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

- Adapting alternative acoustic image reconstruction techniques to the munition detection problem.
- Initial algorithm development through simulation has worked well.
  - SERDP's investment in sonar scattering models aided this program.
- Computational intensity of simulation and reconstruction has slowed progress.
  - Problem is pushing boundaries of models for seafloor scattering.
- Solutions are in place to keep project on track.

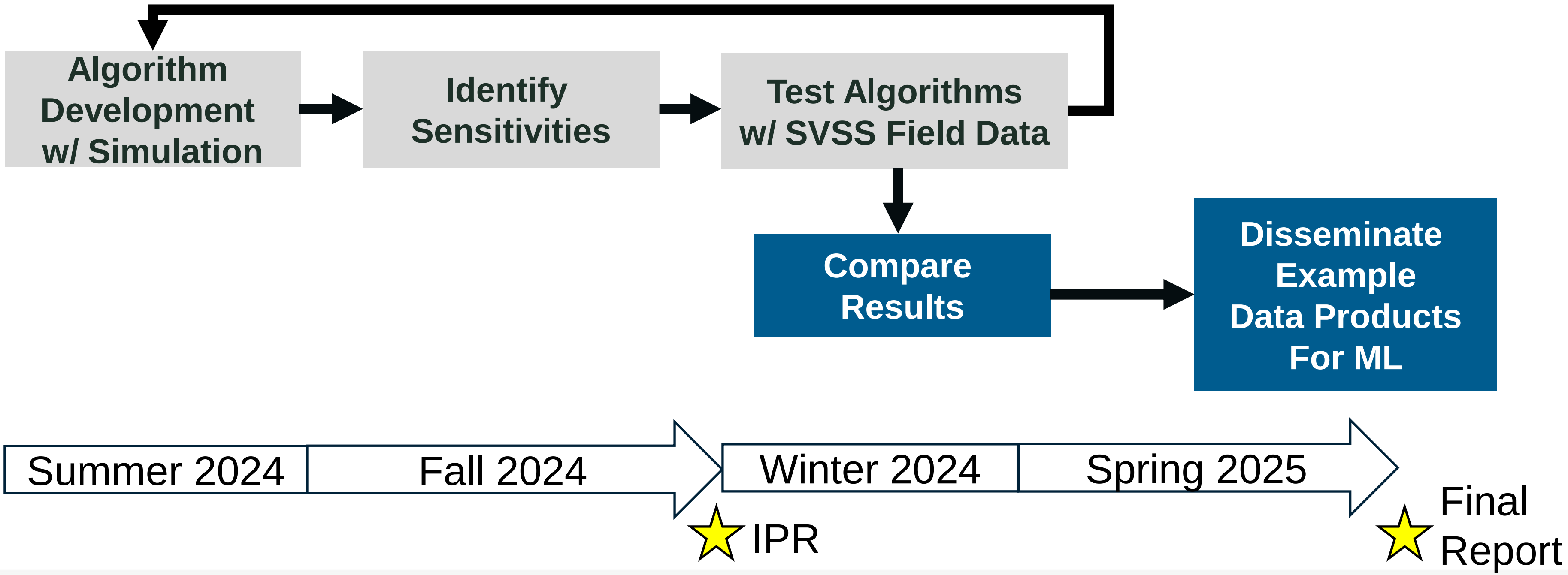
Technical Objective

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

1. Adapt coherence-based reconstruction for munitions surveys to improve image quality and aid detection and classification.

2. Quantitatively and qualitatively assess image quality with field data, comparing to conventional reconstruction.

Technical Approach



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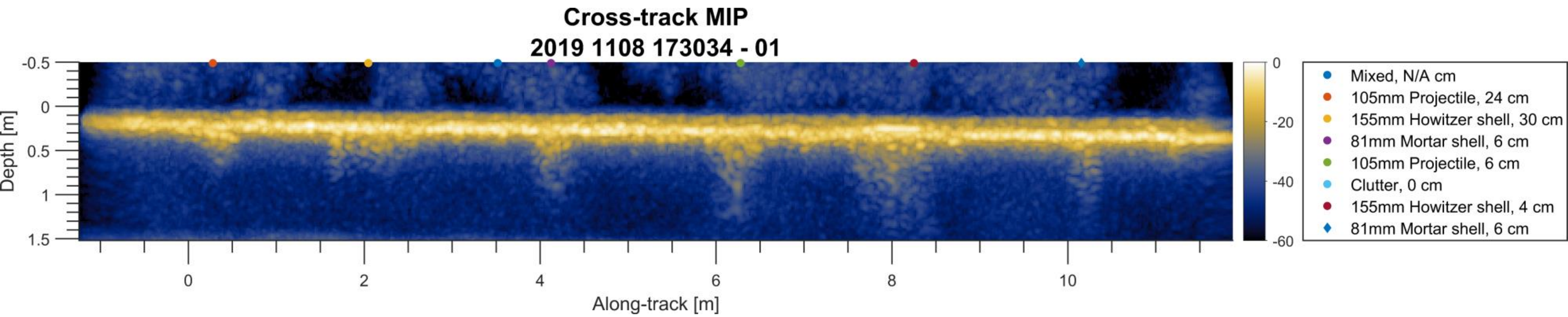
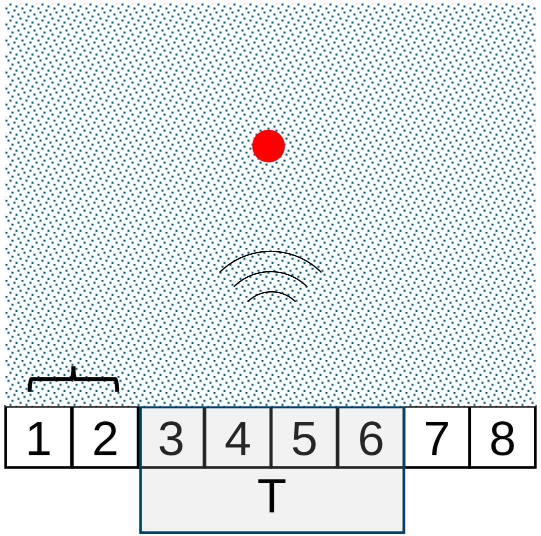
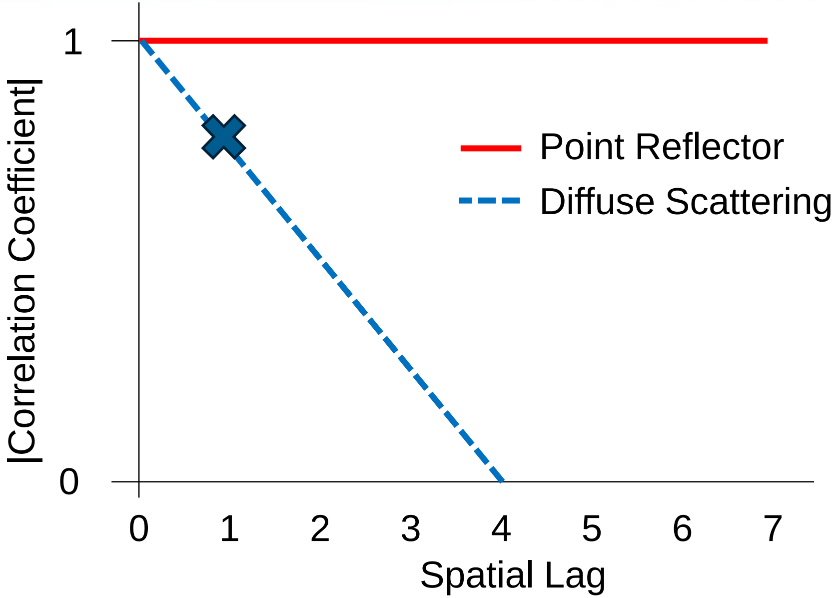
Motivation: UXO sonar surveys



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

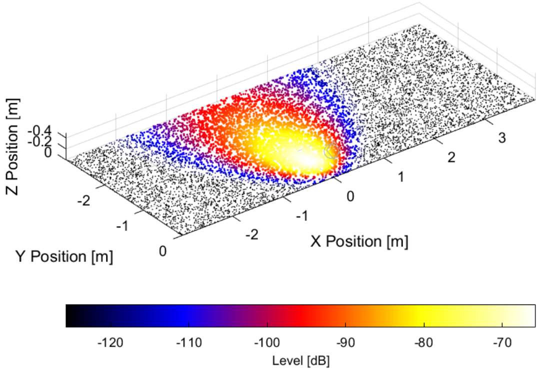
Spatial Coherence: Targets vs. Background

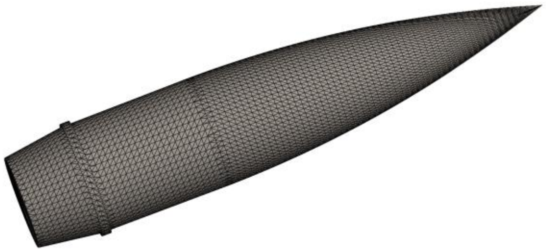


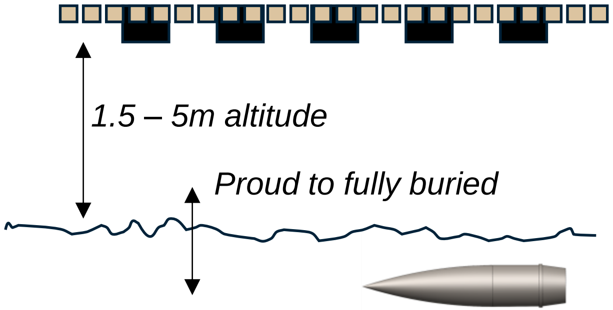


Algorithms attempt to exploit differences in coherence between objects and the environment.

Simulation: Point-based Sonar Signal Model







- Computationally intensive: many points required for coherence to converge.
- “Secondary” effects not simulated: broadband beams, occlusion, multipath, elastic resonances

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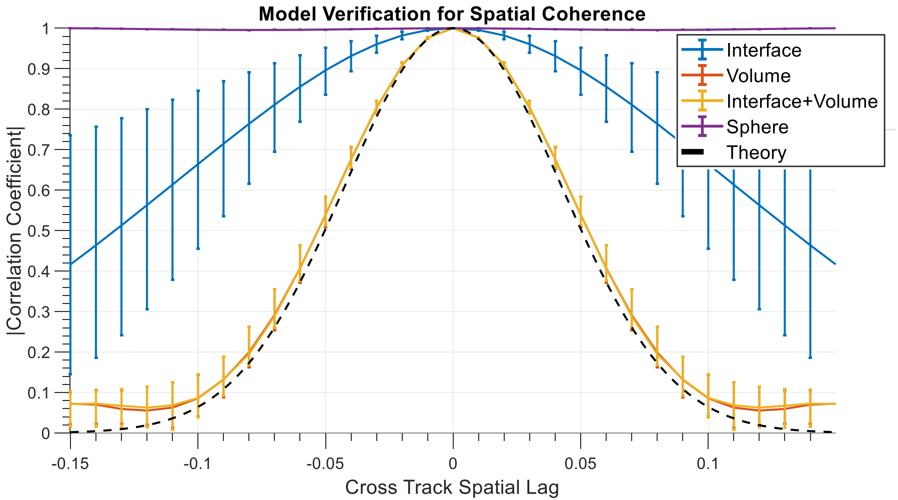
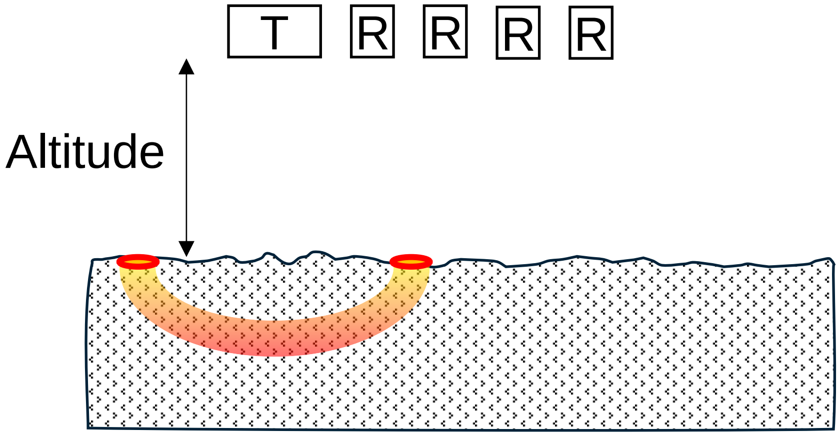
Model Baseline for Simulation



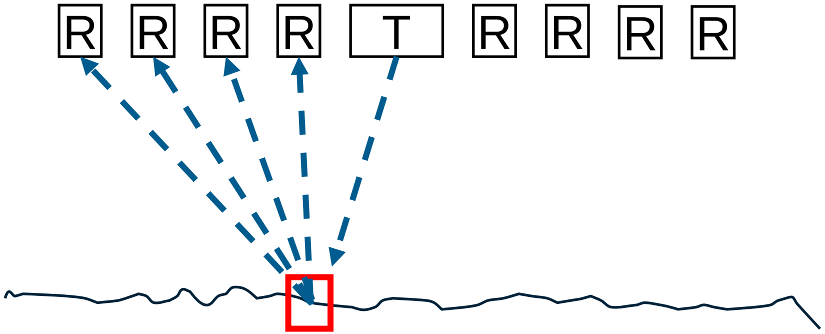


- Spatial coherence in munitions survey geometry not previously studied.
- Approximations break down: far-field, narrowband
- Verification through related theory and controlled laboratory data

Delay and Sum: Conventional Reconstruction

"Backprojecting pressure"

1. Calculate Delays



2. Add up all the signals

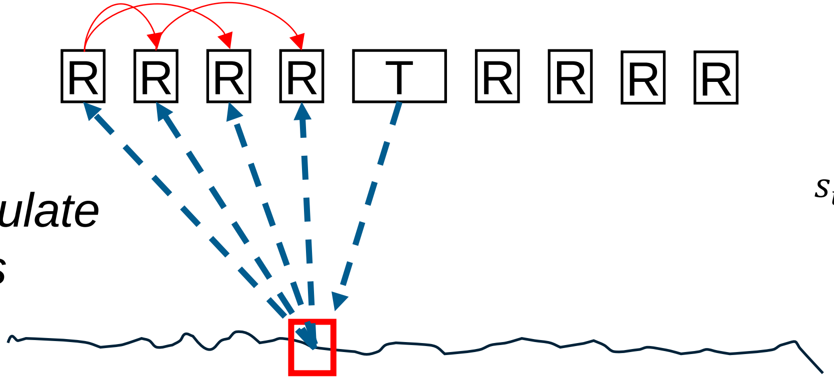
$$D(\bar{\chi}_S) = \sum_i^N p\left(\frac{1}{c}\left(|\bar{\chi}_S - \bar{\chi}_T| + |\bar{\chi}_S - \bar{\chi}_{R_i}|\right)\right)$$

DAS is the standard approach for underwater acoustic imaging.

Delay, Multiply, and Sum: Adaptation

"Backprojecting covariance"

2. Combinatorially multiply pairs of signals



1.Calculate Delays

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

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

3. Sum the covariance matrix

DMAS is readily adaptable.
Further refinement for environmental properties may be warranted.

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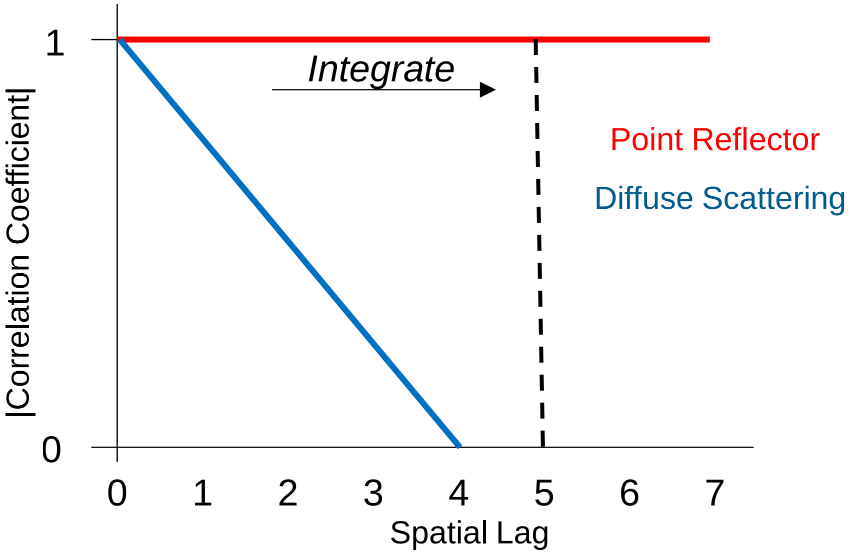
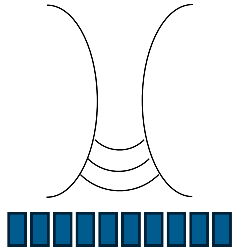
Short-Lag Spatial Coherence: Adaptation

"Spatial Map of Coherence Length"



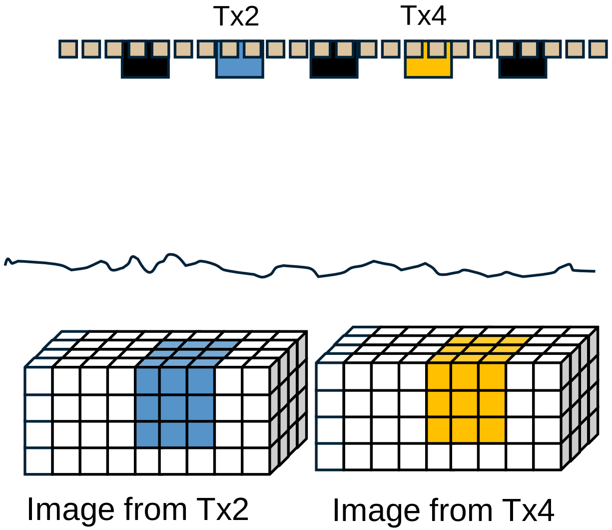
Biomedical:
Converging transmit provides focusing

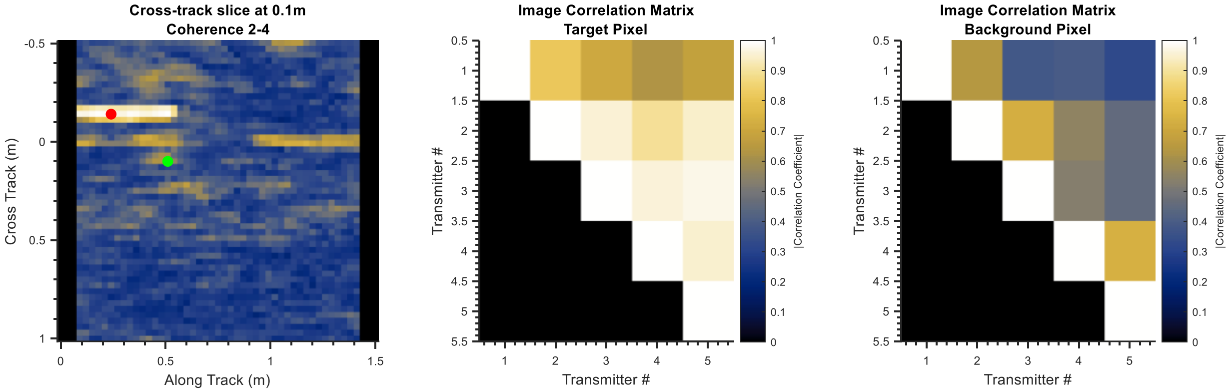


SAS:
Diverging transmit beam, moving array.
Focused only on reconstruction

SLSC algorithms cannot be directly applied.
SAS arrays don't support simultaneous focusing and coherence estimation.

Short-Lag Spatial Coherence: Challenges





SLSC-inspired approaches not viable without changes to array geometry.

But…interesting result relating to occlusion and shadows.

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Image Algorithm Recap

- Short-lag spatial coherence approaches not pursued further.

- Comparisons on simulated data:
  - delay and sum (DAS)
  - delay, multiply and sum (DMAS)

- Multi-static occlusion estimation using coherence

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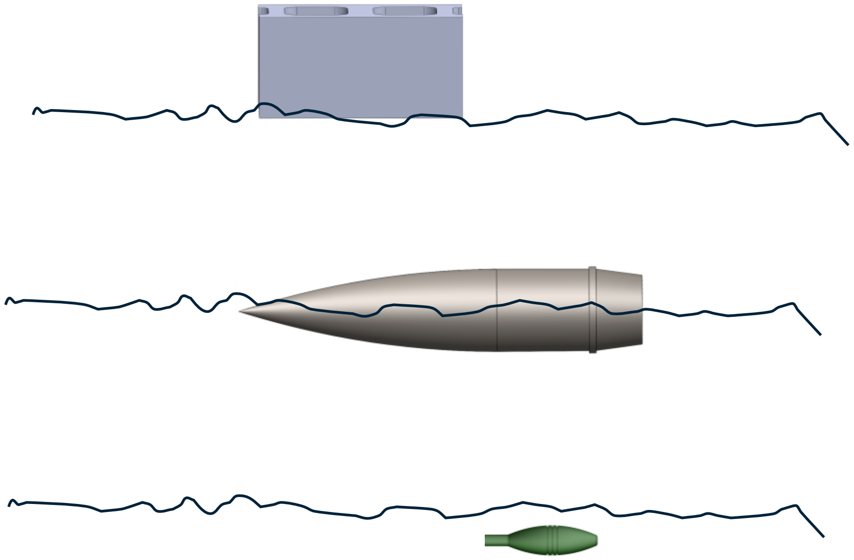
Overview of simulations



- Objects
  - Proud cinder block
  - Partially buried “155mm Howitzer”
  - 3cm buried “60mm mortar”
- Orientations
- Environments
  - Silt
  - Sand
- Uncompensated motion
- Altitude

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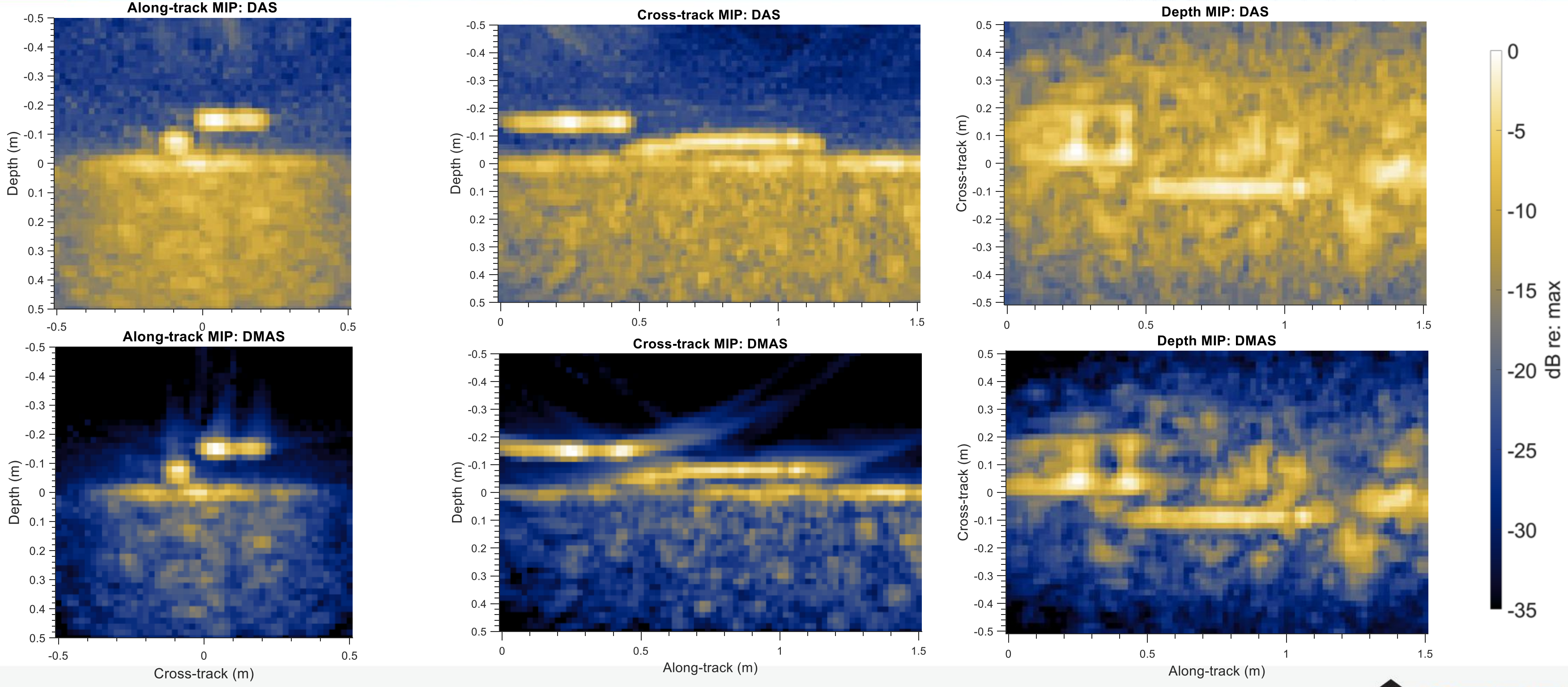
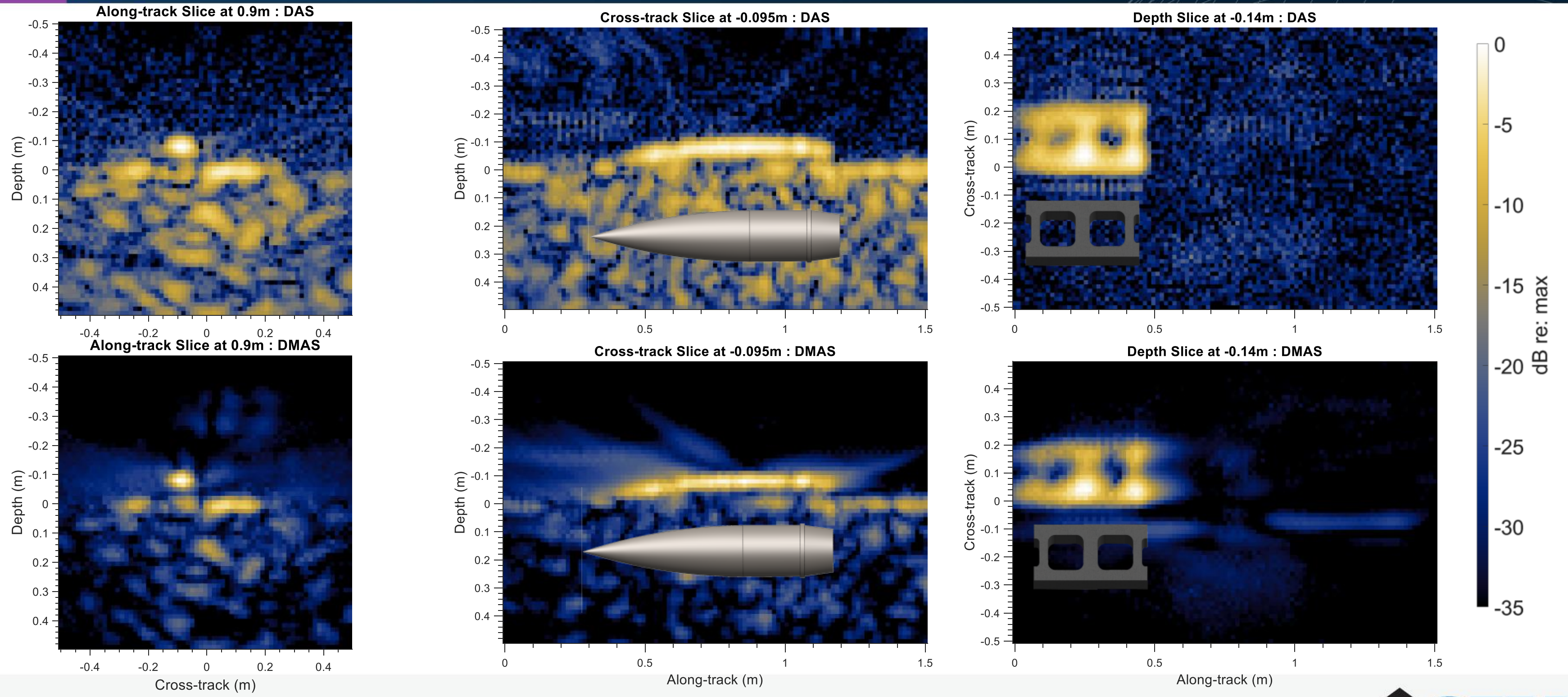
MIP Comparison: DAS vs. DMAS



Slice Comparison: DAS vs. DMAS



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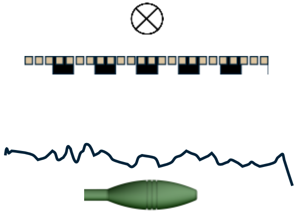
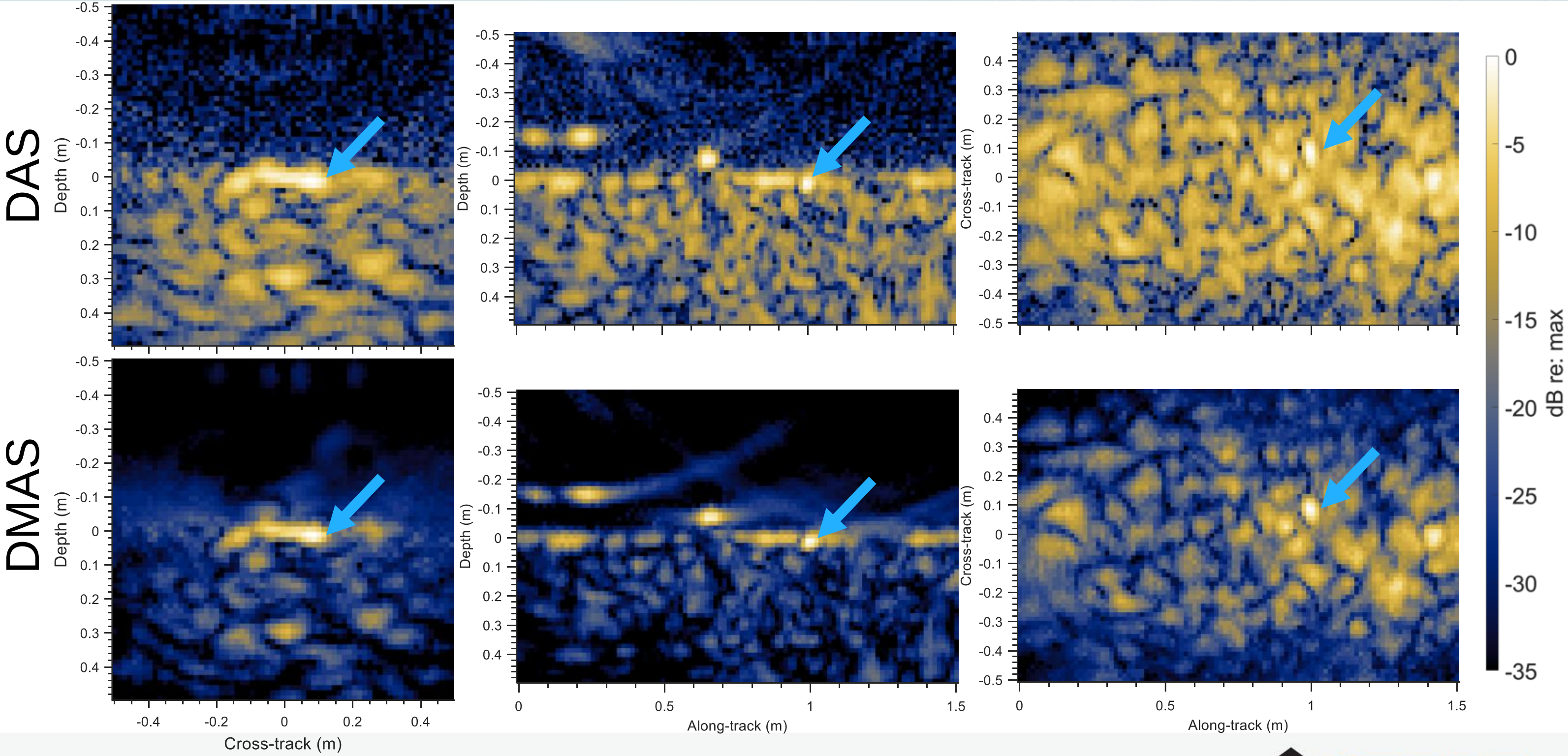
Detectability of Small Targets



Target now rotated so length is parallel to array.



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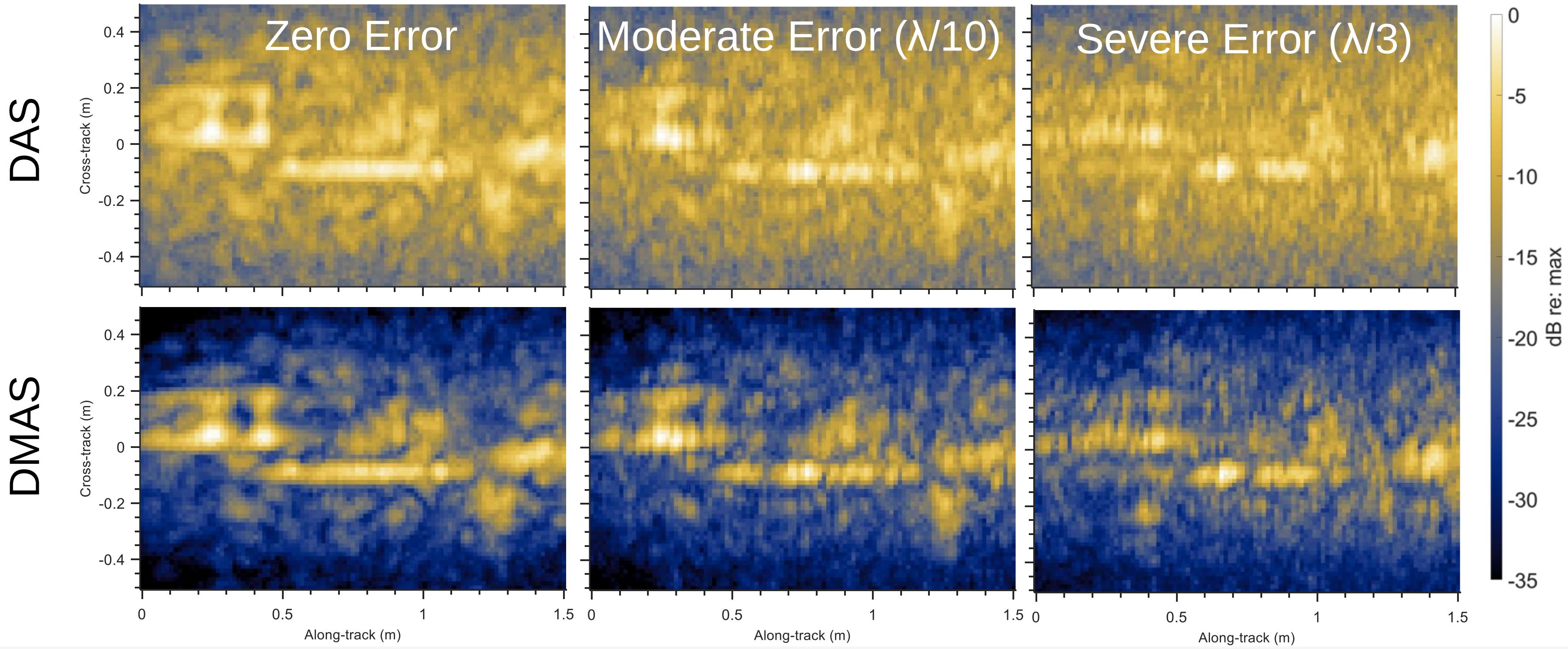
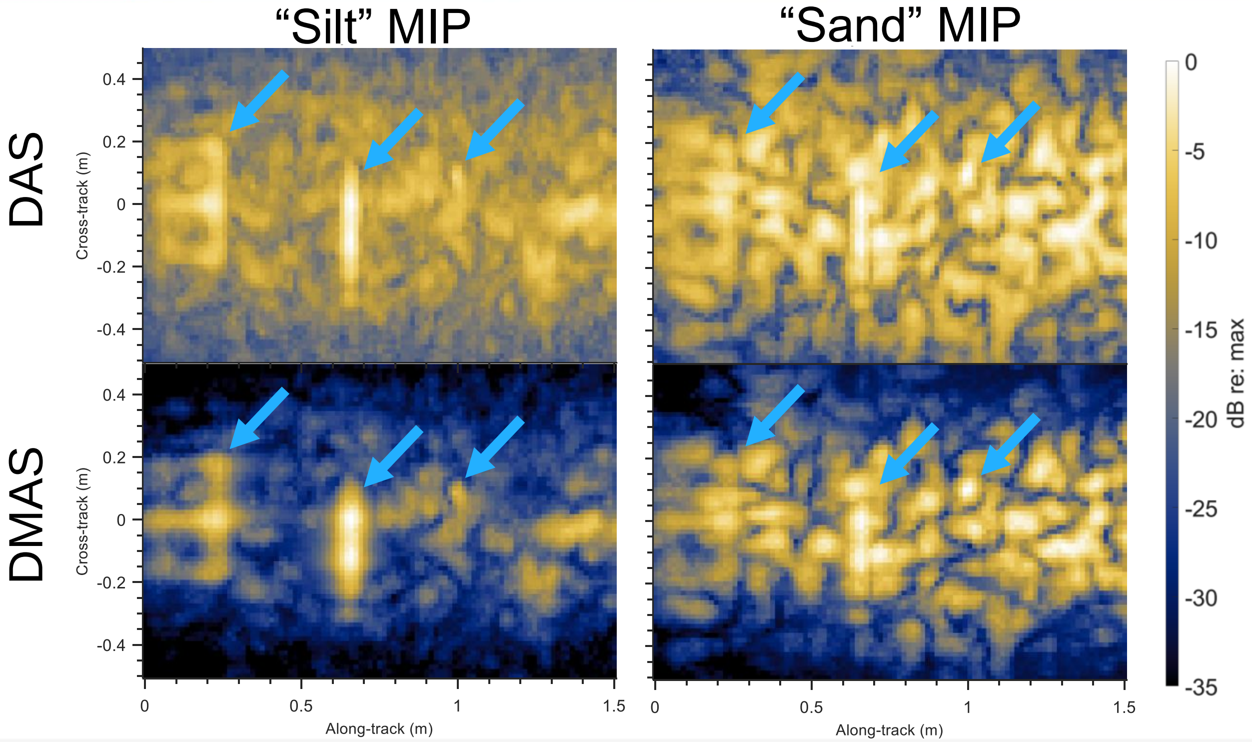
Sensitivity to Motion Error



Sensitivity to Bottom Type



DMAS improves imagery for both sediments.

Simulation may lack fidelity needed for further refinement.

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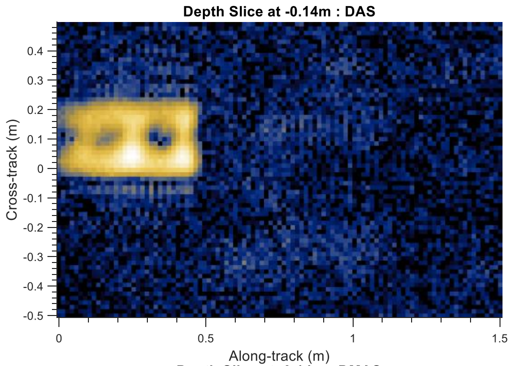
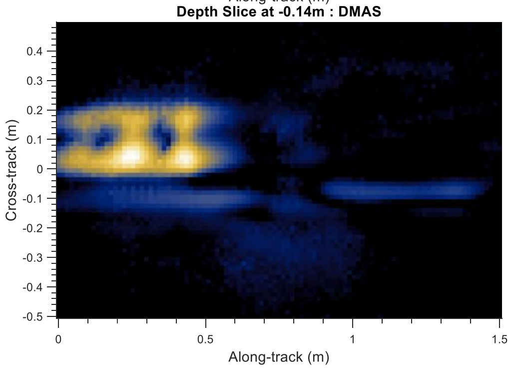
Reconstruction Quality vs. Altitude

1.5m altitude



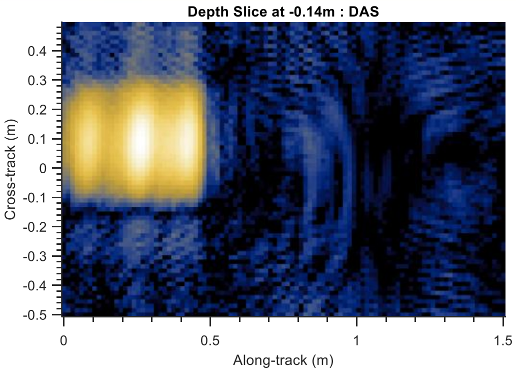


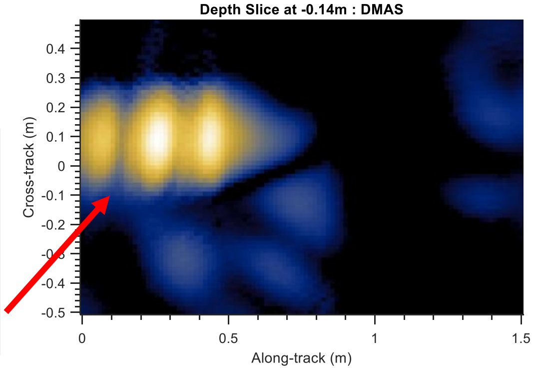
Along-track: synthetic aperture

Cross-track: real aperture

DMAS improvement is greater in along-track because more “elements”

5.0m altitude





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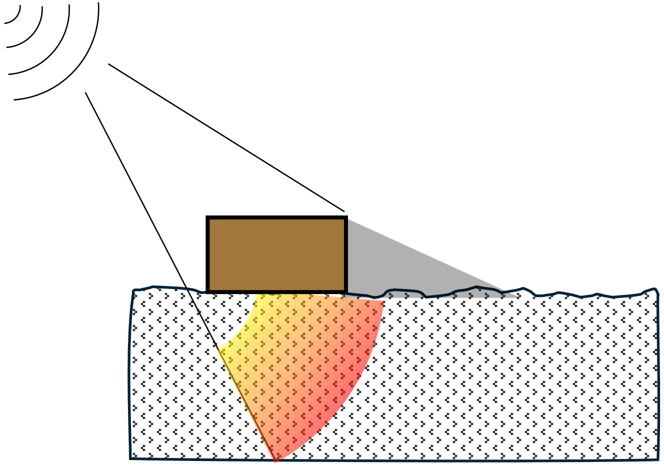
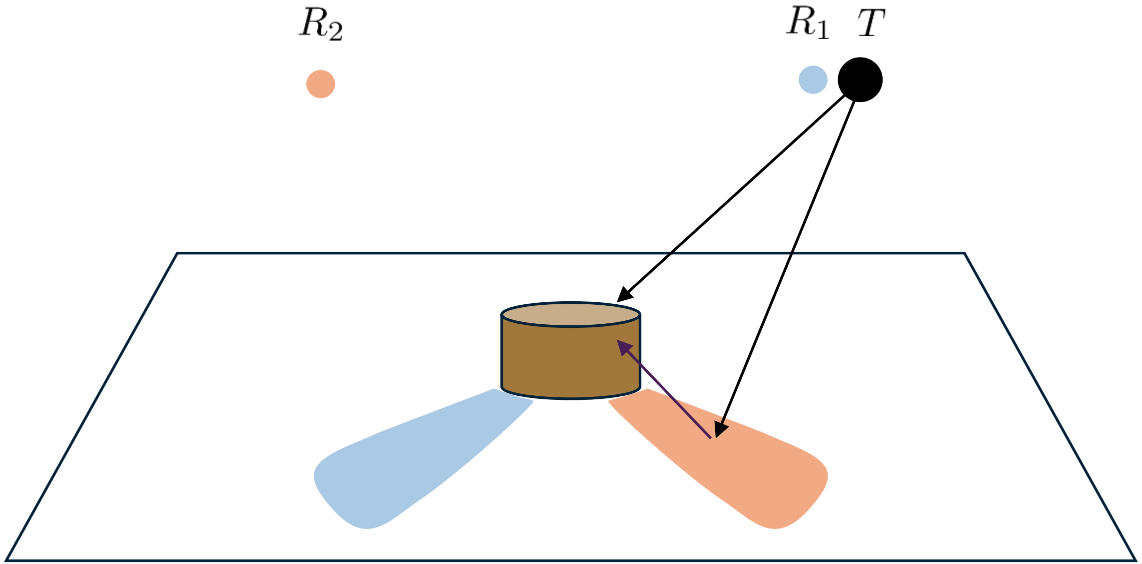
(Un)expected Computational Challenges

- Simulation and reconstruction are both computationally intensive
  - PoSSM simulation
    - Many scattering elements needed for high fidelity
    - GPU accelerated, largely well-optimized
  - Reconstruction
    - Many more operations per voxel
    - Biomedical literature describes challenges and potential solutions
- Reconstruction algorithms required acceleration in R&D to make timely progress.
- Computational resources limited by procurement delays

Occlusion for Multi-static Sonars





Shadows are important features, but rarely observed in images from low frequency SAS systems.

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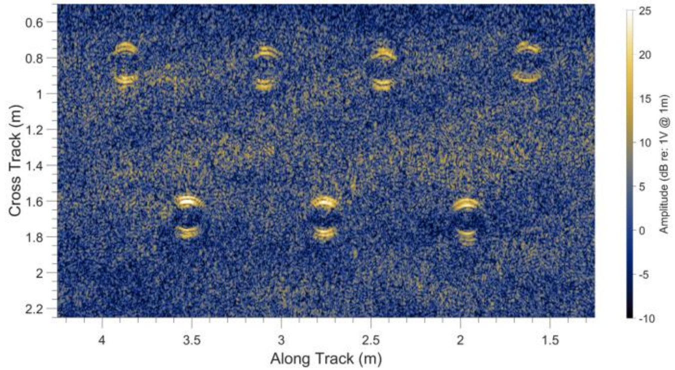
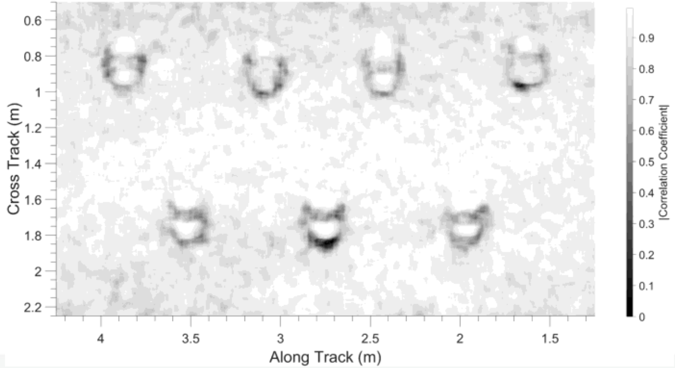
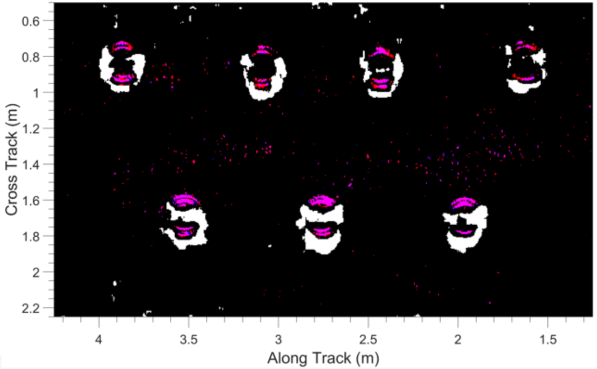
Occlusion Detection with Coherence







Recovered "shadows" provide clues about object height, pose, and burial depth.

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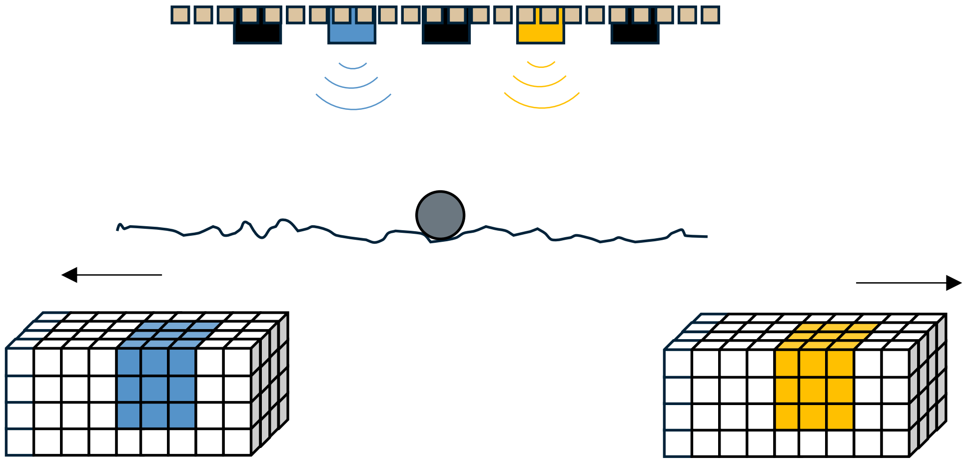
Future Research

- There is valuable information in signal coherence that is not currently being accessed in image reconstruction.
- Initial results show plenty of promise:
  - Speckle rejection, enhanced resolution in simulated data
  - Occlusion and burial with multi-static coherence in laboratory data
- Need to continue with application to field data
  - Focus of remaining effort in this SEED program.
  - Future research recommendations pending these results.
  - Rigorous software acceleration would need to be part of any follow-on effort.

BACKUP MATERIAL

Short-Lag Spatial Coherence: Rotation

Target features appear this side



Target features appear this side

Symmetry to targets yields coherence.
But target self-occlusion requires image flipping to realize it.

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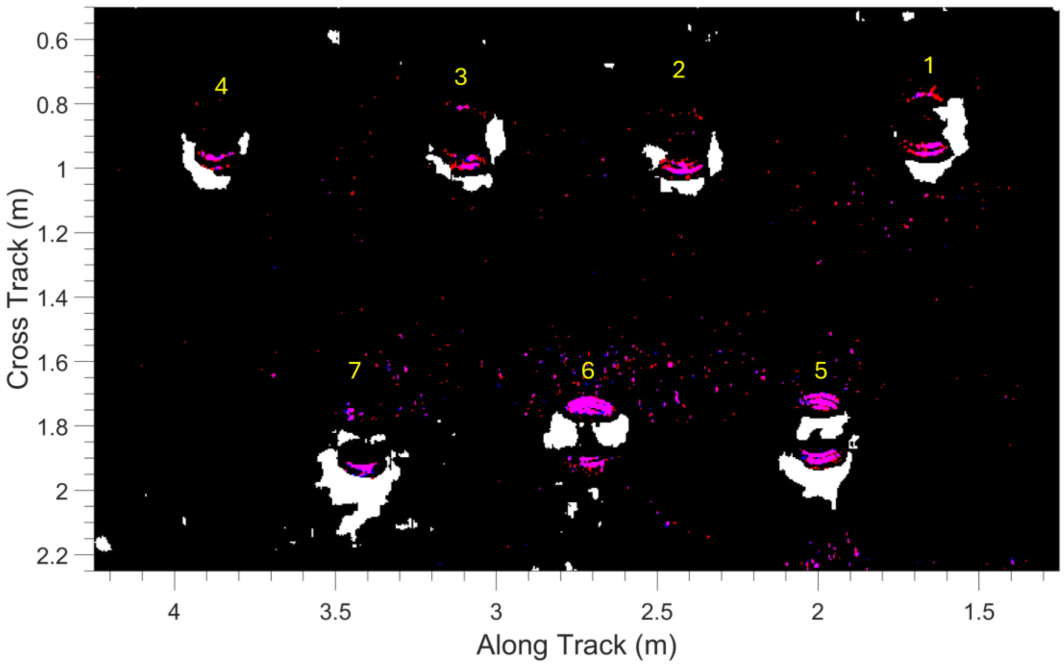
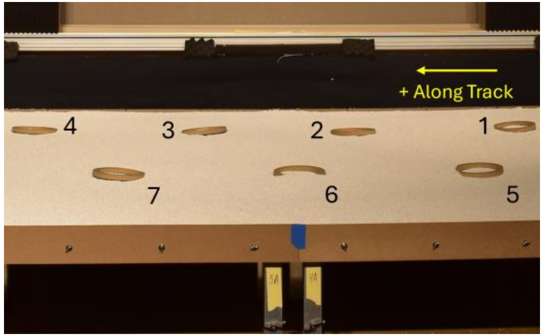
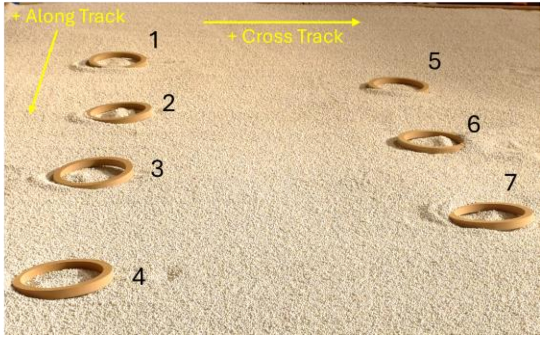
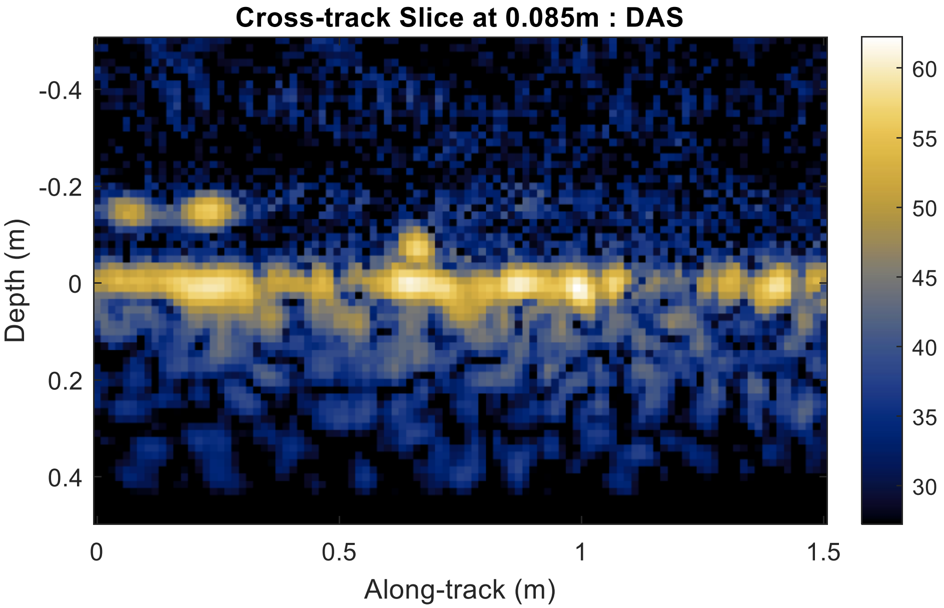
Coherence “shadows” to determine burial

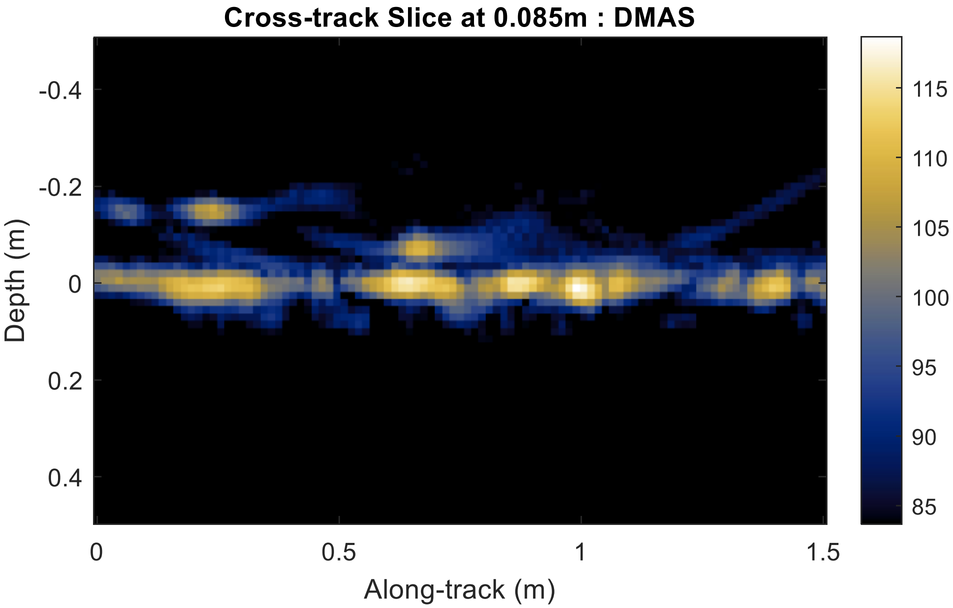






Algorithm comparison: sand background





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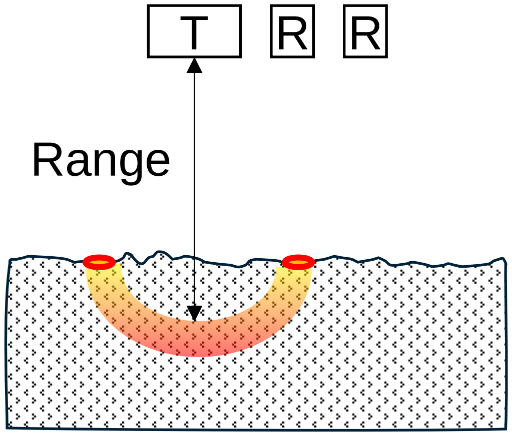
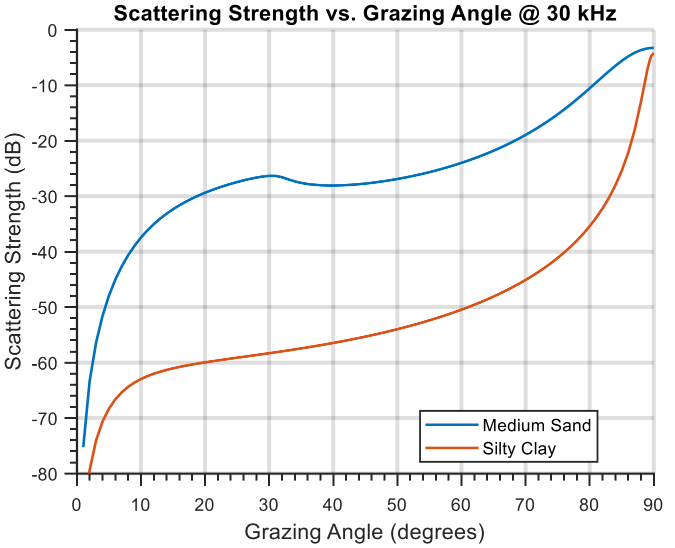
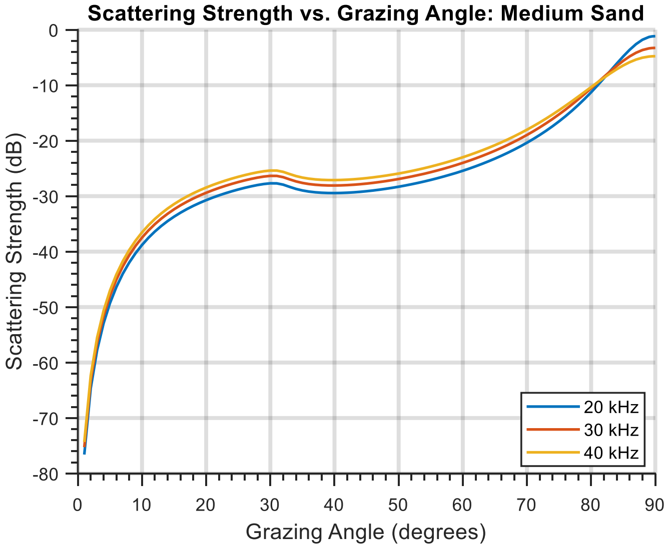
Seafloor’s effect on coherence







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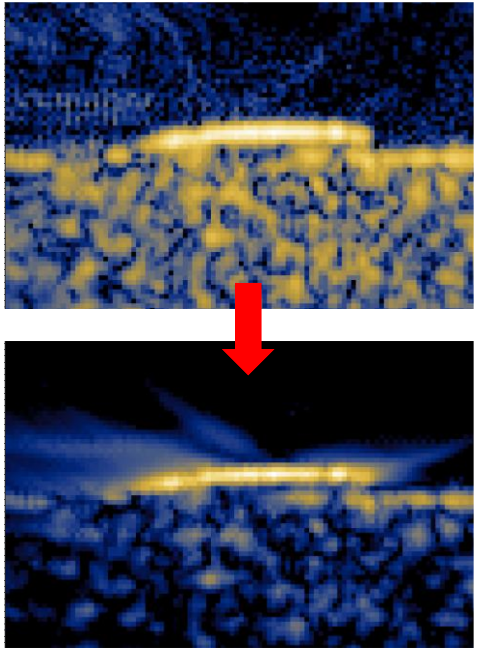
MR24-4520: Spatial Coherence Based Reconstruction for Detection of Underwater Munitions

Performers: Thomas Blanford, University of New Hampshire



Technology Focus

- *Summarize technology or methodology being studied or developed*

Research Objectives

- *Develop coherence-based image reconstruction algorithms to better detect UXO*
- *Sensor agnostic algorithms that can be readily adapted*
- *Assessment of data product's utility in ATR pipeline*

Project Progress and Results

- *Results from simulation and laboratory data demonstrated improved image quality and context about targets*
- *Next step: apply to field data from SERDP sensors*

Technology Transition

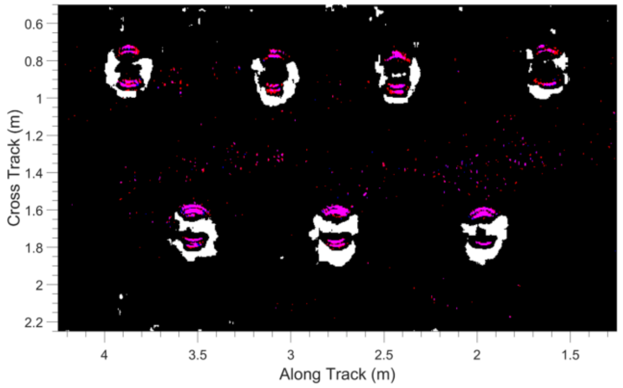
- *Incorporate into an automated target recognition and classification pipeline*
- *Algorithm acceleration*

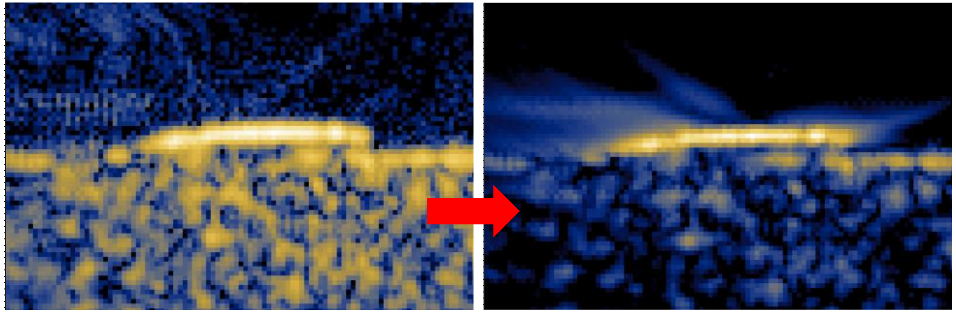
Plain Language Summary

- Sonar image reconstruction algorithms use simple delay-and-sum beamforming.
  - This doesn’t use all the available information in the signals.
- There are expected differences between objects and the background in how similar their signals are across an array.
- By adapting algorithms from biomedical ultrasound, we exploit these differences to improve image quality for better detection and classification of UXO.

Impact to DoD Mission

- Preliminary results show that image quality can be substantively improved through alternative reconstruction with no hardware changes.
- Alternative data products provide additional context about UXO shape, pose, and burial.





Publications

- T.E. Blanford, “Occlusion and height estimation using the coherence of multi-static synthetic aperture sonar images”, JASA-EL, 2024 (in review).

Literature Cited

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