



Spatial Coherence Based Reconstruction for Detection of Underwater Munitions

MR24-4520

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In-Progress Review Meeting

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Project Team



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Research areas:

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

Bottom Line Up Front

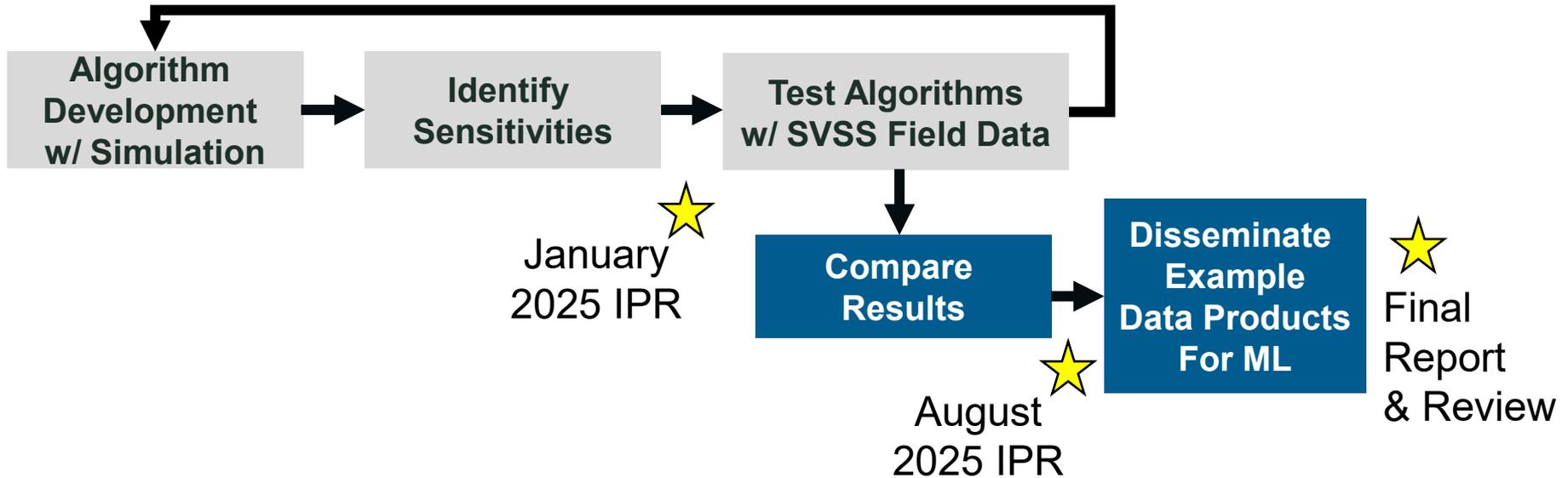
- Goal: Develop acoustic image reconstruction algorithms to improve UXO detection by exploiting differences signal coherence between objects and the seafloor.
 - Working well:
 - DMAS-like algorithms provide clear boost in image quality.
 - Metrics show improvement likely to result in successful detections.
 - Challenges:
 - Physics-based limitations: some targets are still very difficult to detect.

Technical Objective

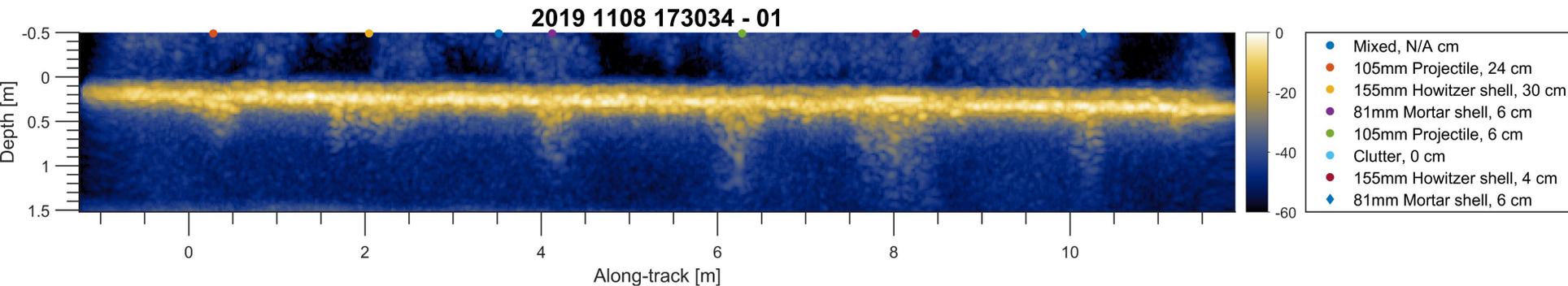
Advances in biomedical ultrasound imaging have used spatial coherence for improved contrast, speckle rejection, and resolution.

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

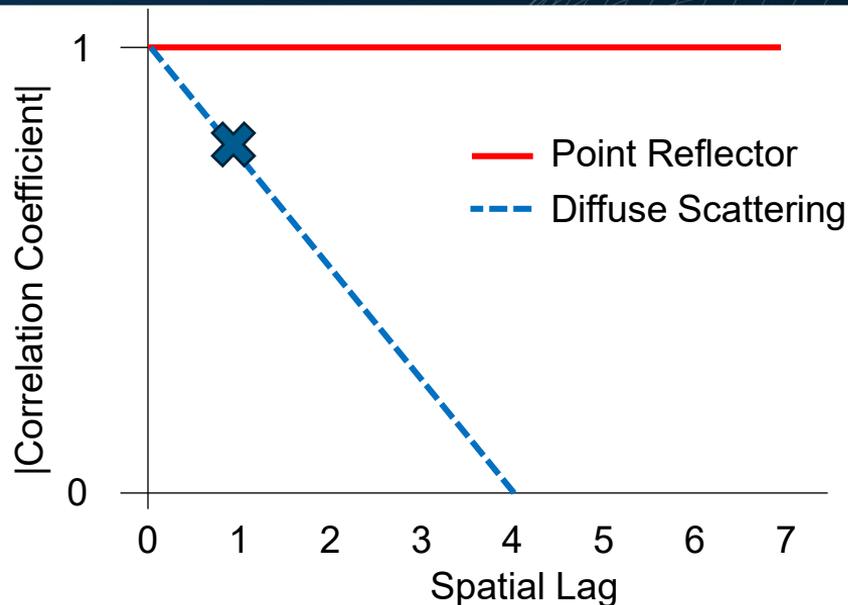
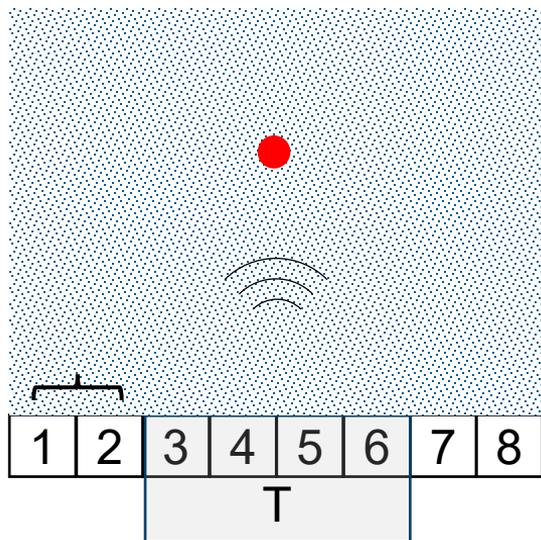


Motivation: existing UXO sonar surveys



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

Spatial Coherence: Targets vs. Background



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

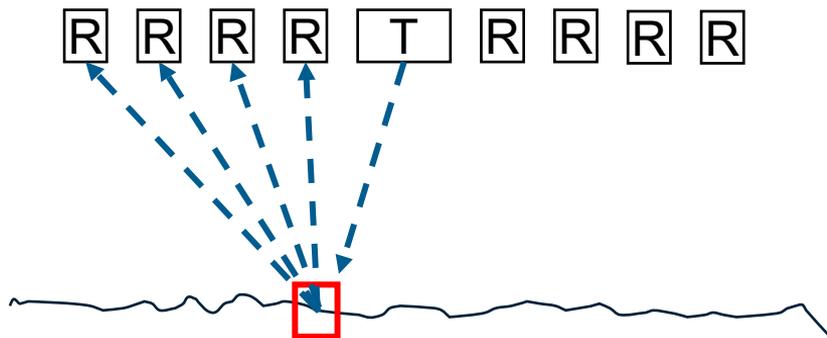
Convention reconstruction: delay and sum

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

Pressure propagates according to a 2nd order PDE

“Backprojecting pressure”

1. Calculate Delays



2. Add up all the signals

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

Coherence-based reconstruction

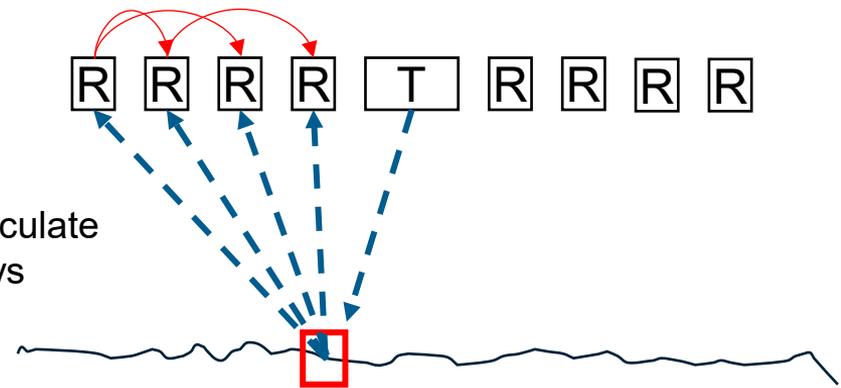
$$\nabla_1^2 \langle p_1 p_2^* \rangle - \frac{1}{c^2} \frac{\partial^2 y}{\partial x^2} \langle p_1 p_2^* \rangle = 0$$

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

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

“Backprojecting complex covariance”

2. Combinatorially multiply pairs of signals



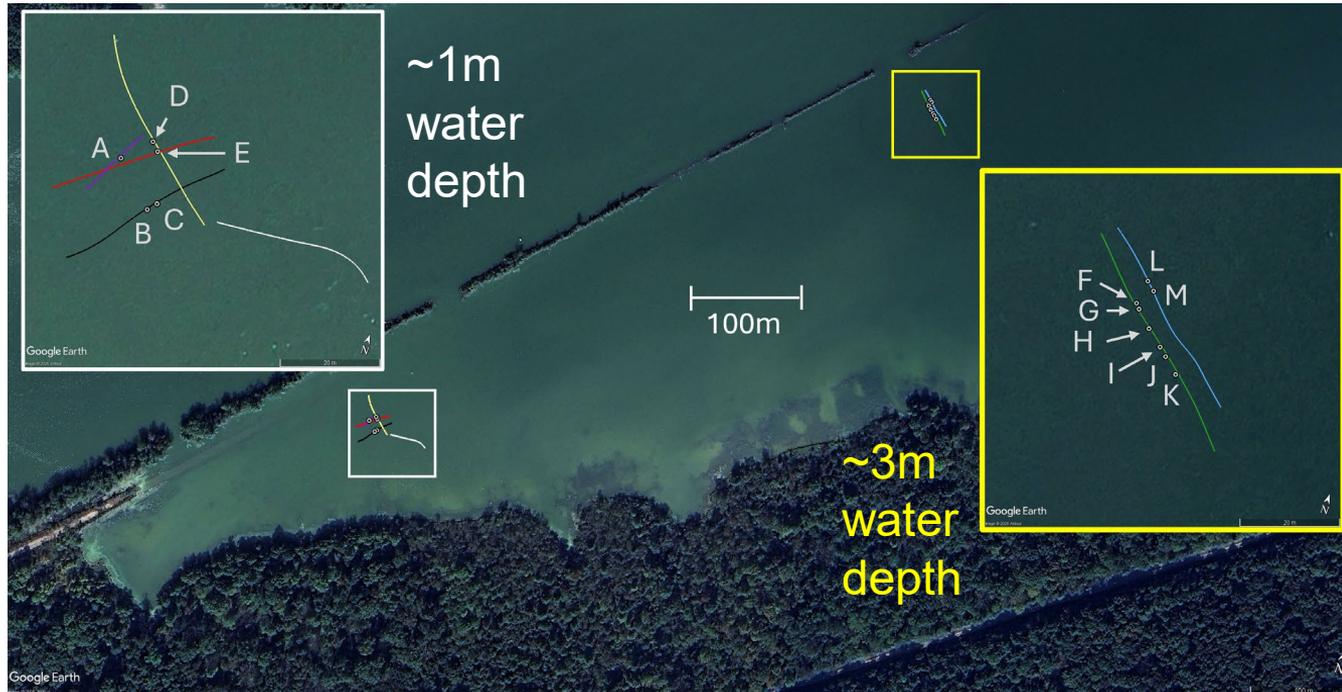
1. Calculate Delays

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

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

3. Sum the covariance matrix

Algorithms were applied to 2019 data collected by the SVSS.

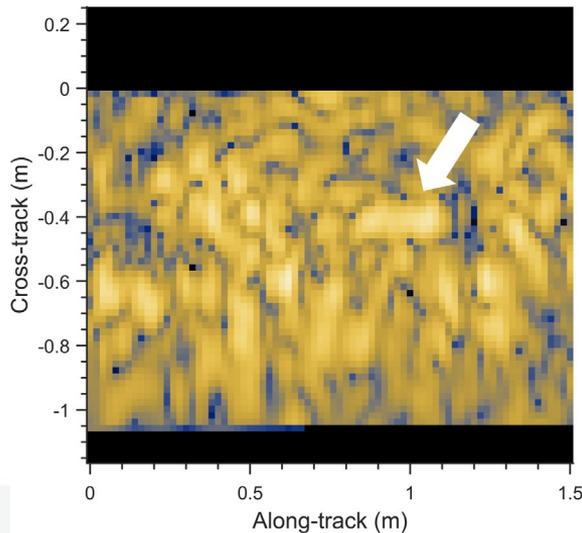
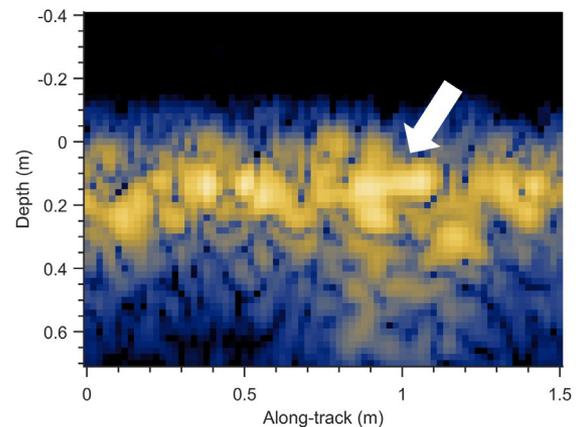


- Objects span a range of:
- Type (UXO, science, clutter)
 - Size
 - Shape
 - Burial Depth

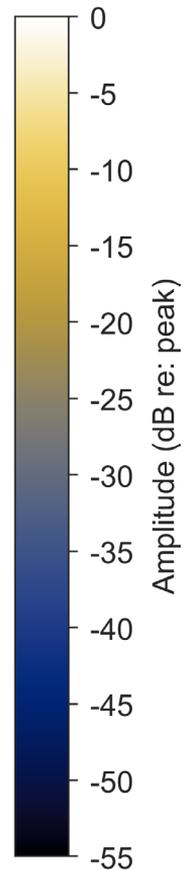
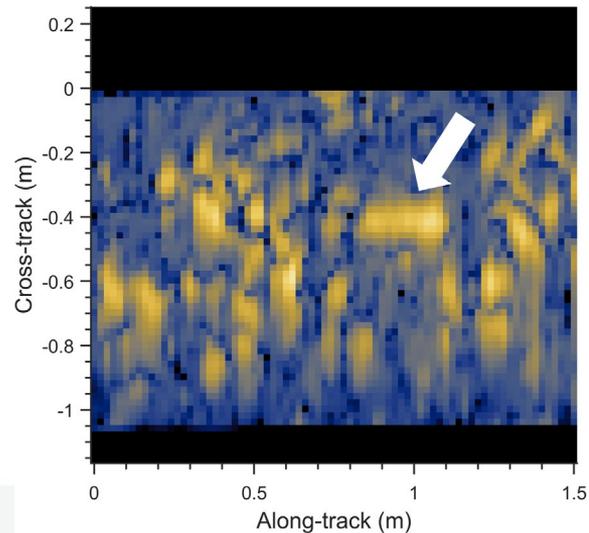
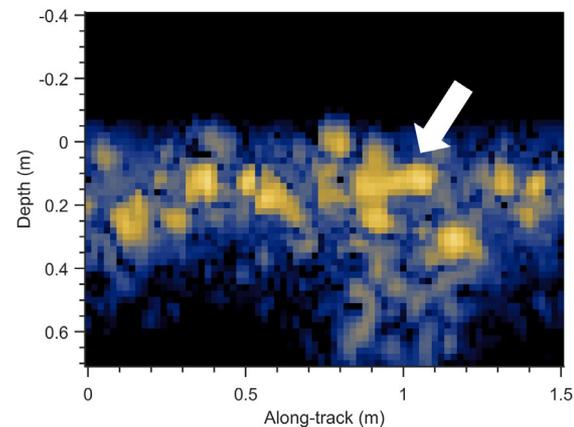


Inert 105mm
Projectile
Depth: 1.3m
Burial: 6cm

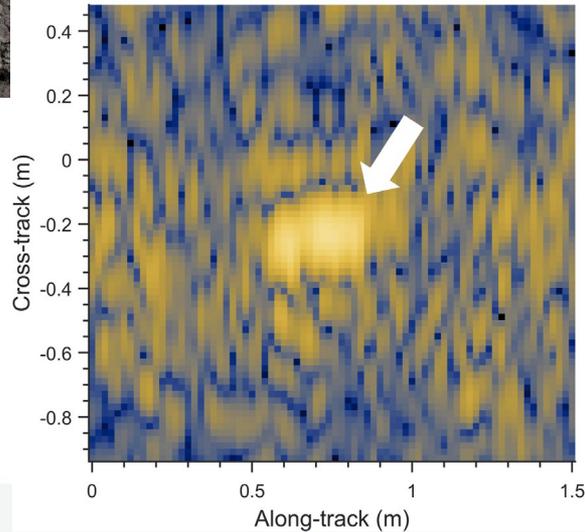
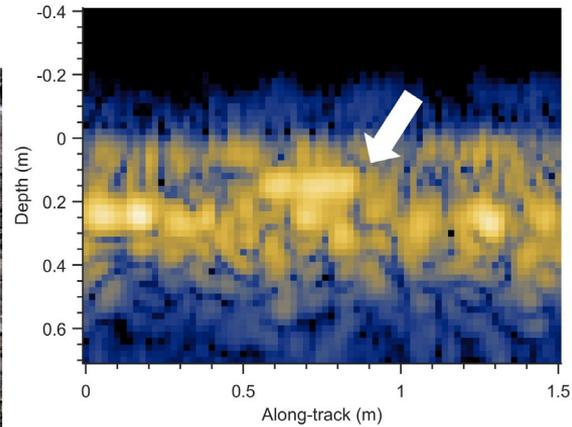
Conventional Reconstruction



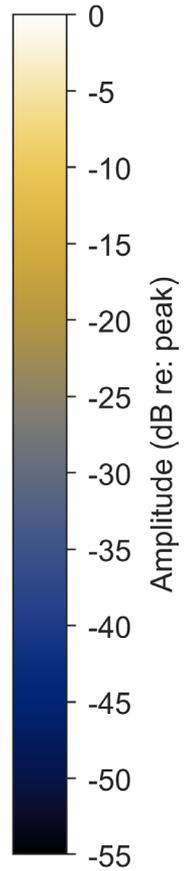
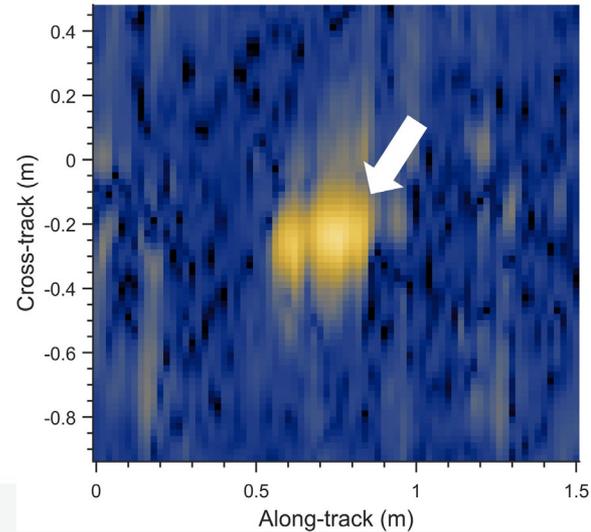
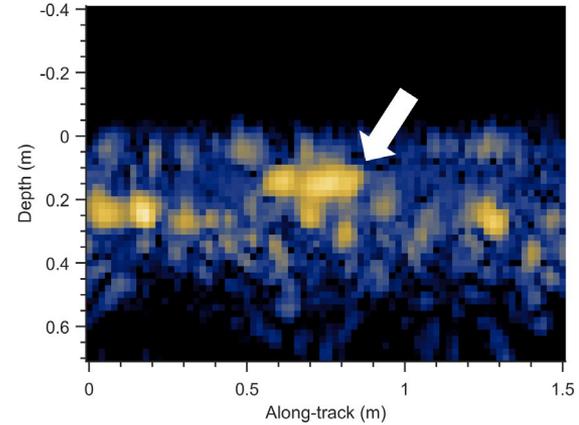
Coherence-based Reconstruction



Conventional Reconstruction



Coherence-based Reconstruction

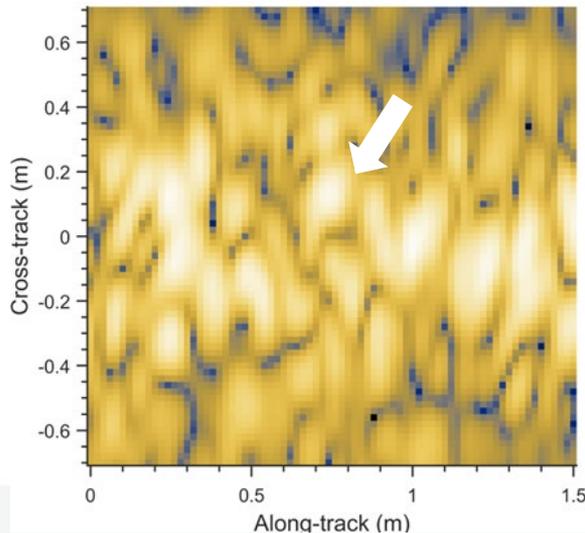
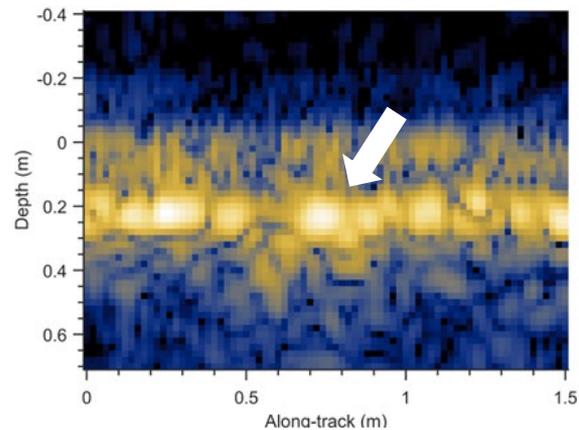


15x30cm
Aluminum
Cylinder
Depth: 2.9m
Burial: 9cm

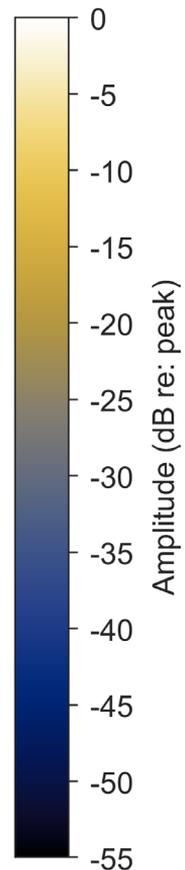
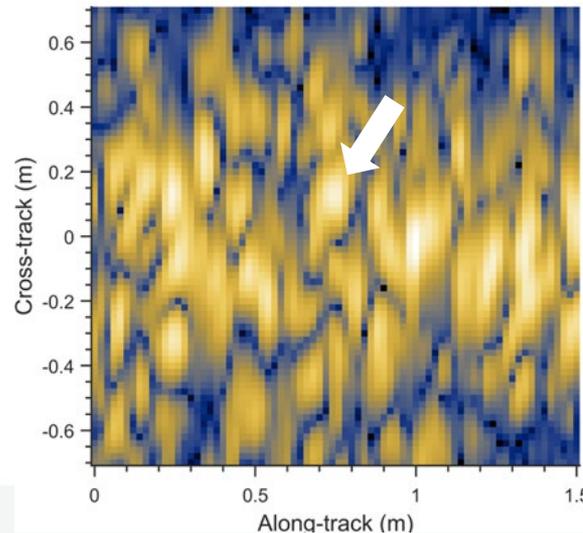
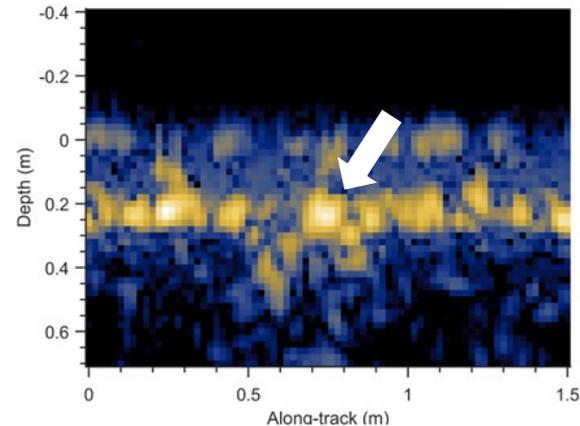


10cm
shotput
Depth: 3.0m
Burial: 16cm

Conventional Reconstruction



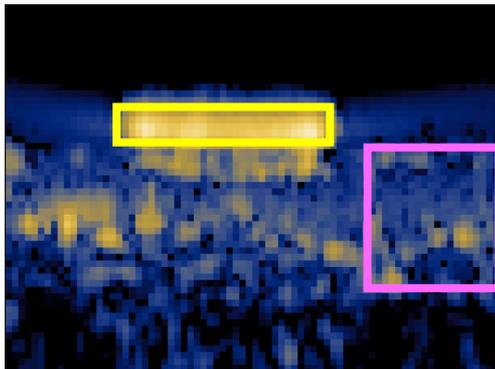
Coherence-based Reconstruction



Quantitative Comparison: Contrast

Contrast

- Common and intuitive
 - Image-domain SNR
- Reported on a decibel scale
- Higher contrast is easier for detection



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

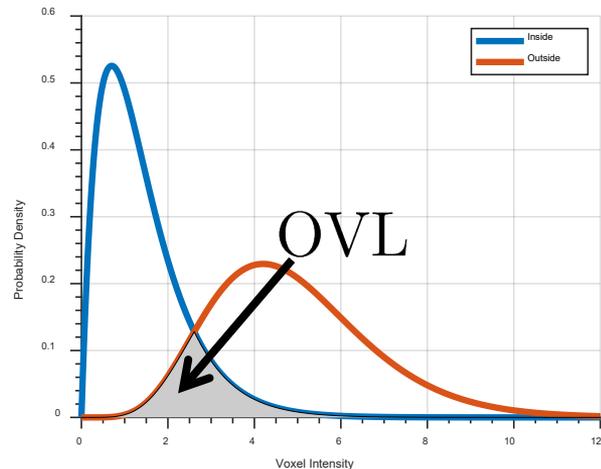
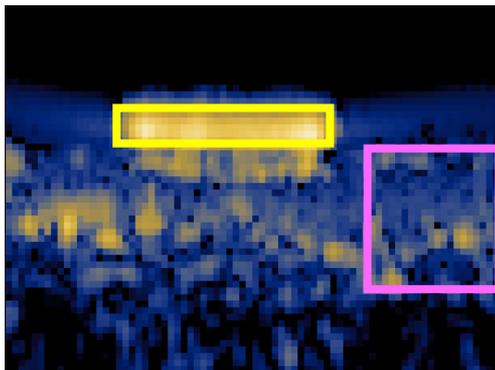
μ_i Mean UXO intensity

μ_o Mean background intensity

Quantitative Comparison: gCNR

Generalized Contrast to Noise Ratio (gCNR)

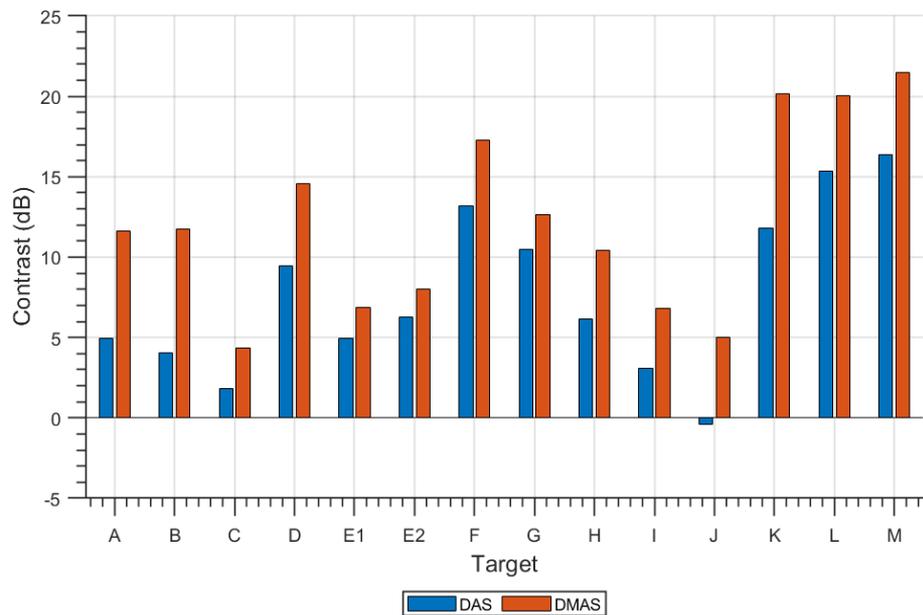
- Accounts for distribution of voxel intensity
- Immune to nonlinear warping
 - Bounded on $[0, 1]$
- Higher values correspond to easier detection.



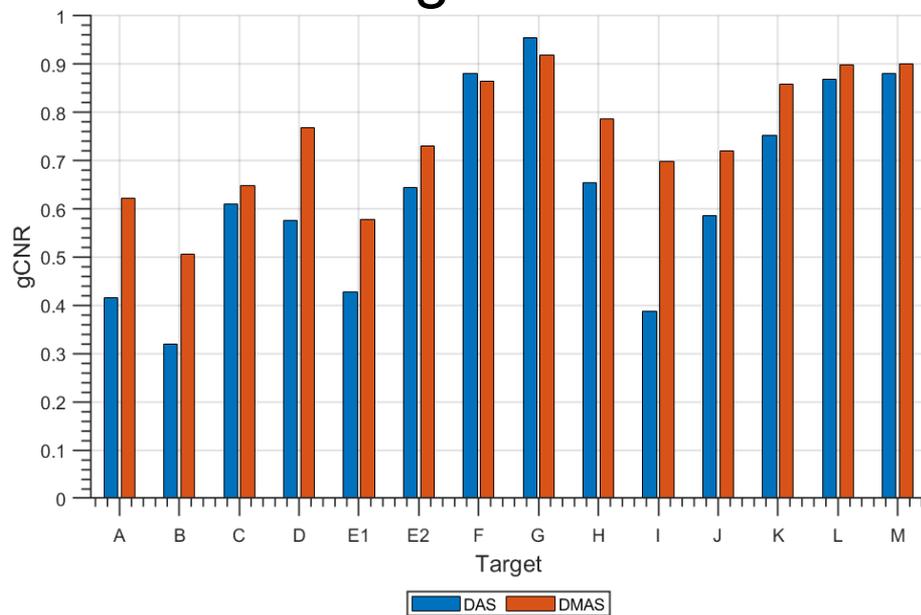
$$\text{gCNR} = 1 - \text{OVL}$$

Metrics show increased image quality

Contrast



gCNR



Summary

- Coherence-based reconstruction algorithms developed for SAS.
 - Theoretical framework provides basis for explainability.
 - Demonstrated on field data
- The reconstruction improves image quality and target detectability.
 - Increased contrast
 - Slightly enhanced resolution
- Exploits information in signals that has previously been discarded.
 - Theoretical guarantee: contrast never worse than conventional DAS.
 - Cost: increased computational load
- Key difference: slight cross-track “blurring”.
 - Paths identified for improvement.

Future Work: Detection

- Adapting detector algorithms to use coherence data products.
 - Pre-processing, normalization, etc.
- Statistical distributions for confidence scores.
 - Theoretical approaches validated by field data.
- Demonstration on new data:
 - Targets
 - Orientations
 - Environments
 - Sensors

Future Work: Classification

- Algorithm refinement
 - Improved point spread function
 - Acceleration
- Data fusion approach for information accessibility:
 - Resonant signature
 - Coherence-recovered geometric shape
 - Multi-look images
- Blind demonstration and scoring



BACKUP MATERIAL

Advances in the approach

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

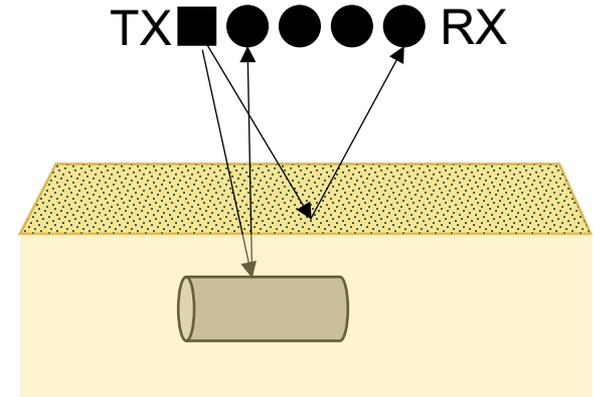
$$f(\xi) = \sum_{i=1}^{N \times M - 1} \sum_{j=i+1}^{N \times M} s_i s_j^*$$

“Backprojecting complex covariance”



$$f(\xi) = \sum_{i=1}^{N \times M - 1} \sum_{j=i+1}^{N \times M} \frac{s_i s_j^*}{\sqrt{|s_i s_j^*|}}$$

“Backprojecting complex co-standard deviation”



A set of 13 objects were analyzed.

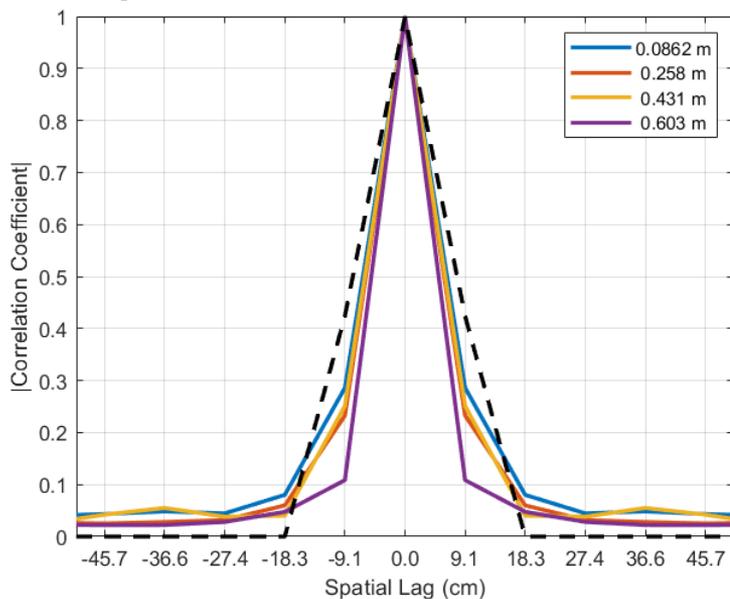
Target	Description	Length	Width	Water Depth	Burial Depth
A	solid concrete cylinder	30.5 cm	15.2 cm	1.3 m	0 cm
B	steel pipe	30.5 cm	11.4 cm	1.2 m	0 cm
C	steel sphere	N/A	10.2 cm	1.2 m	0 cm
D	inert 155 mm howitzer	86.2 cm	15.5 cm	1.3 m	4 cm
E	inert 105 mm projectile	46.1 cm	10.5 cm	1.3 m	6 cm
F	solid aluminum 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:

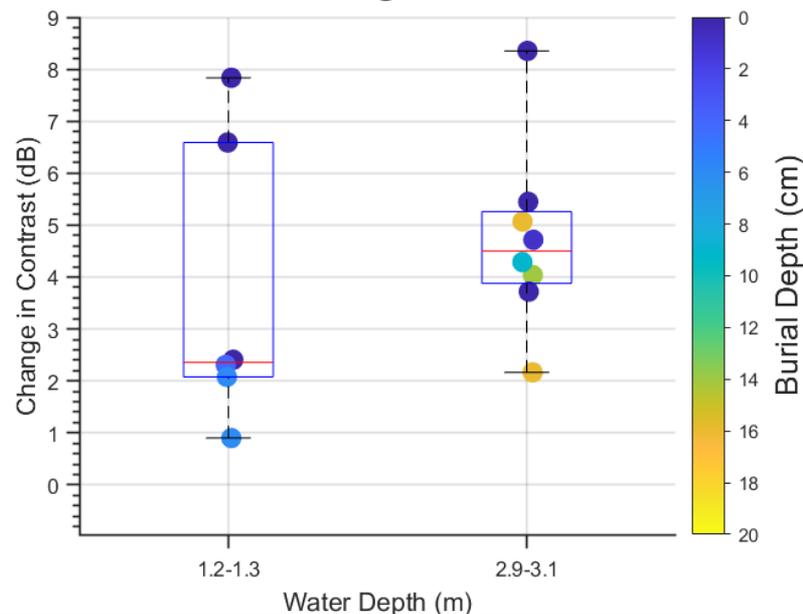
- Type (UXO, science, clutter)
- Size
- Shape
- Water depth
- Burial Depth

Data analysis & modeling explain contrast.

Spatial Coherence of Sediment

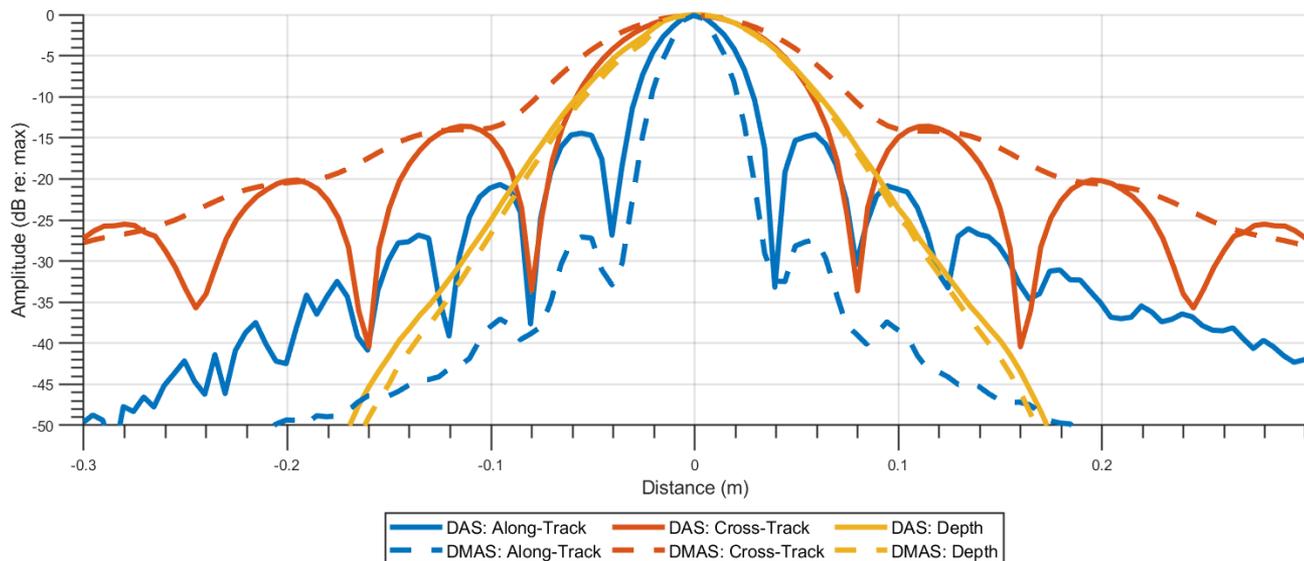
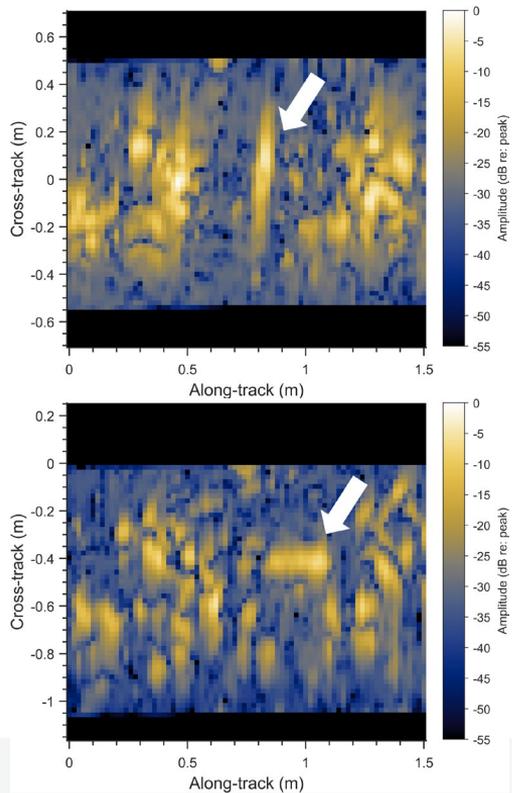


Contrast Change: DAS → DMAS



Modeling shows that contrast will increase with synthetic aperture size.

Point spread function explains appearance.



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

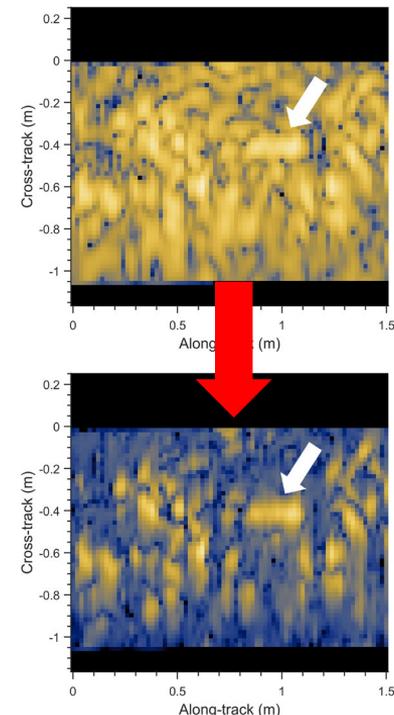
- *Develop sensor agnostic reconstruction algorithms*
- *Demonstrate on field data from a SERDP sonar system*
- *Quantify and explain performance gains*

Project Progress and Results

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

Technology Transition

- *Algorithms are sensor-agnostic and can be applied to all downward-looking SAS systems used by SERDP.*
- *Future work to establish practices for detection and classification.*

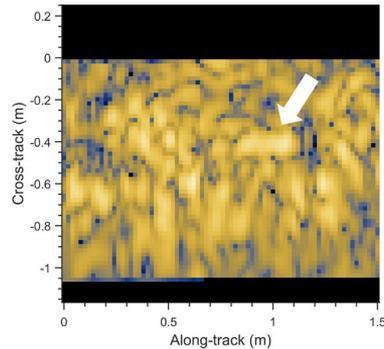


Plain Language Summary

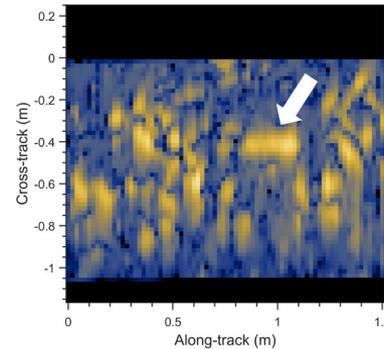
- Current sonar image reconstruction makes it hard to detect UXO when they are buried near the top of the sediment.
- Image reconstruction algorithms, inspired by biomedical ultrasound, are being developed to best exploit differences between UXO and the seafloor.
- The algorithms are sensor agnostic 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

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>
- T.E. Blanford, D.C. Brown, S.F. Johnson; “Application of a Delay, Multiply, and Sum Reconstruction Algorithm to a Synthetic Aperture Imaging Sonar”. *IEEE Journal of Oceanic Engineering* (in review).

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