Applications of the Coupled-Finite/Boundary Element (CFEBE) Technique to Support the UXO Remediation System

Project number: MR21-C1-1275

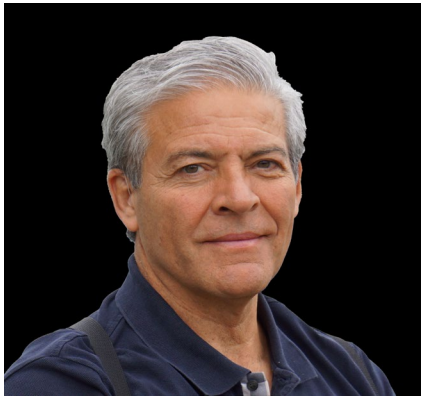
Principal Investigator: Dr. Ahmad T. Abawi

Organization: HLS Research

Final Debrief

January 13, 2026

Project Team



Ahmad T. Abawi
HLS Research

Prof. Petr Krysl
UCSD

Bottom Line Up Front

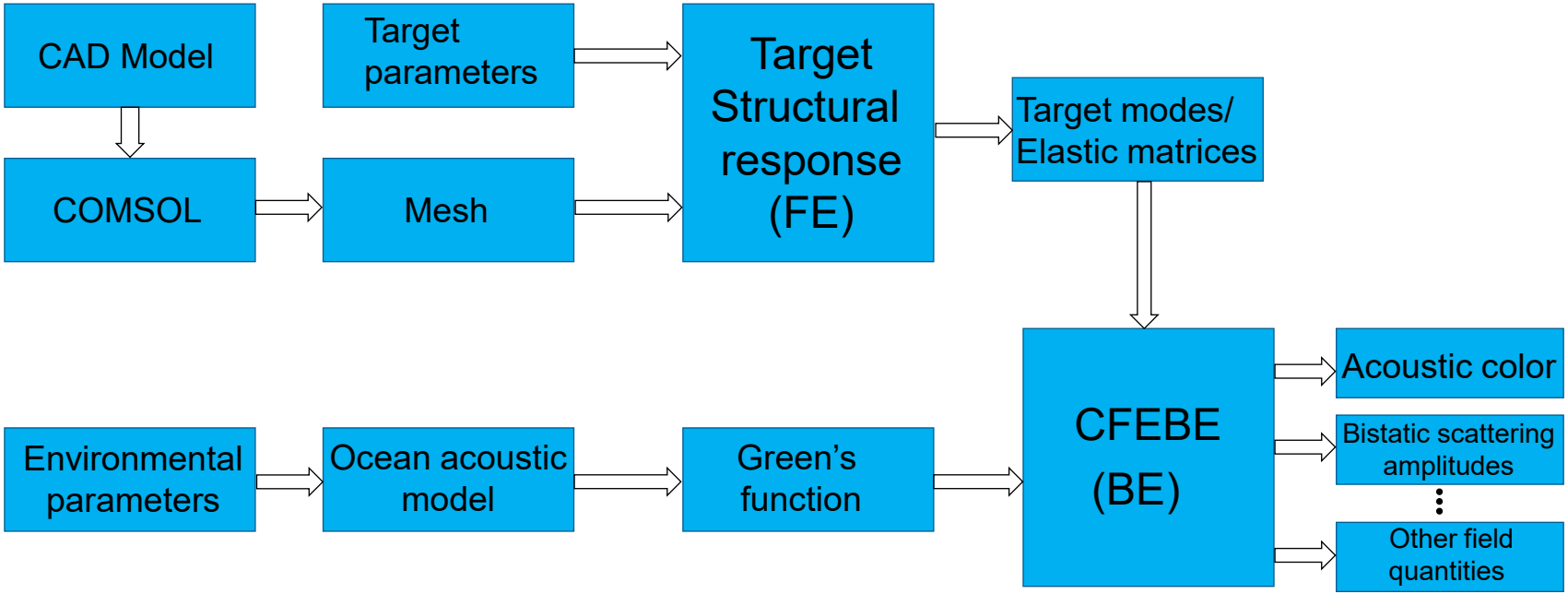
- Continued the computation of bi-static scattering amplitudes for all available UXO targets and delivered data to APL-UW
- Implemented a finite element clustering technique that makes computing scattering from larger targets possible
- The project is at the end of its 4th year (with one-year NCE)

Technical Objective

- The primary objective of this project is to compute the bistatic scattering amplitudes for general-shaped UXOs in free space
  - They are used in the TIER model to include the effects of the sediment and simulate a realistic experimental scenario
- Provide modeling support to SERDP in the physical interpretation and validation of measured data

Technical Approach: Coupled FEBE method

The process of computing bistatic scattering amplitudes



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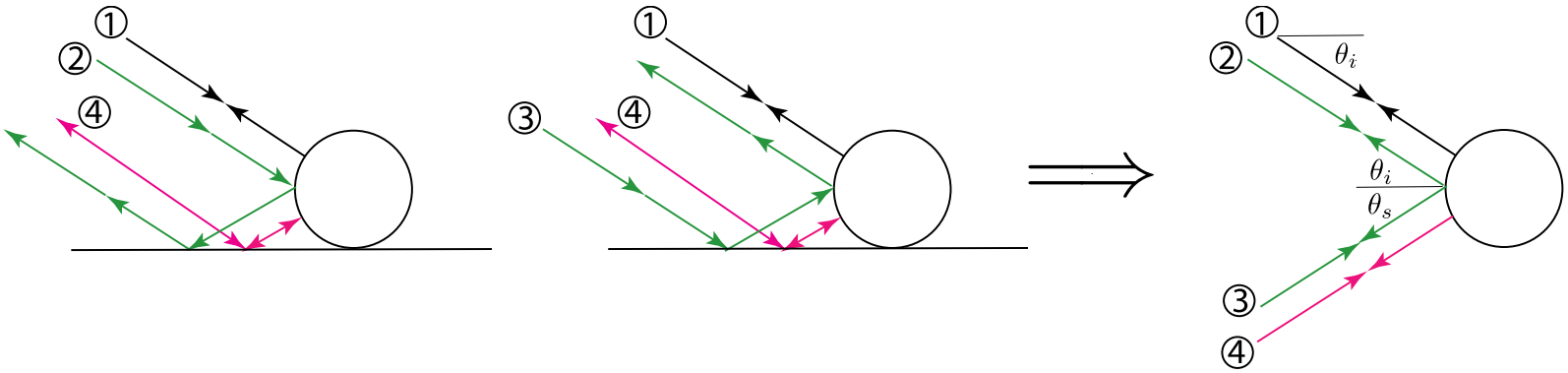
Technical Approach: The TIER model

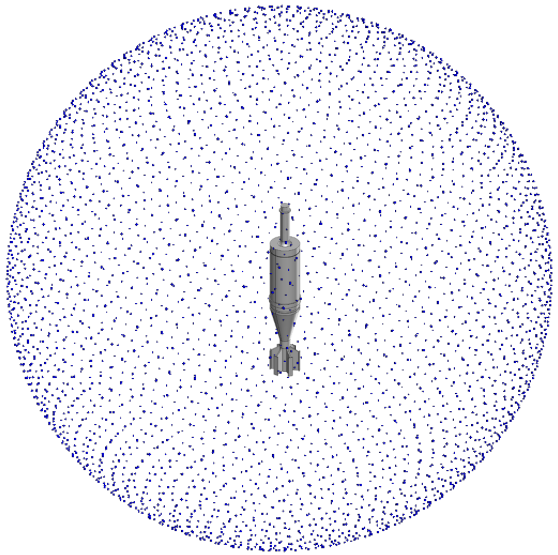
Modeling of scattering from targets at an interface



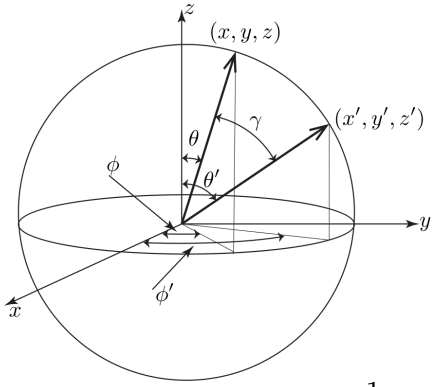
$$P_{scat}(\theta_i,\theta_s) = P(\theta_i,\theta_i)\frac{e^{2ikR_1}}{R_1^2} + 2\mathcal{R}(\theta_s)P(\theta_i,\theta_s)\frac{e^{ik(R_1+R_2)}}{R_1R_2} + \mathcal{R}^2(\theta_s)P(\theta_s,\theta_s)\frac{e^{2ikR_2}}{R_2^2}$$

Williams *et al.*, JASA 2010

Technical Approach



Golden spiral distribution



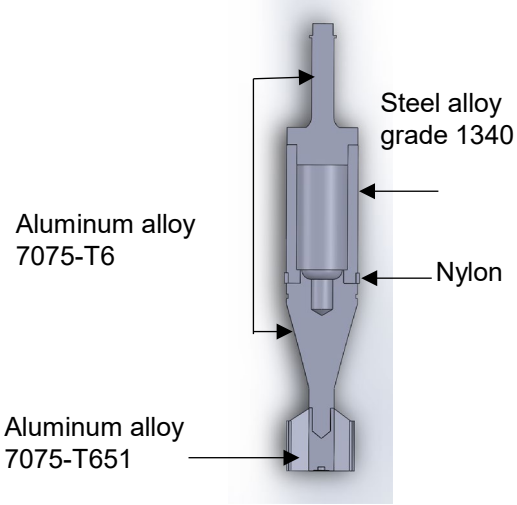
$$p(\gamma) = \frac{ik}{4\pi} \sum_{\ell=0}^{\ell_{max}} b_\ell P_\ell \left(\cos\gamma\right),$$

$$b_\ell = \frac{2\pi}{ik}(2\ell+1) \int_{-1}^{1} p(\gamma) P_\ell(\cos\gamma) d\cos\gamma.$$

To determine all 3788 b_n, that many measurements of $p(\gamma)$ are needed, i.e, number of sources

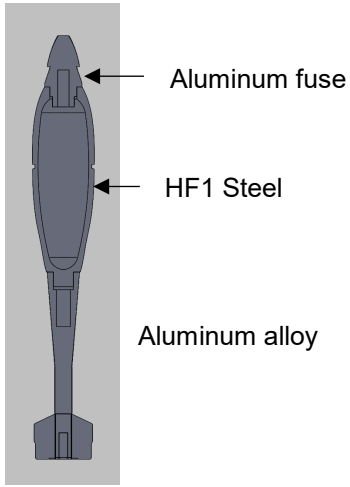
Results: Target material properties

HEAT-105 (Newer Model)
With side hole



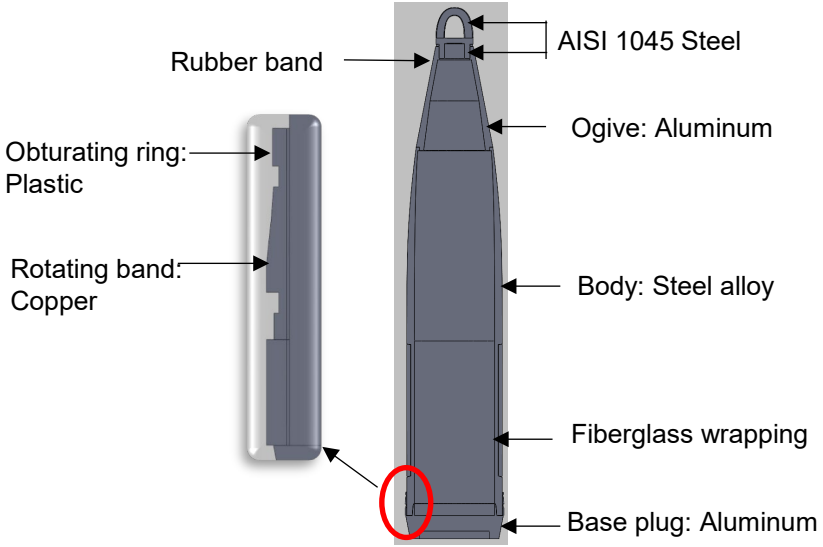
(f)

81mm-M821A-U272



(g)

155mm Howitzer M483A1



(h)

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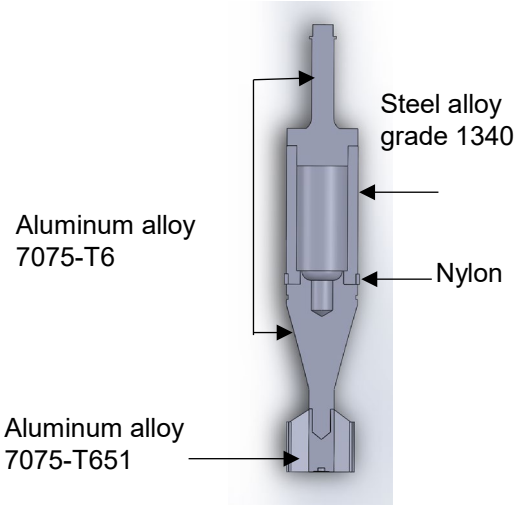
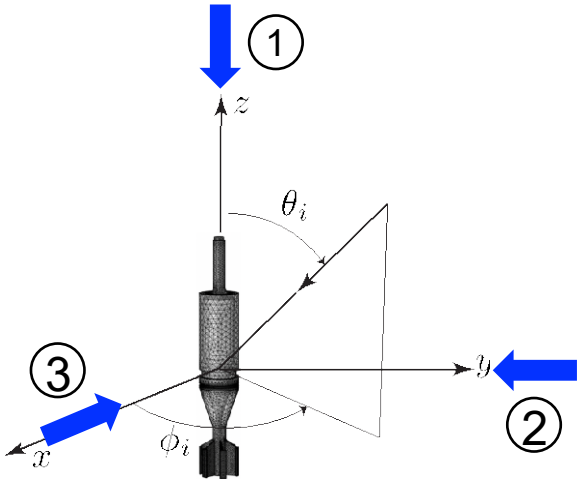
Results: The HEAT-105 Newer Model

HEAT-105 (Newer Model)
With side hole

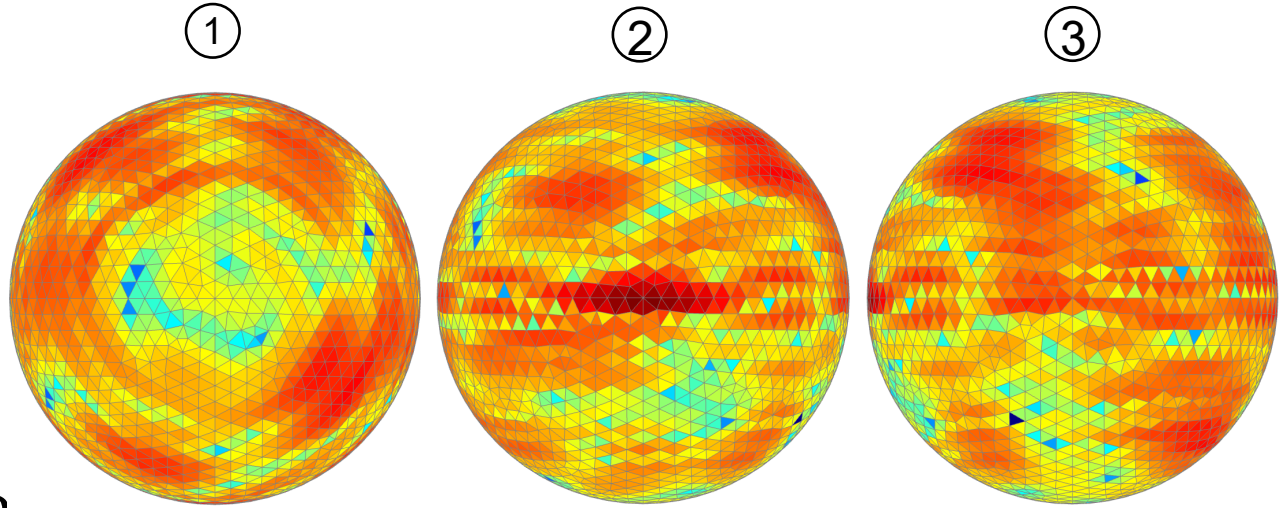


Results

Generation of bistatic scattering amplitudes on the surface of 10-m sphere



$$\phi_i = \pi/2, \theta_i = \pi/2$$



F=30 kHz

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Results: Time-domain acoustic color

- Project the diagonal values of the (4000x4000) pressure matrix onto the surface of a 1-m sphere (source/receiver collocated)
- This results in 4000 pressure values for every frequency
- Fourier transform and take its maximum

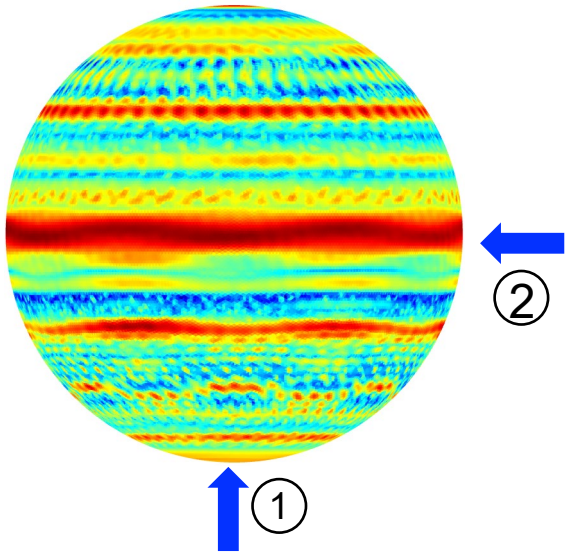
Results: Time-domain acoustic color

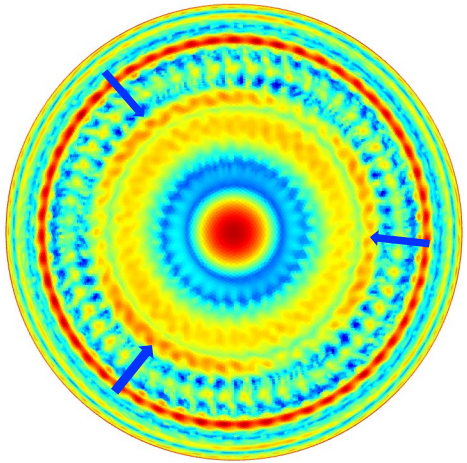
Flooded 105mm HEAT (newer model)

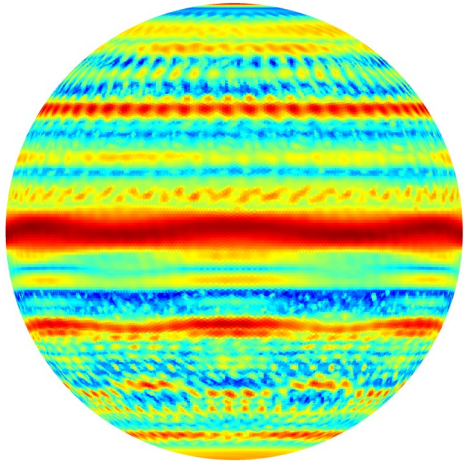
xz-plane

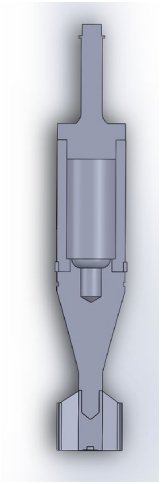
xy-plane

yz-plane









① ② ① ② $max[p(t, \mathbf{x}_i, \mathbf{x}_i)]$

SERDP

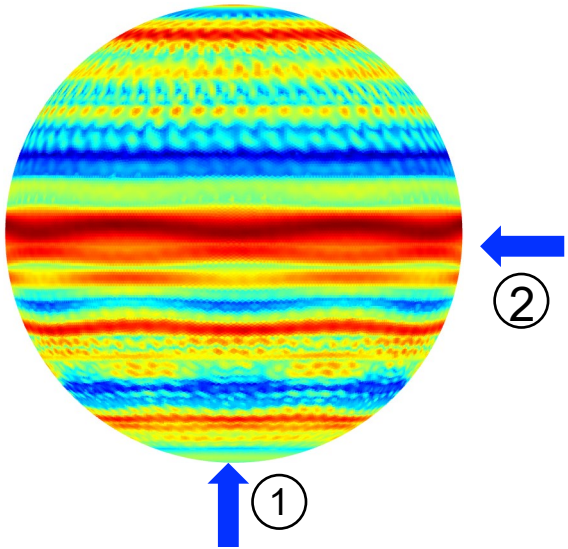
Results: Time-domain acoustic color

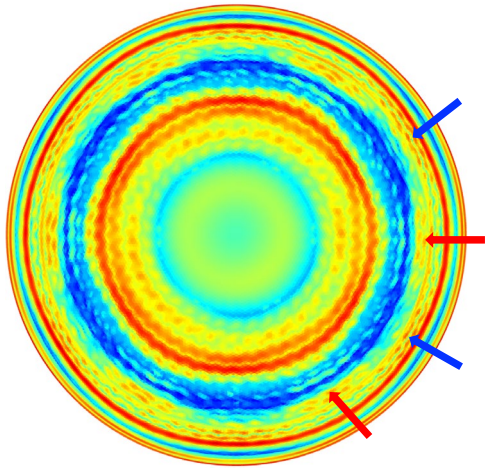
105mm HEAT (newer model)

xz-plane

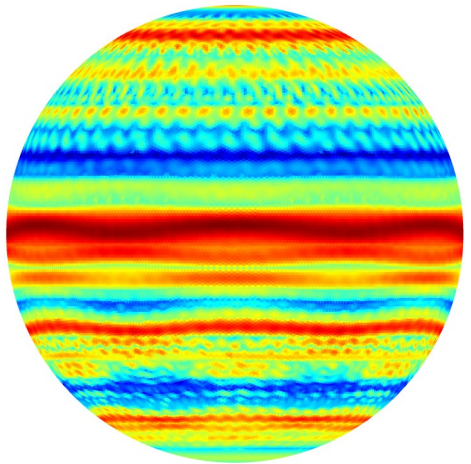
xy-plane

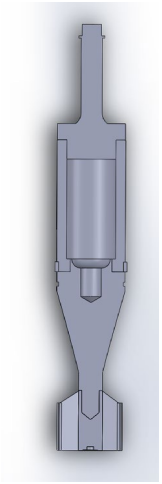
yz-plane





$max[p(t, \mathbf{x}_i, \mathbf{x}_i)]$





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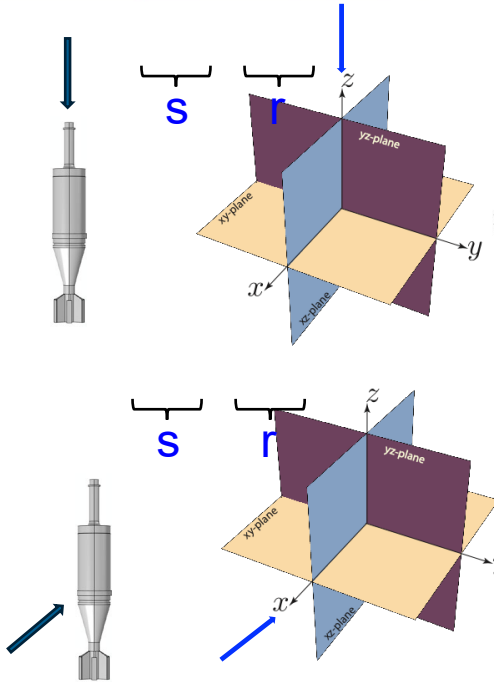
Results: Projection onto coordinate planes

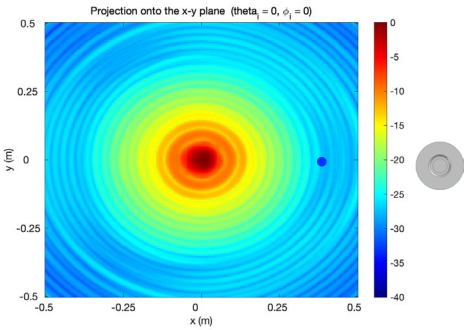
- Fix the incident field
- This results in 4000 pressure values for every frequency at every receiver
- Project onto the coordinate planes
- Fourier transform and take its maximum

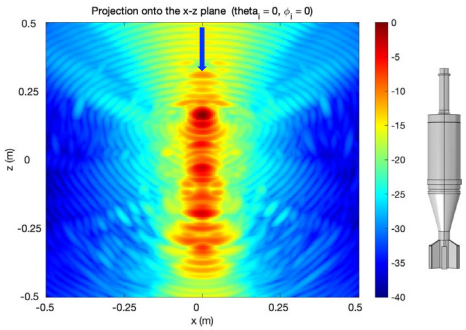
Results: Field projections onto coordinate planes

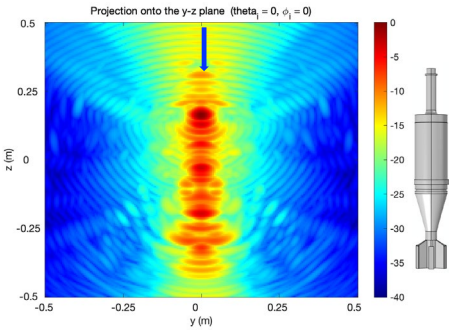
Flooded 105-mm HEAT

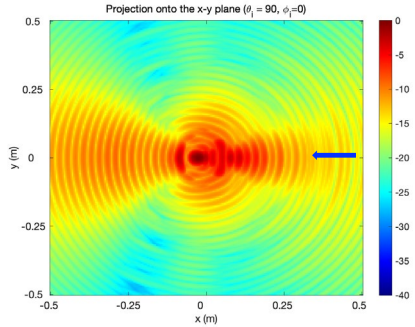


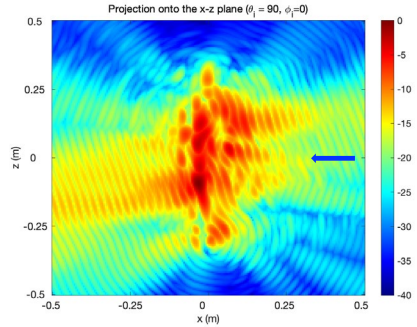
$$max[p(t,(x_{inc},y_{inc},z_{inc}),\mathbf{x}_{rcv})]$$

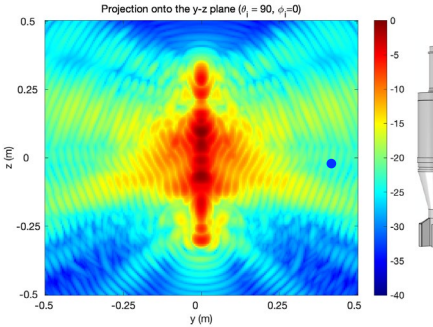












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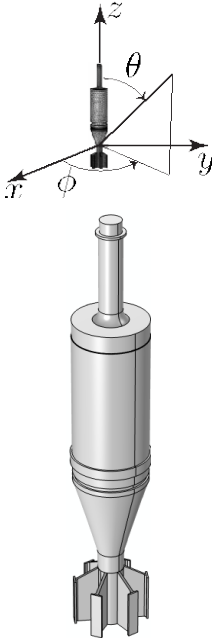
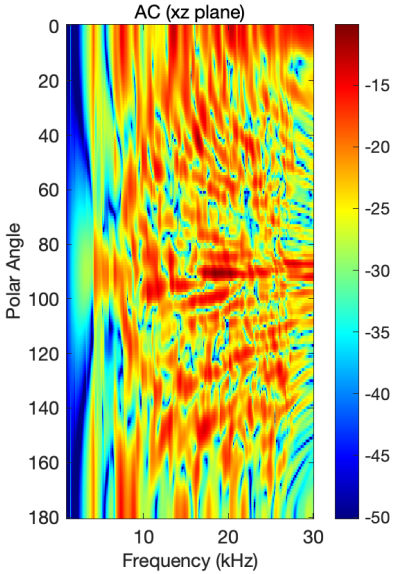
Results: Extracting AC from bistatic data

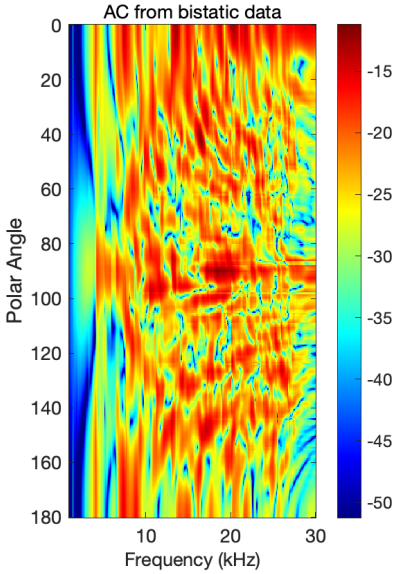
- For acoustic color source and receiver are collocated
- Crudest estimate is to choose the closest points to the red line
- A much better method is to use three closest points and estimate pressure as

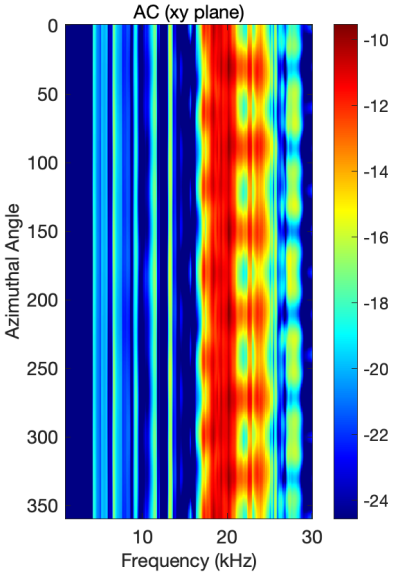
Results



Flooded 105mm HEAT (newer model)







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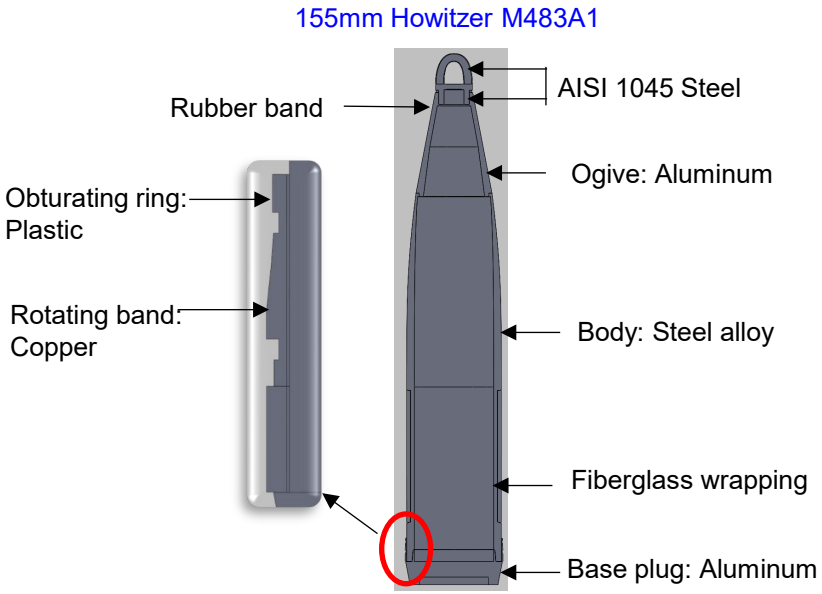
Results: 155mm Howitzer M483A1



Technical Approach:
Reduction of pressure degrees of freedom

- Suppose the original target has 100,000 panels. That is its number of degrees of freedom, = 100,000
- It can be converted to 100,000/200 = 500 clusters
- If a cubic polynomial is used to represent pressure in each cluster, = 5000; that is because a cubic polynomial has 10 coefficients in 2D
- The clustering reduces by a factor of 100,000/500 = 20
- This is huge since the cost of solving a BE problem goes as

acoustics MDPI

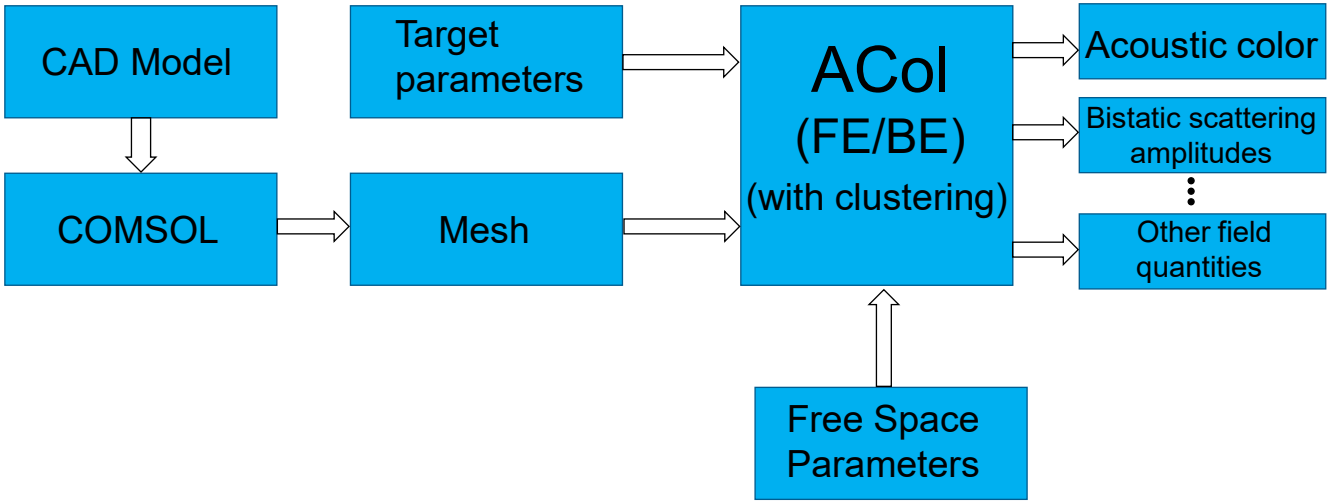
Article

Finite Element–Boundary Element Acoustic Backscattering with Model Reduction of Surface Pressure Based on Coherent Clusters

Petr Krysl [1,*] and Ahmad T. Abawi [2]

Technical Approach: The ACoI model

The process of computing bistatic scattering amplitudes



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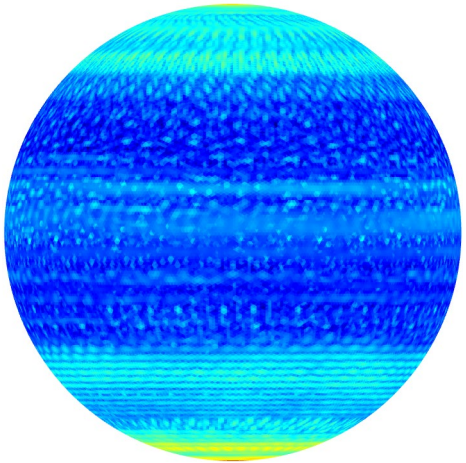
Results: Time-domain acoustic color

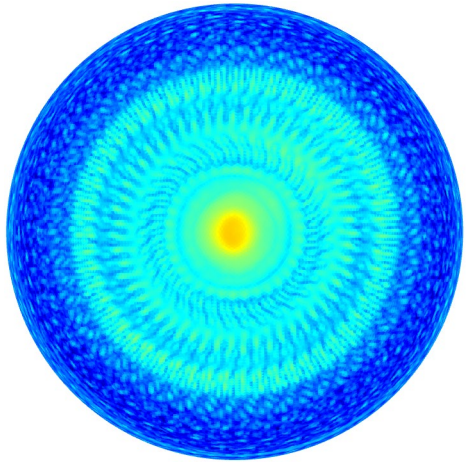
155mm-Howitzer-M483A1

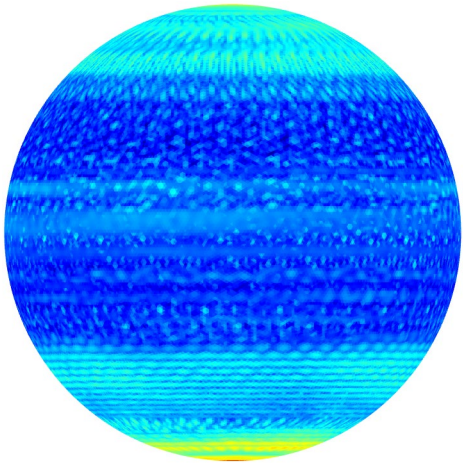
xz-plane

xy-plane

yz-plane







② ①

① $max[p(t, \mathbf{x}_i, \mathbf{x}_i)]$ ②

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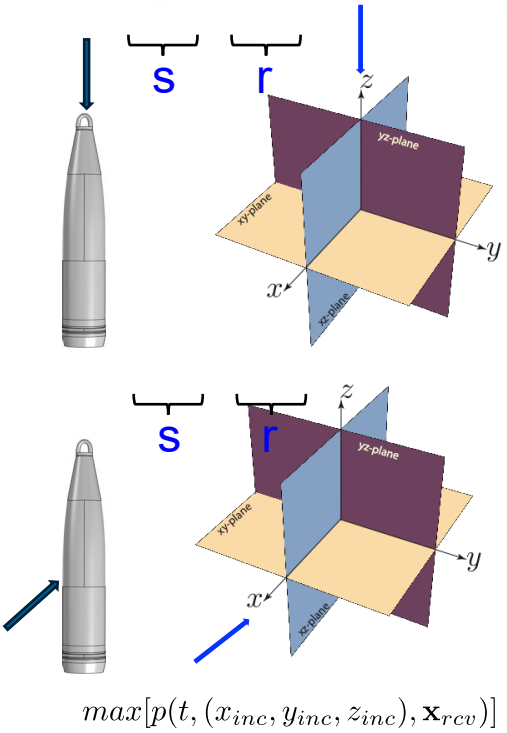
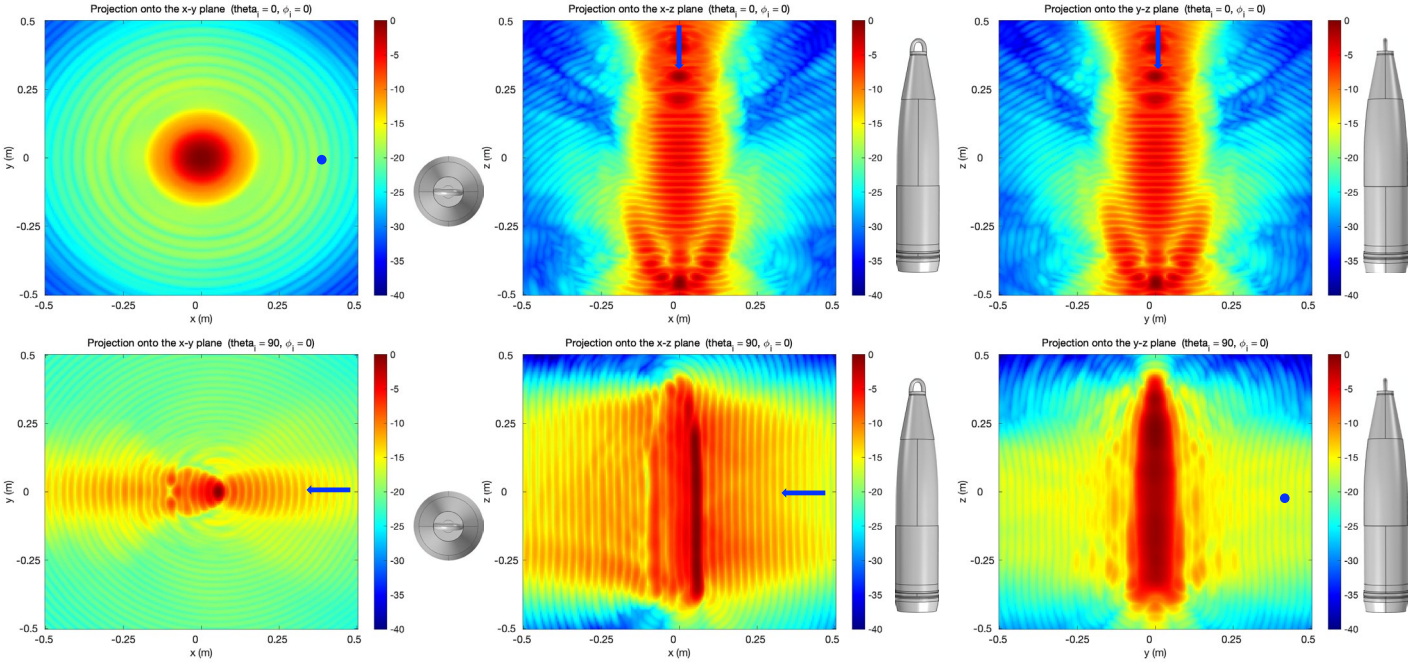
Results: Field projections onto coordinate planes



$$max[p(t,(x_{inc},y_{inc},z_{inc}),\mathbf{x}_{rcv})]$$

155mm-Howitzer-M483A1



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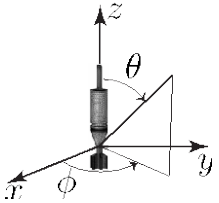
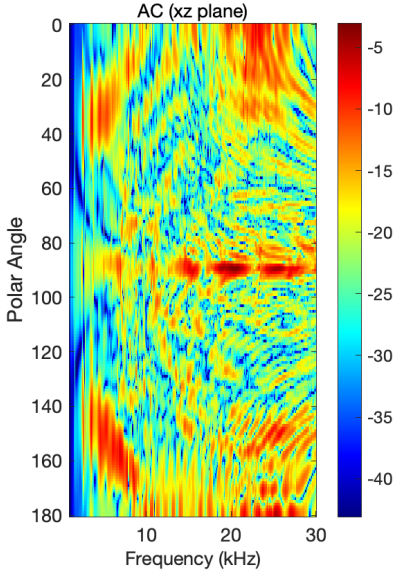
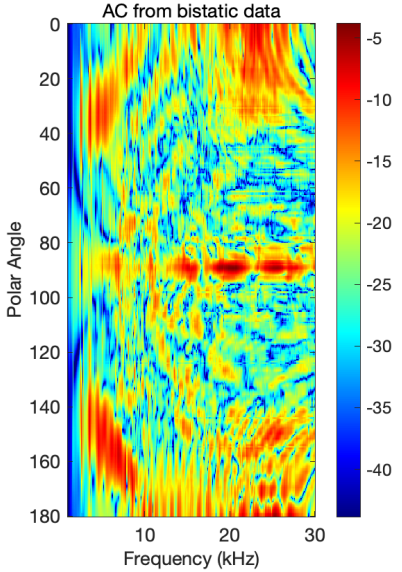
Results



155mm-Howitzer-M483A1





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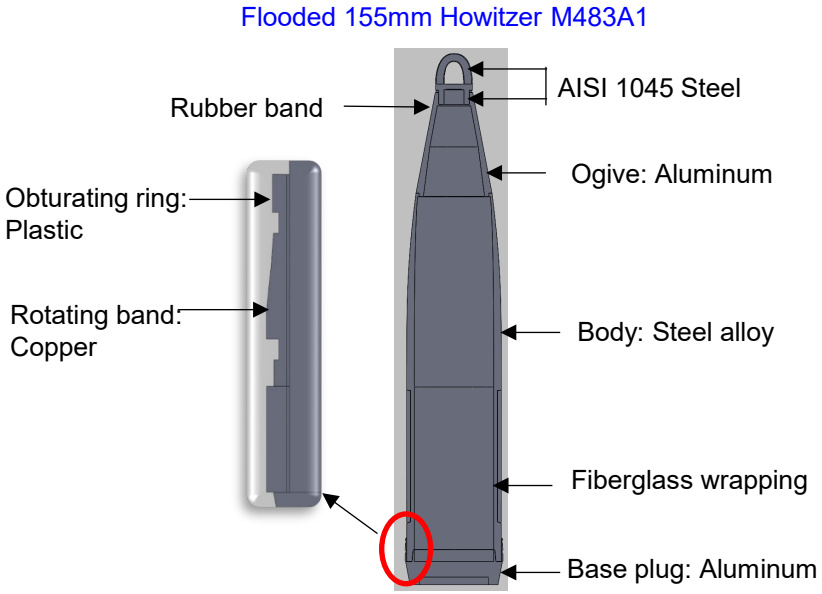
Results: 155mm Howitzer M483A1 with side hole



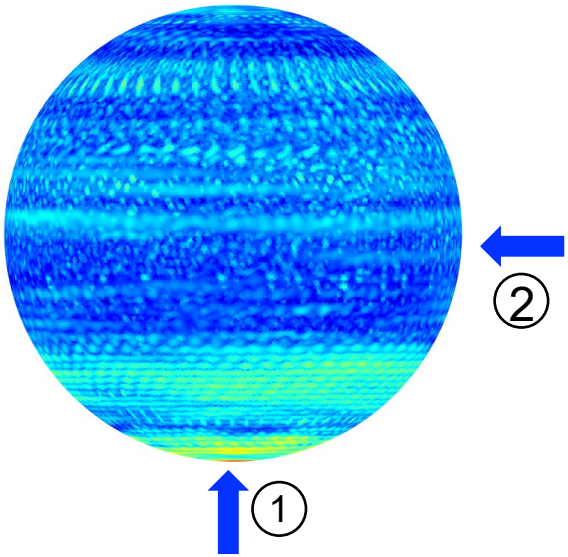
Results: Time-domain acoustic color

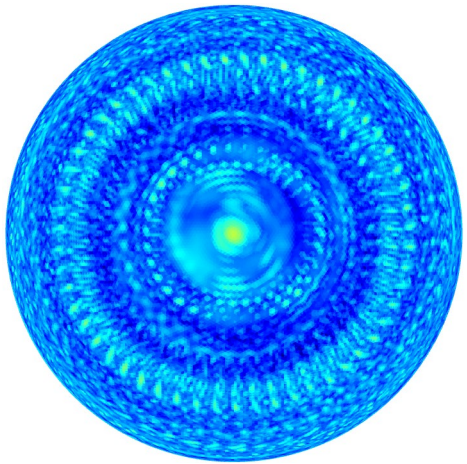
Flooded 155mm-Howitzer-M483A1

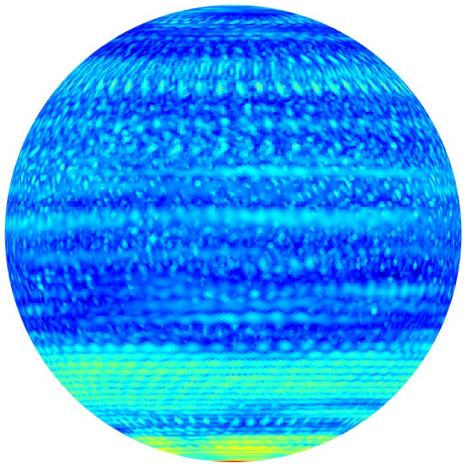
xz-plane

xy-plane

yz-plane



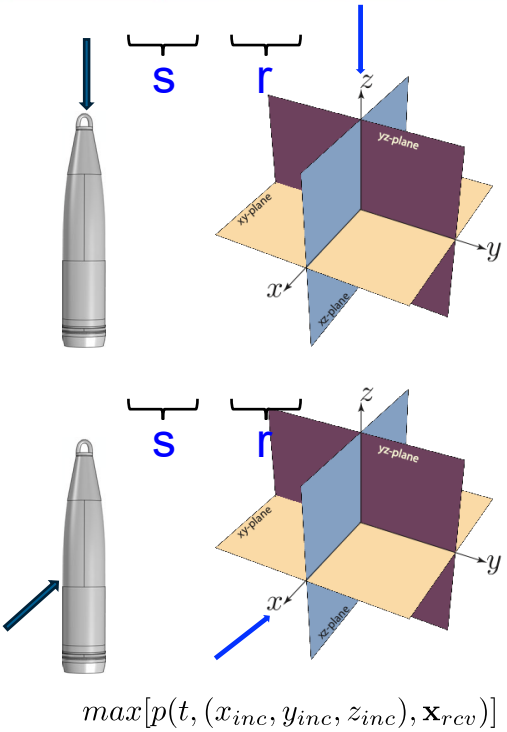




② ① ① $max[p(t, \mathbf{x}_i, \mathbf{x}_i)]$ ②

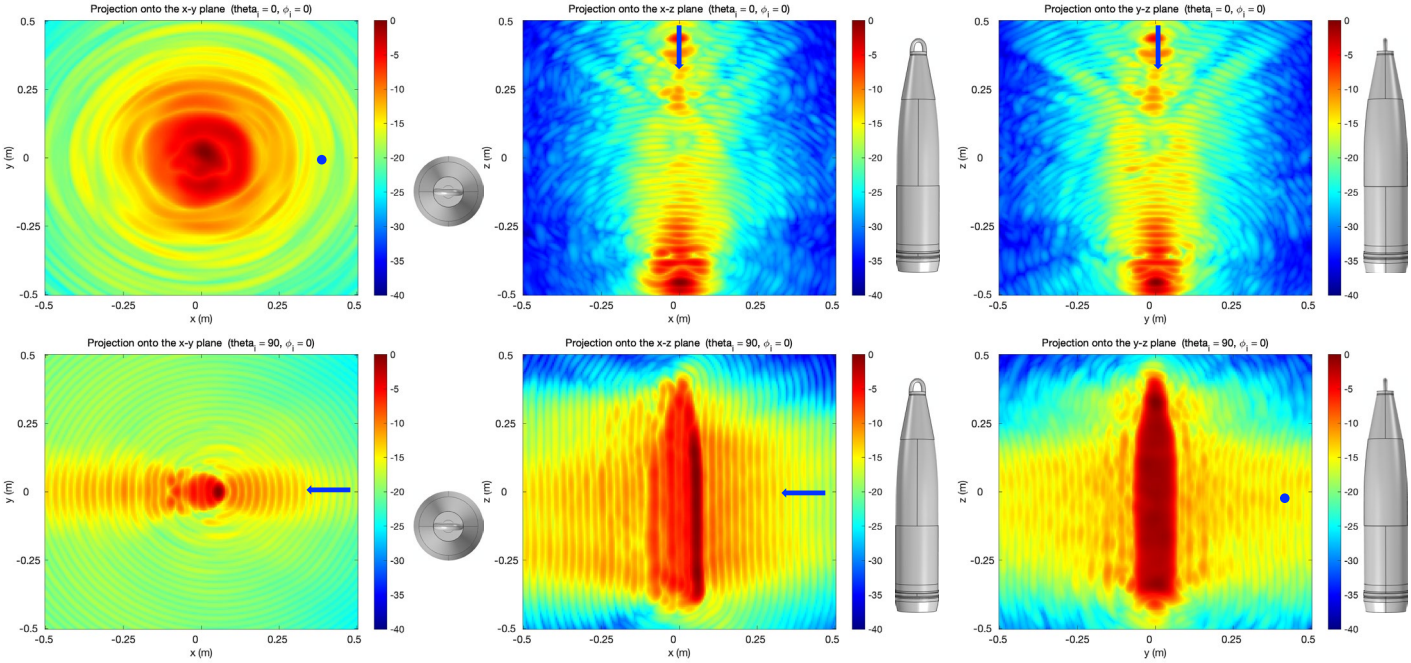
SERDP

Results: Field projections onto coordinate planes



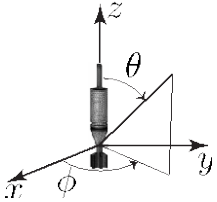
$$max[p(t,(x_{inc},y_{inc},z_{inc}),\mathbf{x}_{rcv})]$$

Flooded 155mm-Howitzer-M483A1

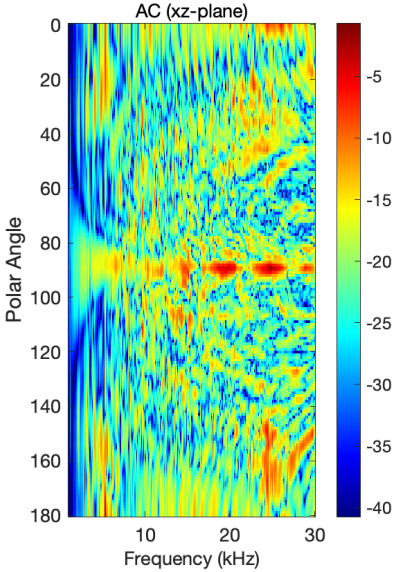


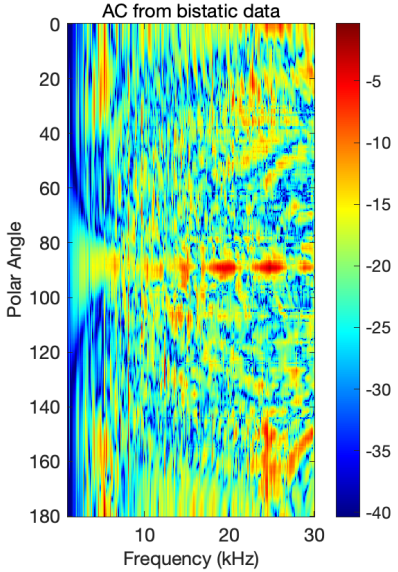
SERDP

Results



Flooded 155mm-Howitzer-M483A1

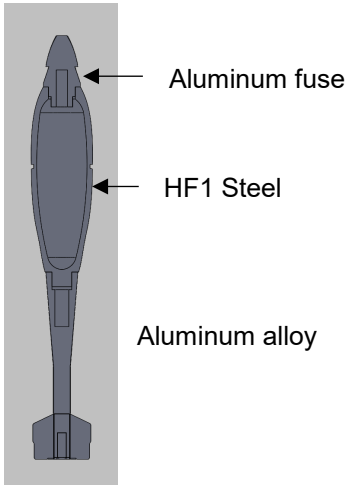




SERDP

Results: 81mm-M821A-U272

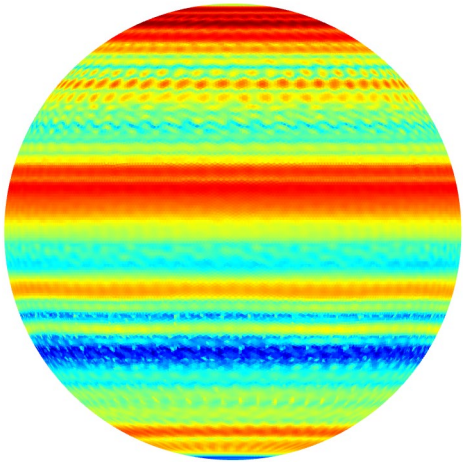
81mm-M821A-U272



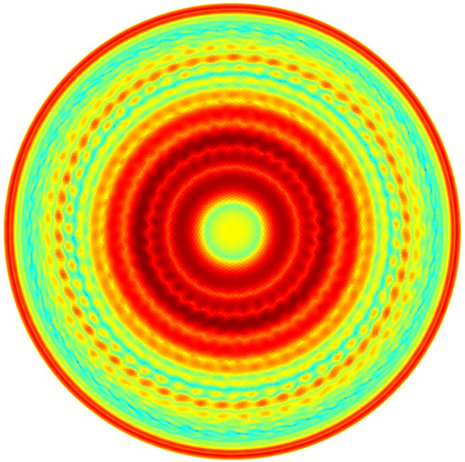
Results: Time-domain acoustic color

81mm-M281A-U272

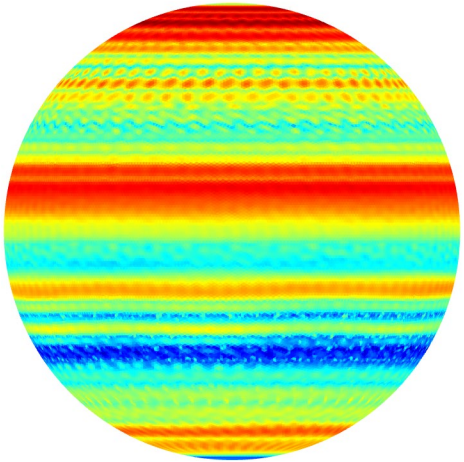
xz-plane



xy-plane



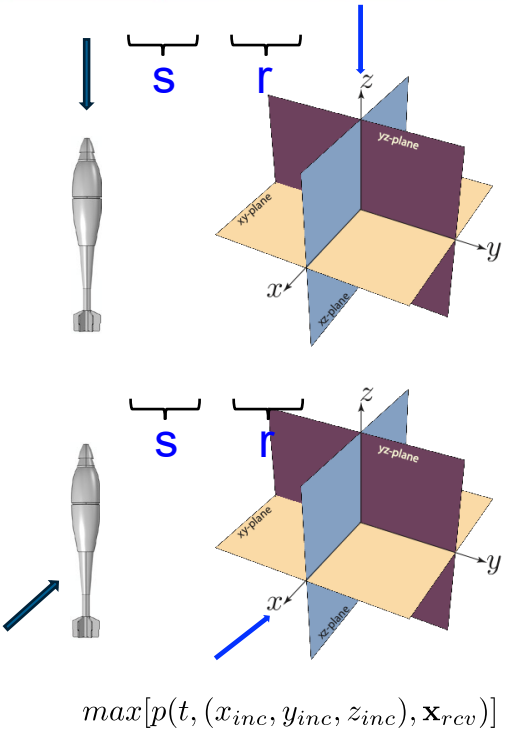
yz-plane



① ② ① $max[p(t, \mathbf{x}_i, \mathbf{x}_i)]$ ②

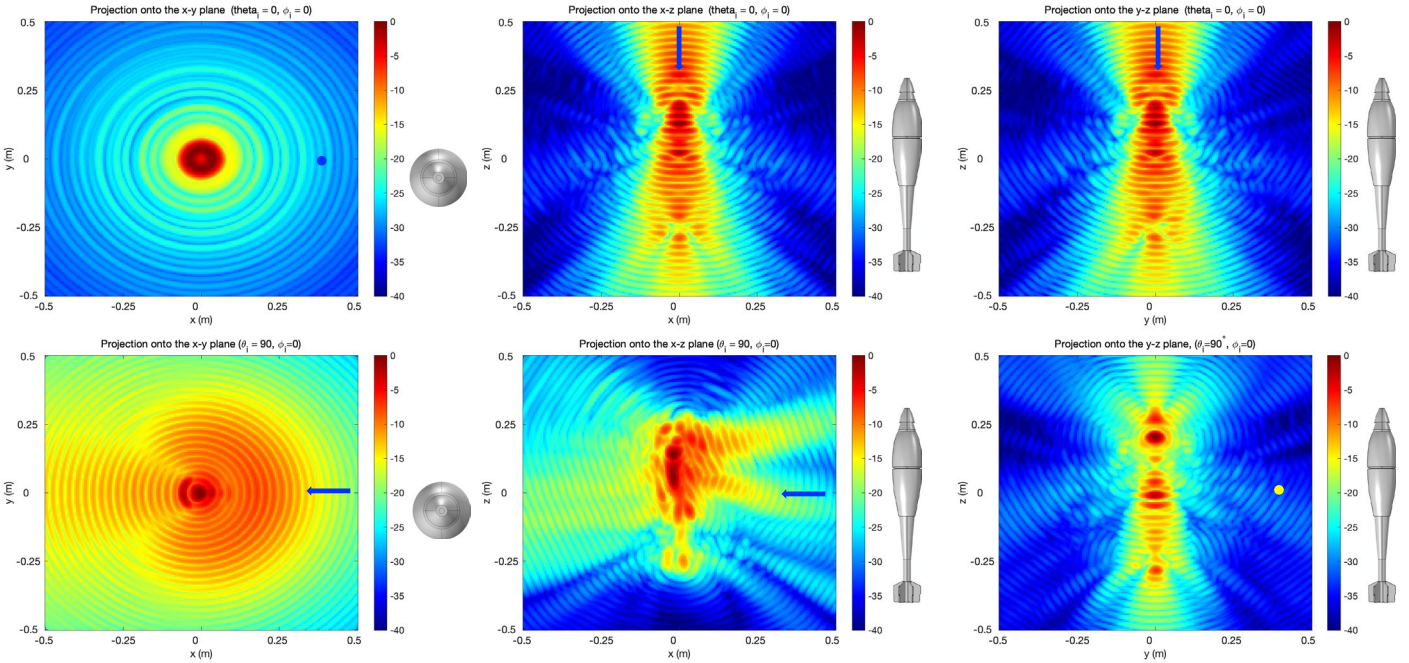
SERDP

Results: Field projections onto coordinate planes



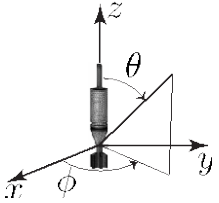
$$max[p(t,(x_{inc},y_{inc},z_{inc}),\mathbf{x}_{rcv})]$$

81mm-M281A-U272

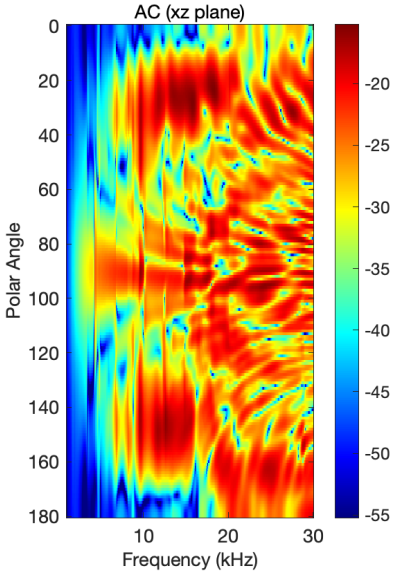


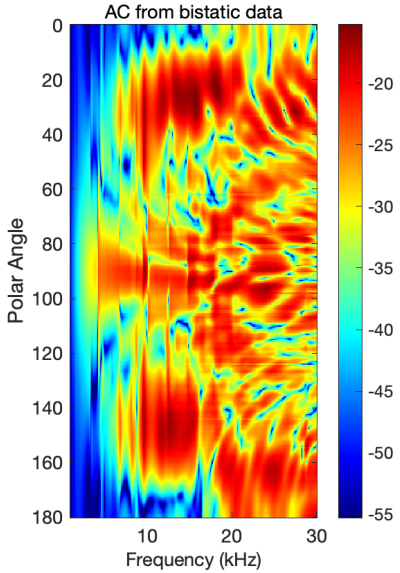
SERDP

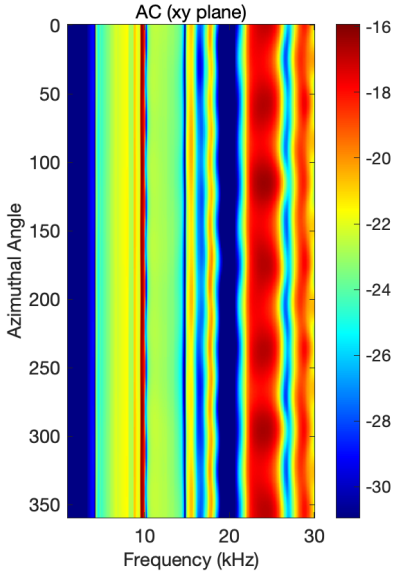
Results

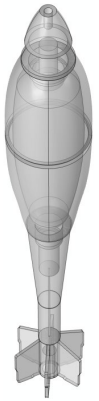


81mm-M281A-U272





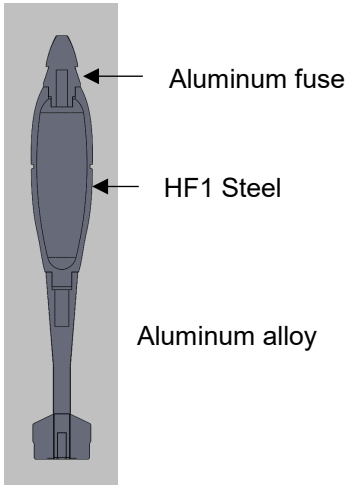




SERDP

Results: 81mm-M821A-U272 with side hole

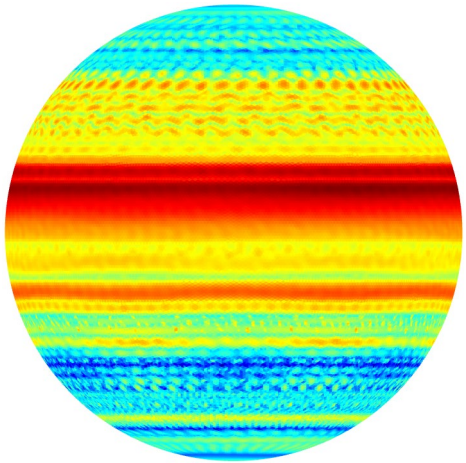
Flooded 81mm-M821A-U272



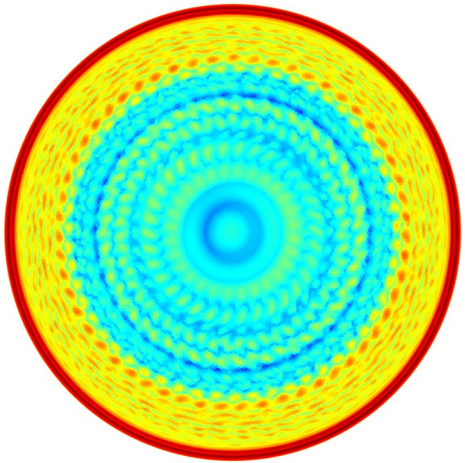
Results: Time-domain acoustic color

81mm-M281A-U272

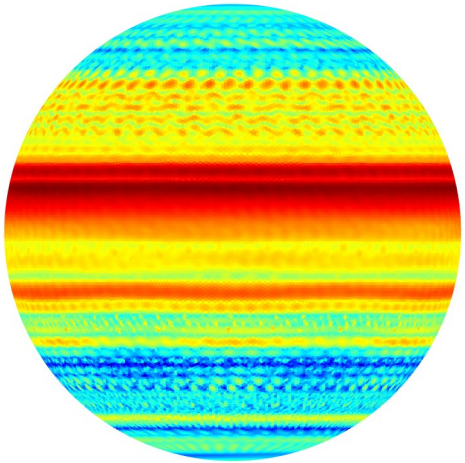
xz-plane



xy-plane



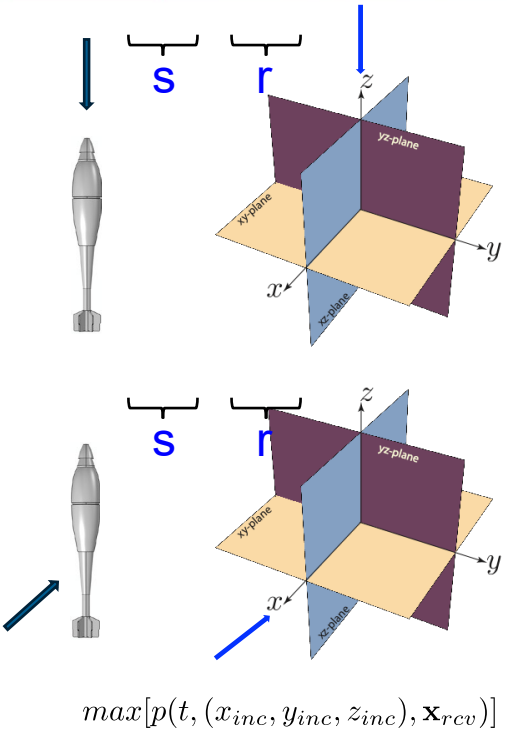
yz-plane



① ② ① $max[p(t, \mathbf{x}_i, \mathbf{x}_i)]$ ②

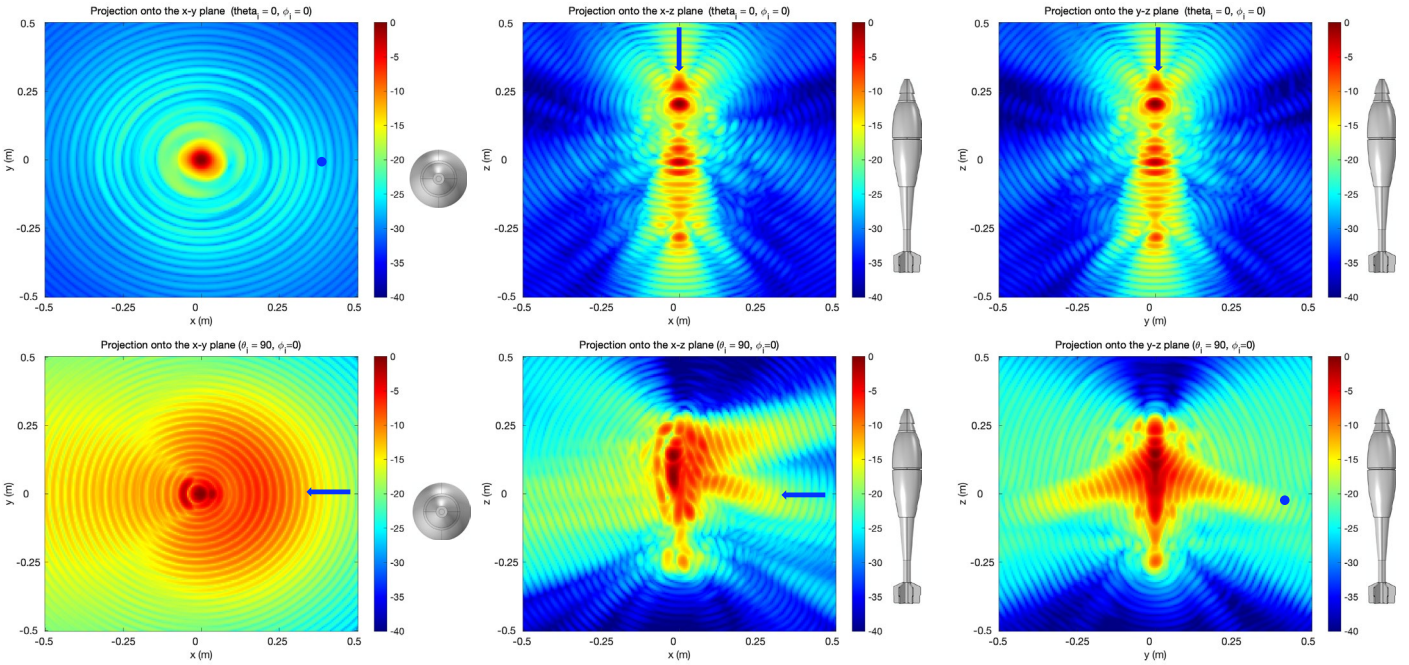
SERDP

Results: Field projections onto coordinate planes



$$max[p(t,(x_{inc},y_{inc},z_{inc}),\mathbf{x}_{rcv})]$$

Flooded 81mm-M281A-U272



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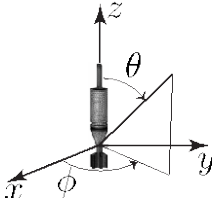
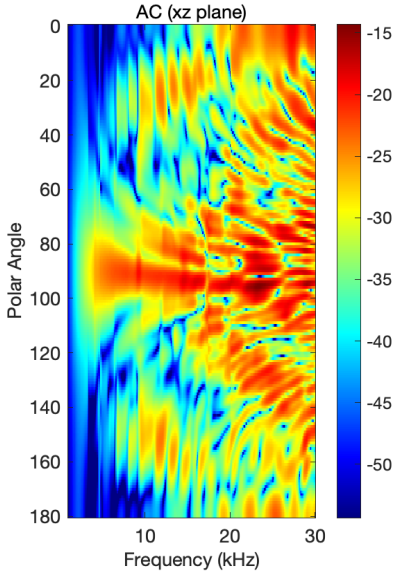
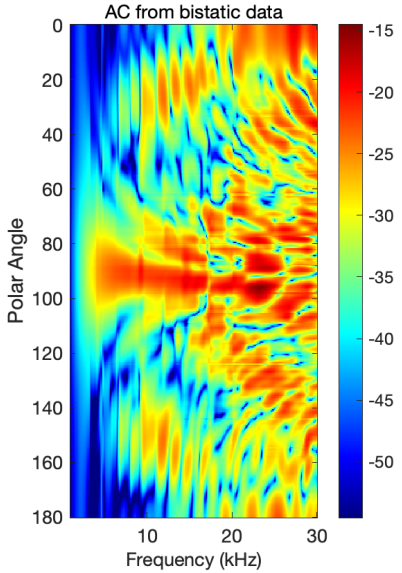
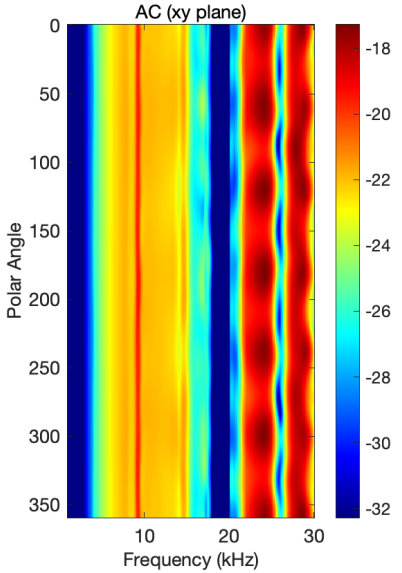
Results

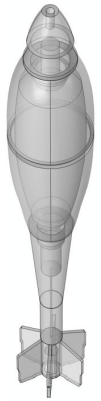
Flooded 81mm-M281A-U272











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Technology Transfer

- This technology is based on finite- and boundary-element modeling with broad applications in many areas of science and engineering, including
  - Acoustic propagation and scattering
    - MCM
    - Detection and localization of underwater scatterers
  - Fluid-structure interaction
    - Modeling of noise from wind turbines
    - Modeling the effects of turbulence on aircraft
  - Seismic propagation and scattering
    - Earthquake modeling
    - Detection and localization of underground scatterers

Backup slides

MR-21-1275: Applications of the Coupled Finite/Boundary Element (CFEBE) Technique to Support the UXO Remediation System

Performers: Ahmad T. Abawi

Technology Focus

- *Development, validation and application of computational tools to aid detection and identification of military munitions (UXOs) found in pond, lakes, rivers, estuaries and coastal ocean areas*

Research Objectives

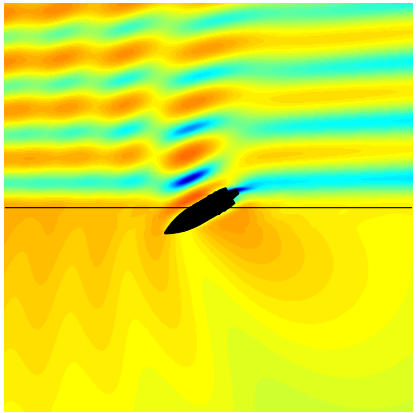
- *Generate bistatic scattering amplitudes for non-axially symmetric targets*
- *Provide modeling support*

Project Progress and Results

- *Modeled and computed bistatic scattering amplitudes for three complex-structured targets*
- *Modeling of more targets is in progress*
- *Implemented algorithmic improvements to substantially reduce computation time and/or model large targets*

Technology Transition

- *This technology has direct application in MCM and ASW. It also has applications in industry ranging from modeling noise generated from wind turbines to detecting and localizing oil reservoirs*



Plain Language Summary

- Produced high fidelity data for acoustic scattering from UXOs in free space for many UXOs
- These data are being used in the TIER model to include the effects of the sidemen and simulate an experimental scenario
- The expected outcome is to help develop the technology to train classifiers using simulated data for automatic detection and classification of UXOs

Impact to DoD Mission

- The most impactful development is that our modeling technique has gotten accurate enough that it can produce simulated data almost to same accuracy as measured data

- Thus, this capability can reduce the need for conducting experiments and save time and money

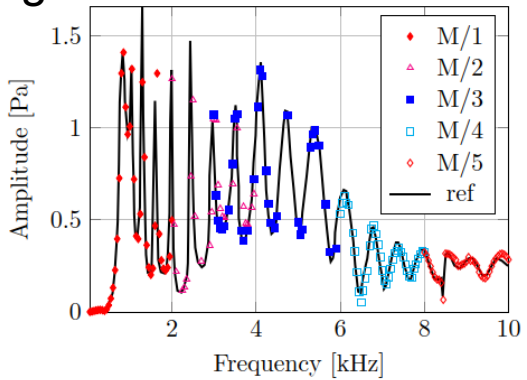
- Our project is advancing DoD capabilities by offering a cheaper alternative in developing technologies that will eventually be used for automatic detection and classification of UXOs

Publications

- Provide a list of all publications, patents, awards, etc. resulting from this work.

Technical Approach:
Example: Hollow aluminum shell

Range covered with five reduced models



Highest frequencies: very large model

Model	1	2	3	4	5
Frequency range	50–2k	2k–4k	3k–6k	6k–8k	8k–10k
Mean elem. size	0.02	0.015	0.01	0.01	0.009
# modes	200	500	600	700	800
# panels	19,068	33,542	75,458	75,458	92,504
# clusters	95	168	377	377	463
# gen. surf. dofs	1995	3528	7917	7917	9723
# gen. int. dofs	70	123	278	278	342

- Full model: machine overwhelmed (not enough memory)
- Reduced model: runs (much reduced memory) and runs an order of magnitude faster because the number of degrees of freedom reduced ~10 times.

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Article

Finite Element–Boundary Element Acoustic Backscattering with Model Reduction of Surface Pressure Based on Coherent Clusters

Petr Krysl [1,*] and Ahmad T. Abawi [2]

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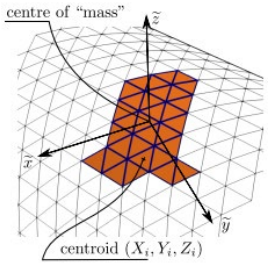
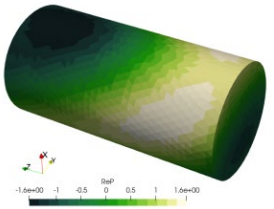
Technical Approach:
Reduction of pressure degrees of freedom

- Form clusters of surface panels
- Expand pressure on each cluster: generalized degrees of freedom
- Represent pressure with generalized degrees of freedom: many fewer than in the full model





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Article

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Literature Cited

1. Petr Krysl, Ahmad T. Abawi, "Automatic CHIEF Point Selection for Finite Element-Boundary Element Acoustic Backscattering", Acoustics, 5(2):522-534, May 2023, https://doi.org/10.3390/acoustics5020031

2. Petr Krysl, Ahmad T. Abawi, "Finite Element-Boundary Element Acoustic Backscattering with Model Reduction of Surface Pressure Based on Coherent Clusters", Acoustics, 5(4), 1016-1035; https://doi.org/10.3390/acoustics 5040058