

FINAL REPORT

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

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August 2023

REPORT DOCUMENTATION PAGE					<i>Form Approved</i> OMB No. 0704-0188	
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1. REPORT DATE (DD-MM-YYYY) 31/08/2023		2. REPORT TYPE ESTCP Final Report			3. DATES COVERED (From - To) 5/18/2018 - 5/17/2023	
4. TITLE AND SUBTITLE Multi-Sensor Towbody (MuST) for Detection, Classification, and Geolocation of Underwater Munitions				5a. CONTRACT NUMBER 18-C-0023		
				5b. GRANT NUMBER		
				5c. PROGRAM ELEMENT NUMBER		
6. AUTHOR(S) Kevin Williams Tim McGinnis University of Washington				5d. PROJECT NUMBER MR18-5004		
				5e. TASK NUMBER		
				5f. WORK UNIT NUMBER		
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) University of Washington Applied Physics Laboratory 1013 NE 40th St Seattle, WA 98105					8. PERFORMING ORGANIZATION REPORT NUMBER MR18-5004	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Environmental Security Technology Certification Program 4800 Mark Center Drive, Suite 16F16 Alexandria, VA 22350-3605					10. SPONSOR/MONITOR'S ACRONYM(S) ESTCP	
					11. SPONSOR/MONITOR'S REPORT NUMBER(S) MR18-5004	
12. DISTRIBUTION/AVAILABILITY STATEMENT DISTRIBUTION STATEMENT A. Approved for public release: distribution unlimited.						
13. SUPPLEMENTARY NOTES						
14. ABSTRACT The goal was to build a ship-deployed towbody instrumented with multiple acoustic sensors for detection/classification/geolocation of munitions on and in ocean sediments. Then to formally demonstrate its capabilities via operation over a region of Sequim Bay, Washington State, where an unknown number of inert UXO and clutter objects had been placed within a 50 meter radius circle at unknown locations.						
15. SUBJECT TERMS Multi-Sensor Towbody, MuST, Detection, Classification, and Geolocation, Underwater Munitions						
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT UNCLASS	18. NUMBER OF PAGES 43	19a. NAME OF RESPONSIBLE PERSON Kevin Williams	
a. REPORT UNCLASS	b. ABSTRACT UNCLASS	c. THIS PAGE UNCLASS			19b. TELEPHONE NUMBER (Include area code) 206-543-3949	

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FINAL REPORT

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ACRONYMS AND ABBREVIATIONS

AC	Acoustic Color
AHRS	Attitude and heading reference system
APL-UW	Applied Physics Laboratory – University of Washington
AUV	Autonomous underwater vehicle
CNN	Convolutional Neural Network
DCL	Detection-classification-localization
eBOSS	EdgeTech Buried Object Scanning System
GPS	Global positioning system
GUI	Graphical User Interface
IDA	Institute for Defense Analysis
INS	Integrated navigation system
MIP	Maximum Intensity Projection
MMI	Man-Machine Interface
MuST	Multi-sensor towbody system
NRE	Non-Recurring Engineering
PC	Personal Computer
PNNL	Pacific Northwest National Laboratory
R/V	Research Vessel
SERDP	Strategic Environmental Research and Development Program
TOI	Target Of Interest
USACE	United States Army Corps of Engineers

ACKNOWLEDGMENTS

The entire APL engineering team's efforts throughout this design, build, initial operation has been above and beyond the call of duty (but typical of all their efforts). A great ship and captain need to be a given – they were. The comments, capabilities, and an-board operation of navigation software supplied by Nick Lesnikowski of David Evans and Associates helped move us from test to operation seamlessly. Finally, the engineering support from both MacArtney (Lars Jorgensen, Hans-Jorgen Hansen) and EdgeTech (Rick Babicz, Kevin Rychert, Jason Sara) was frequent, ongoing, informative, and patient – often while we were in the middle of operation as we sought to solve one or more gremlins.

ABSTRACT

INTRODUCTION AND OBJECTIVES

The goal was to build a ship-deployed towbody instrumented with multiple acoustic sensors for detection/classification/geolocation of munitions on and in ocean sediments. Then to formally demonstrate its capabilities via operation over a region of Sequim Bay, Washington State, where an unknown number of inert UXO and clutter objects had been placed within a 50 meter radius circle at unknown locations.

TECHNOLOGY DESCRIPTION

The baseline MuST system comprises a FOCUS-3 towbody manufactured by MacArtney Underwater Technology, two towbody-mounted sonar systems manufactured by EdgeTech, a suite of towbody orientation and motion sensors, a shipboard handling system and shipboard data acquisition and analysis hardware and software. Together, the sonars can image the top 1-2 m of the sediment with resolution voxels of 2.5 cm x 2.5 cm x 2.5 cm (when operated 5 meters above the water/sediment interface) and image the sediment/water interface with sub-cm pixel resolution.

PERFORMANCE AND COST ASSESSMENT

During the demonstration in Sequim bay in September 2021 there were 42 detections that were subsequently classified as TOI or clutter via a CNN classifier. 18 of 23 UXO were correctly classified. MuST geolocation results were within 2 meters of ground truth measurements for 87.5% of the objects for which both MuST and ground truth measurements existed. Per day costs were O(\$20,000) as operated during the demonstration. Actual daily operation costs and area coverage rate may be tailored to the mission parameters.

IMPLEMENTATION ISSUES

Use of underwater acoustics will always be subject to environmental assessment. However, the source levels of eBOSS are low and the other acoustic systems on MuST operate above 200 kHz. MuST is not an off-the-shelf technology that can be purchased and immediately operated by survey companies. There is significant training required. After that training, however, MuST is no more complicated to operate than other sonar system platforms. The purchase cost O (\$2,000,000) of a fully instrumented MuST will be a barrier for smaller survey companies. An option to lease instead of buy could be viable for those smaller companies if supported by the stakeholder community.

PUBLICATIONS

K. L. Williams, T. M. Marston, T. McGinnis, “Multi-Sensor Towbody”, Sea Technology, Sept. 2021, 8-11.

K. L. Williams, T. Marston, D. Woodruff, S. Cazares, “Results from an informal demonstration of a buried-UXO detection, classification, geo-location system”, Underwater Acoustics Conference and Exhibition (UACE) 2021.

K. L. Williams, T. M. Marston, “Multi-Sensor Towbody (MuST): an expandable platform for detection, classification, and geolocation of Unexploded Ordnance,” Oceans 22, Virginia Beach, Virginia, Oct. 2022.

EXECUTIVE SUMMARY

INTRODUCTION

The U.S. Army Corps of Engineers (USACE) and the U.S. Navy have identified more than 400 underwater sites that are potentially contaminated with munitions. A primary focus of concern is shallow water sites (0-35 m) where the munitions pose a threat to human health and the environment. Acoustics represents one viable means of *detecting and classifying munitions* within such shallow water sites. The effort documented here focused on combining acoustic sensors and associated signal processing and classification software to fulfill the needs of the remediation community.

OBJECTIVES

The objective of the APL-UW effort was to build, test and demonstrate the performance of a system that uses a Multi-Sensor Towbody (MuST) to deploy detection, classification, and geolocation hardware from a surface vessel.

TECHNOLOGY DESCRIPTION

The baseline MuST system comprises a FOCUS-3 towbody manufactured by MacArtney Underwater Technology, two towbody-mounted sonar systems manufactured by EdgeTech, a suite of towbody orientation and motion sensors, a shipboard handling system and shipboard data acquisition and analysis hardware and software. Together, the sonars can image the top 1-2 m of the sediment with resolution voxels of 2.5 cm x 2.5 cm x 2.5 cm (when operated 5 meters above the water/sediment interface) and image the sediment/water interface with sub-cm pixel resolution.

The EdgeTech eBOSS is a wideband sonar that generates multi-aspect imagery of buried, partially buried, and proud targets using omnidirectional projectors that transmit pulses in the 5–25 kHz band and hydrophone arrays mounted on the towbody that measure the backscattering from the seabed. Matched-filtered hydrophone data are coherently summed using time-delay focusing to form an image of the seabed. To improve target imagery resolution, time-delay focusing is extended to hydrophone data collected over several transmissions. With synthetic aperture processing, the along track resolution of target imagery improves with distance traveled while forming the synthetic aperture. The depths of eBOSS seabed imaging depend on the sediment type. In sand, 1–2 m depths are possible, while in mud greater depths can be imaged because of reduced acoustic attenuation and the nearly matched sound speeds of mud and water.

The EdgeTech 2205 is an unpackaged version of the 4125 sidescan sonar system that allows the user to custom configure the electronics and acoustic arrays. This flexibility allows placement that maintains the best towbody control while minimizing the acoustic interference from the body itself. The 2205 provides high-resolution imagery. The 2205 operates at two frequencies: 540 kHz provides wide coverage during survey missions preceding the DCL effort; 1600 kHz is ideally suited to examine the water/sediment interface for very small targets.

PERFORMANCE ASSESSMENT

In total there were 42 detections in the MuST data from the 2021 blind test area that were subsequently classified as TOI or clutter via the CNN classifier. The results of the classification effort were sent to the official ESTCP scorers. The confusion matrices below document performance results. The EBOSS only confusion matrix documents the official performance results as determined by the scorers. The eBOSS+sidescan confusion matrix is derived from additional analysis subsequent to the official scoring where sidescan was used to further interrogate targets that were proud on the bottom. This eliminated 4 of the false positives. In that same matrix the false negatives are given as 5(3). The 3 in parentheses is the number of false negatives if the 60 mm UXO are treated as unresolvable, i.e., not detectable by definition given the 5 m deployment height of MuST. The objective for including this second matrix is simply to allow further insight into possible performance limits in an operational system.

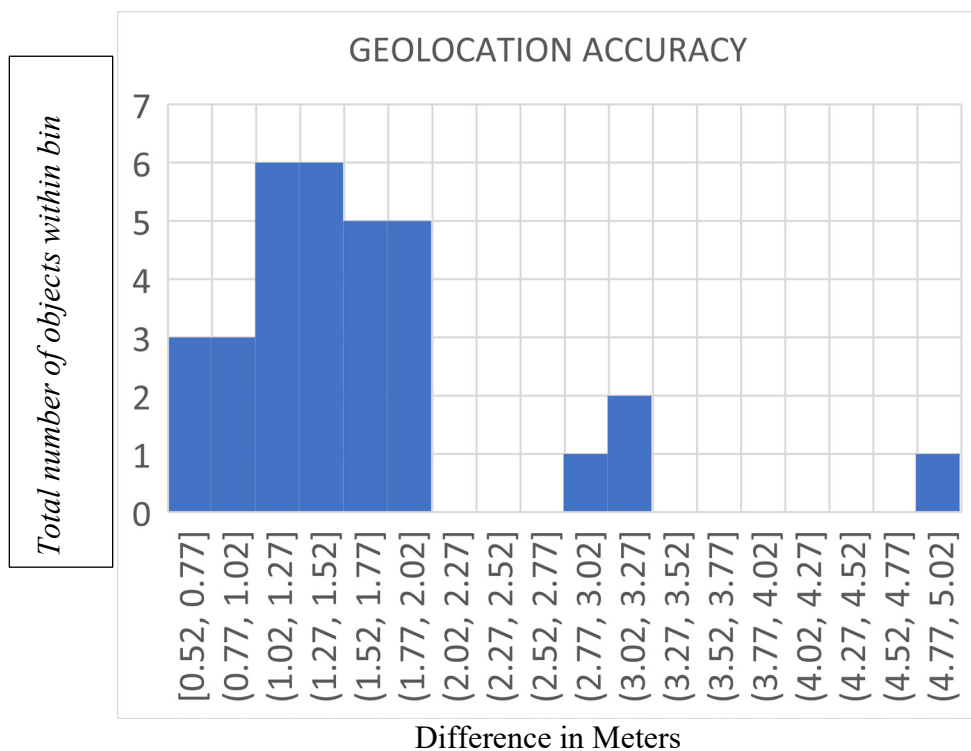
		eBOSS only		eBOSS + sidescan	
		Actual class		Actual Class	
		TOI	clutter	TOI	clutter
p r e d i c t e d c l a s s	TOI	18	9	18	5
	clutter	5	13	5 (3)*	17

• the 3 in parentheses is the false negative number if 60 mm UXO are ignored. That is, 60 mm UXO treated as unresolvable for the MuST deployed 5 m above the bottom

Focusing on the eBOSS only confusion matrix the total number of items (sum of the 4 squares) is 45. This is 3 more than the 42 detections from the MuST analysis. This difference is the result of the fact that one 81 mm and two 60 mm inert UXO were not detected. An additional inference is that 3 of the 5 false negatives are due to lack of detection and 2 are due to misclassification (both of those were 81 mm UXO).

In total there were 32 items that could be used to establish the geolocation accuracy of MuST, as operated during the demonstration. The histogram below bins the difference between the ground truth geolocation given by PNNL and the geolocation via MuST. The abscissa bins are in meters, e.g., [0.52, 0.77] indicates all targets where the magnitude of the difference between MuST geolocations and PNNL ground truth was between 0.52 and 0.77 meters.

Examination of the histogram indicates that 28 of the 32 items had geolocation differences less than 2 meters (to be exact – less than 2.02 meters). The four outliers include three clutter items (bracket, anchor, chair) and one TOI (81 mm). Whether those outliers are due to navigation error of one of the systems, transcribing error, or object relocation by another party (e.g., crabbers, shrimpers) is unknown.



Over the course of 4 days track lines were run at 5 m separation centered on the blue circle (the blind test area) in the figure below. The four different approach angles onto the test area allowed for multiple look angles on any object detected. Those multiple look angles are essential in both the initial rejection of clutter and the down-stream classification algorithms developed to date.



The performance objectives table on the next page further summarizes the information above. The “Detection of all munitions of interest” performance when viewed from the official scoring standpoint (eBOSS only results) is 0.78 (18/23), lower than the objective of 0.94. If the 60 mm UXO are treated as unresolvable for MuST, as operated during this test, the number of false negatives are reduced to 3 and the performance is 0.86 (18/21). As noted above, the objective for including this second performance value is simply to allow further insight into possible performance limits in an operational system.

The geolocation performance (87.5% of seed items with differences of 2 meters or less) is very close to the performance goal. The larger errors of the 4 outliers quite possibly are not the result of inherent MuST geolocation error but due to other factors as discussed above.

The production rate objective was met during the operations. Since the production rate in terms given in the table may not be informative relative to a metric such as (km²/day), it is useful to detail a recent effort using MuST to survey an area for the Navy. We carried out a survey of 1 km² for the Navy using MuST. We modified operations such that we could cover the area in 12 hours (0.67 km²/day). The modification was simply to fly at 10 m above the bottom to increase area coverage rate. This degraded pixel resolution by a factor of two but the targets involved were much larger than inert munitions. The ability to alter area coverage rate (MuST height above bottom) while retaining the ability to detect objects (i.e., have sufficient signal to noise) is a flexibility that is unique to underwater acoustics. In addition, the ability to operate well off the bottom reduces risk to the system as a whole.

Performance Objective	Metric	Data Required	Success Criteria	Performance Achieved*
Detection of all munitions of interest	Percent of seeded UXO detected/correctly classified (Pc)	Location of seeded items	Pc > 0.94 No. False Alarms within blind test area < 5	Pc=0.78 (18/23) (eBOSS only) Pc=0.86 (18/21) (ignoring 60 mm UXO) 9 False Alarms (eBOSS only) 5 False Alarms (eBOSS + sidescan)
Location Accuracy	Difference between PNNL groundtruth and APL estimate of Geolocation	Location of seed items from MCRL to within 0.25 m Estimated locations from analysis of MuST data	Geolocation to within 2 meters for 90% of the TOIs	28 out of 32 87.5%
Production Rate	Number of approach angles completed each day	Log of field work	Completion of all survey lines at each approach angle each day	Completed all survey lines at each approach angle each day

*See text for details

COST ASSESSMENT

MuST is not an off-the-shelf technology that can be purchased and immediately operated by survey companies. There is significant training required. After that training, however, MuST is no more complicated to operate than other sonar system platforms. The purchase cost of a MuST will be a barrier for smaller survey companies.

A path forward where APL builds two more MuST systems for ESTCP (total cost around \$4300k to build two more systems as discussed below) and companies lease those systems, are trained by APL, and then carry out surveys at a specified day rate would seem a viable way forward.

Specific cost categories are given in the table below and described further following the table.

MuST Cost Model – Sequim 2021 Demonstration

Cost Element	Data Tracked During Demonstration	Estimated Costs
Instrument cost	NRE to develop MuST and equipment purchases	\$2,300,000.00
Instrument setup costs	Dock-side mobilization and de-mobilization	3 days \$7,000.00/day
System Operation Tests	Lake Washington testing	2 days \$20,000.00/day 6 personnel 1 survey ship
Survey costs	Day rate for MuST operations – including high altitude reconnaissance to assess in-water hazards, placement of calibration line, and detailed survey of area	\$20,000.00/day 6 personnel 1 survey ship
Detection data processing costs	Postprocessing to develop Mosaic	1 person 1 month \$40,000.00/month/person
Discrimination data processing	Re-train classifiers using calibration line data, classification using Mosaic	1 person 2 months \$40,000.00/month/person
ONE TIME Training costs: Operations	Towbody operations, the ship-board processing stations, surveying considerations	1 week 2 people \$ 10,000.00/week/person
ONE TIME Training costs: Classification	Transferring the ability to develop a Mosaic, training and/or using the classifier	2 weeks 2 people \$10,000.00/week/person

Instrument Cost - NRE to develop MuST and equipment purchases

Reference 1 details the initial design and cost of MuST. To build a second MuST would cost approximately \$2300k, part of this cost is some NRE based on lessons learned in the first MuST development – that is the number quoted in the table above. A third unit should be possible for less than \$2000k (in FY22 dollars) as the NRE costs are further reduced.

Instrument Setup Costs - Dock-side mobilization and de-mobilization

Typically, mobilization of MuST requires 2 to 3 days of dock-side testing on the APL ship. This cost would probably increase for remote deployment on a boat of opportunity. Perhaps as high as 5 days at 10k/day for initial operation on a hired ship.

System Operation Tests - Lake Washington testing

Once dock-side testing is successful we move to Lake Washington to make sure all MuST systems are operational. This involves the entire crew (6 people) typically used to operate MuST, examine data in real time, and set navigation survey lines. This cost also includes the day rate cost of our ship (\$ 4500.00). Thus, the full day cost is the same as when the demonstration was carried out.

Survey Costs - Day rate for MuST operations

Survey cost includes time for high altitude reconnaissance to assess in-water hazards (typically we find the reconnaissance effort to be at least 5 times faster than detailed surveying), placement of calibration line (we believe this can be done in less than 30 minutes – it is our opinion that, once deployed, this line is best left for the duration of the survey with a flyby each morning), and follow-on detailed survey of area. As noted in the “System Operation Tests” section above, day rate for operation involves the entire crew (6 people) typically used to operate MuST, examine data in real time, and set navigation survey lines. This cost includes the day rate cost of our ship (\$ 4500.00).

In an operational scenario the cost of a ship might be higher but some of the crew of a survey ship would typically have the expertise to assist in MuST operation so the survey company could need fewer MuST specific personnel. We would anticipate the day rate cost would be within 20% of the day rate costs quoted for APL operation.

Detection Data Processing Costs - Postprocessing to develop Mosaic

The cost of developing the mosaic for detection will probably go down as a regimented process is developed. There has been a lot of “learning on the fly” so far.

Discrimination Data Processing Costs - Re-train classifiers using calibration line data, classification using Mosaic

As in the detection processing, there has been a steep learning curve as we have developed classifiers. There could be significant reduction in time here. Note also, that we have developed processing to the point that some of the classification effort occurs on-board during the survey. This is not viewed as definitive but allows significant insight on an ongoing basis for both real time operation of MuST and postprocessing.

ONE TIME Training costs: Operations

Typical surveying company staff are already well trained on the operations of various acoustic and non-acoustical surveying hardware. Thus, a majority of the training can occur during an actual surveying effort. An initial training session to present the specific considerations for operation of the towbody, the ship-board processing stations, and surveying considerations should suffice.

ONE TIME Training costs: Classification

Transferring the ability to develop a Mosaic as well as further train and use the classifiers is obviously essential. At this point all of this code is Matlab based so the surveying company will need someone with a Matlab background. Assuming Matlab expertise, we consider walking surveying staff through the details of the code design and operation to be straight forward.

IMPLEMENTATION ISSUES

MuST was built by integrating COTS technology. As such, equipment costs and availability are well defined and will vary according to market forces. However, operational costs are significant (as with any high-tech marine system and associated ship support).

Use of underwater acoustics will always be subject to environmental assessment. However, the source levels of eBOSS are low (about 180 dB/re 1 μ Pa). The other acoustic systems on MuST operate above 200 kHz. PNNL was able to use these facts to reduce operational restrictions. PNNL could best speak to the environmental assessment overhead.

1.0 INTRODUCTION

1.1 BACKGROUND

The baseline MuST system comprises a FOCUS-3 towbody manufactured by MacArtney Underwater Technology, two towbody-mounted sonar systems manufactured by EdgeTech, a suite of towbody orientation and motion sensors, a shipboard handling system and shipboard data acquisition and analysis hardware and software. Together, the sonars can image the top 1-2 m of the sediment with resolution voxels of 2.5 cm x 2.5 cm x 2.5 cm (when operated 5 meters above the water/sediment interface) and image the sediment/water interface with sub-cm pixel resolution.

Initially, two engineering tests of MuST were carried out in Sequim Bay in Washington State (in September 2019, September 2020). In these efforts the Pacific Northwest National Laboratory (PNNL) placed objects on and in the sediment of the bay. The field effort in September of 2020 was designed to be both an engineering test and an informal demonstration. A formal demonstration occurred in September 2021 and was designed around the successes of that 2020 effort. In the 2021 demonstration PNNL was again responsible for placement of all objects along a calibration line and in a blind test site 100 meters in diameter. The MuST system examined the Sequim site over four days (September 27-30, 2021).

1.2 OBJECTIVE OF THE DEMONSTRATION

The goal was to operate the towbody within the area shown in red in Fig. 1. The towbody was deployed from the R/V Robertson and towed at a height of 5 meters above the bottom, approximately 100 m behind the ship, at a speed of 4 kn. Both a calibration line of objects and a blind test area containing the same type of objects were deployed by PNNL near the region of the blue box in Fig. 1. The overall goal was to detect and classify all TOIs in the blind test area and geolocate them within a 2 m radius.

1.3 REGULATORY DRIVERS

The U.S. Army Corps of Engineers (USACE) and the U.S. Navy have identified more than 400 underwater sites that are potentially contaminated with munitions. A primary focus of concern is shallow water sites (0-35 m) where the munitions pose a threat to human health and the environment. Acoustics represents one viable means of *detecting and classifying munitions* within such shallow water sites. The objective of the APL-UW effort was to build, test and demonstrate the performance of a system that uses a Multi-Sensor Towbody (MuST) to deploy detection, classification, and geolocation hardware from a surface vessel.

2.0 TECHNOLOGY

2.1 TECHNOLOGY DESCRIPTION

Figures 2 and 3 give a high-level overview of the MuST system. Figure 2 indicates major mechanical components, whereas Fig. 3 is the functional block diagram. The eBOSS sonar is shown during calibrations on the left side of Fig. 2. The FOCUS-3 towbody and the deployment winch are shown as deployed on the R/V Robertson on the right side of Fig. 2.

The FOCUS-3 is the latest generation remotely operated towed vehicle in the FOCUS and TRIAXUS product line manufactured by MacArtney Underwater Technology. A FOCUS-3 advantage is sufficient width (2 m) to mount the EdgeTech eBOSS receiving array without overhang.

The FOCUS-3 uses proven computer technology and fiber optic telemetry for vehicle and sensor communication providing high-speed data acquisition and transfer capacity. A shipboard PC controls the vehicle based on inputs from the onboard vehicle sensors, according to a pre-programmed flight path. The tow cable is a small-diameter, low-drag electro-optical-mechanical cable that supplies power and transmits control data to the vehicle. Data generated by the onboard instrumentation and sensors are transmitted to the surface via the NEXUS fiber optic multiplexer system. The tow cable and winch, with a combination electrical and fiber optic slip ring, are used for towing operations. The towbody has integrated depth (pressure) and acoustic altimeter sensors as feedback to the control system. To obtain altitude, a separate sound speed sensor (an AML sound velocity Micro-X) is used.

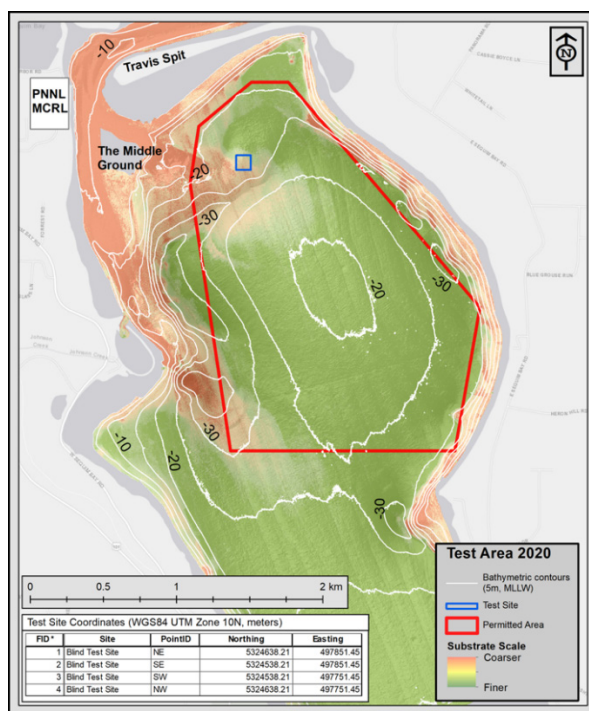


Figure 1. Red Box Indicates the Region Over Which the APL-UW Towbody Was Operated.

The blue area indicates an approximately 100 m x 100 m area where objects are placed on and in the bottom.



Figure 2. MuST Mechanical Components.

Left side - EdgeTech eBOSS, Right side - FOCUS-3 towbody and winch on vessel fantail (eBOSS can be seen at bottom of towbody)

The functional block diagram in Fig. 3 indicates the in-water and shipboard components of the baseline system as well as both the additional elements that could be added to enhance geo-location and the access ports available for up to 4 additional guest sensors.

The system operates at up to 400 m depth at 5 kn with a controllable horizontal movement of ± 80 m. The cable layback ratio is a function of tow speed and is approximately 1:4–1:5 for tow speeds of 3–4 kn. The man–machine interface (MMI) for the FOCUS-3 control console has a Windows operating system. MuST can carry a broad range of sensor packages, offering flexibility and future expansion.

FOCUS-3 towbody features:

- Steerable towed data collection
- Stable in all planes
- Operating depth of 400 m @ 5–6 kn
- High data transmission rates
- Software controlled vertical and horizontal steering functions
- Built-in standard control sensors
- User friendly controls and displays
- Modular rugged and streamlined design
- Low-noise magnetic and acoustic signatures
- High-payload for peripheral equipment
- Quick-change custom buoyancy packs

The FOCUS-3 towbody includes an attitude and heading reference system with a three-axis angular rate gyro, three-axis orthogonal accelerometers, and three-axis magnetometer. AHRS data can be output in a user specified format to an external computer from one of the serial ports on the surface console computer at a rate of 2 Hz.

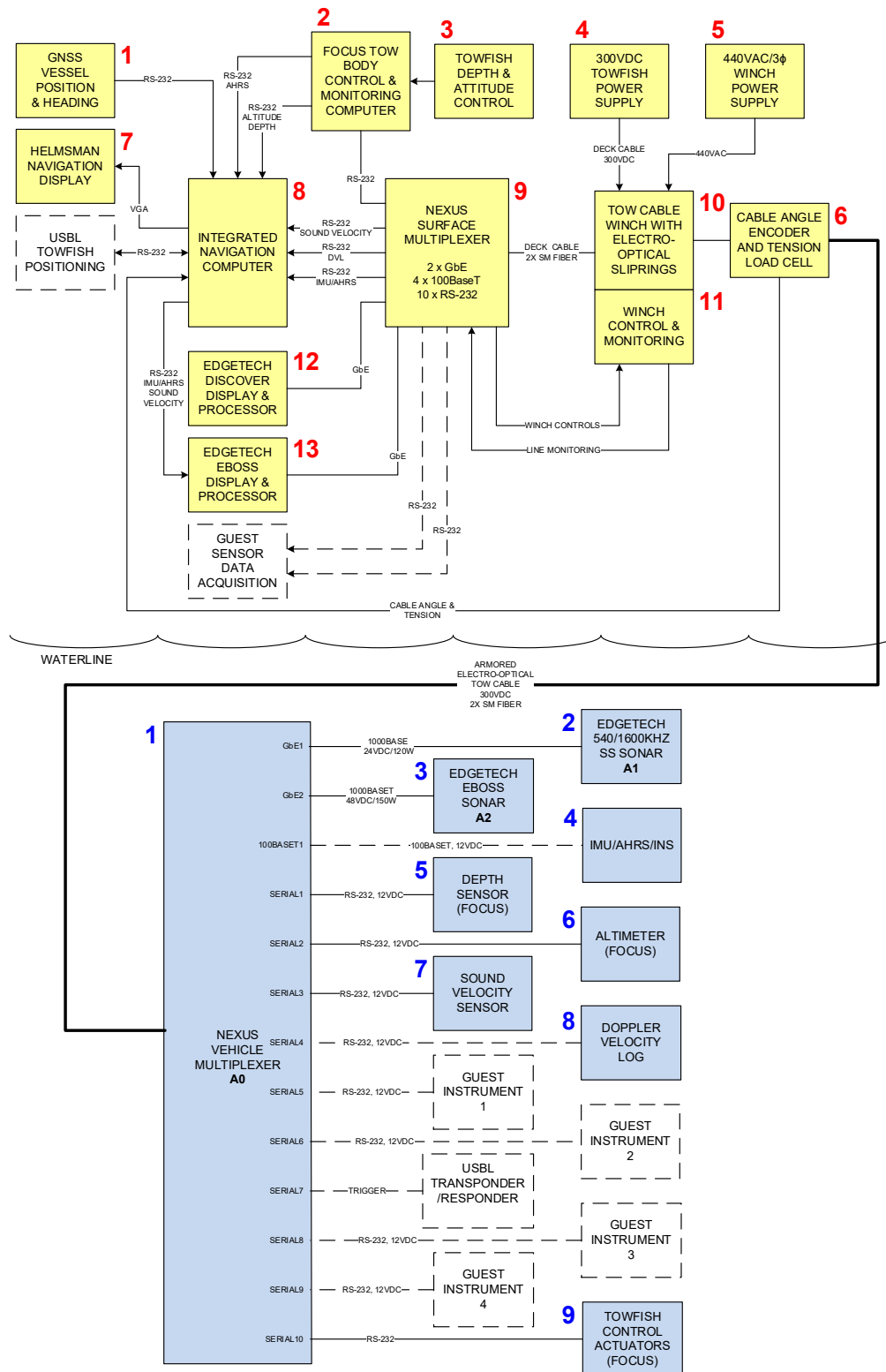


Figure 3. MuST Functional Block Diagram of Shipboard (Yellow) and In-water (Blue) Components with Optional Components (Dashed Boxes and Lines).

The EdgeTech eBOSS is a wideband sonar capable of generating multi-aspect imagery of buried, partially buried, and proud targets using omnidirectional projectors that transmit pulses in the 5–25-kHz band and hydrophone arrays mounted on the towbody that measure the backscattering from the seabed. Matched-filtered hydrophone data are coherently summed using time-delay focusing to form an image of the seabed. To improve target imagery resolution, time-delay focusing is extended to hydrophone data collected over several transmissions. With this synthetic aperture processing, the along track resolution of target imagery improves with distance traveled while forming the synthetic aperture. The use of synthetic aperture processing also allows the along vehicle dimension of the array to be reduced, thereby reducing the hydrophone array drag and surface area and enabling the deployment of eBOSS on AUVs and towbodies.

The depths of seabed imaging depend on the sediment type. In sand, 1–2-m depths are possible, while in mud greater depths can be imaged because of reduced acoustic attenuation and the nearly matched sound speeds of mud and water.

The EdgeTech 2205 is an unpackaged version of the 4125 sidescan sonar system that allows the user to custom configure the electronics and acoustic arrays. This flexibility allows placement that maintains the best towbody control while minimizing the acoustic interference from the body itself. The 2205 provides high-resolution imagery. The 2205 operates at two frequencies: 540 kHz provides wide coverage during survey missions preceding the DCL effort; 1600 kHz is ideally suited to examine the water/sediment interface for very small targets.

2.2 TECHNOLOGY DEVELOPMENT

The design philosophy for the Multi-Sensor Towbody (MuST) was matured as a limited scope SERDP effort¹. The final design was based on the following concepts:

- Design using COTS components whenever possible to reduce design costs and provide industry-based replacement parts and support to enhance system longevity.
- Design using modular components so that the system can be supported by non-engineering staff in the field.
- Minimize weight, size, power needs, and complexity so the system can be hosted on a variety of vessels of opportunity.
- Use a tow cable that has copper conductors for power and fiber-optics for data. A fiber-optic data connection ensures current and future bandwidth requirements will be met to support a variety of high-bandwidth sensors (e.g., acoustics and video).
- Design a system that considers cost and capability with the goal of meeting initial construction and demonstration baseline needs that can also inform and integrate additional capability choices.

The design study developed a set of mechanical and functional requirements and specifications including the mechanical envelope and candidate sensors for the towbody, support vessel systems (winch, tow cable, electronics, and sensors), electrical power and data interfaces, and guest ports for instrument packages that can be hosted on the towbody.

Documentation of the current state of the system and its capabilities can be found in Ref. 2, the results of the informal demonstration carried out in September of 2020 are given in Ref. 3, and both 2020 and 2021 results can be found in Ref. 4.

2.3 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

The U.S. Navy is engaged in similar research under its mine countermeasure programs. Though the sensors used are similar in Navy and non-Navy systems, the operational requirements differ. Time constraints and the requirement of covert operations drive Navy solutions toward autonomous underwater vehicles (AUVs) with automated target recognition to address the detection-classification-localization (DCL) problem. Though capable, the costs — acquisition, modification, operations, maintenance, and updates — for AUVs are not optimal for the remediation task. In addition, the personnel carrying out the remediation may not have the appropriate clearance or background to operate AUVs carrying U.S. Navy instrument packages.

An AUV vehicle with a payload capacity to handle the sonars used (eBOSS and 2205) would be similar to the REMUS 600 (Kongsberg) or the SeaCat (Atlas). These systems have an initial hardware investment of more than one million dollars, plus the cost of the sonar sensors (which is the same for towbody and AUV platforms), most of which represent in-water assets. Integrating the eBOSS sonar heightens risk, because obtaining high cross-range resolution requires incorporating wings on the AUV that can be damaged during deployment, operations, and recovery. Integrating any future guest sensors into the AUV would require consideration of the buoyancy, space, power, and propulsion impacts (with the implied additional NRE for each sensor) to a greater degree than with a towbody.

Given our choice of a relatively large towbody and the housing of control, power, and data storage shipboard, the cost of incorporating new sensors for initial proof of concept tests have proven to be to be low. The chosen towbody requires no modifications to achieve cross-range extent. A towbody solution also allows immediate data access, as well as assessment and real-time alteration of operational strategy as needed. Furthermore, much of the navigation efforts are handled shipboard with continuous access to GPS assets. Finally, the involvement of a man-in-loop for detection and classification tasks, though a concern in naval operations, is a real-time asset for munitions remediation efforts and again points to the utility of the towbody solution. An additional potential advantage is the ability of stakeholders to experience the data acquisition process.

Acoustic systems have a standoff range advantage as compared to electromagnetic systems and have a much richer set of information when the frequency response of the target is used in classification. Height above bottom of 5 meters yields high quality information and allows distance between survey lines up to 15 meters. This increases coverage rate. However, the disadvantage of the acoustic system is that target response can vary significantly with approach angle onto the target. Previous classification work has indicated that, with the current generation of Convolutional Neural Network (CNN) classifiers, this implies that best results are achieved when the target is detected multiple times at different ranges and approach angles.

There is much still to be determined relative to the optimal set of survey line geometries and how this optimization (and thus effective production rate) changes as more training data becomes available and better classifiers are developed.

3.0 PERFORMANCE OBJECTIVES

The performance objections of the demonstration in September 2021 are given in Table 1 and discussed after the table.

Table 1. Performance Objectives

Performance Objective	Metric	Data Required	Success Criteria
Detection of all munitions of interest	Percent of seeded UXO detected/correctly classified (Pc)	Location of seeded items	$P_c > 0.94$ No. False Alarms within blind test area < 5
Location Accuracy	Difference between PNNL groundtruth and APL estimate of Geolocation	Location of seed items from MCRL to within 0.25 m Estimated locations from analysis of MuST data	Geolocation to within 2 meters for 90% of the TOIs
Production Rate	Number of approach angles completed each day	Log of field work	Completion of all survey lines at each approach angle each day

3.1 OBJECTIVE: DETECTION OF ALL MUNITIONS OF INTEREST

3.1.1 Metric

The goal was to reach a probability of correct classification of 0.94 while not having more than 5 false alarms in the blind test area. To obtain this level of performance our results to date, using the current classifiers, implies that the targets need to be viewed at a variety of approach angles. Doing so, eliminates many false detections. The remaining detections are scored via the classification to get to the final binary predictions – UXO, non-UXO.

3.1.2 Location Accuracy

The demonstration in 2021 showed that we can register survey lines in a relative sense to sub-pixel (< 5 cm) resolution. The absolute geolocation error in meters is discussed in the next section.

3.1.3 Data Required

Data from MuST every 3.3 cm in along track direction (60 Hz ping rate and 2 m/s ship speed) is needed. The survey lines need to be acquired at 5 m spacing. The data products needed are voxel results of the order of 2.5 cm x 2.5 cm x 2.5 cm from which the two-dimensional data products can be determined.

3.1.4 Success Criteria

At least two approach angles onto the blind test area are needed. The goal with three approach angles is to reach a probability of correct classification of 0.94.

3.2 OBJECTIVE: LOCATION ACCURACY

3.2.1 Metric

Geolocation to within 2 meters is the goal.

3.2.2 Location Accuracy

Having ground truth for the TOI geolocation within 0.25 meters is requested.

3.2.3 Data Required

GPS fixes of MuST at the beginning and end of each survey line, towbody INS data, and the doppler velocimeter data for speed over ground are all needed.

3.2.4 Success Criteria

Geolocation to within 2 meters for 90% of the TOIs.

3.3 OBJECTIVE: PRODUCTION RATE

3.3.1 Metric

Completion of all survey lines at each approach angle each day.

3.3.2 Location Accuracy

The ship needs to be able to stay on a survey line to within 5 meters. MuST can be flown by the pilot to stay on the survey line to within 2 meters.

3.3.3 Data Required

Real time ship position is needed in the wheelhouse. This navigation data is shown on a continual basis both in the ship's lab and in the pilot house.

3.3.4 Success Criteria

Using 5 m separation between survey lines it takes about 5 to 6 hours to survey one approach angle when all sensors are functioning as designed. Thus, a production rate of one survey approach angle per day is our metric for success. Reaching the operational system production rate goal of 1 km²/day will require increased separation between lines (we anticipate use of 10 m separation per survey line will suffice).

In the long term there will be a tradeoff between number of approach angles, distance between survey lines, and classifier performance that will set the production rate. Development to this point indicates that the production rate sought is possible.

4.0 SITE DESCRIPTION

Sequim Bay has an average water depth of approximately 20 m with a relatively flat bottom and a variety of bottom types (Figure 1). See the PNNL report (PNNL-29345) prepared for SERDP in December 2019 for a full description of the site.

4.1 SITE SELECTION

Sequim Bay was chosen because of the variety of sediment types available and a water depth that allows both efficient diver and MuST operations. In addition, high quality laboratory, logistics, and vessel support are all available. This allows test bed design, and TOI deployment in a variety of sediment types.

4.2 SITE HISTORY

In 2019 and 2020 engineering tests of MuST were carried out in Sequim Bay in Washington State. In these efforts the Pacific Northwest National Laboratory (PNNL) placed objects on and in the sediment of the bay. The field effort in September of 2020 was designed to be both an engineering test and an informal demonstration. The 2021 demonstration was designed around the successes of that 2020 effort.

5.0 TEST DESIGN

5.1 CONCEPTIONAL EXPERIMENTAL DESIGN

The MuST demonstration occurred from Monday to Thursday, the week of Sept. 27, 2021. MuST was operated within the area shown in red in Fig. 1. It was deployed from the R/V Robertson and towed at a height of 5 meters above the bottom, approximately 100 m behind the ship, at a speed of 4 kn. Both a calibration line of objects and a blind test area containing the same type of objects were deployed by PNNL near the region of the blue box in Fig. 1. The test areas were scanned over the course of four days within ten daylight hours of operation each day.

Objects were placed in the designated areas more than three weeks before the towbody test. Objects were deployed and the tow body tested within the dates of July 1, 2021, and October 31, 2021.

Figure 4 shows the cross-track region of the bottom over which data from the eBOSS and 2205 sonars was collected (less than the full beamwidth of the sonars is analyzed). The sonars transmitted 60 times per second (every 16.7 ms) using 4 ms pulses, giving a 24 % duty cycle.

The ship maintained a 4 kn (approximately 2 m/s) speed, with the 60 Hz ping rate, this implies 3.3 cm forward advance of the ship between pings. This spatial separation allows for good synthetic aperture processing in the along-track direction. The 64 receivers and two sources in the across track direction, the synthetic aperture processing in the along-track direction, and the 20 kHz bandwidth results in acoustic image voxels with resolution of approximately (2.5 cm x 2.5 cm x 2.5cm).

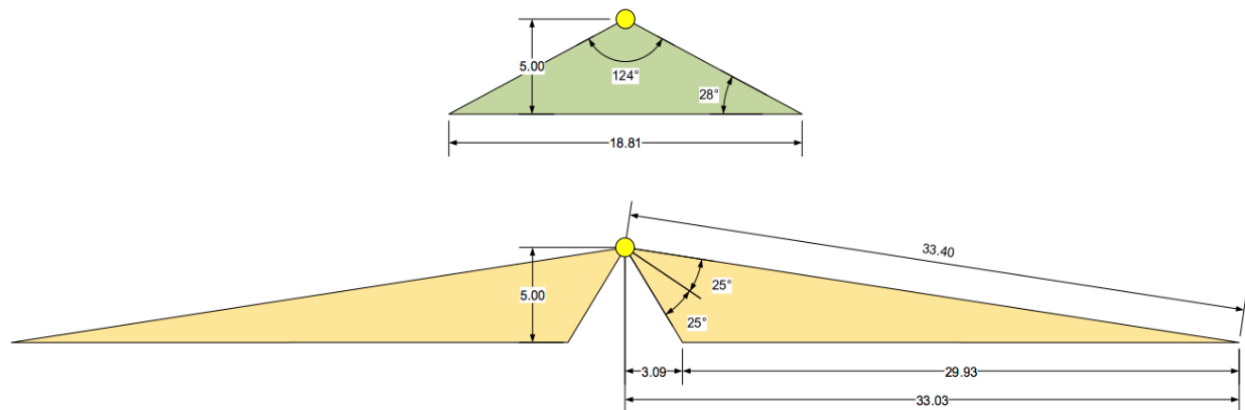


Figure 4. EdgeTech eBOSS (Green) and EdgeTech 2205 500Hz Sidescan Sonar (Yellow) Beam Geometry

Over the course of 4 days track lines were run at 5 m separation centered on the blue box in Fig. 1. The track lines from the Sequim 2021 demonstration are shown in Fig. 5. The four different approach angles onto the test area allowed for multiple look angles on any object detected. Those multiple look angles are essential in both the initial rejection of clutter and the down-stream classification algorithms developed to date.

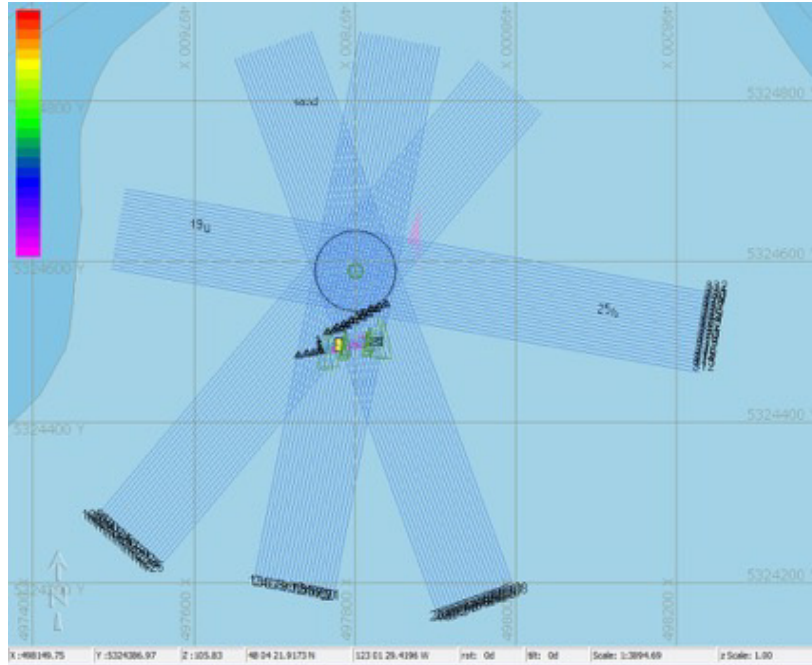


Figure 5. Track Lines Run in the 2021 Demonstration.

Both the processing to image objects detected and the classification algorithms using the data products from those images are now developed to the point that preliminary detections, locations, and classification could be carried out during the demonstration. Since some of the objects were new and the calibration line data from those new objects had not been incorporated into the classifier, a final list of detected objects, their location, and their classification into munitions or clutter were carried out in the fall of 2021/winter of 2022 after the 2021 calibration line data were added to the training data and the classifier retrained.

5.2 SITE PREPARATION

PNNL deployed all targets and supplied the GPS positions for the end points of the calibration line and the center and radius of the blind test area. They determined the GPS positions of all targets and man-made clutter they deployed and made this information available to the official scorers of the demonstration.

5.3 SYSTEM SPECIFICATION

The baseline MuST system comprises a FOCUS-3 towbody manufactured by MacArtney Underwater Technology, two towbody-mounted sonar systems manufactured by EdgeTech, a suite of towbody orientation and motion sensors, a shipboard handling system and shipboard data acquisition and analysis hardware and software. Together, the sonars can image the top 1–2 m of the sediment with resolution voxels of 2.5 cm x 2.5 cm x 2.5 cm and image the sediment/water interface with sub-cm pixel resolution.

5.4 CALIBRATION ACTIVITIES

The MuST system was flown over the calibration line in dedicated line surveys at the beginning of the demonstration. Also, as the blind test area was surveyed there was additional opportunities to acquire data from targets on the calibration line. These data were used to extract training data products to add to the data product set generated during the Sequim 2020 engineering test.

5.5 DATA COLLECTION PROCEDURES

Figure 5 shows the survey lines that were run. At the beginning of a survey line MuST is brought to the surface to allow a GPS fix. MuST is then flown to a height of 5 m above the bottom and remains there as it passes through the survey area. At the end of the run MuST is again brought to the surface for a GPS fix. These two GPS fixes and the INS system data from on-board MuST allowed geolocation to within 2.0 meters for 87.5% of the objects where both ground truth and MuST data was available (as determined from the Sequim 2021 data).

6.0 DATA ANALYSIS AND PRODUCTS

6.1 PREPROCESSING

The raw data was processed using both real aperture and synthetic aperture code immediately after acquisition (within 30 minutes). The code used is designed to be numerically efficient (a 30 minute survey line of data can be processed in less than 10 minutes) at the expense of some resolution. The result of that processing was subsequently analyzed to detect, classify (using training data from Sequim 2020), and geolocate TOIs.

6.2 TARGET SELECTION FOR DETECTION

Figure 6 shows the Matlab application that was used in the detection, classification, and geolocation work carried out as the data was acquired. In practice the data from the preprocessing step are displayed and the operator examines it to find and click on a TOI (Steps 2 and 3 in Fig. 6). A 2 m volume in the vicinity of the TOI is further analyzed to create the data products (Step 4) needed by the classifier (Step 5). The Acoustic Color (AC) and image classifier scores are calculated and displayed on the bottom left. The geolocation of the TOI is displayed on the plot on the top right. The operator has the choice of saving the TOI data and plotting all TOI information to date (bottom right).

The entire chain represented in Fig. 6 for one TOI can be completed in less than 5 minutes. All classification results were viewed as preliminary until the postprocessed calibration data from the 2021 demonstration were added to train the classifier and classification scores from all detections averaged.

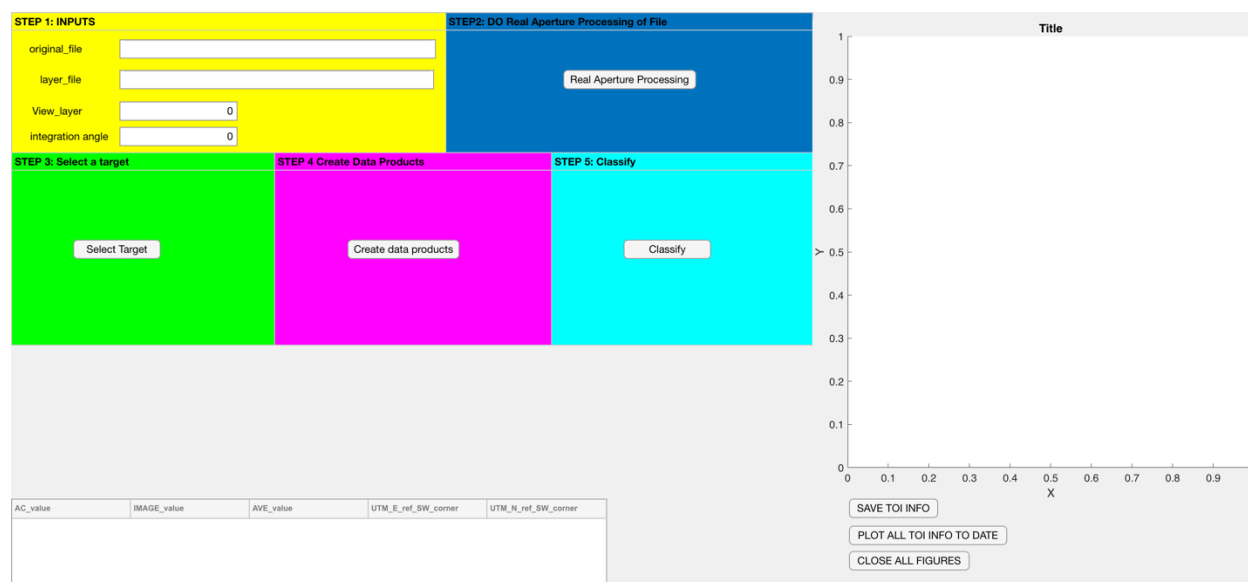


Figure 6. Detection, Classification, and Geolocation GUI to Be Used During the 2021 Demonstration.

6.3 PARAMETER ESTIMATION

The parameter estimation (data products of Fig. 6) is carried out as part of the on-board processing. At present, two-dimensional data products (for both AC and imaging) using Maximum Intensity Projections (MIPs) are the data products produced.

6.4 TRAINING

The initial classification used classifiers trained using 2020 data. Postprocessing over the three months after the demonstration allowed the calibration data from the 2021 demonstration to be added in further training the classifier.

6.5 CLASSIFICATION

Initial classification occurred on-board as described above. Final classification and geolocation occurred after data from the 2021 demonstration calibration line was added and all classification scores for an individual TOI were averaged.

6.6 DATA PRODUCT SPECIFICATION

Figure 7 shows data for one target in the blind test area of the 2020 engineering test. The bottom two lines of that figure show the data products used in the classifier. Postprocessing efforts include determination of how many looks one has at a particular TOI and, of those, how many have sufficient quality to be further used in classification.

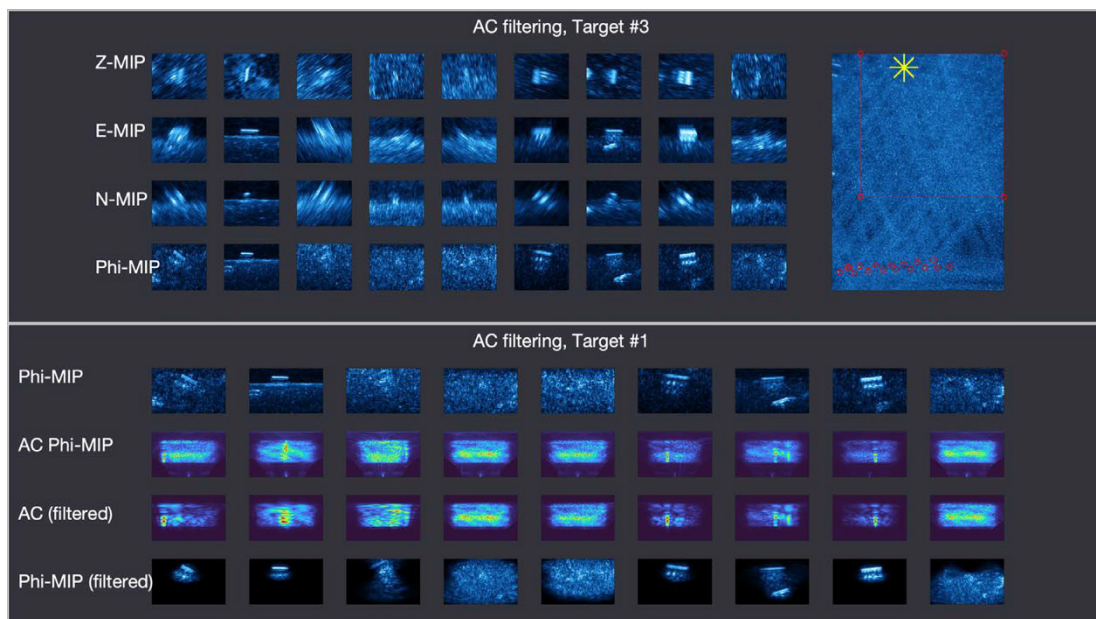


Figure 7. An Example from Sequim 2020 Showing the Data Products Used (Bottom Two Lines of the Figure) in Classifying a TOI in the Blind Test Area of that Engineering Test.

The target was detected in 9 survey lines. Six of the nine detections gave sufficient quality data for use in the classifier.

For postprocessing of the 2021 data an updated mosaicking tool was constructed (Fig. 8) that allowed a target to be chosen, classification data products created, and classification performed. The output was a classification score and geolocation for each target.

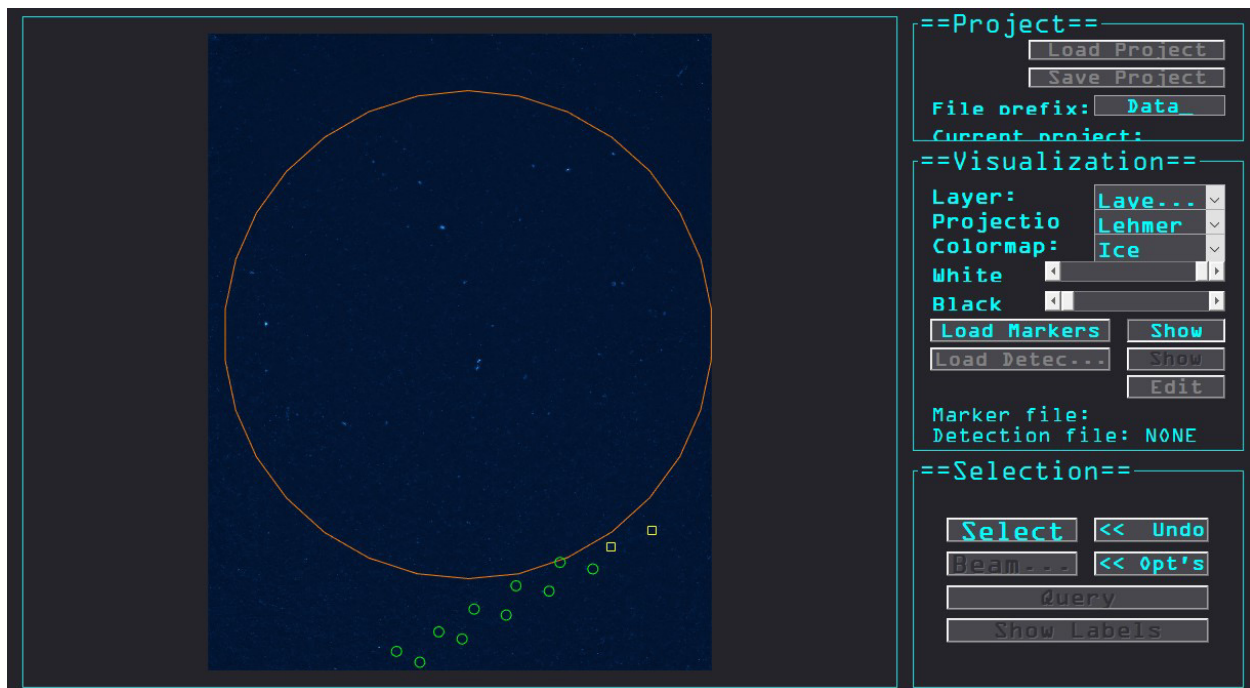


Figure 8. Mosaicking Tool Used in Postprocessing of the 2021 Demonstration Data.

7.0 PERFORMANCE ASSESSMENT

Subsections are provided below for each performance objective in Section 3.

7.1 OBJECTIVE: DETECTION OF ALL MUNITIONS OF INTEREST

In total there were 42 detections in the MuST data from the 2021 blind test area that were subsequently classified as TOI or clutter via the CNN classifier. The results of the classification effort were sent to the official ESTCP scorers. The confusion matrices below document performance results. The EBOSS only confusion matrix documents the official performance results as documented by the scorers. The eBOSS+sidescan confusion matrix is derived from additional analysis after the official scoring where sidescan was used to further interrogate targets that were proud on the bottom. This eliminated 4 of the false positives. In that same matrix the false negatives are given as 5(3). The 3 in parentheses is the number of false negatives if the 60 mm UXO are treated as unresolvable, i.e., not detectable by definition given the 5 m deployment height of MuST. The objective for including this second matrix is simply to allow further insight into possible performance limits in an operational system.

Table 2. Confusion Matrices

		eBOSS only		eBOSS + sidescan	
		Actual class		Actual Class	
		TOI	clutter	TOI	clutter
p r e d i c t e d c l a s s	TOI	18	9	18	5
	clutter	5	13	5 (3)*	17

• the 3 in parentheses is the false negative number if 60 mm UXO are ignored. That is, 60 mm UXO treated as unresolvable for the MuST deployed 5 m above the bottom

Focusing on the eBOSS only confusion matrix the total number of items (sum of the 4 squares) is 45. This is 3 more than the 42 detections from the MuST analysis. This difference is the result of the fact that one 81 mm and two 60 mm inert UXO were not detected. An additional inference is that 3 of the 5 false negatives are due to lack of detection and 2 are due to misclassification (both of those were 81 mm UXO).

A more general inference from the eBOSS only confusion matrix can be made by understanding that the pixel resolution is a function of height above bottom of MuST. This affects the target size that can be adequately resolved. Height above bottom also affects area coverage rate, i.e., higher resolution comes with lower height above bottom and thus lower coverage rate. Lower height above bottom also increases risk to the MuST system via the reduced time to respond to changes in bathymetry and possible undetected obstructions on the bottom. In practice, a high level flyover using the sidescan reduces the obstruction risk but does not eliminate it. The 5 meter operational height chosen was deemed a good tradeoff height for the demonstration but that tradeoff space could vary with requirements placed on any operational scenario.

7.2 OBJECTIVE: LOCATION ACCURACY

It is important to note first that some of the clutter items deployed in the blind test area were not detected by MuST, and likewise, some of the clutter items detected by MuST were natural (i.e., not placed by PNNL). In total there were 32 items that could be used to establish the geolocation accuracy of MuST, as operated during the demonstration. The histogram below bins the difference between the ground truth geolocation given by PNNL and the geolocation via MuST. The abscissa bins are in meters, e.g., [0.52, 0.77] indicates all targets where the magnitude of the difference between MuST geolocations and PNNL ground truth was between 0.52 and 0.77 meters.

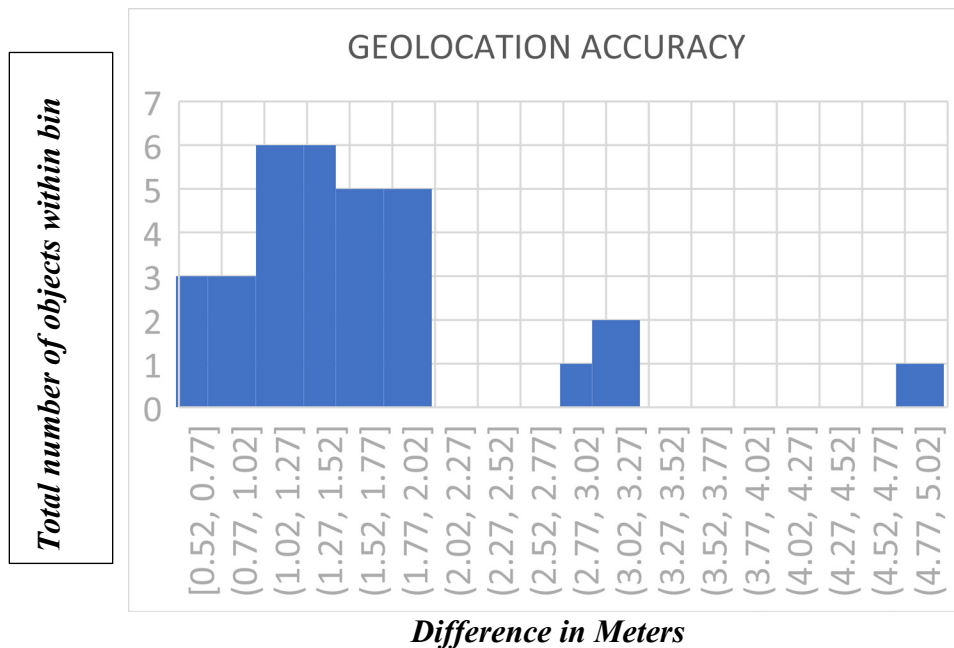


Figure 9. Histogram of the Difference Between the Ground Truth Geolocation Given by PNNL and the Geolocation via MuST.

The horizontal bins are in meters

Examination of the histogram indicates that 28 of the 32 items had geolocation differences less than 2 meters (to be exact – less than 2.02 meters). The four outliers include three clutter items (bracket, anchor, chair) and one TOI (81 mm). Whether those outliers are due to navigation error of one of the systems, transcribing error, or object relocation by another party (e.g., crabbers, shrimpers) is unknown.

Combining Detection, Classification, Location results

The results for detection, classification, and localization were combined by IDA as shown in Figure 10. The Clutter, TOI, and FN (false negative) symbols are the ground truth values. The Dig, Do Not Dig symbols are the MuST results. The five FNs are those indicated in Table 2.

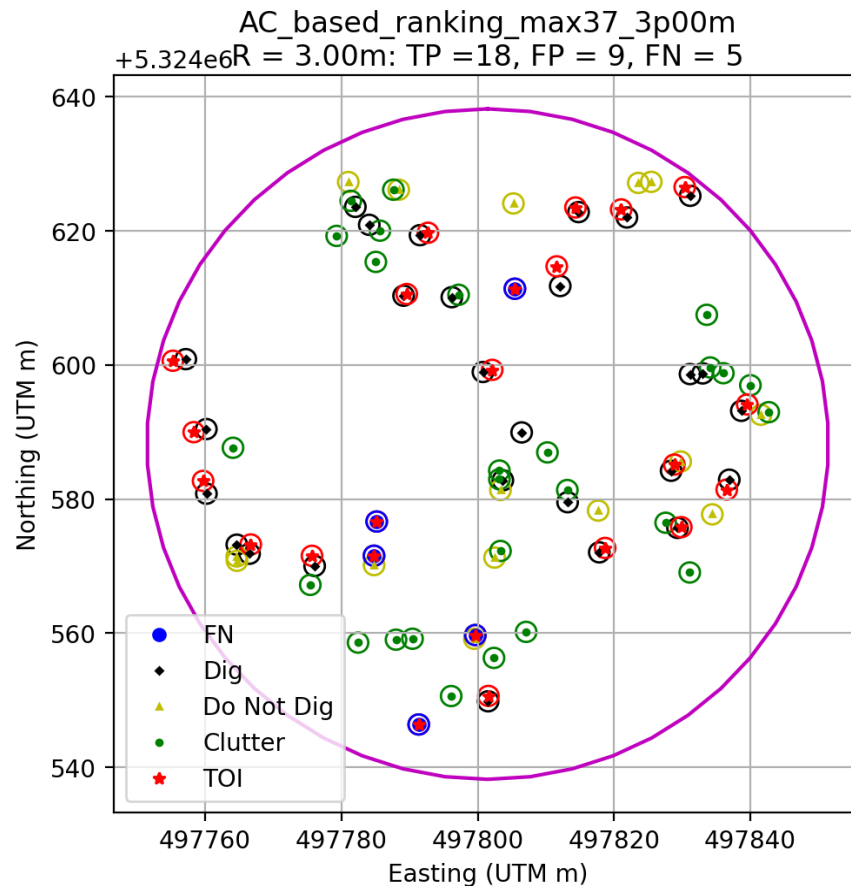


Figure 10. Combination of Classification and Geolocation Information.

Produced by IDA as part of their formal scoring effort.

Figure 11 is another view option for the blind test results, the symbols and locations are from PNNL ground truth and the numbers are the 42 items detected with MuST. The detected objects labeled 14, 17, 18, 20 are the four outliers in Fig. 9.

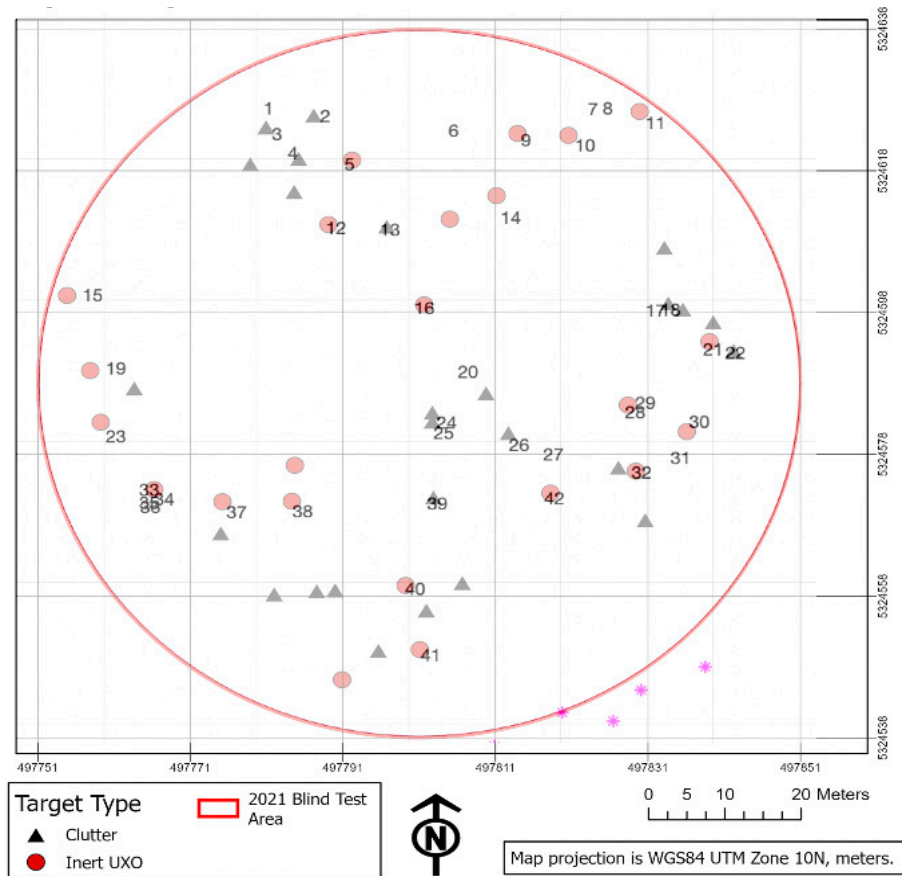


Figure 11. A blind Test Field View Combining a PNNL-supplied Symbol Set and Numbers Indicating MuST Detection Locations

7.3 OBJECTIVE: PRODUCTION RATE

On average, a complete set of survey lines at one approach angle were carried out each day.

7.4 COMMENTS ON PERFORMANCE

The performance objectives table (Table 1) has been augmented in Table 3 with a performance achieved column. The “Detection of all munitions of interest” performance when viewed from the official scoring standpoint (eBOSS only results) is 0.78 (18/23), lower than the objective of 0.94. As noted above, if 60 mm UXO are treated as unresolvable for MuST, as operated during this test, the number of false negatives are reduced to 3 and the performance is 0.86 (18/21). As in table 2, the objective for including this second performance value is simply to allow further insight into possible performance limits in an operational system.

The geolocation performance (87.5% of seed items with differences of 2 meters or less) is very close to the performance goal. The larger errors of the 4 outliers quite possibly are not the result of inherent MuST geolocation error but due to other factors as discussed above.

The production rate objective was met during the operations.

Table 3. Performance Objectives and Performance Achieved

Performance Objective	Metric	Data Required	Success Criteria	Performance Achieved*
Detection of all munitions of interest	Percent of seeded UXO detected/correctly classified (Pc)	Location of seeded items	Pc > 0.94 No. False Alarms within blind test area < 5	Pc=0.78 (18/23) (eBOSS only) Pc=0.86 (18/21) (ignoring 60 mm UXO) 9 False Alarms (eBOSS only) 5 False Alarms (eBOSS + sidescan)
Location Accuracy	Difference between PNNL groundtruth and APL estimate of Geolocation	Location of seed items from MCRL to within 0.25 m Estimated locations from analysis of MuST data	Geolocation to within 2 meters for 90% of the TOIs	28 out of 32 87.5%
Production Rate	Number of approach angles completed each day	Log of field work	Completion of all survey lines at each approach angle each day	Completed all survey lines at each approach angle each day

*See text for details

8.0 COST ASSESSMENT

8.1 COST MODEL

Table 4. MuST Cost Model – Sequim 2021 Demonstration

Cost Element	Data Tracked During Demonstration	Estimated Costs
Instrument cost	NRE to develop MuST and equipment purchases	\$2,300,000.00
Instrument setup costs	Dock-side mobilization and de-mobilization	3 days \$7,000.00/day
System Operation Tests	Lake Washington testing	2 days \$ 20,000.00/day 6 personnel 1 survey ship
Survey costs	Day rate for MuST operations – including high altitude reconnaissance to assess in-water hazards, placement of calibration line, and detailed survey of area	\$ 20,000.00/day 6 personnel 1 survey ship
Detection data processing costs	Postprocessing to develop Mosaic	1 person 1 month \$40,000.00/month/person
Discrimination data processing	Re-train classifiers using calibration line data, classification using Mosaic	1 person 2 months \$40,000.00/month/person
ONE TIME Training costs: Operations	Towbody operations, the ship-board processing stations, surveying considerations	1 week 2 people \$ 10,000.00/week/person
ONE TIME Training costs: Classification	Transferring the ability to develop a Mosaic, training and/or using the classifier	2 weeks 2 people \$10,000.00/week/person

Instrument Cost - NRE to develop MuST and equipment purchases

Reference 1 details the initial design and cost of MuST. Equipment costs (\$1100k) were higher than quoted in the design study by about \$100k due to the need to buy a higher quality INS unit. Also, the cost quoted does not include the multibeam that was recently added. The multibeam would add another \$300 k to the cost. To build a second MuST would cost approximately \$2300k, part of this cost is some NRE based on lessons learned in the first MuST development – that is the number quoted in Table 3. A third unit should be possible for less than \$2000k (in FY22 dollars) as the NRE costs are further reduced.

Instrument Setup Costs - Dock-side mobilization and de-mobilization

Typically, mobilization of MuST requires 2 to 3 days of dock-side testing on the APL ship. This cost would probably increase for remote deployment on a boat of opportunity. Perhaps as high as 5 days at 10k/day for initial operation on a hired ship.

System Operation Tests - Lake Washington testing

Once dock-side testing is successful we move to Lake Washington to make sure all MuST systems are operational. This involves the entire crew (6 people) typically used to operate MuST, examine data in real time, and set navigation survey lines. This cost also includes the day rate cost of our ship (\$ 4500.00). Thus, the full day cost is the same as when the demonstration was carried out.

Survey Costs - Day rate for MuST operations

Survey cost includes time for high altitude reconnaissance to assess in-water hazards (typically we find the reconnaissance effort to be at least 5 times faster than detailed surveying), placement of calibration line (we believe this can be done in less than 30 minutes – it is our opinion that, once deployed, this line is best left for the duration of the survey with a flyby each morning), and follow-on detailed survey of area.

As noted in the “System Operation Tests” section above, day rate for operation involves the entire crew (6 people) typically used to operate MuST, examine data in real time, and set navigation survey lines. This cost includes the day rate cost of our ship (\$ 4500.00).

In an operational scenario the cost of a ship might be higher but some of the crew of a survey ship would typically have the expertise to assist in MuST operation so the survey company could need fewer MuST specific personnel. We would anticipate the day rate cost would be within 20% of the day rate costs quoted for APL operation.

Detection Data Processing Costs - Postprocessing to develop Mosaic

The cost of developing the mosaic for detection will probably go down as a regimented process is developed. There has been a lot of “learning on the fly” so far.

Discrimination Data Processing Costs - Re-train classifiers using calibration line data, classification using Mosaic

As in the detection processing, there has been a steep learning curve as we have developed classifiers. There could be significant reduction in time here. Note also, that we have developed processing to the point that some of the classification effort occurs on-board during the survey. This is not viewed as definitive but allows significant insight on an ongoing basis for both real time operation of MuST and postprocessing.

ONE TIME Training costs: Operations

Typical surveying company staff are already well trained on the operations of various acoustic and non-acoustical surveying hardware. Thus, a majority of the training can occur during an actual surveying effort. An initial training session to present the specific considerations for operation of the towbody, the ship-board processing stations, and surveying considerations should suffice.

ONE TIME Training costs: Classification

Transferring the ability to develop a Mosaic as well as further train and use the classifiers is obviously essential. At this point all of this code is Matlab based so the surveying company will need someone with a Matlab background. Assuming Matlab expertise, we consider walking surveying staff through the details of the code design and operation to be straight forward.

8.2 COST DRIVERS

MuST is not an off-the-shelf technology that can be purchased and immediately operated by survey companies. There is significant training required. After that training, however, MuST is no more complicated to operate than other sonar system platforms. The purchase cost of a MuST will be a barrier for smaller survey companies.

A path forward where APL builds two more MuST systems for ESTCP (total cost around \$4300k to build two more systems as discussed above) and companies lease those systems, are trained by APL, and then carry out surveys at a specified day rate would seem a viable way forward.

8.3 COST BENEFIT

The primary cost benefit of MuST is centered on its area coverage rate as compared to other sensing modalities (e.g., EMI, Magnetics). We have recently carried out a survey of 1 km² for the Navy using MuST. We modified operations such that we could cover the area in 12 hours. The modification was simply to fly at 10 m above the bottom to increase area coverage rate. This degraded pixel resolution by a factor of two but the targets involved were much larger than inert munitions. The ability to alter area coverage rate (MuST height above bottom) while retaining the ability to detect objects (i.e., have sufficient signal to noise) is a flexibility that is unique to underwater acoustics. In addition, the ability to operate well off the bottom reduces risk to the system as a whole.

9.0 IMPLEMENTATION ISSUES

MuST was built by integrating COTS technology. As such, equipment costs and availability are well defined and will vary according to market forces. However, operational costs are significant (as with any high-tech marine system and associated ship support).

Use of underwater acoustics will always be subject to environmental assessment. However, the source levels of eBOSS are low (about 180 dB/re a μPa). The other acoustic systems on MuST operate above 200 kHz. PNNL was able to use these facts to reduce operational restrictions. PNNL could best speak to the environmental assessment overhead.

MuST is not an off-the-shelf technology that can be purchased and immediately operated by survey companies. There is significant training required. After that training, however, MuST is no more complicated to operate than other sonar system platforms. The purchase cost of a MuST will be a barrier for smaller survey companies.

10.0 REFERENCES

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APPENDIX A POINTS OF CONTACT

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