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PHYSICS-BASED FEATURES AND CLASSIFICATION ARCHITECTURE FOR UNDERWATER BURIED TARGETS

MR20-1443

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Final Debrief

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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

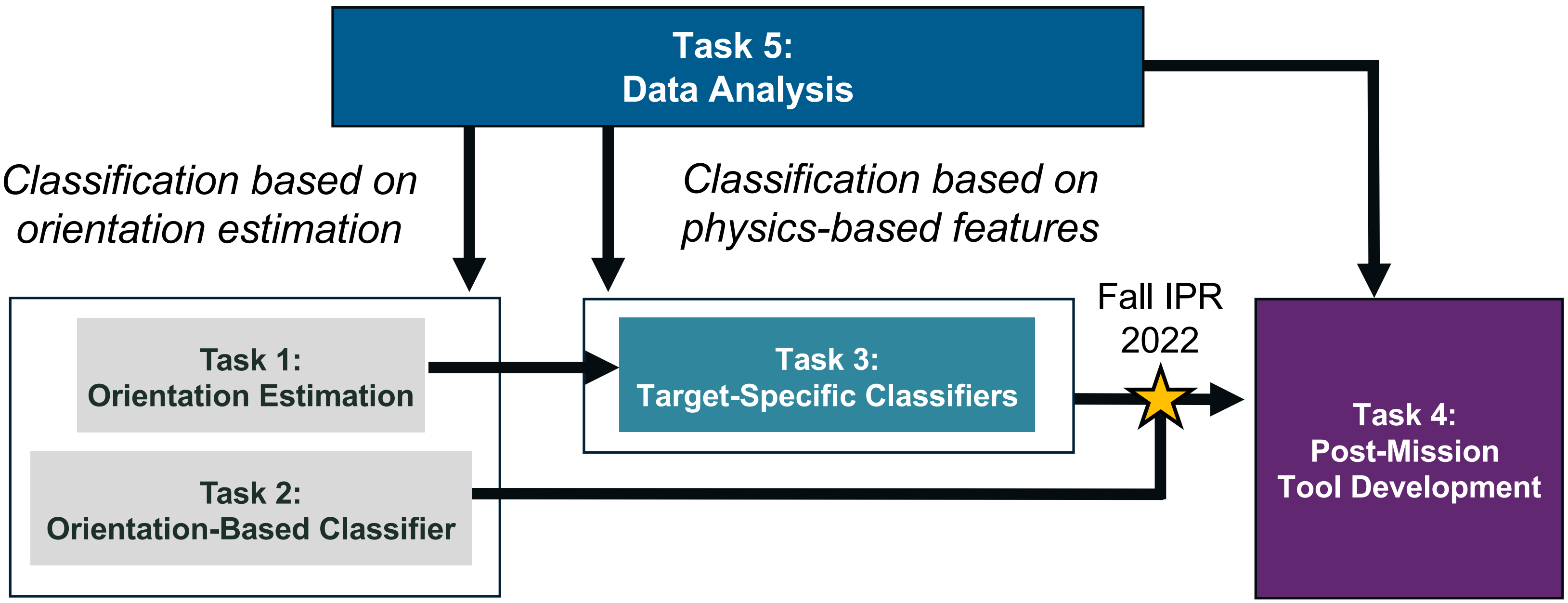
Technical Objective

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



Technical Approach

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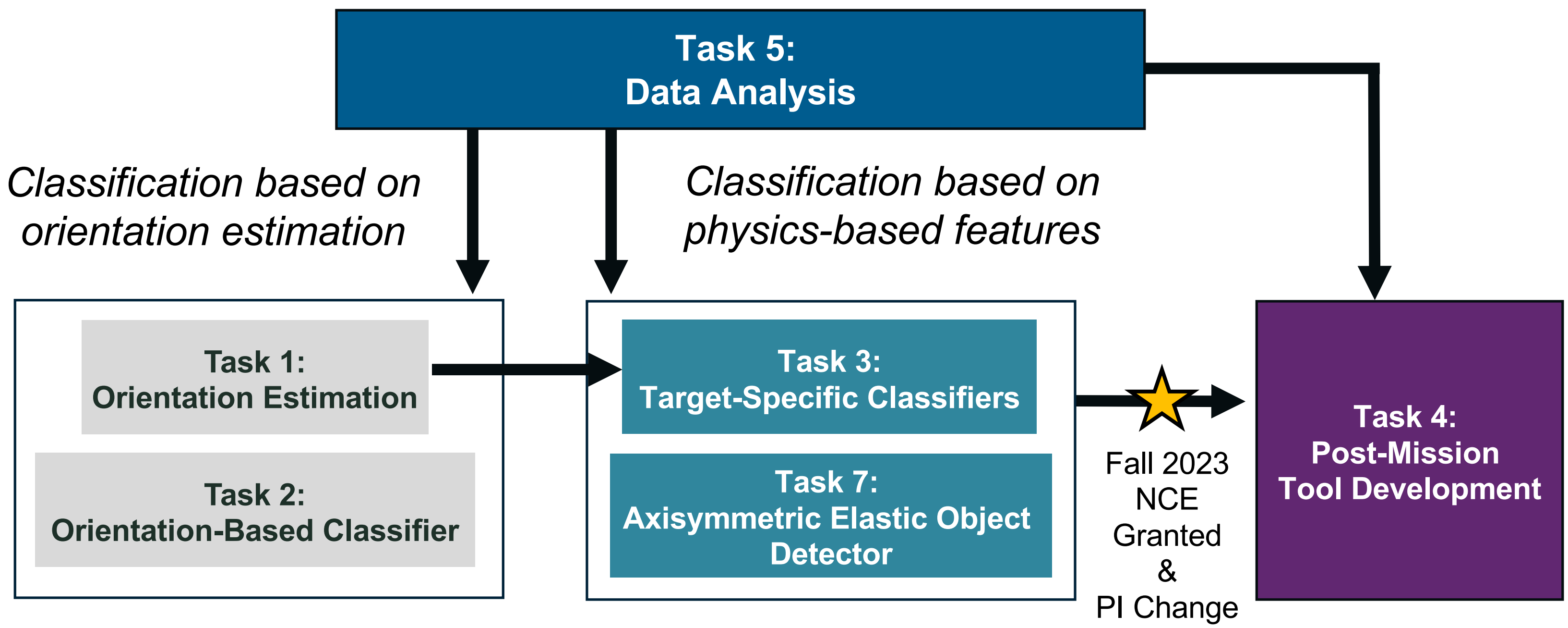
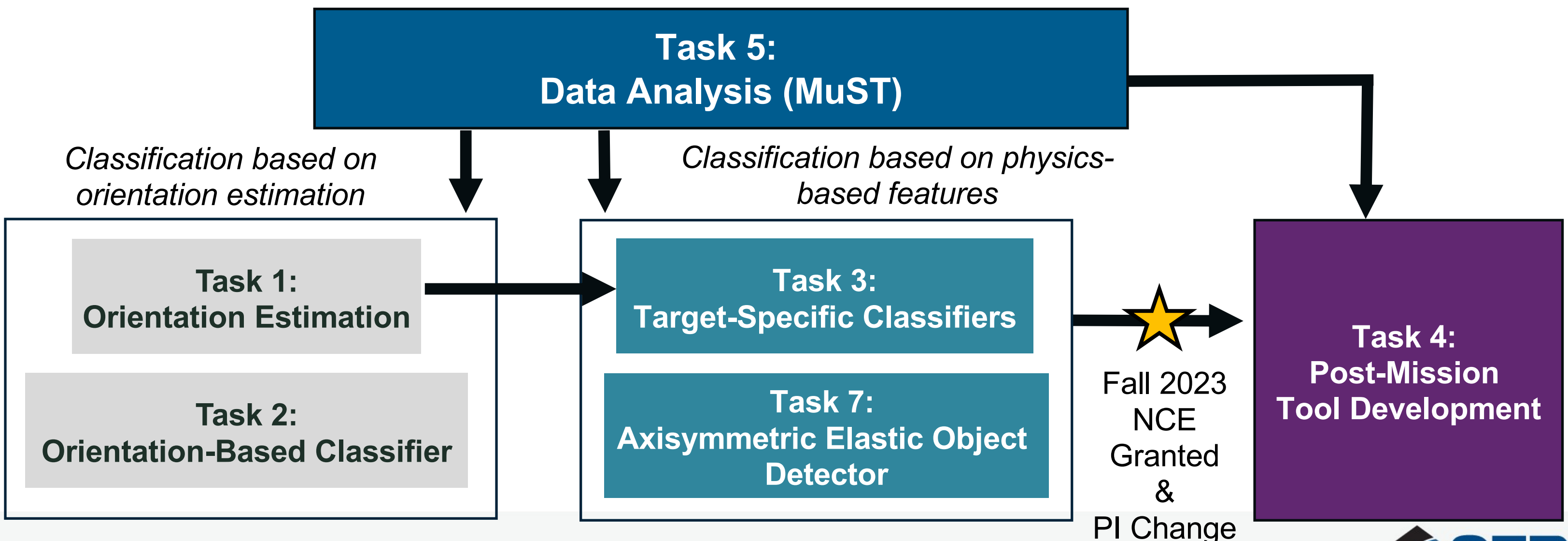


Results – Outline

- Key results from each block are presented in the remainder of this brief
- Tasks 4 and 7 have the most transition potential, and thus are discussed in more depth.



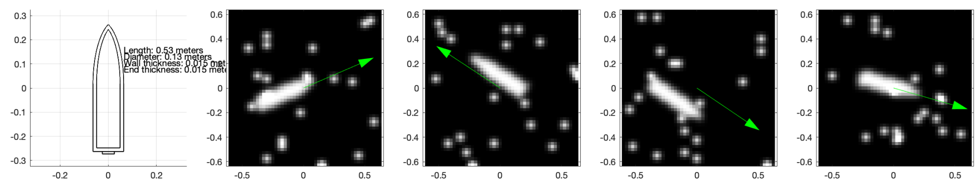
TASK 1

Results – Orientation Estimation

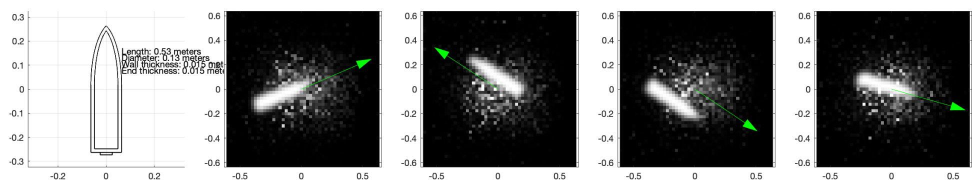
- Physics features being leveraged are a function of target angle, so a rough estimate of target orientation reduces search space and improves roughness and confidence measures.
- Image-Based Estimation: Using image processing and/or machine learning techniques to extract target orientation information 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

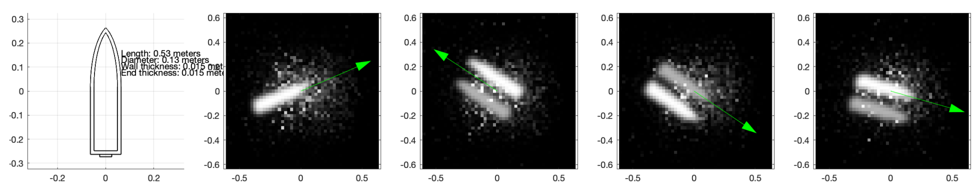
Baseline training simulations



Backgrounds derived from Sequim MuST images



“Crude” addition of elastic response effects



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TASK 1

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

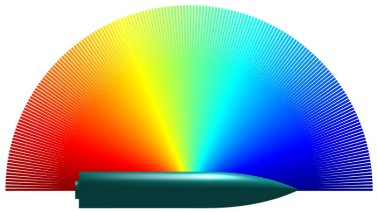
Method Parameters					Error	Error
Method index	Bin width (degrees)	Sequim BG added	Images w/Echoes	Echo Strength	(deg rel to bin center)	(absolute degrees)
1	20	No	0.0	-	21.4	22.0
2	10	No	0.0	-	19.4	19.8
3	20	Yes	0.0	-	22.9	24.7
4	10	Yes	0.0	-	21.6	22.2
5	20	Yes	0.5	0.7	18.8	19.9
6	10	Yes	0.5	0.7	13.5	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

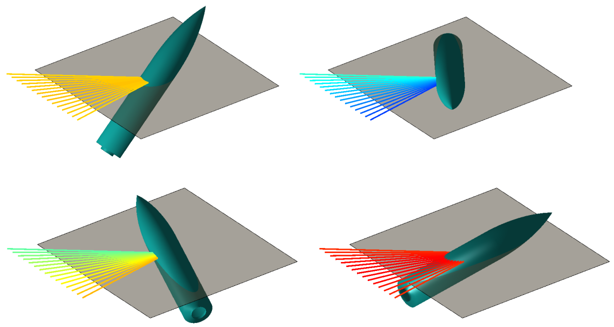
Matched-filter-based orientation estimation

- 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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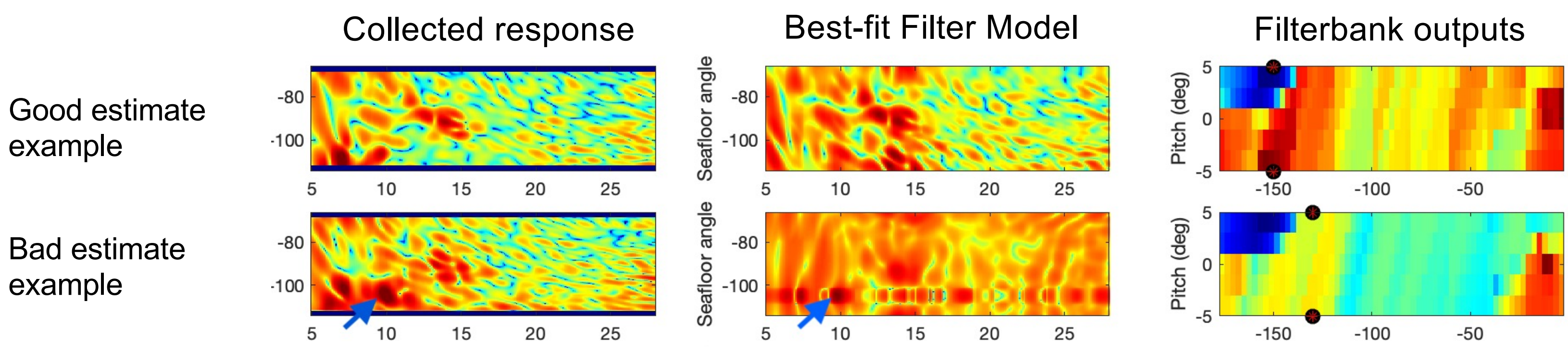
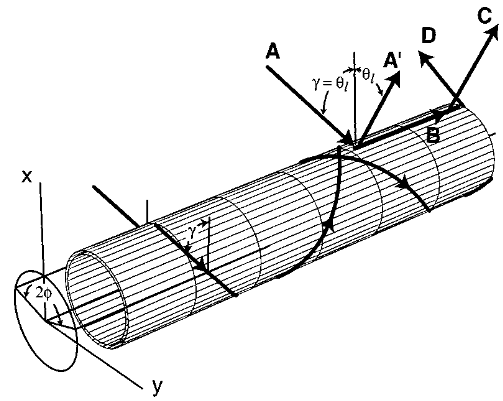
Results – Orientation Estimation

- 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



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

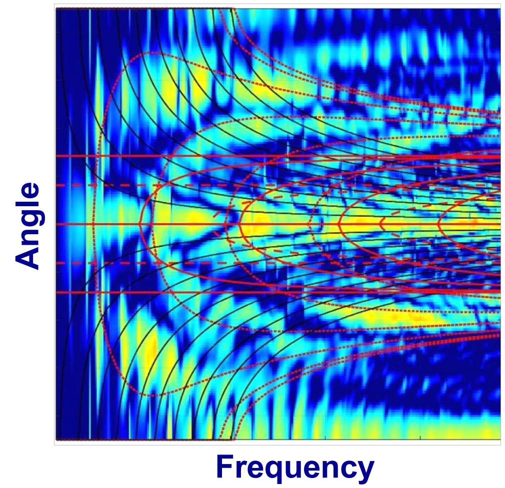


[2] Morse and Marston, IEEE JOE (2001)

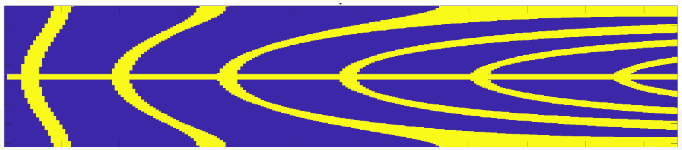
$$\frac{tanh\{(hk_l/2)[1-(c_l/c_s)^2]^{1/2}\}}{tanh\{(hk_l/2)[1-(c_l/c_L)^2]^{1/2}\}} = \frac{[2-(c_l/c_s)^2]^2}{4\{[1-(c_l/c_L)^2][1-(c_l/c_s)^2]\}^{1/2}}$$

Results: Coupling Curve Masks

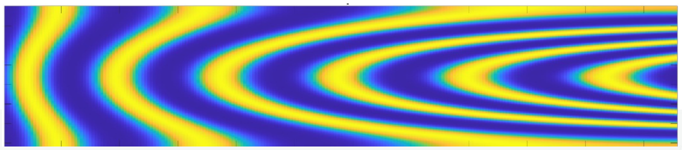
- The guided wave velocities can be used to derive a set of “coupling curves”
- Coupling curves predict where sound can couple into specific resonance wave types in the frequency-angle domain



Baseline Detector
Integrate energy in a binary mask



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



Results: Coupling Curve Masks

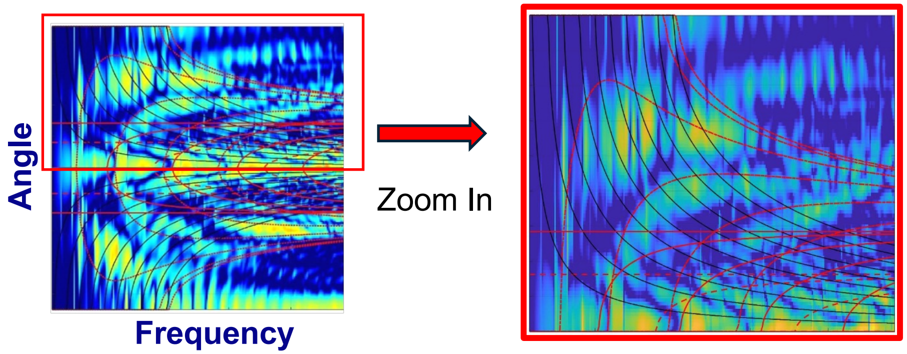
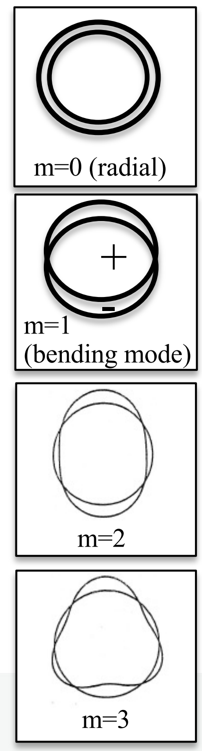


Illustration of the first couple of mode shapes [8]

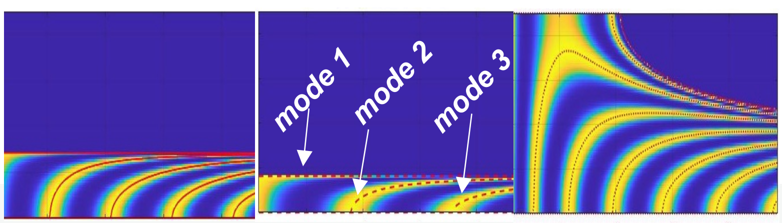


Detectors for 3 wave types

Shear

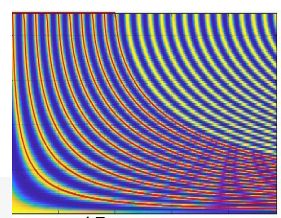
Compressional

Antisymmetric lamb waves



"Matching condition" for the axial projection of incident sound

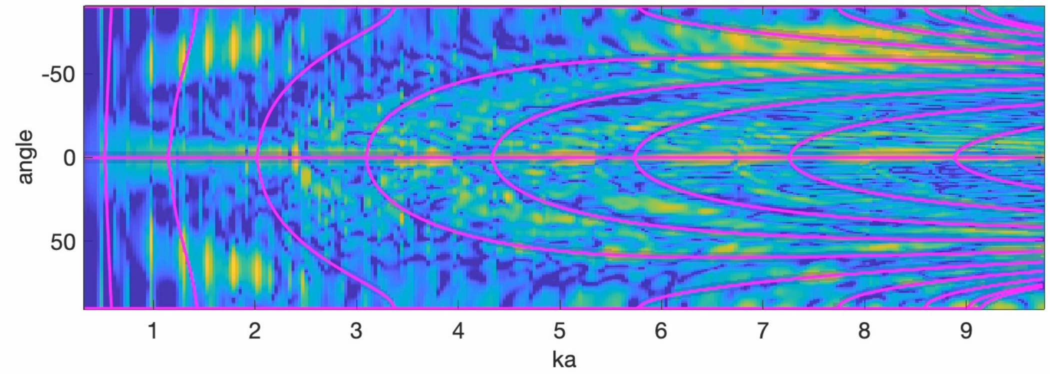
Axial

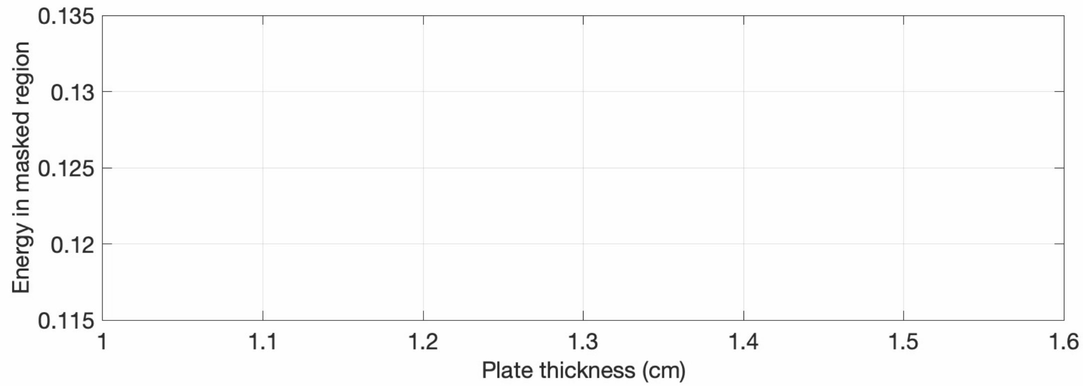


TASK 7

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)**





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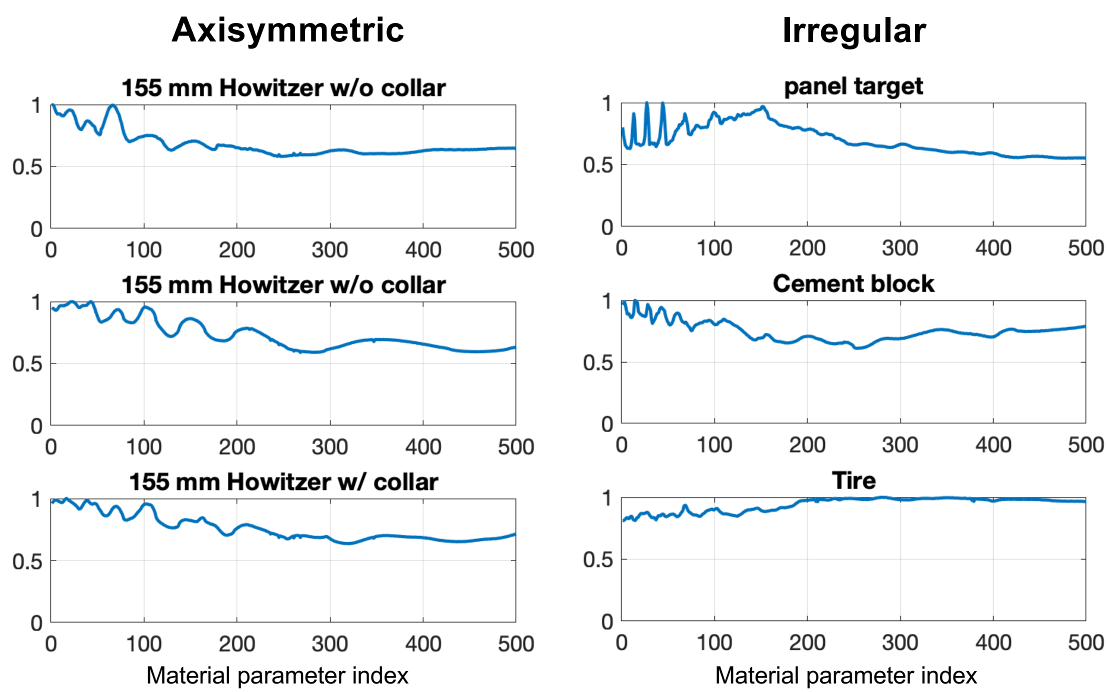
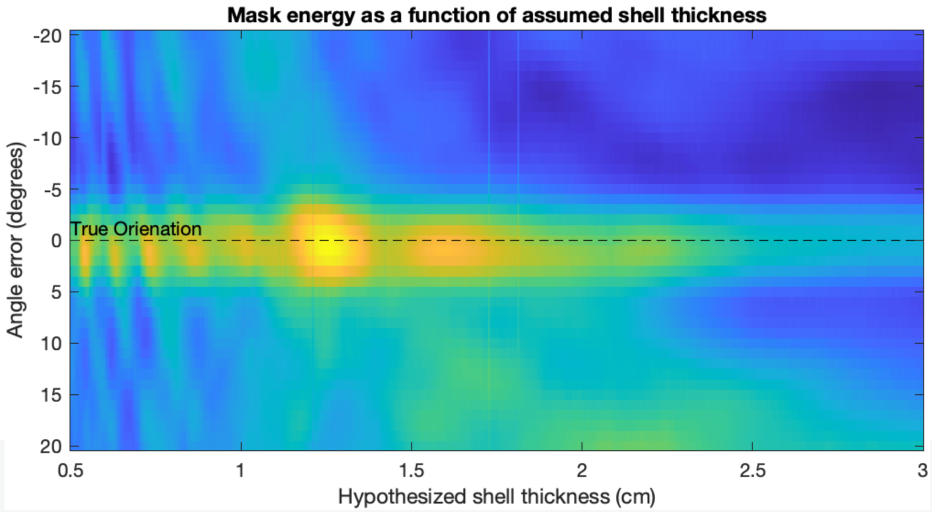
Results: Axisymmetric vs. Irregular Objects



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



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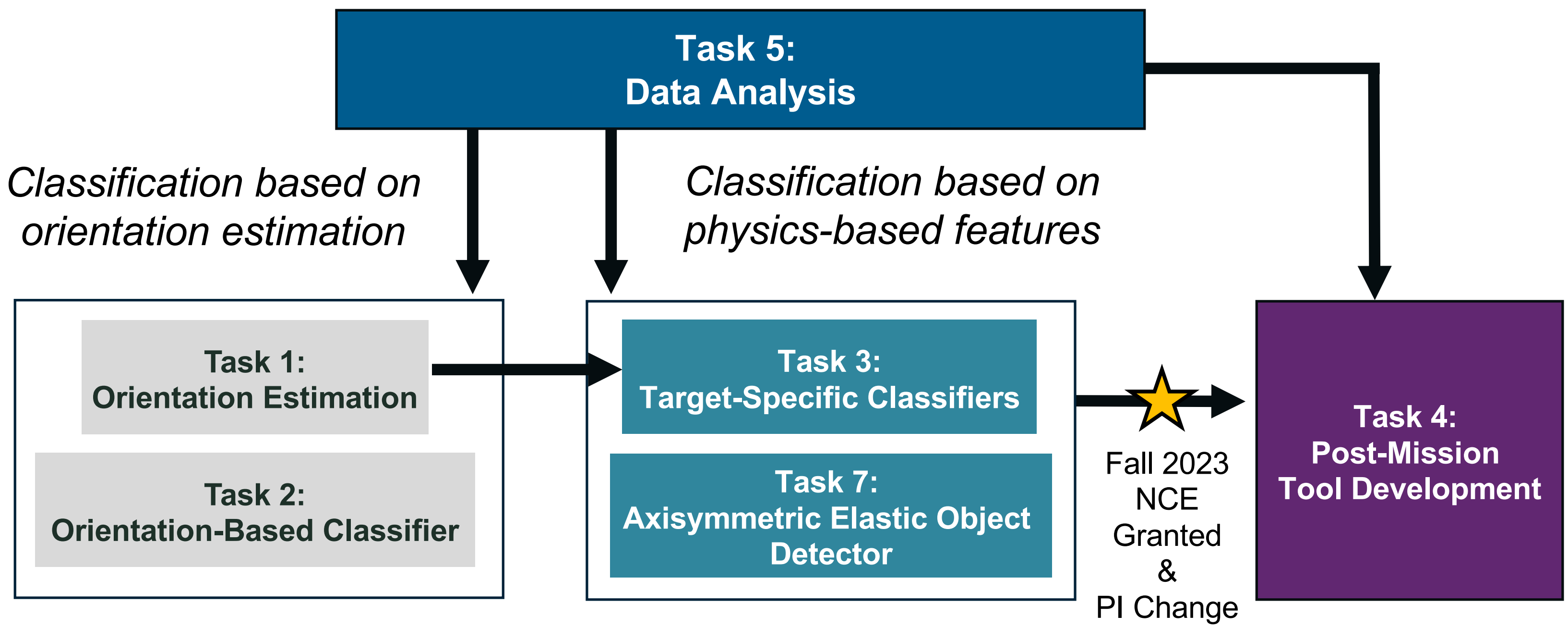
Technical Approach

Technology Focus: MuST System



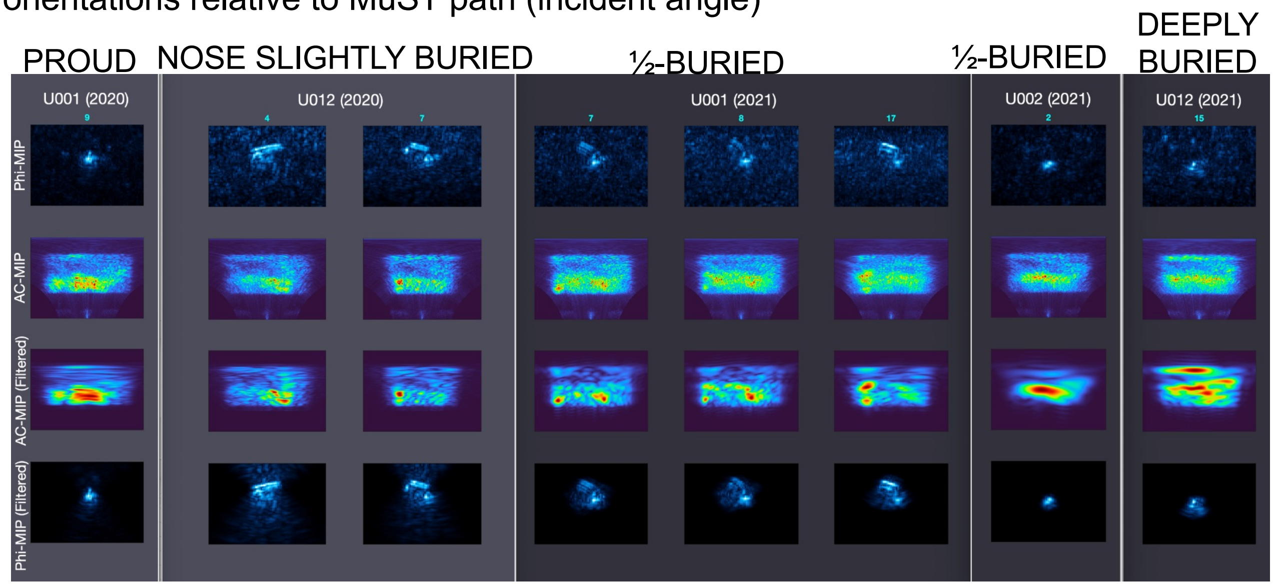
Results: MuST Data Analysis

- 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

TASK 5

Results: MuST Data Analysis

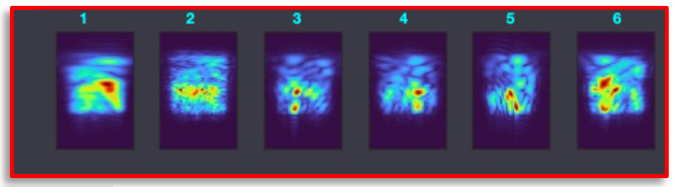
- MuST data collected at Sequim Bay Test Bed in 2020 and 2021 [9]
- Focused on 155 mm Howitzers and 105 mm M60s
- Different burial states and orientations relative to MuST path (incident angle)

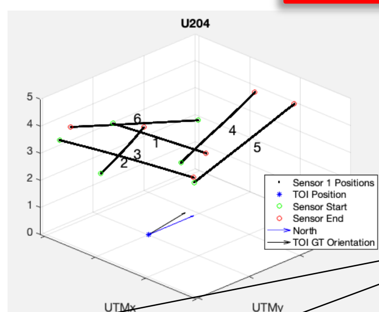


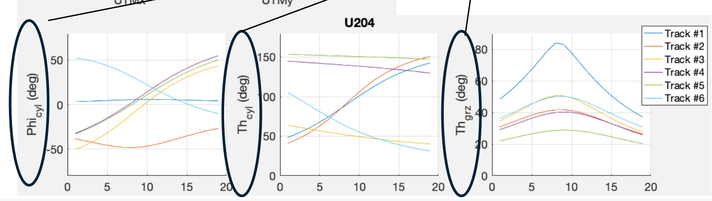
Results: MuST Data Tool Development

- 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

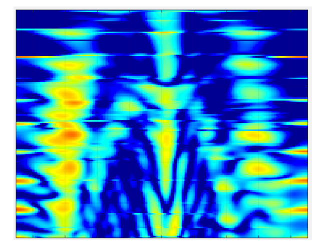






These angles are needed in order to make comparisons to model

MODEL RESULTS



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TASK 4

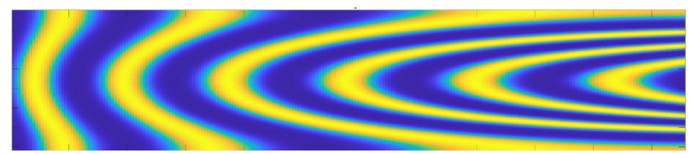
Results: Development of Post-Mission Operator Assist Tool

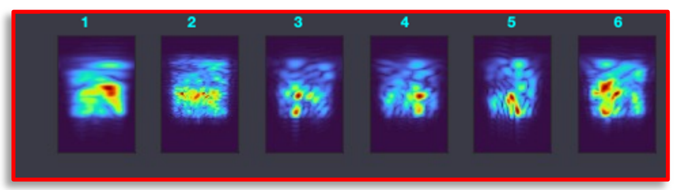
- Leveraging progress from MR23-3978 (PI: España) and MR22-3146 (PI: Marston)
- 20 inert UXO were characterized and modeled
  - These inert UXO were the same items that were deployed during tests of the MuST system at Sequim Bay
  - Coupling curves and corresponding masks are computed (next few slides covers this)
- 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
- Post-processing wavenumber “k-space” widget was developed to facilitate visualization and comparisons of MuST data and TIER simulations, and ultimately create data products that the detector masks can be applied to.

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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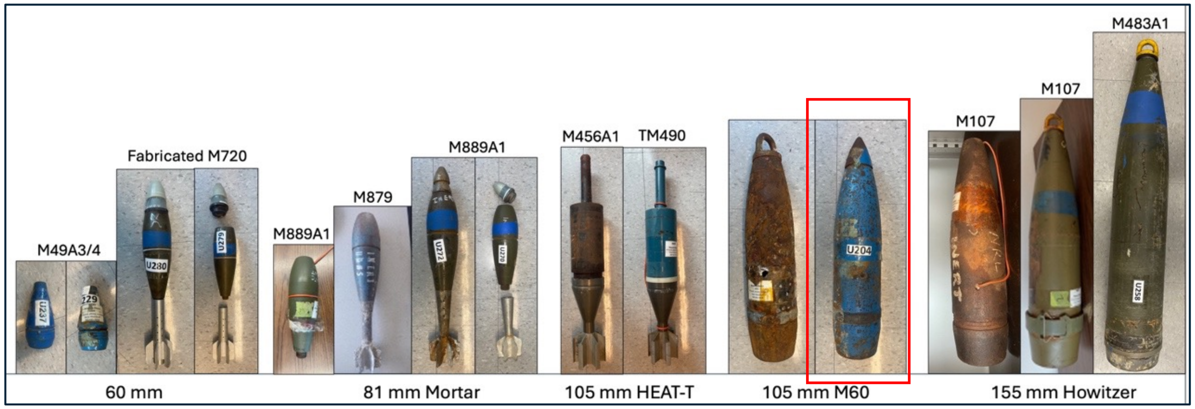
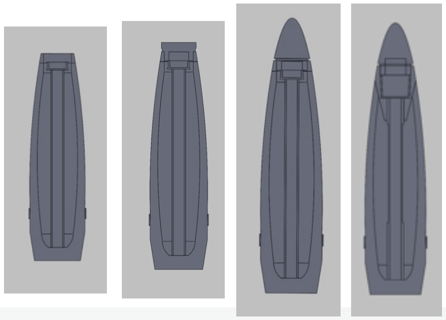
Results: Coupling curve maps for inert UXO

- Inert munitions that were physically characterized
- For each of these objects, several variations of CAD models were created and the acoustic response modeled for inclusion into TIER's database
- All of these have been added to the Axisymmetric Cylindrical Elastic Object Detector Code





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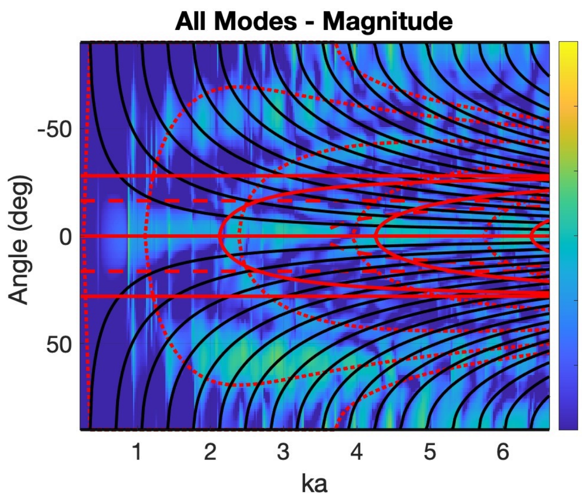
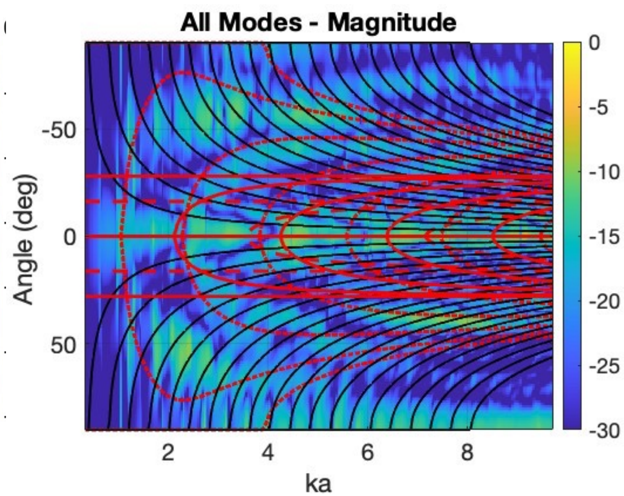
TASK 4

Results: Coupling curve maps for inert UXO

- The detector contains a class of objects
- Each class is defined by a specific diameter, length, shell thickness and material parameters
- The coupling curve maps are calculated for each class
- Two examples are shown on the right





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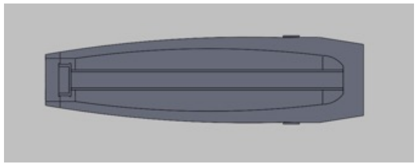
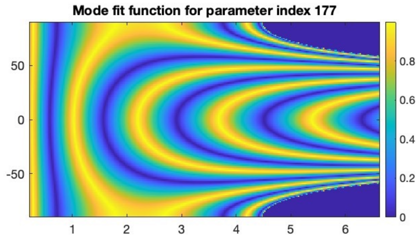
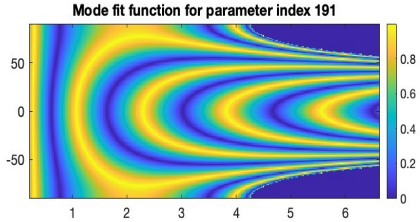
TASK 4

Results: Coupling curve maps for inert UXO

- Recall that the detector can perform parameter sweeps, and is how we envision dealing with the reality of flying over unknown objects
- We focus on sweeping through shell thickness (illustrated previously for Task 7 on slide 16)
- For each "class" of object, coupling curves and corresponding masks are calculated for 500 shell thickness values and archived







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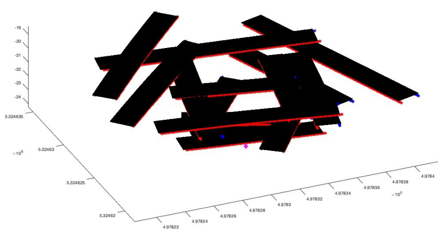
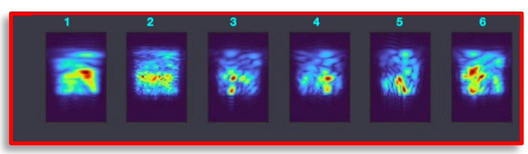
TASK 4

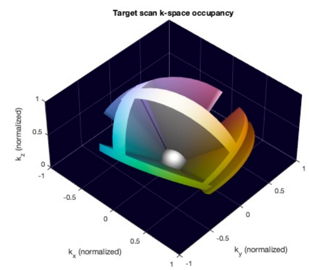
Results: AC templates for MuST and TIER simulations

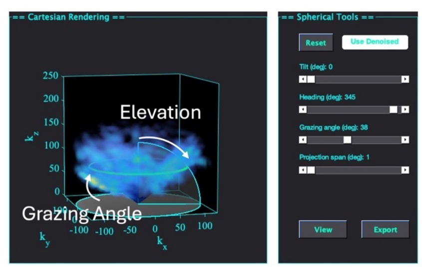
Individual MuST tracks





Aggregate data into 3D wavenumber space

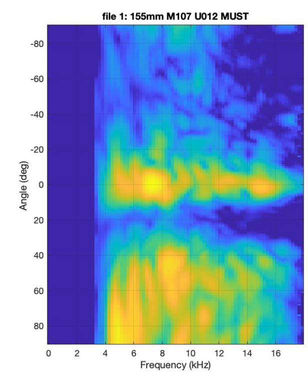




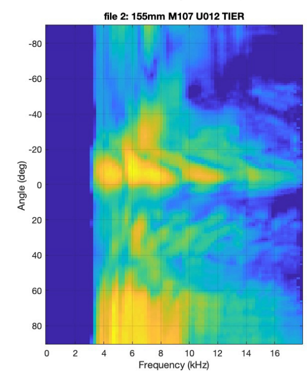
Slices through the 3D wavenumber space produce traditional AC

155 mm Howitzer U012 deeply buried in Sequim Bay

MUST Data



TIER Sims



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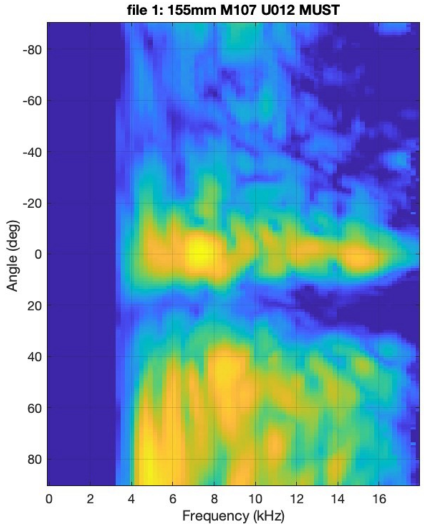
Results: Operator Assist Tool Design

Demonstrate the design and functionality by illustrating its application to MuST data for U012 deeply buried in Sequim Bay 2021

Inputs:

- 2D AC template
  (generated from 3D wavenumber widget)
- Class of objects to test against
  - Class 1: 155mm Howitzer similar to U012
  - Class 2: 105 mm M60
- Desired parameter to sweep over
  - Shell thickness
- Desired detector wave type to test
  - A0 wave and Axial waves



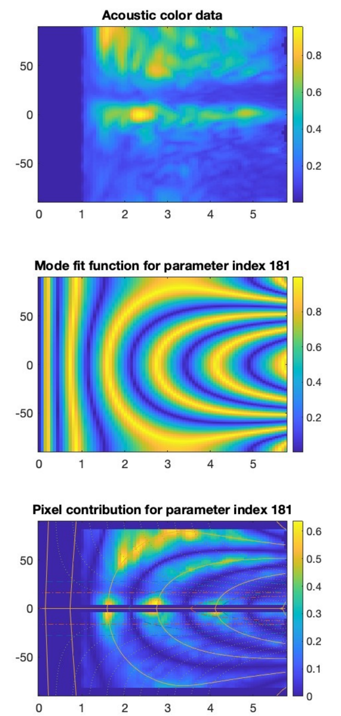
TASK 4

Results: Operator Assist Tool Design

High-level functionality:

- Step 1 – have the coupling curve masks been calculated already for user specified Class, wave type and parameter sweep?
  - *No → compute them and archive for future use*
  - *Yes → load in previously computed masks*
- Step 2 – Prepare the AC plot (excise high-scattering areas of the response)
- Step 3 – Apply each parameter/wave mask to the AC, summing up the energy within the mask
- Step 4 – Plot the integrated energy as a function of the parameter sweep

Intermediate output plots



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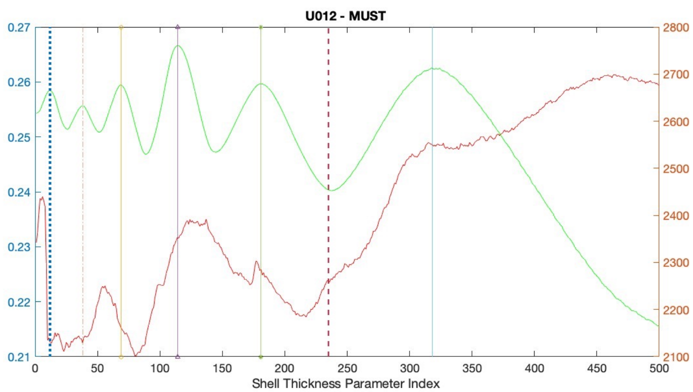
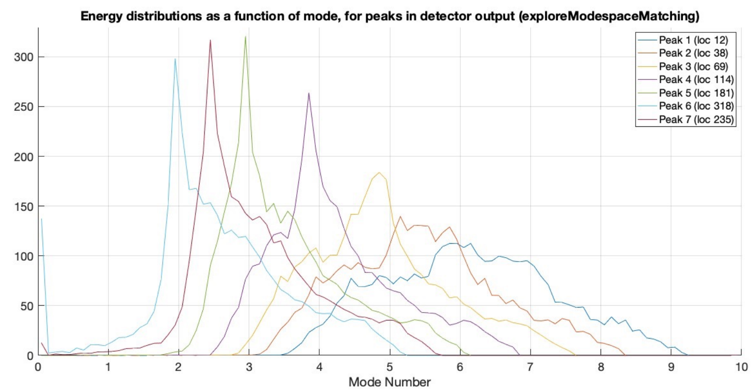
TASK 4

Results: Outputs from the Operator Assist Tool

Final Output: integrated energy as a function of the parameter sweep

Class 1 Detector (155 mm Howitzer U012)
Parameter sweep through shell thickness
Applied to **MuST Data**





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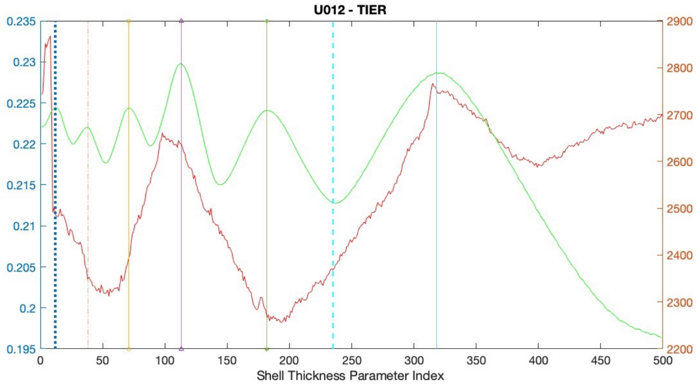
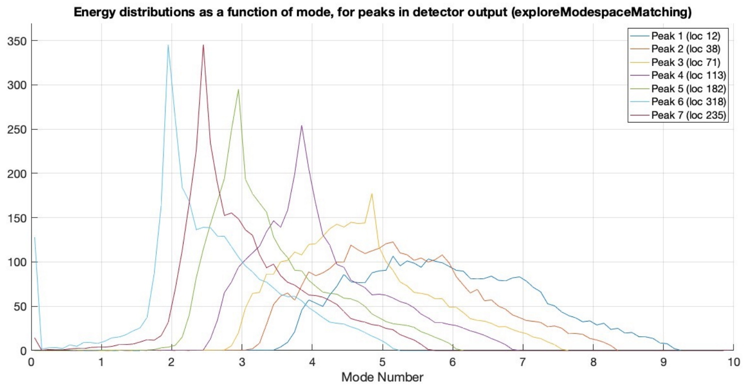
TASK 4

Results: Outputs from the Operator Assist Tool

Final Output: integrated energy as a function of the parameter sweep

Class 1 Detector (155 mm Howitzer U012)
Parameter sweep through shell thickness
Applied to **Synthetic Data (TIER)**





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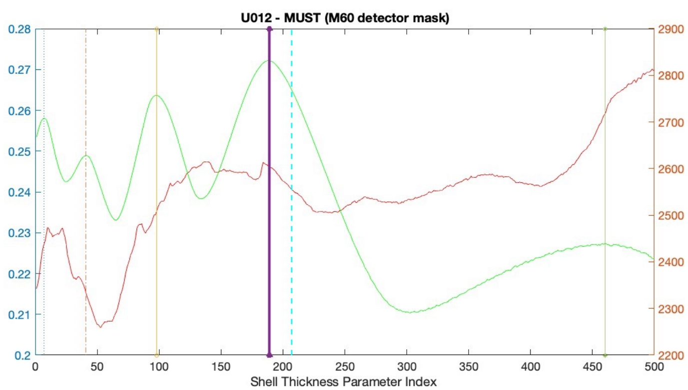
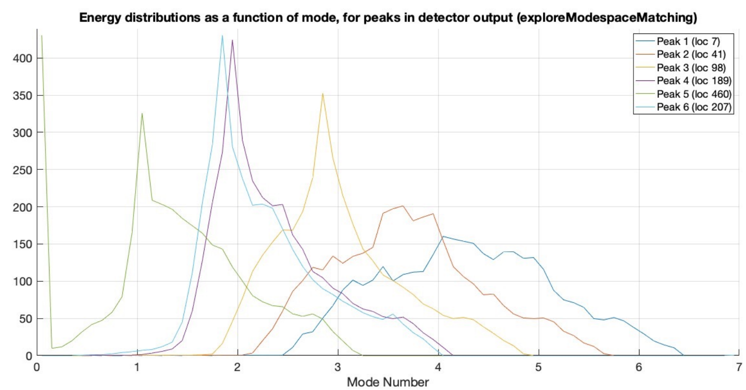
Results: Outputs from the Operator Assist Tool

Class 2 Detector (105 mm M60)
Parameter sweep through shell thickness
Applied to **MuST Data**

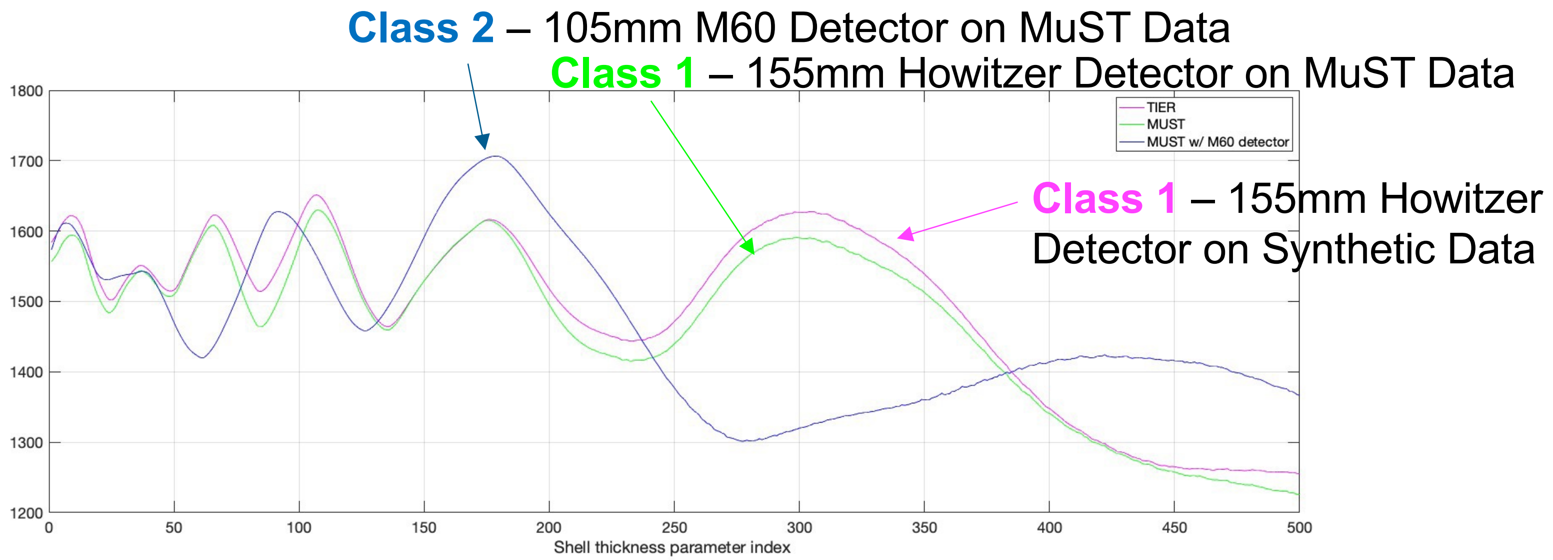
105mm Detector Masks
tested on
155 mm MuST Data





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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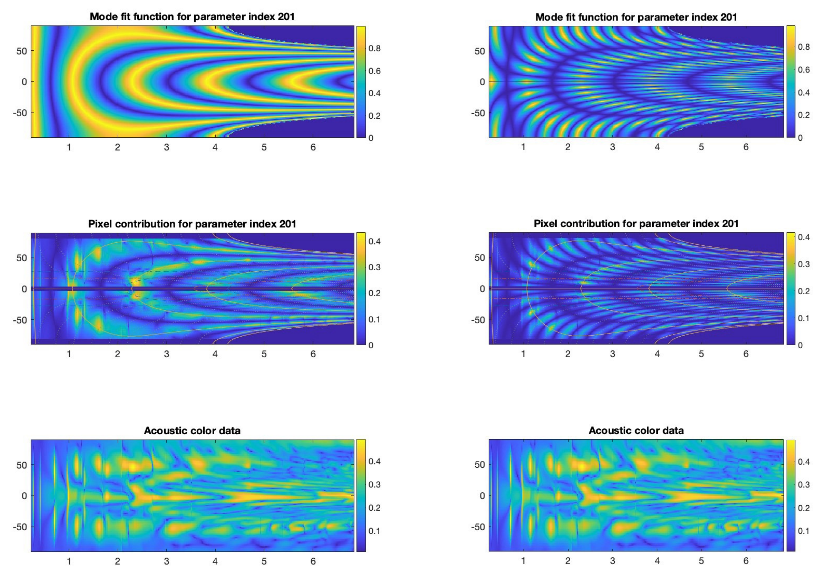
Next Steps

- Final Report will be submitted on 8/18/25
- The Final Report will document additional aspects not covered here:
  - Need for excising areas of the AC plots
  - How to incorporate multiple wave types into one final detector output

A0 wave | A0 wave X Axial Wave



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Technology Transfer

- Dr. España has joined the MuST project teams for SERDP MR22-3146 (PI: Dr. T. Marston) and ESTCP MR23-7596 (PI: Dr. K. Williams).
- She will be part of the upcoming live-site demonstration in Puerto Rico, aiding with MuST-Live processing as well as with the PMA and classification stages in the months following.
- We envision the Axisymmetric Elastic Object Detector as a physics-based classifier that can offer another score that can be considered along-side scores from the existing trained CNN classifier
- We have sufficient data from past Sequim Bay deployments, and the models that can produce artificial data (TIER), to robustly test it against other UXO classes, as well as better understanding the magnitude of known deficiencies

Technology Transfer

- To facilitate the previous vision/goals, the following steps have been taken:
  - The Axisymmetric Cylindrical Elastic Shell Detector and PMA Tool codes have been stored in a repository (internal to APL-UW personnel only)
  - Input data products (synthetic and in-situ), coupling curves and masks have been archived in a shared drive (internal to APL-UW personnel only)
  - A guidance document is in progress that covers the following:
    - Required software to run the detector (Matlab and their toolboxes)
    - Required code modifications to get it to run on a new system
    - Steps to run the detector
    - An example test case, complete with images of the outputs at each step
    - Brief list of known deficiencies of the detector
    - Brief list of future areas for development

Backup slides

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

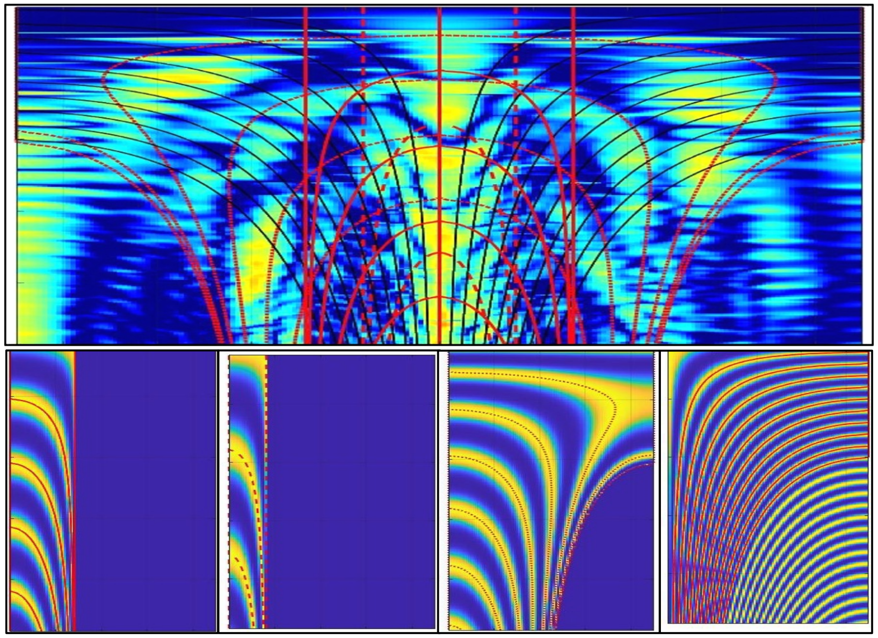
- *Incorporate physics into the detection and identification process*
- *Provide specific post-mission analysis tools to give users relevant information to improve system performance with low workload*

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*

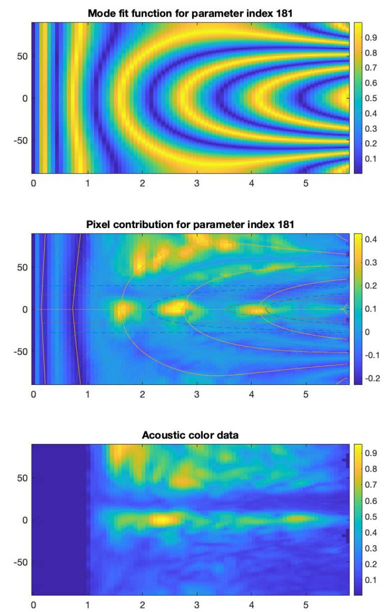


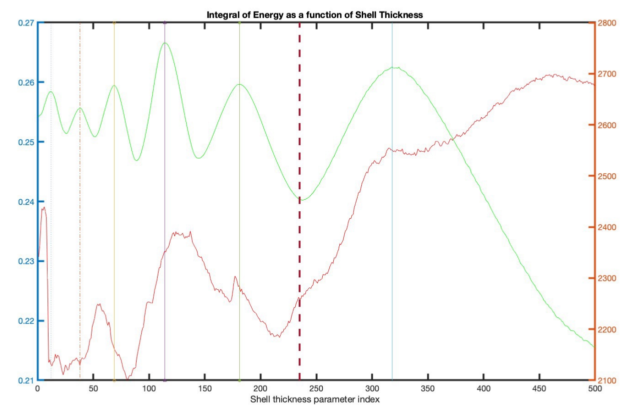
Plain Language Summary

- 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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Publications

- SERDP/ESTCP Webinar on July 25, 2024

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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.
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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.
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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.

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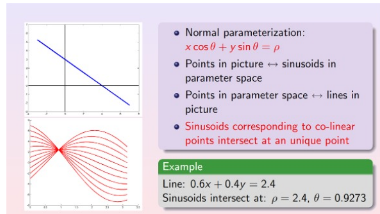
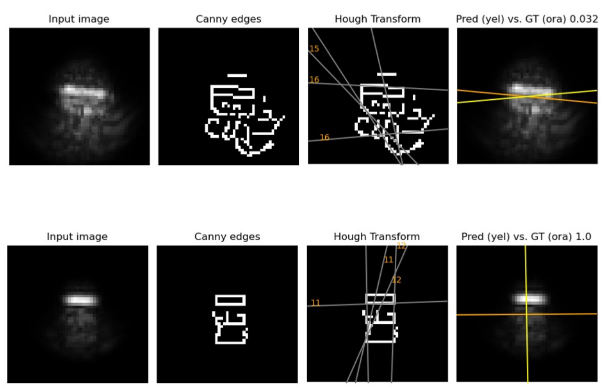
TASK 1

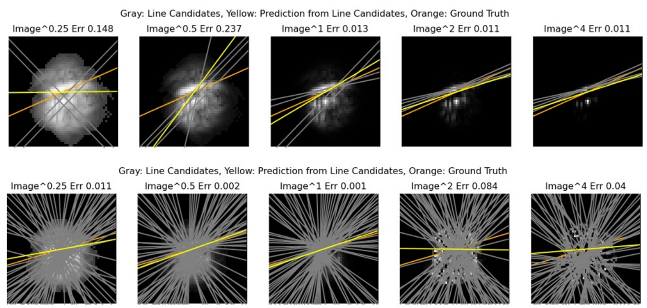
Results – Orientation Estimation

Orientation estimation using classical image processing

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







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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:

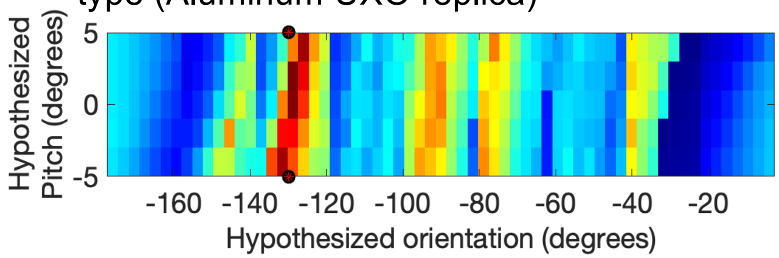
$$L_\theta(\hat{\omega}, \omega^{GT}) = \frac{1}{2}[1 - \cos(2(\hat{\omega} - \omega^{GT}))],$$

- 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

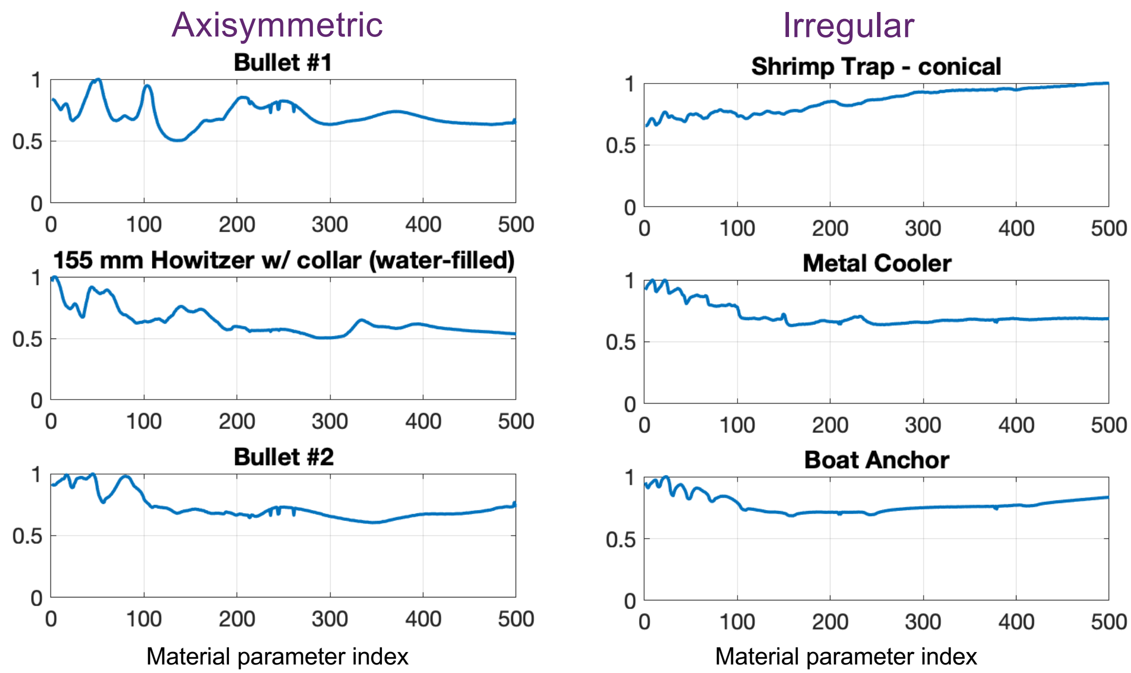
- Basic concept (continued):
  - Perform matched-filter analysis across all hypotheses for all modeled target types
  - Peaks can be used directly to identify best-guess orientation estimates, or combined with other information (image-based processing).
  - Relative fit of responses to particular models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

Elastic Cylindrical Shell Detector: Axisymmetric vs. Irregular Objects



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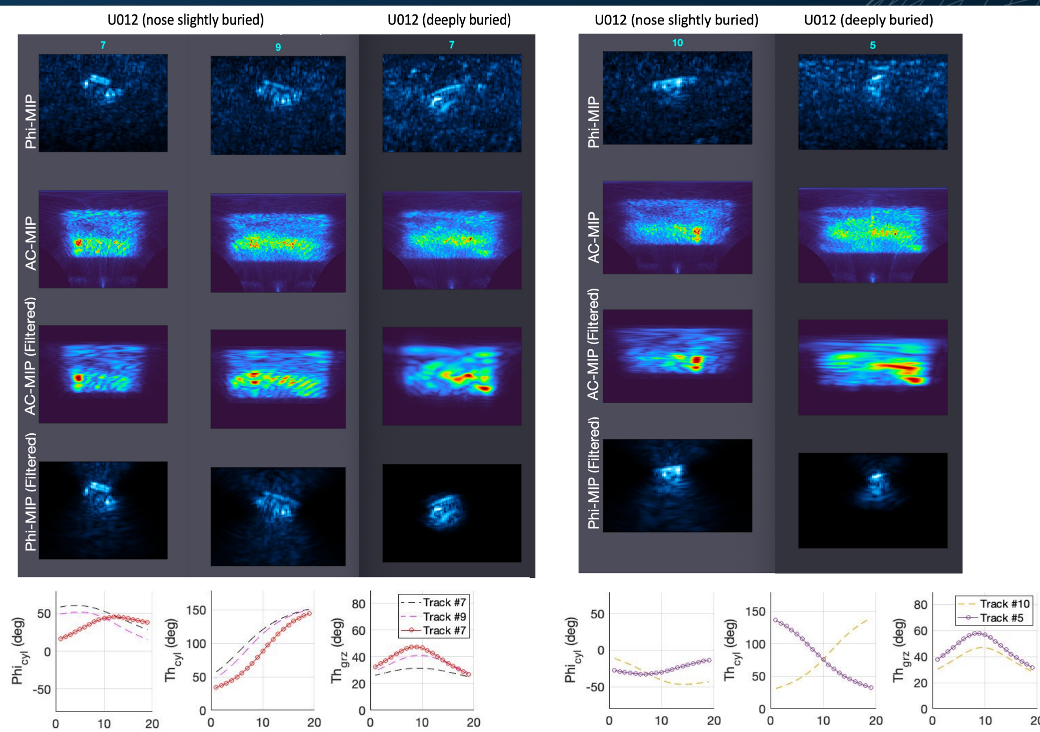
Results: MuST Data Analysis w/ Tools



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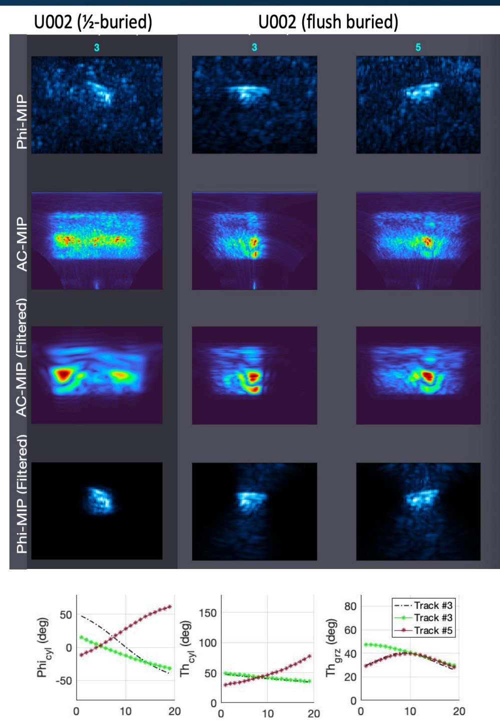
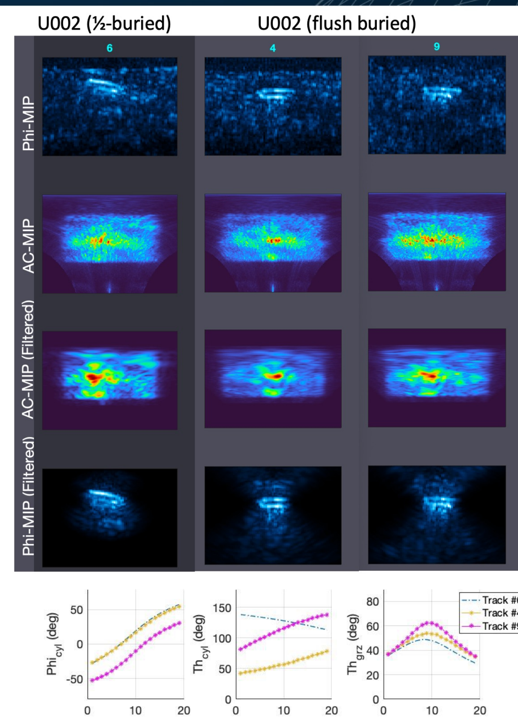
Results: MuST Data Analysis w/ Tools





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