



Advanced Sonar-Based Deep Learning for Underwater UXO Remediation

MR21-3543

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Applied Research Laboratory, Penn State University (ARL-PSU)

In-Progress Review Meeting

20 May 2025

Project Team



**David
Williams**
ARL-PSU

- Solo execution, but data/assistance from Tim Marston (APL/UW), Kevin Williams (APL/UW), Dan Brown (ARL-PSU).

Bottom Line Up Front

- Developing ATR algorithms for proud and buried UXO using acoustic data from downward-looking sonar systems
- Successes: algorithm development; blind test-bed evaluations (partial)
- Challenges: obtaining field data (and auxiliary info) for processing
- Support: N/A

Technical Objective

- Develop **fully automated** detection and classification algorithms for volumetric sonar data from the SVSS and MuST systems
 - No subject-matter-expert human-in-the-loop required

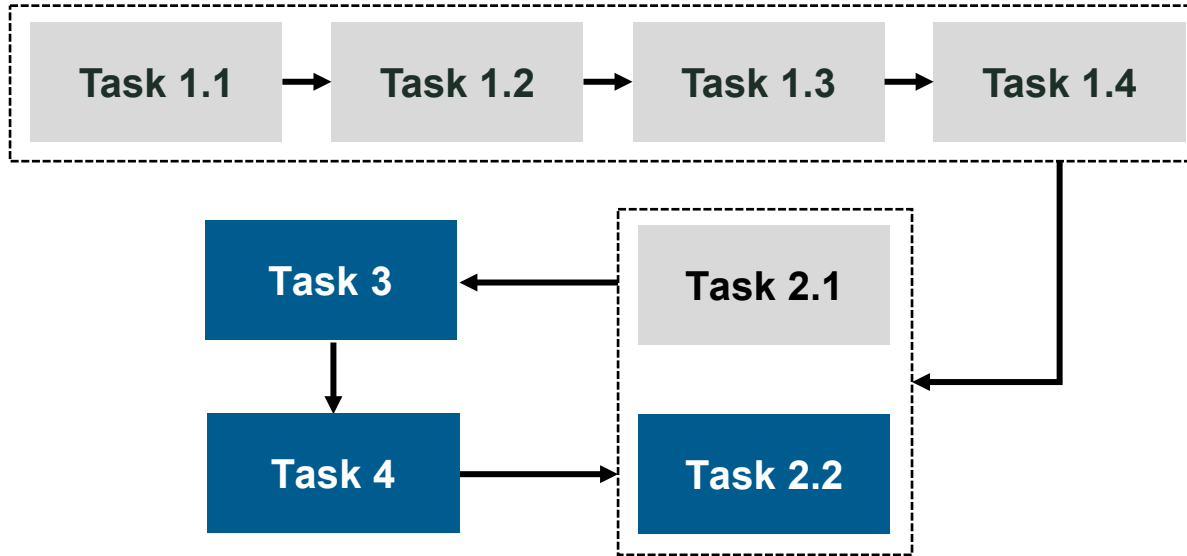
SVSS



MuST



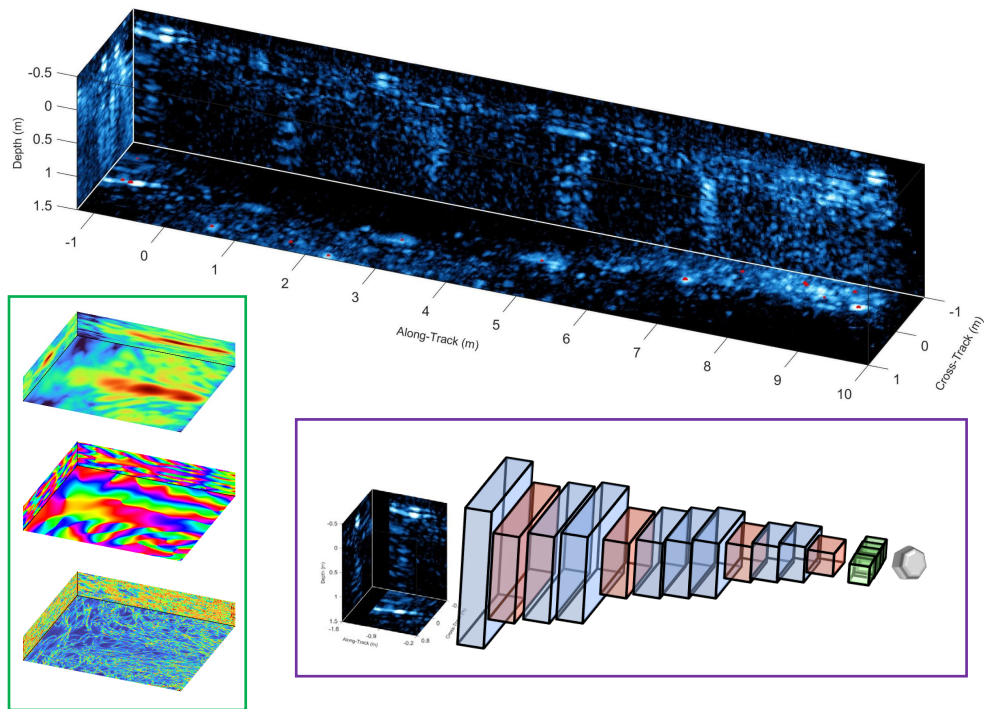
Technical Approach



1. Algorithm development
 1. Data normalization
 2. Detection
 3. Data-representation formulation
 4. Classification
2. Test-bed evaluation
 1. MuST (Sequim 21/22/23)
 2. SVSS (Sequim 24)
3. Analysis of results
4. Algorithm refinement

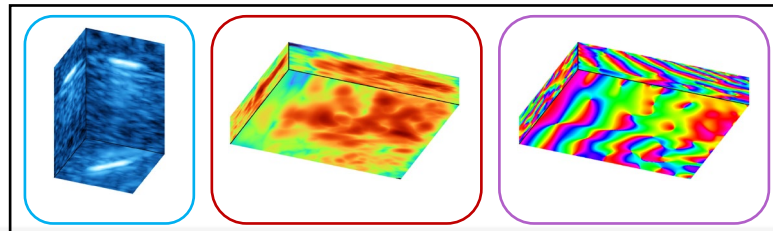
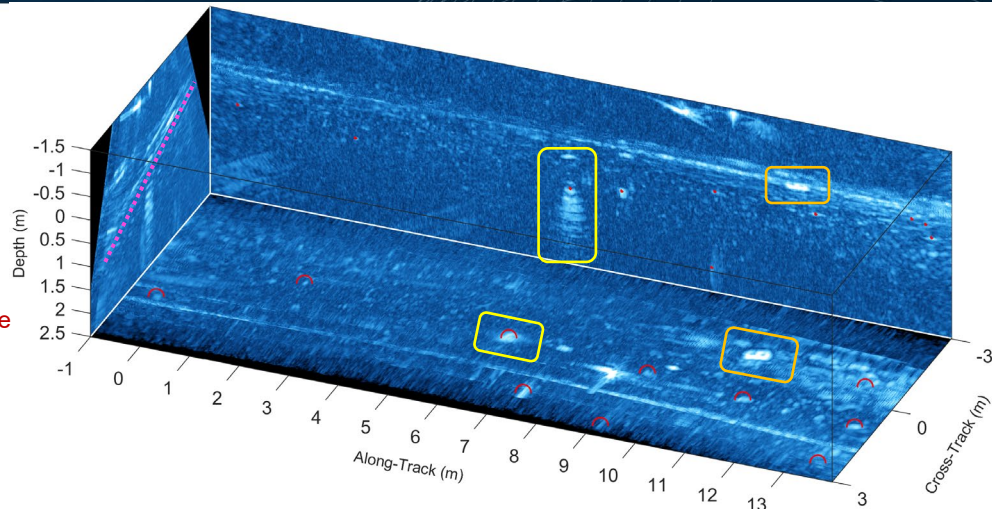
Results to Date (1)

- Developed algorithms for:
 - Data normalization
 - Detection
 - Including variant for resonance detection (shallow water, sloped seafloor, SVSS)
 - Data-representation formulation
 - Image and spectral representations
 - **Small set of hand-crafted physics-based features**
 - Classification
 - *Multi-class* CNN classifiers (**with UXO size prediction**)
 - Multi-look fusion



Results to Date (2): New Developments

- Detector variant for **resonance** detection in shallow water, with sloped seafloor (SVSS)
- Small set of hand-crafted physics-based features
 - Peak energy in 3-d image domain
 - Variance of the gradient of energy vs. depth in 3-d image domain
 - Peak energy in 3-d acoustic color magnitude domain
 - Single-look symmetry of 2-d (phi-MIP) acoustic color magnitude
 - Single-look symmetry of gradient of 2-d (phi-MIP) acoustic color magnitude
 - Mean roughness (opposite of continuity) of 3-d acoustic color phase
- Leverage hand-crafted features (HCF) in classification
 - Filter/reject alarms based on feature values (leverages multi-look)
 - HCF RBF-kernel RVM treated as additional representation in (CNN) classifier ensemble
- Multi-class CNN classifiers with UXO size prediction
 - 5 classes: Large UXO, medium UXO, small UXO, seeded clutter, natural clutter



Results to Date (3): Blind Test (MuST)

- Delivered ATR dig lists for MuST 2023 Sequim Bay blind area in March 2025
 - Multi-look, 3-d multi-representation, multi-class CNN ensemble, **with hand-crafted features**
 - Results received from IDA April 2025
- Did not have access to APL/UW's data-driven repositioning solution, so geolocation errors negatively skewed ROC curve results

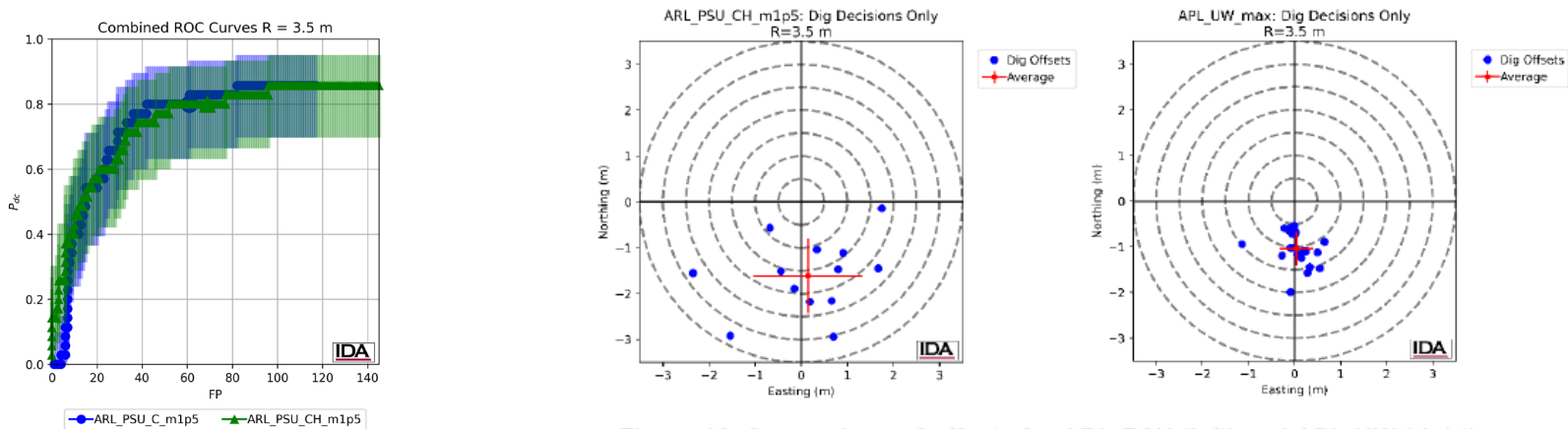


Figure 10. Comparison of offsets for ARL-PSU (left) and APL-UW (right)

Results to Date (4): Blind Test (MuST)

- Did not have access to APL/UW's improved renavigation solution

- 2.0m offset for APL-UW, 3.5m for us (underlying data is the same!)

Impact

- Could not properly establish that multiple detection alarms were associated with the same object
- Multiple dig-list calls of the same **target**, which are counted as false positives
- Multiple dig-list calls of the same **non-target**, which are counted as multiple false positives

- N.B. Monuments had not been in any training data sets; predictions improved with HCF RVM



Rank	Dig Decision	Predicted Object Size	Nearby Objects	Nearby Objects Description	List of other nearby detections
1	Dig	Large (155mm/105mm)	SE Monument	Monument 3 (SE)	19, 28
2	Dig	Large (155mm/105mm)	C205, NW Monur	Scap Metal, Monument 2 (NW)	3, 24, 52
3	Dig	Large (155mm/105mm)	NW Monument	Monument 2 (NW)	2
4	Dig	Large (155mm/105mm)	C005	SCUBA	11, 56
5	Dig	Large (155mm/105mm)	U016	105 mm; HEAT	7
6	Dig	Medium (81mm/60mm)			None
7	Dig	Large (155mm/105mm)	U016	105 mm; HEAT	5, 38
8	Dig	Medium (81mm/60mm)	U224	81 mm; M889A1	None
9	Dig	Large (155mm/105mm)	U207	105 mm; HEAT	32
10	Dig	Large (155mm/105mm)	U010	105 mm; M60	21
11	Dig	Large (155mm/105mm)	C005	SCUBA	4, 56, 101
12	Dig	Medium (81mm/60mm)	U014, C206	105 mm; HEAT, Scrap Metal	30
13	Dig	Large (155mm/105mm)	U211, C200	81 mm; M821, Scrap Metal	26, 85
14	Dig	Large (155mm/105mm)	U234	105 mm; M60	41
15	Dig	Large (155mm/105mm)	U232	105 mm; M60	96
16	Dig	Medium (81mm/60mm)	U004, C001	105 mm; HEAT, Crab Pot	36, 45, 58
17	Dig	Large (155mm/105mm)	U003, U227	105 mm; HEAT, 60 mm; M49	33
18	Dig	Large (155mm/105mm)	U225	81 mm; M889A1	None
19	Dig	Large (155mm/105mm)	SE Monument	Monument 3 (SE)	1, 28
20	Dig	Medium (81mm/60mm)	U205	105 mm; M60	42
21	Dig	Large (155mm/105mm)	U010	105 mm; M60	10
22	Dig	Large (155mm/105mm)	U233	105 mm; M60	25
23	Dig	Medium (81mm/60mm)	U005, U006	81 mm; M821, 81 mm; M821	None
24	Dig	Large (155mm/105mm)			2
25	Dig	Medium (81mm/60mm)			22
26	Dig	Medium (81mm/60mm)	U211, C200	81 mm; M821, Scrap Metal	13, 135
27	Dig	Large (155mm/105mm)	U013	105 mm; HEAT	35
28	Dig	Large (155mm/105mm)	SE Monument	Monument 3 (SE)	1, 19, 60
29	Dig	Medium (81mm/60mm)	U222	81 mm; M889A1	None
30	Dig	Large (155mm/105mm)	U014, C206	105 mm; HEAT, Scrap Metal	12
31	Dig	Medium (81mm/60mm)	U223	81 mm; M889A1	None
32	Dig	Medium (81mm/60mm)	U207	105 mm; HEAT	9
33	Dig	Medium (81mm/60mm)	U003, U227	105 mm; HEAT, 60 mm; M49	17
34	Dig	Medium (81mm/60mm)	U212, CFIN	81 mm; M821, Diver Fin	47

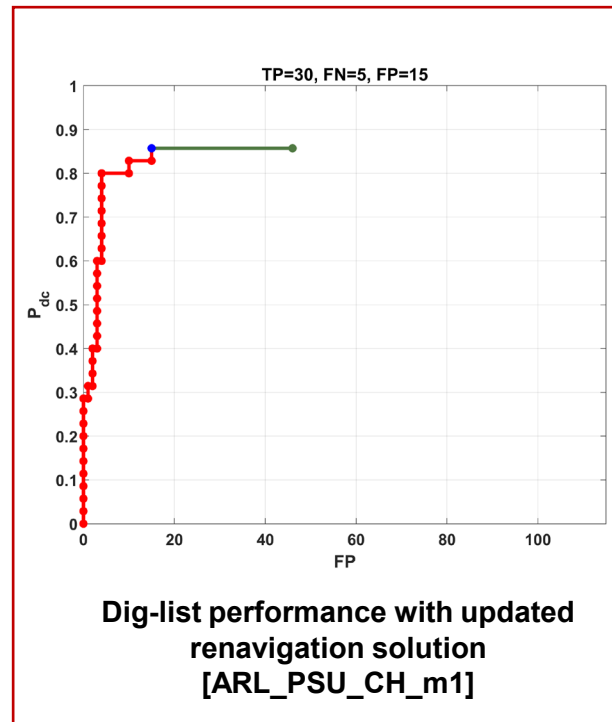
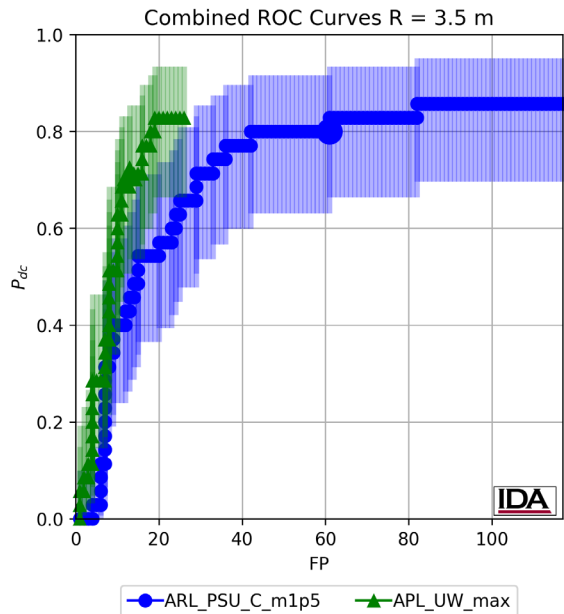
False positive
Successful
UXO detection
Same target,
counts as false
positive
Same clutter
object, counts as
another false
positive

Results to Date (5): Blind Test (MuST)

- If use APL/UW's updated data-driven repositioning information, blind dig-list performance improves dramatically

- P_{dc} rises
- False alarm rate drops
- At same demonstrator threshold:
 - 30 of 35 UXO detected
 - Only 15 false positives
 - 5 UXO missed:
 - U209: 81mm M821 ¾-buried
 - U210: 81mm M821 ½-buried
 - U227: 60mm M49 ¼-buried
 - U228: 60mm M49 ½-buried
 - U238: 60mm M49 ½-buried

- Take-away: the ATR algorithms are working well, as intended



Next Steps [From 5/2024 IPR]

- [1] Exploitation/incorporation of new MuST Sequim Bay 2022 ground-truth
 - Analysis, relabeling, retraining of CNNs
- [1] Extract improved data representations
 - Phase-gradient with 3-d calculation
- [2] Algorithm refinement
 - ~~New CNN architecture design (reduced input data-cubes)~~
 - CNN (re)training
 - Multi-look fusion
- [2] SVSS data processing
 - Data-collection event scheduled for Sequim Bay 9/2024
- [3] SVSS test-bed evaluation (2024 data)
- [3] MuST test-bed evaluation (2023 data)
 - Just obtained (5/2024) data from 2023 Sequim Bay exercise
- [3, 4] Analysis of results
 - Blind test-beds, masking studies
- [4] Final report scheduled for 8/2025

• Timeline Key:

- [1] = May-Aug 2024
- [2] = Sep-Dec 2024
- [3] = Jan-Apr 2025
- [4] = May-Aug 2025

Next Steps

- Remaining activities
 - [1] Use updated MuST renavigation solution to correct Sequim 2023 alarm positions
 - [2] Adapt (*transfer learning*) image-based CNNs trained on MuST data to SVSS data
 - Made possible by unified processing pipeline (normalization, detection, *etc.*)
 - [3] Produce/submit SVSS Sequim 2024 blind dig list
 - [4] Write Final Report
- Final Report planned submission is August 2025 (if delayed, before symposium in November 2025)
 - Depends on when SVSS Sequim data post-mission analysis (PMA) complete, and later when blind results received from IDA

Technology Transfer

- Technology transfer
 - Presentation of research at SAGEEP conference, to munitions response community (completed April 2023)
 - Webinar covering research, to diverse audience (completed April 2024)
 - Detection and classification algorithms (code), to APL/UW MuST team and ARL-PSU SVSS team (in progress)
 - Technical report (methods, performance, concept of operations), for DoD Remedial Program Managers and researchers (future, expected Aug 2025)

Issues

- SVSS post-mission analysis (PMA) of Sequim 2024 data still ongoing, slight delay for dig-list creation
- Not having/leveraging latest data-driven renavigation information from MuST impacts ATR performance
 - *In communication with T. Marston at APL-UW for solution*
 - *Received new navigation solution file for Sequim 2023 data on **5/12/25***

BACKUP MATERIAL

MR21-3543: Advanced Sonar-Based Deep Learning for Underwater UXO Remediation

Performer: ARL-PSU

Technology Focus

- *ATR algorithms for proud and buried UXO using acoustic data from downward-looking sonar systems*

Research Objectives

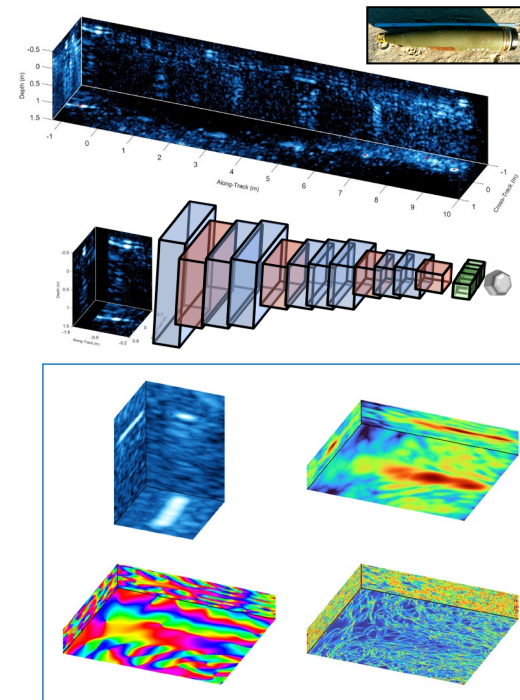
- *Develop detection and classification algorithms for volumetric sonar data from SVSS (ARL-PSU) and MuST (APL/UW) systems*
- *Success based on high detection and low false alarm rates*

Project Progress and Results

- *Developed automated data normalization and detection algorithms*
- *Developed 2-d and 3-d convolutional neural network (CNN) classifiers for multiple data representations (image-based and acoustic-color-derived)*

Technology Transition

- *Deliver ATR algorithms to SVSS and MuST end-users for use in live remediation*

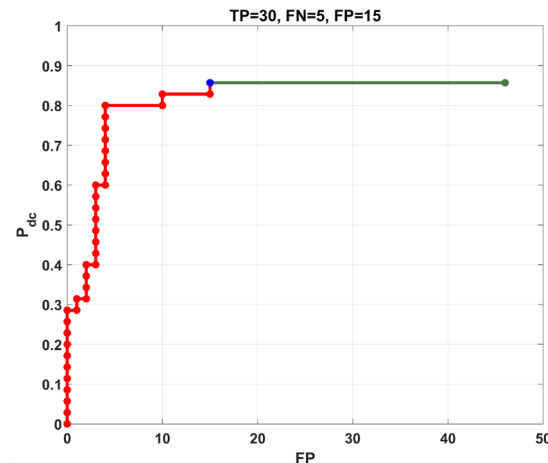
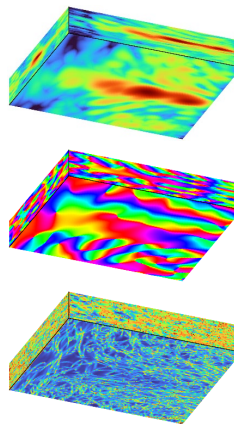
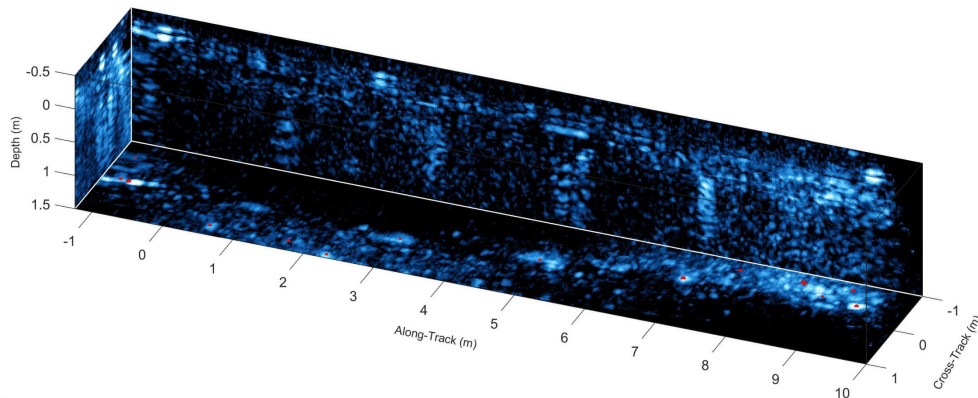


Plain Language Summary

- Many aquatic sites are contaminated with unexploded ordnance (UXO), both proud and buried
 - Two new downward-looking sonar systems developed to address problem
- No automated detection and classification algorithms exist for this new 3-d data
 - This project: address this capability gap
- Expect to deliver automated algorithms that achieve high detection and low false alarm rates
 - Reduce cost at live remediation sites

Impact to DoD Mission

- Demonstrated promising detection and classification algorithm performance on blind UXO test-beds
- Shows technology is feasible for reducing cost of remediation
- Providing DoD with reliable, automated methods for new sensor modality data that fill previous technology gap



Action Items

- [1] Assigned due date: 8/28/2025: “We have interest in understanding the plan for commercialization of this technology, including potential applications, intellectual property considerations, and any plans or strategies for moving forward with commercialization. Please discuss the plan for commercialization and technology transfer details in your Final Report.”
- Response: Will discuss in detail in Final Report. ARL-PSU retains IP ownership, but SERDP/ESTCP granted full unlimited license to use for government work.

Publications

- Publications and Presentations

- D. Williams and D. Brown, “New Target Detection Algorithms for Volumetric Synthetic Aperture Sonar Data,” *Proceedings of Meetings on Acoustics*, Vol. 40, September 2020. [Work presented at the 2020 International Conference on Underwater Acoustics (ICUA)]
- D. Williams and D. Brown, “Three-Dimensional Convolutional Neural Networks for Target Classification With Volumetric Sonar Data,” *Proceedings of Meetings on Acoustics*, Vol. 41, August 2021. [Work presented at the 2021 Underwater Acoustics Conference and Exhibition (UACE)]

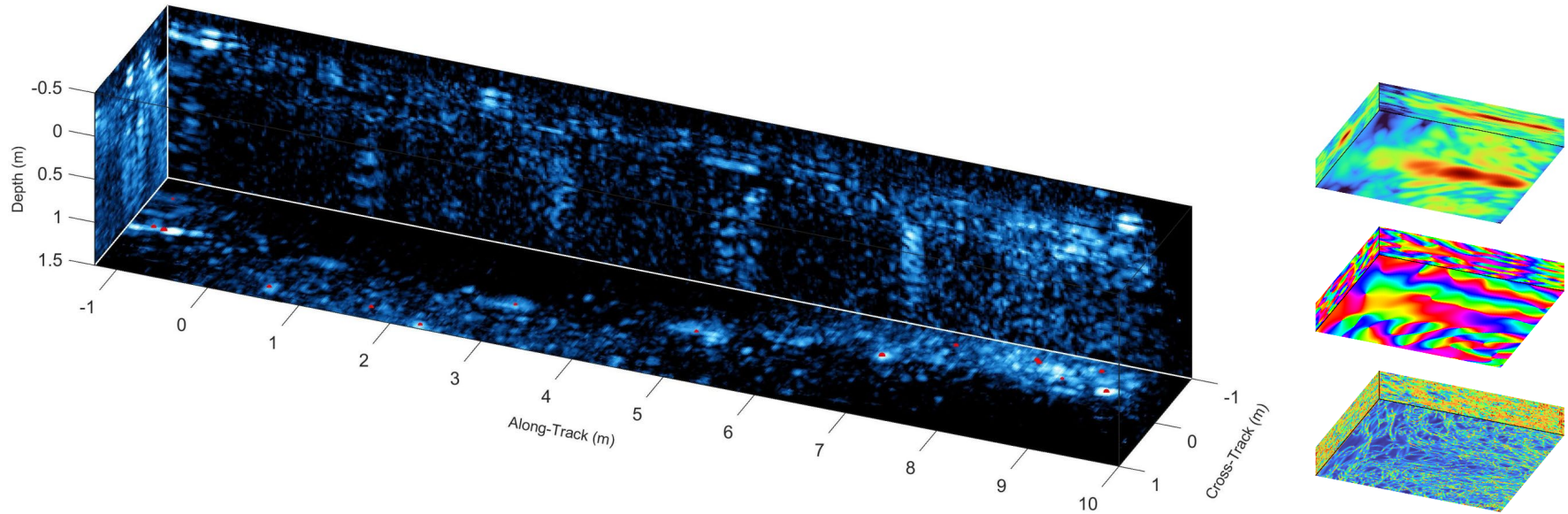
- Presentation

- D. Williams and D. Brown, “Sediment Volume Search Sonar: Automated Detection and Classification Algorithms,” presented at the 35th Symposium on the Application of Geophysics to Engineering and Environmental Problems (SAGEEP) and 2nd Munitions Response Meeting, April 2023.
- D. Williams, “Advanced Sonar-Based Deep Learning for Underwater UXO Remediation,” SERDP/ESTCP Webinar Series, #196, April 2024.

Literature Cited

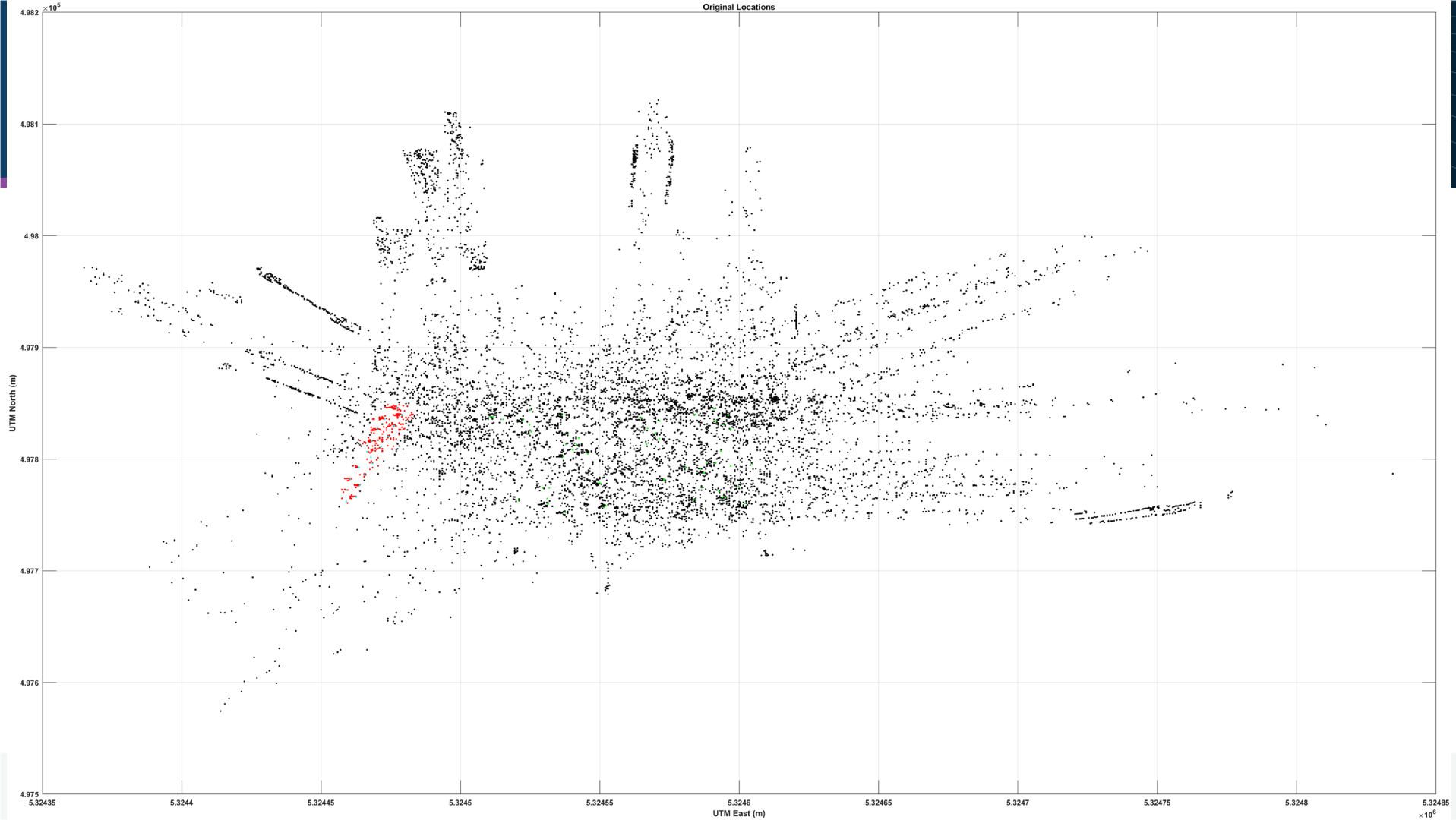
- N/A

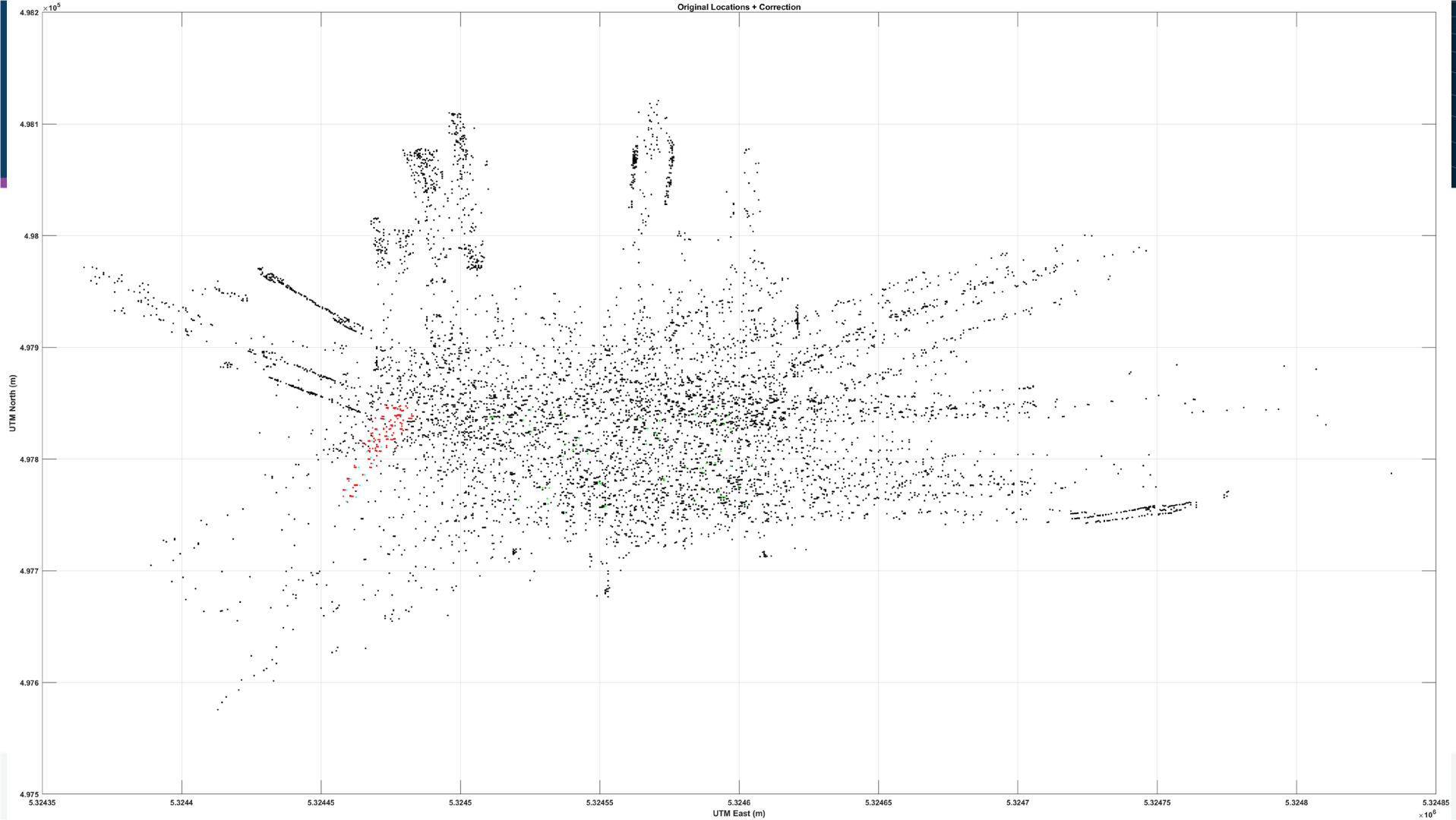
Additional Slide(s) for High-Quality Photos



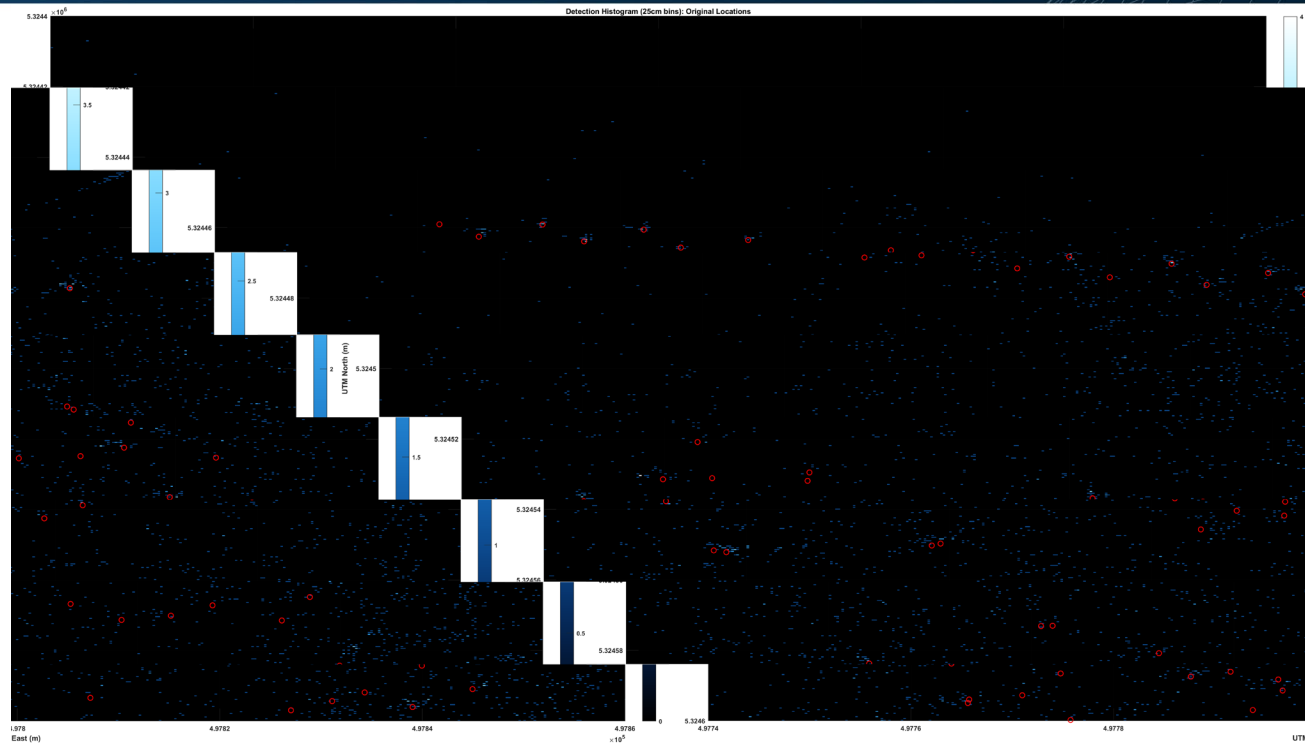
Acronym List

- APL/UW: Applied Physics Laboratory, University of Washington
- ARL-PSU: Applied Research Laboratory, Penn State University
- ATR: Automatic Target Recognition
- CNN: Convolutional Neural Network
- DoD: Department of Defense
- HCF: Hand-crafted features
- MuST: Multi-Sensor Tow-body
- PMA: Post-Mission Analysis
- RBF: Radial Basis Function
- RVM: Relevance Vector Machine
- SAGEEP: Symposium on the Application of Geophysics to Engineering and Environmental Problems
- SVSS: Sediment Volume Search Sonar
- UXO: Unexploded Ordnance





MuST Sequim 2023: Old Positions



MuST Sequim 2023: Corrected Positions

