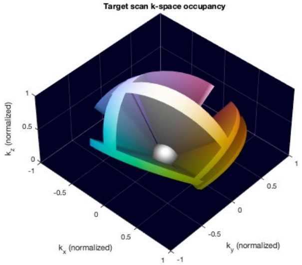
Results: AC templates for MuST and TIER simulations

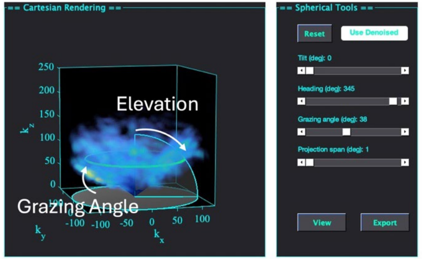
Individual MuST tracks





Aggregate data into 3D wavenumber space

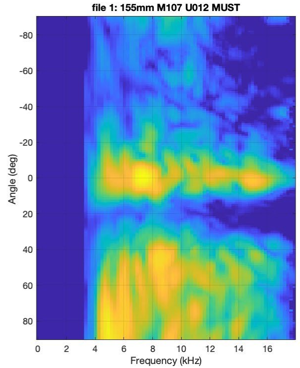




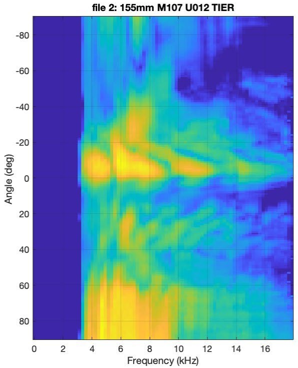
Slices through the 3D wavenumber space produce traditional AC

155 mm Howitzer U012 deeply buried in Sequim Bay

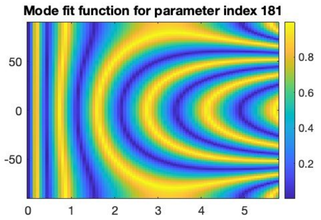
MUST Data

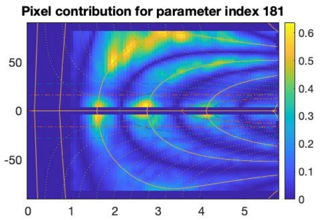


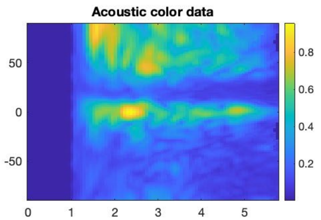
TIER Sims



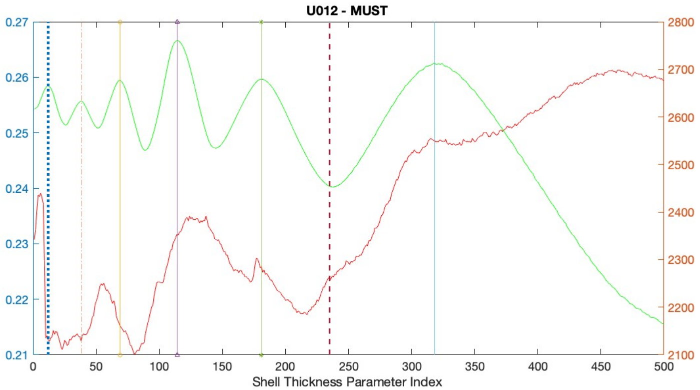
Results: Outputs from the Operator Assist Tool

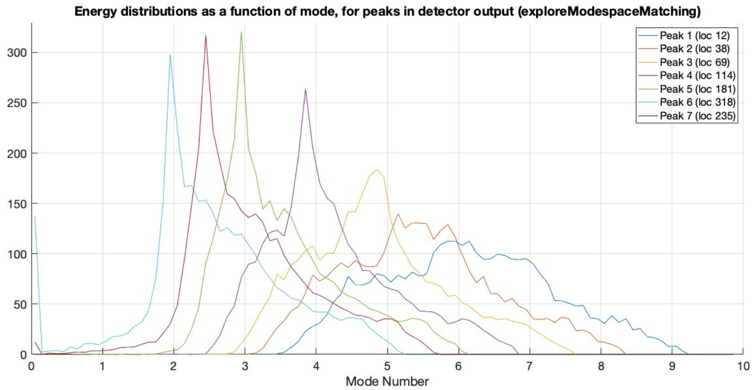






Application of detector to MuST data for U012 deeply buried in Sequim Bay 2021





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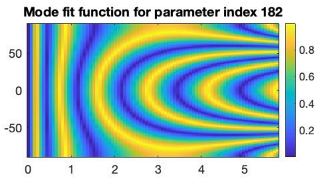
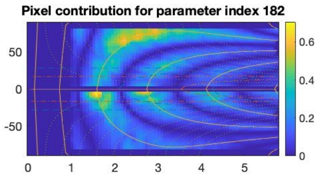
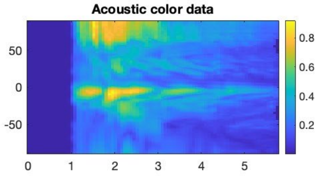
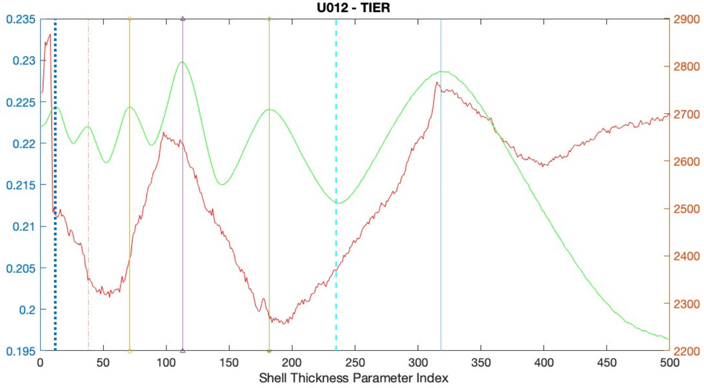
Results: Outputs from the Operator Assist Tool

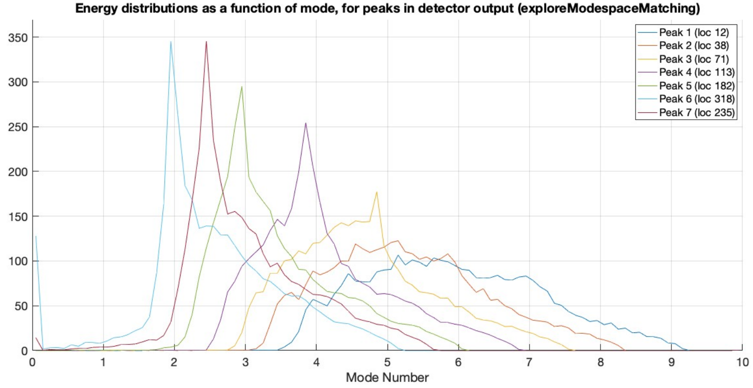
Application of detector to TIER simulation for U012 deeply buried in Sequim Bay 2021





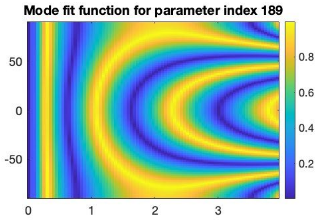


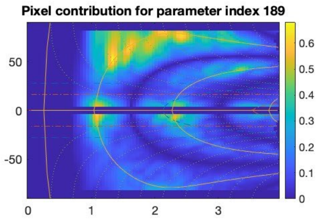


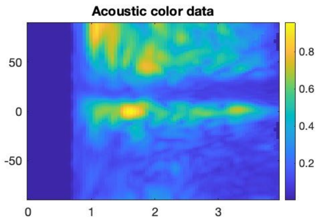


TASK 4

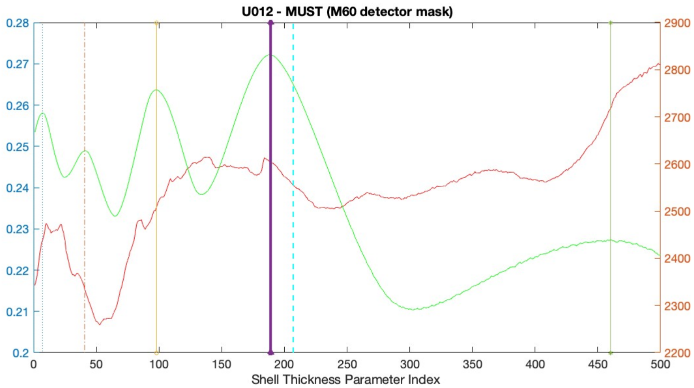
Results: Outputs from the Operator Assist Tool

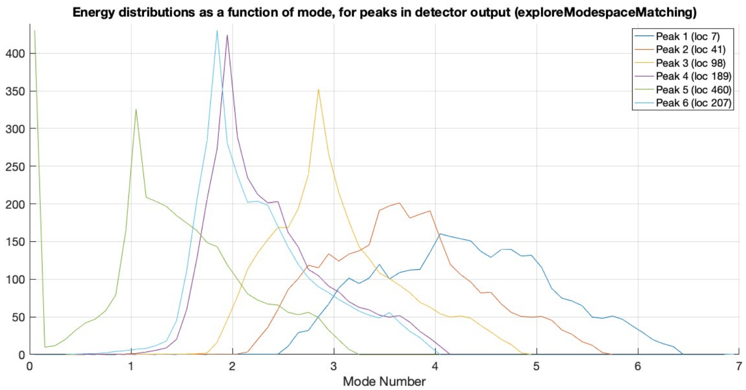






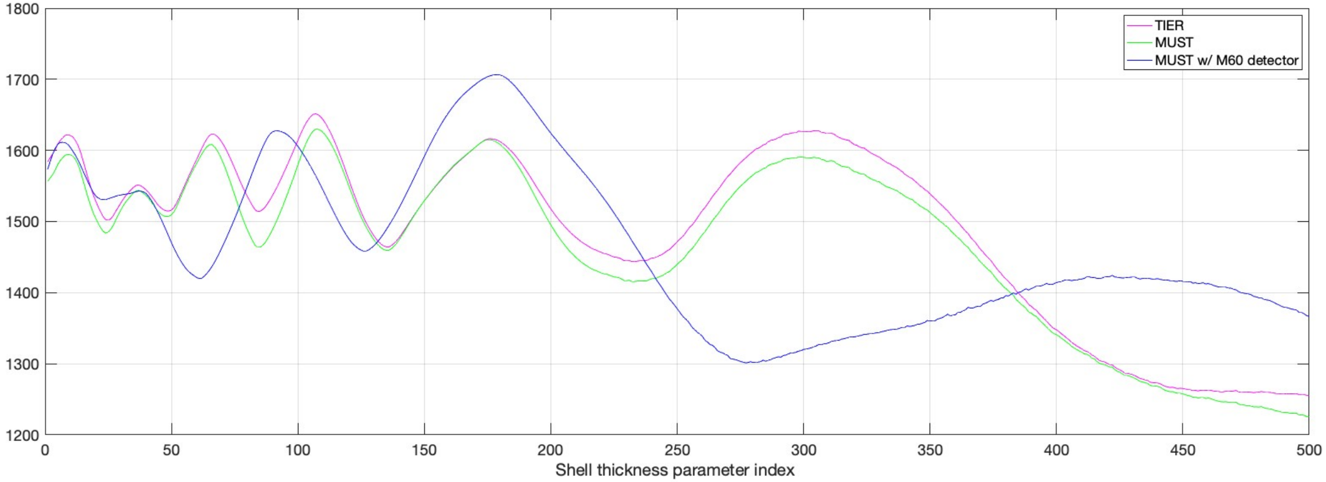
Application of detector to MuST data for U012 deeply buried in Sequim Bay 2021 ***using M60 coupling curve maps***





Results: Comparison of Outputs

- MuST and TIER parameter sweep results look very similar
- They are distinct from the blue curve, which utilized the M60 coupling curve mask



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Next Steps

- Resonance coupling curve masks for inert UXO will be uploaded and archived in a shared MuST project directory at APL-UW.
- Elastic cylindrical object detector research code will be uploaded and archived in a shared MuST project directory at APL-UW.
- White paper submission scheduled for 1/24/25
- Final Report submission scheduled for 2/15/25

Technology Transfer

- Completed:
  - SERDP/ESTCP Webinar presented on July 25, 2024
- In-progress:
  - A white paper illustrating physical properties that are controlling the target scattering behavior, and takes into consideration the effects of measurement and environmental uncertainty.
- Future possibilities:
  - Instruction document on how to run the Axisymmetric Cylindrical Elastic Shell Detector Instruction Document that covers:
    - How to run the detector
    - Illustrates the outputs
    - Discusses known deficiencies of the detector
    - Potential avenues for future R&D and improvements, and identifies where these could be implemented within the underlying source code
  - Presentation at SERDP/ESTCP sidebar and workshops that bring together modelers, system developers and live-site experts

Issues

- No unresolved issues

BACKUP MATERIAL

These charts are required, but will only be briefed if questions arise.

MR20-1443: Physics-Based Features and Classification Architecture for Underwater Buried Targets

Performers: *PI: Dr. Aubrey España (PI), Dr. Lane Owsley (Co-I)*

Technology Focus

- *Transfer of existing physics knowledge to sonar-based detection of UXO in the presence of unknown or incompletely categorized clutter*

Research Objectives

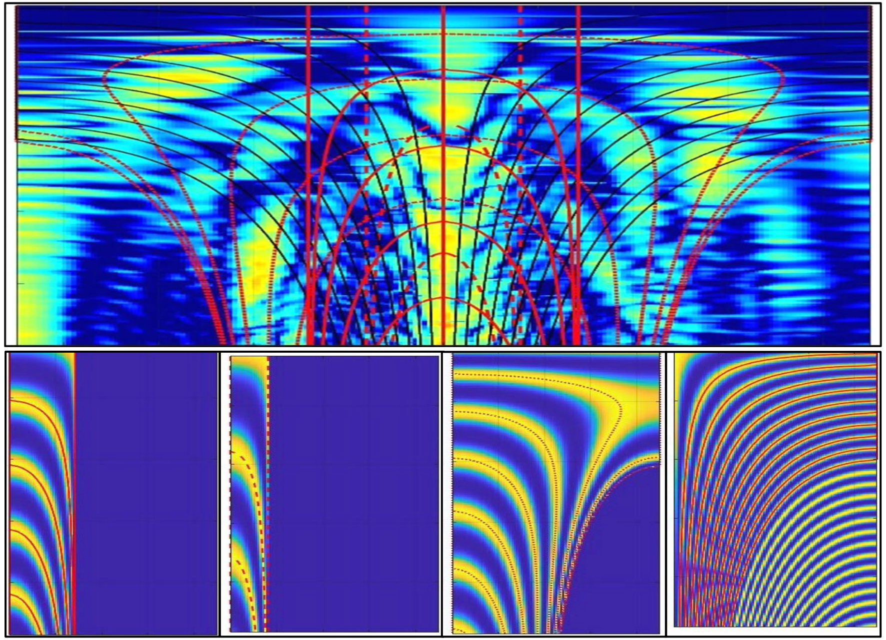
- *Incorporate physics into the detection and identification process*
- *Provide specific post-mission analysis tools to give users relevant information to improve system performance with low workload*

Project Progress and Results

- *Upgraded orientation estimation algorithm*
- *Developed a general detector of cylindrical elastic objects*
- *Demonstrated success of the detector while sweeping through UXO physical parameters*
- *Completed initial development and testing of a post-mission operator-assist tool on MuST data*

Technology Transition

- *Contribution to UXO identification algorithms and post-mission operator-assist for MuST system*



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Plain Language Summary

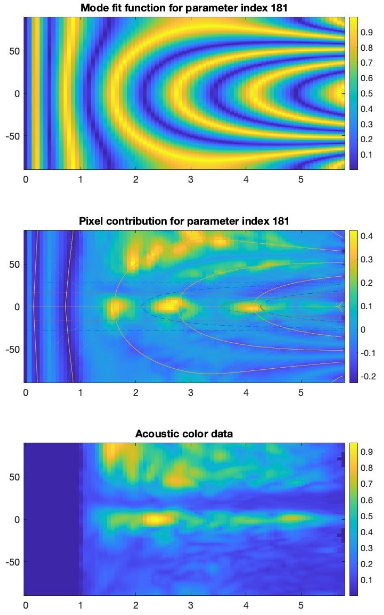
- Modern machine-learning techniques are extremely powerful. *However:*
  - They are most effective with large amounts of data to cover the entire space of variations in target presentation.
  - Compensation for small datasets can involve simplifying the decision boundary to be learned, but this will be harmful if the input space is chosen such that the decision boundary is inherently complex.
  - Systems that rely on complete characterization of the clutter dataset are vulnerable to unpredictable results when faced with field conditions involving novel clutter.
- This project aims to incorporate physics into the detection and classification procedures for sonar-based systems.
- Most UXO are characterized by a cylindrical body, which are known to produce significant enhancements to the acoustic scattering due to surface guided elastic waves
- Creating energy masks that are based on physics theory of different resonant wave types
- Any understanding of the physics that can be leveraged to reduce the complexity of the input space can make the machine-learning system more accurate and robust.

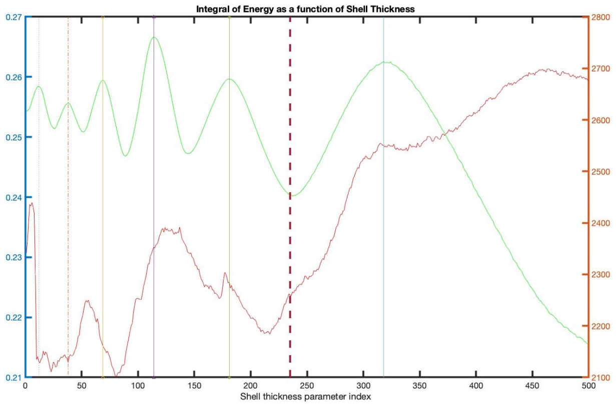
Impact to DoD Mission

- Development and preliminary testing has been completed for the elastic cylindrical shell detector, specifically utilizing MuST data and TIER simulated data for inert UXO deployed at Sequim Bay Test Bed

- This preliminary detector was developed based on the physics of a very basic shape, ***in the free field,*** and remarkably is showing potential capabilities in identifying UXO even when the UXO physical characteristics nor their position within the environment is precisely known

- This detector has been developed into a post-mission analysis tool that can provide the operator with additional information that can improve the UXO identification





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Action Items

- Request: “Thanks for an excellent review! Before the Fall 2022 IPR, please prepare a white paper that clearly illustrates those physical properties that are controlling the target scattering behavior and an estimate of their relative contribution. Also consider the effects of measurement and environmental uncertainty on the physics-based estimations.” (Task 6.5)
- Response (in 2022): white paper will be submitted in February 2023, to accommodate availability of personnel on leave in Fall 2022.
- Follow-up response:
  - There was a family emergency experienced by Dr. Owsley that required Dr. Espana to take over PI duties in Spring 2023. Dr. Espana’s assessment was that the quality of the white paper would be greatly improved following the completion of Tasks 5 and 7.
  - Tasks 5 and 7 were completed in Winter 2024 and the White Paper will be submitted following the 2025 IPR.

Action Items

- Request in June 2024: Submit a document that reconciles the proposal tasks with those listed in SEMS. Include an explanation for any items that were marked OBE. (Task 6.6)
- Response: Reconciliation document was submitted on June 17, 2024. Following this, a meeting was conducted with Program Managers to discuss the document in further detail.

Publications

- SERDP/ESTCP Webinar on July 25, 2024

Literature Cited

1. L. Owsley and A. Espana, “Elastic Target Modeling for Physics-Based Automatic Classification,” SERDP MR-2649 Final Report, May 2020.
2. S. F. Morse and P. L. Marston, “Degradation of meridional ray backscattering enhancements for tilted cylinders by mode conversion: Wide-band observations using a chirped pvdf sheet source," IEEE Journal of Oceanic Engineering, vol. 26, pp. 152-155, 2001.
3. Steven G. Kargl and Philip L. Marston, “Observations and modeling of the backscattering of short tone bursts from a spherical shell: Lamb wave echoes, glory, and axial reverberations,” The Journal of the Acoustical Society of America, vol. 85, no. 3, pp. 1014-1028, 1989.
4. P. L. Marston S. F. Morse and G. Kaduchak, “High-frequency backscattering enhancements by thick finite cylindrical shells in water at oblique incidence: Experiments, interpretation, and calculations," The Journal of the Acoustical Society of America, vol. 103, pp. 785-794, 1998.
5. S. F. Morse and P. L. Marston, “Meridional ray contributions to scattering by tilted cylindrical shells above the coincidence frequency: ray theory and computations," The Journal of the Acoustical Society of America, vol. 106, pp. 2595-2600, 1999.
6. F.J. Blonigen and P. L. Marston, “Leaky helical flexural wave scattering contributions from tilted cylindrical shells: Ray theory and wave-vector anisotropy," The Journal of the Acoustical Society of America, vol. 110, pp. 1764-1769, 2001.
7. N. H. Sun and P. L. Marston, “Ray synthesis of leaky lamb wave contributions to backscattering from thick cylindrical shells," The Journal of the Acoustical Society of America, vol. 91, pp.1398-1402, 1992.
8. A.L. Espana, K.L. Williams, D.S. Plotnick, and P.L. Marston, “Acoustic scattering from a waterfilled cylindrical shell: Measurements, modeling, and interpretation," The Journal of the Acoustical Society of America, vol. 136, pp. 109-121, 2014.
9. K.L. Williams, “Multi-sensor Towbody (MuST) for Detection, Classification, and Geolocation of Underwater Munitions,” SERDP/ESTCP Final Report for MR18-B4-5004, 2021.
10. S. Kargl, A. L. Espana, K. Williams, J. L. Kennedy, and J. Lopes, “Scattering from objects at a water-sediment interface: Experiment, high-speed and high-fidelity models, and physical insight," IEEE Journal of Oceanic Engineering, vol. 40, pp. 632-642, 2015.

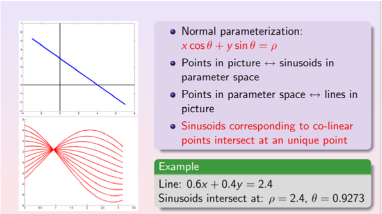
Acronym List

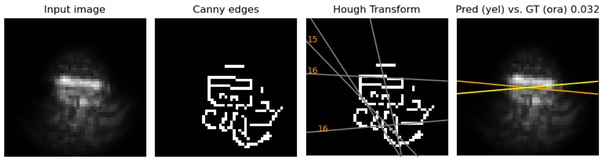
AC	Acoustic Color
APL-UW	Applied Physics Lab – Univ. of Washington
CNN	Convolutional Neural Network
DCL	Detection Classification and Localization
ESTCP	Environmental Security Technology Certification Program
MCM	Mine Counter Measures
MuST	Multi-Sensor Towbody
ONR	Office of Naval Research
SERDP	Strategic Environmental Research and Development Program
TIER	Target-In-the-Environment Response
UXO	UneXploded Ordnance

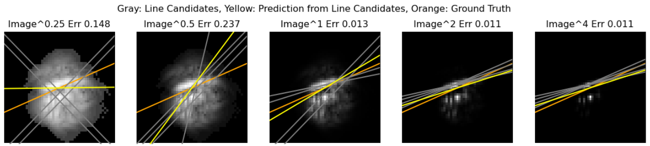
Results – Orientation Estimation

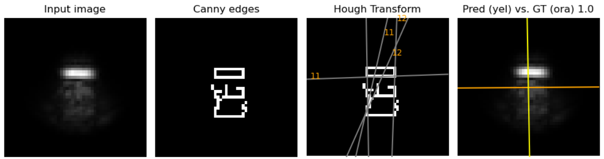
Orientation estimation using classical image processing

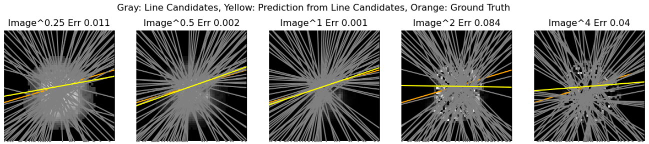
- off-the-shelf baseline: Hough transform
- novel: Hough++(non-linear weighted voting)











Results – Orientation Estimation

CNN based orientation estimation

Baseline neural network adapted from MR18-B4-5004 CNN classifier

Modifications:

- Recast problem as regression rather than classification (output layer is a single continuous-output neuron representing angle, rather than a set of neurons representing angle bin classes)
- Loss function takes into account the wraparound in angle space:

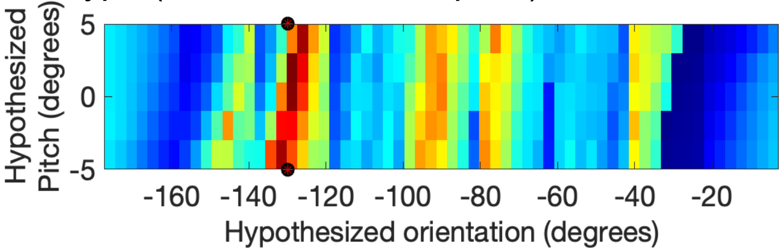
$$L_\theta(\hat{\omega}, \omega^{GT}) = \frac{1}{2}[1 - \cos(2(\hat{\omega} - \omega^{GT}))],$$

- Modified CNN layer connection to match architectures used in similar applications
- **Result: improvement from 13.7 degrees mean error to 10.2**

Results – Orientation Estimation

- Basic concept (continued):
  - Perform matched-filter analysis across all hypotheses for all modeled target types
  - Peaks can be used directly to identify best-guess orientation estimates, or combined with other information (image-based processing).
  - Relative fit of responses to particular models can also be used as part of a classification algorithm

Example filterbank output for a single target type (Aluminum UXO replica)



(The other hypothesis dimensions, positions in x, y, and z, have been collapsed into this figure by taking the maximum filter output over each of these dimensions)

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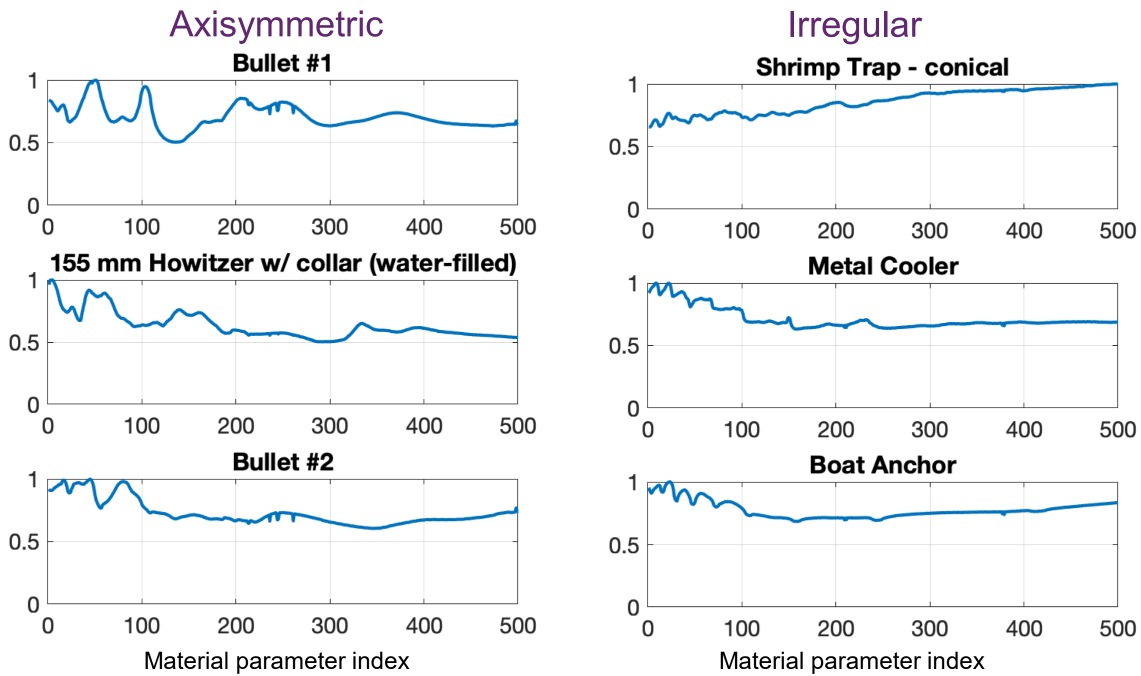
Elastic Cylindrical Shell Detector: Axisymmetric vs. Irregular Objects



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