# Spatial Coherence Based Reconstruction for Detection of Underwater Munitions

MR24-4520

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In-Progress Review Meeting

August 12, 2025

# Project Team

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Research areas:

- Sonar system engineering
- Sonar signal processing
- Coherence of acoustic fields



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# Bottom Line Up Front

- Goal: Develop acoustic image reconstruction algorithms to improve UXO detection by exploiting differences signal coherence between objects and the seafloor.

  - Working well:
    - Initial algorithm development through simulation has aided productivity.
    - DMAS-like algorithms provide clear boost in image quality.

  - Challenges:
    - Physics-based limitations: some targets are still very difficult to detect.

# Technical Objective

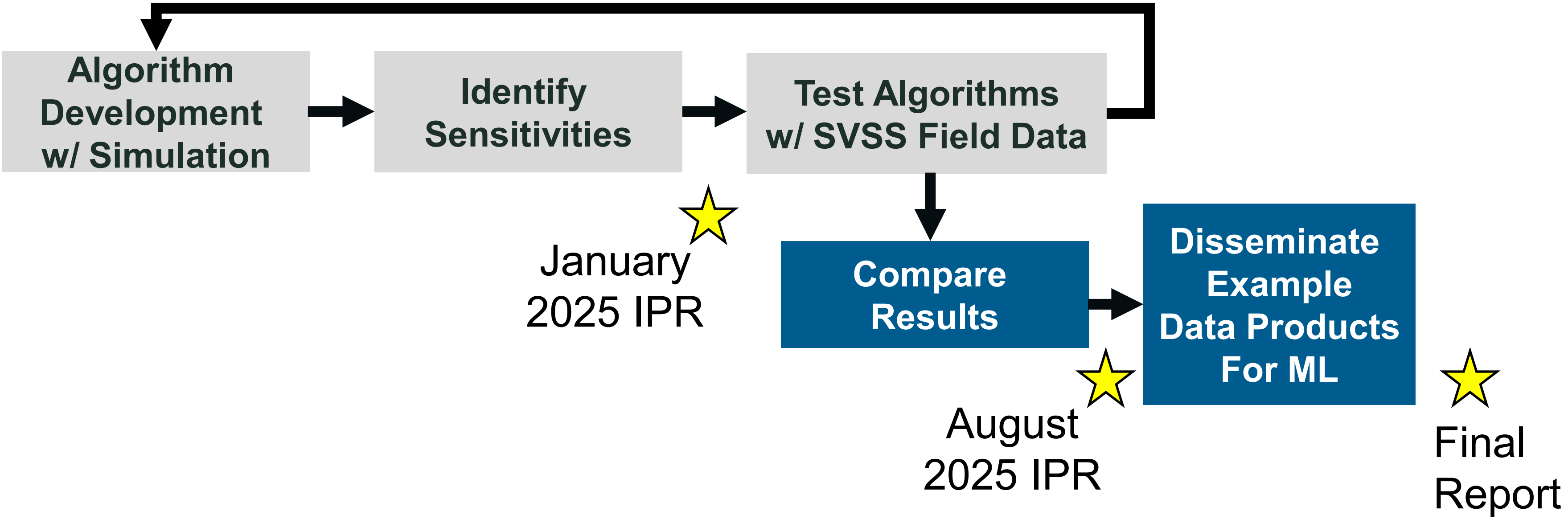
Advances in biomedical ultrasound imaging have used spatial coherence for improved contrast, speckle rejection, and resolution.

1. Adapt coherence-based image reconstruction algorithms for low-frequency synthetic aperture sonar sensing geometry.

2. Apply algorithms to field data from SERDP sensors.

3. Quantitatively and qualitatively compare coherence-based and conventional image reconstruction for a variety of targets and burial depths.

# Technical Approach



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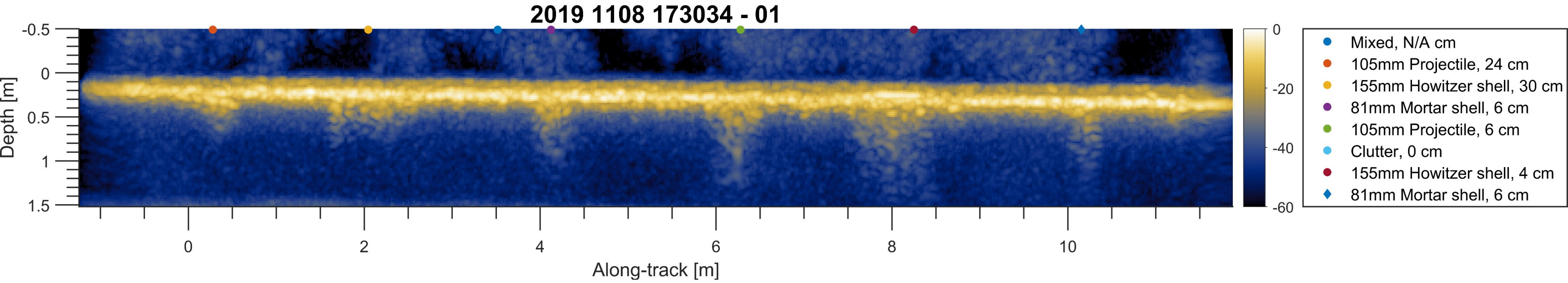
# Motivation: existing UXO sonar surveys




Observing target shape is hindered by strong background and limited resolution.



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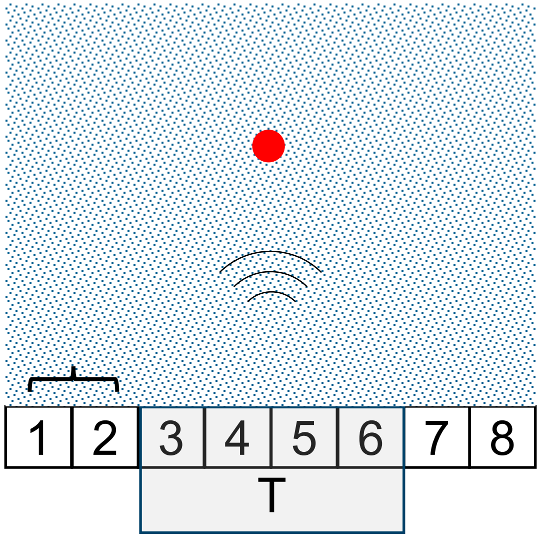
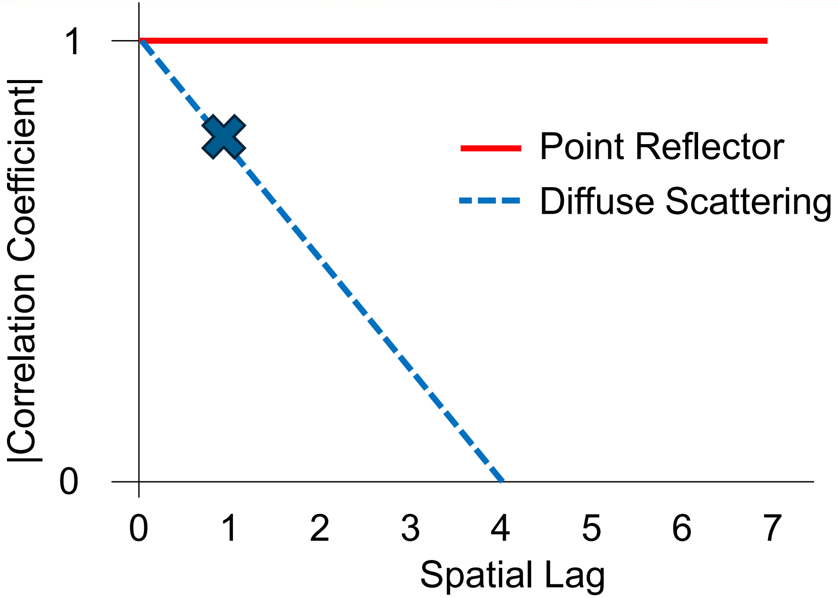
# Spatial Coherence: Targets vs. Background




Algorithms attempt to exploit differences in coherence between objects and the environment.

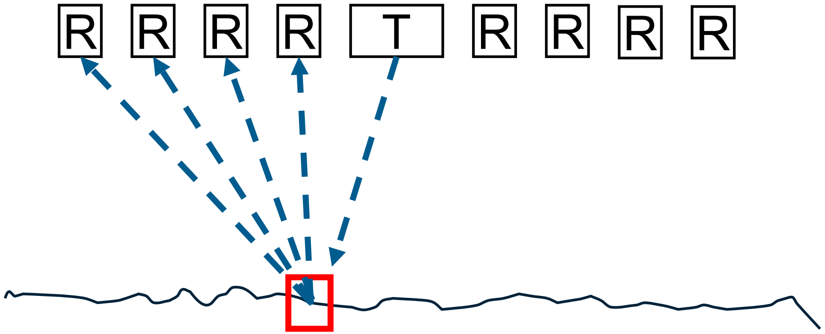
# Convention reconstruction: delay and sum

$$\nabla^2 p - \frac{1}{c^2}\frac{\partial^2 y}{\partial^2 x} p = 0$$

Pressure propagates according to a 2nd order PDE

***"Backprojecting pressure"***

*1. Calculate Delays*




*2. Add up all the signals*

$$D(\bar{\chi}_S) = \sum_{i}^{N} p\left(\frac{1}{c}\left(|\bar{\chi}_S - \bar{\chi}_T| + |\bar{\chi}_S - \bar{\chi}_{R_i}|\right)\right)$$

# Coherence-based reconstruction

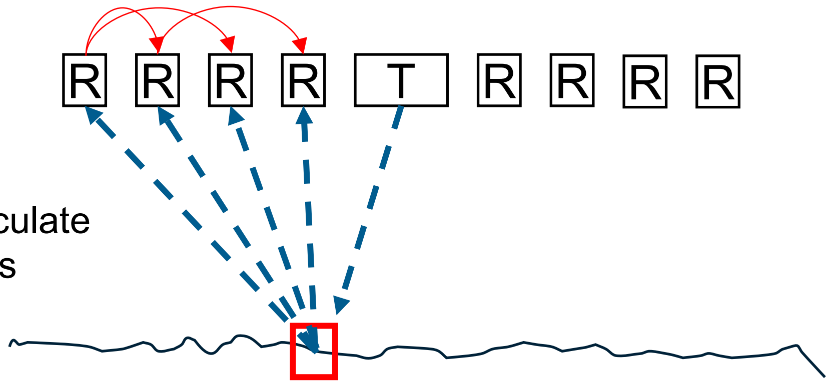
$$\nabla_1^2 \langle p_1 p_2^* \rangle - \frac{1}{c^2} \frac{\partial^2 y}{\partial^2 x} \langle p_1 p_2^* \rangle = 0$$

$$\nabla_2^2 \langle p_1 p_2^* \rangle - \frac{1}{c^2} \frac{\partial^2 y}{\partial^2 x} \langle p_1 p_2^* \rangle = 0$$

Mutual coherence (spatial covariance) propagates according to a pair of 2nd order PDEs

**"Backprojecting complex covariance"**

2. Combinatorially multiply pairs of signals




1.Calculate Delays

$$D(\bar{\chi}_S) = \sum_{i}^{N-1} \sum_{j=i+1}^{N} s_i \, s_j^*$$

$$s_i = \int \mathrm{p}(\bar{\chi}_T, \bar{\chi}_{R_i}, \mathrm{t}) \delta \left( \mathrm{t} - \frac{c}{2} \left( |\bar{\chi}_S - \bar{\chi}_T| + |\bar{\chi}_S - \bar{\chi}_{R_i}| \right) \right) d\bar{\chi}_S$$

3. Sum the covariance matrix



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# Advances in the approach

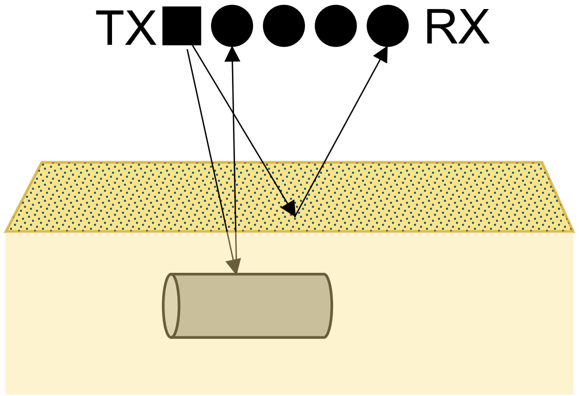
- Theoretical:
  - Connection to propagating field quantities was central to explaining results.
- Practical:
  - Downward-looking sensing geometry required numerical modification.

$$f(\boldsymbol{\xi}) = \sum_{i=1}^{N\times M-1} \sum_{j=i+1}^{N\times M} \boldsymbol{s}_i \boldsymbol{s}_j^*$$

*"Backprojecting complex covariance"*

$$f(\boldsymbol{\xi}) = \sum_{i=1}^{N\times M-1} \sum_{j=i+1}^{N\times M} \frac{\boldsymbol{s}_i \boldsymbol{s}_j^*}{\sqrt{\left|\boldsymbol{s}_i \boldsymbol{s}_j^*\right|}}$$

*"Backprojecting complex co-standard deviation"*



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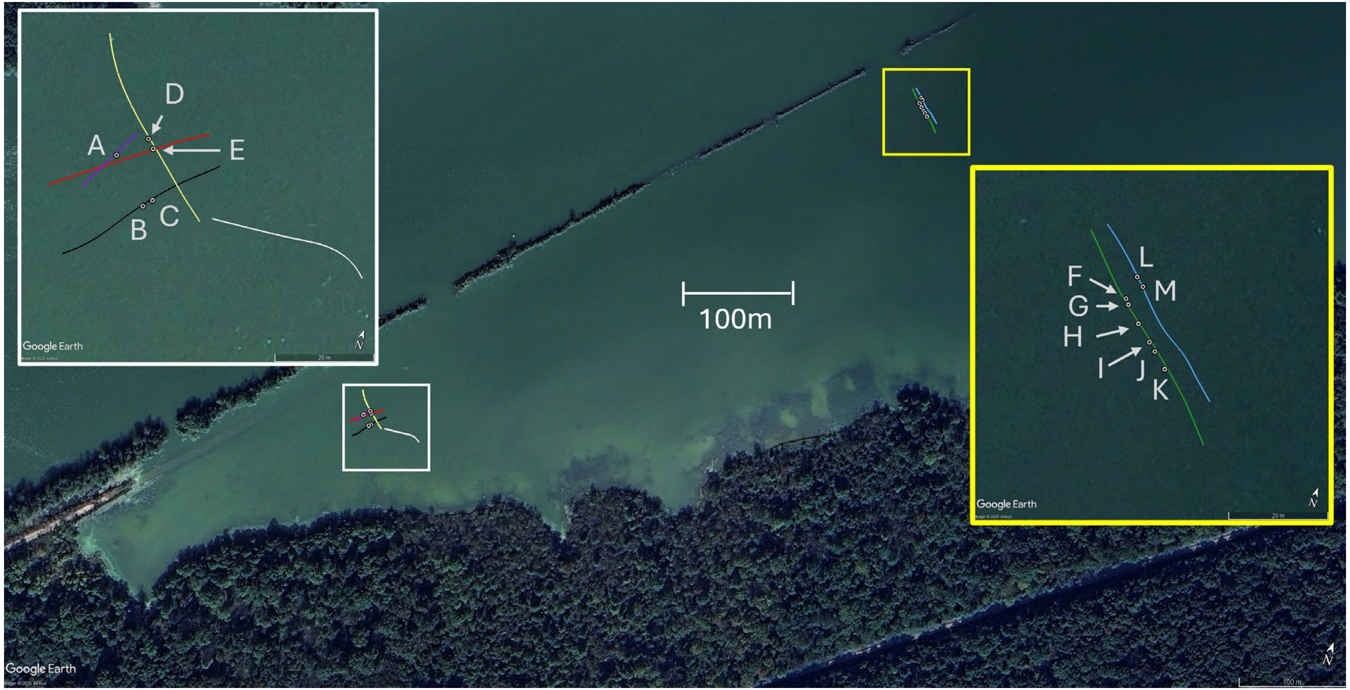
# Algorithms were applied to 2019 data collected by the SVSS.



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# A set of 13 objects were analyzed.

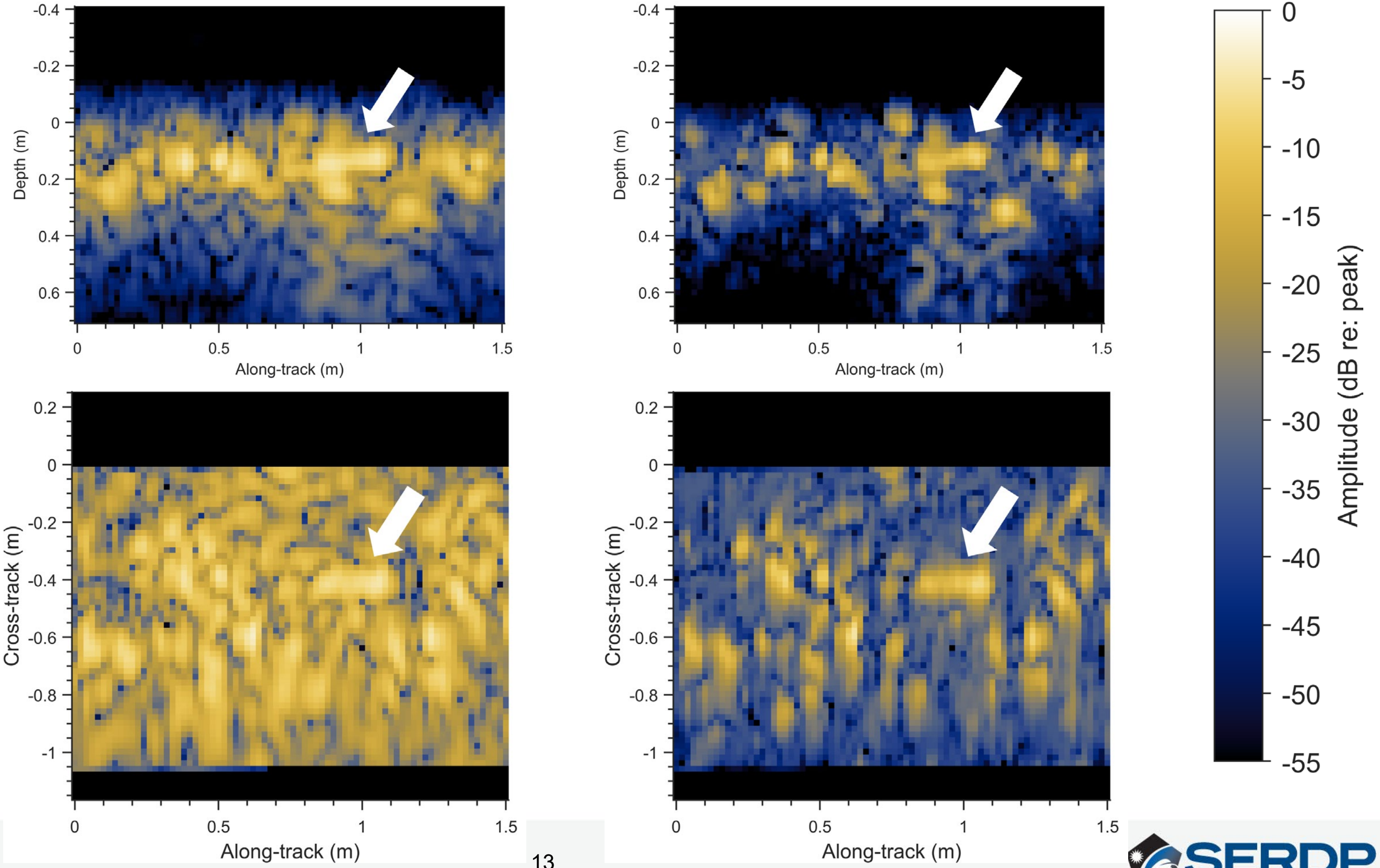
| Target | Description | Length | Width | Water Depth | Burial Depth |
|---|---|---|---|---|---|
| A | solid concrete cylinder | 30.5 cm | 15.2 cm | 1.3 m | 0 cm |
| B | steel pipe | 30.5 cm | 11.4 cm | 1.2 m | 0 cm |
| C | steel sphere | N/A | 10.2 cm | 1.2 m | 0 cm |
| D | inert 155 mm howitzer | 86.2 cm | 15.5 cm | 1.3 m | 4 cm |
| E | inert 105 mm projectile | 46.1 cm | 10.5 cm | 1.3 m | 6 cm |
| F | solid aluminum cylinder | 30.5 cm | 15.2 cm | 3.0 m | 14 cm |
| G | steel sphere | N/A | 10.2 cm | 3.0 m | 16 cm |
| H | solid aluminum cylinder | 30.5 cm | 15.2 cm | 2.9 m | 9 cm |
| I | solid aluminum cylinder | 61 cm | 15.2 cm | 2.9 m | 0 cm |
| J | solid aluminum cylinder | 30.5 cm | 15.2 cm | 3.0 m | 0 cm |
| K | cinder block | 39.7 cm | 19.8 cm | 3.1 m | 0 cm |
| L | concrete pad | 30.5 cm | 30.5 cm | 3.0 m | 1 cm |
| M | concrete pad | 30.5 cm | 30.5 cm | 3.0 m | 16 cm |

Objects span a range of:

- Type (UXO, science, clutter)
- Size
- Shape
- Water depth
- Burial Depth

Inert 105mm Projectile
*Depth*: 1.3m
*Burial*: 6cm

**Conventional Reconstruction** **Coherence-based Reconstruction**



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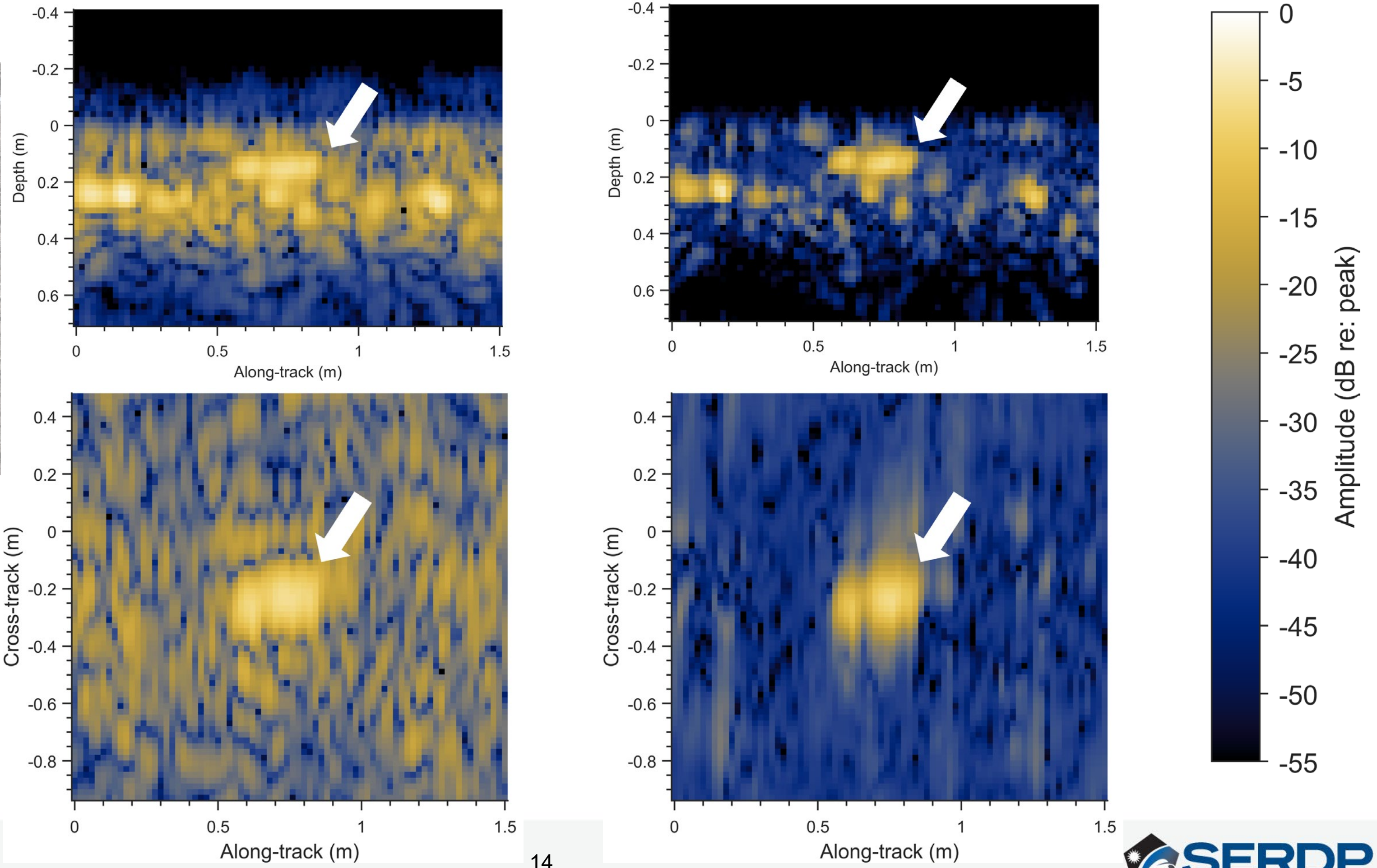
## Conventional Reconstruction

## Coherence-based Reconstruction

15x30cm
Aluminum
Cylinder
*Depth*: 2.9m
*Burial*: 9cm

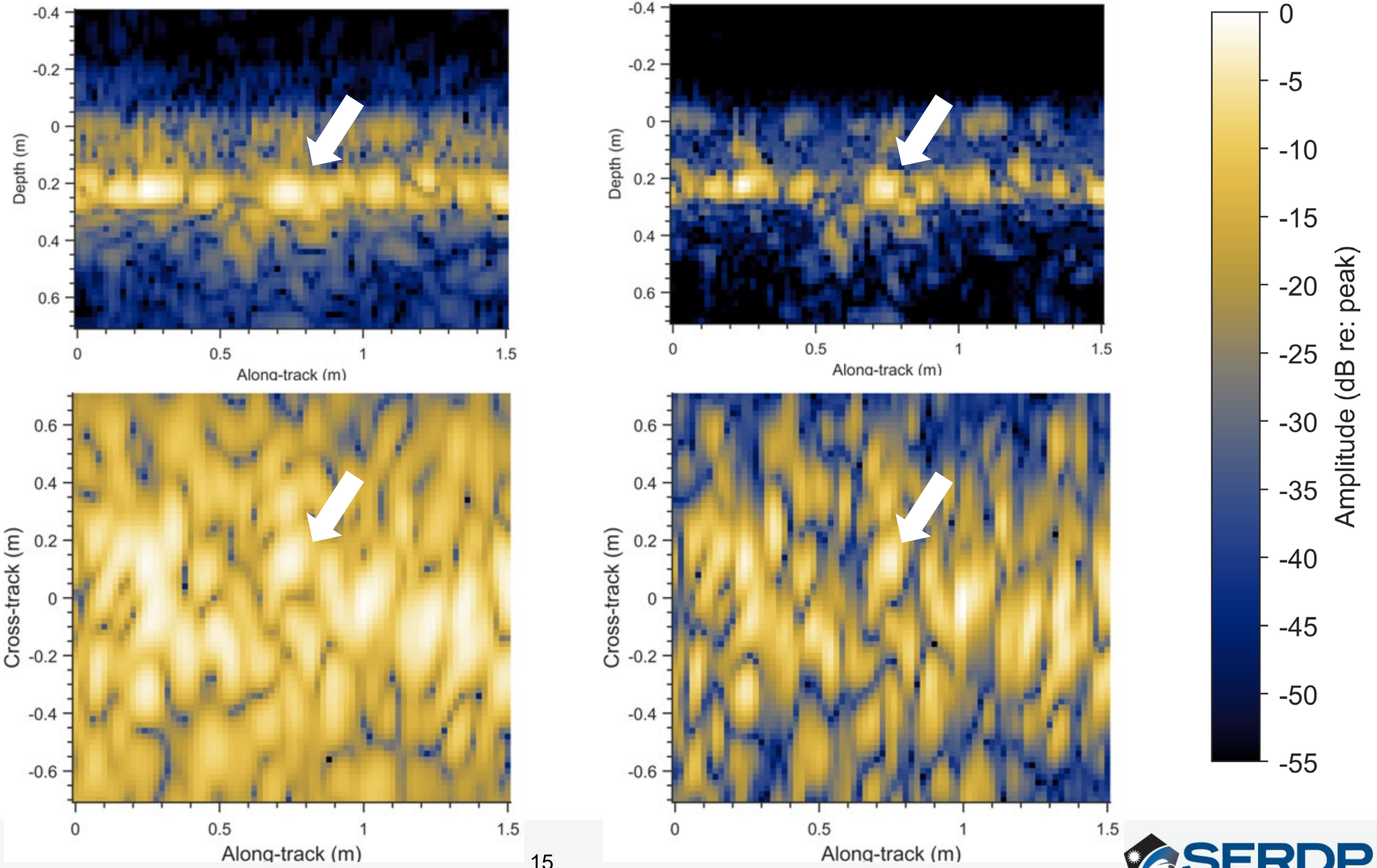


10cm shotput

*Depth*: 3.0m

*Burial*: 16cm

**Conventional Reconstruction** | **Coherence-based Reconstruction**



# Quantitative Comparison Metrics

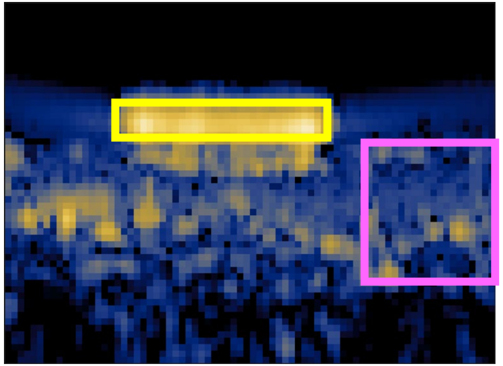
## Contrast

*"common and intuitive"*

$$C = \frac{\mu_i}{\mu_o}$$

$\mu_i$ Mean UXO intensity

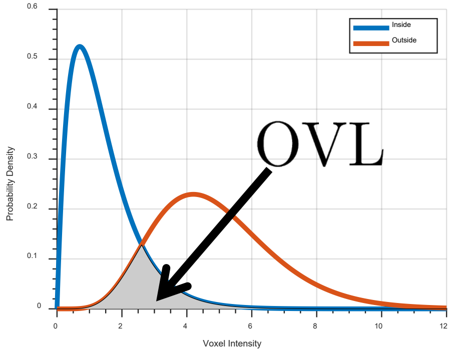
$\mu_o$ Mean background intensity



## Generalized Contrast to Noise Ratio

*"immune to nonlinear warping"*

$$\text{gCNR} = 1 - \text{OVL}$$



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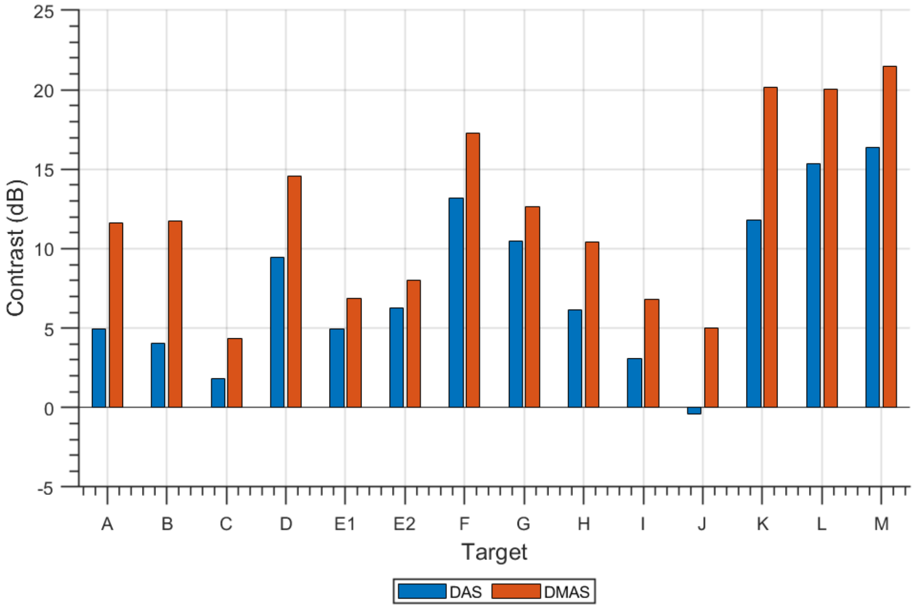
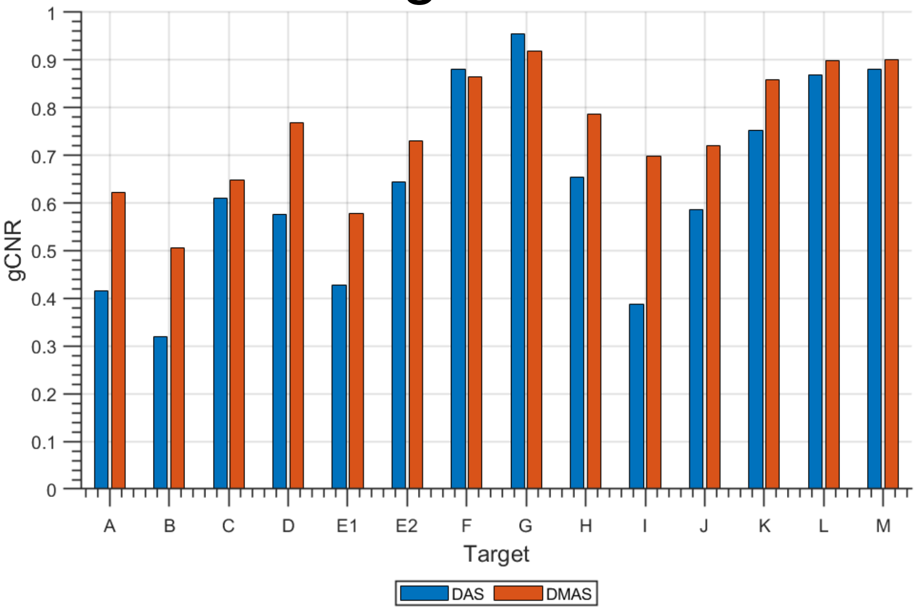
# Metrics show increased image quality

Contrast




gCNR



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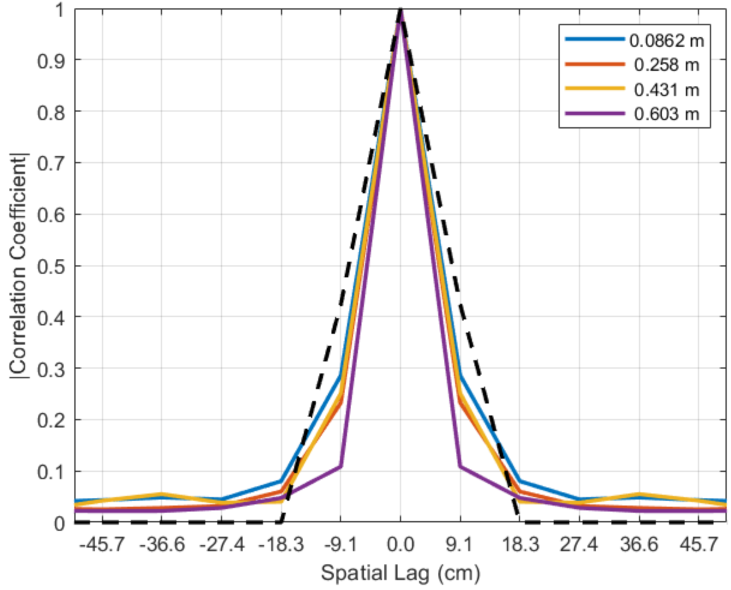
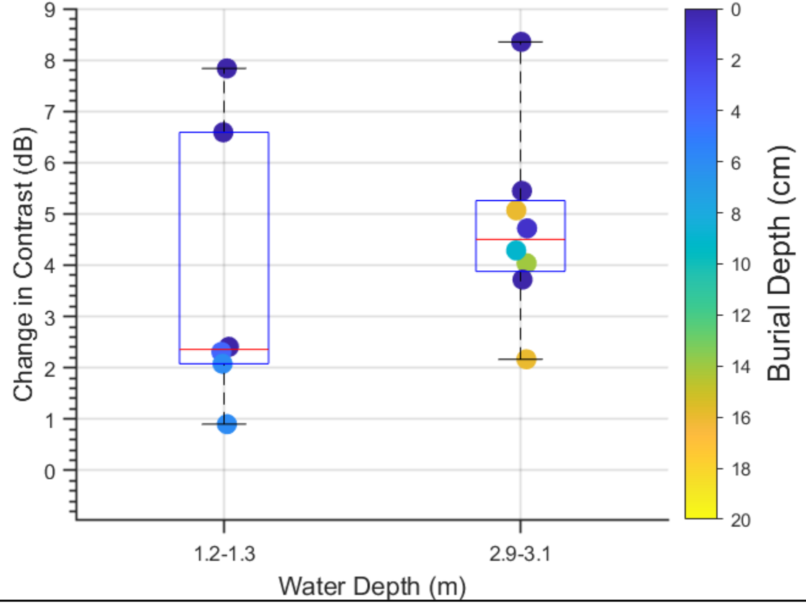
# Data analysis & modeling explain contrast.

## Spatial Coherence of Sediment




## Contrast Change: DAS → DMAS




Modeling shows that contrast will increase with synthetic aperture size.



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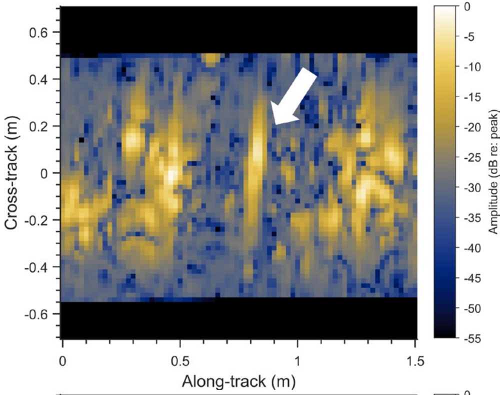
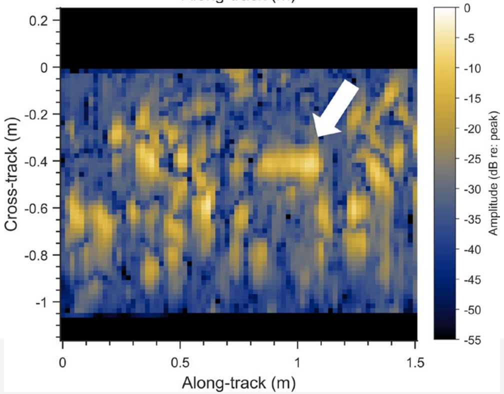
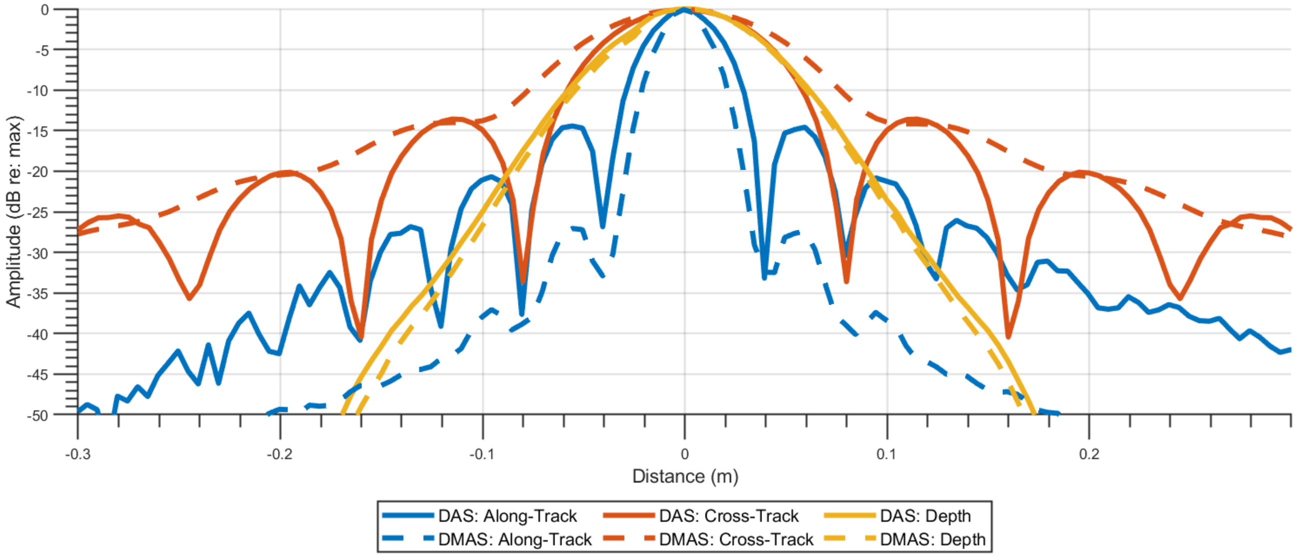
# Point spread function explains appearance.



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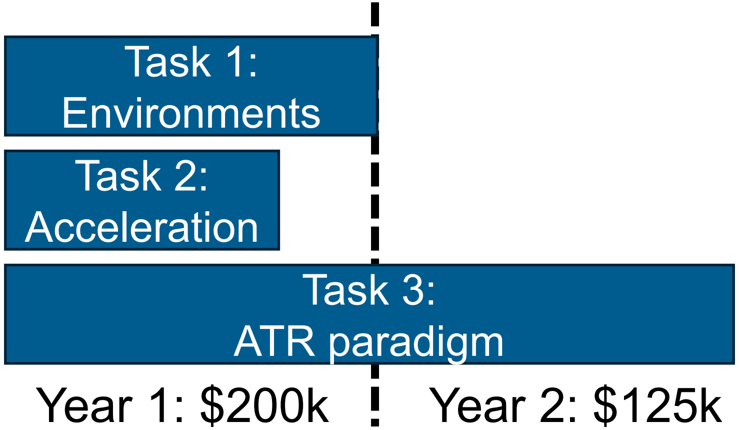
# Summary

- Coherence-based reconstruction algorithms were adapted for SAS and demonstrated on field data.
- The reconstruction improves image quality and target detectability.
  - Increased contrast
  - Slightly enhanced resolution
- The improvements are “free”.
  - Exploits information in signals that has previously been discarded.
- Key difference: slight cross-track “blurring”.
  - Due to non-uniform distribution of spatial coherence sampling.
  - Paths identified for improvement.

# Future Research

1. Evaluation & adaptation for different environments (sand, etc.).
2. Computational acceleration.
3. Demonstration in an ATR paradigm.



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# BACKUP MATERIAL

# MR24-4520: Spatial Coherence Based Reconstruction for Detection of Underwater Munitions

**Performers:** Thomas Blanford (University of New Hampshire)

## Technology Focus

- *Adapt image reconstruction algorithms from biomedical ultrasound to exploit differences in signal coherence between UXO and the seafloor.*

## Research Objectives

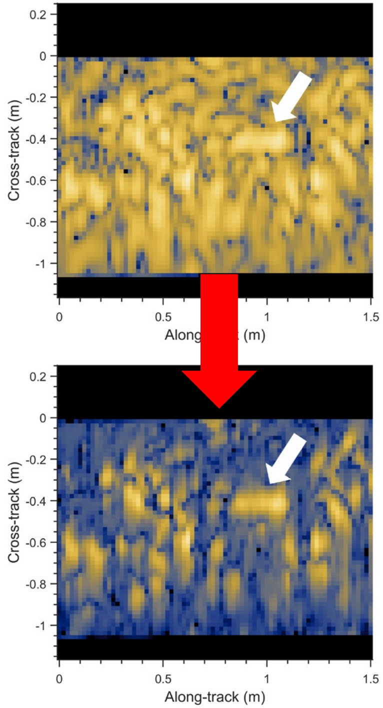
- *Develop sensor agnostic reconstruction algorithms*
- *Demonstrate on field data from a SERDP sonar system*
- *Quantify and explain performance gains*

## Project Progress and Results

- *Reconstruction demonstrated on a set of targets in SVSS field data.*
- *Image quality improvements described quantitatively and qualitatively.*

## Technology Transition

- *Discuss how algorithms can be incorporated into existing SERDP/ESTCP signal processing and target detection processing chains.*

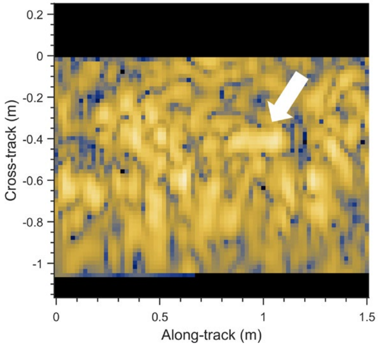


# Plain Language Summary

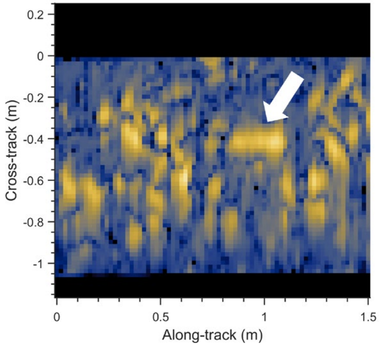
- Current sonar image reconstruction makes it hard to detect UXO when they are buried near the top of the sediment.
- Image reconstruction algorithms, inspired by biomedical ultrasound, are being develop to best exploit differences between UXO and the seafloor.
- The algorithms are sensor agnostic and can be applied to any SERDP sonar sensor to improve image quality.
- By connecting the algorithms to theory, the techniques are both generalizable and explainable.

# Impact to DoD Mission

- Enhanced image quality is demonstrated on field data.
  - Improvement in quality is quantified and is explainable based on acoustic theory.
  - The algorithms exploit acoustic information that has previously been unused.  The performance gains are “free” and don’t require any sensor upgrades or modifications.
  - Demonstration on field data proves the techniques can work in real-world environments to better detect and classify UXO.



Conventional reconstruction of a 105mm projectile



Coherence-based reconstruction of a 105mm projectile



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# Publications

- Thomas E. Blanford; Occlusion and height estimation using the coherence of multi-static synthetic aperture sonar images. *JASA Express Lett.* 1 June 2025; 5 (6): 064802. https://doi.org/10.1121/10.0036836

- Thomas E. Blanford; Applications of coherence to acoustic imaging for munitions response surveys. *J. Acoust. Soc. Am.* 1 April 2025; 157 (4_Supplement): A84. https://doi.org/10.1121/10.0037487

# Literature Cited


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- G. Matrone, A. S. Savoia, G. Caliano and G. Magenes, "The Delay Multiply and Sum Beamforming Algorithm in Ultrasound B-Mode Medical Imaging," in IEEE Transactions on Medical Imaging, vol. 34, no. 4, pp. 940-949, (2015)
- D. Hyun, A. L. C. Crowley and J. J. Dahl, "Efficient Strategies for Estimating the Spatial Coherence of Backscatter," in IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control, vol. 64, no. 3, pp. 500-513, (2017).
- D.C. Brown, S. Johnson, C. Brownstead, J. Calantoni, and G. Fabian, Strategic Environmental Research and Development Program, "Sediment Volume Search Sonar Development," SERDP-ESTCP Final Report MR-2545, (2021).
- D. A. Cook and D. C. Brown, "Synthetic Aperture Sonar Image Contrast Prediction," in IEEE Journal of Oceanic Engineering, vol. 43, no. 2, pp. 523-535, April 2018