INVESTIGATION OF ACOUSTIC SCATTERING FROM UXO WITH LONG-TERM ENVIRONMENTAL AGING

MR21-3582

Kevin Lee, Connor Hodges, Charles Hubbard, David Mitlin, Preston Wilson

The University of Texas at Austin

In Progress Review Meeting

12-JAN-2026

Project Team

Dr. Kevin M. Lee (PI)
Applied Research Laboratories University of Texas at Austin

Dr. Preston S. Wilson (co-PI)
Applied Research Laboratories and Dept. Mech. Eng., University of Texas at Austin

Dr. David Mitlin (co-PI)
Texas Materials Institute and Dept. Mech. Eng., University of Texas at Austin

*SMART Scholar NSWC-Panama City

Connor Hodges* (PhD Candidate, 2026 est. completion)
Applied Research Laboratories University of Texas at Austin

Charlie Hubbard (MS, 2025)**
Applied Research Laboratories University of Texas at Austin

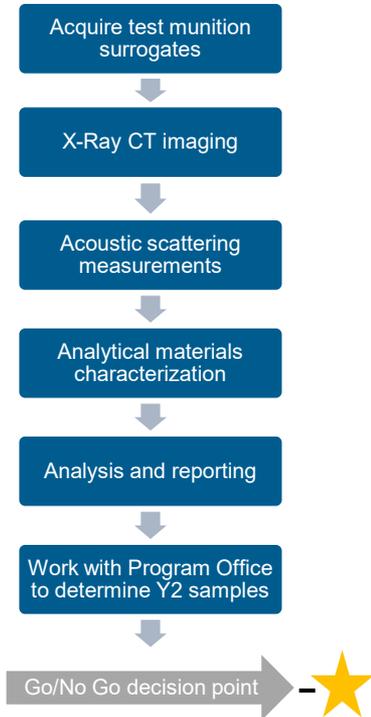**staying on for PhD in related topic

Bottom Line Up Front

- This goal of this project is to investigate the impacts of long-term corrosion on sonar detection and classification of submerged munitions.
- Testing activities have yielded experimental data on real-world corroded samples retrieved from a marine environment.
- Analysis of that data has indicated potential implications for ATR—we expect that signatures of pristine UXO will be different from UXO exposed to the marine environment for long periods of time.
- Collaborations with other SERDP/ESTCP performers have yielded new insights into improved data analysis and feature extraction methods.
- We have had success with translating high-resolution CT imagery into geometries usable in FEM modeling software.
- Efforts are underway to characterize bulk material properties of UXO that are relevant to target response modeling.
- A new collection of UXO was obtained for additional testing.

Technical Objective

- Investigate impacts of long-term environmental aging on the acoustic response of submerged munitions

- Directly compare clean and degraded samples' physical structure, material composition, and acoustic scattering signature

- Provide experimental data on real samples to inform SERDP's target physics modeling efforts and detection/classification efforts
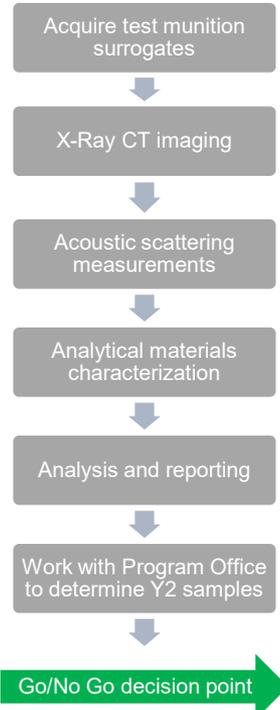
SERDP

Technical Approach

Y1

Acquire test munition surrogates

↓

X-Ray CT imaging

↓

Acoustic scattering measurements

↓

Analytical materials characterization

↓

Analysis and reporting

↓

Work with Program Office to determine Y2 samples

↓

Go/No Go decision point — ⭐

All Y1 tasks addressed

Go/No Go Decision:
- After submission of Year 1 analysis and report

Technical Approach

Y1

Acquire test munition surrogates

↓

X-Ray CT imaging

↓

Acoustic scattering measurements

↓

Analytical materials characterization

↓

Analysis and reporting

↓

Work with Program Office to determine Y2 samples

↓

Go/No Go decision point ⭐

Y2

Continued studies on Y1 samples

↓

Sample modification tests

↓

Bulk materials characterization tests

↓

Data analysis

New sample testing

↓

2.75 M229 rocket tests

↓

Data analysis

All Y1 tasks addressed

Go/No Go Decision:
- After submission of Year 1 analysis and report

Y2 tasks *in progress*:
- Additional Y1 sample tests and data analysis
- New sample testing

SERDP

Technical Approach

Y1

- Acquire test munition surrogates
- X-Ray CT imaging
- Acoustic scattering measurements
- Analytical materials characterization
- Analysis and reporting
- Work with Program Office to determine Y2 samples

Go/No Go decision point

Y2

Continued studies on Y1 samples
- Sample modification tests
- Bulk materials characterization tests
- Data analysis

New sample testing
- 2.75 M229 rocket tests
- Data analysis

Critical Findings Sheet

Final Report & Data Delivery

All Y1 tasks addressed

Go/No Go Decision:
- After submission of Year 1 analysis and report

Y2 tasks *in progress*:
- Additional Y1 sample tests and data analysis
- New sample testing

Project wrap-up
- Technology Transition
- Final Deliverables
- Est. completion: May 2026

SERDP

Results to Date

- AN MK-23 samples
- Acoustic scattering tests
- CT imaging analysis
- Materials characterization tests
- Collaboration with other SERDP/ESTCP teams
- Additional samples for Y2

SERDP

MK23 practice bomblets

- **AN MK-23 cast-iron practice bomblets deployed during WWII training exercises**
  - 19 samples recovered from Martha's Vineyard salt pond after spending approximately eight decades submerged in saltwater environment
  - 1 sample recovered from Duck, NC during 1996 site investigation
  - 4 clean, well preserved specimens obtained for comparison
  - Thanks to Andy Schwartz, U.S. Army Corps of Engineers
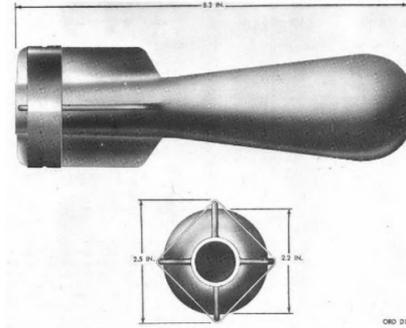
Sample retrieval location

- **Primary retrieval location details**
  - Tisbury Great Pond on Martha's Vineyard, MA
  - Open to Atlantic ocean; cut dredged several times per year since ca. 1700
  - Range of sample burial depths: 10–76 cm
  - Mean sample burial depth: 48 cm

- **Duck sample retrieval location**
  - Found during site investigation in Duck, NC
  - Located inland about 1000 ft from the beach
  - Buried about 6–10 inches

Tisbury Great Pond

Acoustic scattering measurements

- Free-field frequency- and aspect-dependent monostatic target strength measurements
  - Free-field measurements isolate corrosion effects from boundary effects
  - Acoustic frequencies span both structural acoustics and imaging regimes
  - Multiple replicates acquired to ensure repeatability and provide target strength uncertainty bounds

Orientation
(ensonification
direction into page)
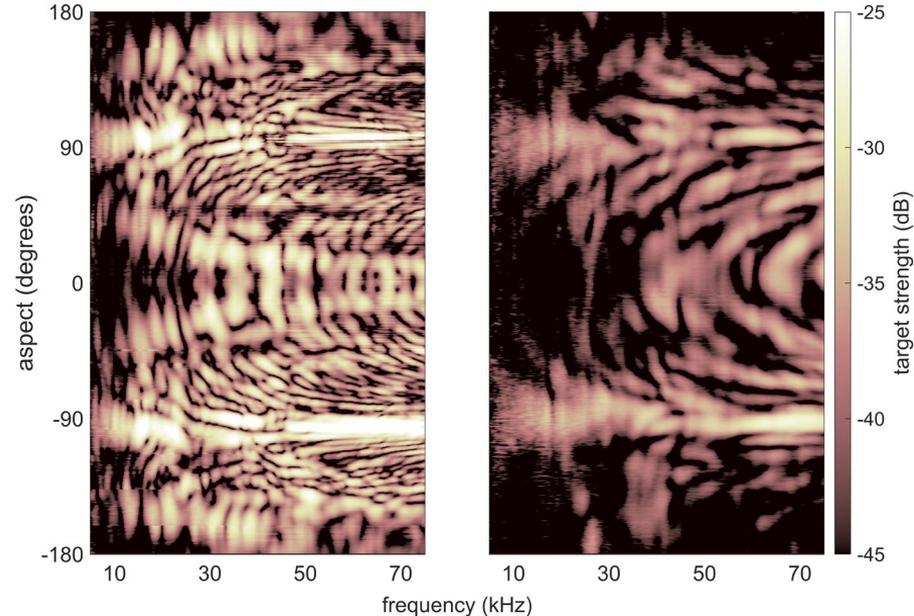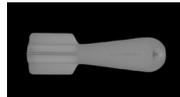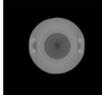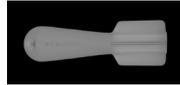
Acoustic test facilities

- Lake Travis Test Station (LTTS), a US Navy sonar calibration and underwater acoustics facility operated by ARL:UT, located 16 miles from the main laboratory
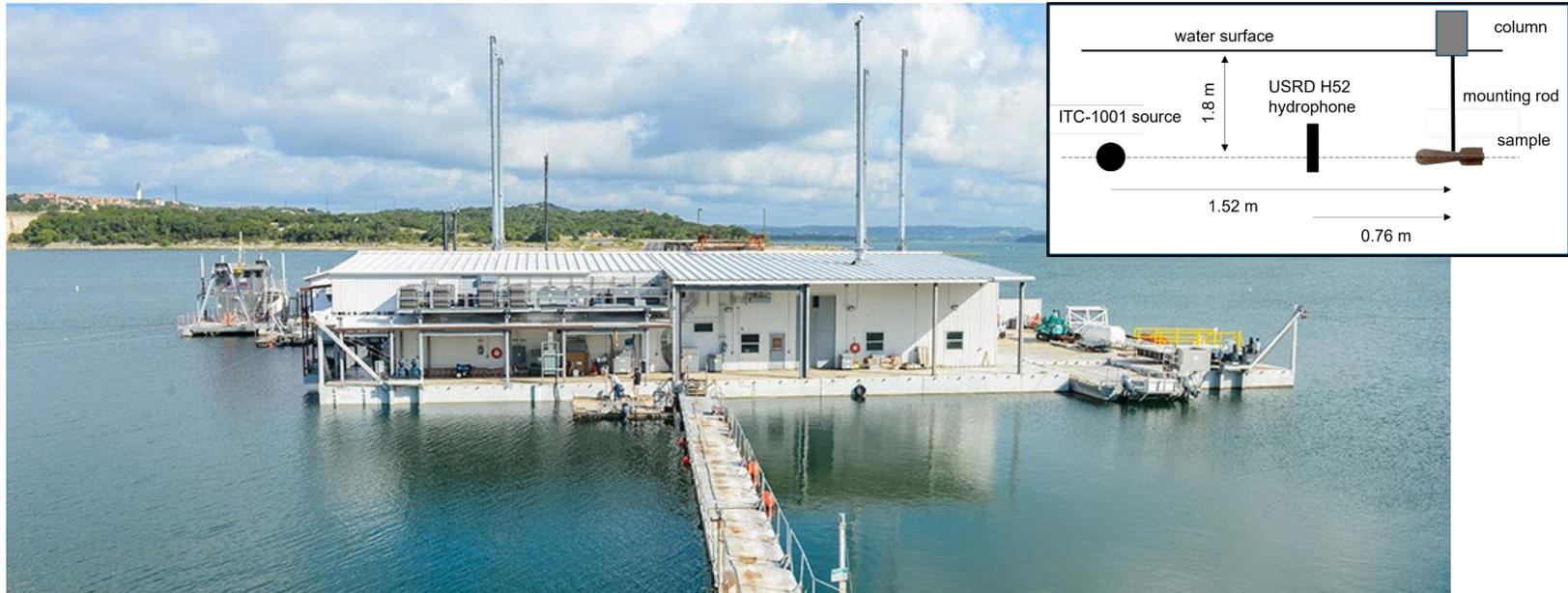
Additional acoustic test facilities

- ARL:UT sonar calibration tank used for additional acoustic measurements in 2025
  - Dimensions: 12' D, 15' W, 60' L
  - Usable frequency band (f > 5 kHz) is adequate for MK23-sized targets
  - Same test geometry as LTTS used
  - Same type of data acquisition system and motorized column as LTTS
  - Higher-precision target positioning than LTTS (no currents, wave motion, or boat wakes)
  - Cost to test is zero (no LTTS usage fees)

column

DAQ system

motorized cart

column

target and test fixture
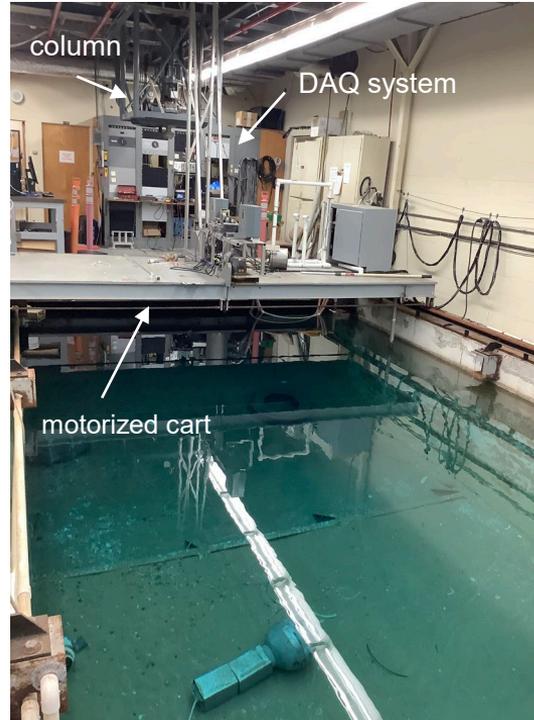
Acoustic color

$$TS = 20 \log_{10} \frac{|P_{sc}(\theta, \omega)|}{|P_i(\omega)|}$$

Tukey Window
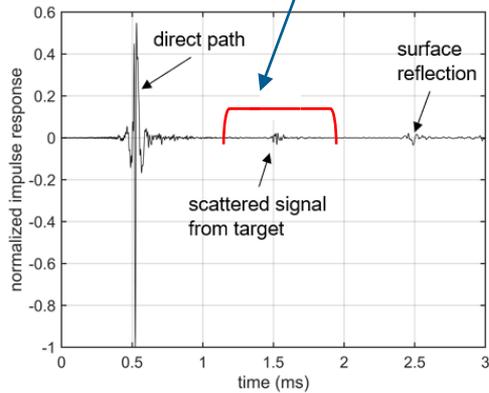
Orientation
(ensonification
direction into page)
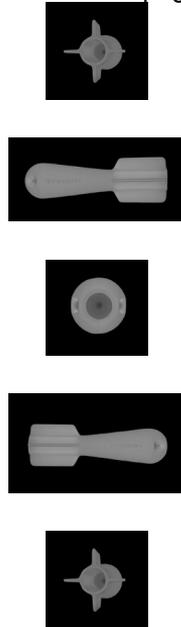
time-domain "butterfly plot"
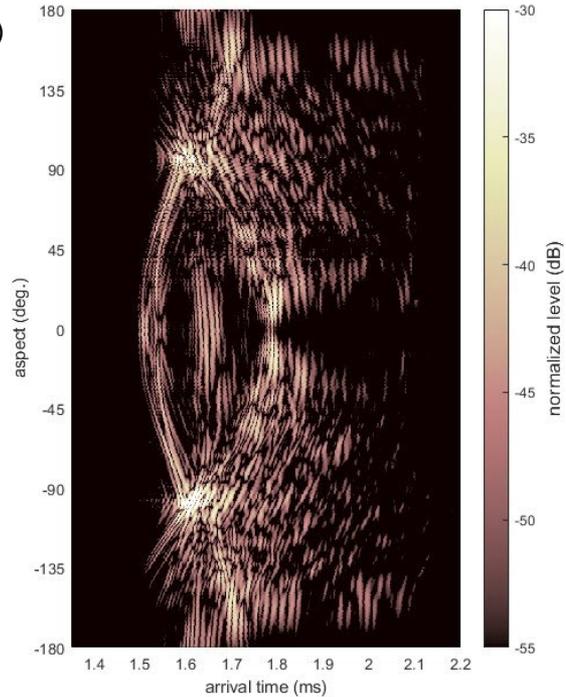
frequency-domain "acoustic color"
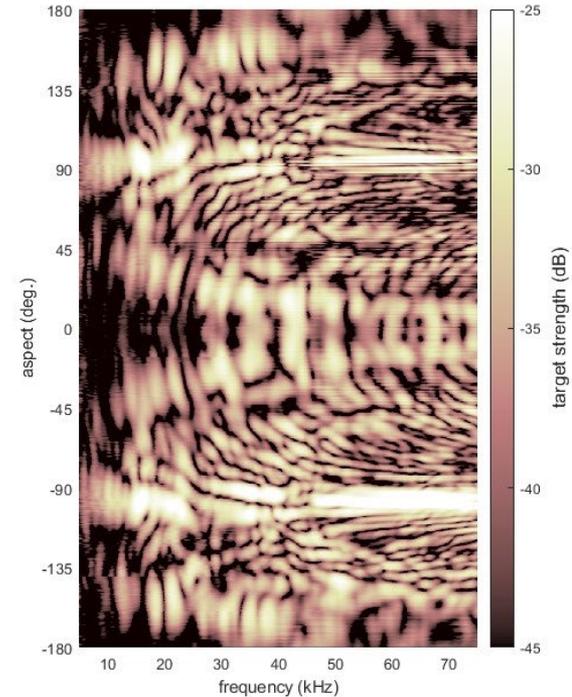
Samples tested

- **4 pristine samples**
  - **3 AN MK-23**
  - **1 AN MK-5 (same geometry, zinc alloy instead of cast iron)**

- **17 corroded samples**
  - 15 AN MK-23 samples from Martha's Vineyard
  - 1 AN MK-23 sample from Duck
  - No corroded samples had tail fins
  - Highly deformed/corroded sample were tested in multiple orientations

- **2 simple geometries**
  - Hollow steel cylinder
  - Solid steel cylinder

- **3 clutter objects**
  - 2 bricks
  - Glass Coke bottle

All simple geometries and clutter objects have similar size to AN MK-23
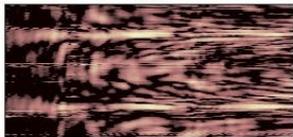
pristine samples

simple geometries
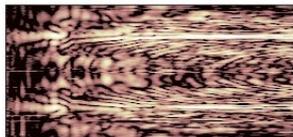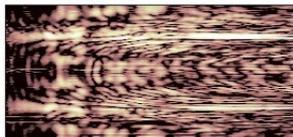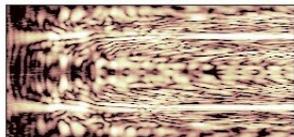
mk23A mk23R mk23P mk5
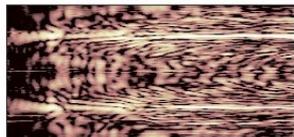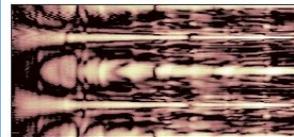
solid hollow
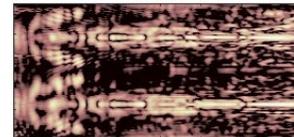
corroded samples
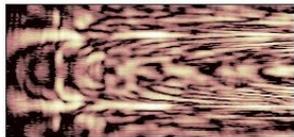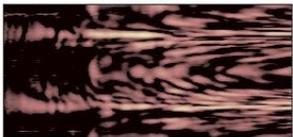
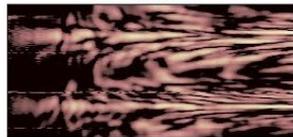duck b001 b003 b005 b006 b008
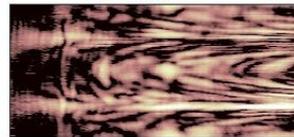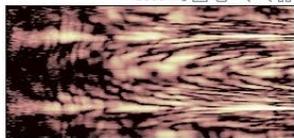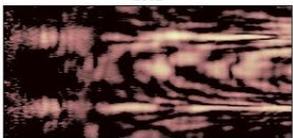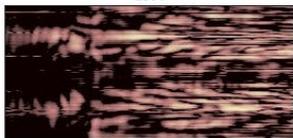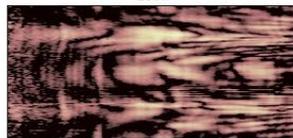
b009 b002 b004 b011 b011 2 b012
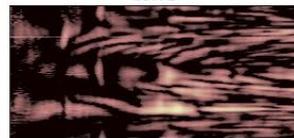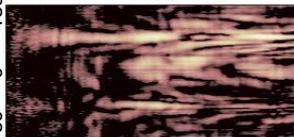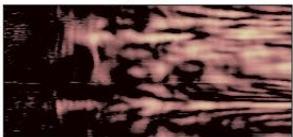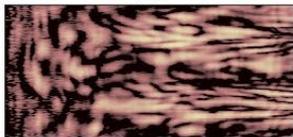
b012 2 b012 3 b013 b013 2 b017 b017 2
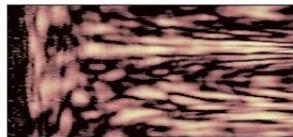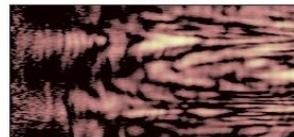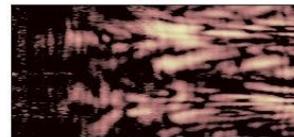
aspect (deg)

frequency (kHz)

tailfin encapsulated in solid sediment/corrosion mixture

objects later determined as clutter from CT scans (dashed boxes)

b018 b018 2
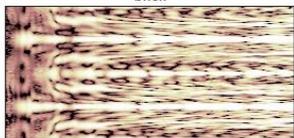
brick brick notch coke
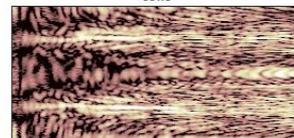
rock

control clutter objects

16

Effect of tail fins on acoustic color

- None of the corroded AN MK-23 samples have tailfins intact.

- All of the corroded samples have some type of filler material (a mixture of sediment and rust and in one case a firing pin.

- None of the pristine samples had filler material.

- Perform additional tests on AN MK-23 to better understand these effects:
  - Presence or absence of prominent geometric features (e.g., tail fins, nose notches)
  - Removal of filler material

- Preliminary test looked at removal of tailfins from one of the pristine samples
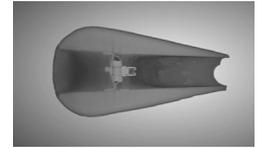
Effect of tail fins on acoustic color

- Flat faces of tailfins have significant impact on acoustic color of pristine sample near broadside (+/- 90 deg).

- When the tail fins are removed, the fine-scale interference pattern changes and the overall target strength reduces at broadside.
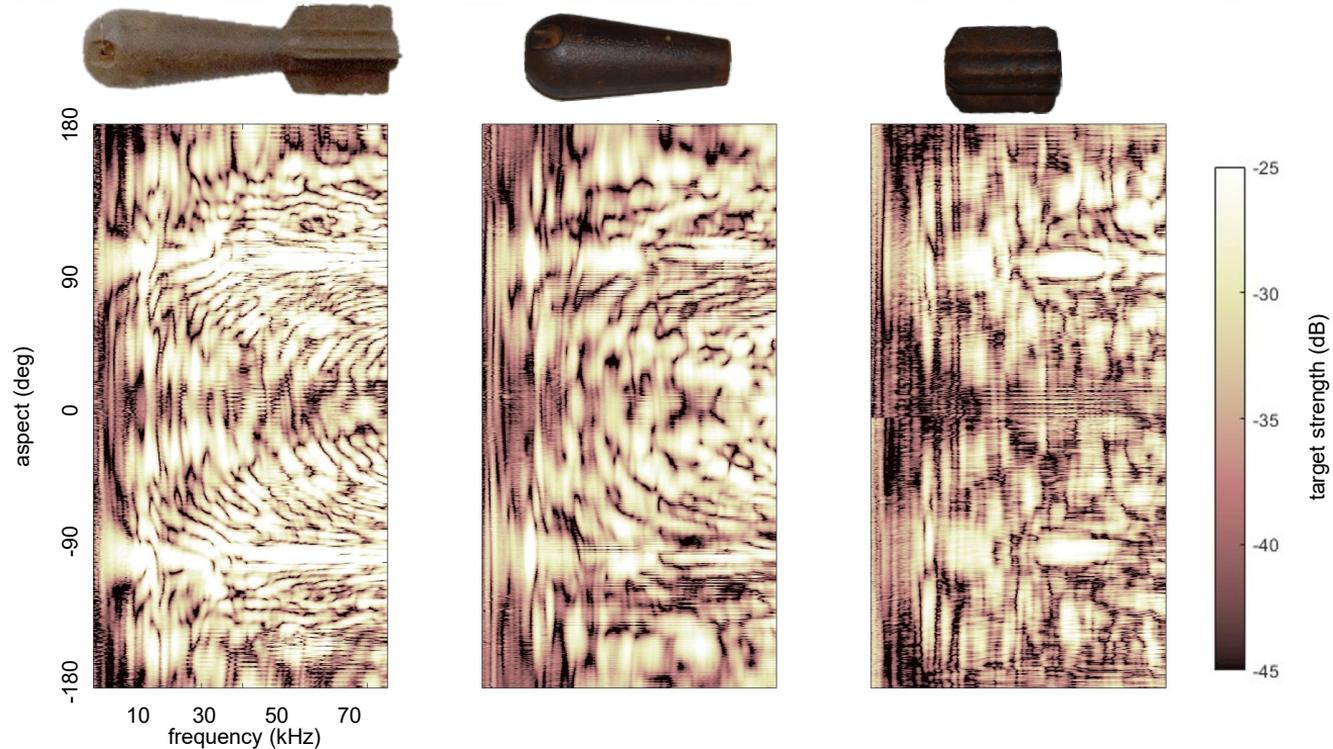
Effect of corrosion on body only

- The absence of tailfins does not completely explain differences between the pristine and corroded targets.

- Comparison with the least corroded sample (Duck) indicates that the filler material also impacts the acoustic color

- Comparison with one of the more corroded samples (b002) indicates further changes to acoustic color which are potentially due to corrosion and additional material loss.

pristine body

Duck

b002
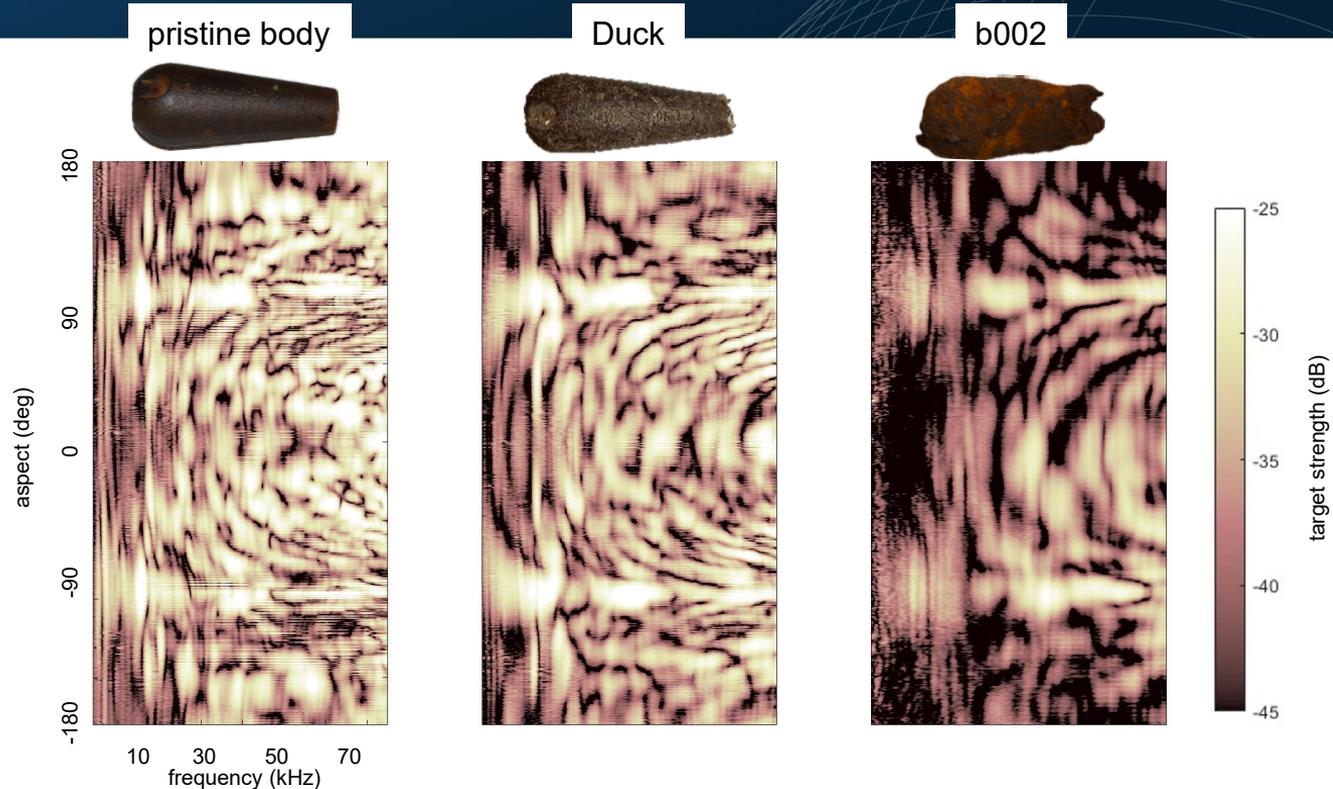
AN MK-23 corrosion groups based on physical characteristics

Clutter

AN MK5 (clutter)

Uncorroded Group

Low Corrosion Group

Moderate Corrosion Group

High Corrosion Group

Iron Cross Sectional Area of Select Samples

- uncorroded
- low corrosion
- moderate corrosion
- high corrosion

Cross-Sectional Area [mm]

Length [mm]
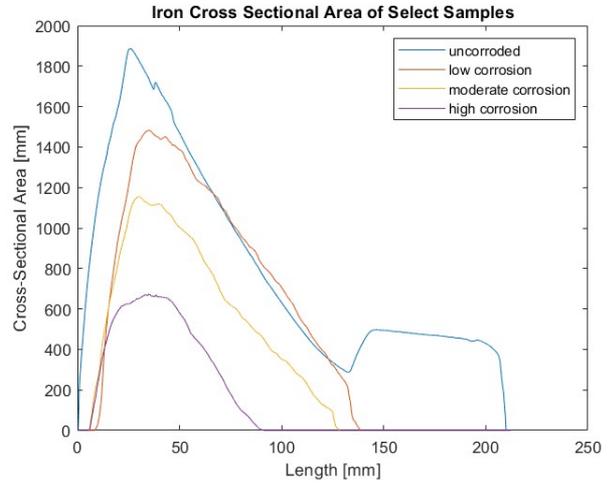
2D cross correlation of full acoustic color

(from acoustic color plots on slide 16)

- Want to compare acoustic color plots to one another
  - Rank the similarity of bomblets to their corroded counterparts
  - Determine which aspects of the acoustic color plot and frequency spectrum are the most similar
  - Full cross correlation gives limited results
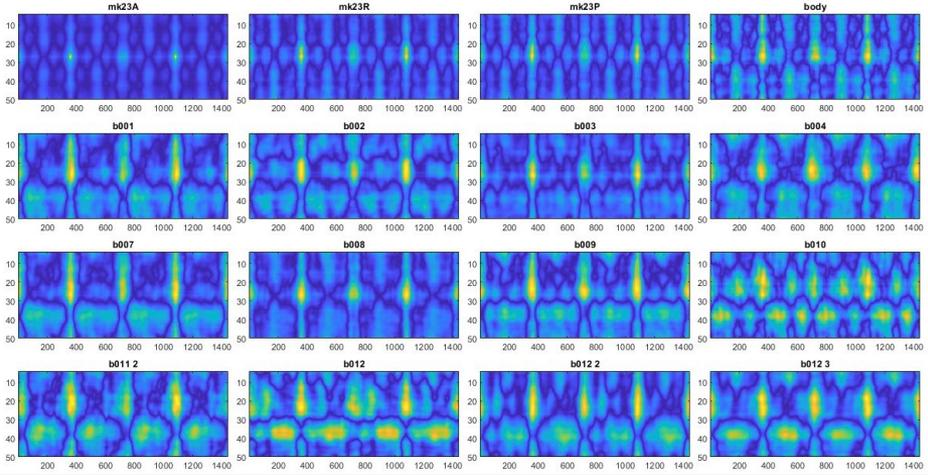
All samples cross correlated with one of the uncorroded samples
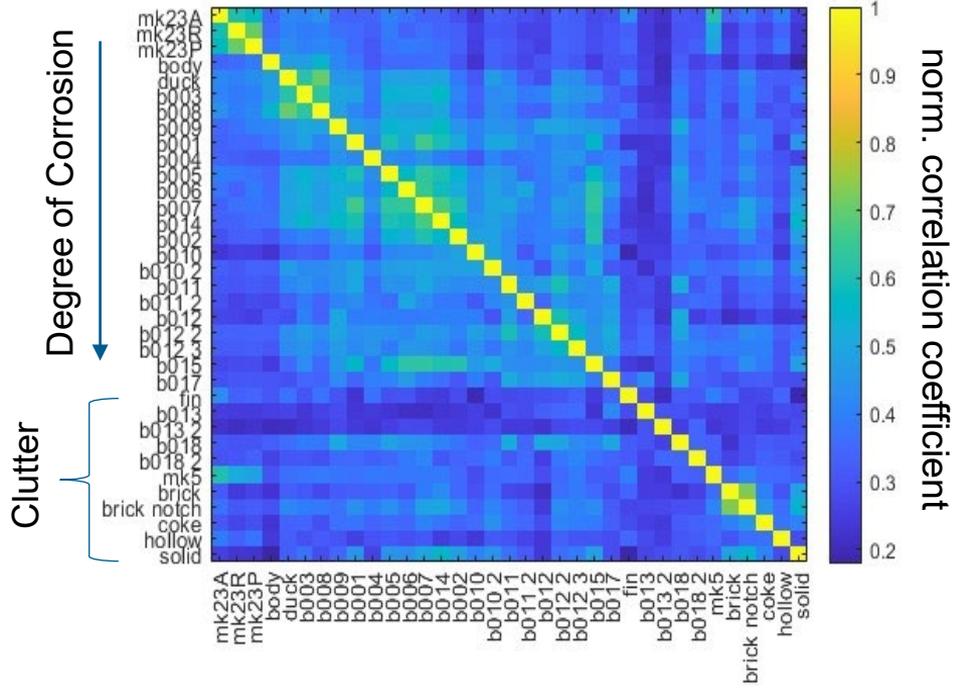
Aspect Angle and Frequency Segmented Analysis

- Segment the data and check for specific aspect angles and frequencies that are important for identification of samples
  - Bandwidth of the frequency range for segmented data was 5 kHz
    - 2 kHz step size
  - Aspect angle was reduced to 60° sections of data to mimic MuST aperture[1]
    - 10° aspect step size
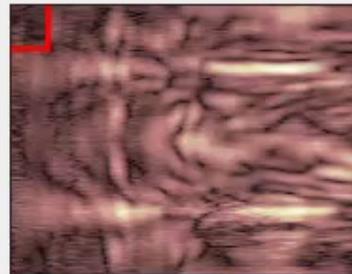
corroded   pristine
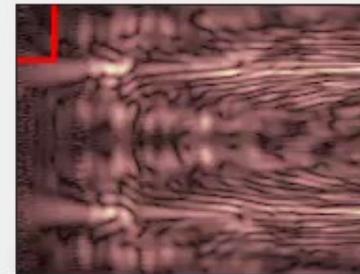
Cross Correlation of Two Boxes   Max From Cross Correlation
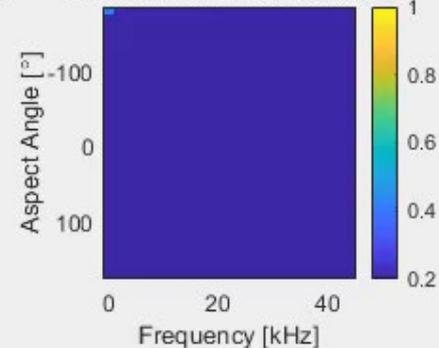
Template matching is a common method in image processing to find location of sample in an image.
https://debuggercafe.com/template-matching-with-opencv/

22

[1] K. Williams, T. McGinnis, "Multi-Sensor Towbody (MuST) for Detection, Classification, and Geolocattion of Underwater Munitions," SERDP Project MR18-5004 Final Report, 2023.

Aspect Angle and Frequency Segmented Analysis

- Comparing bomblet-to-bomblet and bomblet-to-clutter

Bomblet vs. bomblet relations against bomblet vs. clutter relations
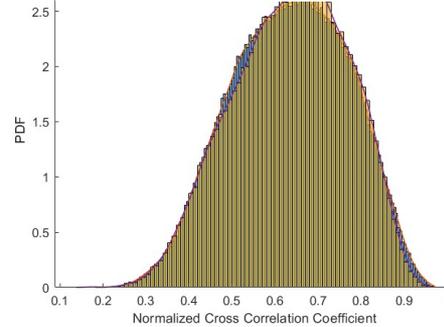
Collection of bomblet to other bomblet relations

Collection of bomblet to clutter relations

23
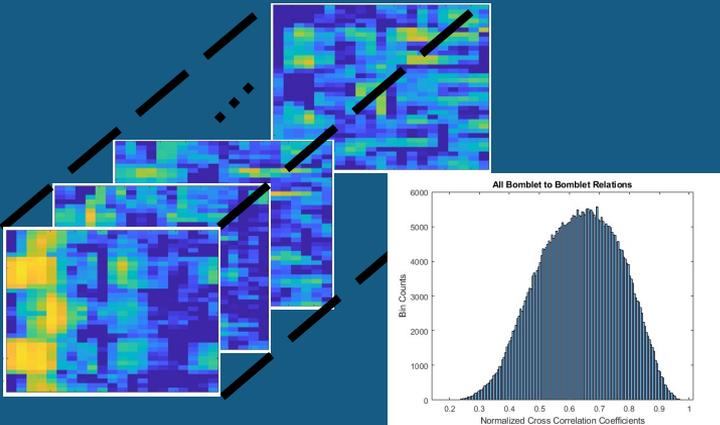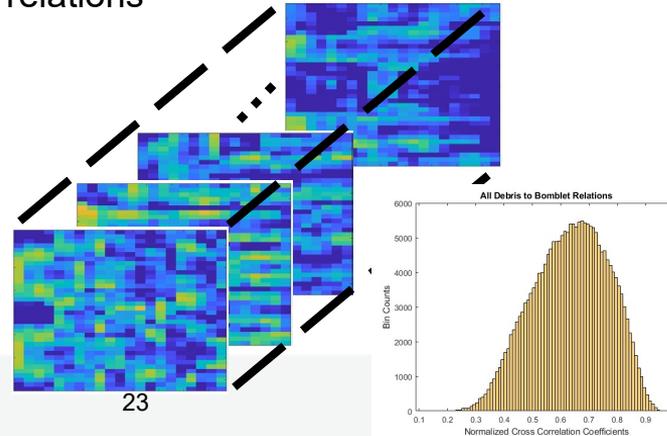
Neyman-Pearson Criterion: Deciding minimum probability error

Collection of bomblet to other bomblet relations
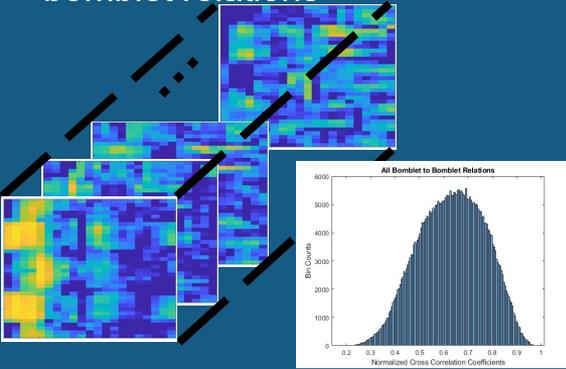
Collection of bomblet to clutter relations
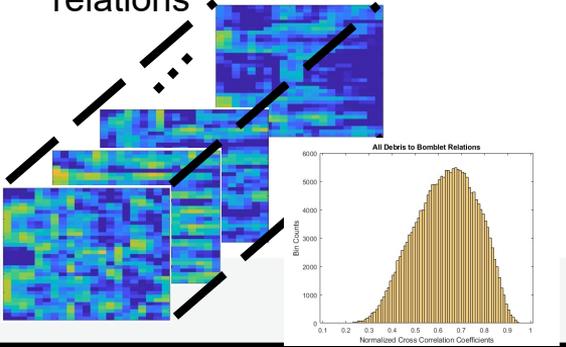
- Criterion maximizes the probability of detection for a given probability of false alarm

- $P_{FA} = 0.5$ was decided as the acceptable limit

24
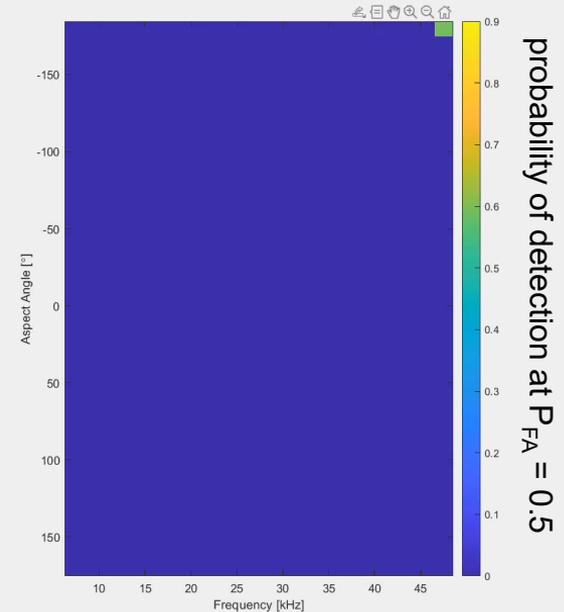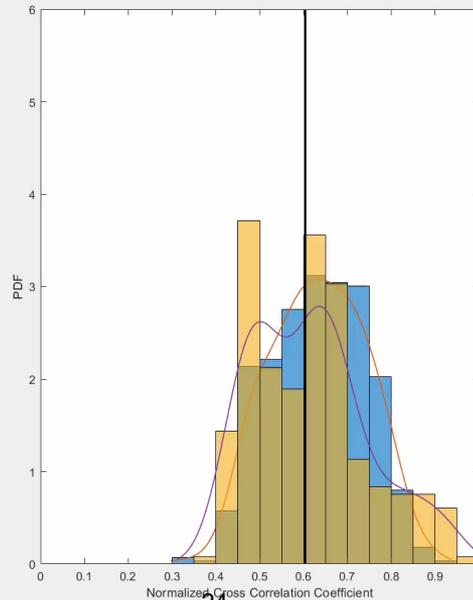
Beat Resonance Matching

Expected value of beat resonance for samples around the nose/tail

Beat Resonance Distribution for c_L = 4350 m/s and c_S = 2809 m/s
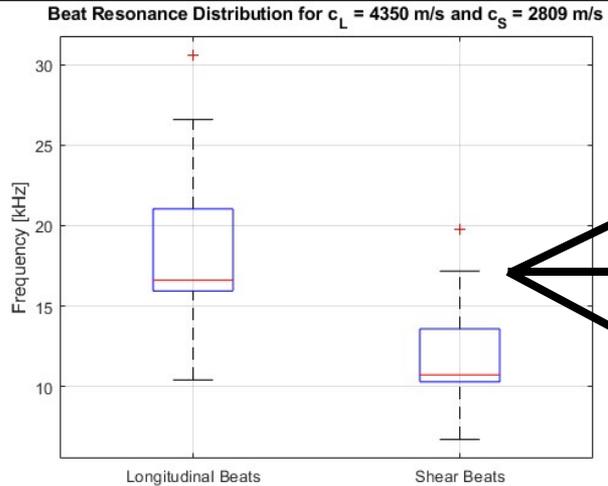
Time it takes sound to travel the full length of the sample and back

Probability of detection given a P_{FA} of 0.5 using all samples as a template

Orientation (ensonification direction into page)

SERDP
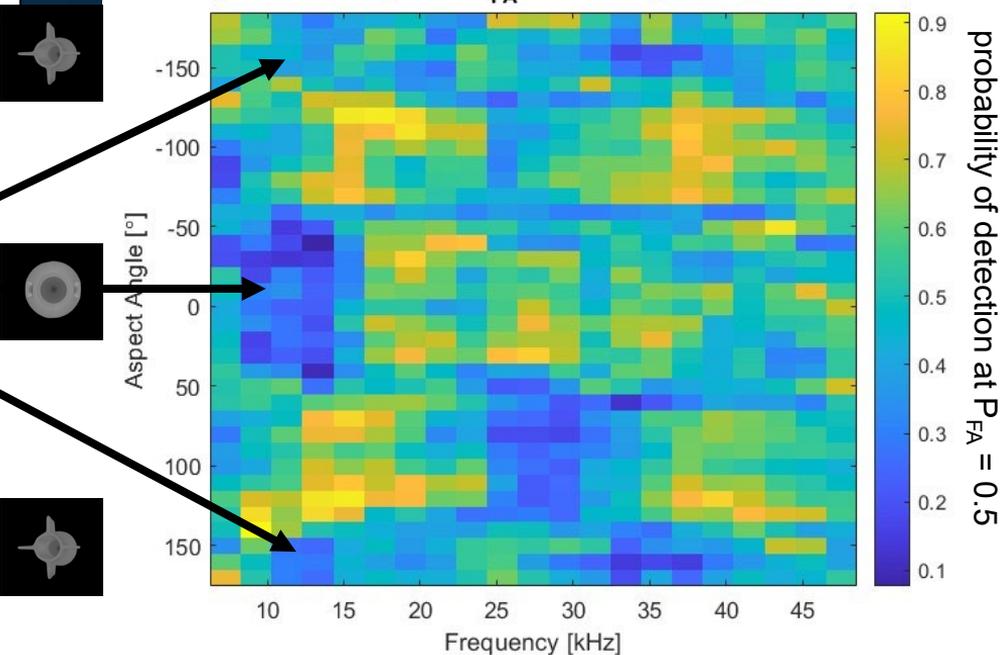
Corrosion Group Relations

- Full aspect angle ($-180°$ to $180°$) from 4-50 kHz was analyzed and evaluated
  - Given all of our information, how likely is a random sample to be detected

Histogram of Bomblet Relations after Normalized Cross Correlation

69% of samples are recovered with $P_{FA} = 0.3$
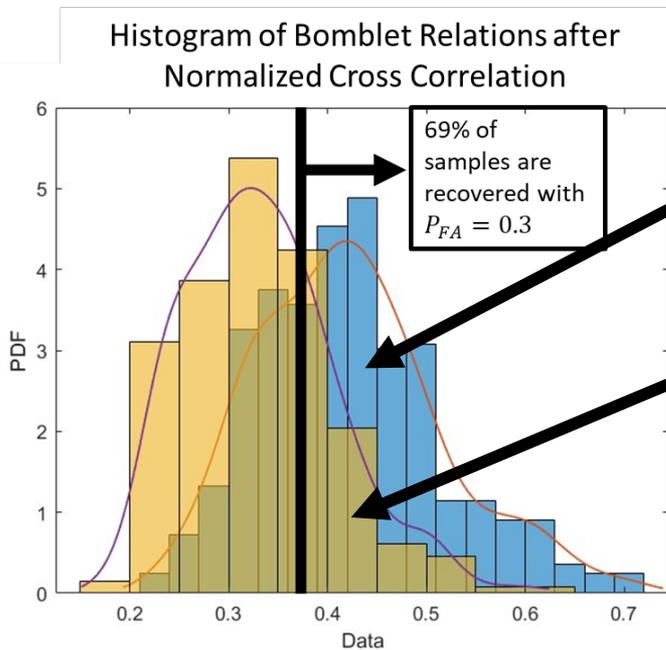
All bomblet relations with respect to other bomblets

All debris relations with respect to bomblets
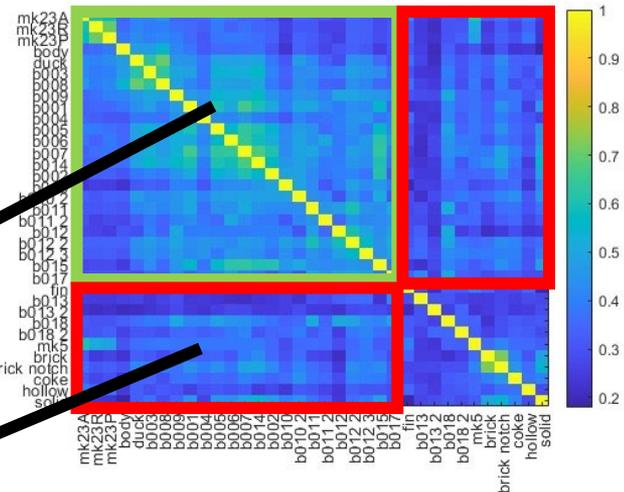
Percent chance of recovery given a false alarm probability of 0.3

- Full aspect angle ($-180°$ to $180°$) from 4-50 kHz was analyzed and evaluated
  - Given all of our information, how likely is a random sample to be detected
  - If a set of uncorroded samples were used as a template for finding samples vs. debris how likely would you detect a sample from each corrosion group

Using an uncorroded sample, you have a 47% chance of detecting a random sample given $P_{FA} = 0.3$

0.47   0.068
1   0.88   0.56
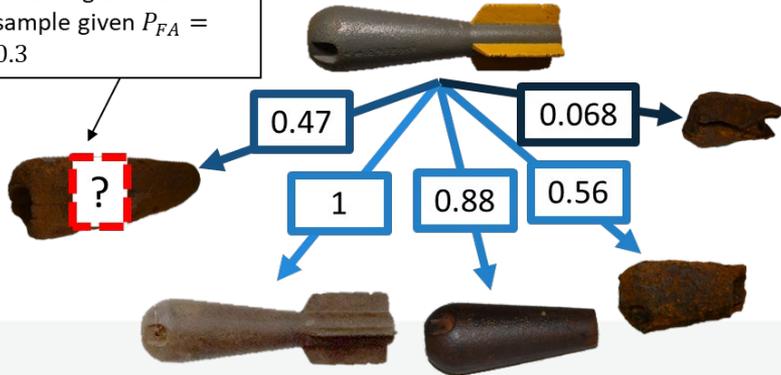
Percent Chance of Recovery Given a False Alarm Probability of 0.3

	all samples	uncorroded	low corrosion	moderate corrosion	high corrosion
all samples	0.69	0.47	0.78	0.68	0.68
uncorroded	0.35	1	0.86	0.056	0.0082
low corrosion	0.73	0.88	1	0.73	0.56
moderate corrosion	0.81	0.56	0.87	0.87	0.87
high corrosion	0.69	0.068	0.63	0.72	0.85

High-resolution imaging

- Micro-computed X-ray tomography (CT)
  - 3D volumetric imaging

UTCT Lab, a national shared multi-user facility at UT-Austin funded by NSF's Earth Sciences Directorate

blet_013_0001
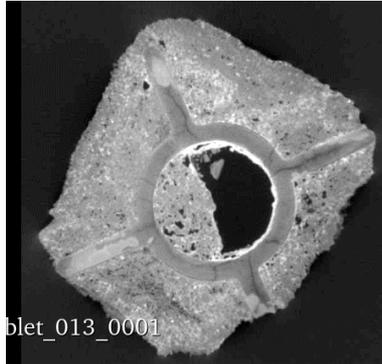
Tail fin section encapsulated in sediment

CT imagery of corroded MK23 sample
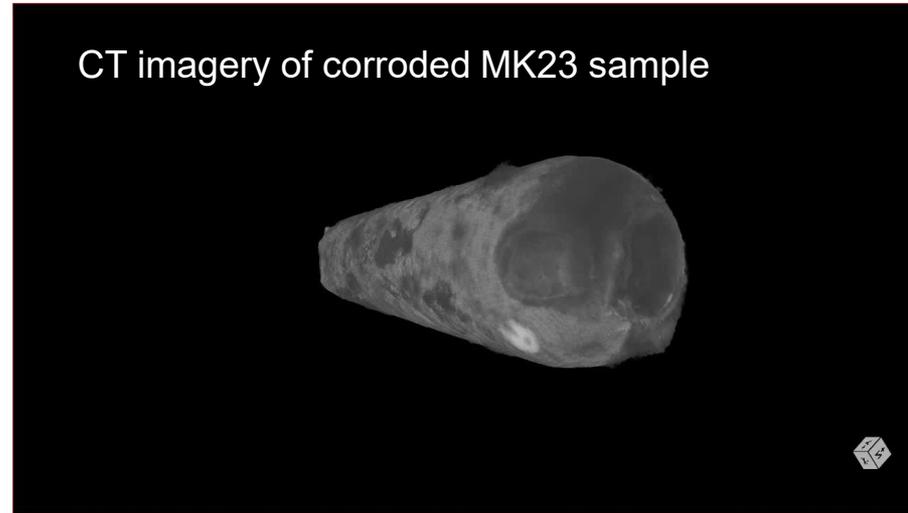
High-resolution imaging

- **Micro-computed X-ray tomography (CT)**
  - 3D volumetric imaging
  - Geometrical analysis

2D cross-sectional CT slice
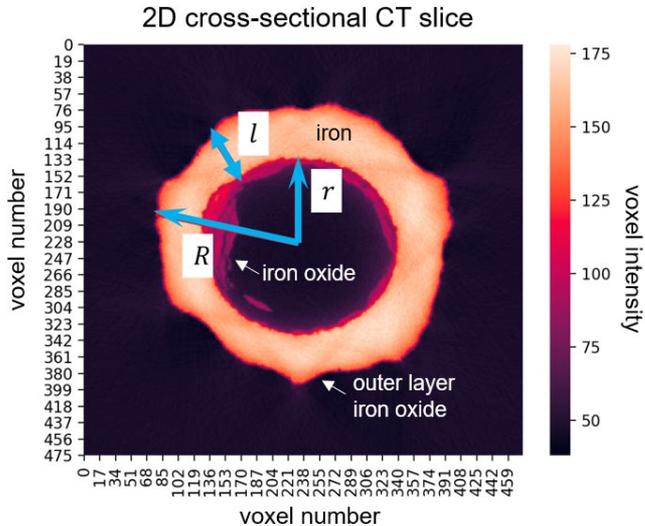
Thresholds based on voxel intensity were applied to distinguish between regions of different materials.

Goal is to automatically segment base materials (cast iron) from corrosion by-products (oxides, rust/sediment mixtures).
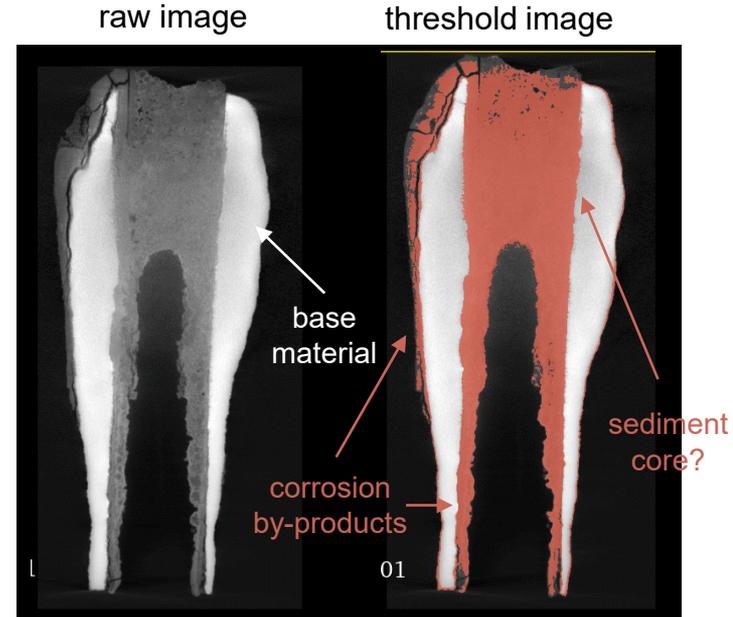
raw image   threshold image

base material

corrosion by-products

sediment core?

FEM geometry generation from CT images

- Last year, we reported issues with converting CT into FEM geometries.

- This year, we developed a new workflow to make the process work
  - Applied 3D Slicer software package to convert CT images into STL files
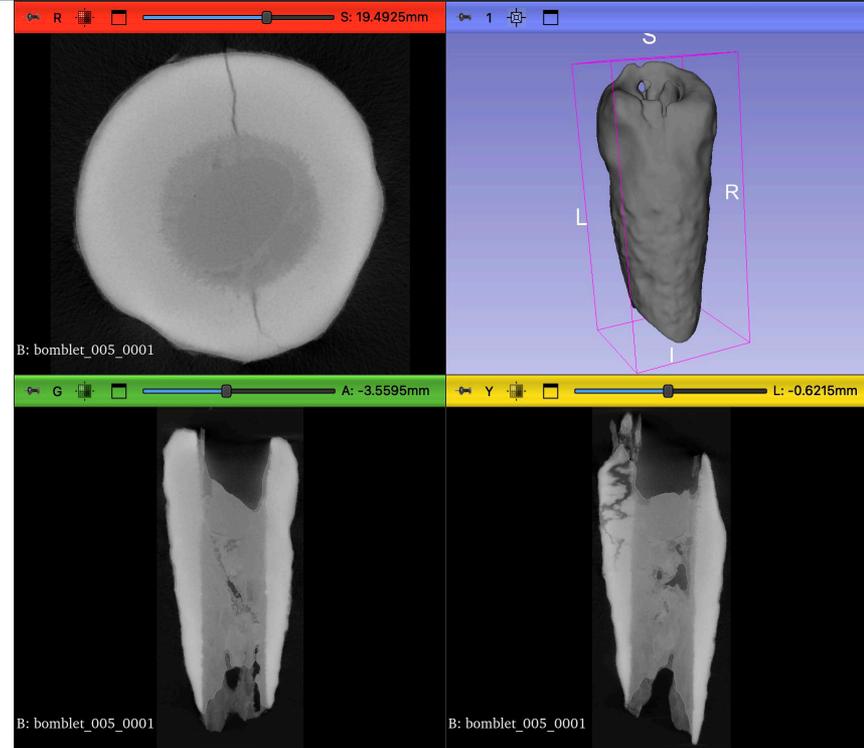
FEM geometry generation from CT images

- Last year, we reported issues with converting CT into FEM geometries.

- This year, we developed a new workflow to make the process work
  - Applied 3D Slicer software package to convert CT images into STL files
  - Loaded 3D Slicer output to Blender to apply smoothing to simplify geometry to acoustically relevant length scales
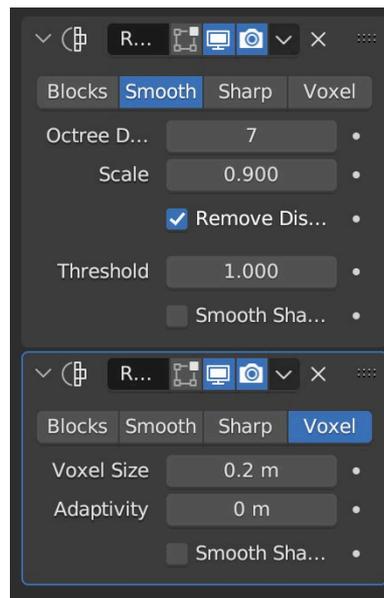
FEM geometry generation from CT images

- Last year, we reported issues with converting CT into FEM geometries.

- This year, we developed a new workflow to make the process work
  - Applied 3D Slicer software package to convert CT images into STL files
  - Loaded 3D Slicer output to Blender to apply smoothing to simplify geometry to acoustically relevant length scales
  - Refined geometries loaded into COMSOL and simulation runs demonstrated
    - Test case: Sample 005
    - Frequency band: 10–60 kHz
    - Defined all domains as cast iron for demo

COMSOL 3D model geometry (left)
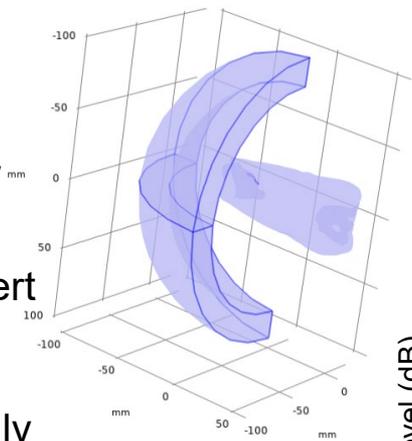
COMSOL test case output (right)
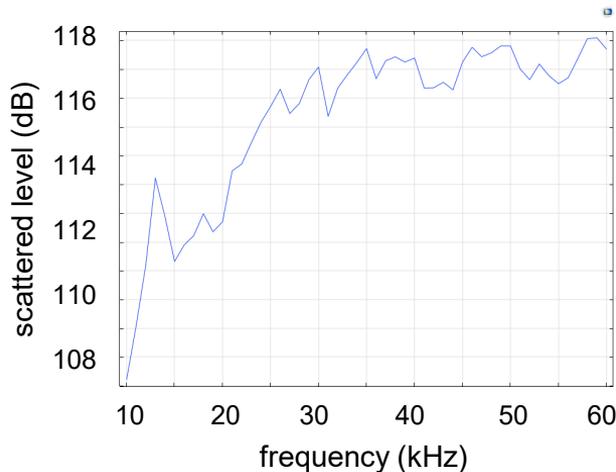
FEM eigenmode analysis

- Eigenmode analysis reveals complex structural modes that likely manifest in acoustic color and are highly dependent on object geometry and material properties

- We are currently investigating methods to quantify such resonances in the acoustic color data and track whether some of these features persist with increasing corrosion.

~26 kHz ring resonance simple cylinder

19 kHz resonance MK23A

26 kHz ring resonance b005

~26 kHz ring resonance simple cone
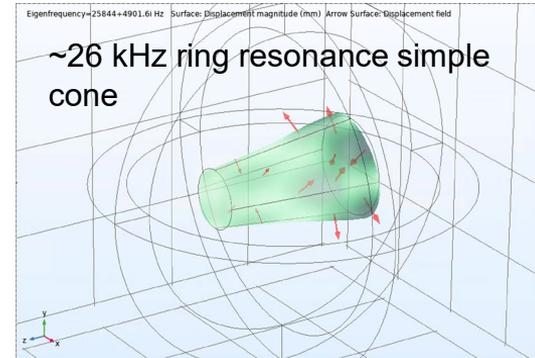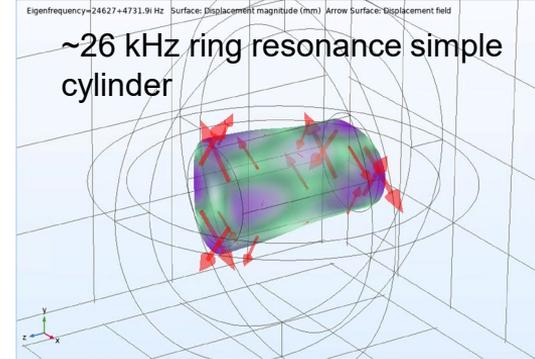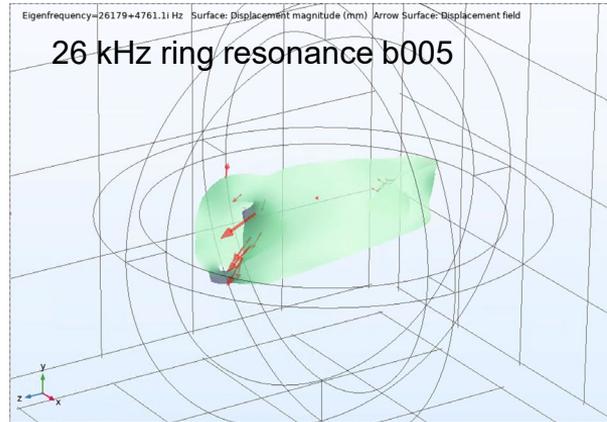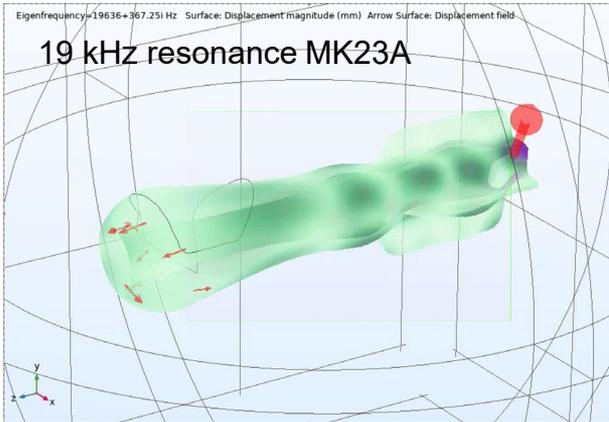
Acoustic Ramifications of Material Characterization and Finite Element Modeling

Uncorroded Core

Corroded Material

Acoustic properties are known:

An elastic solid (cast iron).

Properties can be looked up in a table & verified by measurement.
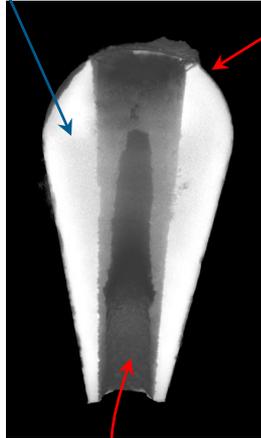
Effective acoustic properties unknown:

Unconsolidated multiphase mixture 1 (rust and sediment particles).

Unconsolidated multiphase mixture 2 (different rust and sediment particles).

Effective acoustic properties:
–most likely measurable/inferable
–potentially predictable with mixture rule

Collaborations with other performers

- David Williams (ARL-PSU): Data feature extraction and t-SNE analysis
  - Initial discussion and collaboration with Dr. Williams lead to investigation of hand-picked features from the acoustic color data (e.g., peak energy, phase roughness). The features were embedded in a lower-dimensional space via t-SNE (t-distributed Stochastic Neighbor Embedding) to see how the samples clustered. We are still working with this methodology.

- Aubrey Espana (APL-UW): Discussions on FEM mesh generation (STL-files) and possible future data sharing
  - We met with Dr. Espana at APL-UW in MAR 2025 to support Dr. Espana's ESTCP pre-proposal for a modeling-based transition-focused effort. As part of this proposal, Dr. Espana wanted to include effects of corrosion on UXO detection and classification performance. Our group agreed to provide STL-files of our targets derived from X-ray CT data as inputs to 3D FEM target scattering models used in the proposed modeling framework.

- Zack Waters (NRL-DC): Shared MK23 data for use in NRL's UXO sonar-system performance modeling
  - Based on a Program Office Action item, we provided MK-23 data to Dr. Waters' group to incorporate into their system performance model, looking at how the response degrades moving from pristine to more and more corroded targets and how this affects the predicted sonar system performance.

Additional samples for Y2

- Several additional UXO were obtained with the help of Andy Schwartz and Andrew Parks in Jan-Feb 2025, but all were from land-based recoveries.

- Based on feedback from the Program Office, there was little interest in measuring most of the samples, with the exception of the 2.75 M229 Rockets in the following configurations:
  - Fuze + warhead + motor
  - Rocket + warhead without fuze
  - Warhead + fuze
  - Warhead only

- Some of these samples also have mechanical damage (e.g. damaged tail) and light corrosion.

- Our plan is to conduct scattering tests on the M229 Rockets in early 2026 at LTTS.

2.75 M229 rockets

81 mm cartridges

155 mm projectiles

Next Steps

- Remaining activities:
  - Complete AN MK-23 additional testing and materials characterization
  - Test M229 Rockets
  - Continue refining data analysis methods to understand corrosion impacts on classification
  - Document STL-file generation process for FEM models
- Reporting and Technology Transfer
  - Critical Findings Sheet, due 2/26/2026
  - Final Report & Data Delivery, due 5/31/2026

Technology Transfer

- Knowledge gained will result in improved scientific understanding of how corrosion-biofouling changes UXO acoustic signatures

- Transition new information to detection, classification, and localization (DCL) performers for improved success in UXO remediation
  - ***Critical Findings Sheet assigned after 2024 IPR, due 2/26/2026***
  - Improve target models and templates
  - Update UXO classification algorithms

- This information will be disseminated to scientific community through publications and to user community via SERDP/ESTCP outreach channels
  - Peer-review journal articles
  - Symposium

Issues

- Describe any unanticipated or unresolved issues.
  - No unresolved issue encountered in the past year.

- Previous year issues:
  - Issue 1: Y2 samples not identified
    - Resolution: Samples ID'ed and obtained
  - Issue 2: Complications encountered in generating FEM meshes from CT data
    - Resolution: Developed new workflow to create STL-files that can be imported into COMSOL and run, while still retaining acoustically relevant features.

BACKUP MATERIAL

These charts are required, but will only be briefed if questions arise.

MR21-3582: Investigation of acoustic scattering from UXO with long-term environmental aging

Performers: Kevin Lee, Preston Wilson, David Mitlin

The University of Texas at Austin

Technology Focus
- *Investigate impacts of long-term environmental aging on the acoustic response of submerged munitions*

Research Objectives
- *Investigate correlation between UXO acoustic signature with corrosion-biofouling products and cross-sectional damage and material loss*

Project Progress and Results
- *High-resolution X-ray CT imaging, acoustic scattering measurements, and corrosion analysis performed on WWII-era samples*
- *Acoustic signatures of highly corroded targets display low correlation to pristine-specimen acoustic signature indicating potential obstacles for sonar-based UXO detection and classification*

Technology Transition
- *Transition improved scientific understanding of corrosion-biofouling changes to UXO acoustic signatures to DCL performers for improved success in UXO remediation.*
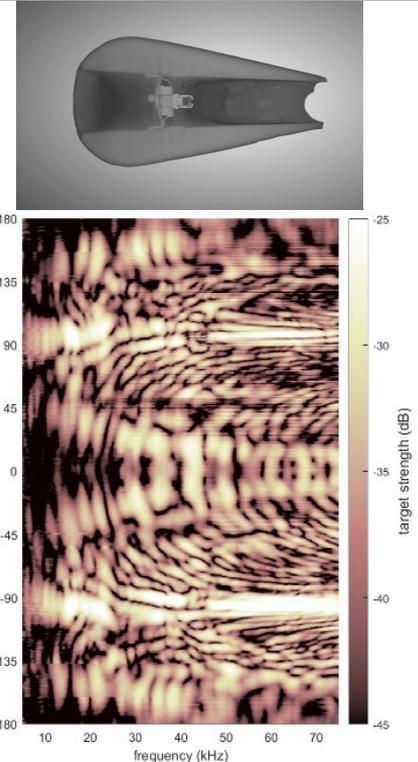
Plain Language Summary

- ## What problem are you addressing?

Sonar-based detection and classification techniques for underwater munitions often rely on knowledge of acoustic responses of pristine targets; however, munitions submerged for extended time periods are subject to corrosion and biofouling, rendering the munitions in a different physical state than when they were fired.

- ## What are you trying to achieve and how are you doing it?

This project is investigating correlations between UXO acoustic signature with corrosion-biofouling damage with the ultimate goal of developing models linking the amount of time submerged in the environment to changes in the acoustic signature. We are doing this by collecting experimental data on real inert munitions to analyze the munitions' acoustic scattering response, three-dimensional geometry, and corrosion profile.

- ## What are the expected outcomes and how is it advancing existing knowledge?

This research will enhance the scientific understanding of the acoustical effects of biofouling, calcification and corrosion of manmade objects, which could have a broader range of application to fields within underwater acoustics outside of sonar-based target detection. The long-term goal of this study is to benefit the Department of Defense by increasing our understanding on this topic, ultimately improving and facilitating sonar detection and classification of UXO and other targets that have been in the water environment long enough for degradation to occur due to biofouling or corrosion.

SERDP

Impact to DoD Mission

- Our project has demonstrated that long-term corrosion impacts sonar-based UXO detection and classification by changing the target's acoustic fingerprint.

- When the acoustic effects of corrosion and biofouling are neglected, sonar-based UXO remediation surveys may have limited success.

- The objective of this study is to benefit DoD by increasing our understanding of how corrosion and biofouling impact UXO DCL efforts.
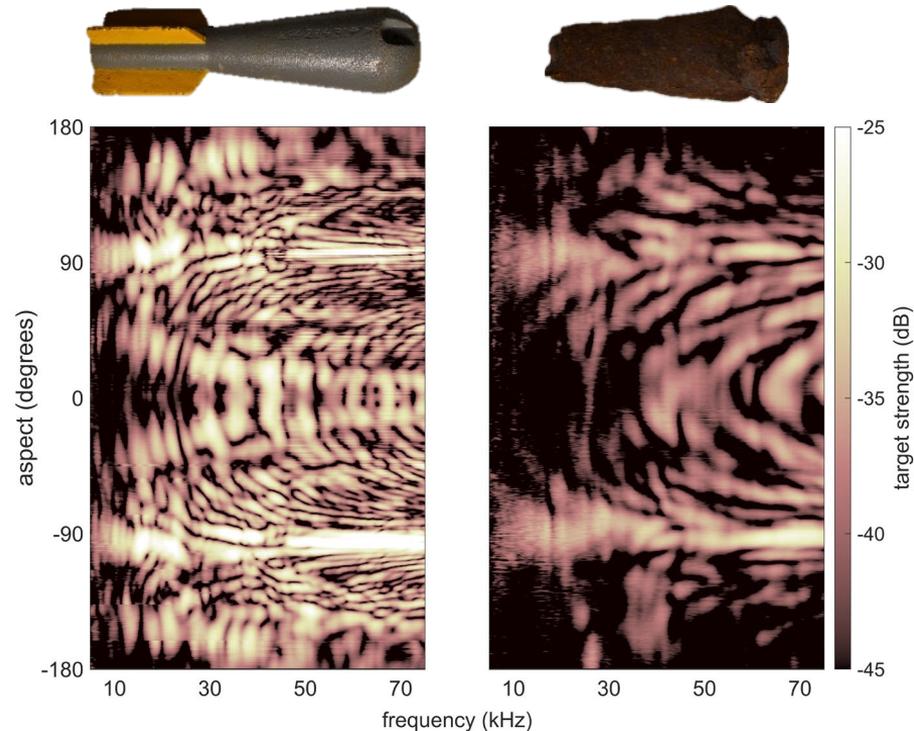
Action Items

3 Comments

ADD NEW COMMENT

Please share modeling results from subtasks 3.2 and 6.2 with Dr. Zachary Waters of project MR23-7753 to inform their structural acoustics model. His email address is zachary.j.waters4.civ@us.navy.mil. As a response to this IPR action item, confirm that you have provided the results to Dr. Waters.
MR21-3582 • Kevin Lee

EXCEL PDF

Kevin Lee Thursday, March 13th at 10:31 AM

Files have been delivered to Zack Waters group at NRL.

Kevin Lee Thursday, March 6th at 9:28 AM

We are still working on getting the data into the appropriate format. Once we have successfully completed the transfer of data to NRL, I will suvmit this action as complete.

Kevin Lee Friday, February 28th at 10:28 AM

We reached out to Dr. Waters and held a meeting on 2/18/25 to discuss patrh forward on data sharing. We are providing the NRL team with a preliminary data set to use in their UXO-detection sonar system performance model, and we will iterate on the format as needed. Briefly, we are providing time-domain scattering data for a subset of clean, moderately corroded, and severaly corroded targets. The NRL team will use this data as inputs to their system performance model they are working on as part of their current ESTCP funding to assess how detection capability degrades as a function of corrosion. A more detailed description of this effort will be given in the next QPR, unless there is s request from the prgram office for more detail before then.

- Our data were shared with the NRL group.

- We have not received feedback on how the data were used or if they were useful.

Action Items

We have added a Technology Transition task to your project plan to more explicitly delineate Technology Transition products and activities. Under this task, we have added subtask 7.1: Critical Findings Sheet. The Critical Findings Fact Sheet should be no more than 1 - 2 pages long and should contain the following sections: Technology Overview; Research Approach; Critical Findings; Point of Contact; One or more images. An example fact sheet has been uploaded to your Miscellaneous Documents. Please note, the Program Office will format the final fact sheet; please focus on the content. 2024 MR October In Progress Review

Pending   Assigned: 10/29/2024   Due Date: 2/27/2026   Subtask: Critical Findings Sheet

Acknowledgment Only

Comment   SUBMIT

- This task is still pending, but we do not anticipate any issues with meeting this deadline.

SERDP

Publications

- **Conference presentations**

- Connor Hodges, Charles Hubbard, Andrew R. McNeese, Vikalp Raj, David Mitlin, Preston S. Wilson, and Kevin M. Lee, , "Effects of severe corrosion on acoustic signatures of underwater munitions," ASA Fall Meeting, Honolulu, HI, 5 DEC 2025.

- Connor Hodges, Charles Hubbard, Andrew R. McNeese, Vikalp Raj, David Mitlin, Preston S.Wilson, and Kevin M. Lee, "Acoustic scattering from inert underwater munitions with severe corrosion damage," J. Acoust. Soc. Am. 157, A41 (2025).

- Charles Hubbard, Connor Hodges, Andrew R. McNeese, Preston S. Wilson, and Kevin M. Lee, "Toward simulation of long-term corrosion effects on acoustic scattering responses of underwater unexploded ordnance," J. Acoust. Soc. Am. 157, A41 (2025).

- **Theses & Dissertations**

- Charles Hubbard, "Towards the Simulation and Classification of Corroded Underwater Unexploded Ordnance Using Active Sonar, MSME Thesis, UT-Austin, August 2025.
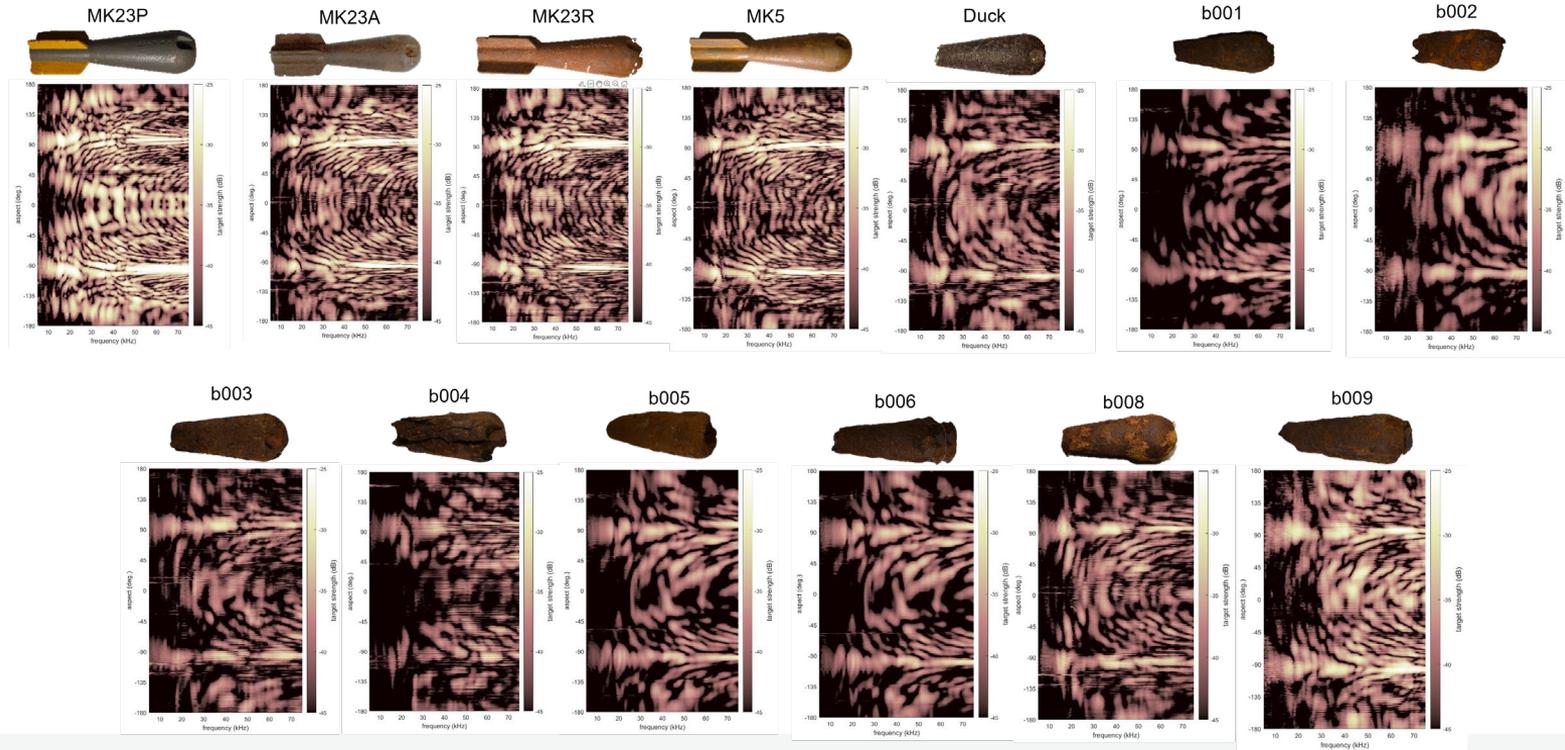
SERDP

Literature Cited

Lim (2015), "Final Report: Data and Processing Tools for Sonar Classification of Underwater UXO," SERDP Project MR-2230, August 2015, Raymond Lim, Naval Surface Warfare Center Panama City
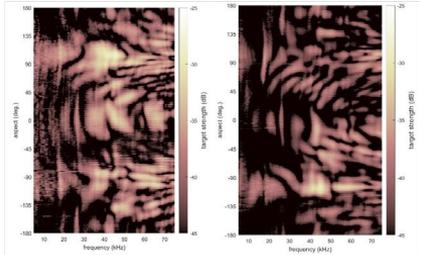https://serdp-estcp.mil/projects/details/8b5a832a-1e49-480f-bf01-9d500f459f60

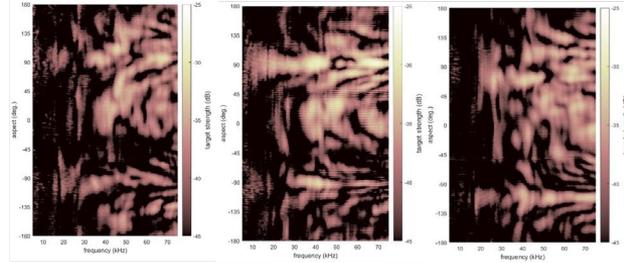H. Medwin and C. S. Clay, *Fundamentals of Acoustical Oceanography*

SERDP

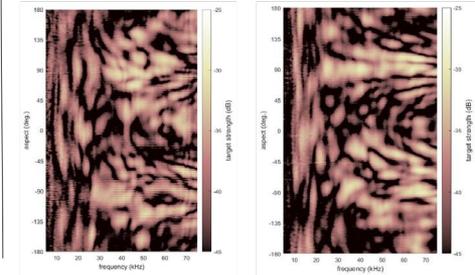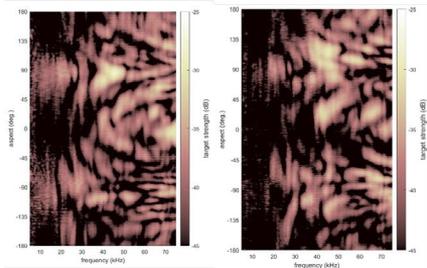# Acoustic color plots (w thumbnails)

Acoustic color plots (w thumbnails)
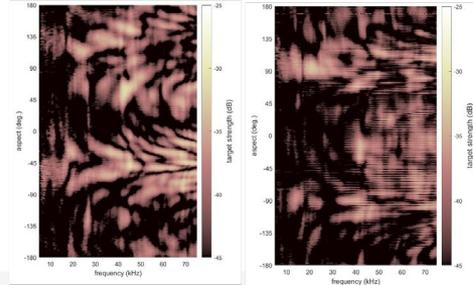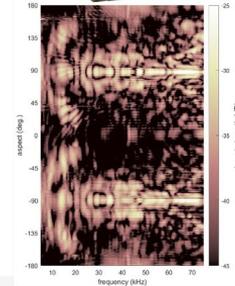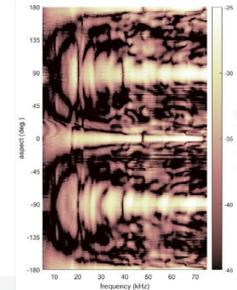

b011

b012

b013

b017

b018

hollow steel cylinder

solid steel cylinder

Acronym List

AI = Artificial Intelligence
ATR = Automated Target Recognition
CT = Computed Tomography
DCL = Detection, Classification, Localization
EDS = Energy Dispersive Spectroscopy
FEM = Finite Element Method
LTTS = Lake Travis Test Station
MK23 = Mark 23 practice bomblet
NSF = National Science Foundation
PI = Principal Investigator
SEM = Scanning Electron Microscope
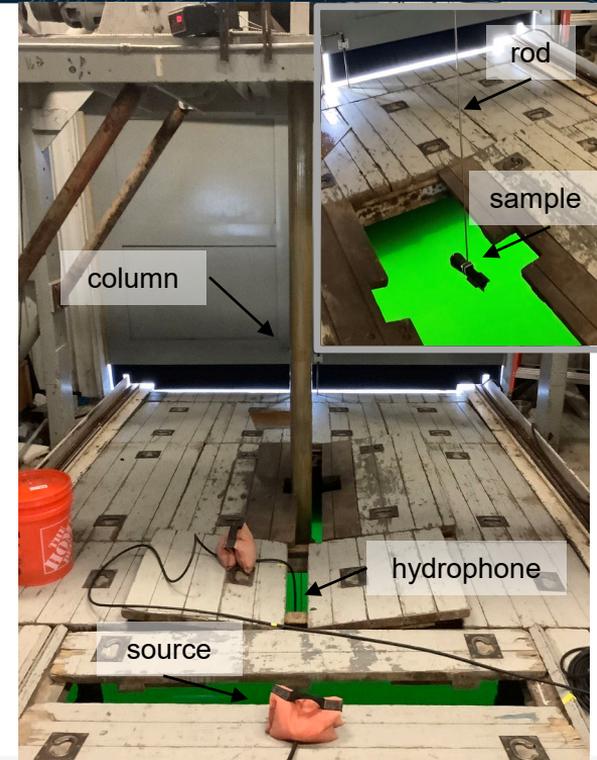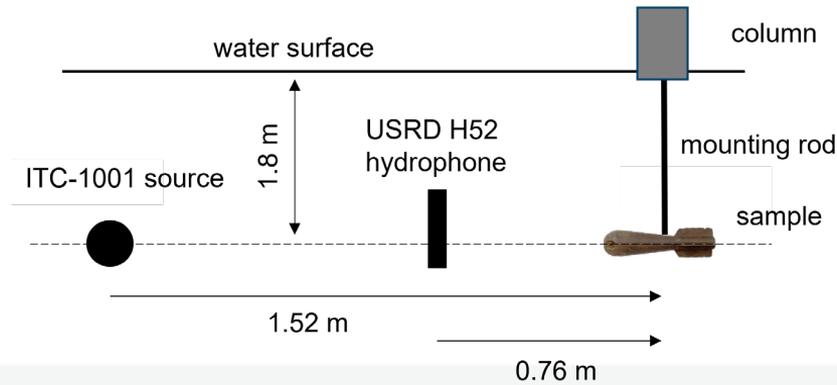SAS = Synthetic Aperture Sonar

TS = Target Strength
t-SNE: t-distributed stochastic neighbor embedding
2D, 3D = two and three dimensional
UT = University of Texas
UTCT = UT X-ray CT lab
UXO = Unexploded Ordnance
WWII = World War II
XRD = X-ray Diffractometer
Y1, Y2 = Years 1 and 2

SERDP

Acoustic test setup and procedure

- Pre-test: Samples soaked in degassed distilled water to remove unwanted air bubbles from cracks, crevices
- Mounting: 2-m-long thin stainless steel mounting rod attached to motorized rotating column
- Acoustic excitation signal transmitted approximately every 0.25 degrees
- Three replicate measurements conducted to assess repeatability
- Measurements acquired without sample (column/fixture only) to establish baseline
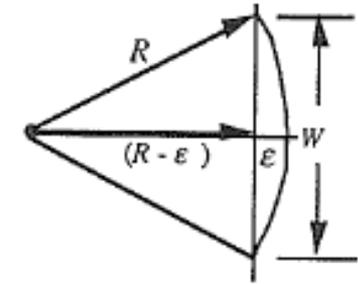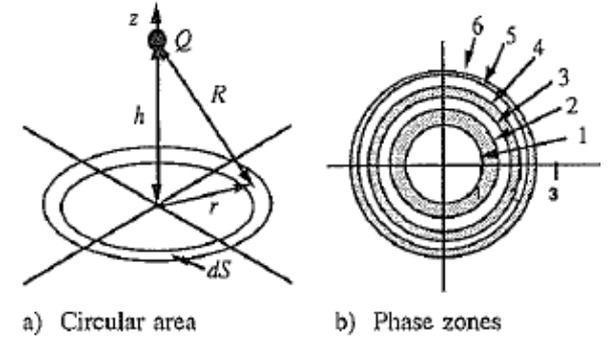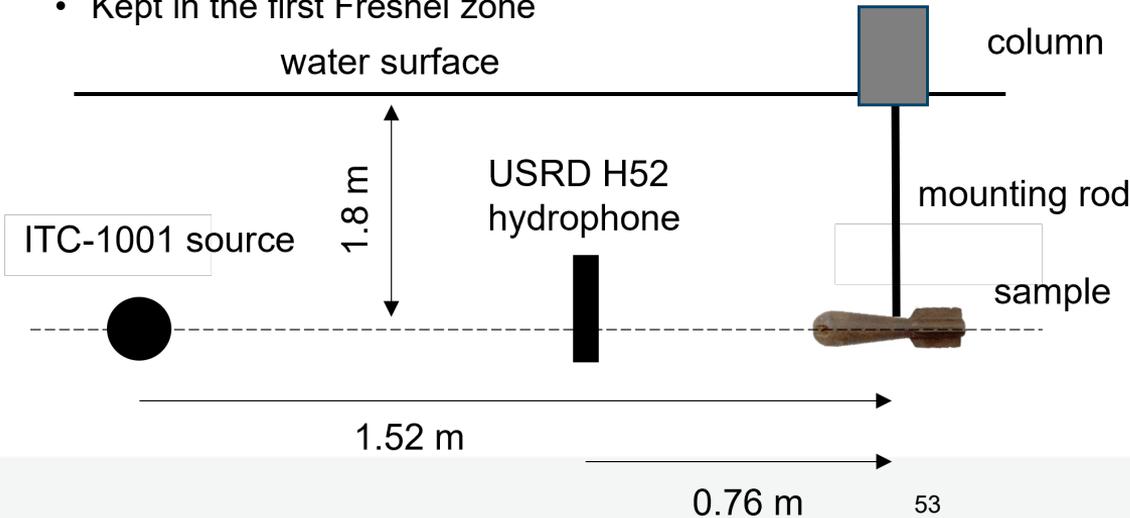
Samples soaking
in degassed water

water surface

column

1.8 m

ITC-1001 source

USRD H52
hydrophone

mounting rod

sample

1.52 m

0.76 m

rod

sample

column

hydrophone

source

Acoustic excitation and signal processing

- Acoustic excitation parameters:
  - Exponential chirp 0.1–100 kHz, 50-ms duration

- Plane wave approximation
  - Distance was set so that sagitta, ε, of a spherically spreading wave is $\leq \frac{\lambda}{8}$
  - Kept in the first Fresnel zone

a) Circular area   b) Phase zones

water surface

column

1.8 m

USRD H52
hydrophone

mounting rod

ITC-1001 source

sample

1.52 m

0.76 m

H. Medwin and C. S. Clay, *Fundamentals of Acoustical Oceanography*[3]

53

Acoustic excitation and signal processing

- Acoustic excitation parameters:
  - Exponential chirp 0.1–100 kHz, 50-ms duration

- Plane wave approximation
  - Distance was set so that sagitta, ε, of a spherically spreading wave is $\leq \frac{\lambda}{8}$
  - Kept in the first Fresnel zone

- Signal processing
  - Deconvolution using inverse filter to obtain impulse response
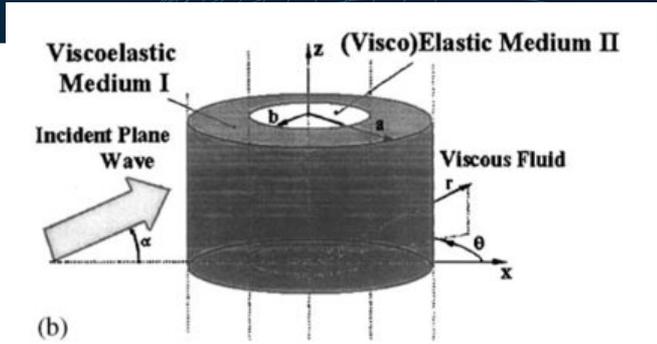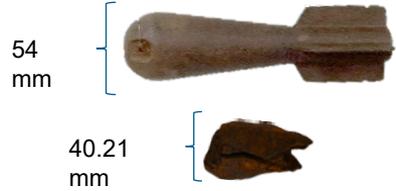 - Coherent subtraction to remove signal scattered from mounting rod (using baseline measurement)

measured acoustic signal

Impulse response after deconvolution

54
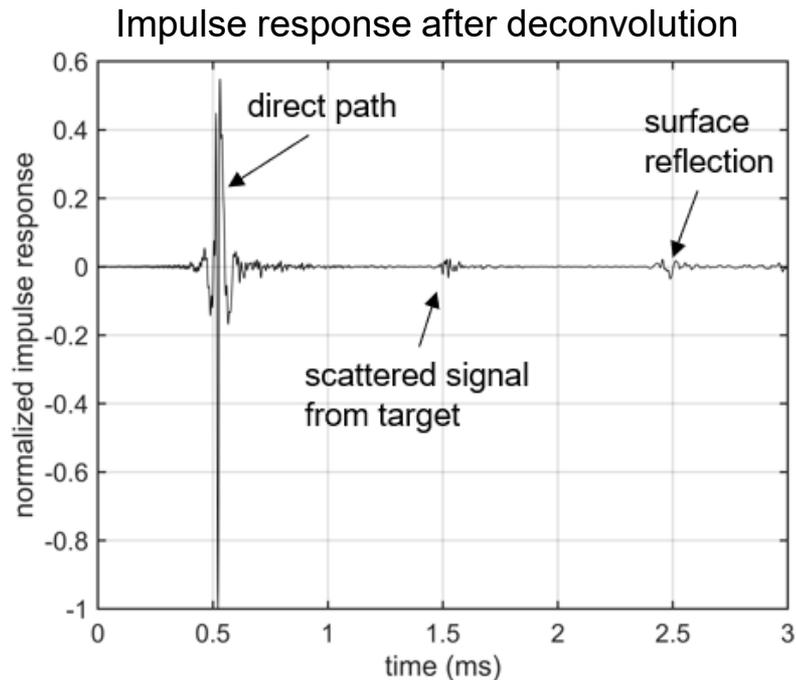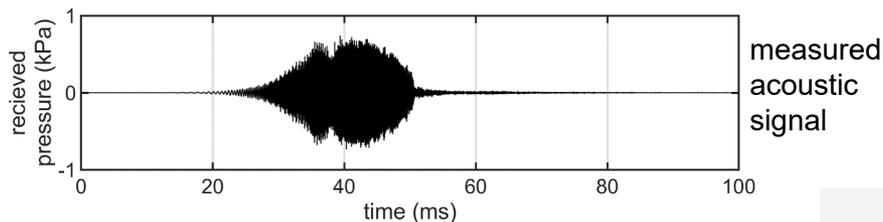
Analytic Model for Infinite Hollow Cylinder

Infinite hollow cylinder[2] with cast iron properties.
Analytic approximation of samples at broadside

54 mm

40.21 mm

Uncorroded Sample Cutaway

Corroded Sample Cutaway
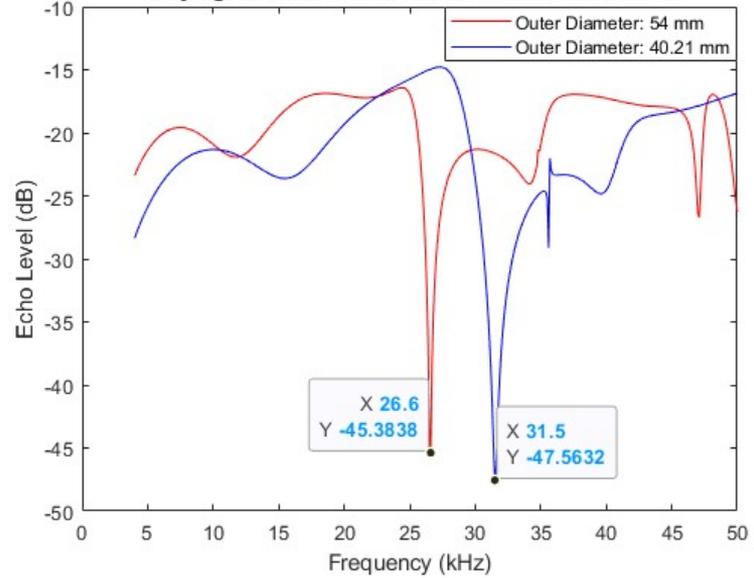
Cast Iron Longitudinal Wave Speed: 4350 [m/s]
Cast Iron Shear Wave Speed: 2809 [m/s]
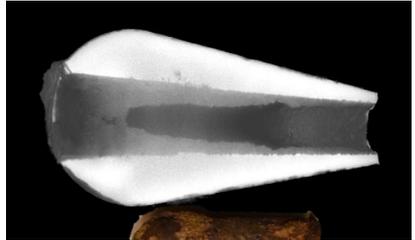
[2] R. D. Doolittle and H. Uberall, "Sound scattering by elastic cylindrical shells," J. Acoust. Soc. Am. 39, 272–275 (1966)

Conclusions from segmentation analysis

- Performed acoustic tests on uncorroded and corroded AN MK-23 samples as well as a variety of debris

- Outlined a method for comparing corroded samples to their uncorroded counterparts and debris
  - Represent data as a distribution and calculate a probability of detection given a probability of false alarm to relate the two

- Showed frequency ranges and aspect angles that maximize our ability to detect corroded samples
  - Due to the variance in structure, resonances show areas of low similarity
  - Highest similarity to other samples occurred around non-resonance frequencies

Probability of detection given a P_{FA} of 0.5 using all samples as a template
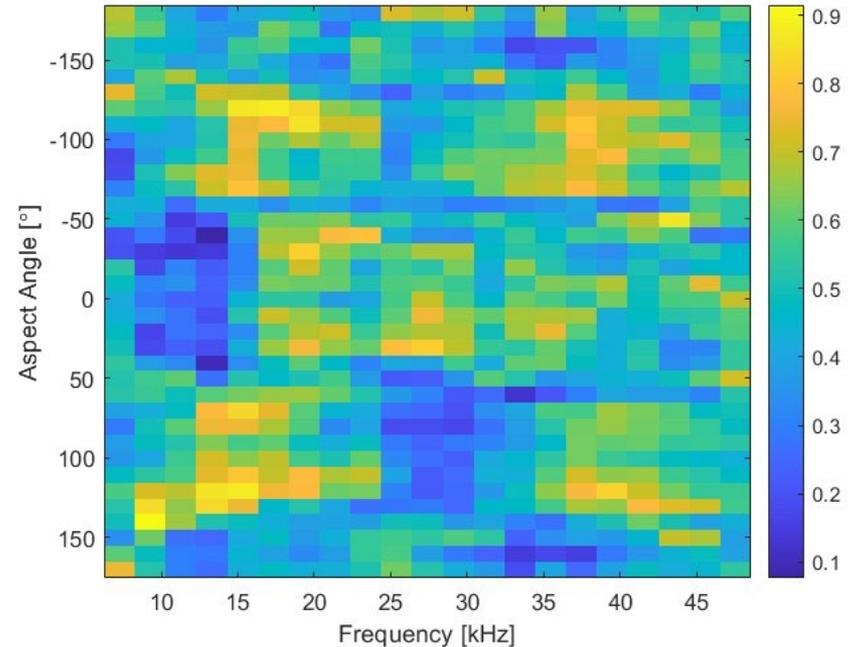
Correlation analysis including clutter

- Correlation matrix sorts samples by acoustic similarity to pristine sample MK-23A (Lim 2015)

- Clutter objects and modified pristine sample included in this analysis

- Clutter objects group lower down on the scale with the most corroded samples

- Modified pristine samples group with objects with higher correlation coefficients

- The isolated tail fin has higher similarity to the full pristine samples than the isolated body

- Simple geometries rank low on the correlation scale

SERDP
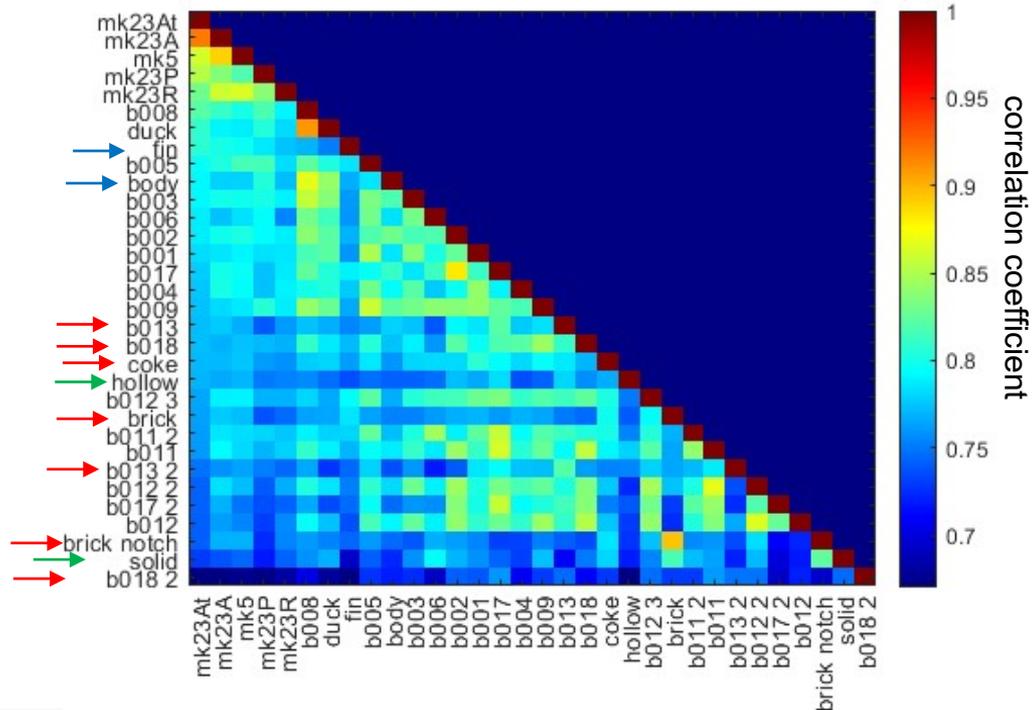
Microscopic materials characterization

- Microscopic materials characterization informs chemical composition of corrosion materials
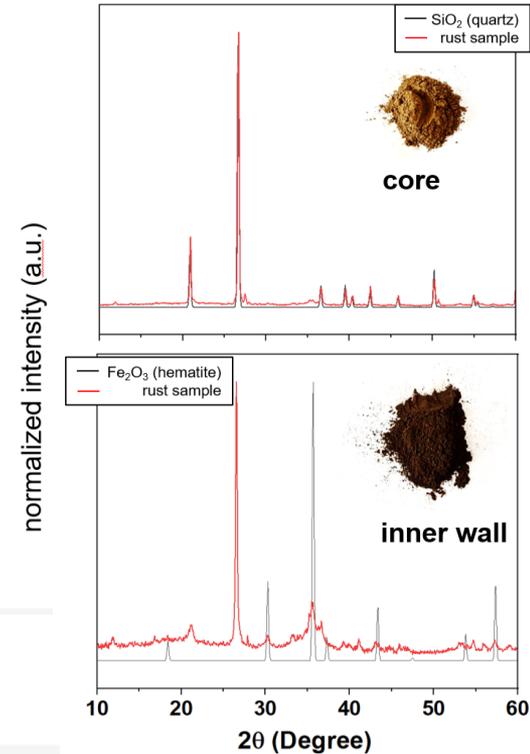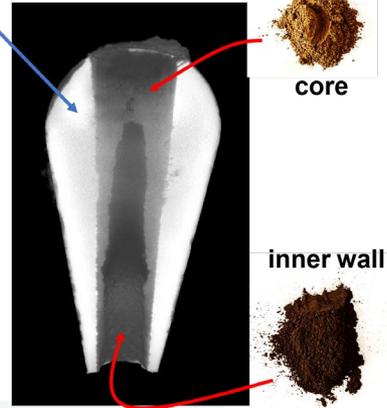 - Scanning Electronic Microscopy (SEM) w/ Energy-dispersive X-ray Spectroscopy (EDXS): Elemental composition distribution
  - X-ray Diffraction analysis (XRD): Crystallographic structure

Uncorroded material

core

inner wall
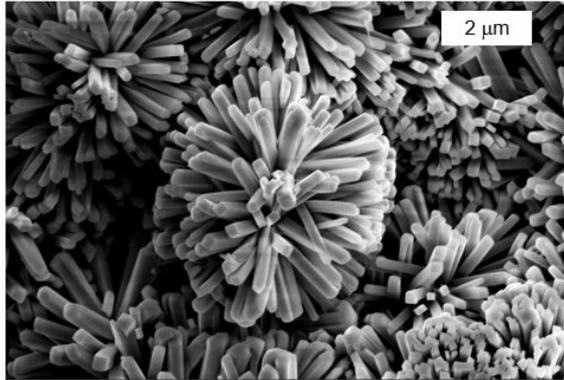
SEM image of oxide crystals

2 μm

Bulk materials characterization

- Bulk material properties are relevant for understanding a target's structural acoustic response
  - Bulk density
  - Compressional wave speed
  - Shear wave speed

- We need to know these parameters for each of the material components as inputs to FEM target response models
  - Uncorroded base material
  - Corrosion components
  - Embedded sediments

Uncorroded material
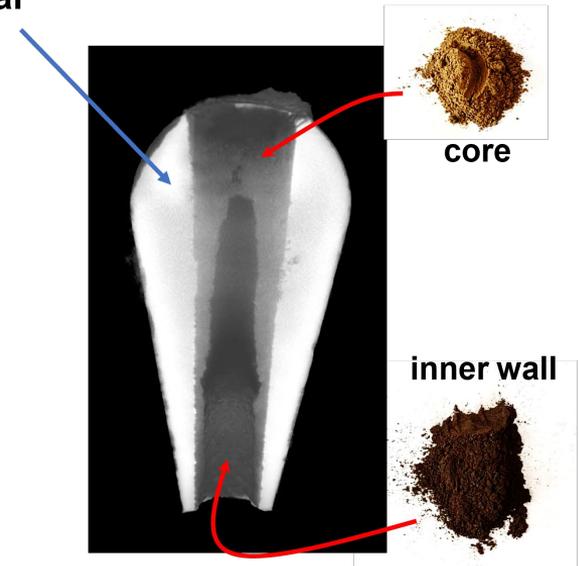
core

inner wall

Elastic wave speed measurements

- Ultrasonic techniques used to measure compressional and shear wave speeds in puck-sized samples
  - Scanning apparatus mapped compressional wave speed over sample cross-section arrival times from multiple internal reflections

stainless steel   cast iron
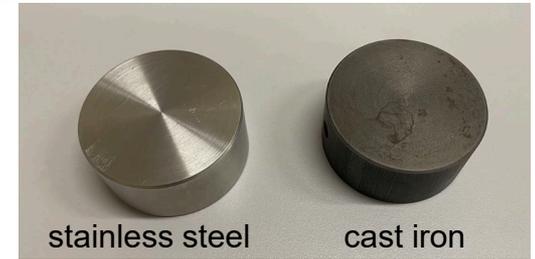
ARL:UT ultrasonics test facility

Schematic of scanning apparatus

Fixture

$a = 6.5\ mm$

1 MHz Ultrasonic Transducer

$D = 5.08\ cm$

Puck

$d = 12\ cm$

[Side]

[3D]

Steel puck mean compressional wave speed
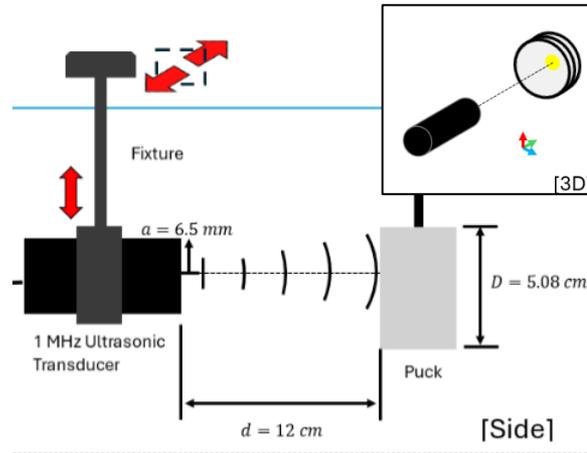
Elastic wave speed measurements

- Ultrasonic techniques used to measure compressional and shear wave speeds in puck-sized samples
  - Scanning apparatus mapped compressional wave speed over sample cross-section arrival times from multiple internal reflections
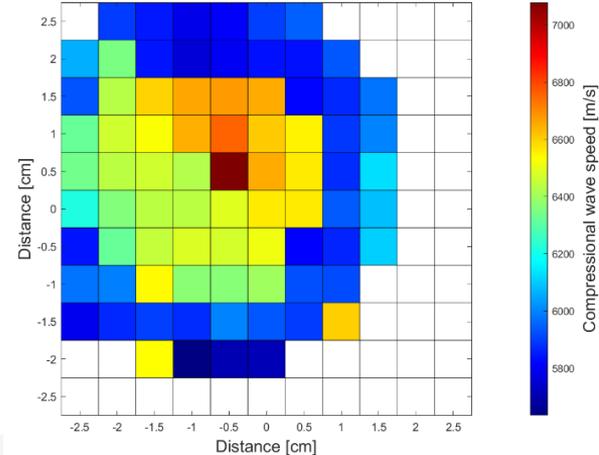 - Contact shear wave transducers measured arrival times of direct path and transmission internal reflections to estimate shear speed

stainless steel   cast iron

direct path

internal reflections

two-way travel times
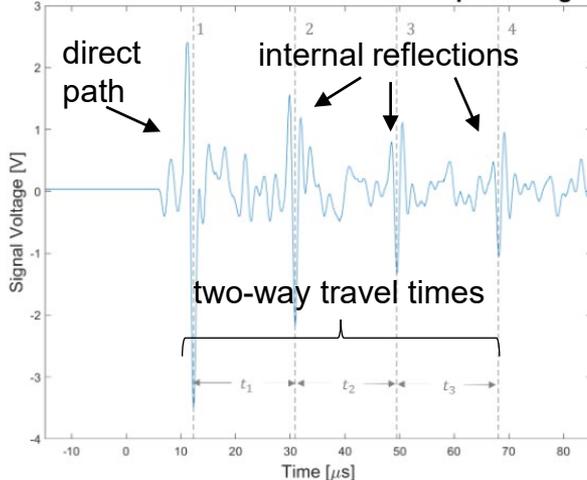
Measurements from cast iron puck, shown left.

stack of weights to ensure repeatable coupling

mounting fixture

source

sample

receiver
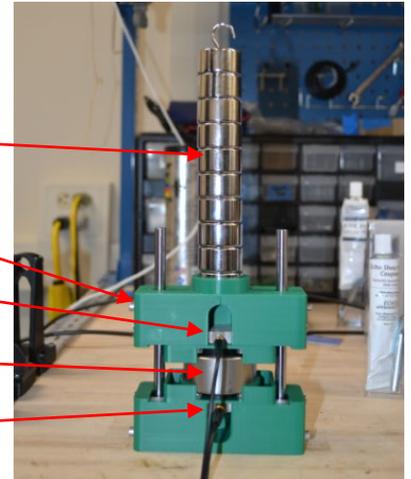
Bulk material properties

	Density [kg/m^3]	Uncertainty [kg/m^3]	Comp. Speed [m/s]	Std. Dev [m/s]	Shear Speed [m/s]	Uncertainty [m/s]
316L Stainless Steel	7844	+186.2 -180.5	6188	523.5	3192.6	±25.75
" Tabulated	7900-8050	--	5700-6100	--	3000-3200	--
Cast Iron	7180	+173.2 -195.3	4580	N/A	2680.9	±21.87
" Tabulated	6800-7300	--	~4500-6000	--	2200-3300	--

Next steps are to use these techniques to measure bulk material properties of MK23 sub-samples, shown right.

Object classification: Feature extraction

- Currently investigating object classification techniques to assess the potential impacts of corrosion on target detection and classification

- Another goal is to track and understand features in the acoustic color that either persist or change with corrosion from a more holistic viewpoint than simple correlation analysis

- Initial discussion and collaboration with David Williams (PSU-ARL) lead to extraction of several features from the data
  - Peak Energy
  - Symmetry
 - Gradient Symmetry
  - Phase Roughness
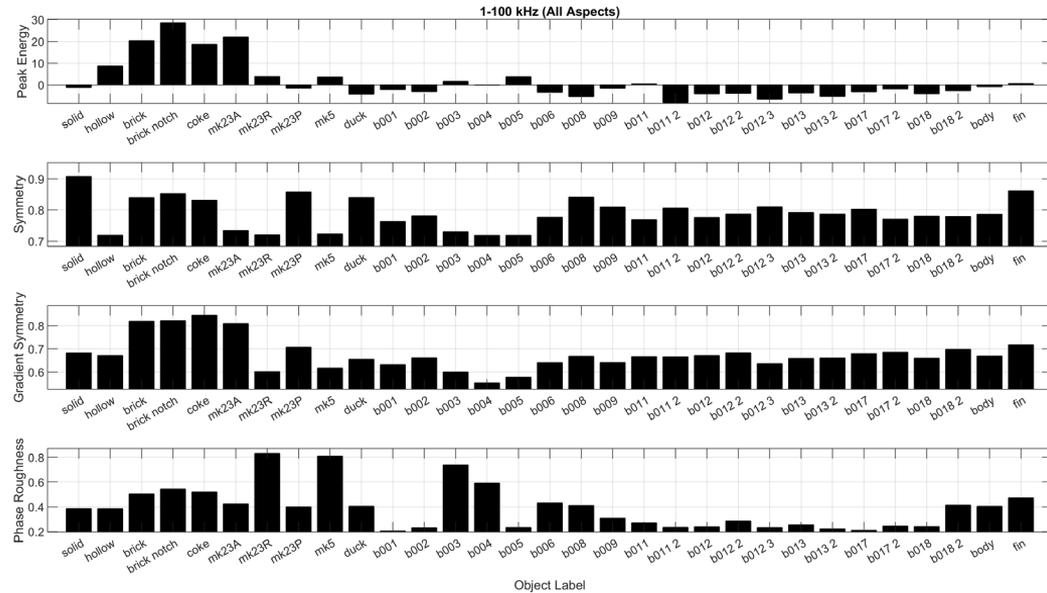
Data feature extraction

- Consider 5 different frequency bands
    - 4-24 kHz (corresponds to MuST system)
    - 15-45 kHz (corresponds to SVSS system)
    - 50-100 kHz
    - 10-100 kHz
    - 1-100 kHz

- Two approaches
    - Extract feature from full 360 degree aspect data
    - Extract feature from ±30 degree sector of data, for different center aspects
        - Corresponds to typical MuST aperture for one look
        - Results in 721-element vector of feature values (vs. center aspect, with 0.5 degree spacing)

- Embed features in a lower-dimensional space via t-SNE (t-distributed Stochastic Neighbor Embedding) to see how the samples cluster

- Human labels applied to data for visualization, but not used by t-SNE

SERDP

t-SNE visualization

- Example plot to right shows how t-SNE groups the samples with respect to phase roughness (full-frequency band, all aspects included)

- Human labels used to rank samples for visualization purposes

  - Corrosion scale from 1-5 with 1 being pristine (green) and 5 being severely corroded (red)

  - Objects with black labels are not MK23 samples

- In this case, the most severely corroded objects are separated from the pristine objects

Data: Phase Roughness: 1-100 kHz
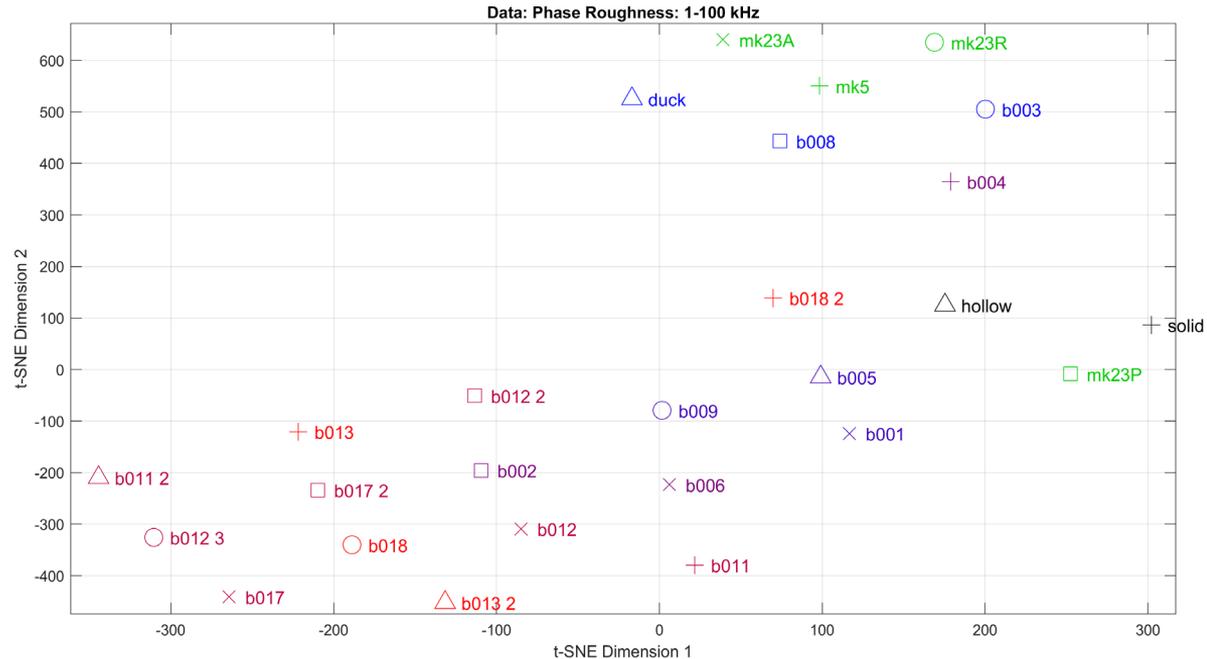
t-SNE visualization

- For some features, the samples grouped together better than others.

- This plot shows how peak energy alone could be a bad way to detect corroded samples.

- Further work is being done to isolate features to group the pristine with corroded samples and exclude clutter.

Data: Peak Energy: 15-45 kHz