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PNNL-30930

Sequim Bay Underwater UXO Prototype Demonstration Site: Field Operations Summary, 2020

April 2021

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U.S. DEPARTMENT OF ENERGY

Prepared for the U.S. Department of Defense, Strategic Environmental Research and Development Program under Contract W74RDV83044655

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Richland, Washington 99354

Summary

This report provides a summary of Pacific Northwest National Laboratory's (PNNL's) activities to initiate Phase II development of the Sequim Bay Underwater UXO Prototype demonstration site (MR-2735) in 2020. Testbed development and field operations were conducted by PNNL's Coastal and Marine Research Laboratory (MCRL) in support of the Strategic Environmental Research and Development Program (SERDP) and Environmental Security Technology Certification Program (ESTCP) underwater Munitions Response (MR) program. A series of standardized underwater unexploded ordnance (UXO) demonstration sites ("testbeds") are being developed by SERDP/ESTCP to test, evaluate, and demonstrate technologies that can detect, geolocate, and classify proud and buried munitions in 0–35 m water depths. As a prototype demonstration site, Sequim Bay is a semi-enclosed marine waterbody containing sand and mud sediments with minimal clutter in 5–30 m water depths. MCRL is located at the entrance to Sequim Bay, where it provides operational, logistical, and facilities support for testbed activities.

The primary objectives of Phase II were to (1) establish a calibration and blind site grid at the Sequim Bay testbed, including placement and retrieval of 30 targets in 25–30 m water depths in sand/mud sediments; (2) provide operational support to the Applied Physics Laboratory – University of Washington (APL-UW) for an engineering field test of their acoustic sensor platform; (3) evaluate target geolocation systems to support accurate placement of targets; and (4) support collection of target ground truth information for scoring protocol development by the MR program. Phase II was accomplished by building on lessons learned from Phase I in 2019, and focused on developing cost-effective, safe, and technically sound approaches that can inform future operations of the Sequim Bay testbed and other underwater demonstration sites.

A calibration (sandy) site and a blind (sandy/muddy) site were chosen in close proximity to each other in Sequim Bay for the 2020 work. The area selected encompassed the 2019 sandy site location and expanded into the mud substrate as well. An existing 5-year MCRL Scientific Research Plan and associated permits for conducting research in Sequim Bay were used to secure authorizations for testbed activities in the bay. Authorizations received between January and September 2020 allowed for the conduct of a variety of testbed activities, including target placement and burial, target retrieval, operation of the APL-UW acoustic sensor platform, and operation of acoustic geolocation and diver navigation equipment.

MCRL provided a demonstration testbed and operational support to APL-UW, a remediation system developer of the Multi-sensor TowBody (MuST) (MR18-5004). APL-UW conducted an engineering field test during fiscal year (FY) 2019 and returned in FY 2020 for further testing in Sequim Bay with the MuST to advance the development of algorithms that detect/classify targets placed on the surface (proud) and buried in the sediment. A total of 30 targets (16 inert UXO, 3 replica munitions, 8 clutter objects, and 3 science targets) were placed at the calibration and blind sites (15 targets at each site) in water of approximately 20–25 m depths. The calibration site targets were placed in an offset linear pattern along a 70 m line by MCRL divers in July 2020. Five UXOs/replicas were buried flush in the sediment at the calibration site. The blind site targets were placed proud in 4 clusters in a 100 x 100 m test grid. Targets were tethered together at each site. The identifications and positions of the targets at the calibration site were known to APL-UW, but only the number of targets was known to APL-UW at the blind site. Additional information about the types of targets and specific locations was not known to them until the independent scoring team had completed their work. The engineering test was conducted in September 2020 by the APL-UW crew operating from their research vessel, *R/V*

Jack Robertson. MCRL provided additional shore support and logistical support as needed. All targets were retrieved from Sequim Bay by MCRL divers in October/November 2020.

As part of the development of the Sequim Bay test bed, three different technologies were evaluated for target geolocation ground truthing over the course of the field season. The first, an inverted long baseline system (iLBL), was deployed for performance evaluation on a limited set of targets. After several hardware failures it was determined the particular commercial iLBL in use was not a viable system for use in the testbed this year. A second acoustic technology, an ultra-short baseline (USBL) system was operated over several weeks in October for ground truth positions of all 30 targets in the testbed. Lastly, a third geolocation system consisting of a Global Navigation Satellite System (GNSS) antenna and receiver housed in a surface buoy and tethered to divers was also used for geolocation of all 30 targets in both September and October. Mean values of the spatial differences in the target geolocation positions from the USBL and two GNSS surface buoy surveys were on the order of 1 m. The use of RTK-GPS input for the USBL system will be implemented in the future for increased performance in target geolocation accuracy.

Overall, the FY 2020 testbed field operations were successful in Sequim Bay. The primary challenge this year was related to COVID-19 events. Risk mitigation protocols were developed and implemented by both PNNL-MCRL and APL-UW allowing for the continuation of field activities. Although several tasks were delayed, including acquisition of leased target geolocation equipment, all planned activities were completed by the end of the field season.

Acknowledgments

We would like to thank David Bradley, Mike Richardson and Herb Nelson for guidance and support from the SERDP/ESTCP program office throughout this project. We also thank Shelley Cazares, Mike Tuley, and Jacob Bartel with the Institute for Defense Analyses for insightful conversations related to target layout, target geolocation and scoring. Gene Fabian provided support for acquiring inert UXO. Collaboration with the APL-UW MuST project team led by Kevin Williams was critical to successful 2020 field operations. We would also like to thank Joe Calantoni and Carter DuVal of NRL for object mobility modeling specific to Sequim Bay. Additional support was provided by PNNL staff including Nikki Sather, Garrett Staines, Mike Sackschewsky, Kris Hand and Ioana Bociu (permitting), Kailan Mackereth and Noelani Boise (marine mammal observations), and Kate Buenau and Susan Ennor (report review and editing).

Acronyms and Abbreviations

AAE	Applied Acoustics Engineering Ltd.
ADCP	Acoustic Doppler Current Profiler
AGR	Acoustic GPS Receiver
APL	Applied Physics Laboratory
DDU	Diver Display Unit
DoD	Department of Defense
DOE	U.S. Department of Energy
EMI	electromagnetic induction
ESTCP	Environmental Security Technology Certification Program
FY	fiscal year
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
HEAT	high-explosive anti-tank (projectile)
IDA	Institute for Defense Analyses
iLBL	inverted Long Baseline
MCRL	Marine and Coastal Research Laboratory
MMO	Marine Mammal Observer
MMPA	Marine Mammal Protection Act
MR	Munitions Response
MuST	Multi-Sensor Towbody
NEPA	National Environmental Policy Act
NRL	Naval Research Laboratory
PNNL	Pacific Northwest National Laboratory
PPK	post processed kinematic
RMSE	root mean square error
RTK	real-time kinematic
SCUBA	self-contained underwater breathing apparatus
SERDP	Strategic Environmental Research and Development Program
USBL	Ultra-short baseline
UW	University of Washington
UXO	unexploded ordnance

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1.0 Introduction

The U.S. Department of Defense (DoD) has identified more than 400 underwater sites in the U.S. that are potentially contaminated with munitions from past military testing exercises and need to be remediated. Many of these sites are in relatively shallow water (0–35 m deep) where the munitions pose a threat to human health and the environment. The Strategic Environmental Research and Development Program/Environmental Security Technology Certification Program (SERDP/ESTCP) Munitions Response (MR) program office is supporting the development and demonstration of innovative technologies that can characterize, remediate, and scientifically manage sites affected by military munitions, including technologies that can detect, characterize, and remediate military munitions at underwater sites.

To address this challenge, SERDP/ESTCP held a workshop in 2018 to establish the requirements, framework, protocols, responsibilities, and timelines for development of multiple underwater unexploded ordnance (UXO) standardized demonstration sites ("testbeds"). Multiple testbeds are currently in the initial phases of development and will ultimately be used to evaluate and formally demonstrate technologies including acoustic, magnetic, electromagnetic induction (EMI), and optical systems designed to detect and classify underwater UXO. The workshop recommended that development of testbeds capitalize on (1) lessons learned from existing DoD-funded projects, (2) leveraging existing underwater testbed environments funded by other programs, and (3) supporting iterative learning from early phases of the testbed development.

Sequim Bay in Washington State was evaluated as a potential testbed between 2016 and 2018. It met suitable criteria with respect to environmental setting and operational, logistical, and facilities support provided by the Pacific Northwest National Laboratory (PNNL). Sequim Bay encompasses 5–30 m deep waters, free of native UXO that feature muddy and sandy sediments. Based on the initial evaluation, MCRL proposed a three-phased approach that was implemented in 2019 to establish a Sequim Bay Underwater UXO testbed as part of the SERDP/ESTCP MR program. Phase I included the placement and retrieval of 20 targets in 20-25 m water depth, provided subsequent operational support for one remediation system developer, and captured lessons learned as part of the development of a prototype testbed. Phase II, documented in this report, developed more formal operating plans for a testbed and supported the design and implementation of a target calibration (sandy) site and blind (sandy/muddy) site layout with follow-on operational support for a remediation system developer. Phase III will expand on lessons learned from Phase II and develop plans for accommodating multiple system demonstrations.

Phase I development of the Sequim Bay testbed was completed during fiscal year (FY) 2019 (Woodruff et al. 2020). Phase II was implemented in FY 2020 by PNNL's Marine and Coastal Research Laboratory (MCRL), including the design and placement of targets at a calibration and blind site, evaluation of underwater target geolocation technologies, and provision of logistics support to the Applied Physics Laboratory – University of Washington (APL-UW) for an engineering field test of their Multi-Sensor Towbody (MuST) in Sequim Bay (MR18-5004).

This report provides a summary of the FY 2020 Phase II Sequim Bay Underwater UXO testbed development activities, including project planning, testbed operations, system developer testing, scoring protocol development, and lessons learned for application during future deployments.

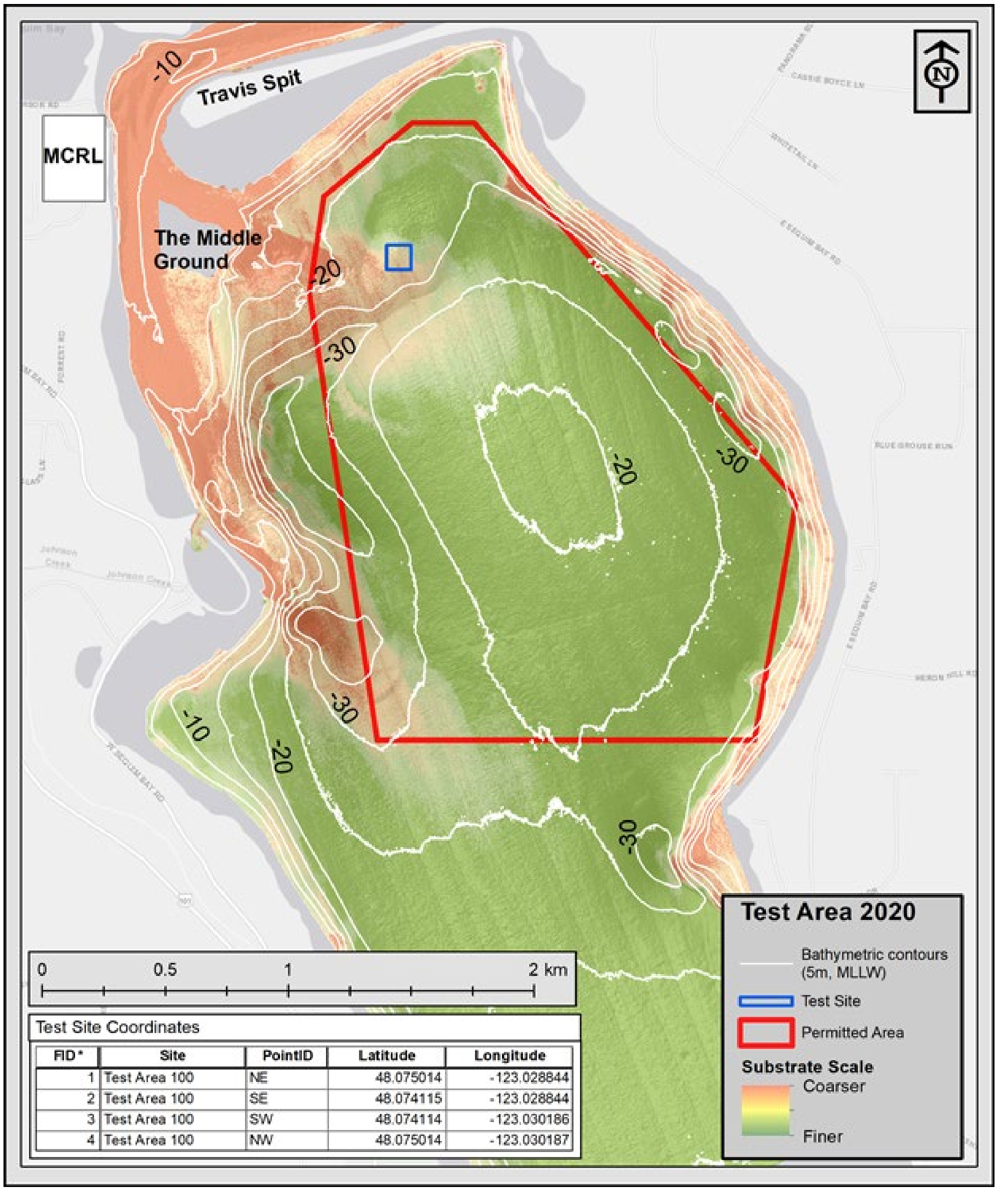
2.0 Project Overview

During Phase I in 2019, MCRL placed 20 targets in Sequim Bay and supported the operation of a remediation system developer (APL-UW) in conducting an engineering test of the MuST to develop algorithms for detection/classification of proud and buried UXO (MR18-5004). Phase I informed the design and next steps by capturing lessons learned (Woodruff et al. 2020), applied during 2020. Phase II tasks in FY2020 included (1) permitting a selected calibration and blind site; (2) acquiring, deploying, and retrieving inert UXO at the demonstration testbed; (3) evaluating geolocation and underwater navigation systems for accurate placement of targets; (4) providing logistics support for APL-UW's engineering test of the MuST; (5) collecting data for developing demonstration site scoring protocols; and (6) field operations reporting.

A test area was selected in Sequim Bay by MCRL with concurrence from the SERDP/ESTCP program office and the remediation system developer, APL_UW (Figure 1). This year's test location incorporated both a calibration site (a line 70 m in length) and a "practice" blind site (100 x 100 m box) (Figure 2). Both sites were located near last year's sandy site. Fifteen targets tethered to each other (science objects, inert and replica munitions, and clutter objects) were emplaced at the calibration site by MCRL divers in early September 2020. Five of these targets (inert munitions) were buried flush with the sediment surface. The numbers, types, and geolocation of the targets at the calibration site were known to APL-UW. Fifteen additional tethered targets were placed in four clusters on the surface at the blind site. The number and types of targets were known to APL-UW prior to their engineering test. The geolocation of the targets was not known until the results of target detection and classification were evaluated by an independent SERDP/ESTCP scoring team (Section 3.4). The engineering test was conducted in mid-September 2020 by the APL-UW team, operating the MuST towbody from their research vessel, *R/V Jack Robertson*. MCRL provided logistic support throughout the FY2020 season. After the completion of the MuST engineering test, all targets were retrieved from Sequim Bay by MCRL divers in October/November and were stored at MCRL for future deployments.

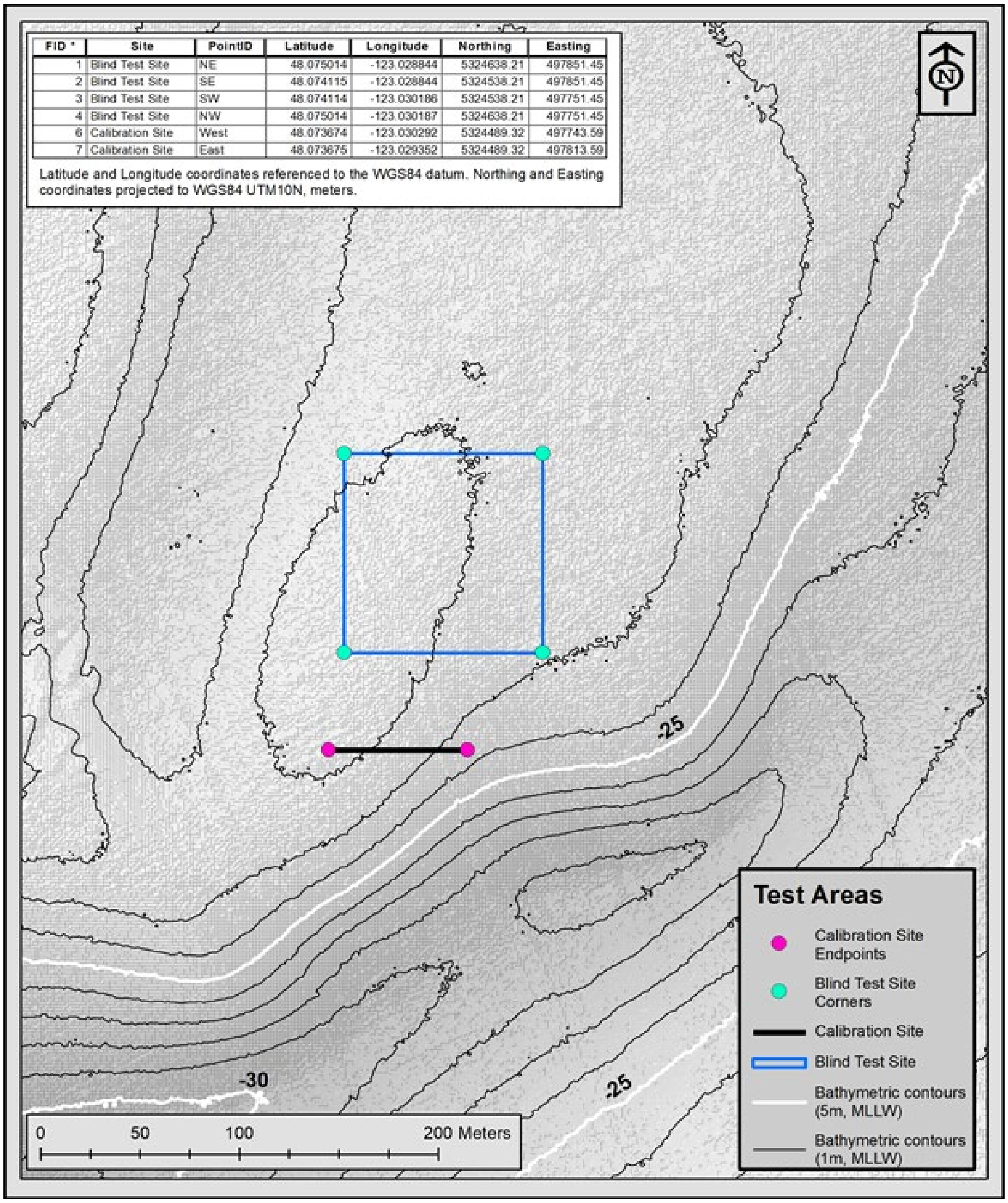
This year's work also involved the testing and comparison of three diver-assisted technologies for accurately geolocating targets on the seafloor. A surface Global Navigation Satellite System (GNSS) buoy tethered to a line held by divers on the seafloor was first tested in 2019. It was evaluated again in 2020 and the results were used for comparison with two additional systems—an ultra-short baseline (USBL) tracking system and an inverted long baseline (iLBL) system. Both systems rely on underwater acoustic transmission between surface Global Positioning System (GPS)-enabled transceivers and an underwater receiver held by divers. Divers compared these systems during project dives throughout the field season as permits and availability of equipment allowed.

As part of Phase II, MCRL worked closely this year with the scoring team to collect target emplacement information (e.g., geoposition, burial depth, orientation, and tilt) for the development of appropriate ground truth metrics by the scoring team. This is an important step in the future development of formally scored demonstrations.



FID*	Site	PointID	Latitude	Longitude
1	Test Area 100	NE	48.075014	-123.028844
2	Test Area 100	SE	48.074115	-123.028844
3	Test Area 100	SW	48.074114	-123.030186
4	Test Area 100	NW	48.075014	-123.030187

Figure 1. Location of the Sequim Bay Underwater Testbed (blue box) for the 2020 field season.



FID *	Site	PointID	Latitude	Longitude	Northing	Easting
1	Blind Test Site	NE	48.075014	-123.028844	5324638.21	497851.45
2	Blind Test Site	SE	48.074115	-123.028844	5324538.21	497851.45
3	Blind Test Site	SW	48.074114	-123.030186	5324538.21	497751.45
4	Blind Test Site	NW	48.075014	-123.030187	5324638.21	497751.45
6	Calibration Site	West	48.073674	-123.030292	5324489.32	497743.59
7	Calibration Site	East	48.073675	-123.029352	5324489.32	497813.59

Latitude and Longitude coordinates referenced to the WGS84 datum. Northing and Easting coordinates projected to WGS84 UTM10N, meters.

Figure 2. Location of the calibration site (black line) and blind site (blue box) in Sequim Bay for 2020.

3.0 Project Planning

Phase II project planning involved the development of an events timeline, associated target placement permitting, target acquisition and storage, and development of scoring criteria.

3.1 Timeline

The timeline of events for Phase II of the Sequim Bay testbed development and operation was similar to that for Phase I in 2019, but some tasks that required the acquisition of goods and services were delayed due to COVID-19. Planning and field operations are summarized in Table 1.

Table 1. Timeline of events for the Phase II prototype demonstration of the Sequim Bay testbed.

2020 Field Season	2019		2020												2021		
	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Mar
Planning																	
Scope/Target field design		■	■	■	■	■	■	■	■								
Permitting (APL-UW MuST)			■	■	■												
Permitting (Navigation/geolocation)						■	■	■	■	■	■						
Target selection/acquisition									■	■							
Scoring Criteria Development										■	■	■	■	■			
Field Operations																	
Preliminary field tests									■								
Finalize site selection									■								
USBL, Diver Nav. geolocation									■	■	■						
Target Placement											■						
MuST Engineering Test											■						
Test Bed Operations support											■						
Target Retrieval												■	■				
Field summary reporting														■	■	■	

Planning and scoping for Phase II began in late 2019 and incorporated lessons learned and the knowledge gained from the previous year's engineering test (Woodruff et al. 2020). The permitting process for placement of targets and the APL-UW's engineering test required less time than the previous year, primarily because the activities were similar and had been previously approved. The permitting process for demonstrating and testing several underwater navigation and geolocation systems required more time (April–September), in part due to the acoustic sources incorporated in the systems. An additional objective this year included providing support to the SERDP/ESTCP program office staff as they began to develop formalized scoring criteria for system developer's detection and location of underwater targets.

Preliminary field work (Section 4.1) and final site selection occurred in July 2020. Several underwater navigation and geolocation systems were also tested and compared between July and October 2020. MCRL divers emplaced all targets in early September, and the APL-UW engineering test occurred in mid-September. Divers retrieved all targets at the end of the field season in late October and early November 2020.

3.2 Permitting

An existing 5-year PNNL-MCRL Scientific Research Plan and associated permits related to the U.S. Department of Energy's (DOE's) marine research activities were used for the 2020 field season activities to the extent possible. The permits and authorizations included the following:

- National Environmental Protection Act (NEPA) – DOE Categorical Exclusion for Aquatic Research
- Section 106 National Historical Preservation Act, Cultural Resources Review – Washington State Historic Preservation Officer
- Endangered Species, Section 7 – U.S. Fish and Wildlife Service
- Endangered Species, Section 7 – National Marine Fisheries Service
- Essential Fish Habitat – National Marine Fisheries Service
- Marine Mammal Protection Act (MMPA) – National Marine Fisheries Service
- U.S. Army Corps of Engineers Individual Permit
- Hydraulic Project Approval – Washington State Department of Fish and Wildlife
- Coastal Zone Management Act – Washington Department of Ecology
- Clallam County Shoreline Exemption
- Aquatic Right of Entry License – Washington State Department of Natural Resources.

Under this Research Plan some SERDP-ESTCP testbed-related activities are allowed, including the placement of targets, survey grids, and diver-installed anchors, as well as the operation of the APL-UW MuST's Doppler Velocity Log sonar and side scan sonar within the physical boundaries of the permitted area (red polygon, Figure 1). Permission for operation of the MuST's sediment-penetrating sonar required additional monitoring of marine mammals based on the planned acoustic frequencies. Permitting concurrence/authorization for this year's APL-UW MuST activities were completed within a 3-month window (January–March 2020).

Permitting for the use of the iLBL system (DiveNET™) and a USBL system was completed within a 6-month timeframe (April through September 2020). Permit approval for the use of these active acoustic systems was based on calculations of isopleths of disturbance from the acoustic amplitudes, frequencies, and durations of system transmissions. These calculations were used to determine the operational interrogation rates allowed for the USBL system and the duration length of time during the day for which each of the systems could be operated (DiveNET™ was fixed in amplitude and transmission rate). The internal PNNL permit review team evaluated these acoustic impacts using existing permit criteria for acoustics in the testbed area. Concurrence/authorization for these activities were completed within a month for each new system as it was brought in for trials.

3.3 Target Acquisition and Storage

Targets used for the 2020 engineering test included inert UXO/replicas, science targets, and clutter objects (Section 4.2). Many of the targets from the 2019 PNNL-MCRL inventory were used again in 2020. To complete the target design layout for 2020 (30 objects), additional inert UXOs were acquired and transferred to PNNL from the U.S. Army Aberdeen Training Center in

August 2020. APL-UW and PNNL-MCRL selected the target types with final concurrence from the SERDP/ESTCP program office. In early September 2020, all targets were deployed at the calibration and blind sites by MCRL divers. All items were retrieved in the fall and are housed at MCRL in secured, covered storage facilities with appropriate tagging and paperwork.

3.4 Scoring Criteria Development

The design and implementation of a quantitative scoring process is a critical part of demonstrating the performance of technologies and systems used to detect and classify UXO underwater. Lessons learned from earlier terrestrial demonstrations can be leveraged to some extent, but the underwater environment presents unique and complex challenges that need to be resolved. The Institute of Defense Analyses (IDA) developed and implemented the scoring process for the SERDP/ESTCP terrestrial demonstrations in the 2000s and 2010s (Cazares et al. 2018). IDA and a scoring team are working in partnership with test site managers (including PNNL-MCRL team members) to develop appropriate protocols for scoring blind tests in underwater environments. As part of the Phase II development of the Sequim Bay testbed, PNNL worked closely with the scoring team to collect information for the development of appropriate ground truth metrics related to targets that will be needed to score blind site demonstrations in the future.

Some target information was collected during the conduct of an initial inventory (e.g., type, length, width, dimensions) (Section 4.1.4). The blind site demonstration this year offered allowed the divers to collect additional ground truth information during target emplacement and before retrieving targets from both the calibration and blind sites for further evaluation by the scoring team. Details are described in Section 4.2.2.1.

4.0 Testbed Operations

Testbed operations involved conducting preliminary field tasks and establishing target fields.

4.1 Preliminary Field Tasks

Preliminary field tasks included the selection of a blind site, assessment of target movement, target inventory and labeling, and associated diving support.

4.1.1 Blind Site Selection

Based on previous experience gained from 2019 field efforts working with challenging sediment conditions at the mud site (i.e., reduced visibility due to flocculent material), for the 2020 field efforts, MCRL divers identified a new area that had a more consolidated mud substrate for the 100 x 100 m blind site. In July 2020, MCRL divers visited two locations that had been identified by APL-UW MuST results in 2019 as potential sites. Unfortunately, these sites were also problematic because they featured extremely soft sediment or lacked enough operating space, given the turning radius of the *R/V Jack Robertson*, to tow the MuST. In August 2020, PNNL identified another potential blind site testbed area in Sequim Bay based on bathymetric data and knowledge of sediment characteristics in the area. Diver exploration of the area indicated that it contained a workable mud substrate and a depth similar to the 2019 sand site. It was located near the north end of the sand site and provided enough operating room for the vessel towing the MuST. After receiving concurrence from APL-UW, this became the blind site testing area for 2020 (Figure 2).

4.1.2 Target burial techniques

In July, the MCRL divers practiced burying an 81 mm mortar at the sandy calibration site to determine if use of a hand trowel would be an effective method for burying targets at that site. The divers placed the target on the seafloor and dug a trench between themselves and the mortar using a hand trowel. After placing the target in the hole, visibility was significantly reduced for up to 5 minutes by sediment resuspension after the diver covered the target with the loose sediment. No part of the mortar could be seen after visibility returned. The sediment was relatively easy to excavate, and the target hole did not cave in as sediment was removed. Although burying an 81 mm mortar was successful using this method, a larger projectile (e.g. 155 mm Howitzer) would require significantly more time and effort to bury. This approach was satisfactory for burial flush with the sediment surface, but deeper burial requirements in the future may require a different methodology.

4.1.3 Assessing Target Movement

During the 2019 field operations, several targets were observed to have moved to the opposite side of the calibration baseline or changed orientation between the target deployment in July 2019 and the engineering test in September 2019. Several approaches were used to determine the cause. The first approach was to assess the potential for movement based on current velocities and potential target mobility. In 2020, an Acoustic Doppler Current Profiler (ADCP – Nortek Signature 500) was deployed in the test bed area to collect current velocity data during the strong spring tidal cycle, July 2 – 10, 2020. PNNL shared this ADCP data, sediment characteristics, target descriptions (length, diameter, weight, photo), and a map of target movement from 2019 with Joe Calantoni and Carter DuVal of the Naval Research Laboratory (NRL) Stennis for object mobility modeling. Their results showed that certain types of targets might be susceptible to mobility when initially deployed. After several tidal cycles, these objects settle into the sediment, where mobility becomes much less likely. Based on these mobility modeling results, divers will nudge objects into the bottom during future deployment operations as appropriate, significantly reducing the potential for mobility.

The second approach involved placement of 2 clutter objects observed to have substantially moved and one UXO that re-oriented into the dominant current direction during the 2019 deployment. These objects were placed near the calibration site in 2020 with repeated diver visits to specifically look for target movement. Between July 6 and July 9, 2020, the three targets were deployed at this site along a 10m long north-south baseline that was secured at each end with a screw anchor. These targets included a hollow aluminum cylinder, a crab trap, and a 105 mm high-explosive anti-tank (HEAT) projectile.

A diver placed each target parallel to the baseline with its “nose” pointed north. Each target touched the baseline on its near side. Each target was equipped with a 3 m long tether. The tethers were coiled and placed underneath the target, allowing the target up to 3 m of movement. Each of the three targets was marked with tape on the upward-facing side. This tape was used as a standard measurement point to document movement of the targets over time. During each dive, the divers noted that the targets appeared to be where they had been originally placed next to the baseline. All target tape marks were facing up. The divers’ qualitative observations indicated that even during a period of large tidal exchange of up to 10.9 ft (resulting in stronger-than-normal bottom currents up to 1 m/s), the targets did not appear to substantially move. NRL modeling indicated mobility for the 105 mm HEAT UXO was unlikely and in agreement with these observations, while the probability of movement for the hollow cylinder was significantly more. A possible explanation for this could include the parameterization of the model where the current direction was broadside to the hollow cylinder, while in the field the hollow cylinder was placed nearly in line with the dominant current direction, significantly reducing the force required for rotational motion and movement.

4.1.4 Target Inventory and Labeling

Science targets, clutter, munitions, and replica munitions were inventoried and labeled before being deployed. A permanent record of the following information is kept for each target:

- type/nomenclature (e.g., 105 mm projectile, M60)
- origination before shipment to PNNL (e.g., Naval Research Laboratory [NRL], Army)
- current owner (e.g., PNNL, APL-UW)
- PNNL unique ID number (e.g., U013, C004)
- PNNL property tag number (internal tracking for inert munitions)
- serial number (if present from originator’s shipping manifest)
- category (i.e., UXO, Replica, Clutter, Science)
- length
- width
- diameter
- weight
- description (e.g., hollow, screw cap intact, general condition).

Before deployment, white marine paint was used to write “INERT” and the PNNL-specific number on targets owned by PNNL. The PNNL ID number was also painted or hand-written on the remaining targets using a black permanent marker. A label printed on waterproof paper that read, “Research Object – If found, please contact [name, phone number]” was attached to each clutter and science target. A waterproof paper label that read, "INERT – Research Object – If found, please contact [name, phone number]" was attached to inert UXO and replica munitions. These labels were attached using clear "Gorilla" tape and that showed little signs of wear throughout the duration of the 2020 deployment.

4.1.5 Diver Effort for Preliminary Work

Divers worked in teams of two for all diving efforts for safety and efficiency. Minimizing the number of people on the bottom reduced stirring up the sediment, which affected visibility at the sites.

The diving effort for the preliminary field work was completed in eight dives and is summarized in Table 2.

Table 2. Summary of dives conducted during the preliminary phase of 2020 fieldwork.

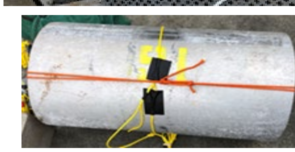
Date (2020)	Task	Max. Depth (ft)	Bottom Time (min)	Number (dives/day)
July 6	ADCP, deploy 3 targets	80	57	2
July 7	Geolocation technology trials (DiveNET™)	73	32	1
July 8	Geolocation technology trials (DiveNET™)	73	28	1
July 9	ADCP/target recovery	74	23	1
July 10	New Blind Site search	76	38	2
August 12	New Blind Site search	78	28	1
	Totals for Preliminary Work		**206**	**8**

4.2 Targets

The types of targets used in 2020 are shown in Table 3 and included inert UXO, a replica munition, clutter objects, and science targets. Deployment of the targets occurred September 2–16, 2020.

Table 3. Types of targets used for the FY 2020 engineering test in Sequim Bay.

Type	Description	Length (cm)	Width (cm)	Weight (kg)	Photo
Inert Munition	155 mm Howitzer replica	59	20	40.6	
	155 mm Howitzer M107	60	15.5	36.5	

Type	Description	Length (cm)	Width (cm)	Weight (kg)	Photo
	105 mm projectile, HEAT	65	9	10.9	
	105 mm projectile, M60	39	10	13.4	
	81 mm M889A mortar	26	8	2.9	
	crab trap	60	60	4.1	
	scuba tank	65	18	14.7	
Clutter	anchor	48	30	5.4	
	cement block	40	20	18.1	
Science	hollow aluminum cylinder	61	32	17.2	
	solid aluminum cylinder	61	31	126	

Similar to Phase I efforts in 2019, a tether was attached to all targets prior to their deployment to aid diver navigation and facilitate recovery. APL-UW researchers indicated the paracord and large quick-disconnect plastic buckle tether system used in 2019 was visible to the MuST towbody. To mitigate for this, the system was redesigned in 2020. All baselines, harnesses, and tethers were constructed of 1/8” (approximately 3 mm) Amsteel line. Loops were spliced to minimize profiles and where necessary, a small (1 3/8” x 1/2”) wooden toggle was used for the connections between baselines, tethers, and harnesses (Figure 3). While the toggles were intended to make connections easier for the divers, in poor visibility it was easier to tie the lines to the harnesses.

Figure 3. Wooden toggle button used to attach the tethers to the targets. A loop spliced into the end of the line was wrapped around the target and then "buttoned" onto the toggle.

4.2.1 Target Emplacement

Fifteen targets were placed at each site (30 targets total) (Table 4).

Table 4. Targets placed at the calibration and blind sites.

Type	Description	Blind Site (number of items)	Calibration Site (number of items)	Total number
Inert UXO	155 mm Howitzer M107	1	2	3
Inert UXO	105 mm projectile M60	3	2	5
Inert UXO	105 mm projectile HEAT	2	2	4
Inert UXO	81 mm mortar M889A	2	2	4
Replica	155 mm Howitzer	1	2	3
Clutter	SCUBA tank	1	1	2
Clutter	Crab pot	1	1	2
Clutter	Anchor	1	1	2
Clutter	Cement block	1	1	2
Science	Solid cylinder	1	1	2
Science	Hollow cylinder	1	0	1
	Total number of objects	**15**	**15**	**30**

The specific target layouts for each site are described in Sections 4.2.1.1 and 4.2.1.2. Prior to each dive mission, a set of targets for each site was identified and loaded on the deployment vessel. The targets were deployed by attaching them individually or in a bag to a downline with carabiners and then allowing them to freefall to the seafloor. Divers descended the downline and placed targets in their planned positions. The divers recorded the unique PNNL-identifier and target layout location for each target as they were placed in position on the seafloor.

4.2.1.1 Calibration Site

The calibration site was designed to have a layout similar to the one used in 2019. A 70 m long baseline consisting of 1/8” Amsteel line was laid down in an east-west configuration anchored at each end by one of the larger targets. The remaining targets were placed along the baseline at 5 m intervals, alternately offset to each side of the baseline with 2 m tethers. A summary of targets used and placement configuration is shown in Figure 4.

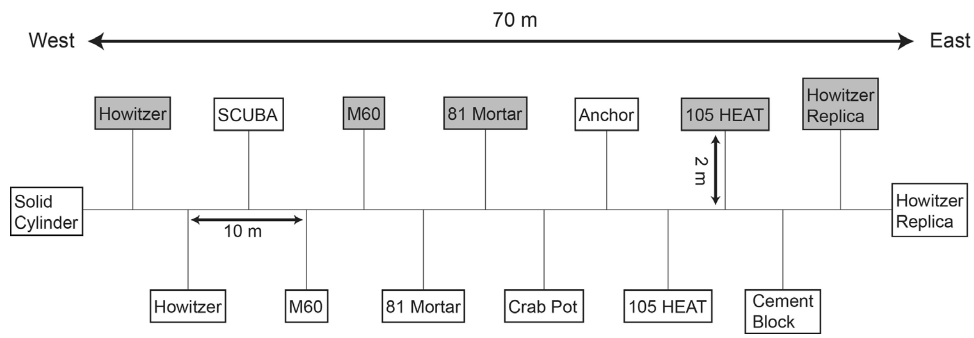


Figure 4. Layout of the targets at the calibration site. Targets shaded gray were buried flush with the sediment surface. Targets shown in white were placed proud on the surface. Numbers indicate the distance along the baseline.

For each target that did not have a connection point for a tether (e.g., a hole, a transfer ring, the mesh of the crab trap, etc.), a harness (e.g., Figure 5) was attached for easier handling of the target and a tether connection point. The tethers were spliced onto the baseline to prevent sliding and to maintain their position along the baseline. Each of these tethered junctions was marked with a coded hose washer so the divers could identify their position along the baseline by touch when working in low visibility conditions.

Figure 5. Examples of harnesses placed on a 81 mm mortar (left) and a 105 mm HEAT projectile (right).

At the calibration site, the baseline was deployed first as a reference for the remaining targets, and it was anchored by the solid aluminum cylinder on the western end and Howitzer replica on the eastern end. Uplines with surface buoys were attached to either end of the calibration baseline during the target deployment operations to facilitate the divers' locating the baseline and deploying targets in planned positions.

The targets were deployed from the surface vessel by dropping them to the seafloor along the surface buoy downlines. Divers then moved them into position along the baseline for attachment to a tether. Five inert munitions on the northern side of the baseline were buried flush with the sediment surface (Figure 4). All other targets were emplaced proud on the seafloor. After the last target was deployed and all measurements were recorded, the uplines were removed to eliminate entanglement hazards.

4.2.1.2 Blind Site

The blind site was designed to provide a more random and haphazard pattern of target deployment for the APL-UW engineering test. Four clusters of targets were dispersed throughout the site (Figure 6). Each cluster was oriented around a central target with tethers attached radially to the other targets in the cluster. All UXO targets were deployed at least 9 m apart to avoid detection overlap during the engineering test, although some clutter objects were placed closer to the UXO.

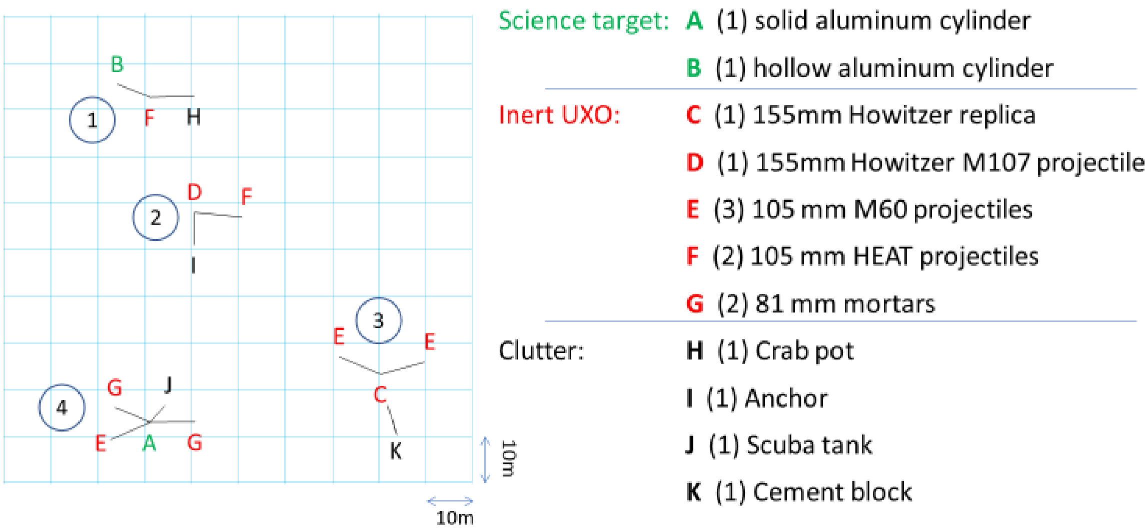


Figure 6. Blind site design showing the approximate locations of the 15 targets in the 100 x 100 m blind test grid. Circled numbers indicate the cluster number. The list on the right provides the target key and the number of each target type in parentheses ( ).

Targets and lines were prepared prior to their deployment similar to the calibration site (Figure 7). Harnesses were attached to the targets when needed, and tethers were connected to the radially placed targets on the outer edge of each cluster.

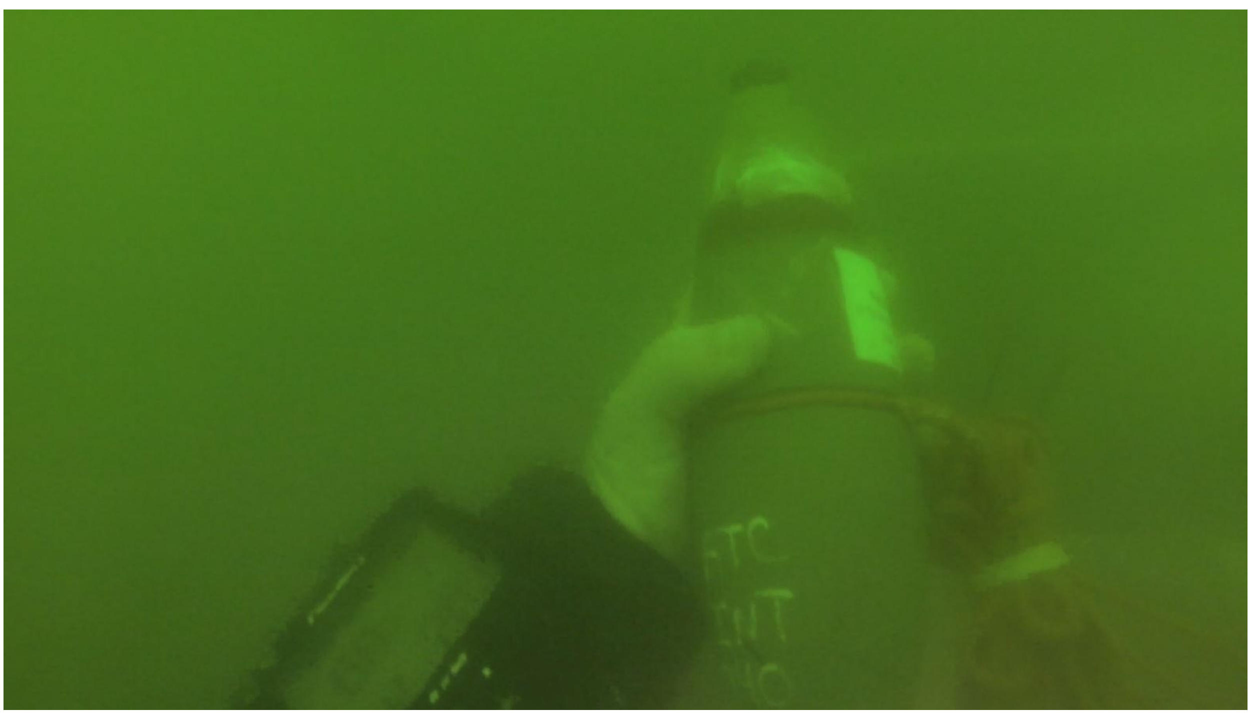


Figure 7. Diver preparing to deploy a 81 mm mortar at the Blind Site. Note the tether is attached to the target and bundled with a rubber band (lower right).

The deployment of blind site targets was performed one cluster at a time during individual dives. The targets for a cluster were dropped from the support vessel down an upline to the center position of the cluster. The divers descended the upline to the target bundles on the seafloor and placed individual targets in a pre-determined radial pattern for each cluster. All targets at the blind site were deployed proud on the substrate, and the descriptive ground truth information for targets (e.g. orientation, tilt, burial depth) was measured and recorded. The divers attempted to push the tether lines into the soft substrate to avoid later detection by the MuST. Once all the targets were deployed, the upline to the center of the cluster was removed to avoid entanglement.

4.2.1.3 Diver Effort for Target Deployments

The divers performed 11 dives between September 2 and 16, 2020, to deploy targets in the calibration and blind sites and collect the first geolocation positions for each target. A summary of the dives can be found in Table 5. During dive deployment and recovery operations, the divers communicated directly with the surface vessel crew via an Ocean Technology Systems© wireless communication system (Aquacom STX-101 surface deck box and SSB-2010 transceivers; www.oceantechnologysystems.com). Divers also recorded video of targets *in situ* with a GoPro camera in an underwater housing (gopro.com/en/us/).

Table 5. Summary of dives conducted during target deployment during 2020 field operations.

Date (2020)	Task	Max. Depth (ft)	Bottom Time (min)	Number (Dives/day)
September 2	Calibration Site baseline install	77	30	1
September 3	Target deployment	80	66	2
September 4	Target deployment and burial	78	34	1
September 8	Target burial	80	29	1
September 9	Target geolocation (surface buoy)	81	63	2
September 10	Target deployment and geolocation	79	30	1
September 11	Target deployment and geolocation	77	58	2
September 16	Target deployment and geolocation	70	31	1
	Totals for Target Deployments		**341**	**11**

4.2.2 Target Recovery

The recovery of the targets was conducted in two phases. In the first phase, a series of dives was conducted to collect descriptive data from each target to inform the scoring process (Section 4.2.2.1). This included collection of geolocation information from each target, as described in Section 4.2.3, and information related to burial depth, orientation, and tilt. The second phase included the recovery of the targets, baselines, and tethers from each site (Section 4.2.2.2)

4.2.2.1 Target Ground Truth Information Acquisition

A full suite of ground truth data and descriptive information was recorded for each target during retrieval operations. A subset of information was documented earlier during target placement. The information collected included the following:

- the relative position of each target along the baseline at the calibration site or cluster grouping at the blind site
- target type
- unique PNNL identification number
- the coordinates of the fiducial point of each emplaced target in Universal Transverse Mercator UTM units to 2 decimal points, and latitude/longitude (WGS 84) to 7 decimal points
- the burial depth of each target to the top center (within 5 cm)
- the azimuth (orientation) of each target (within 10°, magnetic north)
- the inclination (tilt) of each target (within 5° from horizontal)
- other diver observations (e.g., biofouling, tether status—taut, loose, disconnected)

Ground truth information collected for the calibration site and blind site is shown in Table 6 (a) and (b).

Table 6. Ground truth information collected by divers during recovery of targets from (a) the calibration site, and (b) the blind site.

(a)

Date	PNNL ID	Target Type	Description	Target Emplacement	Burial Depth[(a)]	Diver Compass Orientation (deg magnetic)	Tilt (deg)
10/23/2020	R003	Replica	Howitzer Replica	proud		300	0-5
10/23/2020	R002	Replica	Howitzer Replica	flush burial	< 1 cm	180	0-5
10/23/2020	C008	Clutter	Cement Block	proud		250	0-5
10/23/2020	U016	UXO	105 mm HEAT	flush burial	1-2 cm	260	0-5
10/23/2020	U018	UXO	105 mm HEAT	proud		150	0-5
10/23/2020	S001	Science	Solid cylinder	proud		330	0-5

10/23/2020	U002	UXO	155 mm Howitzer	flush burial	< 1 cm	250	0-5
10/23/2020	U001	UXO	155 mm Howitzer	proud		70	0-5
10/23/2020	C005	Clutter	SCUBA tank	proud		30	0-5
10/23/2020	U010	UXO	105 mm M60	proud		60	0-5
10/23/2020	U009	UXO	105 mm M60	flush burial	1 cm	40	0-5
10/23/2020	U019	UXO	81 mm mortar	proud		220	0-5
10/23/2020	U020	UXO	81 mm mortar	flush burial	1 cm	260	0-5
10/23/2020	C001	Clutter	Crab trap	proud		60	0-5
10/23/2020	C003	Clutter	Anchor	proud		320	25

(b)

Date	PNNL ID	Target Type	Description	Target Emplacement	Burial Depth[(a)]	Diver Compass Orientation (deg magnetic)	Tilt (deg)
10/20/2020	U013	UXO	105 mm HEAT	partial burial	nose buried	240	0-5
10/20/2020	C002	clutter	crab trap	proud		270	0-5
10/20/2020	S004	Science	Hollow Cylinder	proud		140	0-5
10/20/2020	U012	UXO	155 mm Howitzer	proud	nose slightly buried	230	0-5
10/20/2020	U014	UXO	105 mm HEAT	partial burial	1/2 buried along length	280	0-5
10/20/2020	C004	clutter	Anchor	partial burial	flukes buried	50	25
10/21/2020	R001	Replica	Howitzer Replica	proud		310	0-5
10/21/2020	U011	UXO	105 mm M60	partial burial	<1/2 buried	325	0-5
10/21/2020	C007	clutter	Cement Block	proud		170	0-5
10/21/2020	U007	UXO	105 mm M60	partial burial	3/4 buried	60	0-5
10/20/2020	S002	Science	Solid cylinder	proud		330	0-5
10/19/2020	C006	Clutter	scuba tank	proud		90	0-5
10/19/2020	U015**	UXO	81 mm mortar	proud		350	0-5
10/20/2020	U008	UXO	105 mm M60	partial burial	1/2 buried	10	0-5
10/20/2020	U017	UXO	81 mm mortar	partial burial	1/4 buried	270	0-5

The methods used by the divers to collect ground truth data during target retrieval required proficiency and teamwork. One diver approached a target, usually following the tether, swimming slowly while staying off the bottom to minimize resuspension of sediments and subsequent reduction of visibility. The second diver stayed at a distance. This allowed one diver to get an initial visual assessment of the site, verify the position on the baseline, identify the target (if not buried), relay information to the surface vessel about the target site and status, and plan a course of action to collect the remaining data. The data collection process differed depending on whether the target was proud or buried.

Proud Targets. If a target was visible, divers would estimate the extent to which the target had become buried in the sediment (e.g., one quarter, one half) and obtain a bearing/azimuth measurement of the target using an underwater dive compass. For orientation bearing/azimuth measurements, the divers would align their body over the target and place an underwater dive compass (i.e., Trident SCUBA compass) in line with the target orientation. Care was taken to not get too close to ferrous targets that might affect the compass reading. The underwater compass could be read to the nearest 5˚ (magnetic). Orientation was determined by the "nose" of the object if the shape allowed (e.g., the point of the UXO, the neck of the SCUBA tank, the flukes on the anchor) and orientation was parallel to the longest straight edge on non-directional targets (e.g., the cement block and the crab trap). In the latter cases, a benchmark such as the "do not disturb label" was used when possible to help describe the orientation. The divers used a dual-scale inclinometer (i.e., Rieker Inc. Model #2145-05-B, Figure 8) to determine the tilt/pitch of targets. This inclinometer has two fluid-filled tube and ball gauges, one scaled to ± 45˚ in 5˚ increments and a finer-scale gauge ±5˚ in 1˚ increments. For pitch measurements, the divers placed the inclinometer approximately halfway along the centerline of a target and as close to the overall incline of the object, accounting for curved sides of smaller UXO (e.g., 81 mm mortar).

Buried Targets. Buried targets were located by the divers by locating where a tether entered the substrate. The divers would gently probe the substrate with a finger or dive knife near the tether entry point to determine the target orientation while minimizing sediment disturbance. The divers would then create a shallow trench along the long axis of the target with a finger in order to place a ruler marked with 1 cm increments to measure burial depth. The divers then measured the pitch/tilt of the target using the inclinometer. Target bearing was also measured using the compass. These methods were similar to those used for proud targets, but there was increased uncertainty in these measurements because of a lack of visual confirmation of the buried target shapes. It should also be noted that the methods used for the buried target measurements were possible because of the shallow burial depth.

Figure 8. Inclinometer used to determine the pitch of the targets while on the bottom of Sequim Bay. Photo on the right shows the inclinometer being used on an 81 mm mortar during retrieval.

The geolocation of all the targets prior to their retrieval using diver-assisted methods is described below in Section 4.2.3.

4.2.2.2 Retrieval of the Targets

After the APL-UW engineering test and subsequent target data were collected, efforts focused on recovering the targets, baseline, and tethers from both sites. Uplines with surface buoys were deployed at both sites for diver reference to the target fields and to facilitate recoveries of the targets and lines by the surface vessel.

Targets were raised to the surface one at a time by the surface vessel; smaller targets were brought to a central location underwater and bundled together for retrieval. The divers brought down lifting lines in SCUBA catch bags to which a messenger float was attached to the surface-bound end and carabiners on the deep end. After locating a target on the seafloor, the divers would release the messenger float to the surface and attach the other end of the lifting line to the target for recovery. Several targets could be readied for retrieval with a messenger float and lifting line by the divers during each dive. The support vessel could then locate the messenger floats on the surface and recover the attached targets. The tethers and baseline were left attached to targets and removed with the lift lines, thereby ensuring that nothing was left on the sea floor at the end of the field season.

4.2.2.3 Diver Effort for Geolocation, Ground Truth Collection, and Recovery of Targets

Target geolocation and ground truth collection were completed in 10 dives during the first phase of target recovery between October 1 and 23, 2020 (Table 7). The retrieval of the targets was completed in seven dives between October 26 and November 6, 2020.

Table 7. Summary of dives conducted during the recovery phase of the project.

Date (2020)	Task	Max. Depth (ft)	Bottom Time (min)	Number (dives/day)
Target geopositioning and ground truth				
October 1	USBL system trial	81	31	1
October 6	iLBL system trial	80	25	1
October 8	USBL + surface GNSS positioning	82	64	2
October 9	iLBL system trial	81	20	1
October 19	USBL + surface GNSS positioning & target data measurements	77	31	1
October 20	USBL + surface GNSS positioning & target data measurements	77	52	2
October 21	USBL + surface GNSS positioning & target data measurements	81	29	1
October 23	Target data measurements	82	27	1
	Totals Target Geopositioning and ground truth		**279**	**10**
Target Recovery				
October 26	Target recovery	78	27	1
October 27	Target recovery	81	26	1
October 29	Target recovery	83	27	1
November 2	Target recovery	76	27	1

November 3	Target recovery	80	22	1
November 6	Target recovery	79	33	2
	Totals Target Recovery		**162**	**7**

4.2.3 Target Geolocation

Three diver-assisted methods and technologies were trialed and compared for seafloor target geolocation during the 2020 field season. The first approach was used in 2019 and consisted of a surface GNSS system on a buoy tethered to a line held by divers on the seafloor targets. The other two methods relied on underwater acoustic transmission between surface GPS-enabled transceivers and an underwater receiver held by divers over the seafloor targets.

4.2.3.1 Surface Global Navigation Satellite System

In both 2019 and 2020, target geolocation was conducted using a Trimble Zephyr 3 GNSS antenna and Trimble Geo7x data logger housed in a small buoy floating at the surface. During survey operations, a surface GNSS buoy tether was held by a diver near the seafloor and when in position over the fiducial point of a target (e.g., the nose of pointed UXO), the diver would take up any slack in the line and, using the diver underwater communication system, alert the supporting surface vessel they were in position. The surface support then commenced a 2-minute dwell period over the target, while the GNSS system sampled at 1 Hz. At the end of the 2 minutes, the surface vessel notified the diver to proceed to the next target. At the depths of both the calibration and blind sites (20–25 m), bottom time was a limiting factor; roughly 7–8 targets were surveyed by an individual diver during each survey operation. To overcome this limitation, two identical GNSS buoy systems were deployed at the calibration site during the GNSS surface buoy surveys, one per diver. The surface vessel coordinated simultaneous dwell times for the divers through the wireless, underwater communication system to survey different targets along the calibration line. Due to diver safety considerations, this technique was only used at the calibration site where the close proximity of the targets allowed the divers to maintain a close distance to each other for potential safety support. The GNSS surface buoy surveys of the targets were conducted in both September and October for system comparison over time and for comparison with other geolocation systems.

Upon recovery of the targets, the raw GNSS buoy data were differentially corrected with nearby base station data and time trimmed according to the dwell periods over the fiducial points of the targets. A mean position for each target was calculated from the reduced point cloud and a root mean square error statistic was produced describing the spatial variability in the points about the mean as a measure of precision.

4.2.3.2 Ultra-Short Baseline Tracking System

Underwater geolocation positioning surveys of the target field were also conducted using an advanced acoustic-based unit. The EasyTrak™ Nexus Lite portable Applied Acoustics Engineering Ltd. (AAE) USBL tracking system was leased from Subsea Technologies, Inc. for a period of 4 weeks spanning late September and early October. This system has a proven track record in the oil and gas industry for underwater position tracking of divers and remotely operated vehicles. The USBL underwater positioning and tracking system is centered on a multi-element, single transceiver that transmits and receives acoustic signals to/from subsea targets from which range, bearing, and depth information can be determined. The acoustic transceiver unit was mounted on a pole 1.3 m below the keel of the MCRL vessel, and spatial offsets were measured from the external GNSS antenna mounted with a clear view of the sky to provide surface geolocation input data for the USBL system. As allowed by permit for active acoustics in the Sequim Bay testbed area this year, the USBL system was configured to automatically operate and update the position estimate of the mini-beacon responder at a 5-second ping rate. The transceiver interrogated the mini-beacon responder held by a diver over the target fiducial point, defined as the nose of pointed UXO or the center of mid-point of square or rectangular targets (e.g. crab pot, cement block). The beacon replied at a pre-determined turn-around time and the measured two-way travel time was used to determine the range to the target. Based on the phase delay of the acoustic arrival from the beacon to the internal transceiver array, a bearing and pitch angle to the target beacon were also calculated. The range, bearing, and pitch were combined with the measured spatial offsets (x,y,z) of the transceiver head to the surface GNSS antenna to produce an underwater three-dimensional geolocation estimate for each interrogation/reply cycle.

The USBL surveys were conducted simultaneously with the October surface GNSS buoy target geolocation surveys. The effort resulted in concurrent USBL position estimates calculated at 5-second intervals over the 2-minute dwell periods for up to 24 USBL points per target. The EasyTrak™ software was configured to log only the estimates during the target dwell periods. The software also provided an estimate of the quality of the localization from each ping cycle based on the received strength of signal and confounding multi-path arrivals. The position quality was indicated in a real-time graphic display for the system operator at red, yellow, and green levels relative to the increasing confidence in the estimated position. Geolocation data were logged with red positions flagged with poor quality and green and yellow marked equivalently in the database.

4.2.3.3 Inverted Long Baseline Positioning System

In July, an iLBL positioning system was tested as part of the untethered movement tests and the specifics of its usage can be found in Section 4.1.3. The system, manufactured by DiveNET™, includes four surface Acoustic GPS Receivers (AGRs) that communicate position to a Diver Display Unit (DDU). The DDU computes its horizontal position relative to the AGR and can store points and a track, and can provide navigation information to the diver. The "marked points" and track can be exported to a computer on the surface.

Tests of the system involved the divers marking points multiple times and resting near a point for a period of time in order to store enough track data for analysis. Prior to testing, the divers familiarized themselves with the two-button DDU and its interface. After placement of targets, the divers performed repeat markings of target positions during three dives. Diver track data was also acquired while swimming between targets for geolocation analysis.

The results from the tests were inconclusive. A combination of hardware and software issues prevented a complete data analysis. The system was returned to the vendor for repair and, because of COVID restrictions, a vendor representative was unable to make the journey to Sequim Bay to provide additional recommendations for this application.

4.2.3.4 Comparison of Target Geolocation Systems

Spatial comparisons of the target positions from the September and October surface GNSS buoy and the USBL system surveys showed the differences in target geolocations both in time (surface GNSS surveys in September and October) and between the methods (GNSS surface buoy and USBL) for the calibration site (Figure 9) and the blind site (Figure 10). The point cloud data from all three survey efforts revealed the significantly larger variability in the USBL-derived positions compared to the post processed kinematic (PPK)-corrected surface GNSS survey points. This is largely attributed to the positional error introduced by a lack of real-time kinematic (RTK) correction for the surface GNSS data input to the USBL system. The positional accuracy of the Trimble R8 system used for the USBL surface data input is listed as 0.5 m in the horizontal plane and, when combined with the 1% slant range accuracy listed by AAE for the USBL at 50 m, results in a combined theoretical error of 1 m. The positional accuracy of the PPK corrected surface GNSS system is < 5 cm.

The mean geolocation positions for the point clusters are shown with a surrounding circle of RMSE radius that indicates the variability about the mean position for each target (Figure 9 [lower] and Figure 11 closeup view (20 x 20 m) of each cluster). For spatial reference of the target clusters in the blind site, mean positions from the survey efforts are shown within the entire 100 x 100 m blind test area in Figure 12.

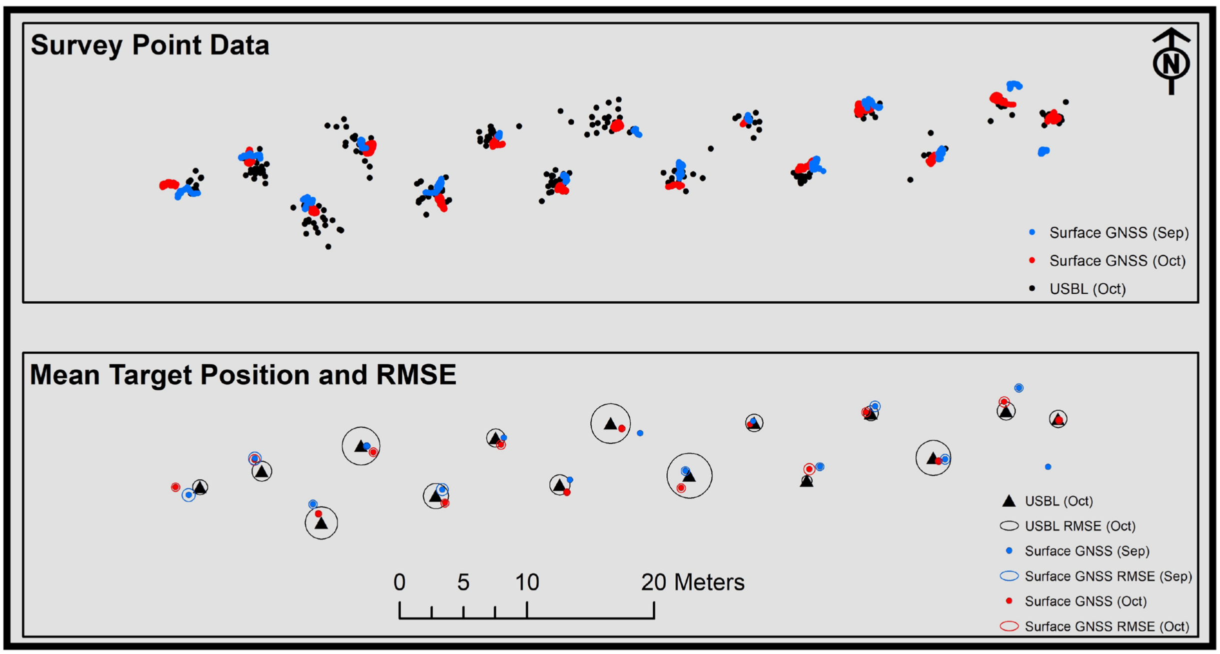


Figure 9. Maps of target geolocation positions along the calibration site baseline derived from the surface GNSS buoy surveys and the USBL positioning systems.

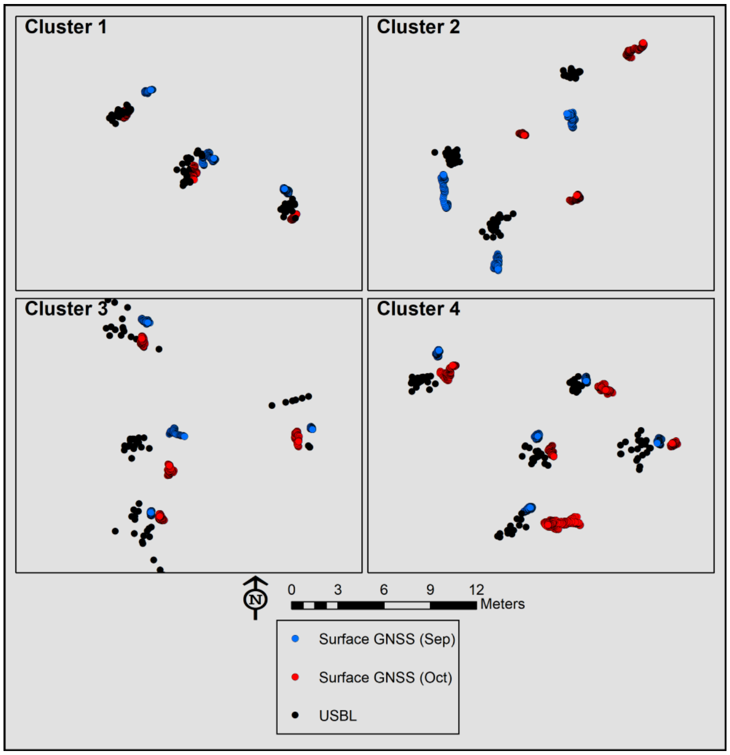


Figure 10. Target point clouds from processed positions for each cluster at the blind site, collected by the surface GNSS and USBL systems.

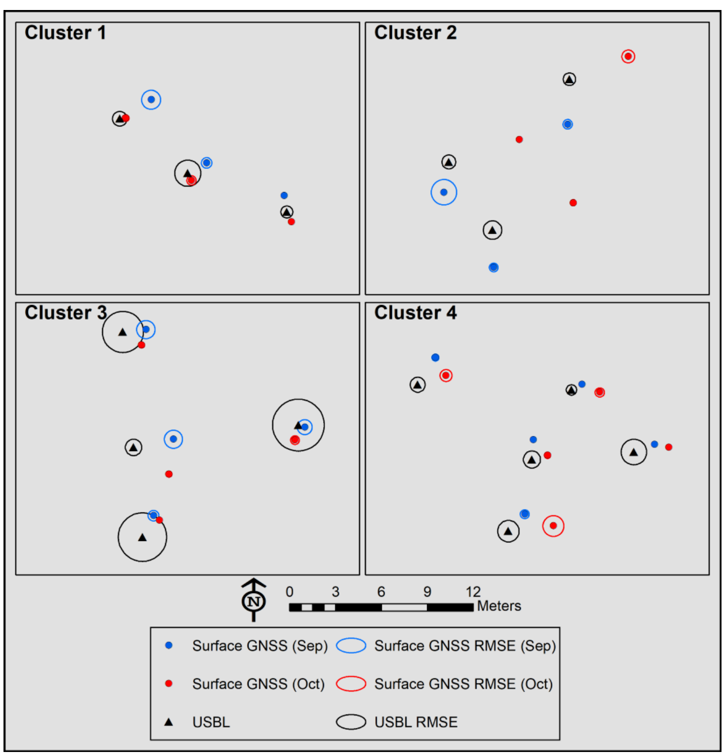


Figure 11. Relative mean target positions and associated RMSE for targets within each cluster at the blind site.

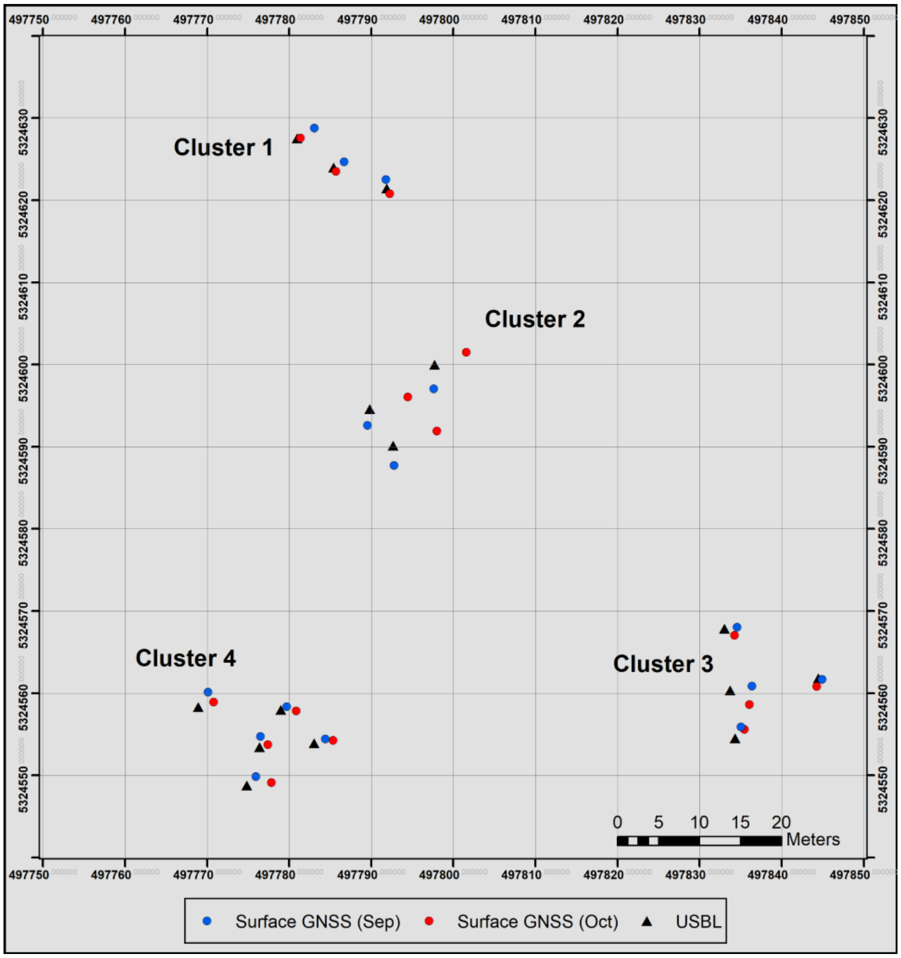


Figure 12. Blind site cluster locations relative to the 100 x 100 m site grid. Points represent mean target position as determined by the surface GNSS and USBL systems in September and October.

To further quantify the spatial differences between the target positioning from these survey efforts, the measured offsets between the target geolocations of the September and October surface GNSS buoy surveys (n= 27) were calculated as well as the spatial differences between the USBL-derived positions and both surface GNSS survey positions (n = 57) (Figure 13).

During an October survey of the Cluster #2 targets in the blind site, the divers experienced a severe current near the bottom, which made it difficult to hold station over the targets. The divers also noted significant visible scope in the line heading toward the surface, which they had not observed during previous survey operations. This resulted in a large spatial discrepancy (6–7 m) between the two GNSS surface buoy geopositions for Cluster #2 targets collected in September and October as well as the geopositions measured by the USBL. These data were subsequently removed from the analysis as outliers, but they provided valuable information about the environmental condition limitations of the surface GNSS buoy approach.

The measured spatial differences in the target positions between the survey methods and dates (Figure 13) show mean values on the order of 1 m (USBL = 1.3 m, std = 0.8 m; surface GNSS buoy = 1.2 m, std = 0.6 m) with similar standard deviation values. The distribution in USBL-measured offsets in target position is positively skewed with the majority of spatial differences in target geolocation less than the mean value of 1.3 m. As a measure of precision, the distributions in RMSE for each method at each target are shown in (Figure 14). The mean RMSE for the surface GNSS buoy measurements (n = 57) was 0.3 m with a standard deviation of 0.1 m, while the mean RMSE for the USBL measurements (n = 27) was 0.9 m with a standard deviation of 0.4 m.

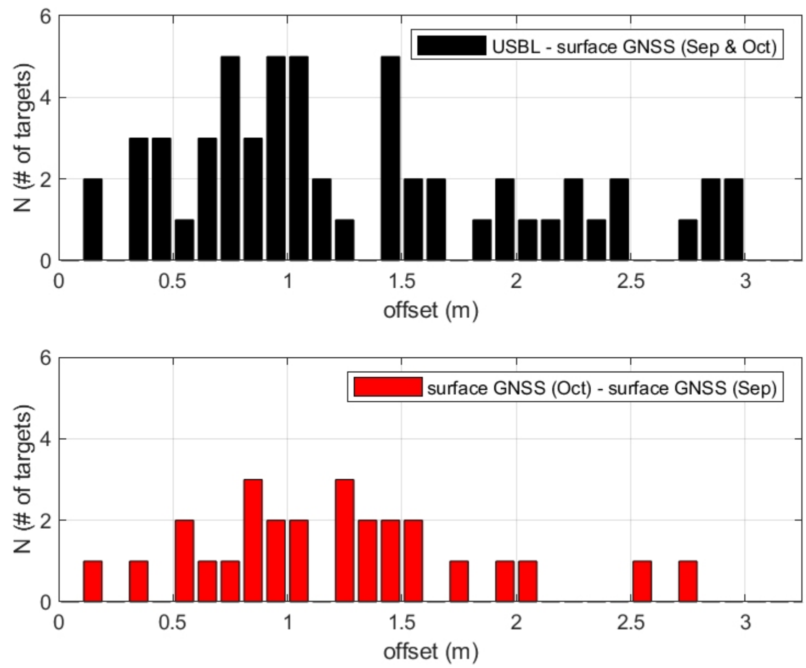


Figure 13. Empirical distributions of measured spatial differences for each target between the geolocation techniques (upper graph) and survey times (lower graph).

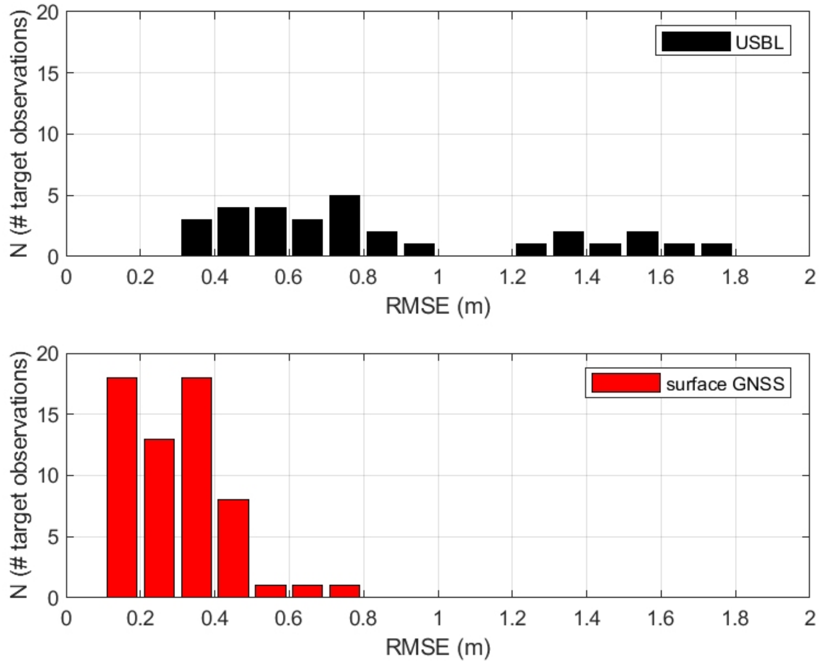


Figure 14. Distributions of root mean square error (RMSE) for each target position derived from the USBL and surface GNSS buoy geolocation techniques.

The factor of 3 increase in the mean RMSE of the USBL-derived positions at each target from the PPK-corrected surface GNSS buoy measurements is attributed to several factors. As previously mentioned, an RTK-GPS input was not used with the USBL system which introduced horizontal error estimates on the order of 0.5 m for the initial position. Combining this initial GNSS error (0.5 m) with the USBL system error of 1% of slant range at an average ranging distance of 50 m during the USBL surveys, resulted in theoretical combined error of 1 m for the USBL system. In addition, although the USBL system incorporates advanced algorithms for reducing the effects of multi-path reflections in shallow water, complexity in acoustic propagation is likely to have some effect on system performance and may be another contributing factor to the observed spatial variability in the USBL point clouds. Similarly, because of the limited bottom time for divers at these working depths (20–25 m), both green (good) and yellow (medium) quality USBL position fixes were used in the analysis to increase the number of observations for a more robust mean target location. With an RTK-GPS input for the USBL system, and more time for surveying each target to accept only “green/ good” quality fixes, the USBL system should consistently produce sub-meter accuracy for seafloor target geolocation positioning. Furthermore, the USBL system is not weather-limited and can be used for positioning throughout the operational range of environmental conditions for the divers. It also has an added advantage of diver tracking and waypoint navigation capability when combined with the diver/surface vessel underwater communication system. A drawback of the USBL system, and with other acoustic-based systems, is that designated marine mammal observers are required during operations to remain in compliance with permitting regulations.

The performance of the PPK-corrected surface GNSS buoy approach for target geolocation was influenced by the local weather (winds) and environmental conditions (waves, currents). Line scope from the seafloor target to the surface GNSS antenna was introduced by mean flows and wind affecting the relationship between the surface position measurement and geolocation of the seafloor target. Positional error will increase with working depths. This approach produced reliable results under calm environmental conditions (< 10 knots wind speeds and minimal currents) and is cost-effective. In addition, since this survey technique does not use active acoustics, it does not require additional personnel for marine mammal observations. A drawback of this method is that without a data feed to the support vessel or real-time display it does not provide any subsurface diver navigational support for locating seafloor targets. A summary comparison of geopositioning system attributes is provided in Table 8.

Table 8. Summary comparison of geopositioning system attributes.

System Attribute	USBL	Surface GNSS
Weather and environmental conditions (winds, waves, currents) affecting position accuracy	Nominal affect	Reduced accuracy
System performance influenced by additional acoustic sources or elevated ambient conditions	Reduced performance	Nominal effect
Provides underwater diver navigational assistance	Yes	No
Additional marine mammal observers for permit authorization	Required	Not required
Permitting review and consent	Required	Not required
Operation limited by presence of nearby marine mammals under permit conditions	Yes	No

5.0 Engineering Test

The APL-UW team conducted their engineering test of the MuST in Sequim Bay between September 21 and 24, 2020, using their research vessel *R/V Jack Robertson*. The vessel travelled from Seattle to Sequim Bay on September 20 and moored at John Wayne Marina in the bay for the duration of the field activities.

5.1.1 Shore-based Support

Logistic and facilities support at MCRL was available to the APL-UW staff during the engineering test, as needed. In large part, their operations were self-sustaining on the *R/V Robertson* and the MuST towbody; hence, additional shore-based support was not required during the week of testing. Two MCRL staff members were observers on the vessel during one day of testing.

5.1.2 Marine Mammal Observations

As part of the PNNL-MCRL permit requirements, a trained or designated PNNL-MCRL Marine Mammal Observer (MMO) was positioned on the MCRL dock 30 minutes prior to and during acoustic operations of the MuST to monitor for entry of marine mammals, specifically cetaceans (whales, dolphins, porpoise), into Sequim Bay. MCRL observers communicated with an APL-UW observer aboard the *R/V Robertson* who concurrently monitored a 250 m mitigation zone around the sound source. *Orcinus orca* (killer whale) presence anywhere in Sequim Bay, regardless of the mitigation zone, would have resulted in the cessation of all acoustic activity until it was confirmed that the whale had left the bay. Other cetaceans entering the mitigation zone would have resulted in a temporary shutdown of acoustic activity. No cetaceans were observed in Sequim Bay during the 4 days of testing. Pinnipeds, specifically harbor seals (*Phoca vitulina*), were occasionally present in the study area and, while their presence did not require a shutdown of acoustic activity, they were visually monitored for behaviors indicative of stress or injury. None were noted.

In addition to marine mammal observations during APL-UW MuST activities, observations were also required when the two acoustic target geolocation systems were trialed (i.e., Applied Acoustics USBL and DiveNET™). Two MCRL MMOs monitored these activities; one was stationed on the MCRL dock and one was located on the vessel using the acoustic systems. The same protocols and guidelines used for the MuST activities were employed for the geolocation systems.

6.0 Lessons Learned and Future Deployments

Despite significant challenges related to COVID-19, the FY 2020 field operations were accomplished with mitigation measures in place. Pre-planning with the SERDP/ESTCP program office, collaborative discussions with APL-UW and IDA, and the experience from 2019 activities and the work history of MCRL staff in Sequim Bay led to an expanded test bed and associated field operations. The testbed operations this year placed greater emphasis on target placement proficiency—the ability to precisely place, geolocate, and collect descriptive data of the targets —while ensuring their recovery at the end of the field season. Lessons learned from this initial stage of Phase II will inform future testbed operations and deployments. Listed below are some of the modifications that were made this year, and challenges that were encountered as well as possible solutions. It is recognized that one solution may not address every circumstance, especially with respect to varying remediation system developers' requirements and target grid layouts.

- Test site locations. Similar to 2019, two separate testing areas were used in 2020, a calibration site and a blind site. After exploring several areas for substrates conducive to hand burial of targets in sand and that also allowed for more ease in recovering buried targets in softer mud, the delineated calibration and blind sites were in relatively close proximity (Figure 2). Despite the close spacing (~75 m) between the calibration and blind sites, there were no operational issues during the APL-UW engineering test and the site locations were reported to work well for the APL-UW MuST team. Targets in the sandy dominated calibration site were buried by hand relatively easily, while targets in the mud-dominated blind site experienced some self-burial during the period of deployment. The characteristics of these sites may lend themselves to amenable locations for future target field deployments and testing activities.
- Target placement and retrieval. To date, the most challenging part of field operations has been the placement and retrieval of the target objects. Possible solutions to these challenges will vary depending on future target layout designs, remediation systems being deployed, and the duration of deployments. It is suggested that future activities aim for flexibility to the extent possible when considering options, and tailoring solutions to a particular mission or field season's mission. With that caveat, the following observations based on this year's testing could inform future activities:
  - Target handling. Targets (clutter, scientific, and inert UXO/replicas) deployed during the 2020 field season were not physically altered to enhance the ease of their deployment and recovery. While some clutter targets (e.g., the anchor and crab trap) and several UXO (M60 and Howitzers delivered with metal loop tops screwed on to the pointed end), could be easily attached to the lifting lines for deployment/recovery, many of the targets offered no secure attachment point. In the cases without a lifting point, a harness made of 1/8" Amsteel line was rigged using any available grooves or structure on the target shape (fins, abrupt taper) for attachment. Although this method worked well for several targets, harnesses on the smooth targets (e.g., Howitzer replica) were able to slip off and did not provide a trustworthy connection point for deployment and recovery. If targets have an attachment point "built-in" or modified (e.g., a hole drilled in the object), the need for a harness would be eliminated. The divers found the targets with these attachments easier to find, more secure, and easier to handle underwater than targets with harnesses.
  - Target array design. For the FY 2020 engineering test, targets were placed offset a short distance to either side of a linear baseline at the calibration site. Aside from providing

assurance for target recovery with attached tethers, the baseline also supported diver navigation during deployment and recovery procedures. The proximity of targets to each other provided efficiency for deployment, measurement, and recovery operations. The target field design at the calibration site worked well and is highly recommended in future years if requested by remediation system developers. The blind site was designed in consultation with the SERDP/ESTCP program office and IDA. Deploying targets in small separate clusters worked well for the 2020 season from an operations standpoint. Several (4–5) targets could be sent down on a single line and then deployed during a single dive and the resulting target field would appear to be relatively random. A balance between diver operations for target deployments and recoveries, and the target field design preferences of the scoring team should be addressed early in the planning stages of testing for each developer use of the testbed. Pre-planning and thoughtfully carried out logistics helped assure an efficient and successful testing operation this past year.

– Underwater visibility. The general visibility at both sites varied by day influenced primarily by plankton productivity in the water column or resuspension of bottom sediments. The blind site location (in muddy substrate) was much better with respect to visibility in comparison to the mud site used in 2019. There was still a soft layer of fine sediment in the area that was easily disturbed, creating periods of little to no visibility for diver operations, but the practice of having only one dive team (i.e., one buddy pair) in the water at a time at a site was effective this year and should be continued in the future.

– Water depth. The > 20 m diver working depth of the calibration and blind site test areas in 2020 continued to present logistical challenges related to bottom time limitations for the dive team. New technologies being considered for geopositioning this next year will reduce the number of dives and bottom time required by the divers to complete testbed operations. Additionally, future remediation technologies and tow-bodies being tested may not require as large a turning radius for the supporting vessel, allowing the target area to move to shallower water.

– Target baselines and tethers. Similar to 2019, a baseline at the calibration site and tethers at both sites were used to connect targets in 2020. The 70 m baseline at the calibration site served to orient the divers in low visibility, allowing for efficient deployment/recovery operations and assurance of target recovery. Nevertheless, it is recognized that baselines increase the risk of targets being moved if a line is caught by an anchor or fishing gear. In addition, a baseline may be detected by certain sensor technologies (e.g., acoustic) as a long linear feature, and therefore may be inappropriate for use in blind test target layouts. Tethers were used in both areas for attaching targets directly to the baseline (calibration site) or to a central, heavier target (blind site). Tethers were spliced directly to the baseline, thereby avoiding the plastic slide release buckles used in 2019 and were either tied directly to or connected with a small loop and toggle on the target side, providing efficient and secure connection points. Discussion between PNNL-MCRL, the SERDP/ESTCP program office, IDA, and others (e.g., NRL) about types of materials used for baselines and tethers involved identifying line that would be strong enough to handle deployment stresses, recoveries, and potential snagging events; be easy for the divers to handle to minimize entanglement; and ideally be subtly visible to the divers for navigation at the site. Types of lines discussed included monofilament and braided Dacron fishing lines, which were avoided due to entanglement concerns and difficulty of use for divers. This year, a high-performance Dyneema line (Amsteel Blue, 1/8” diameter) was used for tethers and baselines. Amsteel is readily available in many colors, is easy to splice, has a very high breaking strength, and was easy for divers to handle in the water. Future target deployments requiring baselines and tethers will use the smallest practical size (7/64”) Amsteel braid to further reduce its visibility.

- Target burial. In 2020, PNNL-MCRL permits allowed for the burial of up to 5 inert UXO targets by divers using hand-held trowels. This method allowed target burial just below the sediment surface of one UXO per dive for larger targets (e.g., 155 mm Howitzer) and two UXOs for smaller targets (e.g., 81 mm mortar). Burial of targets beyond surficial depth may require more than one dive per target. Other tools and technologies used to bury targets (e.g., hydrojet stingers to liquify the sediment) exist, but would require additional permitting and will require PNNL divers to experiment and determine the time and effort involved to achieve the preferred target burial depth. Mechanized target handling and burial by automated rigs outfitted with water jets or other similar technologies for sediment fluidization would be beneficial for future emplacement and burial of targets (e.g. MR20-1220).
- Timing of target placement and testing. Because of COVID-19-related delays in the 2020 scheduled operations, the target deployments concluded in September only 5 days prior to APL-UW's engineering testing activities. This did not allow ample time for the sediment that was disturbed during the target deployment activities to settle. The sediment disturbance along the baseline of the calibration site was particularly visible in the MuST data. It is intended that future target deployments will occur with sufficient time (e.g., at least 30 days) between target deployment and testing to allow for sediment disturbances from emplacement to “heal,” thereby reducing the deployment footprint.
- Target geopositioning and diver navigation. Comparisons of the tethered surface GNSS buoy (used in 2019 and 2020) and the USBL (2020) methods demonstrated these approaches differed on the order of 1 m in target geopositioning. This difference would likely be significantly reduced using RTK-GPS input for the USBL or any other advanced geolocation system. Furthermore, to evaluate the accuracy of a system, consistency in geopositions must be evaluated over several repetitive surveys during a range of environmental conditions (e.g. wind waves, currents). Based on lessons learned from the 2020 field season, a geolocation positioning system demonstration area will be set up in the spring of 2021 and several systems (e.g., USBL, V-NAV™, Artemis Pro™ tablet) will be trialed for accuracy and precision comparisons. PNNL-MCRL will use an RTK-GPS base station and several rover units to support the data input needs of these advanced positioning systems. Post analysis, a system will be selected for geolocating the seeded target field in the 2021 calibration and blind testbed areas.
- Permitting. Permitting for the 2020 placement of 30 targets and the subsequent engineering test in Sequim Bay was successful. The application process for renewal of existing permits for an additional 5 years is currently under way. In the future, each new technology that is brought forward by remediation system developers will need to be compared to pre-permitted conditions (e.g., acoustic signatures) to assure they meet the criteria in the permit authorization for Sequim Bay. A majority, if not all, of the proposed future remediation system technologies currently funded by SERDP/ESTCP have been included in the permit renewal request for Sequim Bay activities. However, proposed testing that falls outside the conditions allowed by the permitting agencies would require a new permit with a potentially lengthy time to secure authorization (e.g. 6 months) depending on the type of permit.
- Test deployment scheduling. Throughout the year, Sequim Bay attracts recreational, commercial, and tribal fishermen. During crab and shrimp seasons, boat traffic increases

and marking buoys are present in the bay. These markers can impede a research vessel running along pre-determined track lines. In addition, the fishing activity may introduce additional, undocumented clutter to the study area (e.g. crab traps). Shrimp and crab seasons are generally predictable, but specific dates for openings and closings may not be set until a few days beforehand, especially for tribal fisheries. September has generally been inactive with respect to fisheries, although 2020 was an exception with an unexpected crab fishery opening coinciding with the engineering test. In addition, recreational crabbing and additional tribal fisheries were active during target deployment/recovery operations this past year. This did not interfere with testbed operations, however acknowledging the potential for delay and adding additional contingency time into scheduling is advised in the future. Similarly, seasonal wildfire smoke created hazardous air quality in Sequim Bay during the late summer/fall. This produced potential scheduling challenges for conducting the engineering test, however mitigation measures were put in place to allow continued test bed operations. While somewhat unprecedented, this may also be a recurring theme in the future.

7.0 References

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