Acoustic Response of Underwater Objects: Numerical Models and At-Sea measurements

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Outline of Presentation

- Overview of the numerical models

  Key requirements: high-fidelity and high-speed model

- Target in the environmental response model (TIER) model

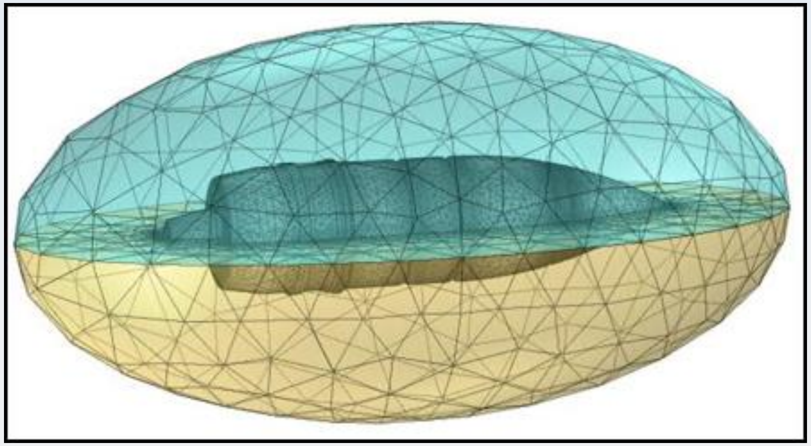
  - ❖ TIER compared to the Hybrid model (validation)
  - ❖ TIER applied to a target in different environments
  - ❖ TIER in shallow water (target at 1 and 5 water depths from source/receiver)

- Summary

SG Kargl et al, *IEEE J. Ocean. Eng.,* **40**, 632-642, (2015)
DS Plotnick et al, *J. Acoust. Soc. Am*., **137**, 470-480, (2015)
AL España et al, *J. Acoust. Soc. Am*., **136**, 109-121, (2014)
SG Kargl et al, *IEEE J. Ocean. Eng*., **37**, 516-532, (2012)
M Zampolli et al, *J. Comp.* Acoust., **20**, p 1240007 (14 pp), (2012)
KL Williams et al, *J. Acoust. Soc. Am*., **127**, 3356-3371, (2010)

Overview of Numerical Models

- Full 3D finite element model
  - High fidelity, but computationally intensive (both hardware and time)
  - Number of nodes in FE mesh increases with frequency
  - Number of nodes in FE mesh increases with complexity of target
  - Change in the sediment type necessitates a new target scattering solution
  - Used for validation of other models



3D FE Mesh for a solid replica of 100-mm UXO

M Zampolli et al, *J. Comp.* Acoust., **20**, p 1240007 (14 pp), (2012)

KL Williams et al, *J. Acoust. Soc. Am.*, **127**, 3356-3371, (2010)

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- Hybrid model
  - Exploits cylindrical symmetry of objects for a 2D finite-element model
  - Field propagated by discrete Helmholtz integral
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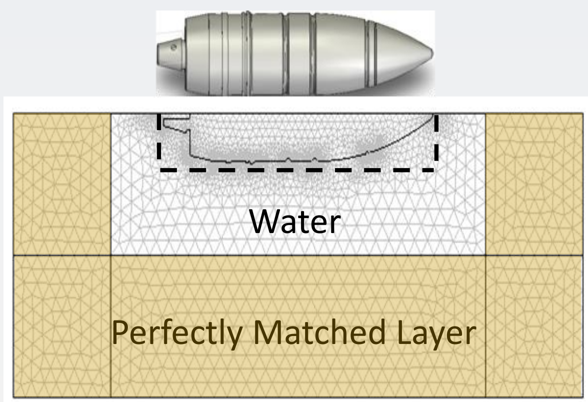
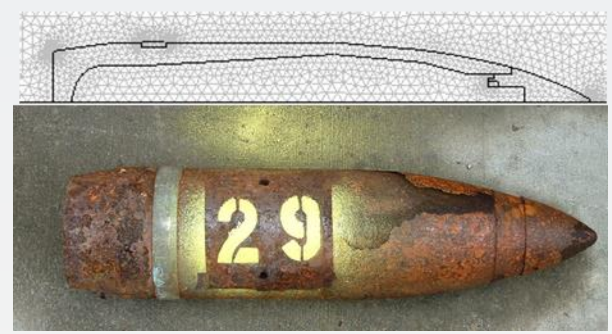
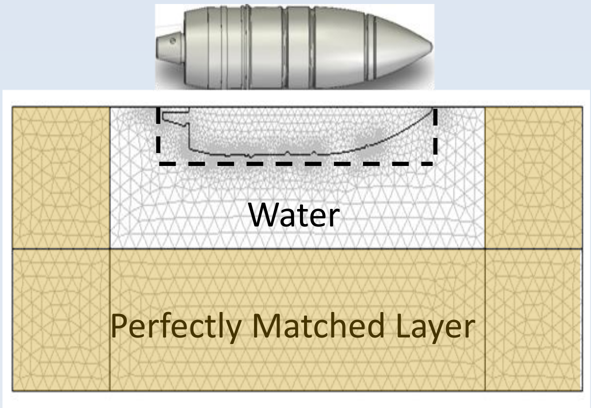
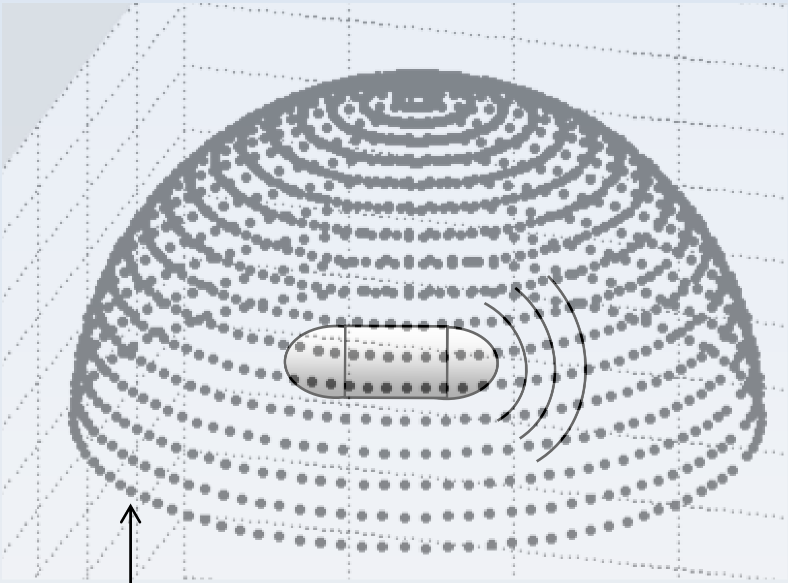




Hybrid Model





- Axisymmetric target allows separation of the 3D problem into a series of independent 2D azimuthal Fourier modal sub-problems.
- Pressure and normal derivatives are sampled along a cylindrical surface surrounding the target (indicated by the dashed line in above image).
- Pressure is propagated from the sampling surface to a field point using the discrete sum representation of the Helmholtz integral.

Discrete Helmholtz Integral

$$p_i = \sum_j \left[\frac{\partial G_{ij}}{\partial n_j} p_j - \frac{\partial p_j}{\partial n_j} G_{ij} \right] dA_j$$

Freefield Green Function

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

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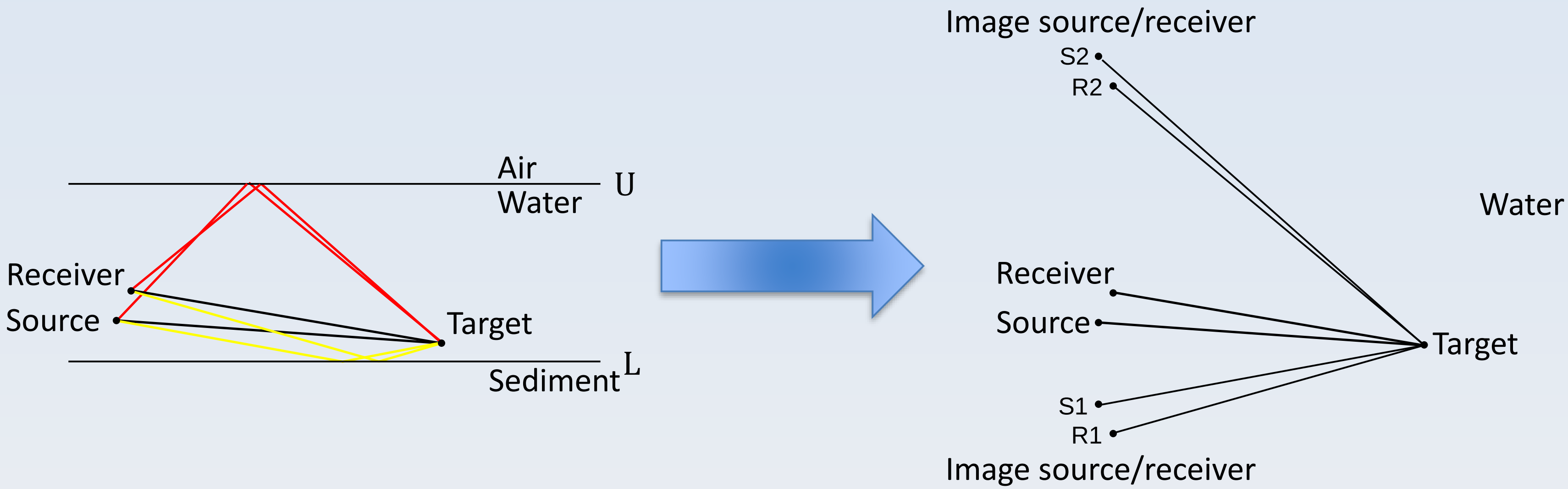
- Target in the environment response (TIER) model
  - Acoustic ray model describes propagation (and environment)
  - Free-field target scattering accounts for interaction of sound with target
  - Target scattering leverages tabulated scattering amplitudes from Hybrid model
  - Change in the sediment type does not require a new target scattering solution

Target in the Environment Response (TIER) Model

Waveguide Scattering Problem

Equivalent Free-Field Scattering Problem



Contribution of the *i* th source and *j* th receiver to the spectrum of scattered field

$$P_{ij}(\omega) = \left[U^{n(j)} L^{m(j)} \frac{\exp(i\omega t_{jt})}{d_{jt}} \right] \left[U^{n(i)} L^{m(i)} \frac{\exp(i\omega t_{ti})}{d_{ti}} \right] f(\hat{r}_i, \hat{r}_j, \omega) r_0 P_{src}(\omega)$$

Target to receiver propagator

Source to target propagator

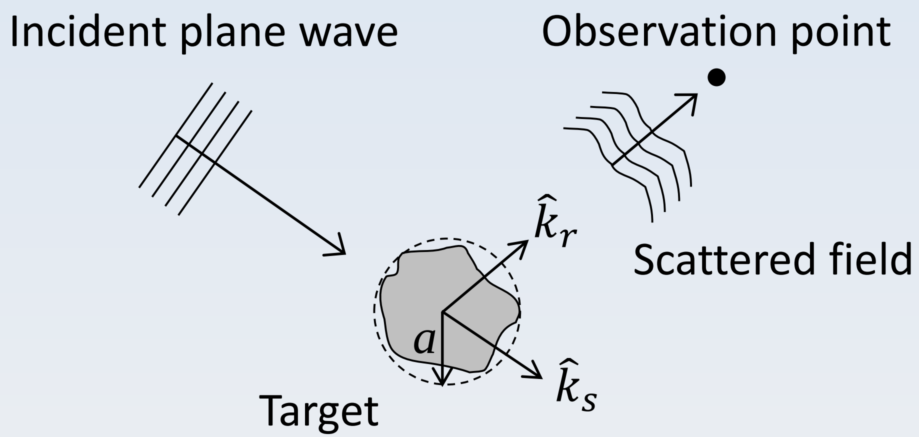
Scattering amplitude

Spectrum of incident field

SG Kargl et al, *IEEE J. Ocean. Eng.*, **40**, 632-642, (2015)

Target in the Environment Response (TIER) Model

Free-field Scattering in Infinite Medium



$$p_s \approx p_0 f\left(\hat{k}_s, \hat{k}_r, \omega\right) \frac{\exp(ikr)}{r}$$

Scattering amplitude, $f\,(k_s,k_r,\omega)$, contains all the information about the target (e.g., material properties and directionality of scattered field).

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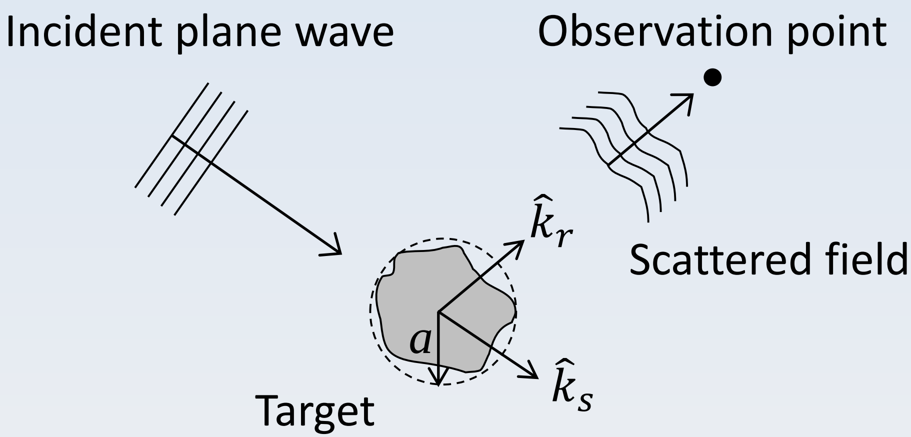

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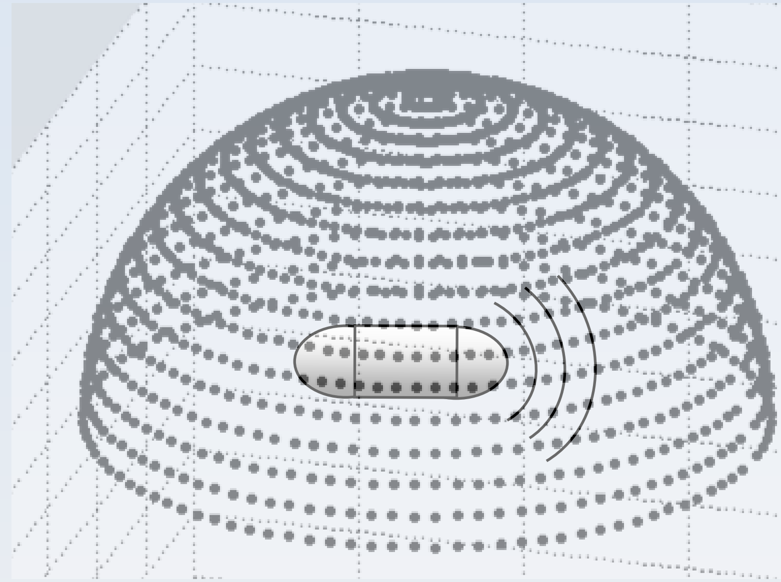


Each discrete pressure p_i on the hemisphere is converted to a scattering amplitude in a look-up table:

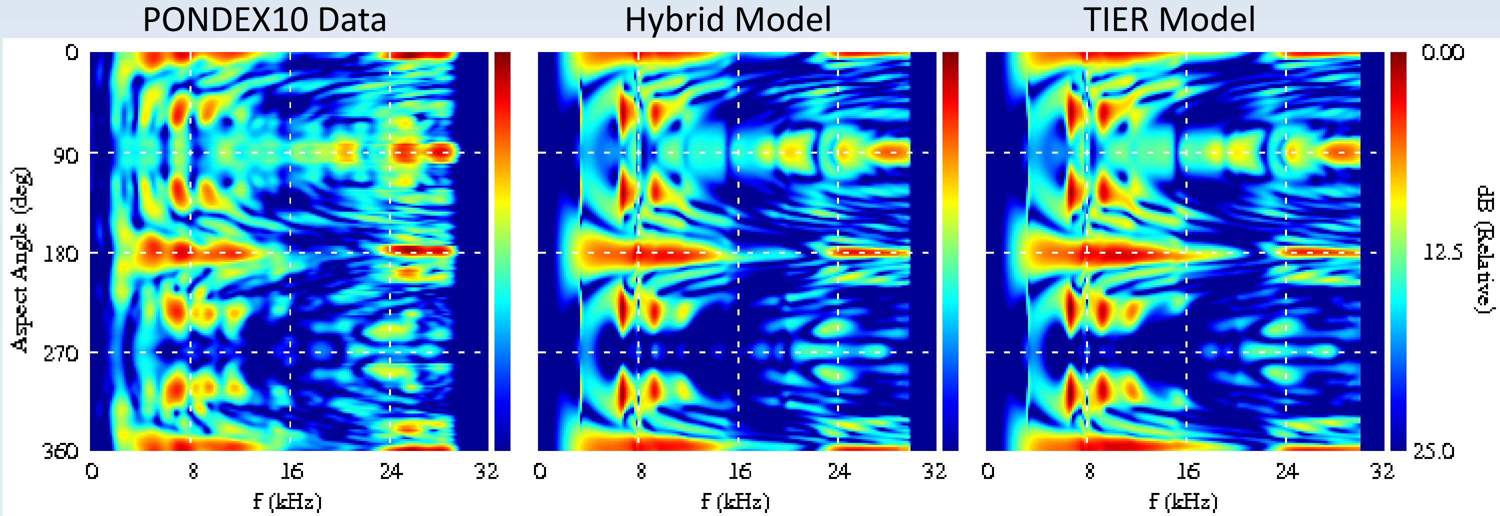
$$f_{lmn} = f\left(\hat{k}_i, \hat{k}_s\right) \approx \frac{p_i}{p_0} R_0 \exp(-ikR_0)$$

The subscripts *l* and *m* are associated with scattering angles and *n* corresponds to a discrete angular frequency, ω_n.

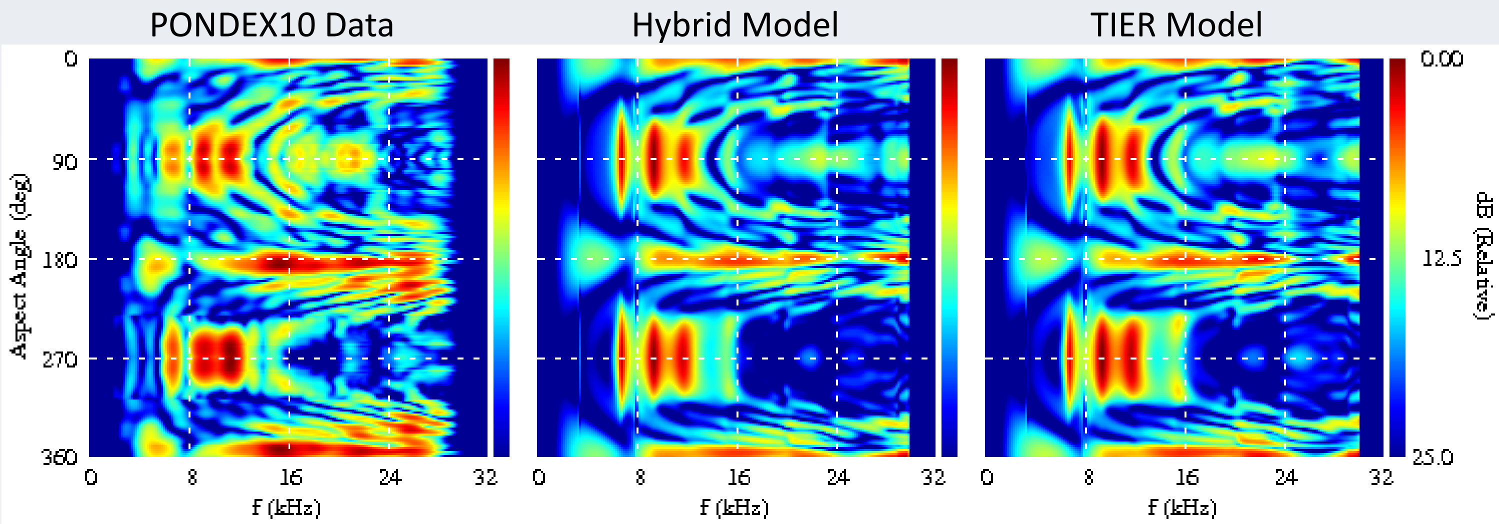
TIER Model versus Hybrid Model

APL Rail-Tower

10 m range



5 m range



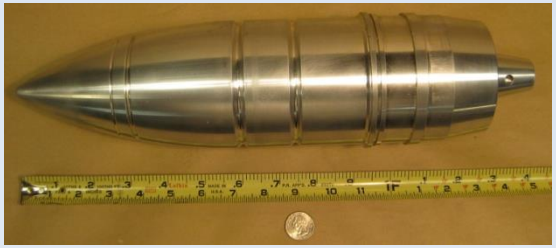
TIER Model with Different Environments

Circular SAS with 10 m radius

Target at center of circular SAS path

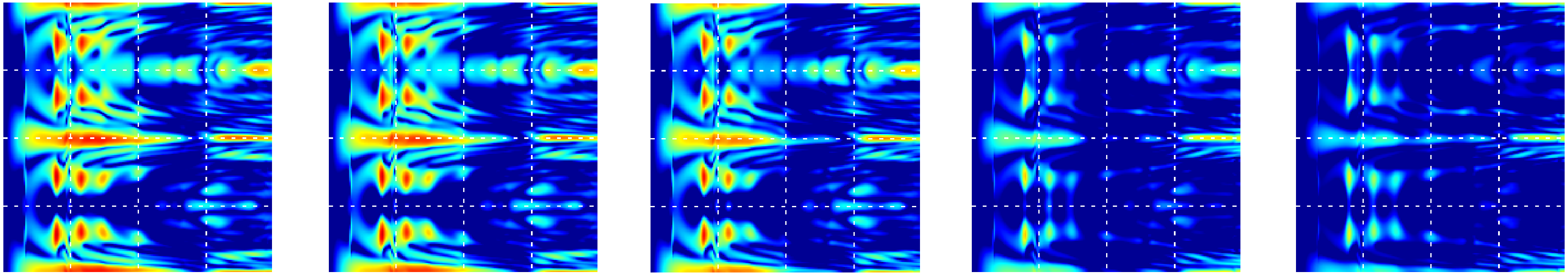
Source/receiver 3.8 m above sand sediment (giving θ_g = 20.8°)

Water sound speed: 1464 m/s



Acoustic Color Templates

Hard Sand ⟶ Soft Sand / Silt ⟶ Mud



c_s = 1764 m/s	c_s = 1690 m/s	c_s = 1614 m/s	c_s = 1540 m/s	c_s = 1464 m/s
θ_c = 33.9°	θ_c = 30.0°	θ_c = 24.9°	θ_c = 18.1°	θ_c = 0°

The above color scale represent absolute TS on -5 to -33 dB range.
The TS for a proud target on mud is ~14 dB down compared to the same target on hard sand.

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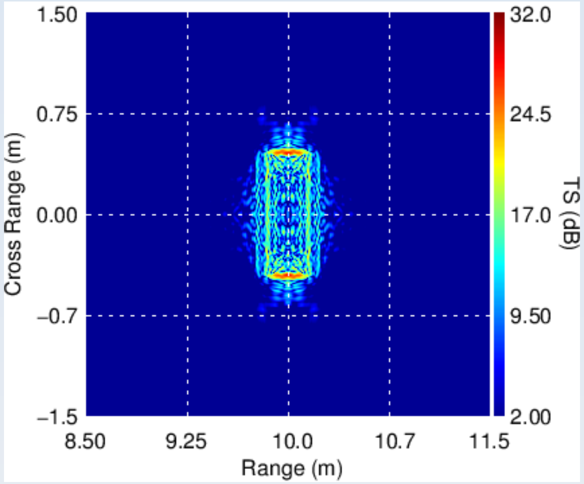
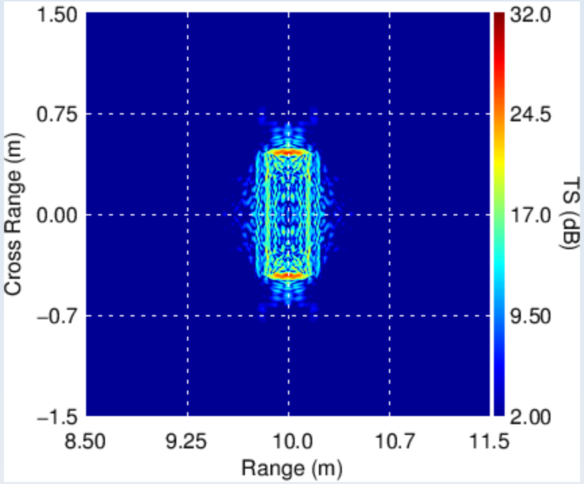
TIER Model in Shallow Water (SAS Images)

Circular SAS image, CSAS path R = 10 m, 3:1 aluminum cylinder





2 Sources
2 Receivers

3 Sources
3 Receivers

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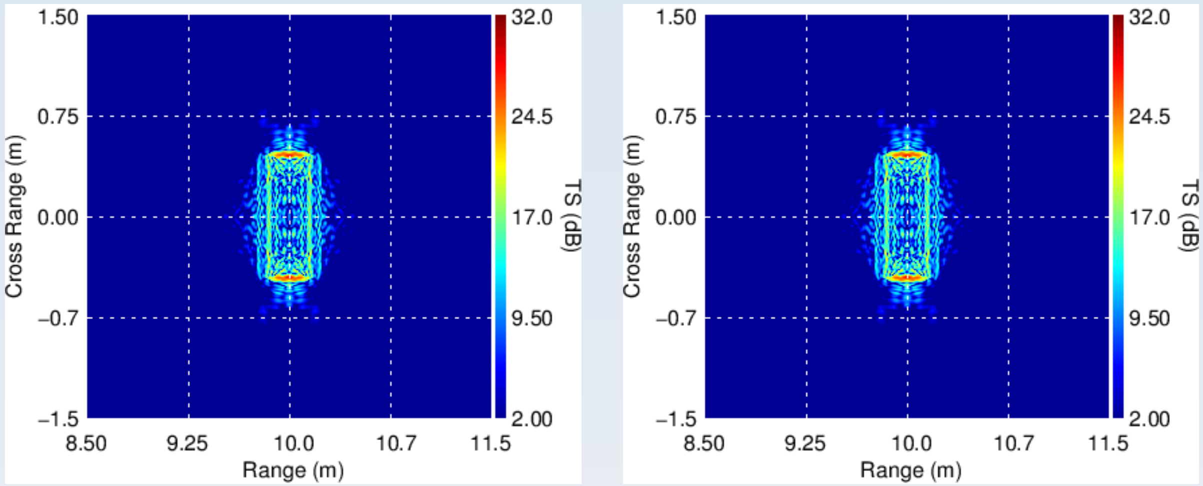

2 Sources
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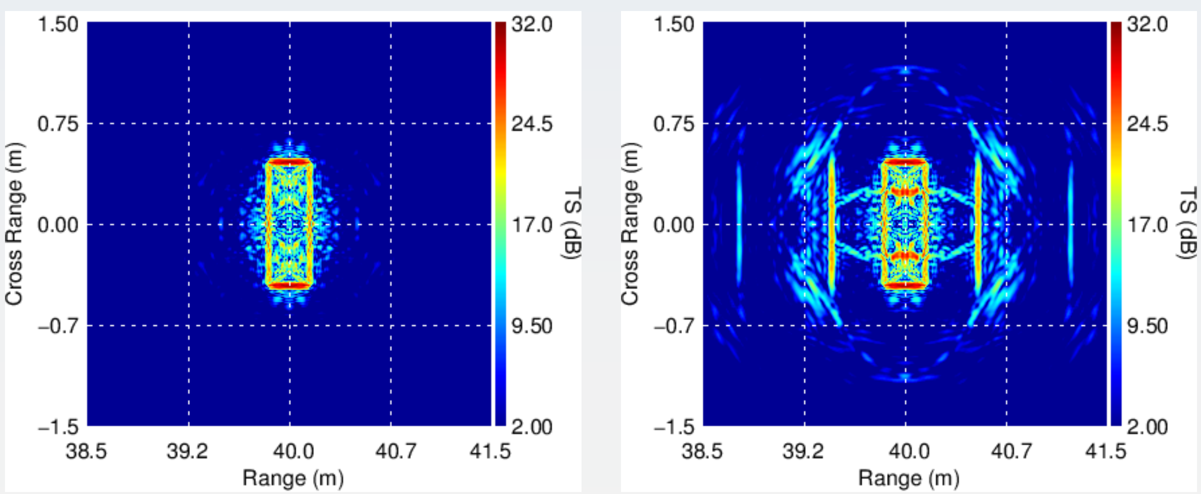
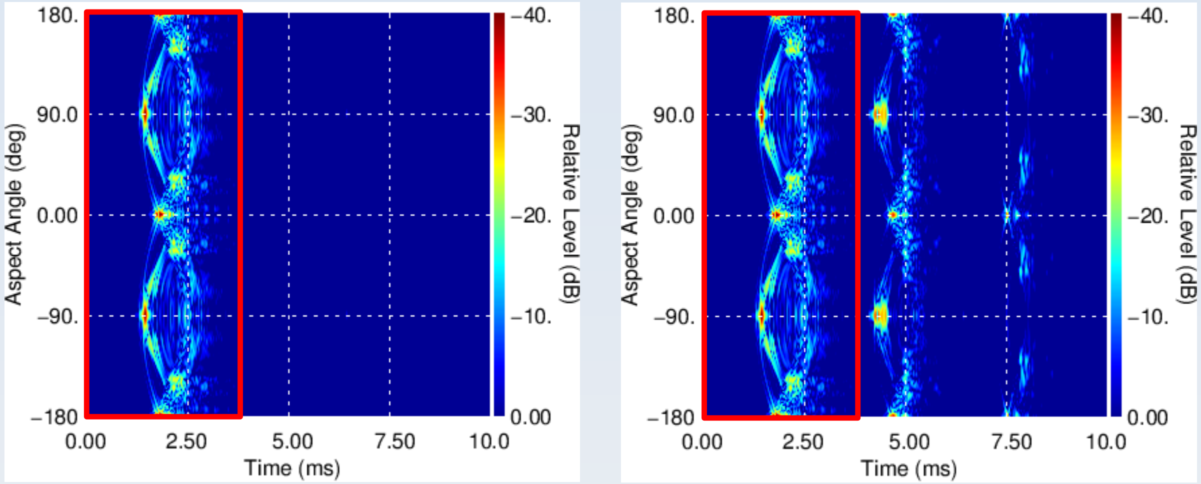
Circular SAS image, CSAS path R = 40 m, 3:1 aluminum cylinder



TIER Model in Shallow Water (Time Domain)

Pulse-compressed signals, CSAS path R = 10 m, 3:1 aluminum cylinder



2 Sources
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3 Sources
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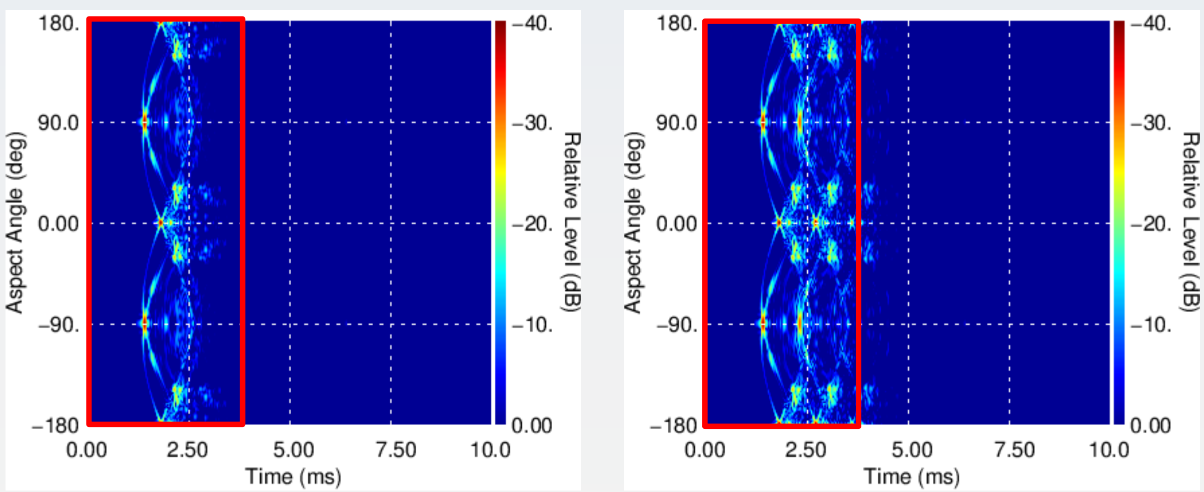

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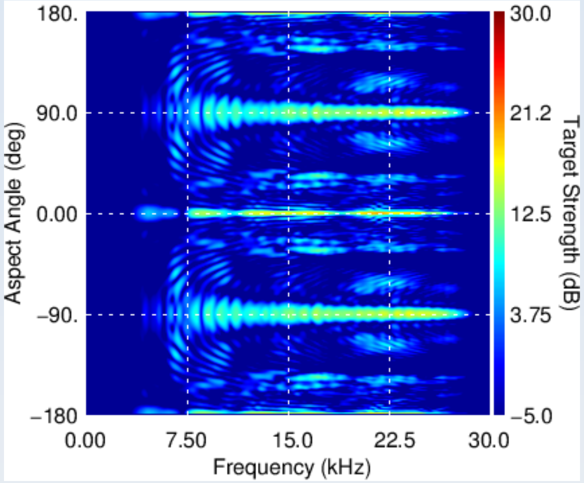
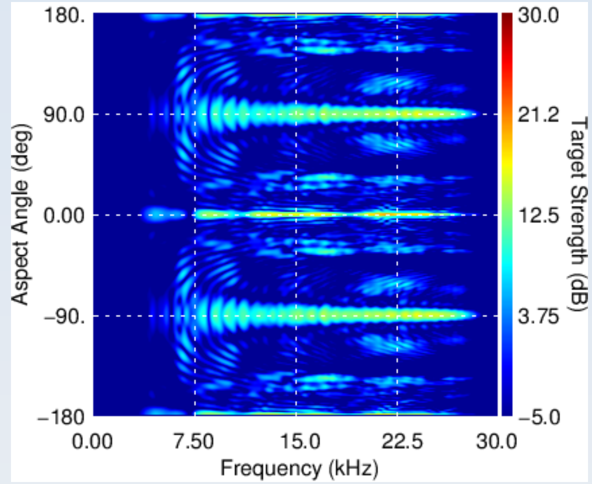
TIER Model in Shallow Water (Frequency Domain)

Acoustic color templates, CSAS path R = 10 m, 3:1 aluminum cylinder





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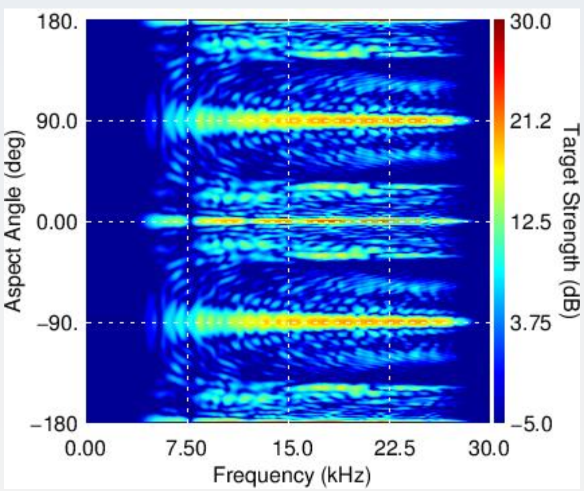
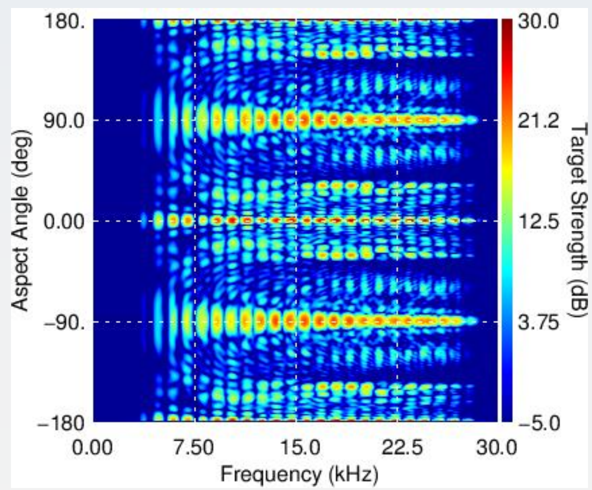
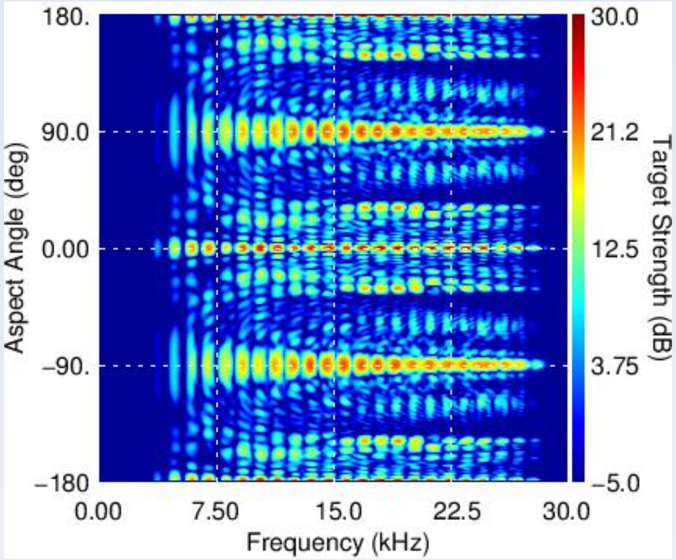


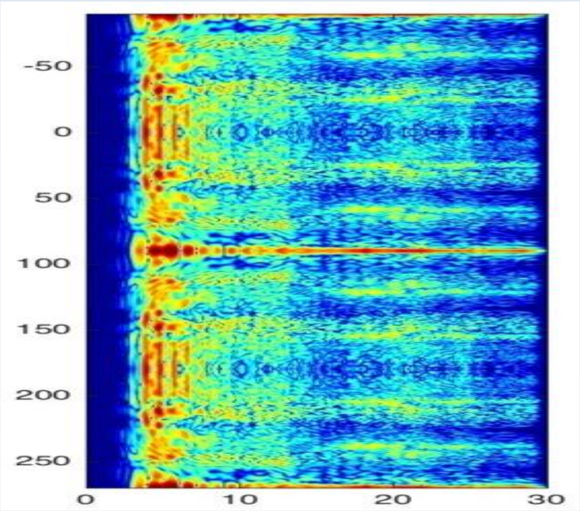


TIER Model vs Data in Shallow Water

TIER Model



BAYEX14 Data



Evidence of modulation of acoustic color template in BAYEX14 data

Target sank into a mud layer of 15 to 30 cm thickness

Summary

- Overviews of the Hybrid and TIER models
  - ✓ Models apply to free-field, proud, partially buried and buried targets
  - ✓ Hybrid models provides insight into the mechanisms in the elastic response of the target
  - ✓ TIER model retains high fidelity of Hybrid model, but is computationally fast
  - ✓ TIER model can provide large sets of data for training and testing classifiers
- TIER simulations in a shallow water capture observed modulation in the acoustic color template. TIER demonstrated the modulation is a result of interference of additional air-water reflected ray paths.