Elastic Target Modeling for Physics-Based Automatic Classification

MR-2649

Dr. Lane Owsley
Applied Physics Laboratory, University of Washington

In-Progress Review Meeting
17 May 2018

SERDP
DOD ▪ EPA ▪ DOE

MR-2649: Elastic Target Modeling for Physics-Based Automatic Classification

Performers:

- Applied Physics Laboratory, University of Washington

Technology Focus

- Transfer of existing physics knowledge to sonar-based automatic classification of UXO

Research Objectives

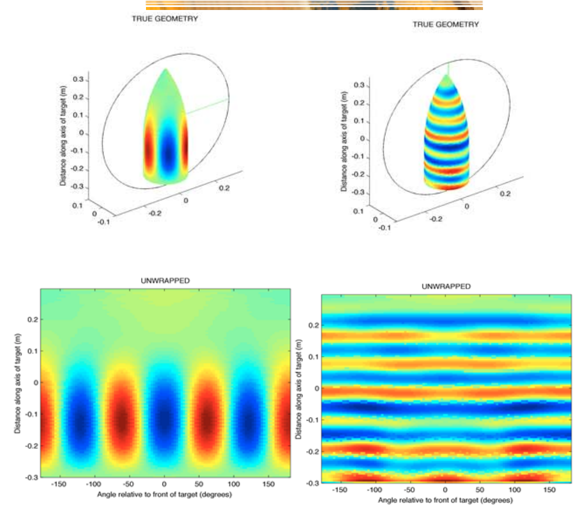
- Identify methods for constraining the physics of elastic targets to isolate components of acoustic returns and predict their behavior in different environments
- Use features identified and analyzed in that process to improve classification performance and robustness

Project Progress and Results

- Performed sea trials to gather data for validation of feature sets
- Isolated initial classes of features based on underlying physics
- Began analysis of current classification systems to identify opportunities for incorporation of physics

Technology Transition

- Develop feature sets, classifier architectures, and robustness measures for an Operations/Classification Package currently under development



Social Media Content

"Elastic Target Modeling for Physics-Based Automatic Classification," presented at SAGEEP 2018 (Invited Talk)

Project Team (all at UW-APL)

Dr. Lane Owsley (PI)
Expertise in signal processing and sonar signal processing, automatic classification.

Dr. Aubrey L. España (Co-PI)
Expertise in finite-element analysis of the acoustic response of targets.

Dr. Warren Fox
Expertise in sonar systems, statistical signal processing, and underwater acoustics

Funded separately:

Dr. Steven G. Kargl (PI for MR-2505)
Expertise in acoustic wave propagation and target scattering.

Dr. Kevin L. Williams (PI for MR-2501)
Expertise in at-sea field measurements and reduction of sonar data to acoustic templates used in classifications schemes.

Problem Statement

SERDP MRSON-16-01: Detection and classification of military munitions found at underwater sites "in a ***variety of conditions*** …"

A fielded system must be confidently assessed in terms of its robustness to new conditions.

- Full field testing across all conditions/targets is impossible
- Need: a deeper understanding of how the classifier operates and how it would need to adapt to new environments.

Technical Objective

Improve the state of the art in acoustic detection and classification of UXO underwater, across a wide range of sediment types and burial states

- Use a new approach to modeling to enable the physics-based interpretation of acoustic returns from UXO
  - ♦ Break down returns into individual components based on elasticity, direction and depth of travel, coupling location
  - ♦ Separately analyze effects of sediment, burial, and multipath on each component
- Develop feature sets, classifier architectures, and robustness measures for an Operations/Classification Package currently under development

Technical Objective: Five Year Vision

MR-2231

FY12-15
- TREX13 (sand) & BAYEX14 (mud)
- Validated models, HF+LF classifiers

MR-2505
Operations/Classification Package

Year 1
- Develop classification algorithms
- Generate sets of simulated data
- Operational protocols

Year 2
- Experiment in an acoustically hard environment (high clutter)
- Test trained classifiers

HERE

Year 3
- Retrain/modify classifiers
- Test trained classifiers on Puget Sound tow body data

MR-2501
Tow Body Package

Year 1
- Towbody design study
- Follow-on proposal for prototype

ESTCP MR18-5004

HERE

Year 1
- Towbody construction
- Dock-side testing/calibration

Year 2
- Engineering Test (Puget Sound)
- Test internal sensors/hardware
- Test operational protocol

MR-2649 (This Project)

Year 1
- Physics decomposition modeling
- Physics-based feature representation & robustness analysis
- Target manufacture

HERE

Year 2
- Continue modeling and feature representation
- Test on rail and tow-body data

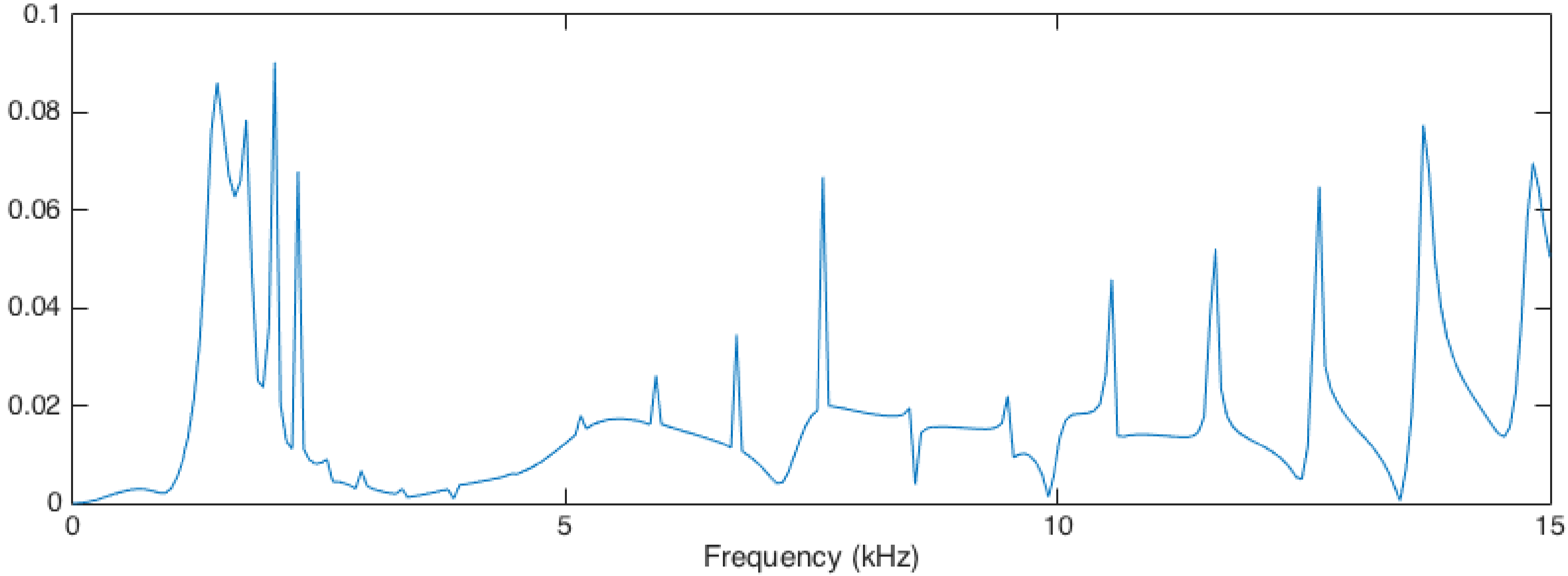
Year 3
- Improve signal processing, feature extraction and classifier design
- Performance prediction
- Guidance on interrogation scenarios

Years 4,5
- Field demonstration of towbody with classification package (Sequim Bay)

Technical Approach Background: Interpretation of Returns Using Classical Physics

For simple shapes, we can predict the response analytically and interpret specific features of the return. See, for example, the resonant peaks below.

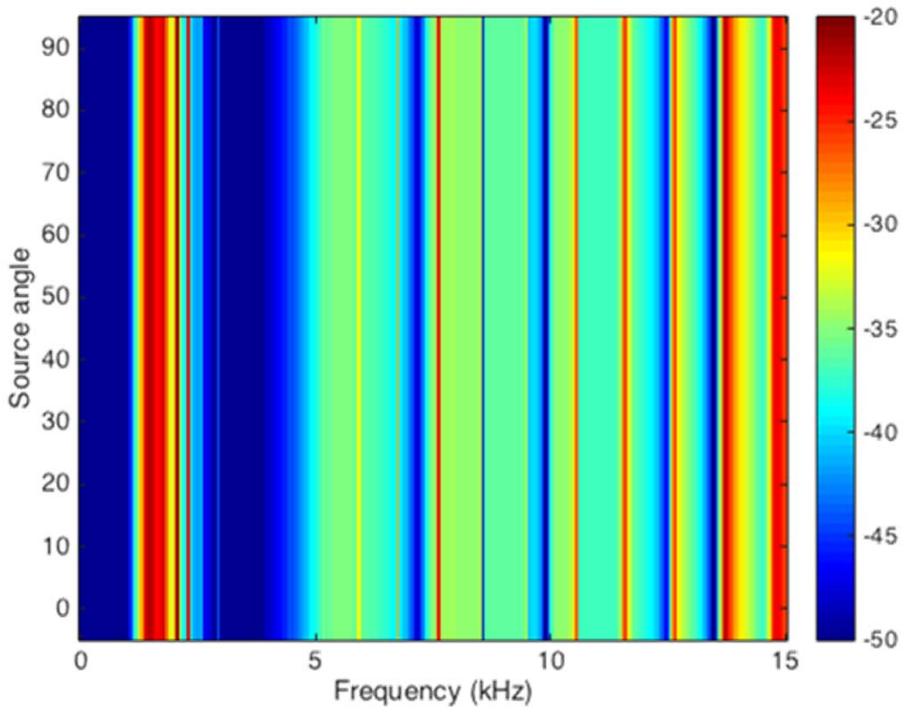
Scattered response of a sphere as a function of the frequency of the incident wave



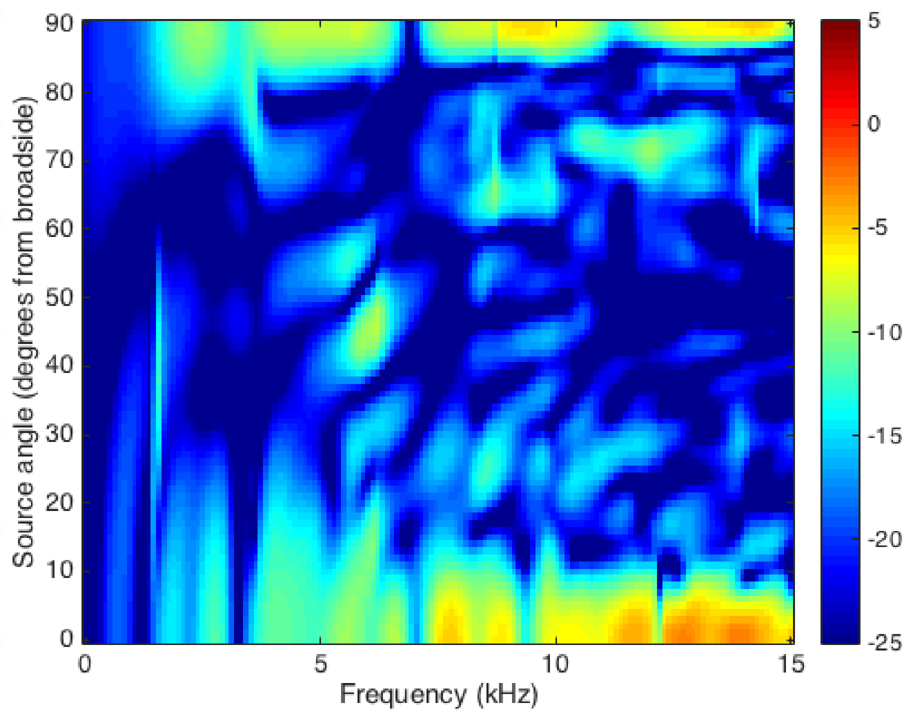
Technical Approach Background: Limitations of analytic modeling

- Even “simple” shapes produce returns that quickly become too complicated to definitively interpret

Sphere (same data as previous slide)

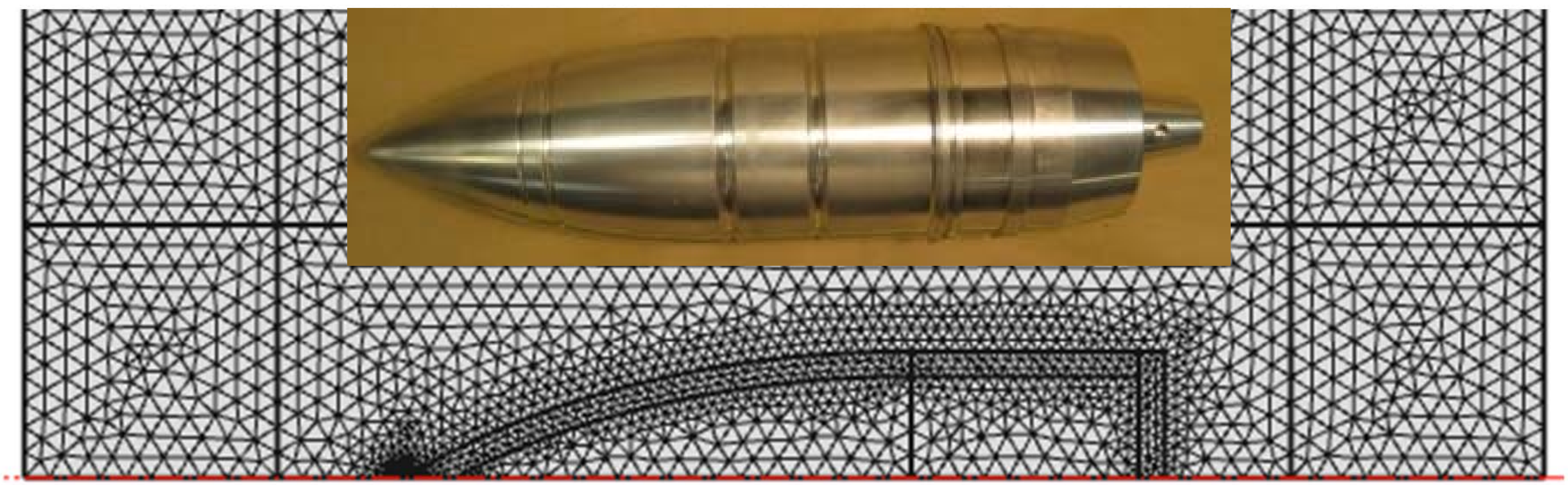


Cylinder



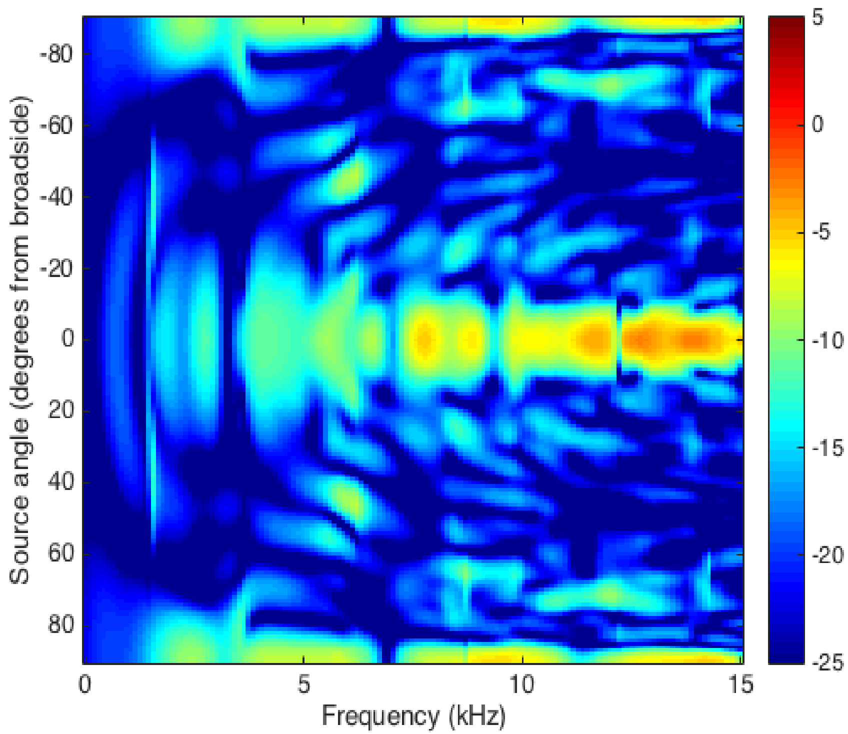
Technical Approach:
Finite Element (FE) modeling

- The physics of the most interesting shapes is too complicated to model mathematically, but
- If we look at a small enough region, the local physics will be simple
- Finite element modeling divides (meshes) a complicated shape into small regions with simple physics, each of which imposes boundary conditions on its neighbors.



- Thus modeling the physics becomes a case of solving (many) simultaneous equations.

Technical Approach:
Challenge of Standard FE Modeling: Interpretability



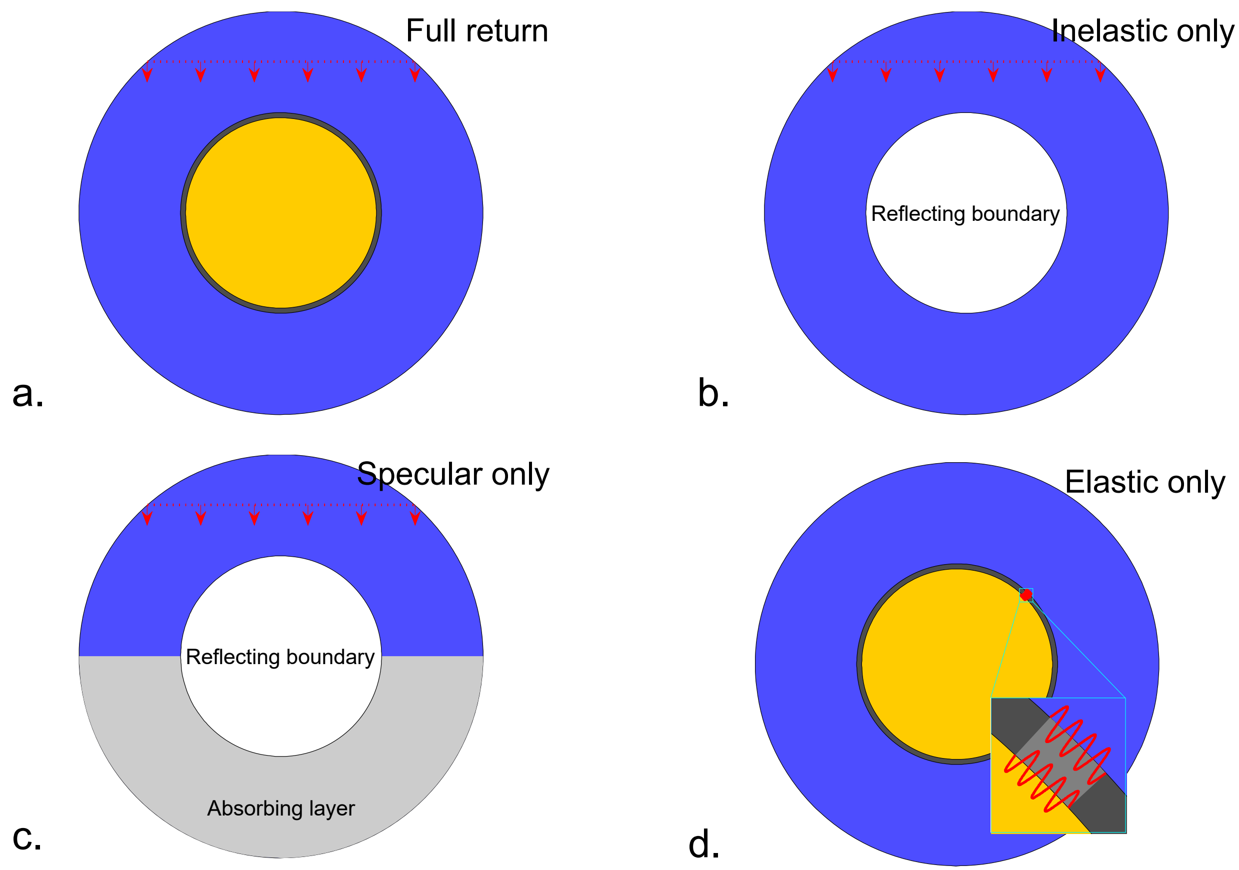
The goal of standard FE modeling is to reproduce true physics as accurately as possible (which makes sense)

This means that, though we have greatly widened the class of shapes we can model, the modeled returns are (of course) just as complicated as the true returns

But an FE model is just math, and nothing forces us to model all the physics at once…

Technical Approach:
Physics-Based Component Isolation Methods

Under previously funded projects (including SERDP SEED effort), we modified the standard FE approach to isolate the components of the response due to specific physical mechanisms



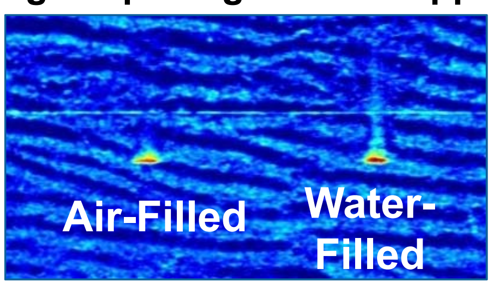
Results

- Task 4: Sea Trials
  - ♦ Overview of science target experiments
  - ♦ Model/Data Comparison
  - ♦ Target geometry/materials analysis and model update
- Task 6: Modeling
  - ♦ Use of internal physics to guide component isolation
    - Overview
    - Example: Bending
    - Example: Shear strain inflection lines
    - Example: Normal Displacement
  - ♦ Modal analysis
- Task 8: Classification & Analysis

Task 4: Sea Trials
Experiment Overview

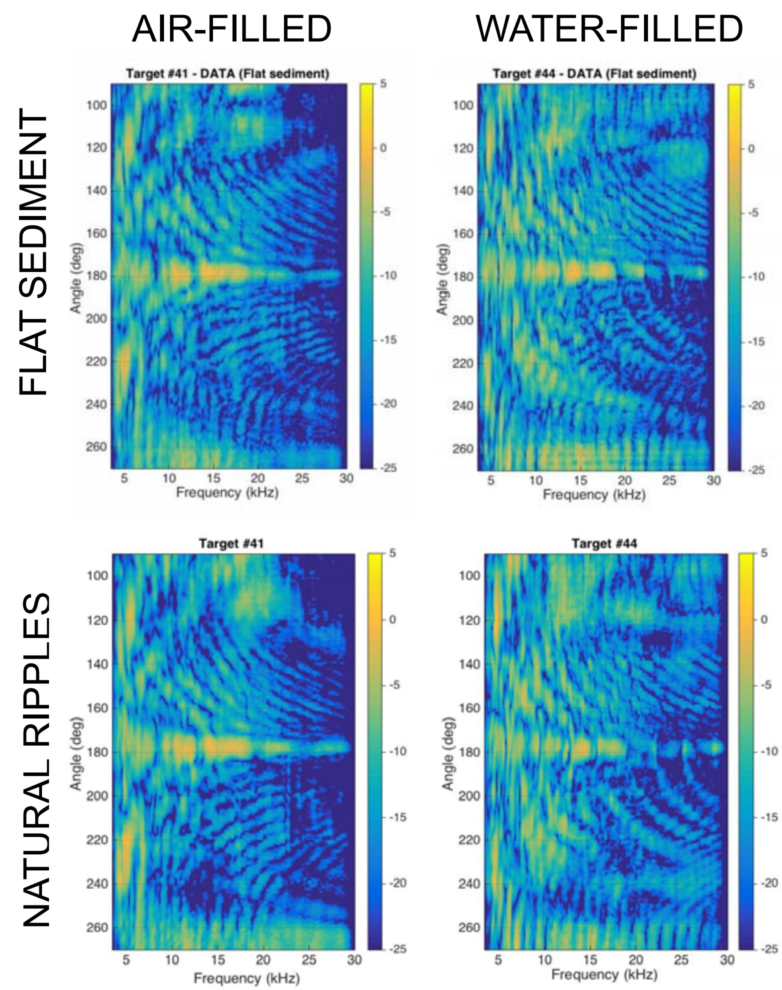
- CLUTTEREX17 – Joint SERDP(MR-2505) and ONR effort, Panama City Beach FL, July 2017
- Investigated the acoustic response of UXO and science objects, in the presence of clutter
- Under this current effort:
- Manufactured targets similar in size and shape to 155mm Howitzer
- 3 types of filler (air, water, isopropyl alcohol)
- Deployed during CLUTTEREX17:
  - Ranges: 15m, 40m
  - Bottom type: Flat, natural ripple pattern, small scale ripples (made with garden rake)

SAS Image depicting Natural Ripple Pattern



- Also deployed in ‘blind data sets,’ with multiple targets and clutter items, randomly placed and manipulated

Range = 15m

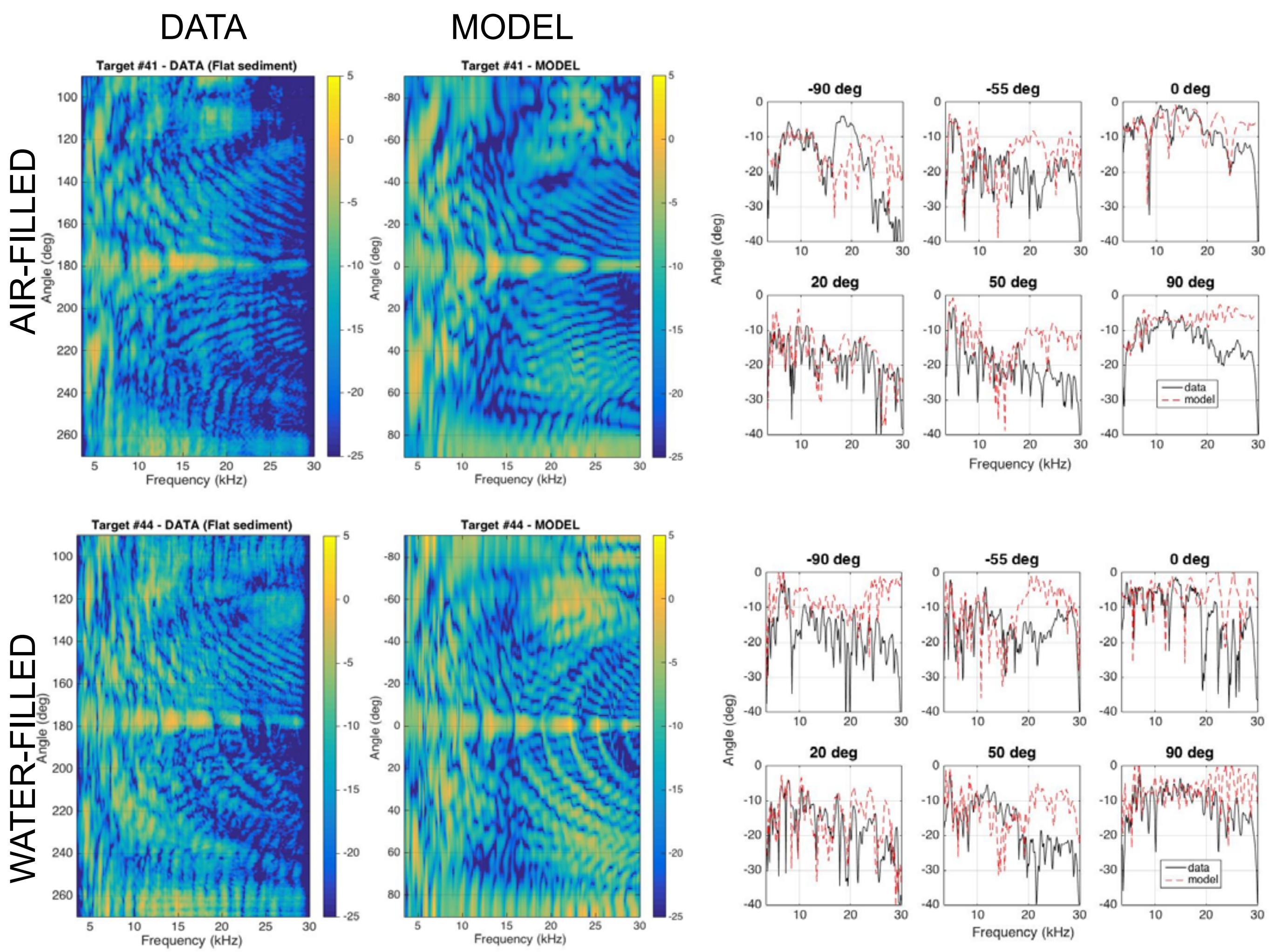


Task 4: Sea Trials
Model/Data Comparison

- Flat Sediment
- Range = 15m

- Model-data agree well from 3-15 kHz

- Discrepancies observed >15kHz



Task 4: Sea Trials

Model/Data Reconciliation

- Initial modeling results showed significant enough variations from collected data to warrant further study
- Past experience with better model fits suggests the source of error may be in the modeling geometry and/or material properties
    - Careful measurement of the target has revealed some deviations from the specs which have been incorporated into a new model
    - Material samples have been sent to Jermaine Kennedy at NSWC for testing

Task 6: Modeling

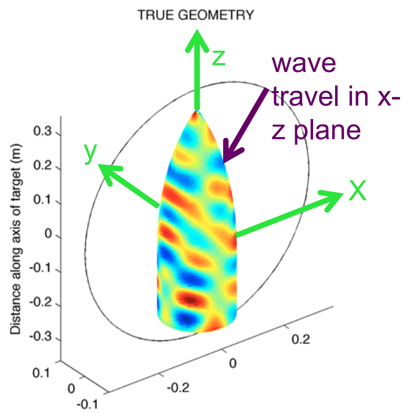
Isolating Components of the Elastic Response

- Goal: Using COMSOL FE modeling environment, constrain solid mechanics in ways that isolate contributors to the complete return
- Approach: Analyze the full return in-depth to identify possible characteristics of individual behaviors and use COMSOL to enforce these characteristics, by
  - Modifying the loading or excitation
  - Modifying the physical properties of the material
  - Constraining or impede the movement
- Important: All isolated return components are validated in the context of the complete return

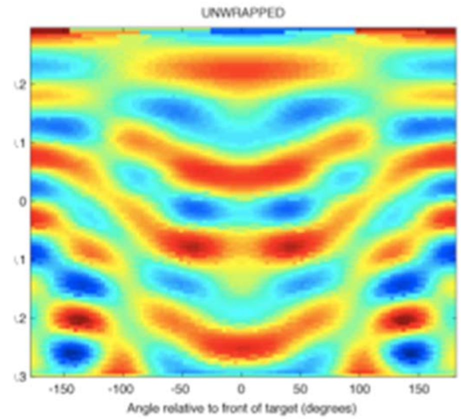
Task 6: Modeling

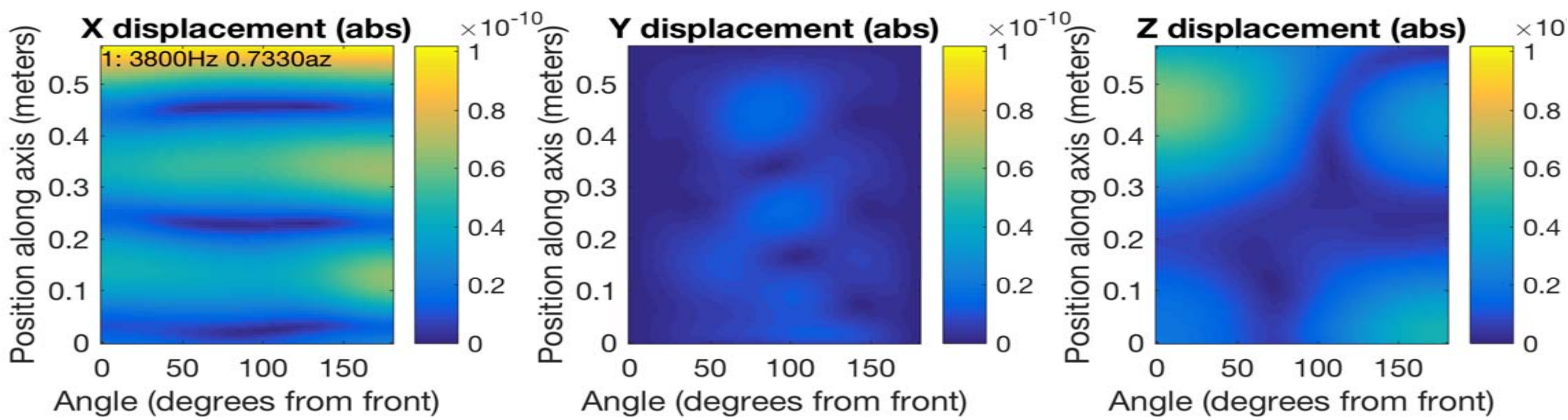
Bending: Internal Displacement

True 3D physics map



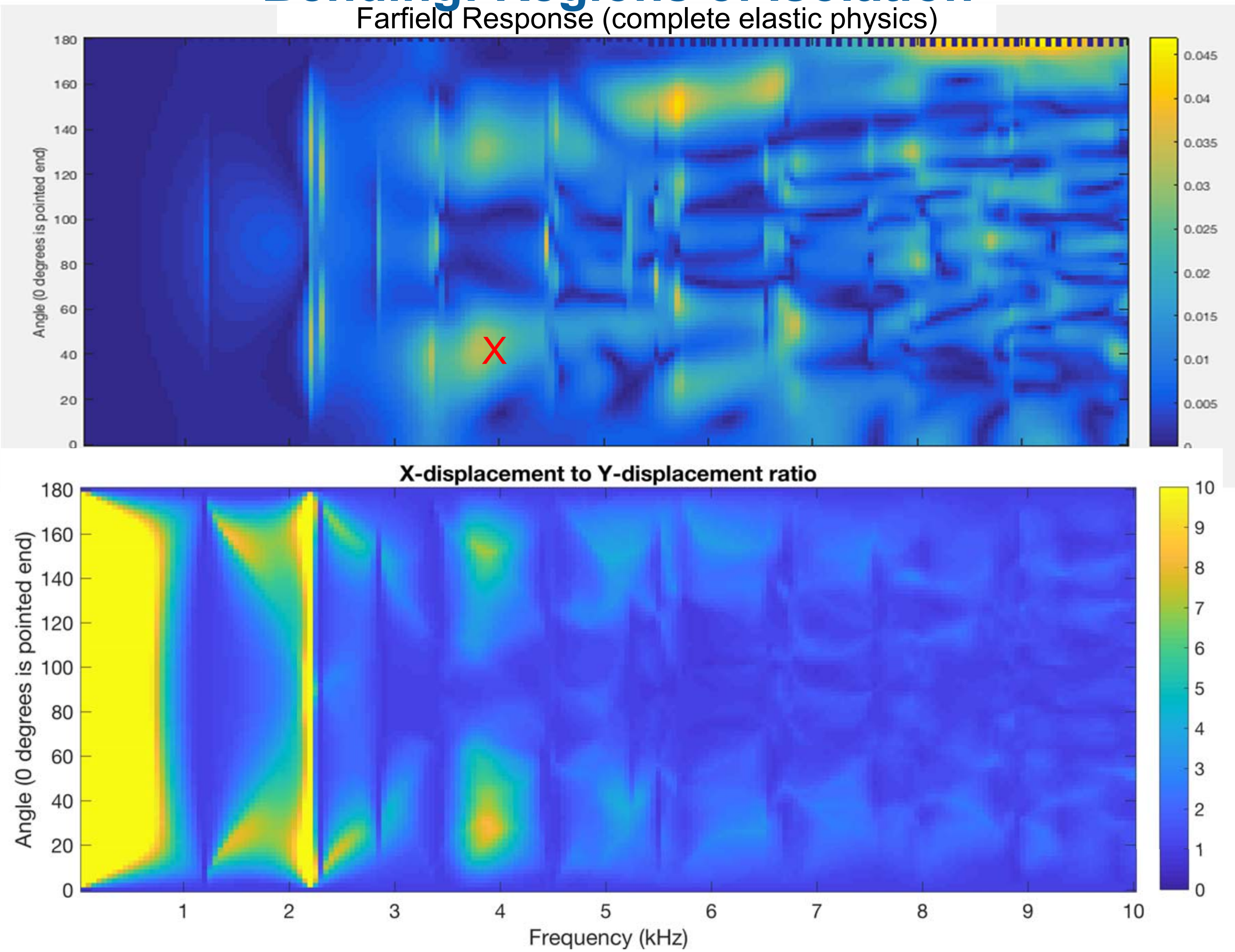
"Unwrapped" physics for visualization





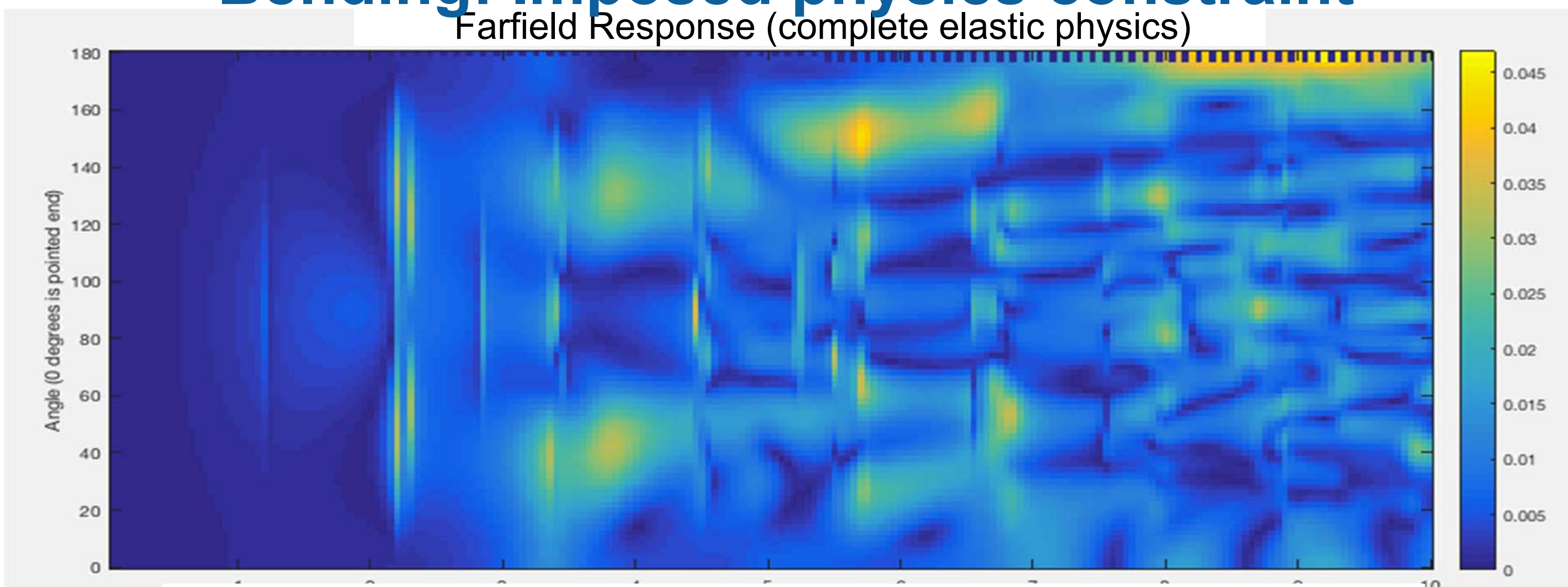
Task 6: Modeling

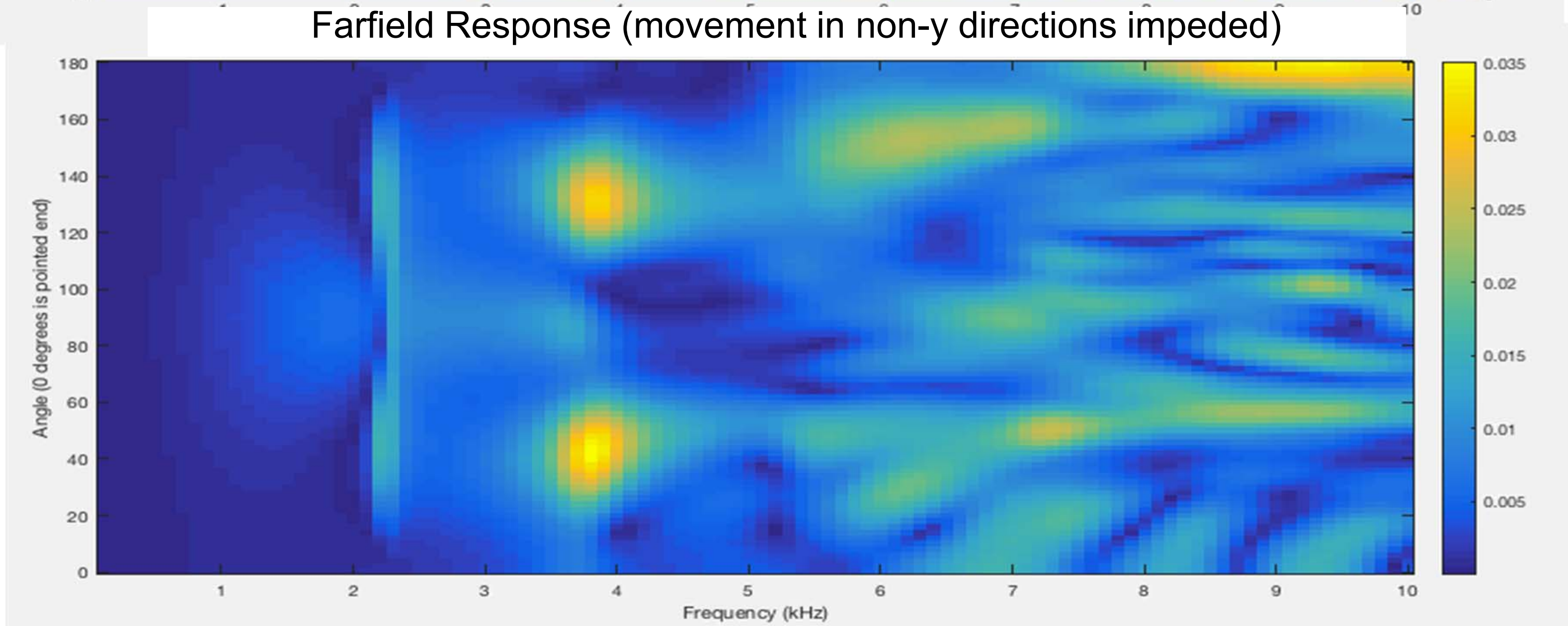
Bending: Regions of Isolation



Task 6: Modeling

Bending: Imposed physics constraint

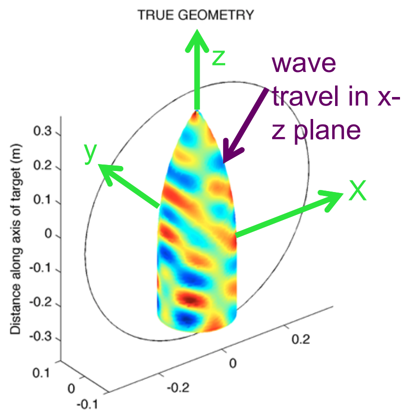




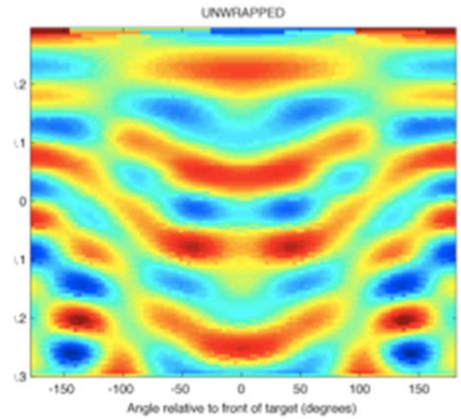
Task 6: Modeling

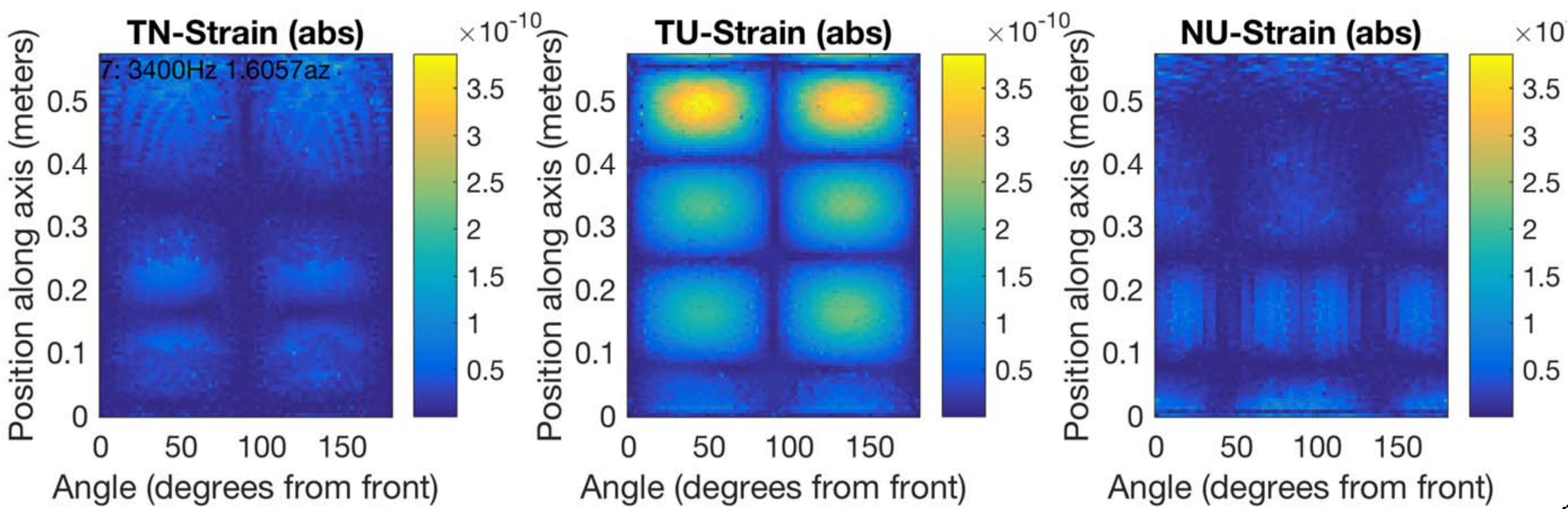
Inflection Lines: Shear Strain

True 3D physics map



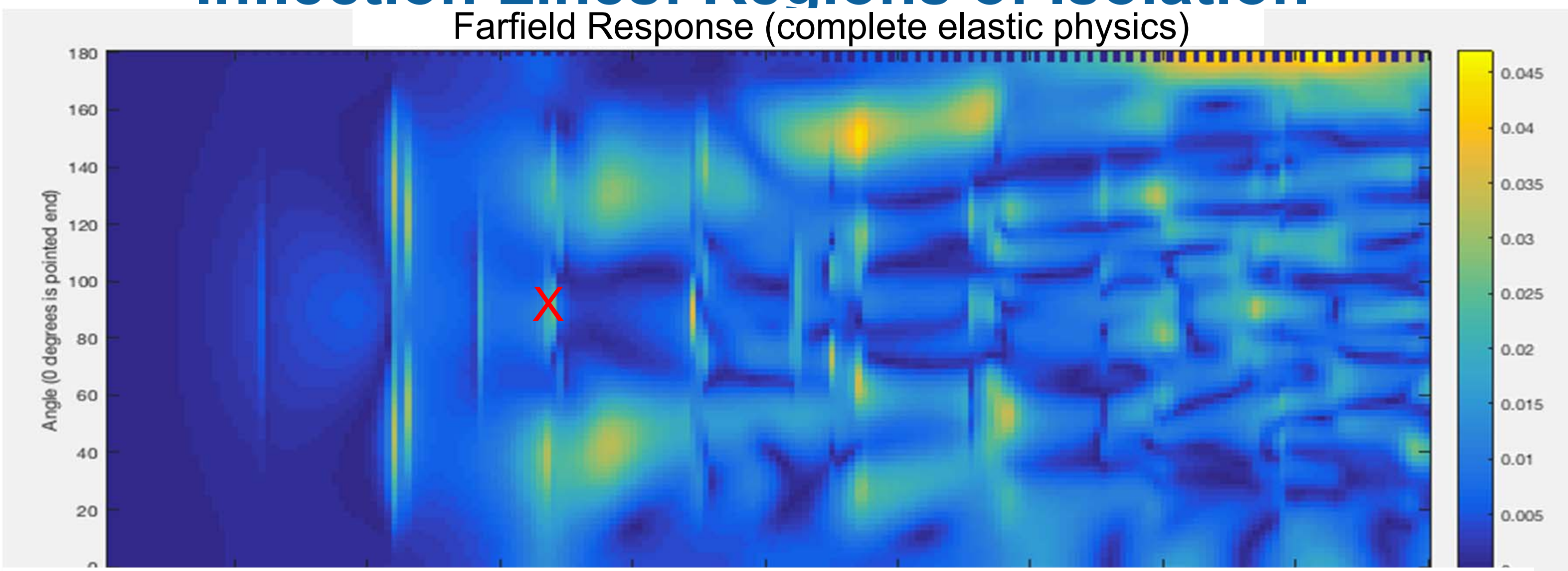
"Unwrapped" physics for visualization

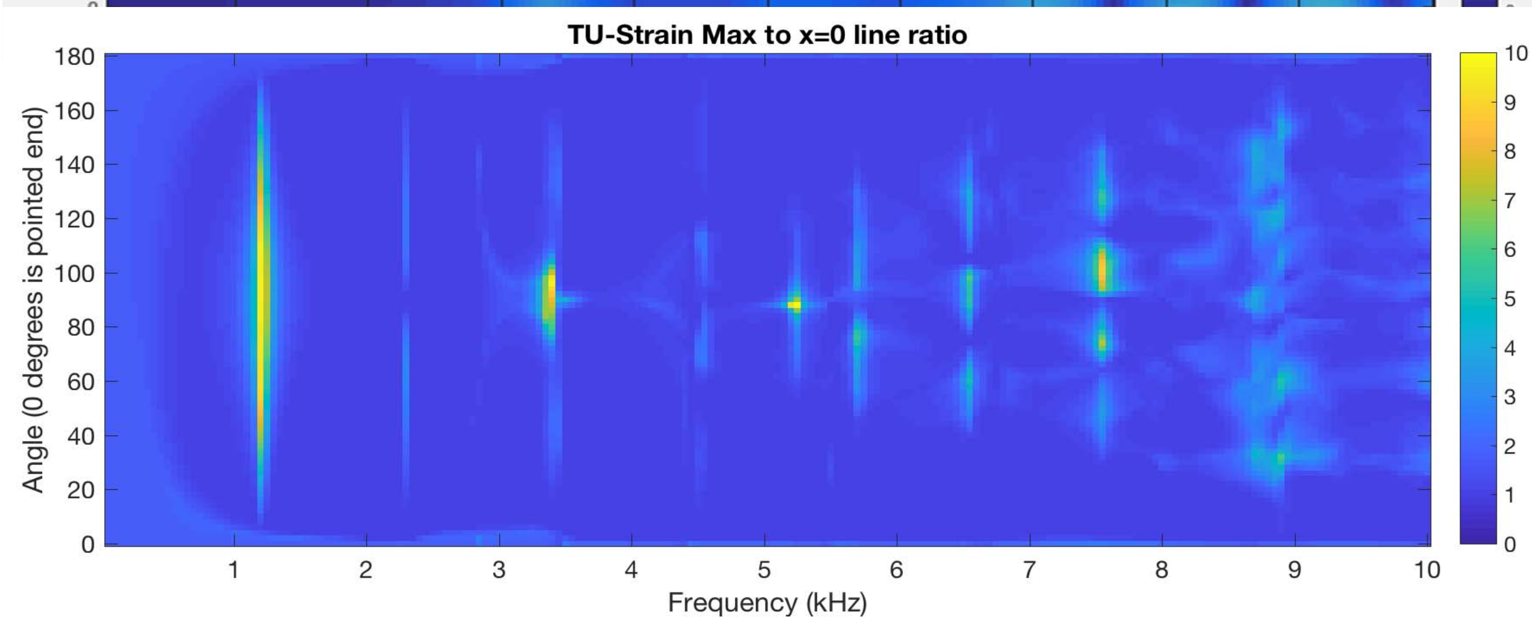




Task 6: Modeling

Inflection Lines: Regions of Isolation

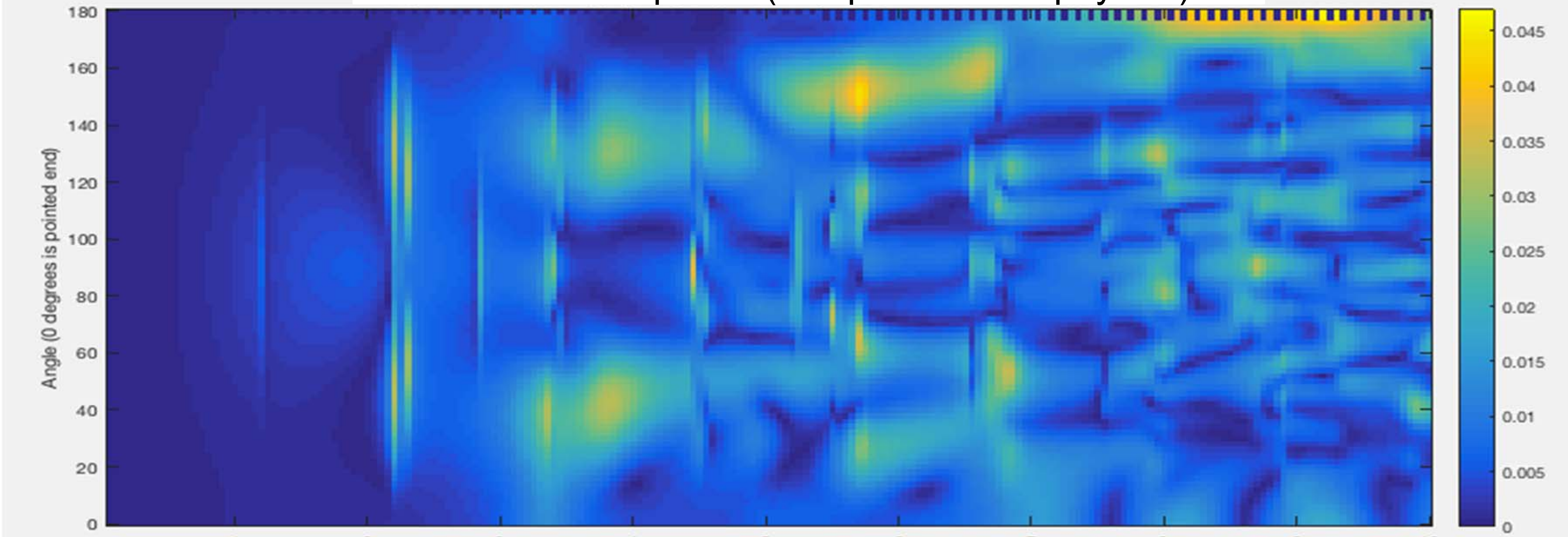




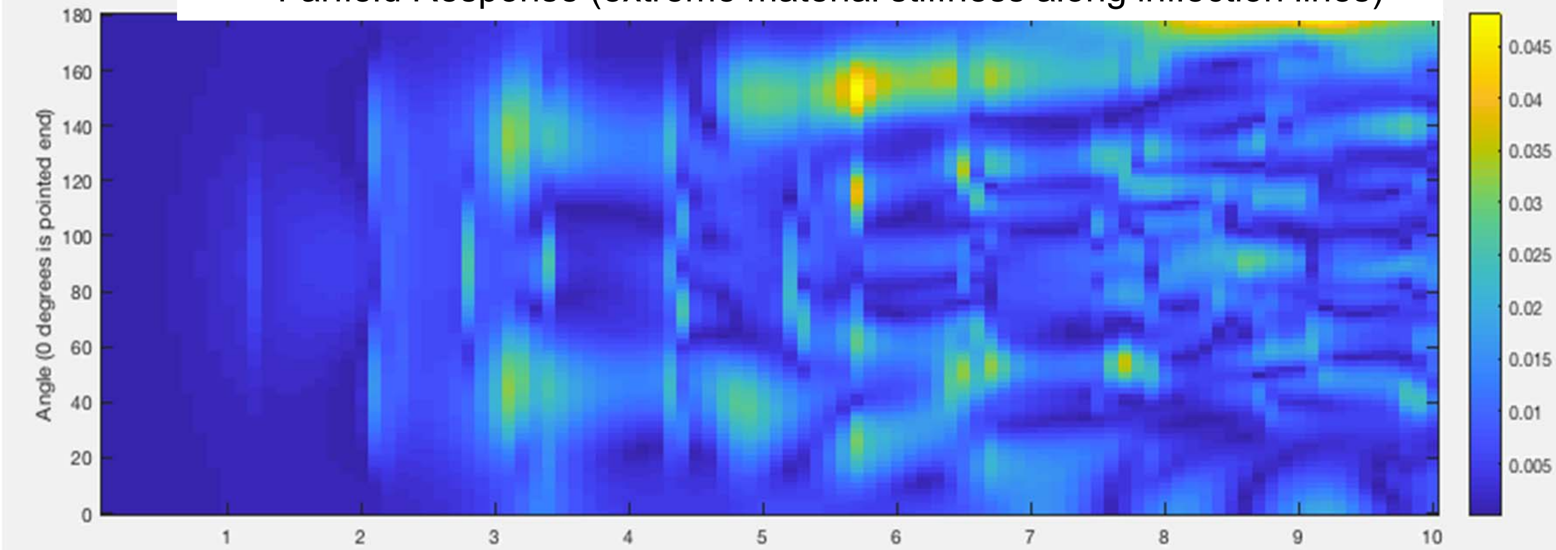
Task 6: Modeling

Inflection Lines: Imposed physics constraint

Farfield Response (complete elastic physics)



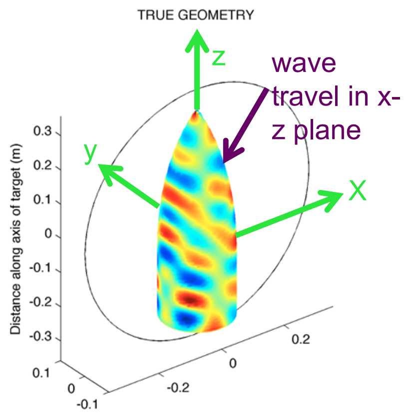
Farfield Response (extreme material stiffness along inflection lines)



Task 6: Modeling

Dominated by Normal Displacement

True 3D physics map



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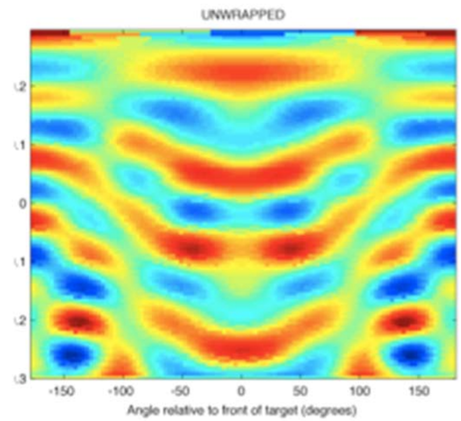
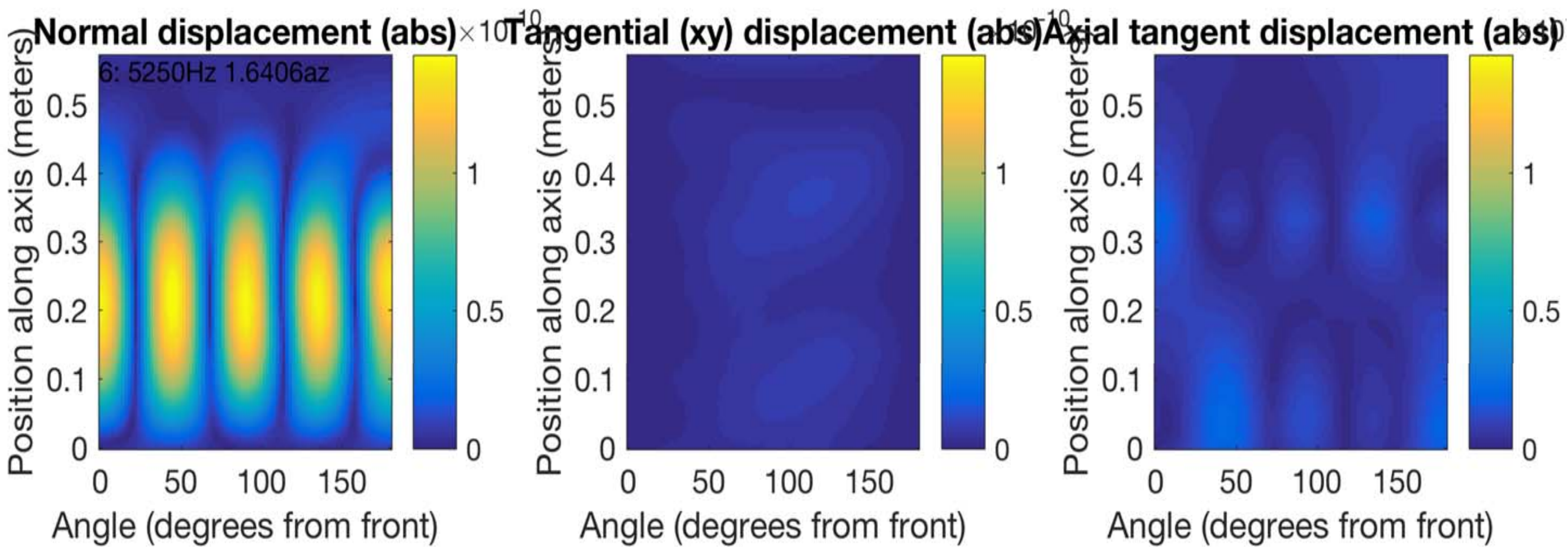
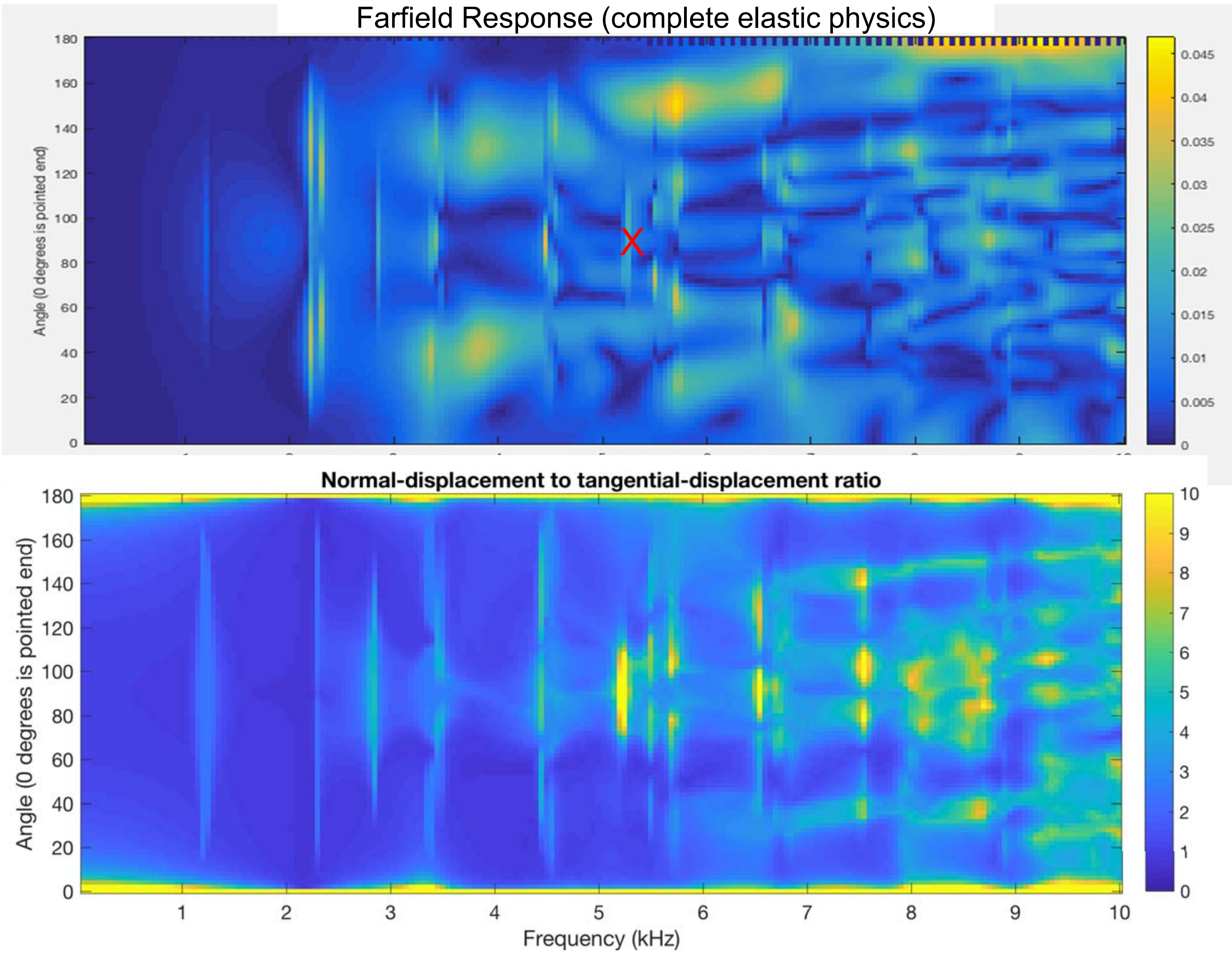




Task 6: Modeling

Normal Displacement: Regions of Isolation

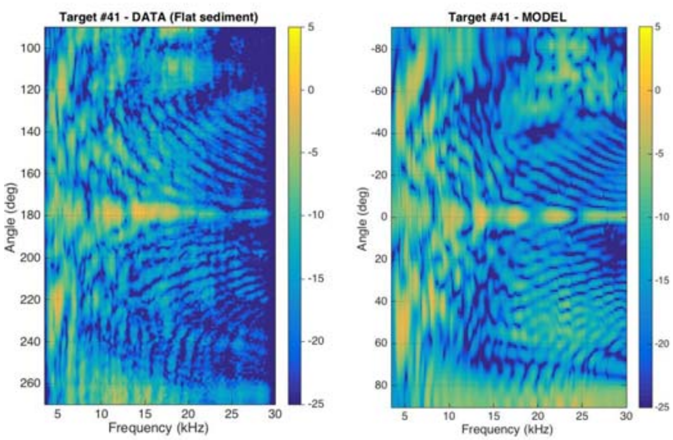


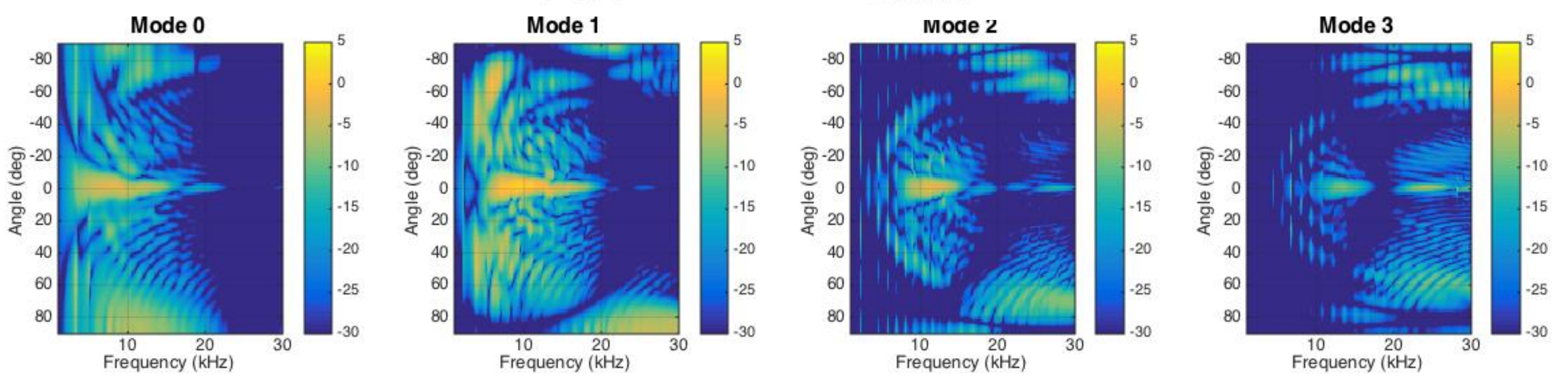
Task 6: Modeling

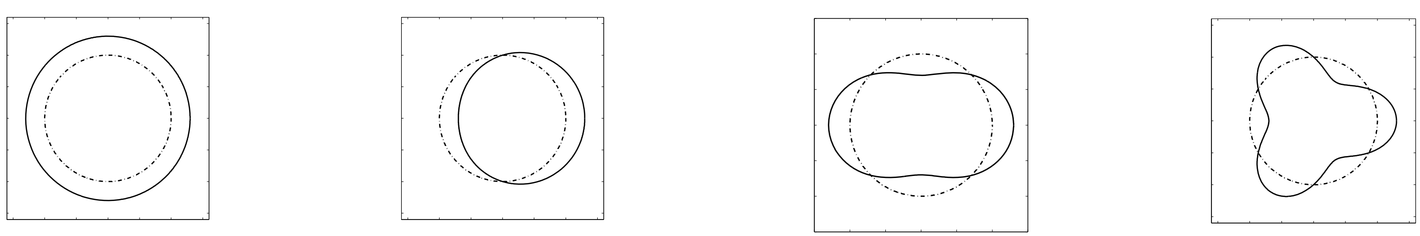
Modal Analysis

DATA MODEL

AIR-FILLED







Task 8: Classification & Analysis

- Going under the hood of current classification system to understand:
  - Patterns of errors and opportunities for improvement
  - Value added through “naïve” physics inclusion, to identify directions for development of feature sets
  - Sensitivity to expected sources of variation
- Understanding effects of target BOSS system on appropriate features/classification structures
  - Change in relative importance of sources of variation
  - Very different manifestation in acoustic color space
  - Incorporation of imaging (i.e. orientation) would allow for very different classification structures

Transition Plan

- Improvements made to feature extraction and classifier architecture will be incorporated into the Operations/Classification Package in MR-2505, and ultimately into the MR-2501 Tow Body Package.

- As feature sets are developed, we will predict the effects of environment on these features and make the results available for performance estimation of systems other than those being developed at UW-APL.

- Any training and testing data sets generated within this effort, specifically utilizing any physics decomposition approaches, will be made available to the DoD community upon request.

Transition Plan: Five Year Vision

MR-2231

FY12-15
- TREX13 (sand) & BAYEX14 (mud)
- Validated models, HF+LF classifiers

MR-2649 (This Project)

Year 1
- Physics decomposition modeling
- Physics-based feature representation & robustness analysis
- Target manufacture

HERE

Year 2
- Continue modeling and feature representation
- Test on rail and tow-body data

Year 3
- Improve signal processing, feature extraction and classifier design
- Performance prediction
- Guidance on interrogation scenarios

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Year 1
- Develop classification algorithms
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MR-2501 Tow Body Package

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- Towbody construction
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Year 2
- Engineering Test (Puget Sound)
- Test internal sensors/hardware
- Test operational protocol

Years 4,5
- Field demonstration of towbody with classification package (Sequim Bay)

Issues

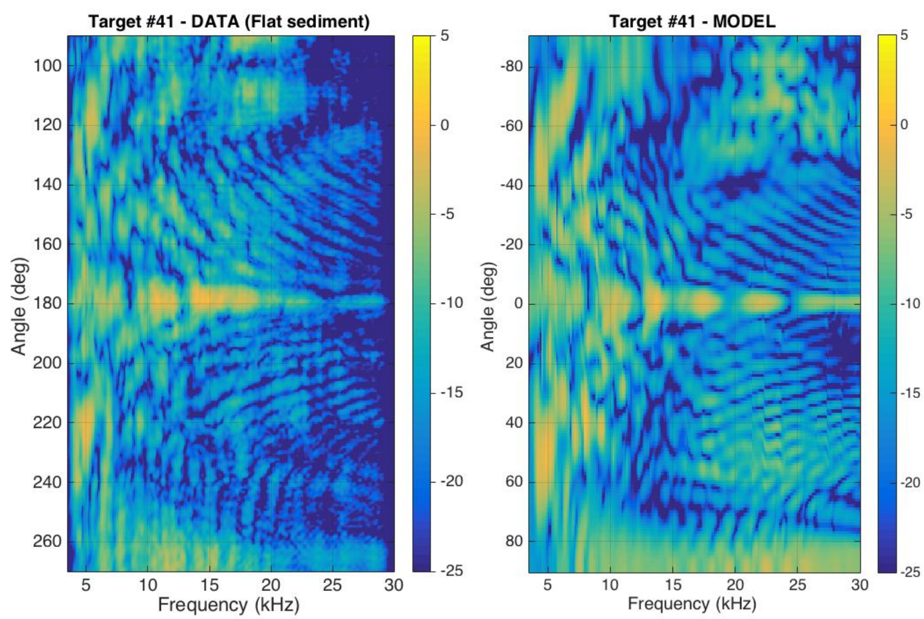
- Move to full-3D modeling for most of the constraints has resulted in a decision to delay the schedule by three months. This is a best-guess of the amount of extra time required.

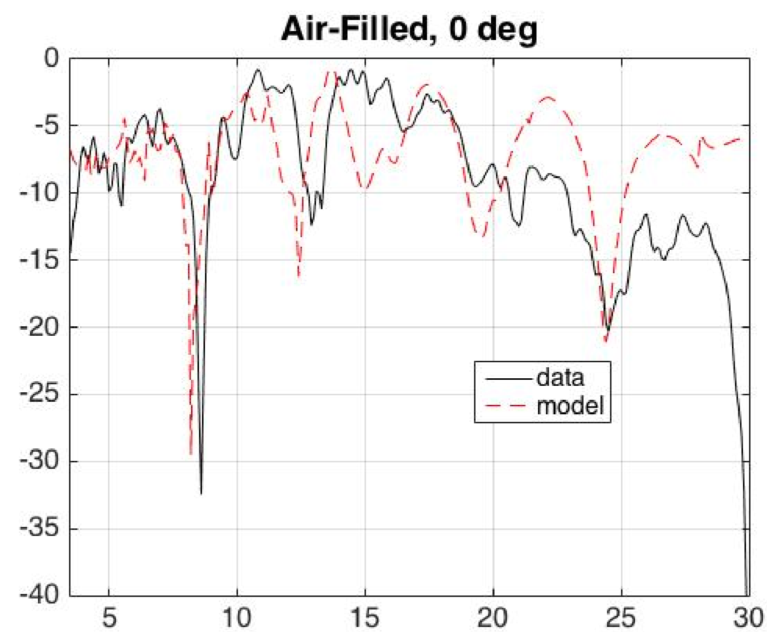
BACKUP MATERIAL

Task 4: Sea Trials
Model/Data Comparison

Air-Filled Shell, 15m range, flat sediment

DATA MODEL



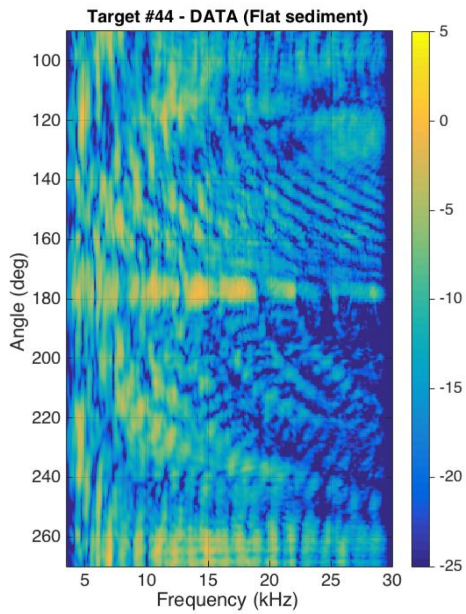


Task 4: Sea Trials

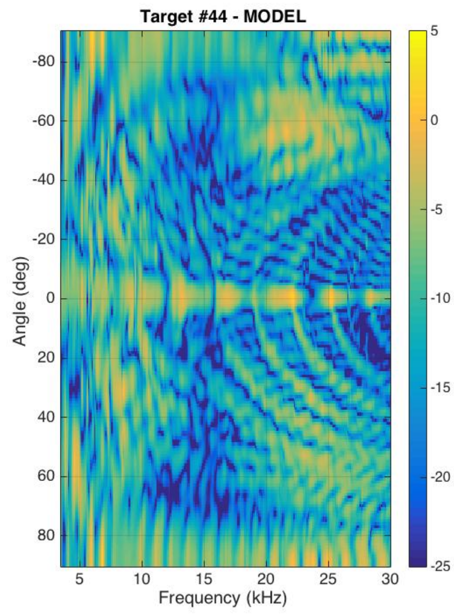
Model/Data Comparison

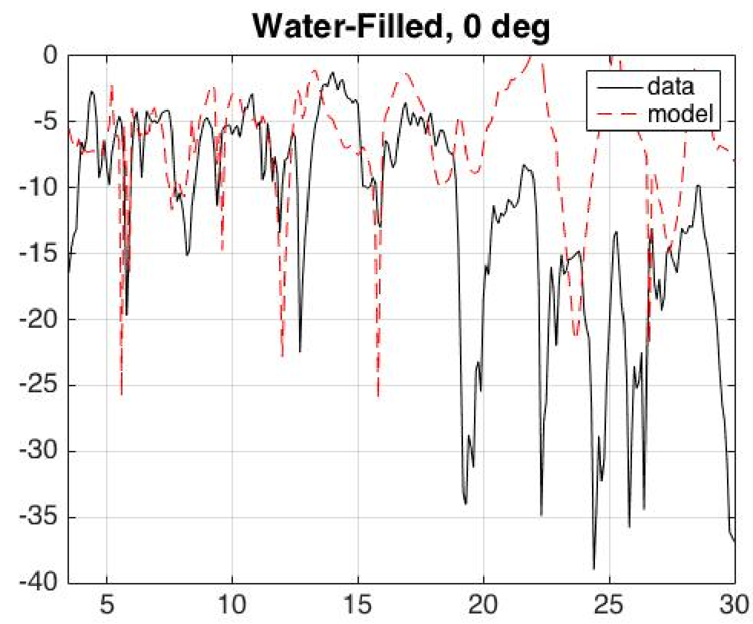
Water-Filled Shell, 15m range, flat sediment

DATA



MODEL





COMSOL Customization: Elasticity Modification

- In the "complete" physics model, the basic physical properties that define the solid mechanics are
  - ♦ isotropic (the material reacts the same regardless of orientation)
  - ♦ defined by the observed behavior of the material through:
    - Density
    - Young's modulus (tensile stress / extensional strain)
    - Poisson's ratio (transverse strain / axial strain)
- By re-defining the material as orthotropic, we can control the material properties along different dimensions separately, for example to simultaneously
  - ♦ allow normal physics in one direction
  - ♦ restrict bending and/or compression in other directions

COMSOL Customization: Elasticity Modification

- In isotropic materials, the material properties that define stress and strain relationships are independent of orientation
  - ⎨ : Poisson's ratio (signed ratio of transverse strain to resulting axial strain)
  - E: Young's modulus (ratio of axial stress to axial strain)
  - G: Shear modulus (ratio of shear stress to shear strain)
  - For isotropic materials, G=E/2/(1+⎨)
- where
  - σ: stress (force per unit area on a small region)
  - ∑: strain (displacement of particles relative to reference length)

Comsol Customization: Elasticity Modification

- We can use the orthotropic elasticity matrix specification of material properties to prevent bending or compression in certain planes or axes while retaining normal behavior in other directions

$$\begin{bmatrix} \varepsilon_{xx} \\ \varepsilon_{yy} \\ \varepsilon_{zz} \\ \varepsilon_{xy} \\ \varepsilon_{yz} \\ \varepsilon_{xz} \end{bmatrix} = \begin{bmatrix} \frac{1}{E_x} & -\frac{\nu_{yx}}{E_y} & -\frac{\nu_{zx}}{E_z} & 0 & 0 & 0 \\ -\frac{\nu_{xy}}{E_x} & \frac{1}{E_y} & -\frac{\nu_{zy}}{E_z} & 0 & 0 & 0 \\ -\frac{\nu_{xz}}{E_x} & -\frac{\nu_{yz}}{E_y} & \frac{1}{E_z} & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{G_{xy}} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{G_{yz}} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1}{G_{xz}} \end{bmatrix} \begin{bmatrix} \sigma_{xx} \\ \sigma_{yy} \\ \sigma_{zz} \\ \sigma_{xy} \\ \sigma_{yz} \\ \sigma_{xz} \end{bmatrix}$$

COMSOL Customization: Spring Foundation

- Allows for a less restrictive version of prescribed displacement constraints
  - Some movement may be necessary for energy transfer
  - Deviations from idealized concepts can be incorporated
- Basic idea like an actual spring: force exerted on object in opposition to displacement from spring base, but…
  - Spring “base” is in the “ether” at 0 displacement
  - Can be defined volumetrically, so acts on every particle
  - Supports non-isotropic springs; i.e. can restrict x-movement but leave y-movement free
  - Nonlinear springs allow for, for example, no resistance to small movement

Details: Hybrid 2D FE/Propagation Model

- This hybrid technique can be used for axisymmetric objects (note: deployment of object within the global operational geometry ***does not*** have to be axisymmetric).
- Incident field is decomposed numerically on the target surface via FFT
- 3-D result is built up from multiple 2-D finite element (FE) calculations performed using COMSOL
- Pressure and derivatives are sampled along a cylindrical surface surrounding the UXO, indicated by the dashed line (drawing not to scale).
- These sampled pressure and derivatives are propagated from the sampling surface to the desired observation point using the discrete sum representation of the Helmholtz integral

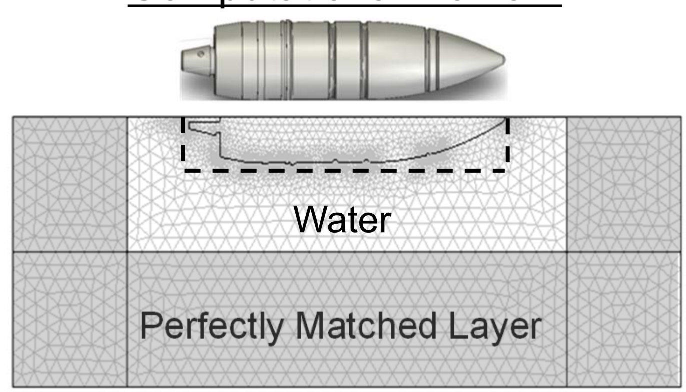
Discrete Helmholtz Integral

$$p(\vec{r}_i) = \sum_j \left(\frac{\partial G_{ij}}{\partial n_j} p_j - \frac{\partial p_j}{\partial n_j} G_{ij} \right) dA_j$$

Freefield Green Function

$$G_{ij} = \frac{\exp(-ik|\vec{r}_i - \vec{r}_j|)}{4\pi|\vec{r}_i - \vec{r}_j|}$$

Computational Domain



Details: Hybrid 2D FE/Propagation Model

- Implementation of this modeling technique requires manipulation of the Variational Equations (or weak expressions) within COMSOL.

3-D → 2-D Axisym.

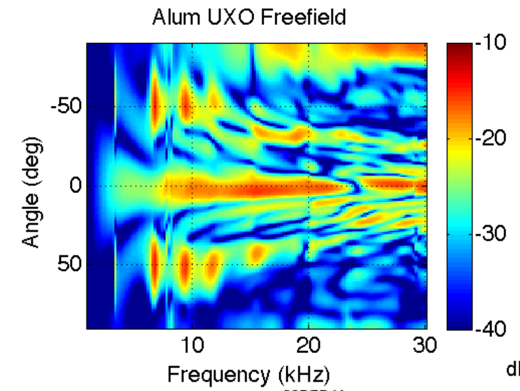
Fluid domains	$\int_{\Omega_f} \left(\nabla \cdot \left(\frac{1}{\omega^2 \rho_f} \nabla p \right) + \frac{1}{\rho_f c_f^2} p \right) \delta p \, d\Omega + \int_{\delta\Omega_f} \frac{1}{\omega^2 \rho_f} \left(\nabla p^{applied} - \nabla p \right) \cdot \mathbf{n} \, \delta p \, dS = 0$
Elastic domains	$\sum_{i,j=1}^{3} \int_{\Omega_S} \left(-\omega^2 \rho_S \, u_i \, \delta u_i + \sigma_{ij} \delta \epsilon_{ij} \right) d\Omega - \int_{\delta\Omega_S} \mathbf{t} \cdot \delta \mathbf{u} \, dS = 0$
Apply azimuthal decomposition, followed by explicit integration over theta $\int_0^{2\pi} d\theta$	$\begin{pmatrix} p(r,\theta,z) \\ u(r,\theta,z) \\ v(r,\theta,z) \\ w(r,\theta,z) \end{pmatrix} = \sum_{m=-\infty}^{\infty} \begin{pmatrix} p_m(r,z) \\ u_m(r,z) \\ v_m(r,z) \\ w_m(r,z) \end{pmatrix} exp(im\theta)$

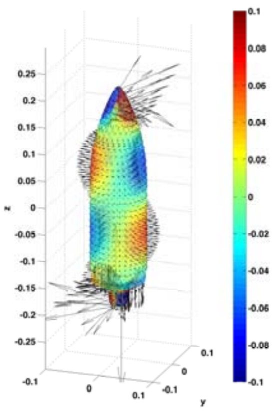
- As additional Physics-Based Component Isolation techniques are developed, these manipulations to the weak expressions will need to be updated.
- Full 3D FE models will help inform and validate these updates.

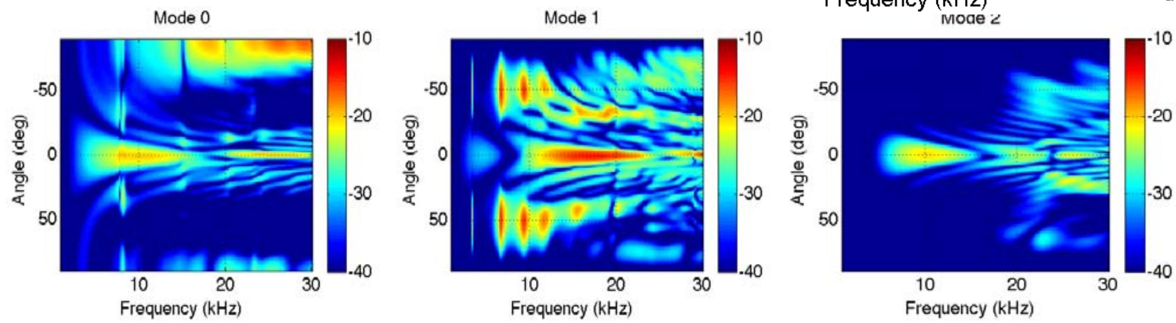
2-D/3-D Decomposition

- Full response is complicated and difficult to interpret

- Isolating individual components based on physics may aid in the design of better feature sets







- Goal is to identify robust, physics-based features (example below shows full response of UXO as a function of burial depth)