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From Basic Research to a Prototype Towbody Platform: Progress on Underwater Unexploded Ordnance Remediation

April 23, 2020

SERDP DOD • EPA • DOE | ESTCP

Welcome and Introductions

Jennifer Nyman, Ph.D., P.E.
Webinar Facilitator

Webinar Agenda

- **Webinar Logistics** (5 minutes)
  Dr. Jennifer Nyman, Geosyntec Consultants

- **Overview of SERDP and ESTCP** (5 minutes)
  Dr. David Bradley, SERDP and ESTCP

- **From Basic Research to a Prototype Towbody Platform: Progress on Underwater Unexploded Ordnance Remediation** (55 minutes + Q&A)
  Dr. Steven G. Kargl, University of Washington

Zoom Instructions

- Download Zoom
  - https://zoom.us/download
- If you cannot download Zoom, you can view the slides using an internet browser
  - Create a free Zoom account (https://zoom.us/signup)
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  - https://www.youtube.com/user/SERDPESTCP

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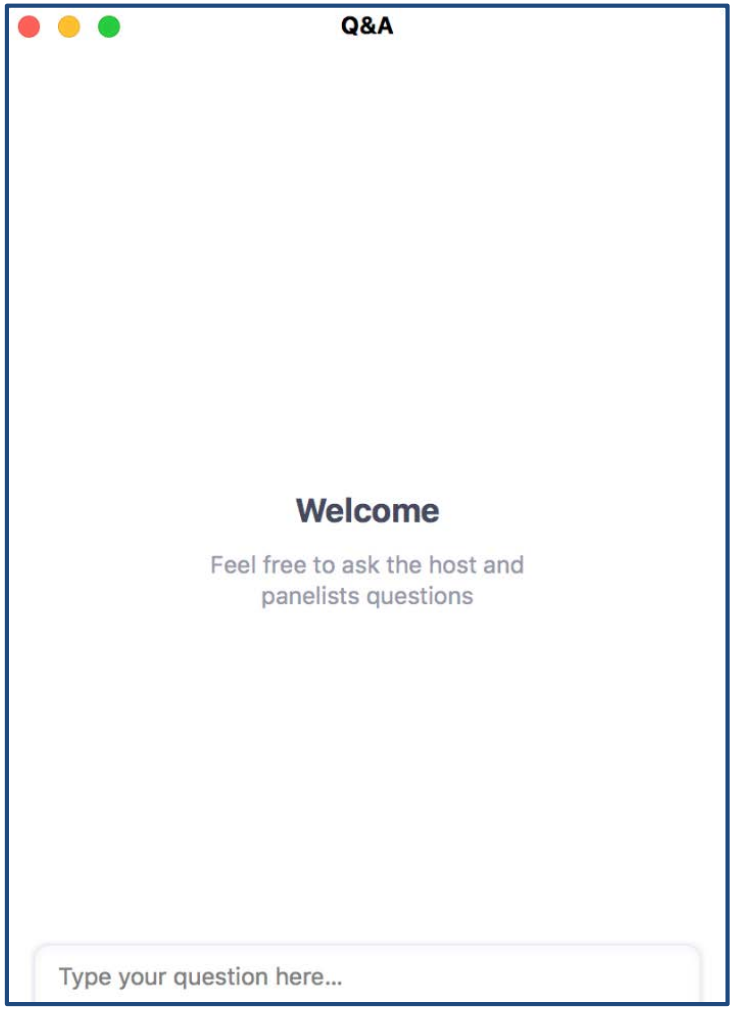
- Find the Q&A button on your control bar and type in your question(s)
- Make sure to add your organization name at the end of your question so that we can identify you during the Q&A sessions



SERDP and ESTCP Overview

David L. Bradley, Ph.D.
SERDP and ESTCP

SERDP

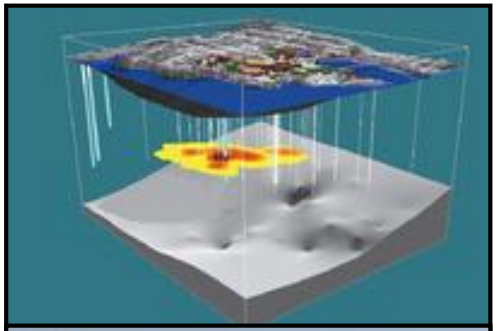
- Strategic Environmental Research and Development Program
- Established by Congress in FY 1991
  - DoD, DOE and EPA partnership
- SERDP is a requirements driven program which identifies high-priority environmental science and technology investment opportunities that address DoD requirements
  - Advanced technology development to address near term needs
  - Fundamental research to impact real world environmental management

ESTCP

- Environmental Security Technology Certification Program
- Demonstrate innovative cost-effective environmental and energy technologies
  - Capitalize on past investments
  - Transition technology out of the lab
- Promote implementation
  - Facilitate regulatory acceptance

Program Areas

- Environmental Restoration
- Installation Energy and Water
- Munitions Response
- Resource Conservation and Resiliency
- Weapons Systems and Platforms



Munitions Response

- Munitions on land
  - Classification
- Munitions underwater
  - Wide area and detailed surveys
  - Cost-effective recovery and disposal
  - Characteristics of munitions underwater, their environment and mobility

SERDP and ESTCP Webinar Series

Date	Topic
May 7, 2020	Innovative Technologies for PFAS Destruction in Investigation Derived Wastes
May 21, 2020	Analysis of Defense Related Ecosystem Services
June 4, 2020	Waste Reduction and Treatment in Armed Forces Vessel Environments
June 18, 2020	Predicting PFAS Fate and Transport in Subsurface Environments, and Treatment
July 23, 2020	PFAS Fate, Transport and Treatment
August 20, 2020	Addressing Threatened and Endangered Species on DoD Lands

For upcoming webinars, please visit

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From Basic Research to a Prototype Towbody Platform: Progress on Underwater Unexploded Ordnance Remediation

Steven G. Kargl, Ph.D.
University of Washington

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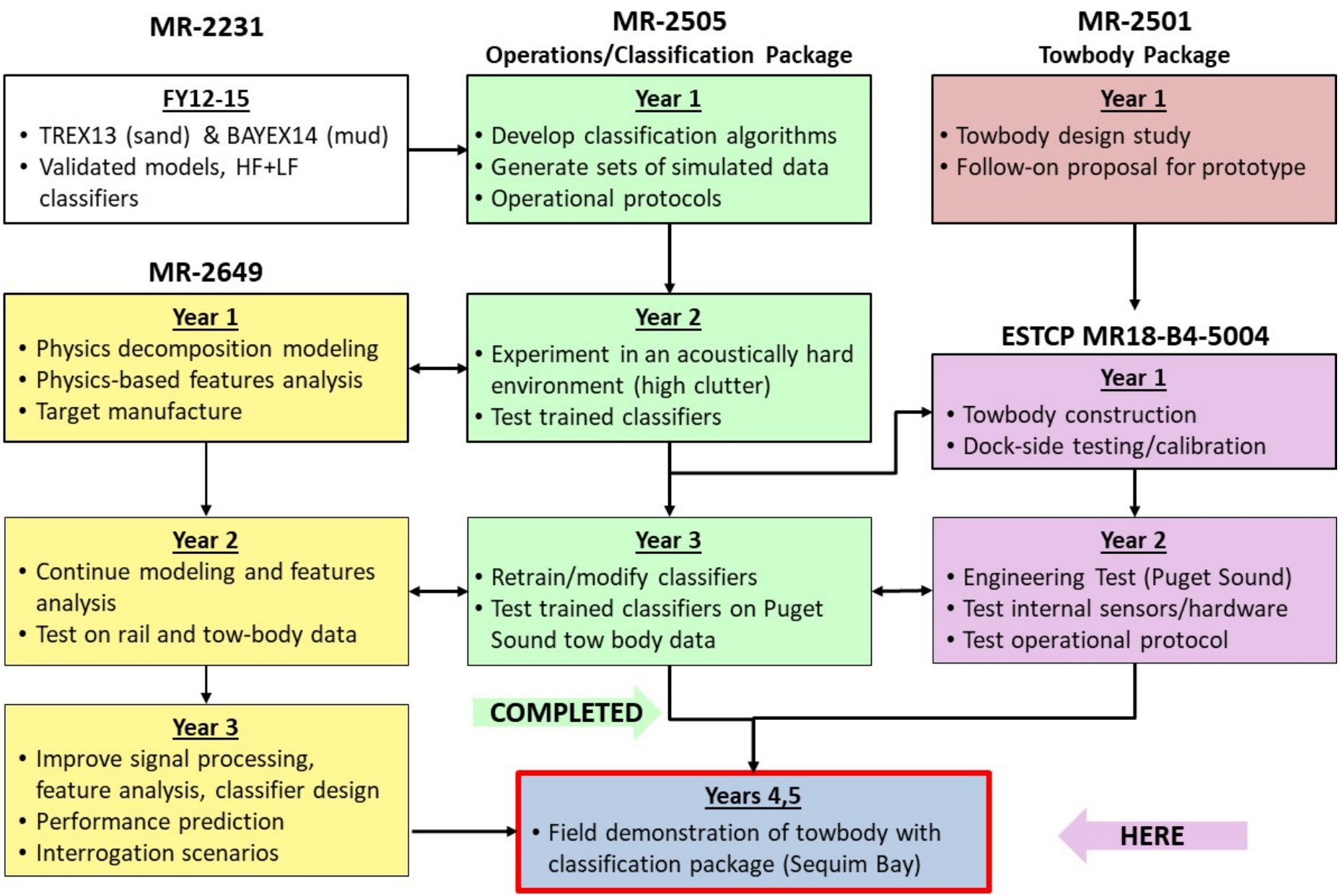
Presentation Outline

- Five-year vision
- Part 1: Basic research
  - Project team and collaborator
  - At-sea experiments
  - Numerical models
  - Classification via Gaussian mixture model
- Part 2: Applied system development
  - Project team and collaborator
  - Multi-Sensor Towbody (MuST)
  - Sea test at Sequim, WA


MR-2231
FY12-15
• TREX13 (sand) & BAYEX14 (mud)
• Validated models, HF+LF classifiers
MR-2505
Operations/Classification Package
Year 1
• Develop classification algorithms
• Generate sets of simulated data
• Operational protocols
MR-2501
Towbody Package
Year 1
• Towbody design study
• Follow-on proposal for prototype
MR-2649
Year 1
• Physics decomposition modeling
• Physics-based features analysis
• Target manufacture
Year 2
• Experiment in an acoustically hard environment (high clutter)
• Test trained classifiers
ESTCP MR18-B4-5004
Year 1
• Towbody construction
• Dock-side testing/calibration
Year 2
• Continue modeling and features analysis
• Test on rail and tow-body data
Year 3
• Retrain/modify classifiers
• Test trained classifiers on Puget Sound tow body data
Year 2
• Engineering Test (Puget Sound)
• Test internal sensors/hardware
• Test operational protocol
COMPLETED
Year 3
• Improve signal processing, feature analysis, classifier design
• Performance prediction
• Interrogation scenarios
Years 4,5
• Field demonstration of towbody with classification package (Sequim Bay)
HERE

Project Team for MR-2505

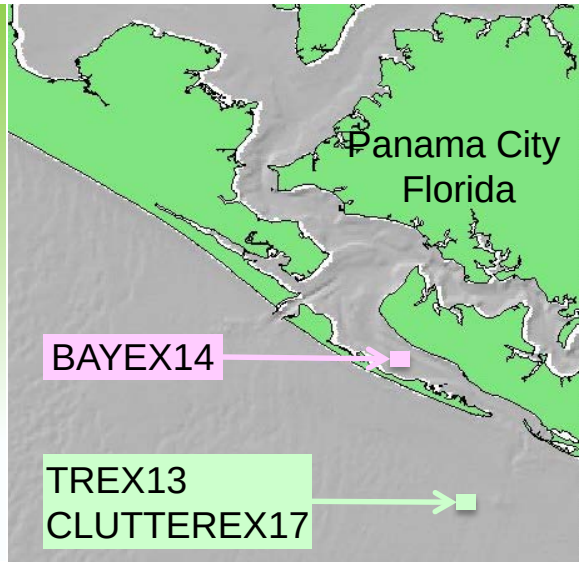
- Dr. Steven G. Kargl (PI)
  - Expertise in acoustic wave propagation and target scattering
- Dr. Aubrey L. España (Co-PI)
  - Expertise in finite-element analysis of the acoustic response of targets
- Dr. Kevin L. Williams
  - Expertise in at-sea field measurements and reduction of sonar data to acoustic templates used in classifications schemes.
- Dr. Jack McLaughlin
  - An expert in signal processing with applications to target detection and classification

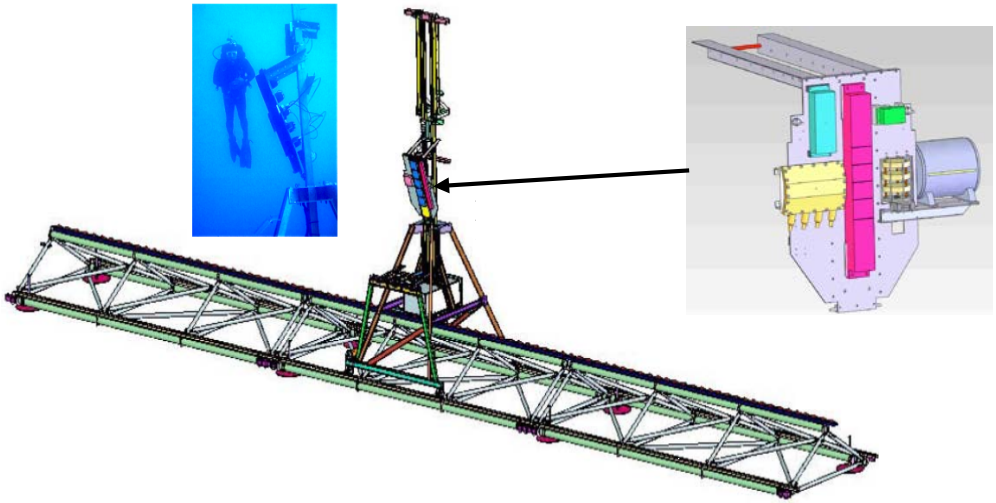
Collaborators

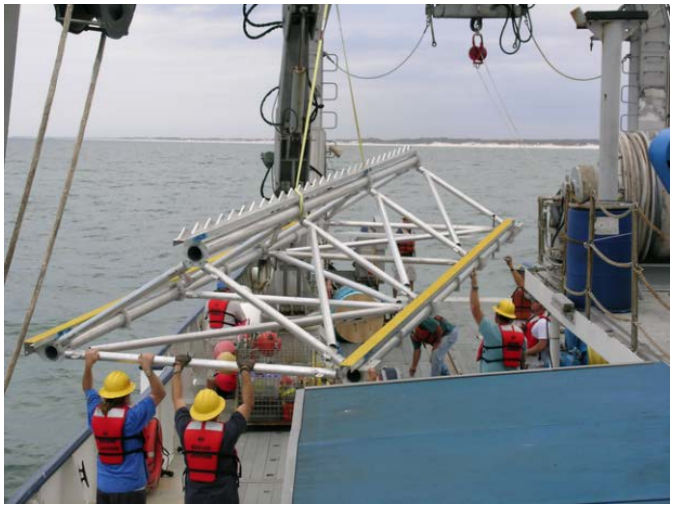
- APL-UW Acoustics Department
  - Williams, Kargl, Espana, Tim Marston, Dan Plotnick, Todd Hefner
- APL-UW Ocean Engineering Department
  - Russel Light, Vern Miller, Eric Boget, Paul Aguilar, Ben Brand, Avery Snyder, Mike Ohmart, Nick Michel-Hart, Mike Kenney, …
- Naval Surface Warfare Center, Panama City
  - Joseph Lopes, Raymond Lim, Jermaine Kennedy, David Malphurs, ….
- University of Delaware
  - Crew of Research Vessel Hugh R. Sharp
- Targets deployed for…
  - Philip Marston (Washington State University)
  - Dan Cook (Georgia Tech Research Institute)
  - Dan Brown (ARL Penn State)
- Model comparisons...
  - Ahmad Abawi (HLSR, Inc.)
- Data provided to ...
  - David Williams (CMRE, NATO Italy)
  - Mo Azimi (Colorado State University)

At-Sea Measurements

- Target and Reverberation Experiment 2013 (TREX13)
- Bay Experiment 2014 (BAYEX14)
- Clutter Experiment 2017 (CLUTTEREX17)
- 42-m rail length. Tower moves at 5 cm/s
- Sources: 1-30 & 100-200 kHz Chirp, 6 ms duration
- LF receiver: 6 channel vertical array (1 MHz sample rate)
- HF receiver: single element hydrophone
- 10 cm horizontal aperture on LF receiver array
- 2 Hz repetition rate



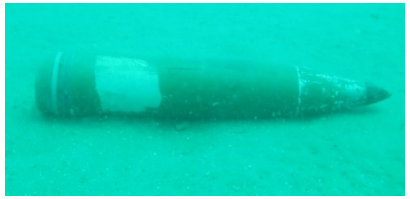




In-Situ Photos

TREX13

Proud Targets



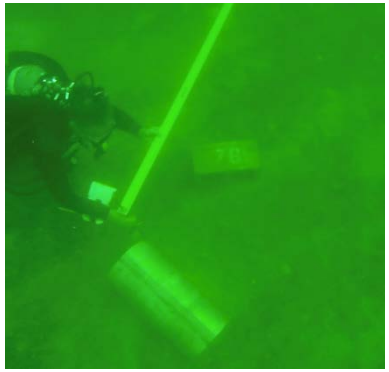
Partial Burial

Full Burial

Oblique Burial

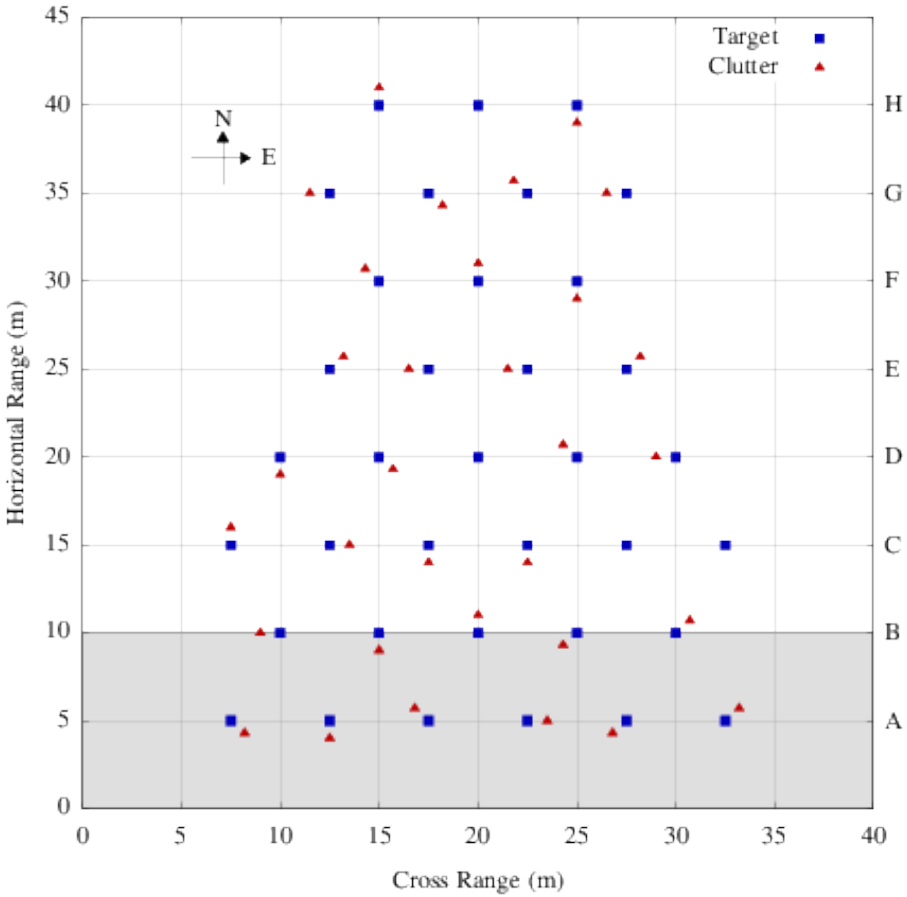
BAYEX14

CLUTTEREX17



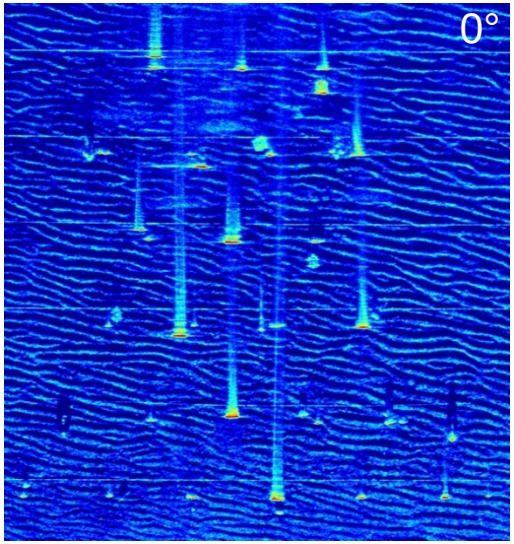
CLUTTEREX17

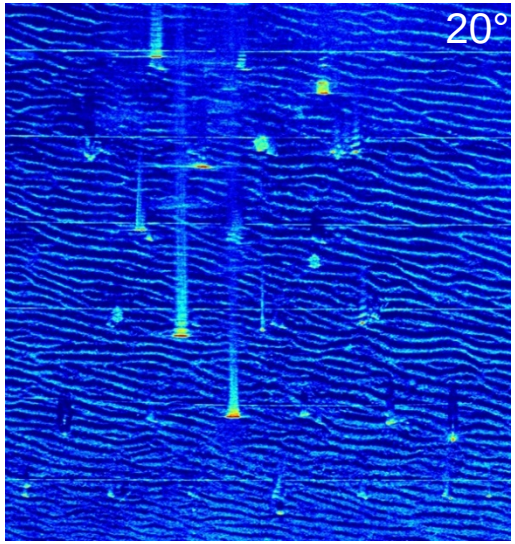
- 17 inert munitions
- 20 science targets
- 10 man-made clutter object types
- Targets manipulated by divers
- Clutter objects placed and left undisturbed
- Simultaneous transmission of LF and HF signals facilitates co-registration
- 3 target fields on fixed grids
- 25 target fields with random distributions and orientations

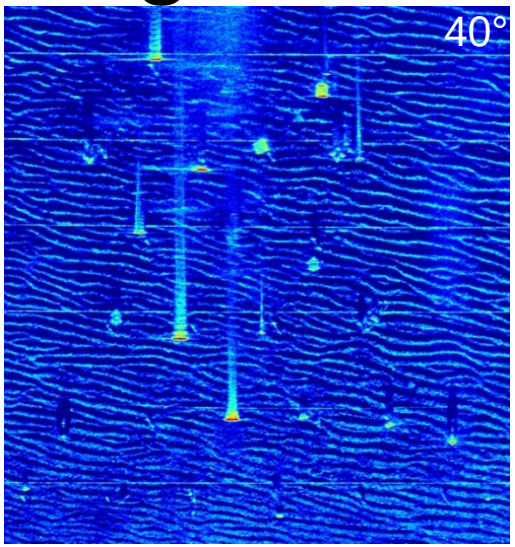


CLUTTEREX17 SAS Images

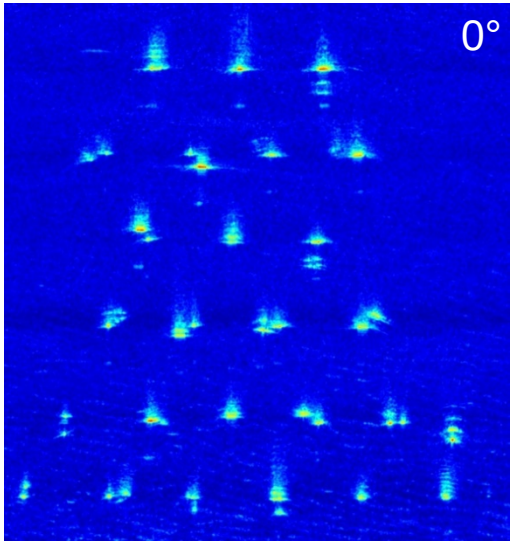
HF SAS

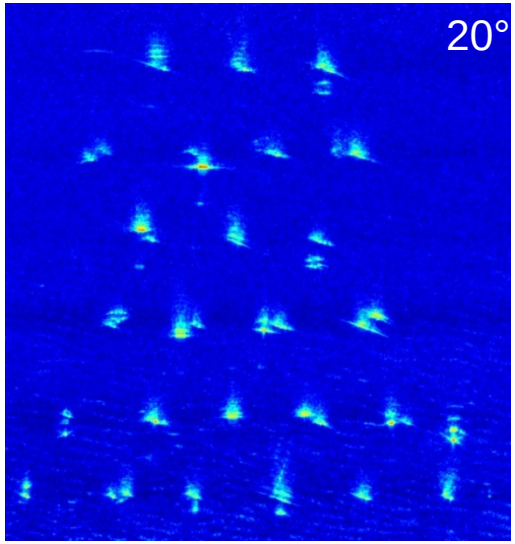


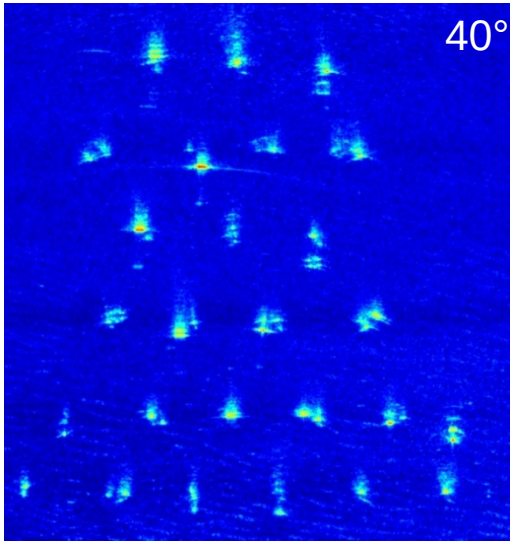




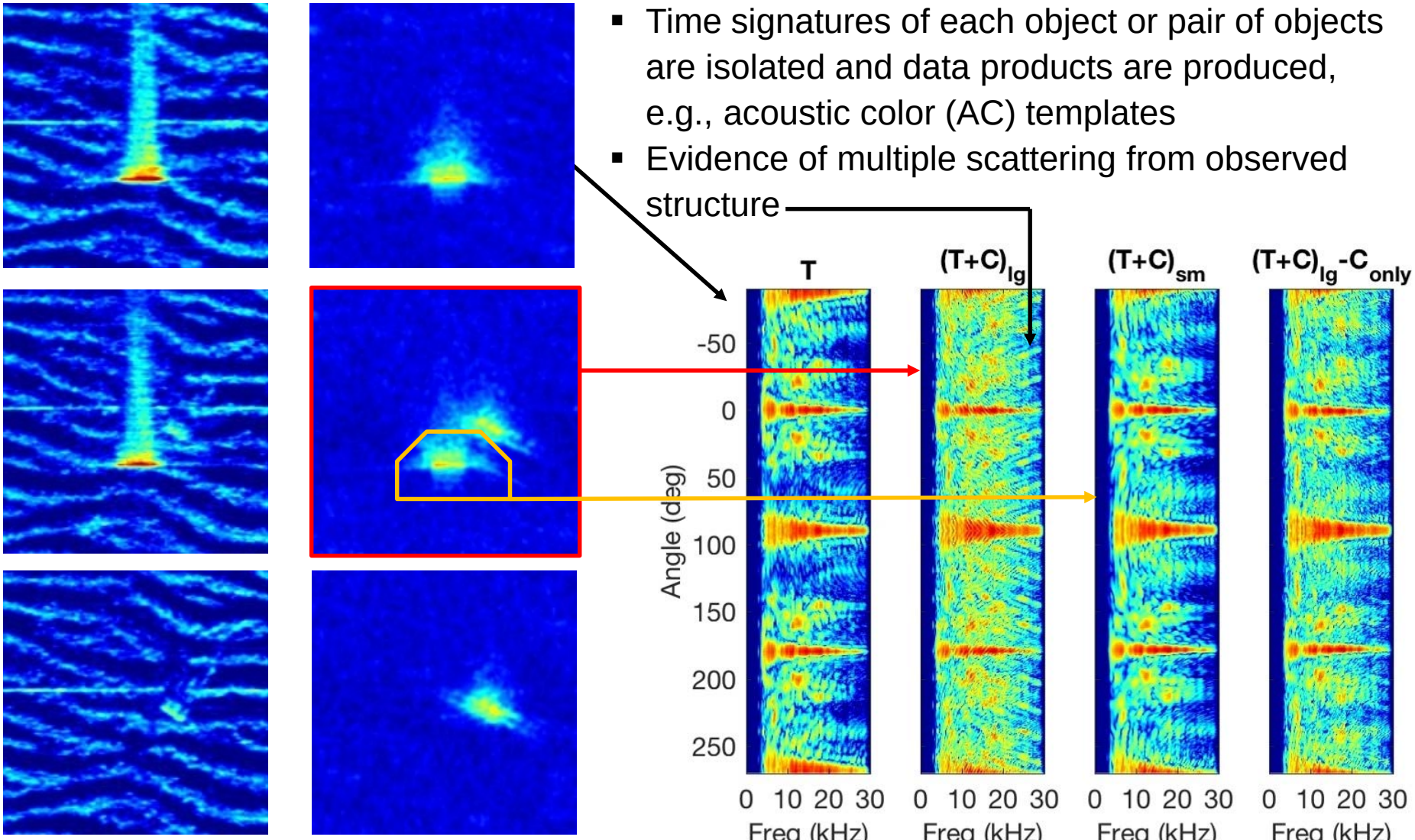
LF SAS







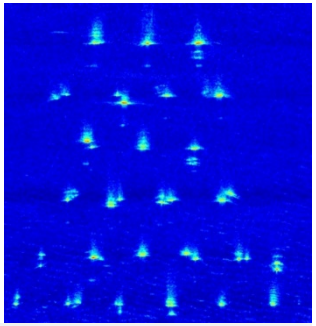
CLUTTEREX17

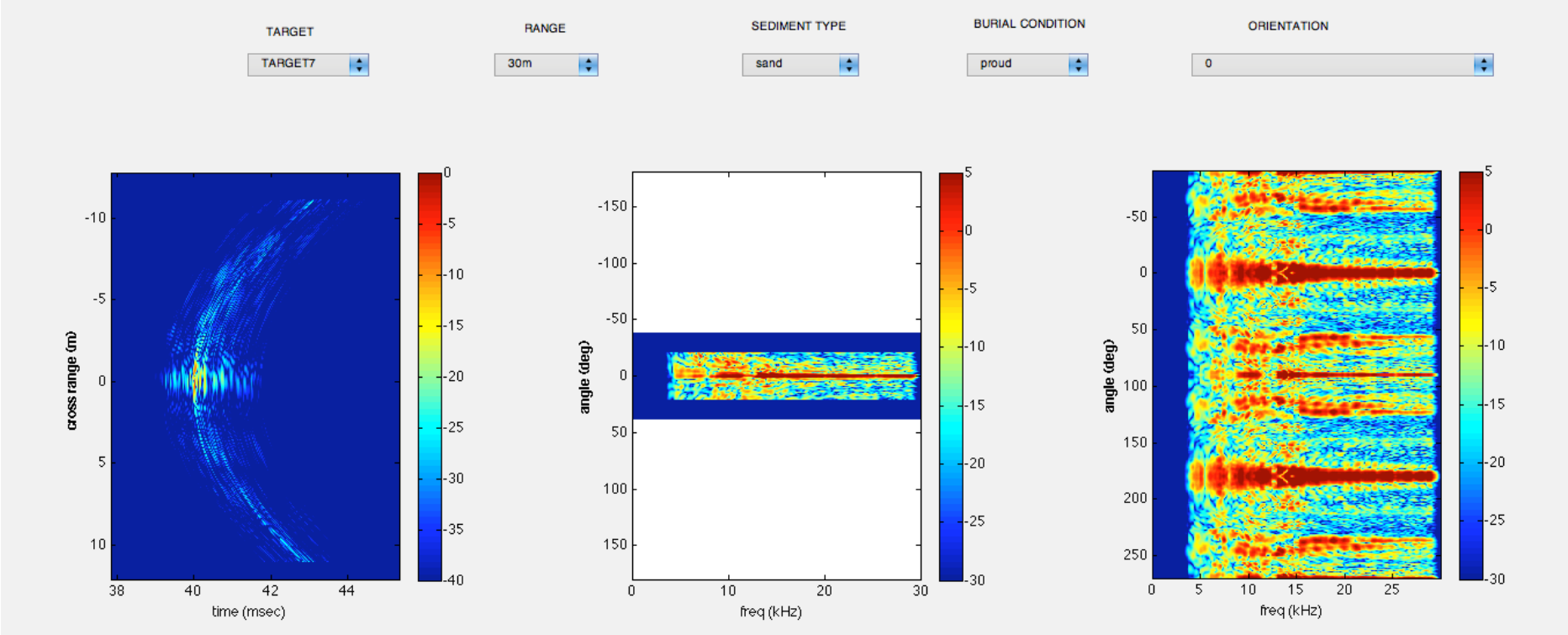


- Time signatures of each object or pair of objects are isolated and data products are produced, e.g., acoustic color (AC) templates
- Evidence of multiple scattering from observed structure

Experimental Data Repository

- Data from TREX13, BAYEX14, and CLUTTEREX17 have been archived
  - 2987 time signatures
  - 295 acoustic color templates
  - Proud, partly buried, buried targets
  - Mud and sand environments
  - Ranges from 5 m to 40 m
- MATLAB GUI provided with repository to explore data
- Data repository available upon request

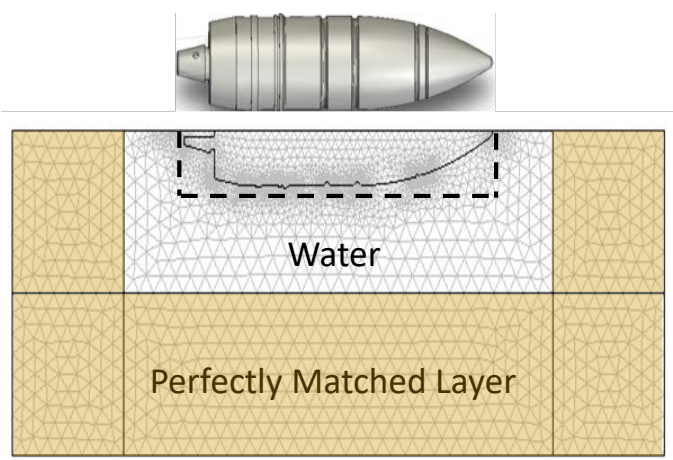


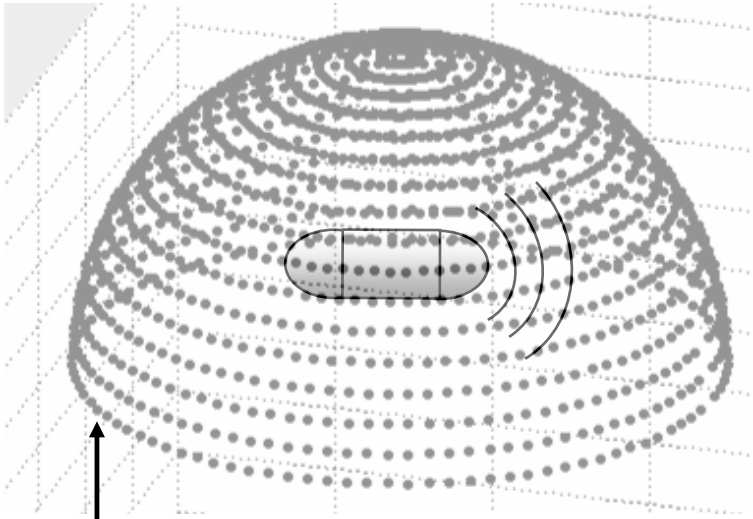


Hybrid Model

Combine finite-element model for target response with Helmholtz integral propagation

- Axisymmetric target (i.e., cylindrical symmetry)
- Pressure and normal derivatives are sampled on surface surrounding the target
- Pressure propagated from sampling surface to a field point using the Helmholtz integral





Discrete Helmholtz Integral

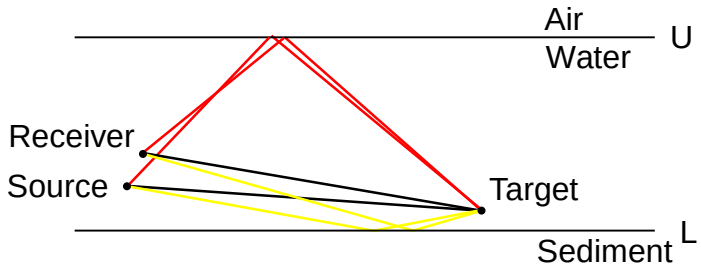
$$p_i = \sum_j \left[\frac{\partial G_{ij}}{\partial n_j} p_j - \frac{\partial p_j}{\partial n_j} G_{ij} \right] dA_j$$

Freefield Green Function

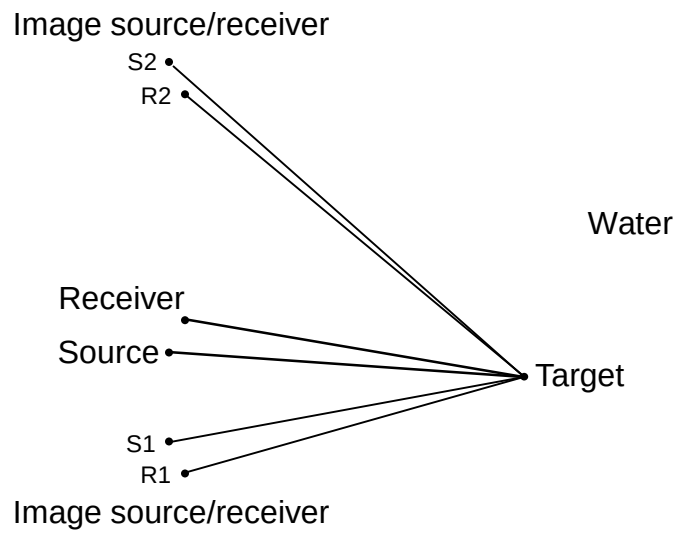
$$G_{ij} = \frac{\exp(-ik|\bar{r}_i - \bar{r}_j|)}{4\pi|\bar{r}_i - \bar{r}_j|}$$

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

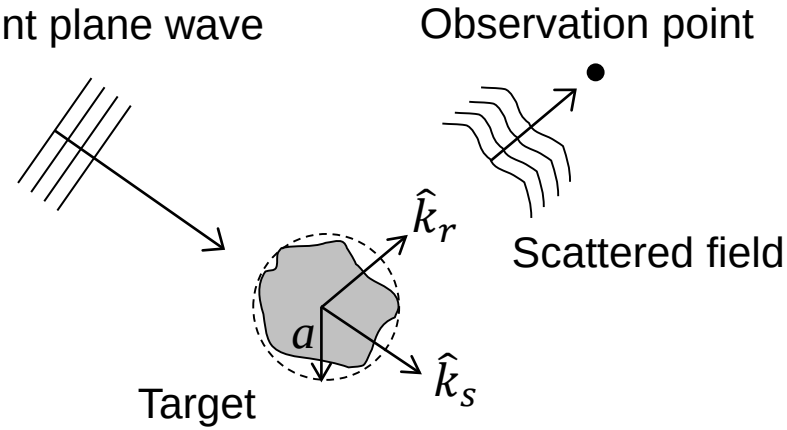
Source to target propagator

Scattering amplitude

Spectrum of incident field

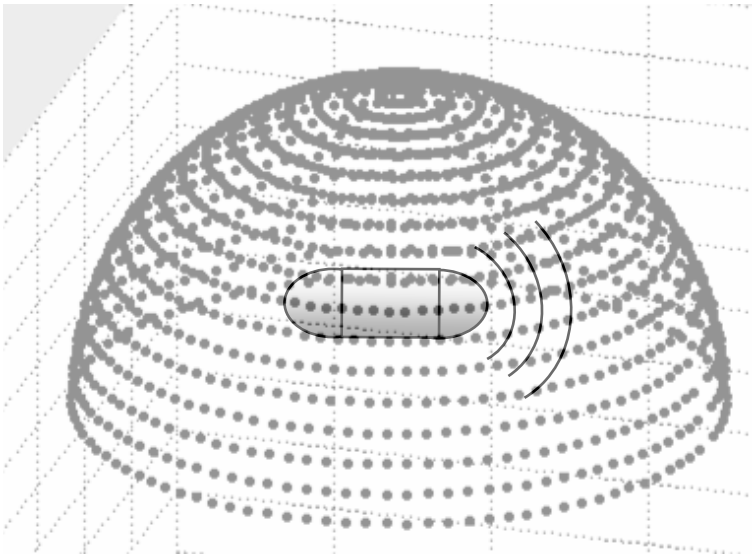
TIER Model

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, $f\left(\hat{k}_s, \hat{k}_r, \omega\right)$, contains all the information about the target



p_i on the hemisphere converted to a scattering amplitude in a look-up table:

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

Subscripts l and m are associated with scattering angles, and n corresponds to angular frequency, ω_n

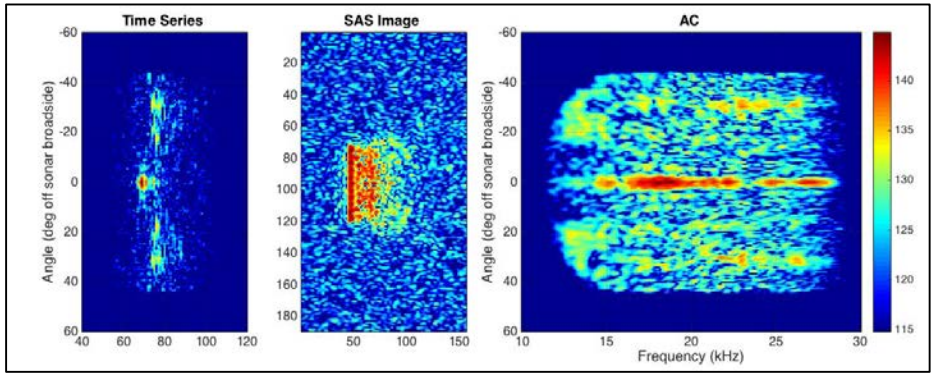
TIER Simulations

- Linear SAS simulation with 50 m cross range
- 12 targets and 2 clutter objects (i.e., compact collection of point scatterers)
- Objects placed at 14 horizontal ranges from 8 to 38 m
- Targets visit all ranges
- Targets are rotated from -80° to 80° in 20° increments at each range
- 14 environments from APL-UW TR-9407 (e.g., mud, silt, sand, cobble, rock)
- 882 data sets (14 environments X 7 ranges X 9 rotations)
- 882 data sets contain 12384 independent objects
- Background noise due to reverberation from canonical seafloor (results provided by Denton Woods from NSWC-PCD under an ONR-funded project)

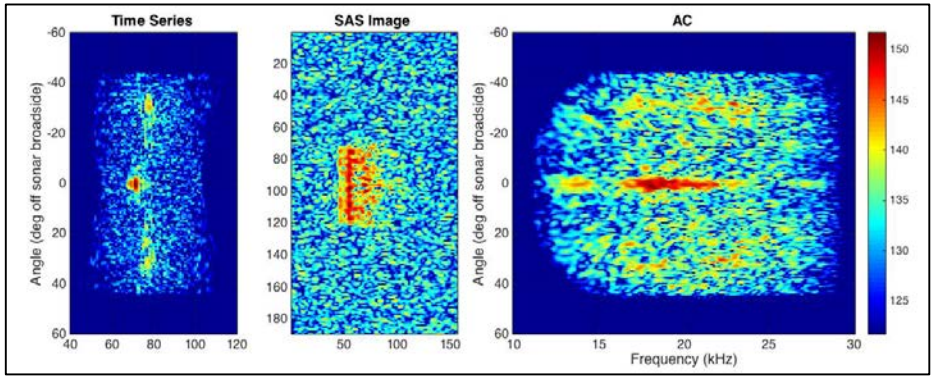
TIER Simulations

2 ft long, 1 ft diameter solid aluminum cylinder
Approximate range: 10 m

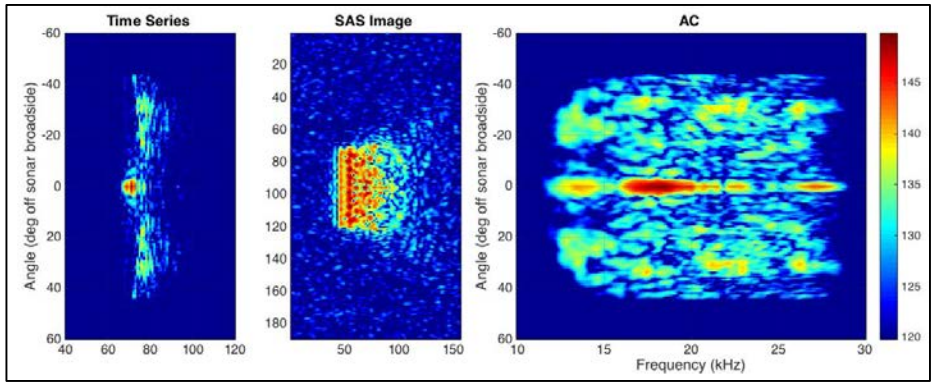
Very Fine Sand



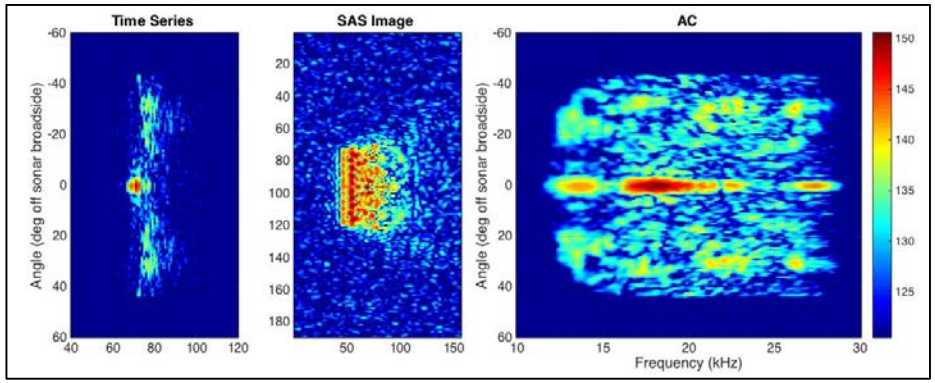
Rocky Bottom



Medium Sand



Coarse Sand



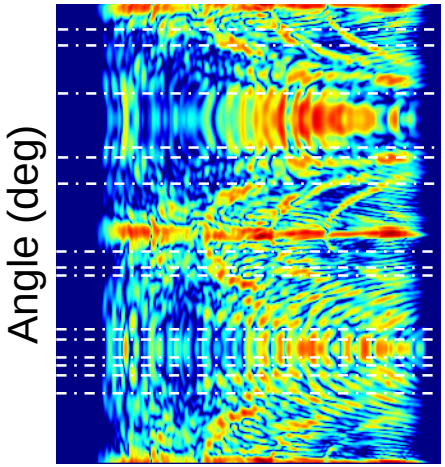
Gaussian Mixture Model

- GMM is a generative classifier. A model is trained for an individual object
- Individual spectral vectors randomly drawn from AC templates
- Metric is based on L2 norm (i.e., distance in a multidimensional vector space)
- Evaluation of a GMM provides a probability for classification as specific target

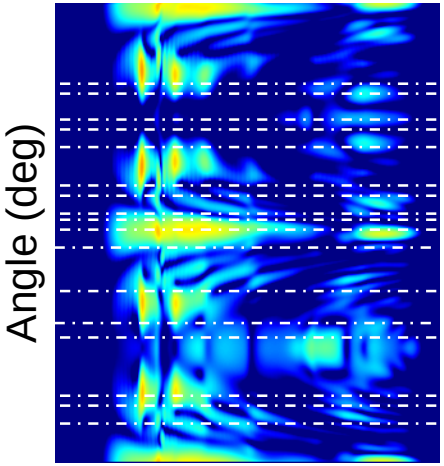
$$G(\boldsymbol{x}|\boldsymbol{\mu},\boldsymbol{\Sigma}) = \frac{exp\{-(\boldsymbol{x}-\boldsymbol{\mu})^T\boldsymbol{\Sigma}^{-1}(\boldsymbol{x}-\boldsymbol{\mu})\}}{(2\pi)^{n/2}|\boldsymbol{\Sigma}|^{1/2}}$$

- $\boldsymbol{x}$ is spectral vector
- $\boldsymbol{\mu}$ is mean spectral vector
- $\boldsymbol{\Sigma}$ is covariance matrix

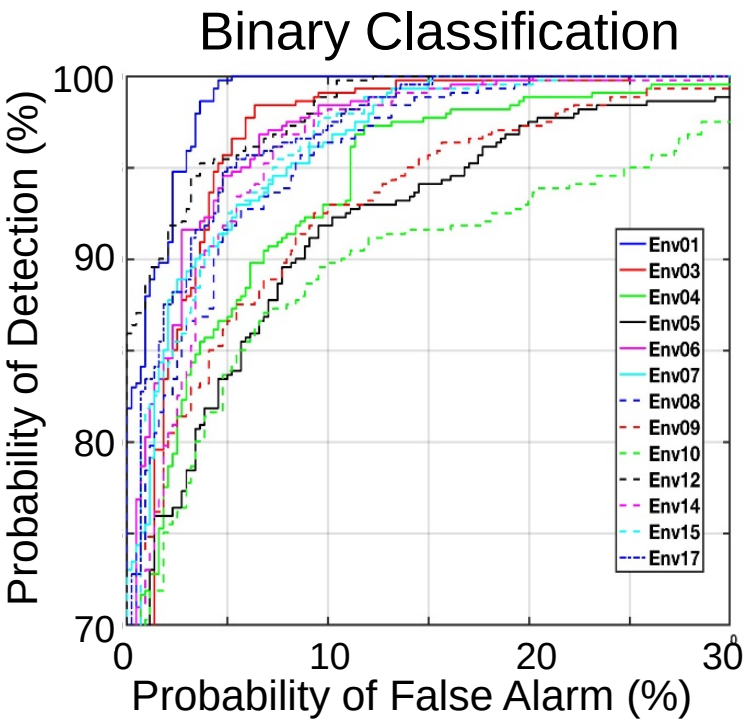
155-mm Howitzer with H_2O

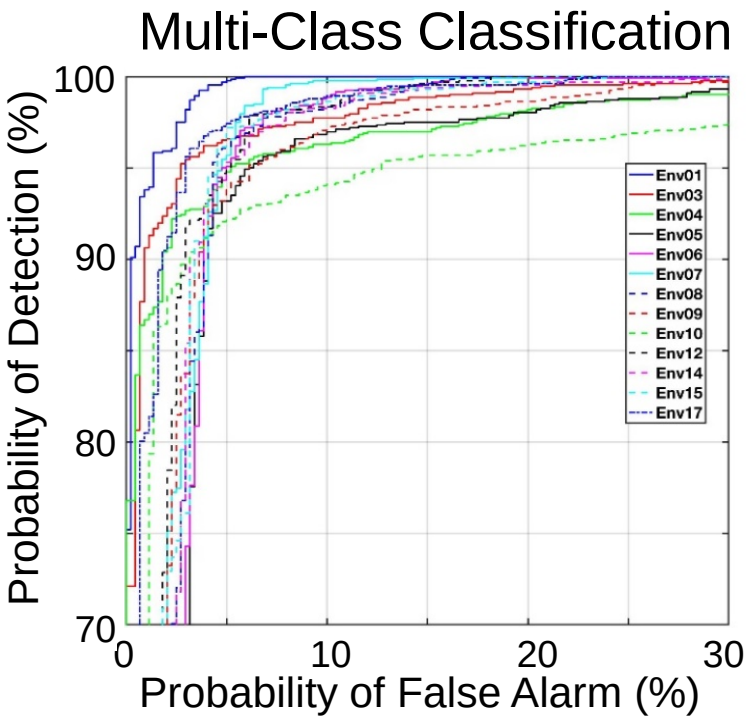


100-mm Aluminum UXO



Gaussian Mixture Model





GMM Confusion Matrices

Two-class problem

Environment 1

True Class	Assigned Class	
	100-mm	155-mm
100-mm	252	0
155-mm	0	189

Environment 10

True Class	Assigned Class	
	100-mm	155-mm
100-mm	246	6
155-mm	4	185

Environment 17

True Class	Assigned Class	
	100-mm	155-mm
100-mm	247	5
155-mm	0	189

Four-class problem

Environment 1

True Class	Assigned Class			
	Class 1	Class 2	Class 3	Class 4
Class 1	252	0	3	0
Class 2	0	189	0	0
Class 3	15	0	174	0
Class 4	0	0	0	126

Environment 10

True Class	Assigned Class			
	Class 1	Class 2	Class 3	Class 4
Class 1	245	4	3	0
Class 2	4	185	0	0
Class 3	22	4	163	0
Class 4	8	0	1	17

Class 1: 100-mm UXO
Class 2: 155-mm howitzer
Class 3: Aluminum pipe and cylinder
Class 4: drum and scuba tank

Part 1: Conclusions

- When clutter objects are close to targets of interest, target signatures from may be compromised by multiple scattering effects
- The environment and the scattering geometry within that environment affect measured target strengths, and by extension must be included in any modeling effort
- Gaussian mixture models for a multi-class problem may aid in the discrimination of target-of-interest from clutter

Q&A Session 1

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Part 2

MR18-B4-5004: Multi-Sensor Towbody (MuST) for Detection, Classification, and Geolocation of Underwater Munitions

Project Team for MR18-B4-5004

- Dr. Kevin L. Williams
  - Principal investigator, overall project lead
- Tim McGinnis (Head of APL-UW Ocean Engineering)
  - Leading the integration of commercial-of-the-shelf (COTS) components and system development for MuST
- Vendors selected for COTS
  - EdgeTech: Low and high frequency sonars
  - MacArtney Underwater Technology: Focus 3 Towbody

Technical Objective

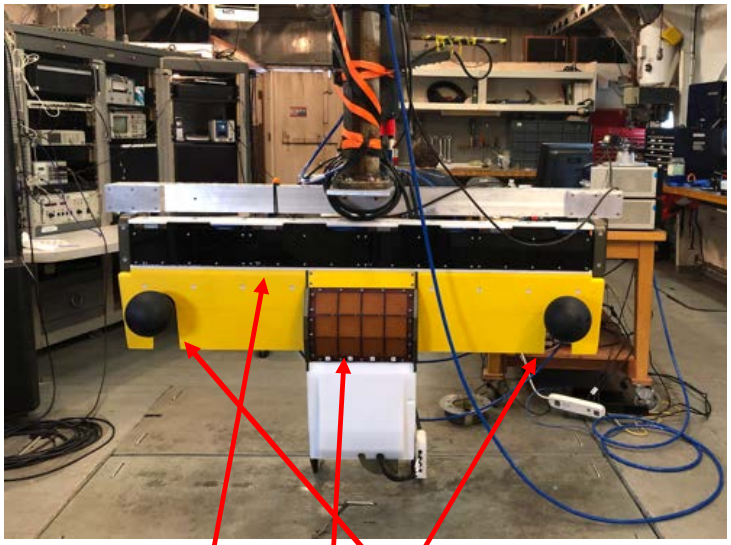
- Build and demonstrate the performance of a platform in detection, classification, and geolocation of underwater munitions
- Address the current lack of operational solutions for buried munitions
- SERDP studies using acoustics indicate:
  - Sonars in the kHz to 10's of kHz frequency range are viable solutions
  - Multiple data products from sonar data are useful (e.g., SAS imaging and acoustic color templates)

MuST Progress to Date

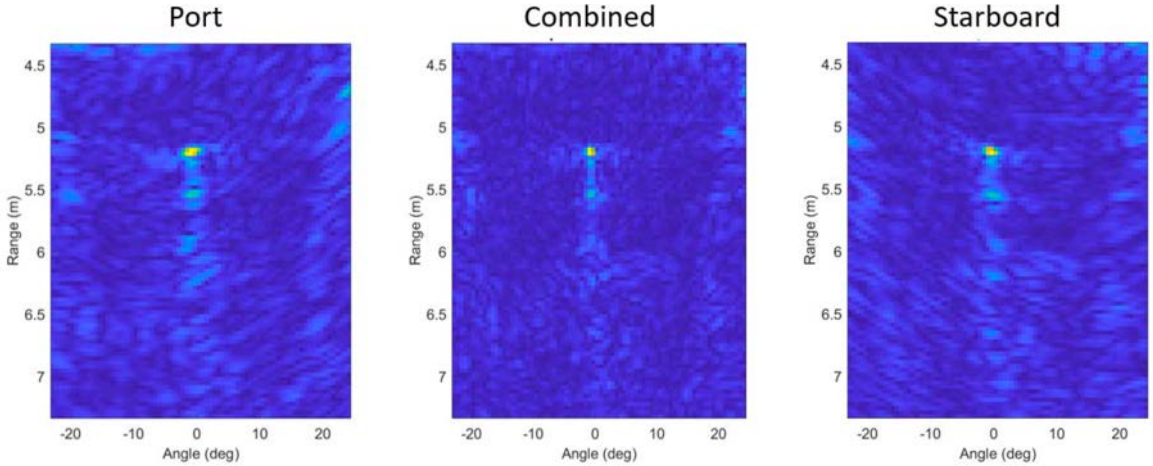
Task	Completion Date
Delivery of components	October - December 2018
Delivery of towbody	January 2019
Site acceptance test of towbody	February 2019
Integration of all components	February - June 2019
Initial calibration of eBOSS	April 2019
Placing munitions and clutter in Sequim Bay	July 2019
Lake Washington test	August 2019
Sequim Bay test	September 2019

eBOSS: LF Sonar

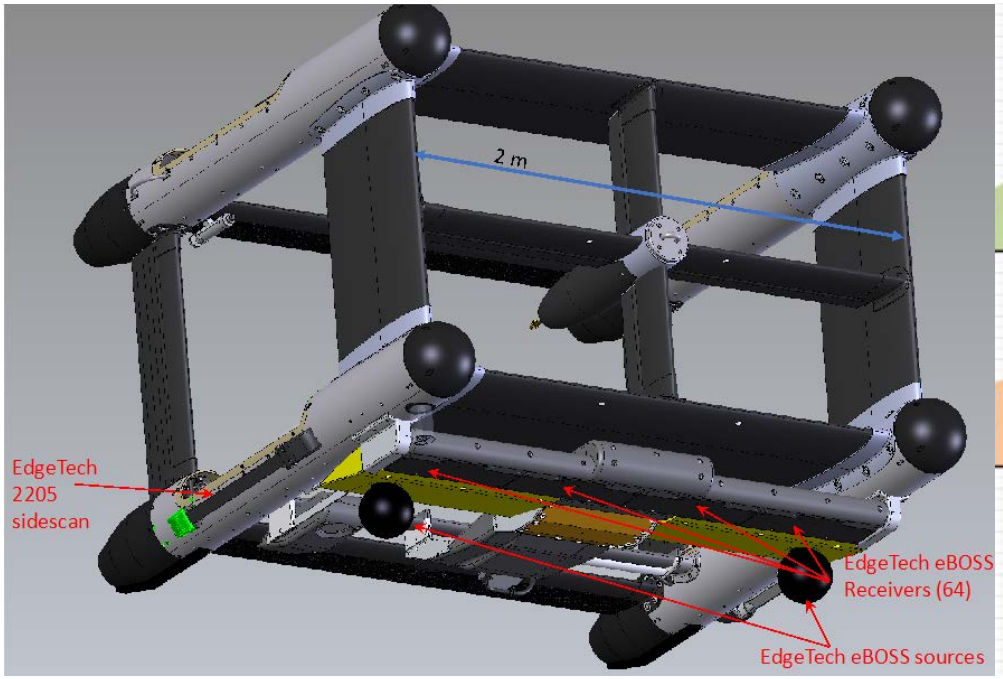
- eBOSS wing as mounted in APL calibration facility
- Initially receiver arrays were noisy with large variability in sensitivity (traced to new manufacturing technique)
- Images of an aluminum pipe taken during calibration
- Tests real and synthetic aperture algorithms and resolution enhancement of two sources

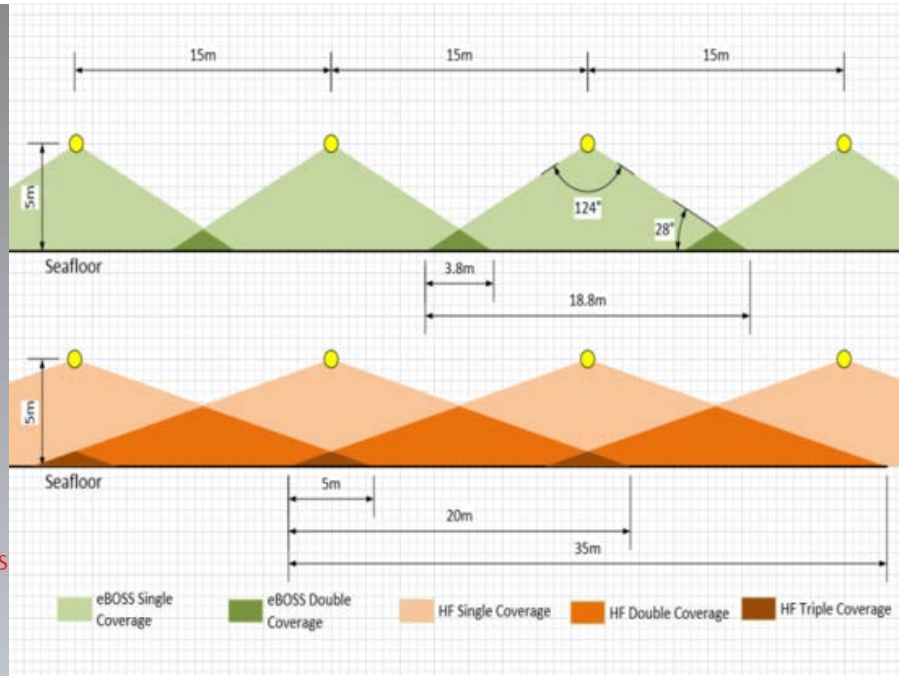


eBOSS Sources
CLUTTEREX Source
64-element receive array



Sea Floor Coverage





- 5 m elevation above sea floor allows a 15 m separation between survey tracks
- Low frequency band has 18.8 m footprint with 3.8 m overlap
- High frequency band has 35 m footprint with 20 m double coverage and 5 m triple coverage

Demonstration Criteria

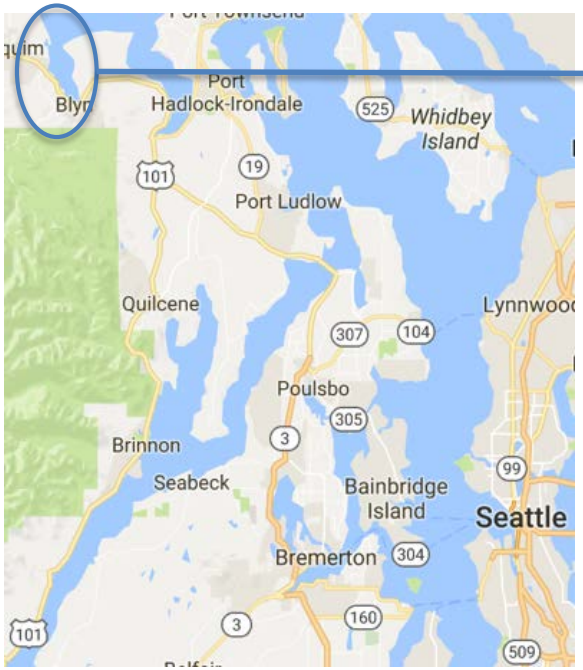
Performance Objective	Metric	Data Required	Success Criteria
Detection of all munitions of interest	Percent detected and correctly classified	Location of items	$P_c > 0.94$ @ $P_{fa} < 0.1$
Location accuracy	Average error and standard deviation in item locations	▪ Location of items from MSL to within 0.25 m ▪ Estimated location from analysis of navigation data	Navigation-based location error standard deviation < 2 m
Production rate	Number of km^2 of data collection per day	Log of field work	1 km^2 per day

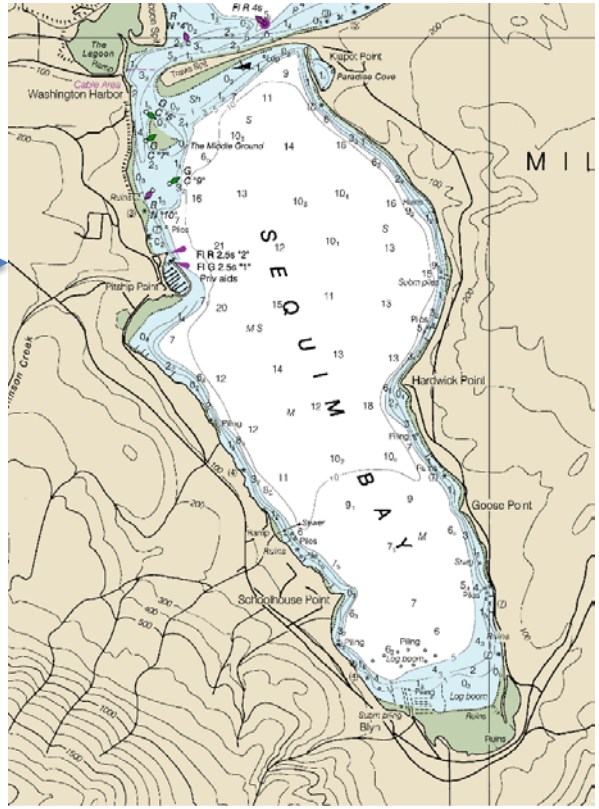
If target field assumed to contain 50 munitions and 50 clutter items

- $P_c = 0.94$ infers 3 missed munitions out of 50
- $P_{fa} = 0.1$ implies 5 of the clutters items are mislabeled

Demonstration Site: Sequim Bay

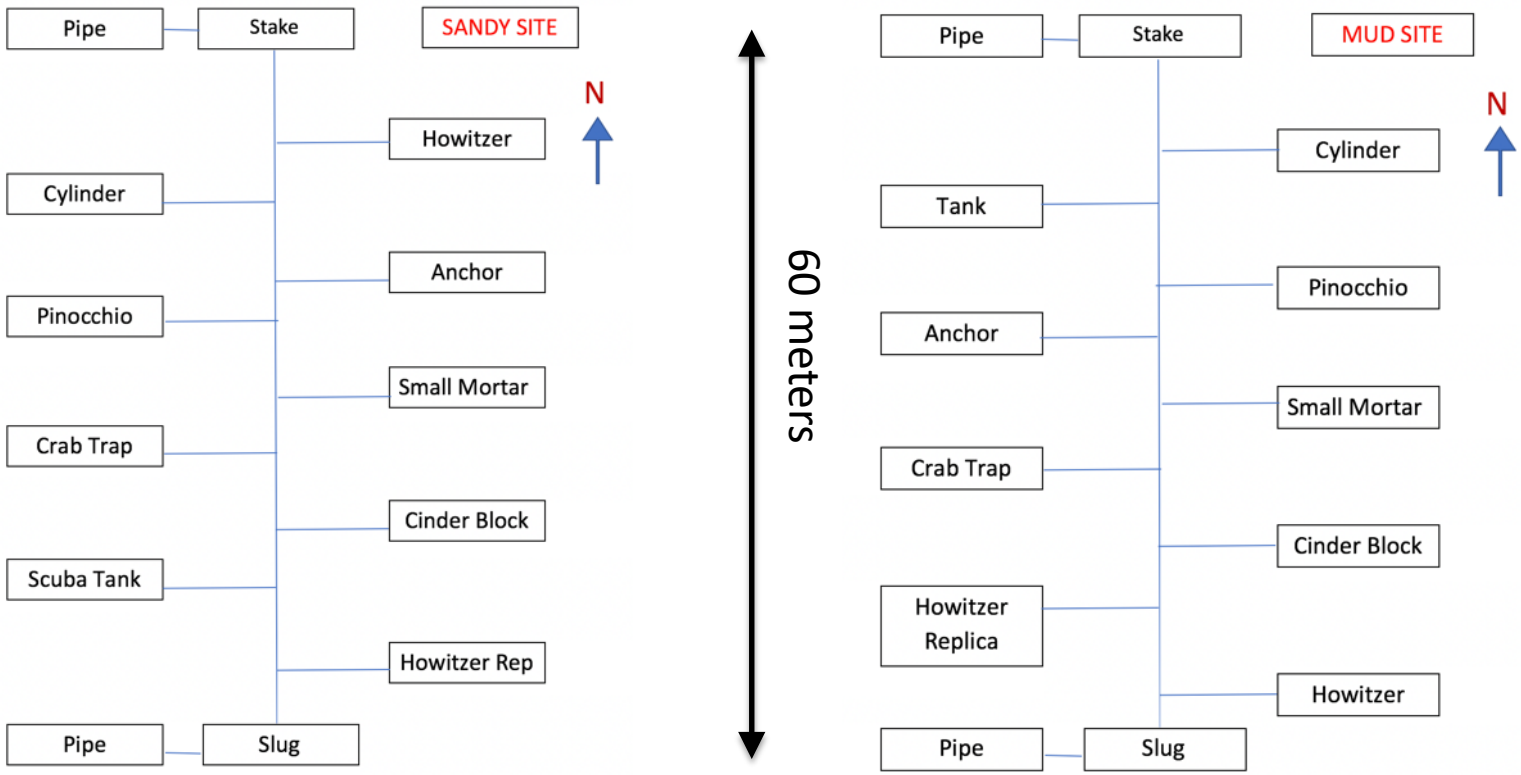
- Average water depth of approximately 20 m
- Relatively flat bottom and a variety of bottom types
- Local DOE facility for support
  - Test bed construction
  - On-site laboratory facilities





Sequim Bay Target Deployment

Joint APL/PNNL four day effort - total of 24 objects in two locations

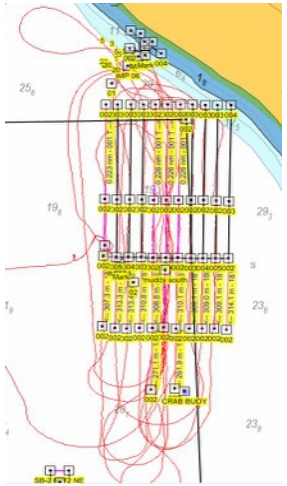


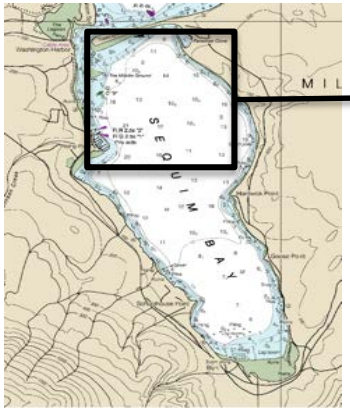
Sequim Bay Comments

- New receiver panels received the week before the test – they proved much more reliable
- Goal was to get data on targets and clutter for two sediment types
- This data is essential for further SAS algorithm development as well as detection and classification code development over the next several months
- The four day effort proved very successful
  - Data on the two target fields at multiple angles, different ping rates, different heights above bottom
  - Wide area survey over a 500 x 1700 meter area
  - this data will also be useful to test our ability to invert for sediment structure down to at least 2 meters below the sediment/water interface
- Step through some details in the next several slides

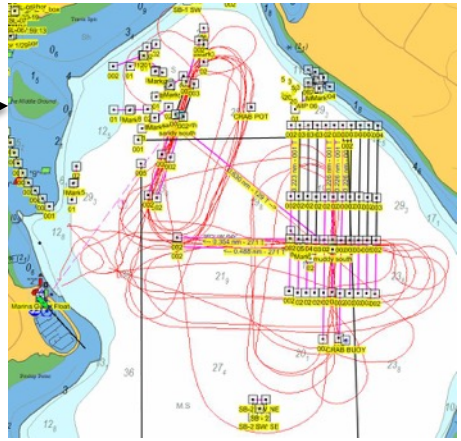
Sequim Bay: GPS Ship Tracks

Sept. 9





Sept. 10



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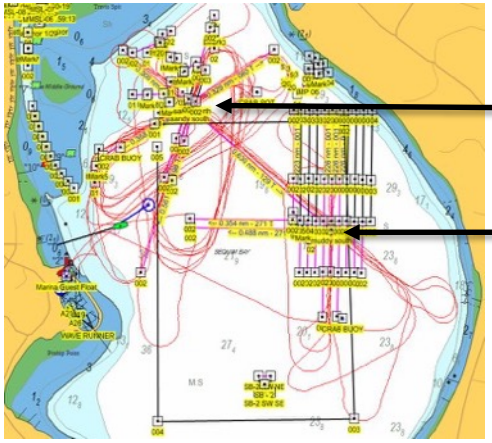
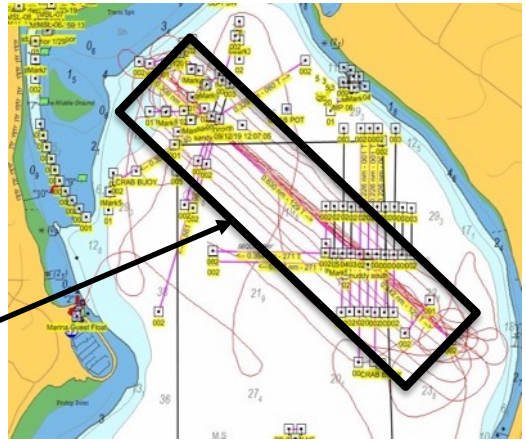


Sand site

Mud site

≈ 0.5 x 1.7 km^2

Sept. 12



High-Frequency Sidescan Sonar

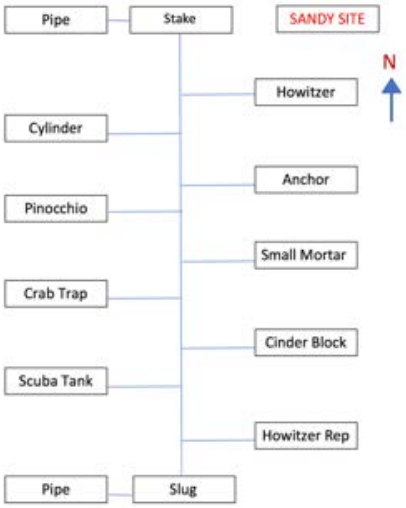
Broad survey

Mud area

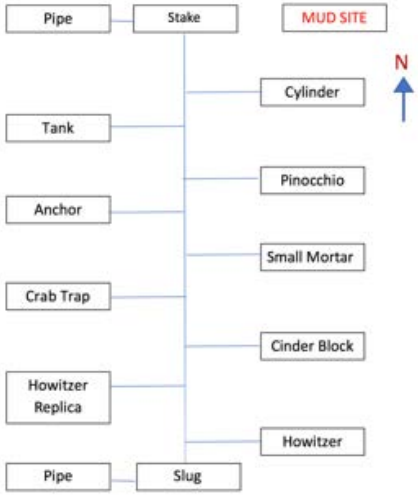
Mud target line

High-Frequency Sidescan Sonar

Sand target line



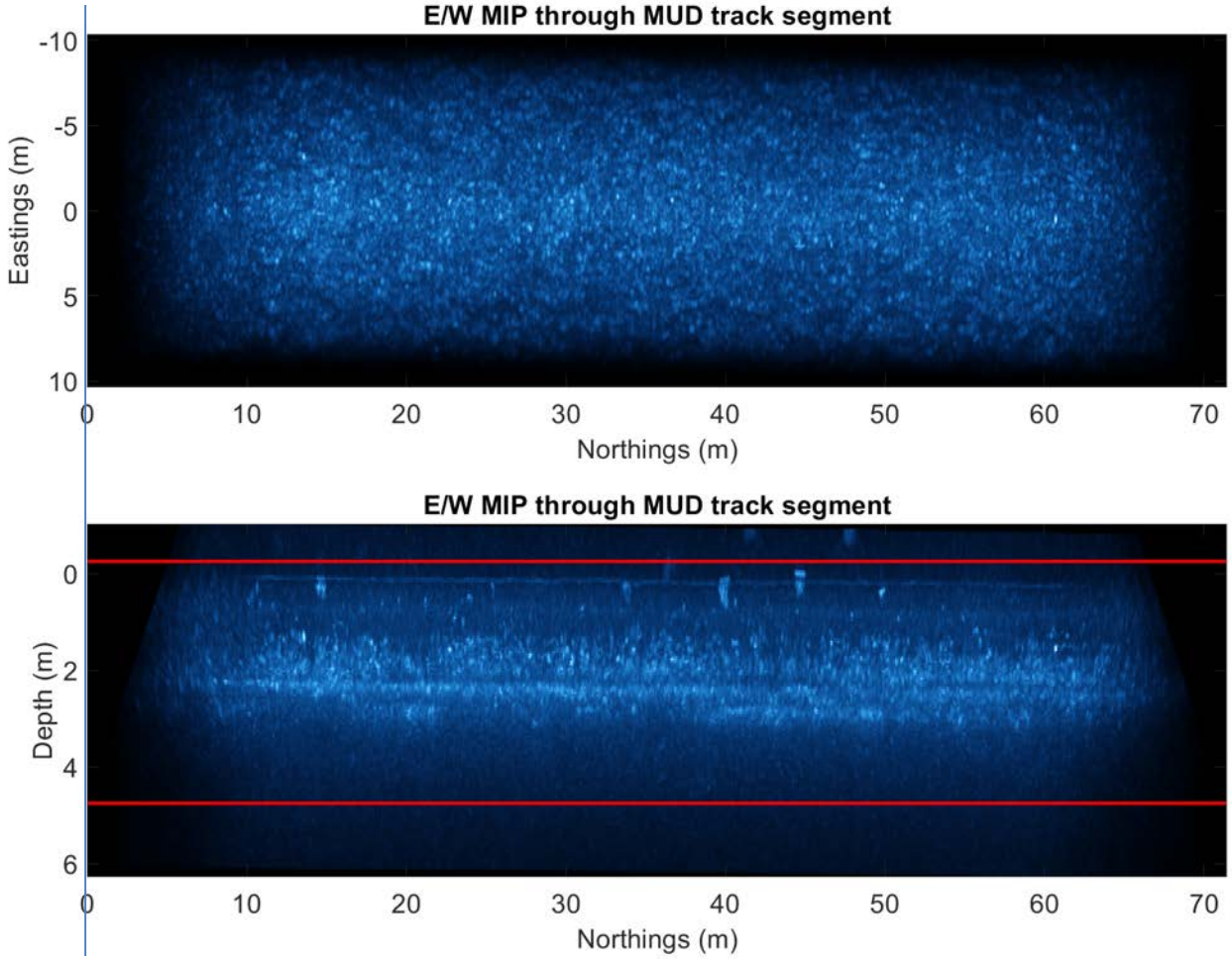
Mud target line



eBOSS Mud Site

- 2000 pings (some targets not included)
- 120 degree integration angle (real aperture processing)
- 90 degree integration angle (synthetic aperture processing)
- eBOSS source configuration (left/right alternating pings)
- Fast Factorized Back Projection (FFBP) imaging algorithm
- 5x5x5 cm^3 voxels (under-sampled for memory restrictions)
  - Future update will reduce size of voxel and make complex

Maximum Intensity Projection (MIP)



- MIP through full volume obscure targets
- Z-dim. is getting sliced in half each iteration
- Targets visible in last few slices

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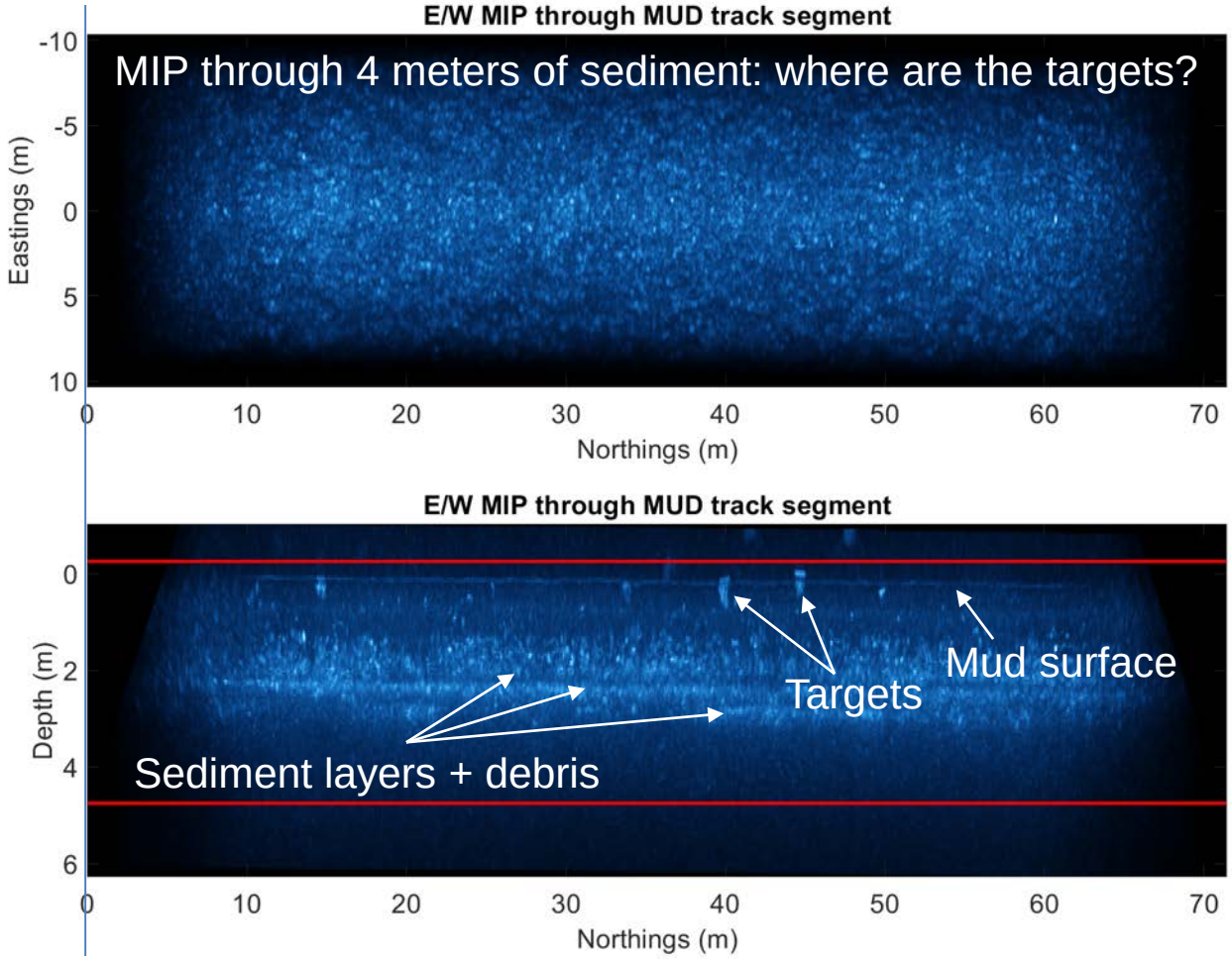

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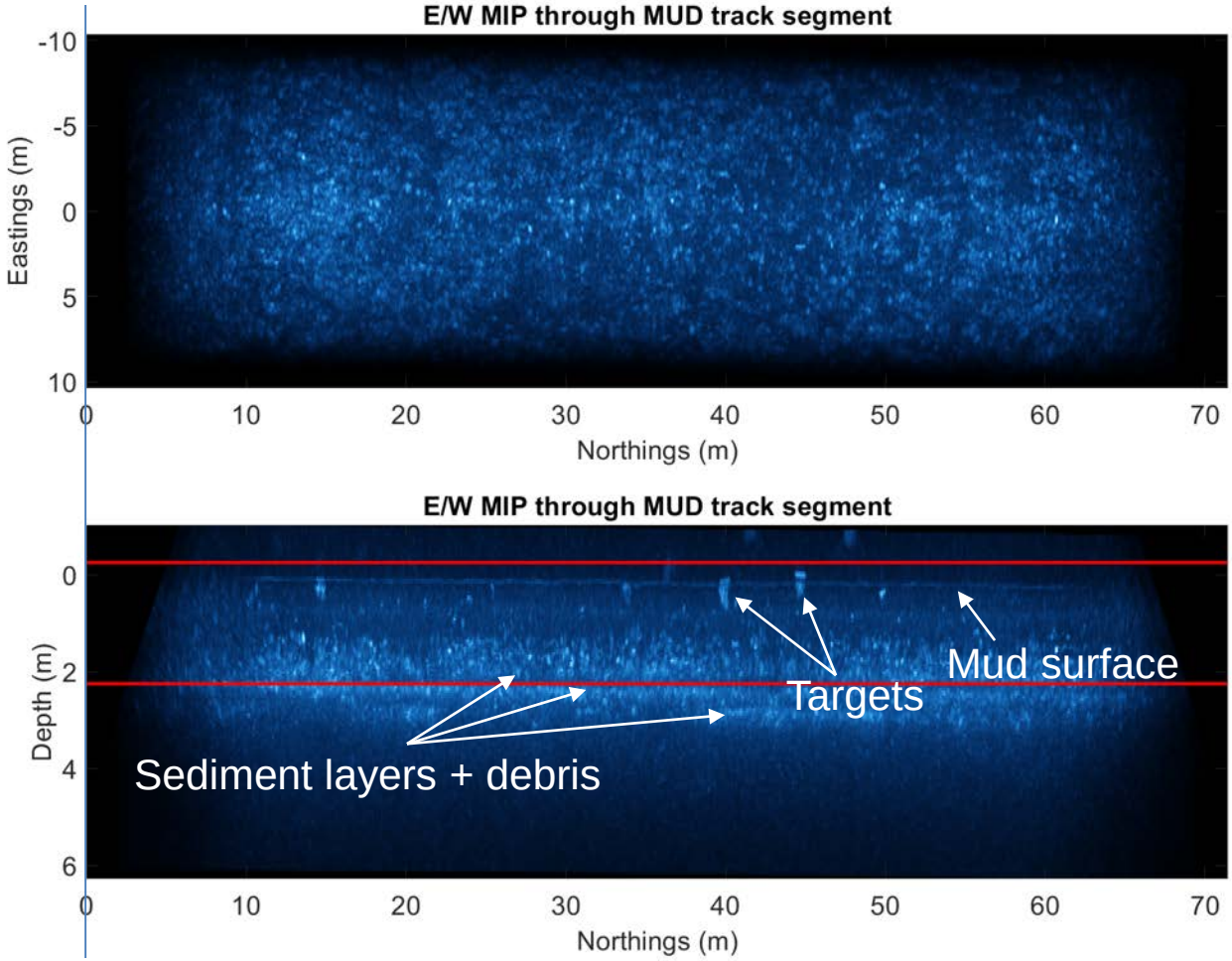

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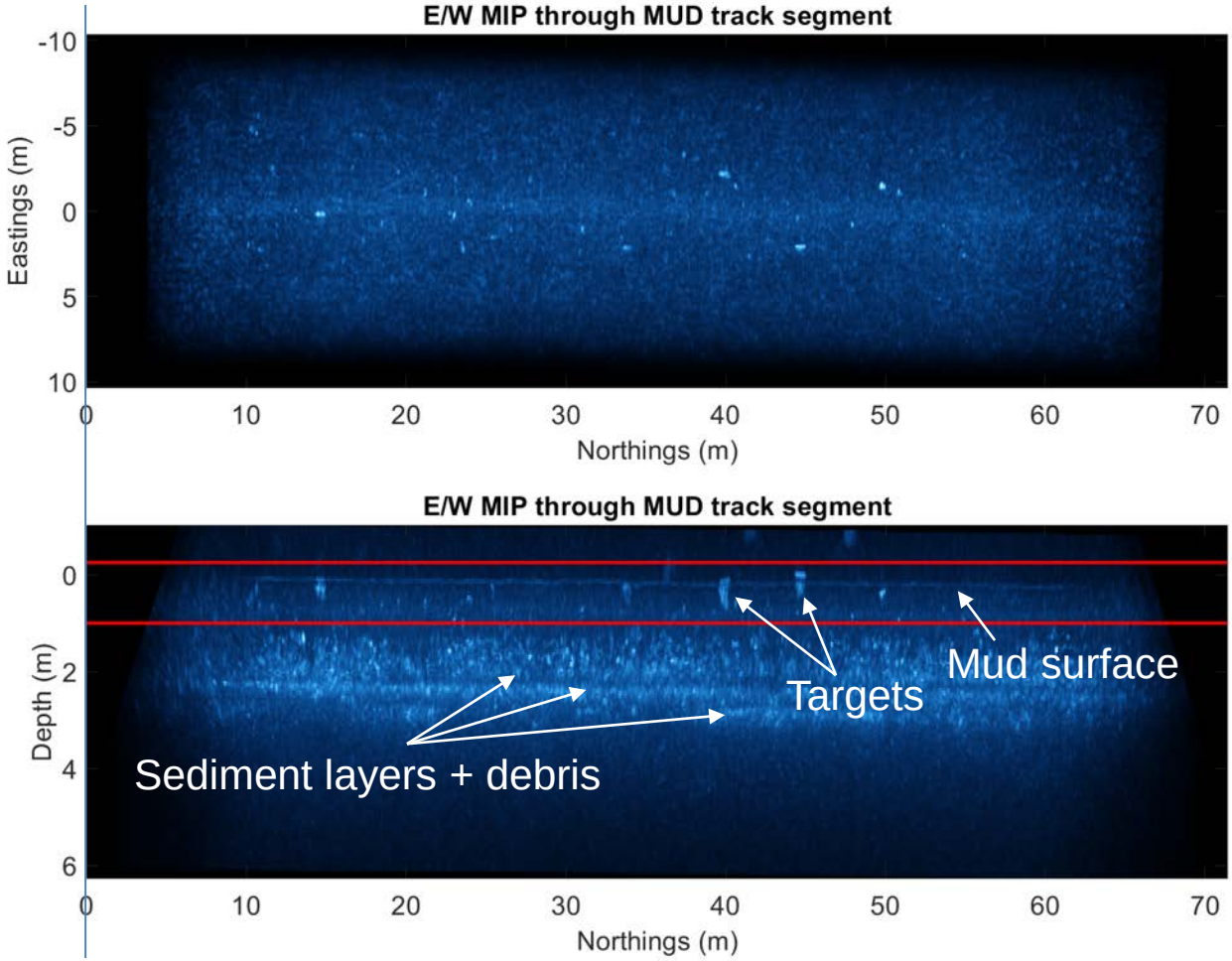

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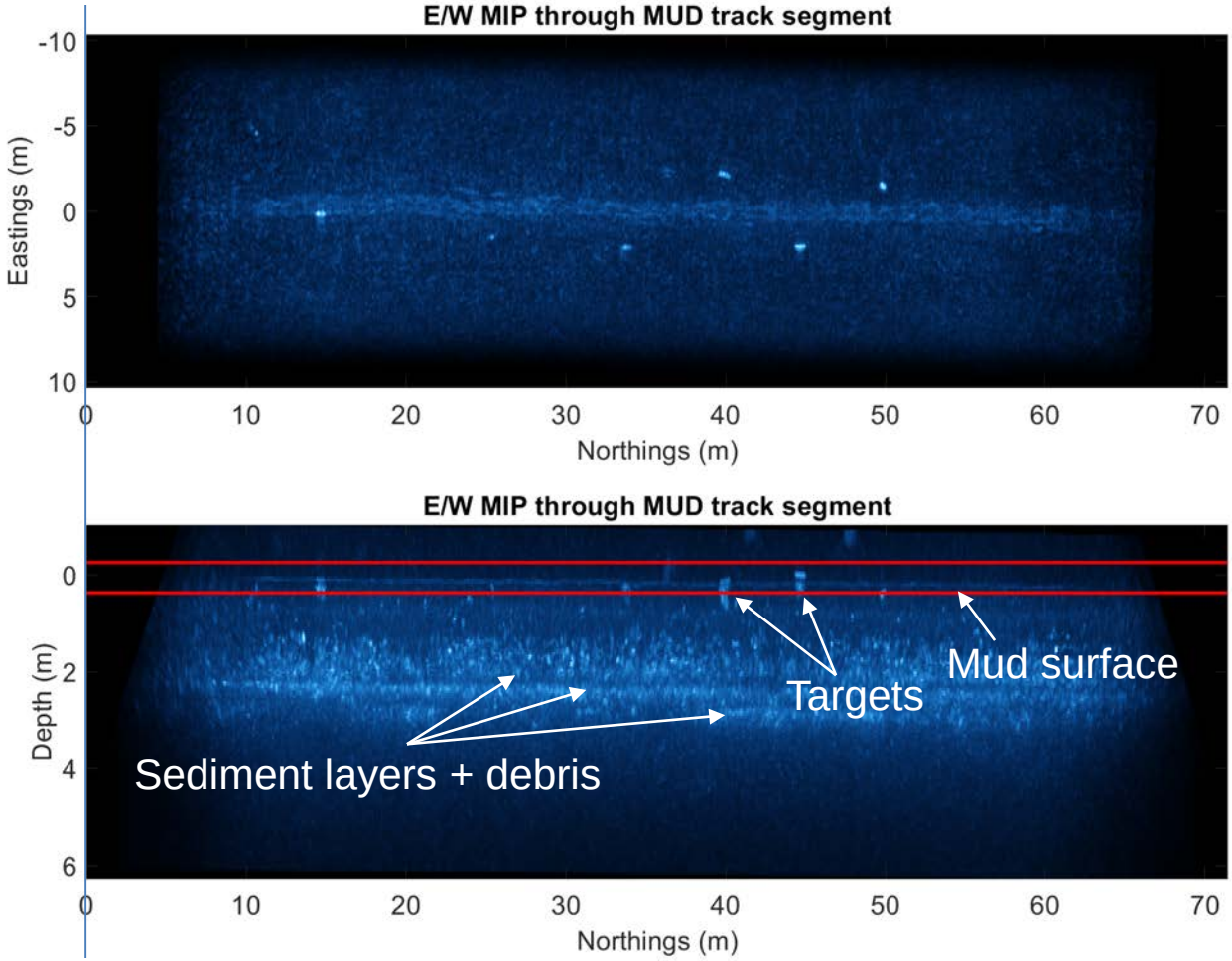

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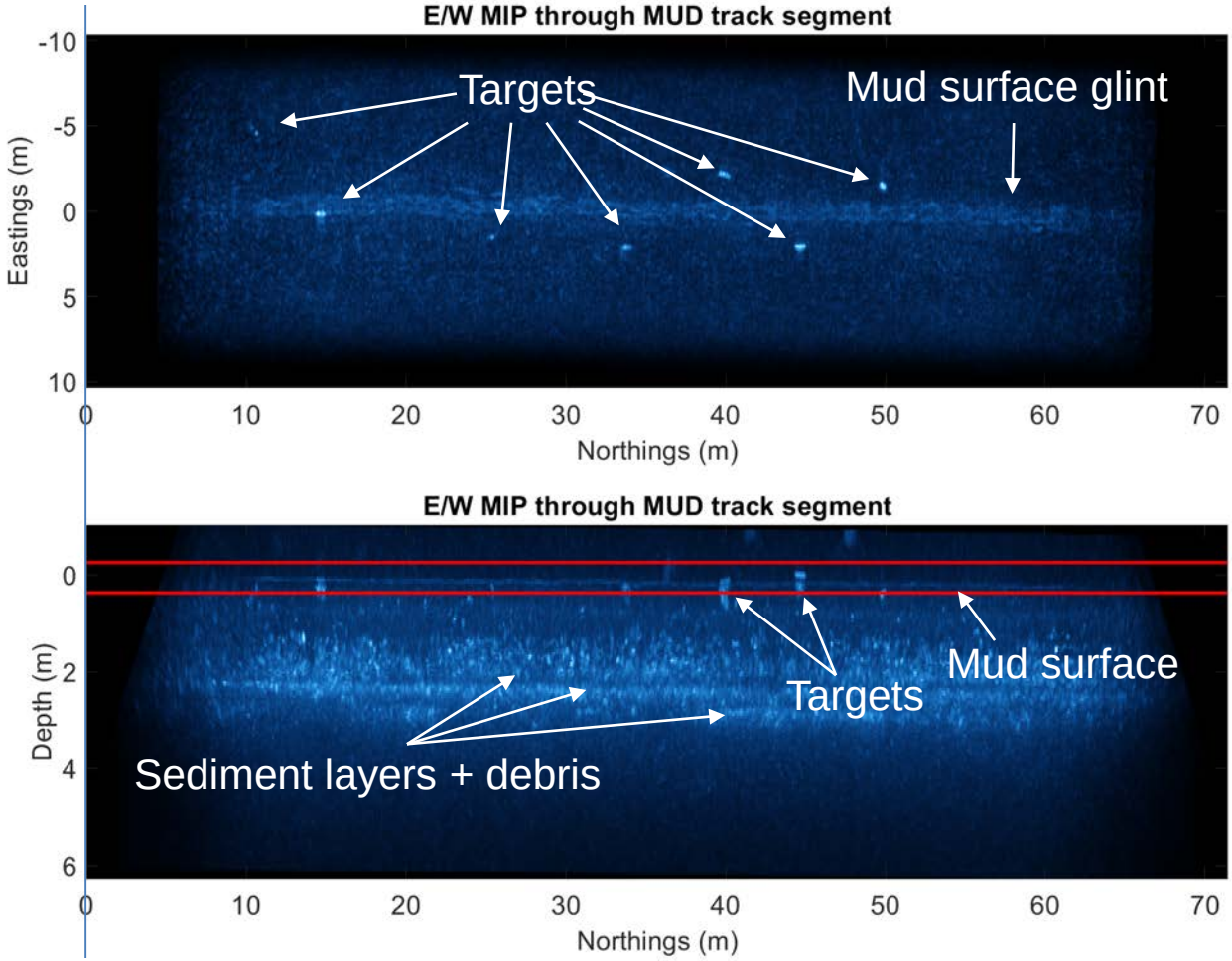

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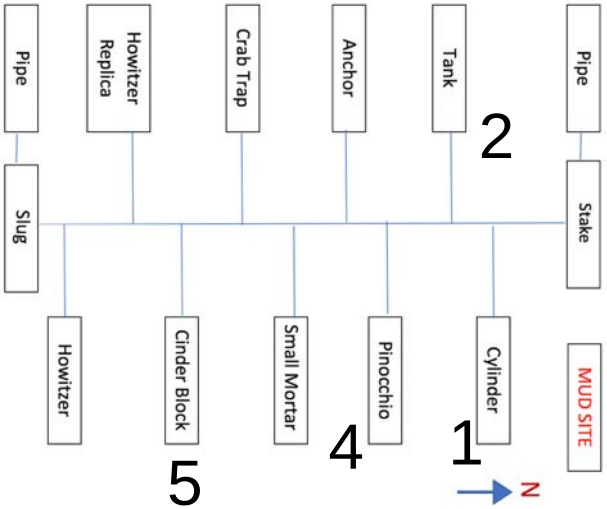
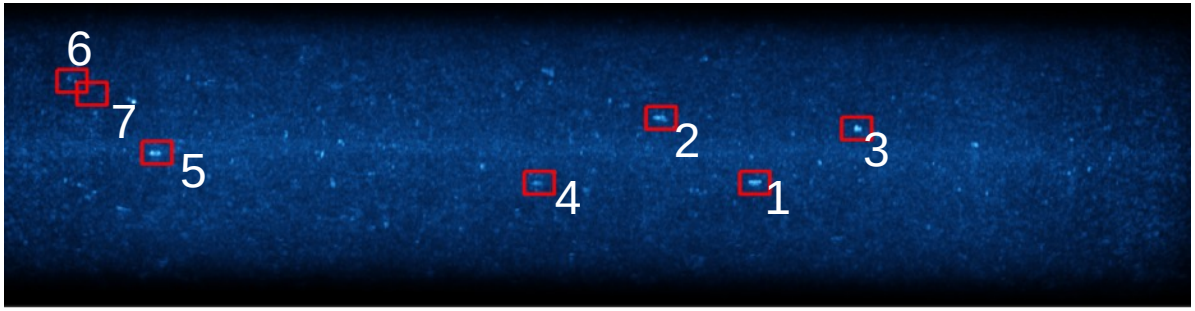
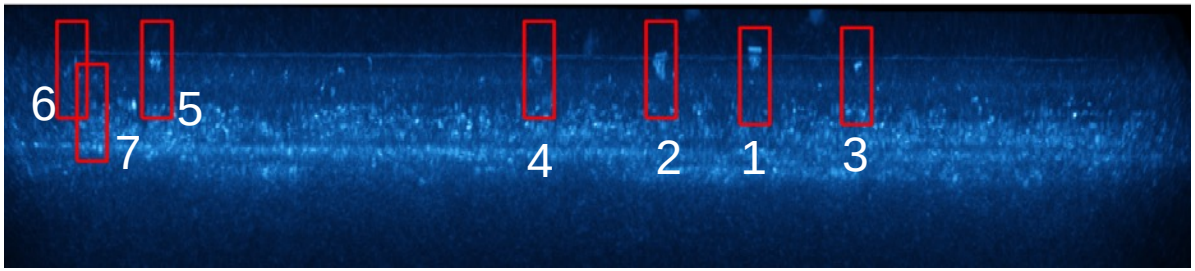
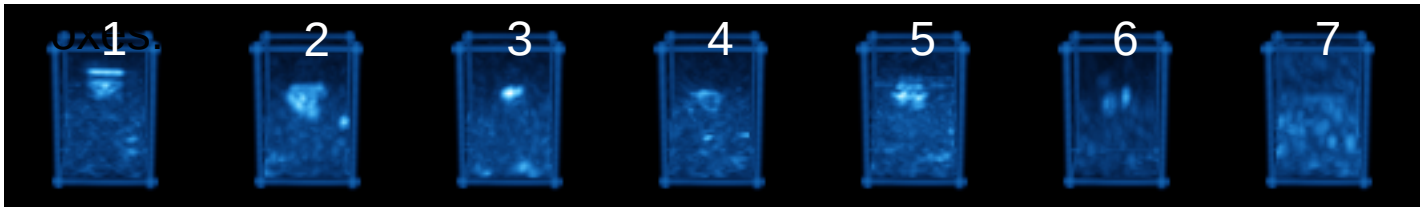
Volume Rending







1.5 x 1.5 x 2.25 m. ROI



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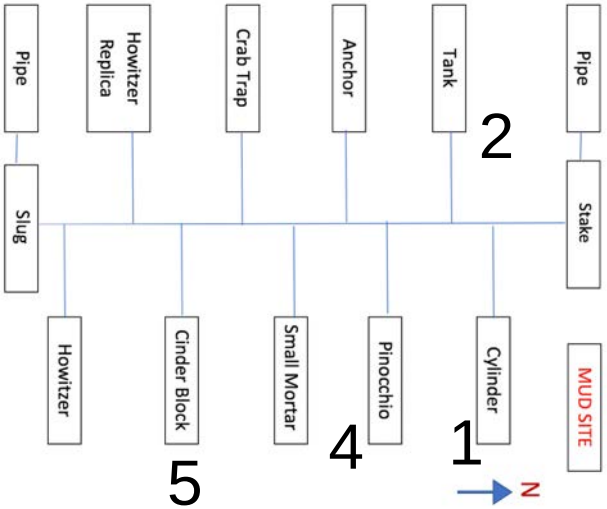

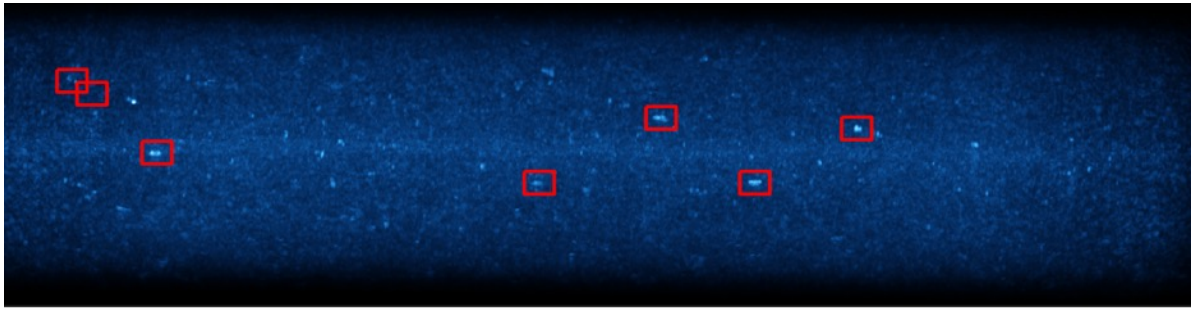

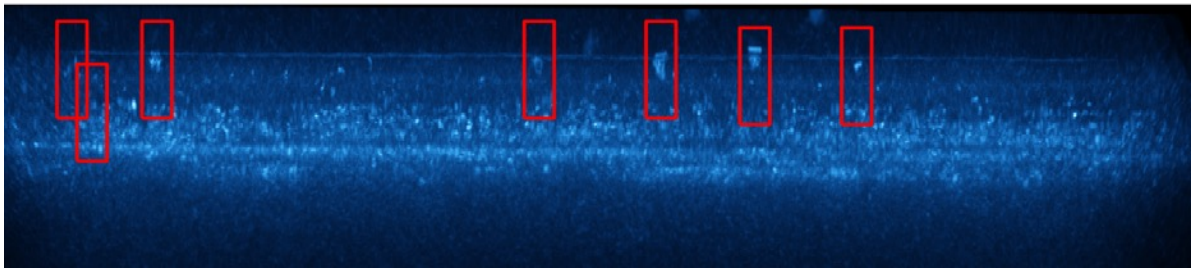

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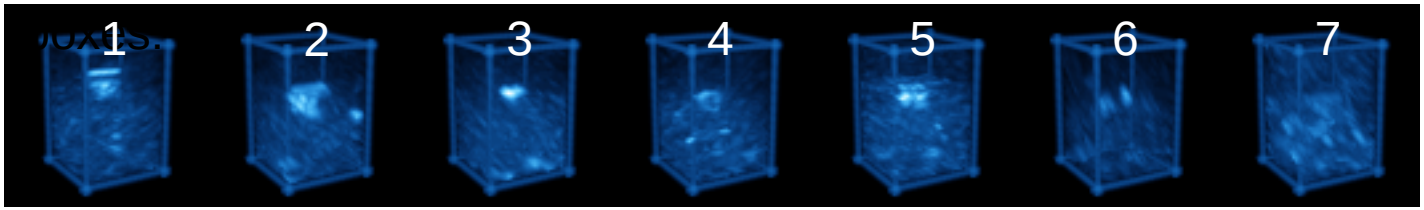

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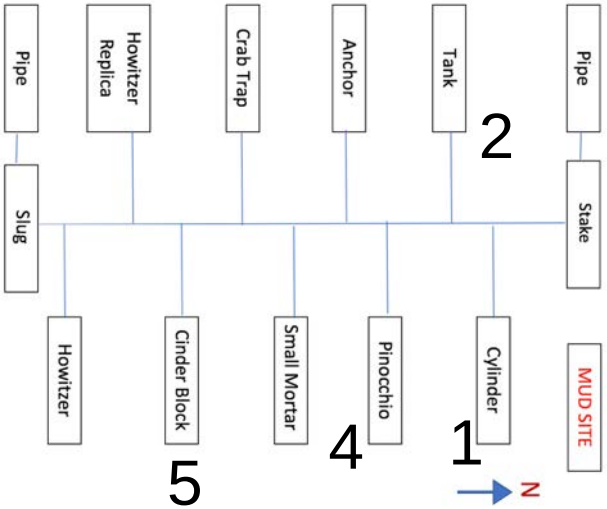

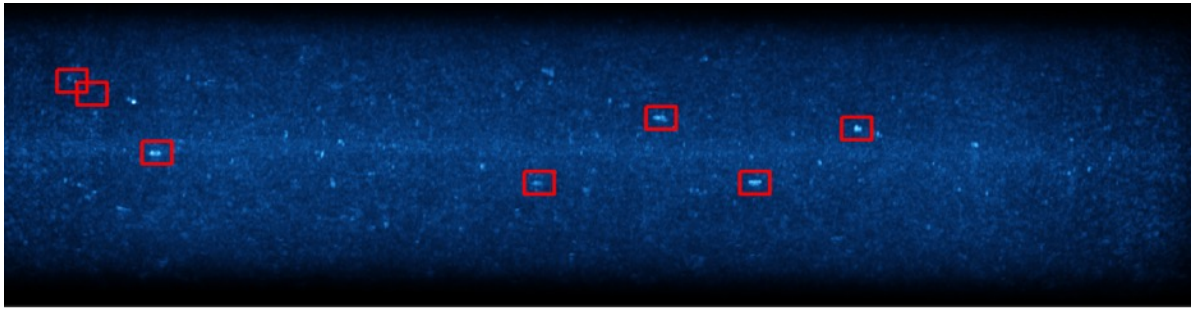

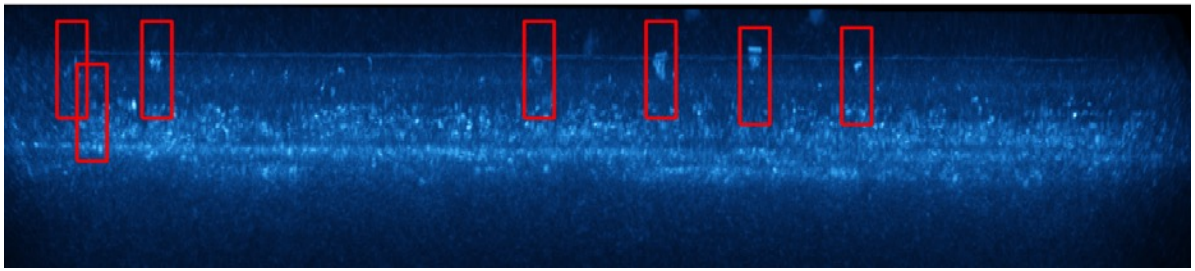

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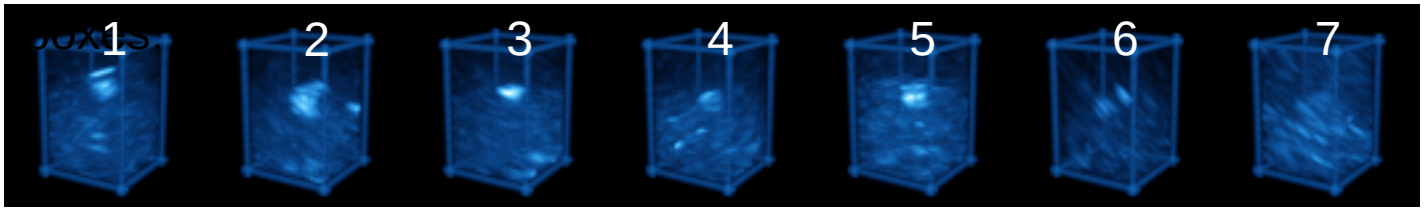

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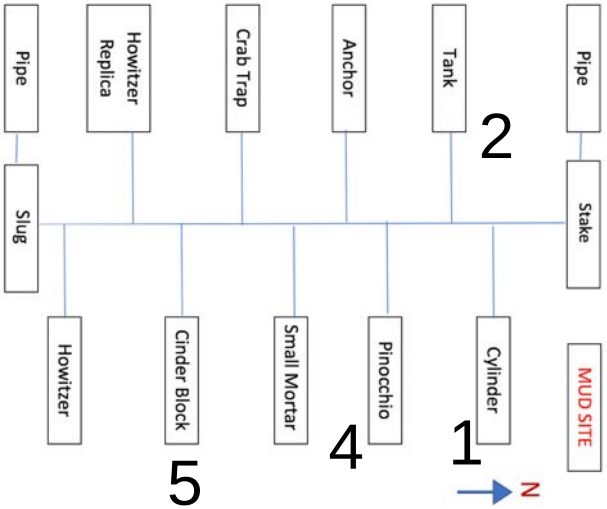

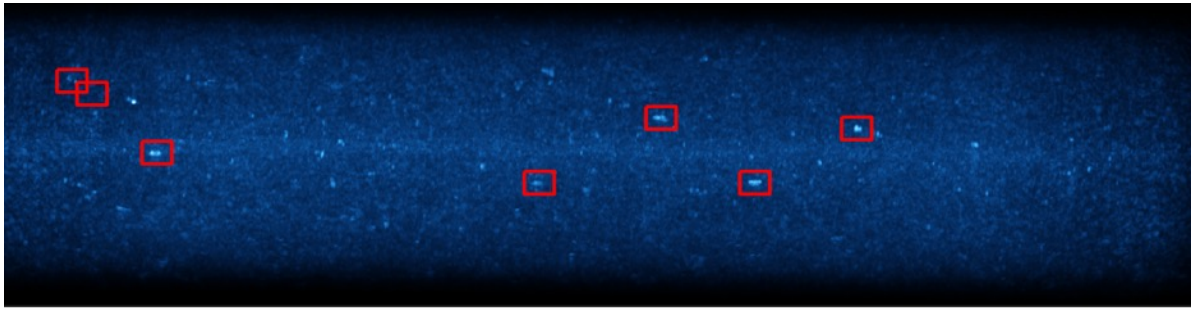

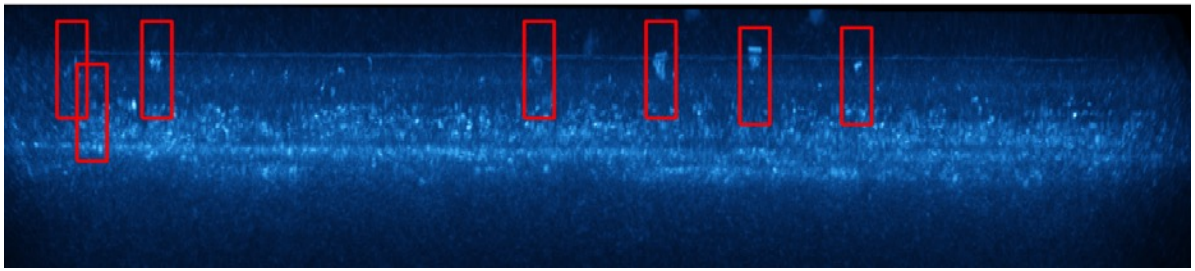

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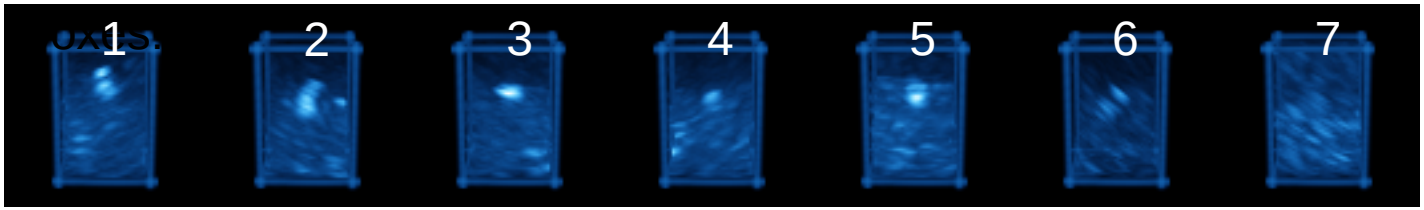
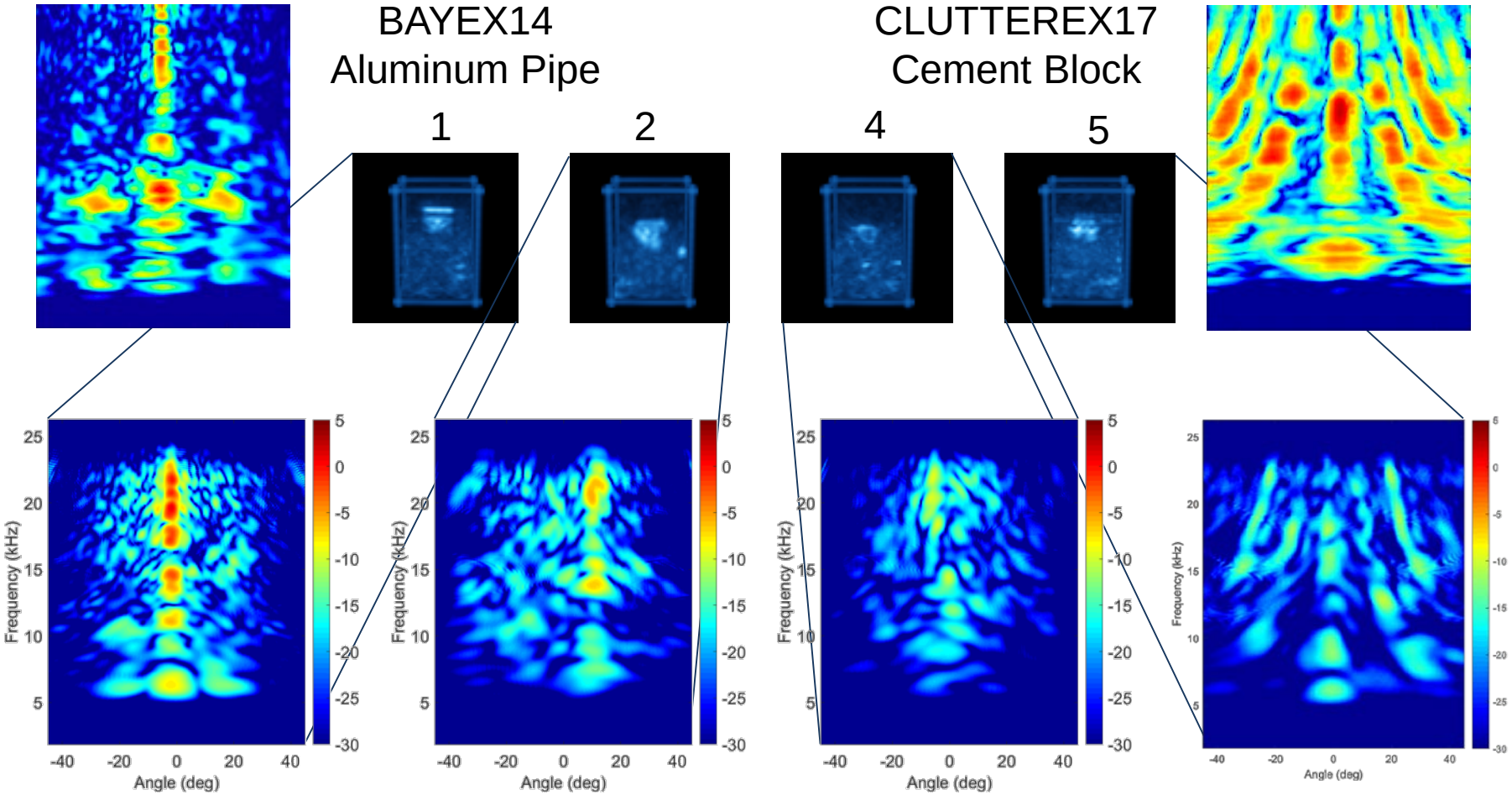


Acoustic Color Extraction



Lessons Learned

- 3D AC generation + high resolution patch imaging currently under development
- Showed mud because that was the harder set
- There are a lot of “targets” in the SAS imagery in mud, and SAS beamforming works very well. The trick is to look in the right layer
- At the moment AC images have no spreading-loss or directivity corrections applied
- Angles past ±40 degree in along-track were noisy (probably due to along-track aliasing)

Lessons Learned (Cont'd)

- New manufacturing technique of eBOSS receive panels caused initial failures. Second batch of receive panels worked well. Final batch to be delivered in the next few months
- Panel issues have made system calibration difficult to this point
- The system will need to be fielded by experienced ocean contractor team (probably need 4 to 5 people)
- Effort will need to be put in making user friendly signal processing packages

Benefits to DoD

- Integration of knowledge gained under SERDP projects (1665, 2231, and 2505) into the MuST under MR18-B4-5004 provides a low cost platform for munition remediation in water depth of 15 to 100 m
- MuST is designed for the addition of alternative sensor modalities
- Ship-board electronics package (e.g., navigation, data acquisition, and storage) minimizes cost due to the risk of towbody (e.g., striking an obstacle)
- Blind test is schedule for third quarter of 2020

Citations

- AL España et al, J. Acoust. Soc. Am., 136, 109-121, (2014)
- 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)
- SG Kargl et al, IEEE J. Ocean. Eng., 40, 632-642, (2015)

For additional information, please visit

https://serdp-estcp.org/Program-Areas/Munitions-Response/Munitions-Underwater/MR-2505

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kargl@uw.edu; 206-685-4677

SERDP DOD • EPA • DOE | ESTCP

Q&A Session 2

SERDP DOD • EPA • DOE | ESTCP

The next webinar is on May 7, 2020

Innovative Technologies for PFAS Destruction in Investigation Derived Wastes

SERDP DOD • EPA • DOE | ESTCP

Survey Reminder

Please take a moment to complete the survey that will pop up on your screen when the webinar ends

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