

Sequim Bay Underwater UXO Demonstration Site: Field Operations Summary, 2021

May 2022

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Summary

This report provides a summary of the Pacific Northwest National Laboratory's (PNNL's) activities to initiate operational development (Phase III) of the Sequim Bay Underwater Unexploded Ordnance (UXO) Demonstration Site in Washington State. More than 400 underwater locations in the U.S. have been identified by the U.S. Department of Defense (DoD) to contain munitions from past military training and weapons testing, posing a threat to human health and the environment. To address the challenge posed by this threat the Strategic Environmental Research and Development Program (SERDP) and Environmental Security Technology Certification Program (ESTCP) underwater Munitions Response (MR) program is developing standardized UXO demonstration sites ("testbeds") to rigorously evaluate technologies that can detect, geolocate, and classify proud and buried munitions in 0–35 m water depths. Sequim Bay in Washington is one of four demonstration sites located in U.S. coastal waters. PNNL-Sequim is located near the entrance to Sequim Bay, where it provides operational, logistical, and facilities support for testbed activities.

The primary objectives of the initiation of Phase III were as follows:

1. Establish a calibration and blind site grid at the Sequim Bay testbed, including placement, geolocation and retrieval of a variety of inert UXO and clutter items on sand/mud sediments in ~25 m deep water.
2. Provide operational support for a formally scored demonstration of the Applied Physics Laboratory – University of Washington (APL-UW) multisensory towbody (MuST) and provide field support for an engineering test of the Black Tusk Geophysics/Tetra Tech UltraTEMA-4, an electromagnetic induction (EMI) technology.
3. Evaluate target geolocation systems to support accurate placement of targets.
4. Collect target ground-truth data and environmental site information to support testing and evaluation scoring protocols.
5. Provide logistic support for sediment characterization in the testbed by SERDP collaborators (Virginia Tech and APL-UW).

During Phase I and II (2019 and 2020), PNNL focused on permitting, developing testbed designs, and establishing diver techniques for accurate placement, geolocation, and recovery of targets from the seafloor. Phase III moved to an operational state, capitalizing on lessons learned from Phases I and II, with a focus on developing cost-effective, safe, and technically sound approaches that can inform future operations of the Sequim Bay testbed and other underwater demonstration sites.

The 2021 testbed was located in the same vicinity as 2020. The site plan included a 100 m diameter "blind" site circle and two calibration sites; one for the MuST technology and one for the EMI UltraTEMA-4 technology. A total of 77 targets were emplaced at the underwater demonstrations site for 2021 field operations by PNNL divers. Fifty targets were emplaced in the blind site, including 23 inert and replica munitions and 27 clutter items. An additional 15 objects were emplaced along a 74 m calibration line for the MuST system (10 inert UXO items, 2 Howitzer replicas, and 3 clutter objects). The remaining 12 targets were medium and large metal ISO (industry standard object) pipes placed along a 64 m EMI calibration line for the UltraTEMA-4 system. All targets were placed proud on the seabed surface, with the exception of four that were buried flush with the seabed in the MuST calibration line.

Ground-truth information collected by PNNL divers for each target included target type, placement characteristics in/on the seabed, and underwater geolocation. The information from the calibration lines was provided to the technology developers prior to their respective demonstration and engineering tests. All information related to the blind site targets was withheld until the results of a formally scored target detection and classification were evaluated by the Institute for Defense Analyses (IDA), the independent SERDP/ESTCP scoring team. The demonstration by APL-UW was conducted during the last week of September 2021, followed by a Black Tusk UltraTEMA-4 engineering test the next week. After the field trials, targets were retrieved from Sequim Bay by PNNL divers and stored at PNNL-Sequim for deployments in future years.

The FY 2021 field operations were executed effectively with expanded scope. Early planning with the SERDP/ESTCP program office and collaborative discussions with APL-UW, Black Tusk, Virginia Tech, and IDA resulted in successful remediation technology demonstrations and collection of sediment characterization data. The primary challenge again this year was related to COVID-19 events. Risk mitigation protocols, adaptive management, and flexibility implemented by PNNL and all collaborators allowed continued and successful completion of field activities.

Acknowledgments

We thank David Bradley and Herb Nelson for their guidance and support from the SERDP/ESTCP program office throughout this project. We also thank Mike Richardson, Shelley Cazares, Mike Tuley, and Jacob Bartel with the Institute for Defense Analyses for insightful conversations related to target layout, target geolocation, and scoring. Collaboration with project teams was critical to successful 2021 field operations including APL-UW (Kevin Williams-PI), Black Tusk Geophysics and Tetra Tech (Steve Billings-PI), Virginia Tech (Nina Stark-PI) and APL-UW (Todd Hefner-PI). Additional support was provided by PNNL staff, including field crew members Kate Hall, Garrett Staines, and Eric Fischer; the permitting team (Jim Becker, Kris Hand and Ioana Bociu); and Kate Buenau, Susan Ennor and Susan Tackett (report review and editing).

Acronyms and Abbreviations

ADCP	Acoustic Doppler Current Profiler
APL	Applied Physics Laboratory
CTD	conductivity, temperature, depth
DoD	U.S. Department of Defense
eBOSS	EdgeTech Buried Object Scanning System
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
ISO	industry standard object
MCRL	Marine and Coastal Research Laboratory
MR	Munitions Response
MuST	Multi-Sensor Towbody
PFFP	portable free-fall penetrometer
PNNL	Pacific Northwest National Laboratory
RTK	real-time kinematic
SERDP	Strategic Environmental Research and Development Program
TEMA	towed electromagnetic array
USBL	Ultra-short baseline
UW	University of Washington
UXO	unexploded ordnance
VNav™	Vector Navigation

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1.0 Introduction

More than 400 underwater locations in the United States at current and former U.S. Department of Defense (DoD) sites are known to contain munitions from past military training and weapons testing. Many of these sites are in relatively shallow coastal waters (0–35 m deep) where they pose a threat to human health and the environment. The DoD's Strategic Environmental Research and Development Program (SERDP) and Environmental Security Technology Certification Program (ESTCP) Munitions Response (MR) program are addressing the issue by supporting the development and demonstration of technologies that can detect, characterize, and remediate military munitions in underwater sites. An important component of this initiative is development of underwater unexploded ordnance (UXO) standardized demonstration sites ("testbeds") for early demonstration and verification of these detection and classification systems. Testbeds currently in the early phase of development include Moku o Lo'e, HI; Panama City, FL; La Spezia, Italy; and Sequim Bay, WA. These testbeds will be used to evaluate and formally demonstrate technologies, including acoustic, magnetic, electromagnetic induction (EMI), and optical systems designed to detect and classify underwater UXO.

Sequim Bay, WA was evaluated as a potential testbed between 2016 and 2018 by the Pacific Northwest National Laboratory (PNNL) (SERDP project MR-2735). Based on the site location, environmental characteristics, and available logistical and operational support provided by PNNL, the SERDP/ESTCP MR program initiated a three-phased approach to formally establish an underwater UXO testbed in Sequim Bay. During Phase I and II (2019 and 2020) of the Sequim Bay underwater demonstration site, PNNL focused on permitting, development of a test bed design, and establishing techniques for accurate placement, geolocation, and recovery of targets from the seafloor.

In 2019, PNNL implemented Phase I, the placement of and retrieval of a nominal number of targets in Sequim Bay and operational support for an engineering test of the Applied Physics Laboratory – University of Washington's (APL-UW's) multisensory towbody (MuST) detection and classification technology (Woodruff et al. 2020). Phase II, implemented in 2020, expanded the number and type of targets placed, and added a calibration/verification site and an informally scored "blind" site of targets for the MuST technology (Woodruff et al. 2021). PNNL hosted the APL-UW team to conduct engineering tests of the MuST in 2019 and 2020 for development of their training datasets at the calibration sites, and informal collection of target detection and classification data at a blind site.

The first year of formal operation of the Sequim Bay Underwater UXO demonstration site in 2021 (Phase III – Year 1) included a significant expansion of testbed operations. This report summarizes 2021 activities, which involved planning and permitting, test bed design and layout, target geolocation technology advances, system developer demonstrations, including a formal demonstration of the MuST technology and an engineering test of the Black Tusk Geophysics/Tetra Tech UltraTEMA-4 technology, and seafloor and sediment characterization by Virginia Tech and APL-UW.

2.0 Project Overview

During this past year, the first year of Phase III (2021)—testbed operations were expanded to include a formally scored demonstration of APL-UW’s MuST technology and development of other aspects of the test bed, capitalizing on lessons learned from previous years (Woodruff et al. 2020, 2021). Phase III tasks in 2021 included (1) planning and permitting all test bed activities for the field season; (2) evaluating geolocation and underwater navigation systems for accurate placement of targets; (3) acquiring, deploying, and retrieving inert UXO and clutter items at the demonstration testbed; (4) collecting target ground-truth data and environmental site information; (5) hosting APL-UW’s demonstration of the MuST technology and Black Tusk/Tetra Tech’s engineering test of the UltraTEMA-4 technology; (6) and providing logistic support for sediment characterization in the testbed by SERDP collaborators.

In 2021, PNNL-Sequim staff, with concurrence from the SERDP/ESTCP program office, selected a test area in Sequim Bay (Figure 1). This year’s test bed was located in the same vicinity as 2020 and included site design modifications and expansion (Figure 2). The site plan included a 100 m diameter “blind” site circle and two calibration sites—one line of targets for the MuST and one line of targets for the UltraTEMA-4.

PNNL divers emplaced a variety of targets at the Sequim Bay UXO demonstration site during 2021. Fifty targets were emplaced in the blind site, including 23 inert and replica munitions and 27 clutter items. An additional 15 objects were emplaced along a 74 m calibration line for the MuST system (10 inert UXO items, 2 Howitzer replicas, and 3 clutter objects). The remaining 12 targets were well characterized ISO (industry standard objects) pipes (Nelson et al. 2009) placed along a 64 m EMI calibration line for the UltraTEMA-4. All targets placed along the calibration lines were on the seabed surface (proud) with the exception of four that were buried flush with the seabed in the MuST calibration line.

PNNL divers collected a suite of ground-truth data including target metadata (e.g., geolocation, burial depth, tilt, orientation) and environmental characterization data (e.g., wave height, wind speed, turbidity) during field operations to augment a rigorous scoring process by the Institute for Defense Analyses (IDA). The calibration line information was provided to the technology developers prior to their respective demonstration and engineering tests. All information related to the blind site targets was withheld until the results of a formally scored target detection and classification were evaluated by IDA, the independent SERDP/ESTCP scoring team. The demonstration of the MuST technology was conducted during the last week of September 2021, followed by an UltraTEMA-4 engineering test the next week. PNNL divers retrieved and stored the targets at the end of field operations for deployments in future years.

An important aspect of target detection and classification is understanding the surrounding seabed environment. Two SERDP collaborators conducted sediment characterization work in Sequim Bay this year to augment data previously collected in 2019. In late October, Dr. Nina Stark (Virginia Tech) conducted a portable free-fall penetrometer (PFFP) sediment survey to assess the shear strength, density, and pore pressure response of upper layer sediments in the underwater testbed (SERDP project MR21-1265, *Rapid Soil Classification and Integration of Soil Characteristics for UXO Site Characterization and Risk Assessment*). Dr. Todd Hefner (APL-UW) followed this effort in mid-November with a multibeam sonar survey of the same area as part of SERDP project MR18-1406 (*Demonstration of Physics-based Inversions of Multibeam Echosounder for Sediment Properties*). Throughout the field season, PNNL provided logistical and operational support to all collaborators and technology developers.

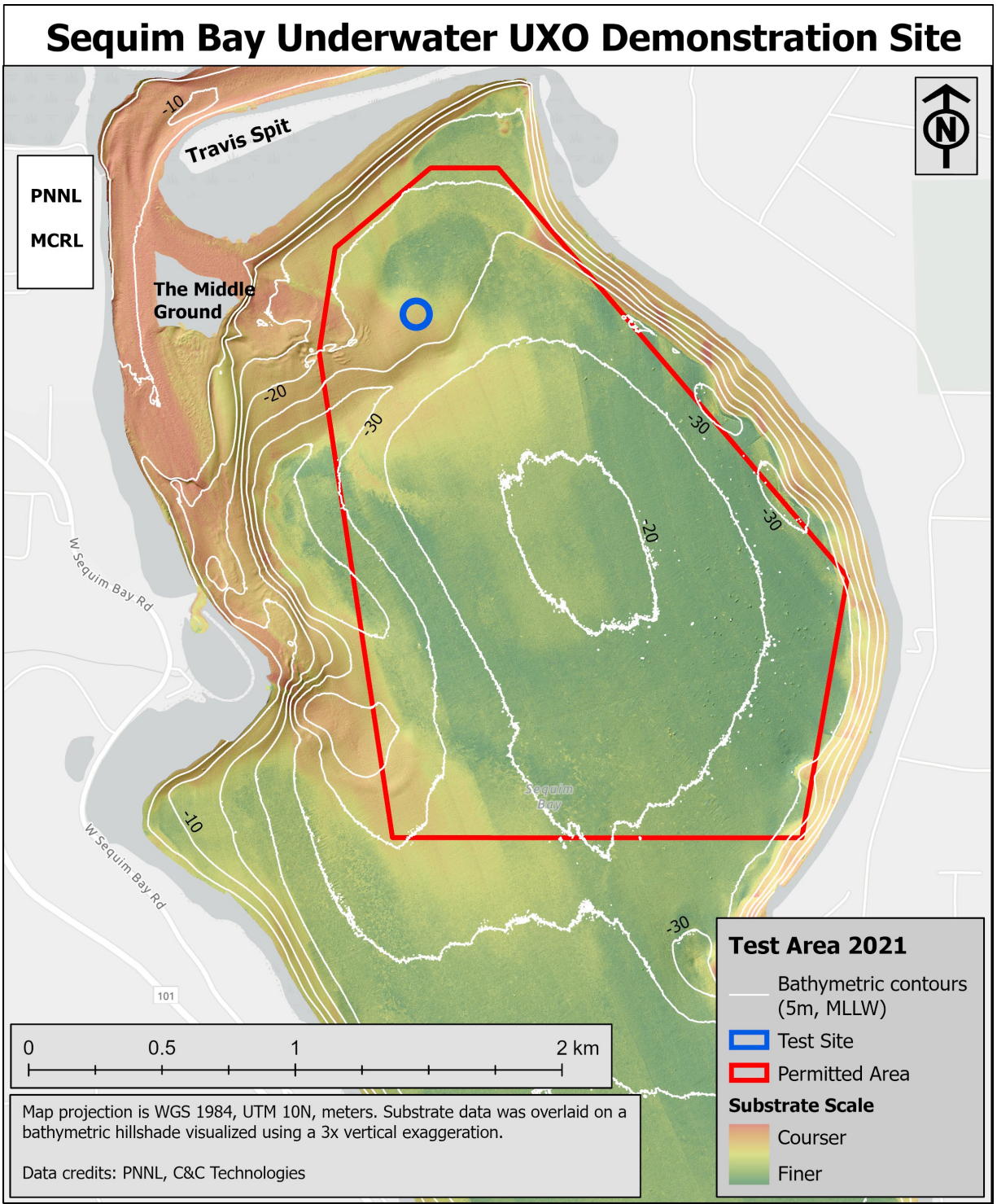


Figure 1. Location of the Sequim Bay underwater demonstration site (blue circle) for the 2021 field season.

This year’s work continued progress toward identifying the most cost-efficient, diver-assisted, underwater target geolocation technology system for testbed operations. Three technologies were compared: (1) an Applied Acoustics Vector Navigation (VNav™) acoustic system, (2) an

iXblue Gaps™ ultra-short baseline (USBL), and (3) an RTK-GPS surface buoy tethered to divers, which has been used during the past two years. The divers compared technologies and methods at three locations under a range of environmental conditions prior to target deployments during the summer.

As part of the first year of Phase III testbed operations, data collected at the blind site by APL-UW's MuST technology was formally scored by IDA. PNNL collected a suite of ground-truth data, including target metadata (e.g., geolocation, burial depth, orientation, tilt) and environmental characterization data (e.g., wave height, wind speed, turbidity) during field operations to augment a rigorous scoring process conducted by IDA.

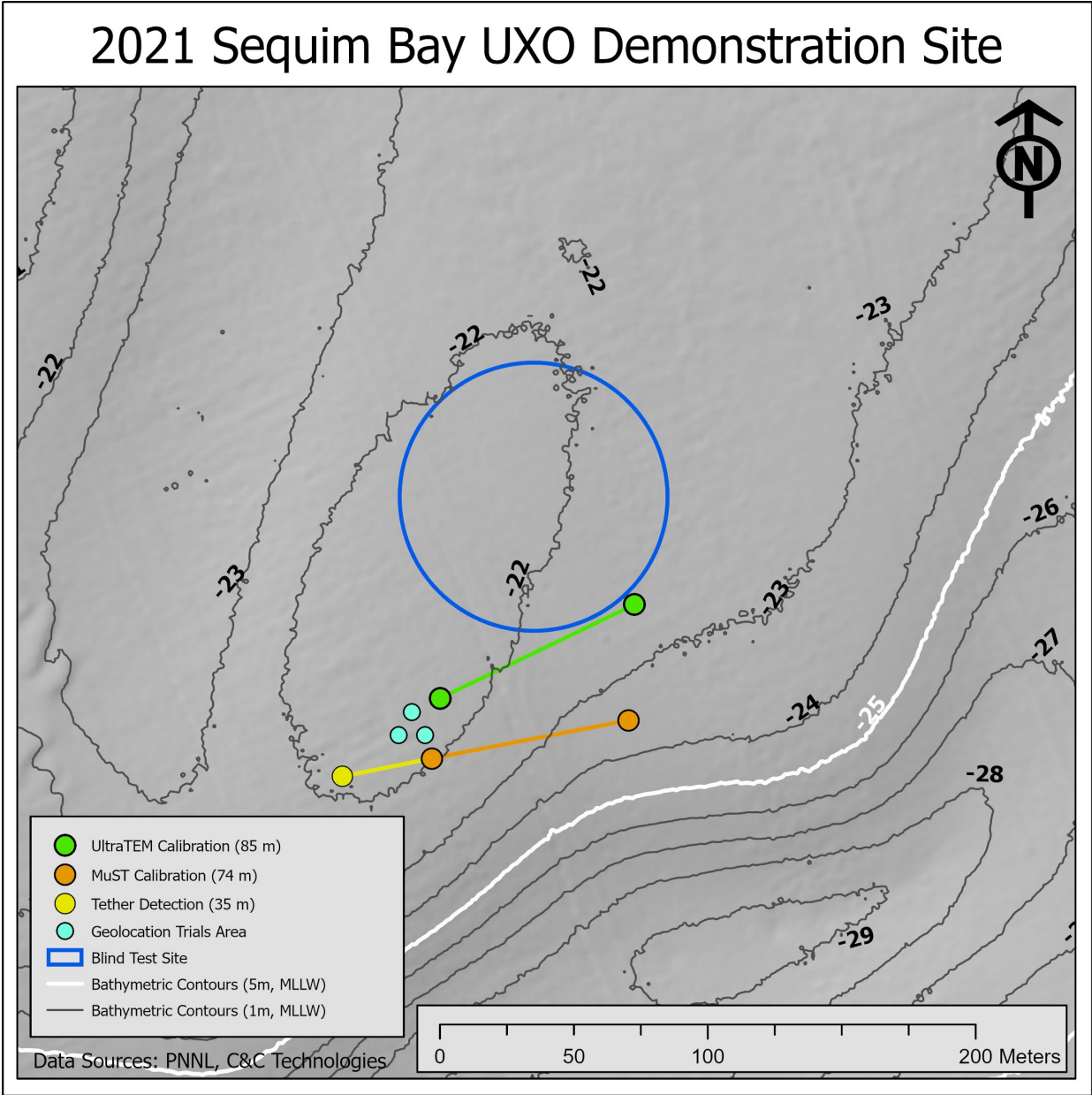


Figure 2. Location of the blind site (blue circle) relative to the MuST (orange line) and UltraTEMA-4 (green line) calibration locations in Sequim Bay in 2021.

3.0 Project Planning

Management of the Sequim Bay underwater demonstration test site involved early planning and scoping of the target field design, acquisition of targets, coordination with multiple technology developers and collaborators, and permitting for technologies used at the test site.

3.1 Timeline

The overall timing of events in 2021 was similar to 2020. However, additional activities, technology developers, and collaborators added complexity to the planning and coordination of events. Table 1 summarizes the planning and field operations for 2021.

Table 1. Timeline of events for the 2021 Sequim Bay demonstration test site activities.

2021 Sequim Bay Test Site Activities	2020		2021											2022	
	Dec	Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sept	Oct	Nov	Dec	Jan	Feb
Administrative/Planning/Operational Support															
Scoping/Target Field Design															
Permitting for Test Site/Technology Use															
Target Selection/Acquisition/Inventory/Preparation															
Hosting Test Site Observers															
Field Operations															
Geolocation Technology Test Trials															
Environmental Characterization															
Target Placement (PNNL)															
MuST Demonstration (APL-UW, Williams-PI) Sept 27 - 30th															
UltraTEM Engineering Test (Black Tusk, Billings-PI) Oct 4-8th															
PFFP & sediment collection (Virginia Tech, Stark-PI) Oct 25-29th															
Target Geolocation/Ground Truthing															
Multibeam Survey (APL-UW, Hefner-PI) Nov 16-20th															
Target Retrieval (PNNL)															
Field Summary Reporting															

Planning and scoping for the first formally scored demonstration, as well as additional testbed activities, began in late 2020 and incorporated knowledge and lessons learned from previous years (Woodruff et al. 2020, 2019). Planning and operational support were dominated by activities related to target test site design and the permitting of new activities. Previously permitted activities (e.g., MuST technology use, target placement) required less time and effort to receive concurrence.

Field operations (Section 4.0) were coordinated between technologies demonstrators, on-site collaborators/observers, and PNNL staff emplacing targets and collecting ground-truth information. Most of these activities occurred between July and November of 2021. The flexibility of all participants, including the accommodation of COVID-19 protocols, recreational crabbing activities, and changing weather patterns, allowed for effective project execution.

3.2 Environmental Permit Authorizations

An existing 5-year PNNL Scientific Research Plan and associated environmental authorizations related to the U.S. Department of Energy’s marine research activities were used for the 2021 field season activities to the extent possible. The permits and authorizations included those related to and received from the following:

- *National Environmental Protection Act* – U.S. Department of Energy’s Categorical Exclusion for Aquatic Research
- Section 106 of the *National Historical Preservation Act*, Cultural Resources Review – Washington State Historic Preservation Officer
- *Endangered Species Act*, 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 – 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, certain SERDP/ESTCP testbed-related activities were already approved. Activities included the placement of targets, survey grids, and diver-installed anchors, as well as operation of APL-UW’s Doppler velocity log sonar, side scan sonar, eBOSS SAS sonar, multibeam sonar. Three additional proposed 2021 activities were evaluated internally by PNNL for compliance within the existing envelope of the Research Plan shown in the permitted area (Figure 1): (1) Virginia Tech’s sediment characterization field work (i.e., PFFP measurements and sediment collection), (2) deployment of an acoustic doppler current profiler (ADCP) at the test site, and (3) the use of an iXblue GAPS USBL acoustic tracking system. Concurrence/ authorization for each activity was granted prior to work commencing.

As part of the PNNL permit requirements, a trained marine mammal observer or designated observer was aboard the research vessel during geolocation equipment trials and for two acoustic-related activities: (1) operation of the MuST and (2) operation of the iXblue GAPS M7 USBL acoustic tracking system on the UltraTEMA-4. Observations of cetaceans (whales) within a prescribed area around the acoustic source would have resulted in a temporary shutdown of acoustic activity. Observations of killer whales specifically (*Orcinus orca*) 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. Their presence was not expected and was not observed during any test activities. Harbor seals (*Phoca vitulina*) were occasionally present in the study area and, while their presence does not require a shutdown of acoustic activity, they were visually monitored for behaviors indicative of stress or injury. No such behavior was observed.

3.3 Target Acquisition and Storage

Targets from the PNNL inventory (described by Woodruff et al. [2021]) were supplemented with additional targets from the U.S. Army Aberdeen Training Center, selected by PNNL and the SERDP program office. All targets are labeled and inventoried as described by Woodruff et al. (2021). Targets were deployed between July and September 2021. All items were retrieved after testing and the collection of ground-truth data ground-truth was completed. The targets are








stored at PNNL-Sequim in secured, covered storage facilities with appropriate tagging and paperwork.








3.4 Test Bed Design

The 2021 testbed was in the same location as 2020, but the design was more complex than in previous years. The general layout is shown in Figure 2. The design included a line of targets specific to MuST technology calibration described in Section 3.4.1, and a line of targets specific to UltraTEMA-4 technology (Section 3.4.2). A blind site, located just north of the calibration lines, included inert UXO and clutter items (Section 3.4.3). The blind site provided the basis for an independently scored evaluation of the MuST technology.

The types of targets used in 2021 are listed in Table 2. Target types included inert munitions, EMI targets (ISO pipes), and a variety of clutter items.

Table 2. Types of targets used in the Sequim Bay underwater test bed during 2021.

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	
	105 mm projectile, high-explosive anti-tank (projectile) (HEAT)	65	9	10.9	
	105 mm projectile, M60	39	10	13.4	
	81 mm mortar, M889	26	8	2.9	
	81 mm projectile, M821	43	8	3.9	
	60 mm mortar, M49	15	6	0.9	

Type	Description	Length (cm)	Width (cm)	Weight (kg)	Photo
EMI Targets	49 mm shell, L70	21	4	0.9	
	Medium ISO pipe	20.4	5.8	0.9	
	Large ISO pipe	65	18	4.1	
	Insulated copper wire	10 m	0.4	3.3	
Example Clutter	Scuba tank	65	18	14.7	
	Anchor	48	30	5.4	
	Cement block	40	20	18.1	

The numbers of each object type (inert UXO, EMI targets, clutter items) emplaced at each of the three sites are listed in Table 3. A total of 77 objects were emplaced in the testbed, including 50 items in the blind site, 15 in the MuST calibration line, and 12 in the UltraTEMA-4 calibration line.

Table 3. Targets placed at the calibration and blind sites.

Type	Description	Number of Objects by Site			Total Number of Objects
		Blind Site	MuST Calibration Line	EMI Calibration Line	
Replica	155 mm Howitzer replica	1	2	0	3
Inert UXO	155 mm Howitzer M107	1	2	0	3
Inert UXO	105 mm projectile HEAT	3	2	0	5
Inert UXO	105 mm projectile M60	4	2	0	6
Inert UXO	81 mm mortar M889	7	1	0	8

Type	Description	Number of Objects by Site			Total Number of Objects
		Blind Site	MuST Calibration Line	EMI Calibration Line	
Inert UXO	81 mm mortar M821	5	1	0	6
Inert UXO	60 mm mortar M49	2	1	0	3
Inert UXO	49 mm shell L70	0	1	0	1
ISO Pipe	ISO Pipe	0	0	12	12
Clutter	Anchor	1	1	0	2
Clutter	Cement Block	1	1	0	2
Clutter	Scuba Tank	1	1	0	2
Clutter	Additional blind site clutter (e.g., crab traps, scrap metal, boat hook, propeller, ladder, chain, radar reflector)	24	0	0	24
Total # of Objects in Site		50	15	12	77

3.4.1 Calibration Site Design for MuST Technology

The MuST calibration site was similar to the site used in 2020. A 74 m long baseline consisting of 3/8" (9.5 mm) Everson Proline groundline was placed 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 made of 1/8" Amsteel line. The placement configuration is shown in Figure 3. Four targets were buried flush with the sediment (155 mm Howitzer, 155 mm Howitzer replica, 105 mm M60, 105 mm HEAT). Other inert UXO and clutter were placed proud on the surface.

As part of ESTCP project MR21-7211, *Scattering Strength of Target Lines Used to Facilitate Relocation/Recovery*, three types of tether lines were added on the surface to the west end of the calibration line (Figure 3): 10-meter segments of 550 paracord (approximately 1/8" 7-strand nylon kernmantle line), polycord, and 1/8" Amsteel Blue (12-strand single braid Dyneema). Lines used to facilitate target placement/recovery can potentially interfere with assessment of sonar-based UXO detection systems. Acoustic assessments of these lines by the MuST will be used to support the development of a model-based capability to predict detectability of lines in testbed environments.

MuST Calibration Line 2021

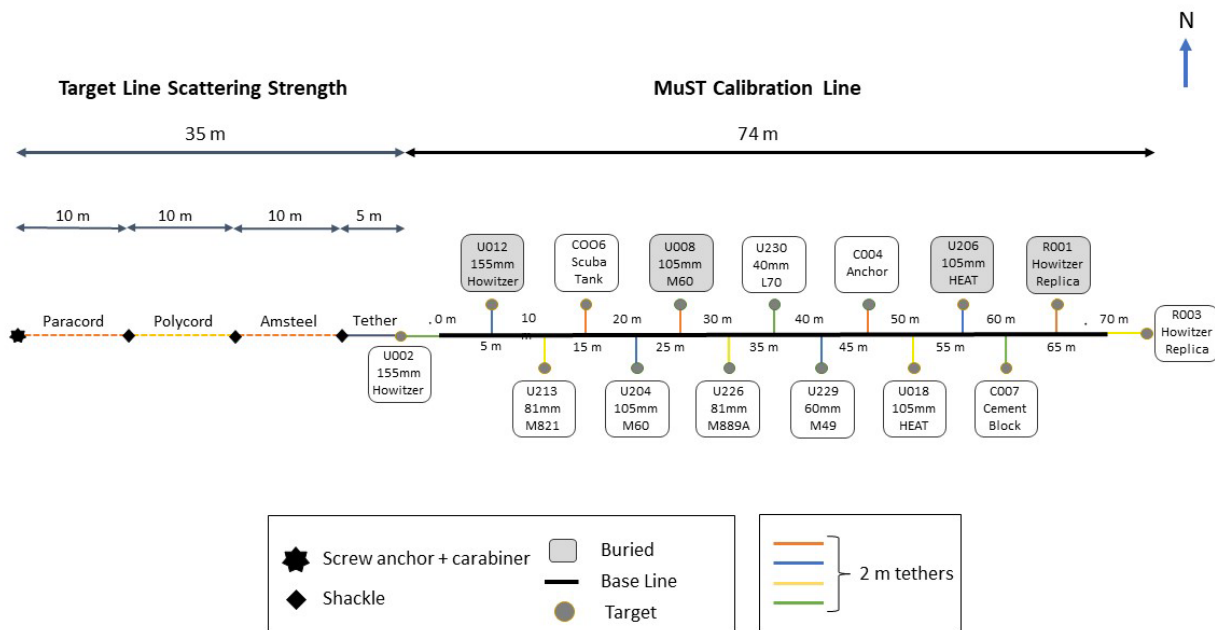


Figure 3. Layout of the targets at the MuST calibration site. Targets shaded gray were buried flush with the sediment surface. Additional target lines on the left were part of the Scattering Strength experiment. Numbers indicate the distance along the baseline.

3.4.2 Calibration Site Design for EMI Technology

The EMI UltraTEMA-4 calibration site was added to the testbed in 2021. A 65 m long baseline similar to the MuST calibration line was placed north of the MuST line and just south of the blind site (Figure 2). The line was anchored at each end with helical screw anchors and populated with 12 ISO steel pipes (six medium – 8” long schedule 40 – 2” diameter, and 6 large – 12” long schedule 40 – 4” diameter) (Figure 4, Table 3). Two of each size of pipe were placed either vertically in the substrate (z-orientation), parallel to the baseline (x-orientation), or perpendicular to the baseline (y-orientation). The targets were placed along the baseline at 5 m intervals, alternately offset to each side of the baseline with 2 m tethers, similar to the placement used at the MuST calibration site. A 10 m length of insulated copper wire ([2/0 AWG copper welding wire leads](#)) was placed at each end of the baseline, and secured at the proximal end with a screw anchor and at the distal end with a plastic stake. Both ends of one wire were sealed with Scotchcast splicing resin. The other copper wire was unsealed.

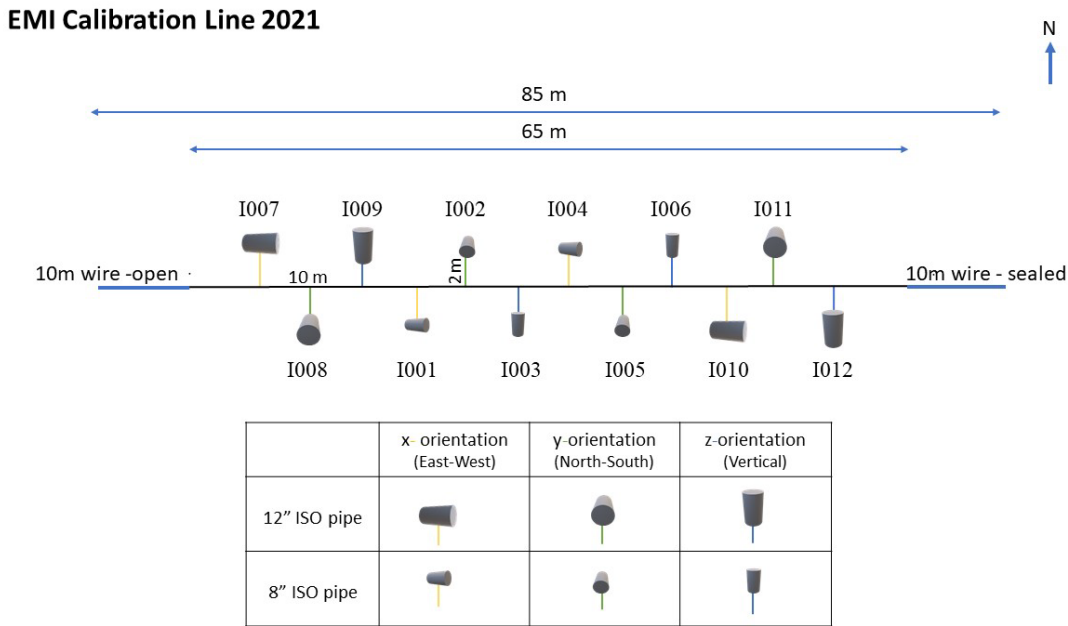


Figure 4. Target design layout of the EMI calibration site. Targets were oriented parallel to the baseline, perpendicular to the baseline, or vertically.

3.4.3 Blind Site Design

The Sequim Bay “blind” site location (Figure 1) was similar to 2020, but the configuration was changed from a 100 m square to a 100 m diameter circle (Figure 2). This modification allowed for more efficient coverage by the MuST with fewer passes required for overlapping coverage of multiple azimuthal angles (Williams et al. 2021). Divers placed 23 inert UXO and 27 clutter items in 10 clusters within the blind site grid (Figure 5). Each cluster was oriented around a central target with tethers attached to the other targets in the cluster. The number and location of items placed in the blind site were not known to APL-UW until their detection and classification results had been scored by IDA. Diver deployment methods are discussed in Section 4.3.

Underwater environments present unique and complex challenges with respect to target placement, geolocation of targets for both testbed managers and technology demonstrators, and subsequent scoring. Ground-truthing, data collection, and scoring challenges at underwater demonstration sites including Sequim Bay are discussed by Cazares and Bartel (2021). In 2021, the MuST demonstration was “officially” scored by IDA to determine how well the MuST could detect and classify UXO in the blind site. To avoid scoring ambiguities for the IDA assessment, the UXO-to-UXO target distances called for at least 9 m apart, and UXO-to-clutter distances to be at least 3 m apart. Distances between clutter items could be <3 m.

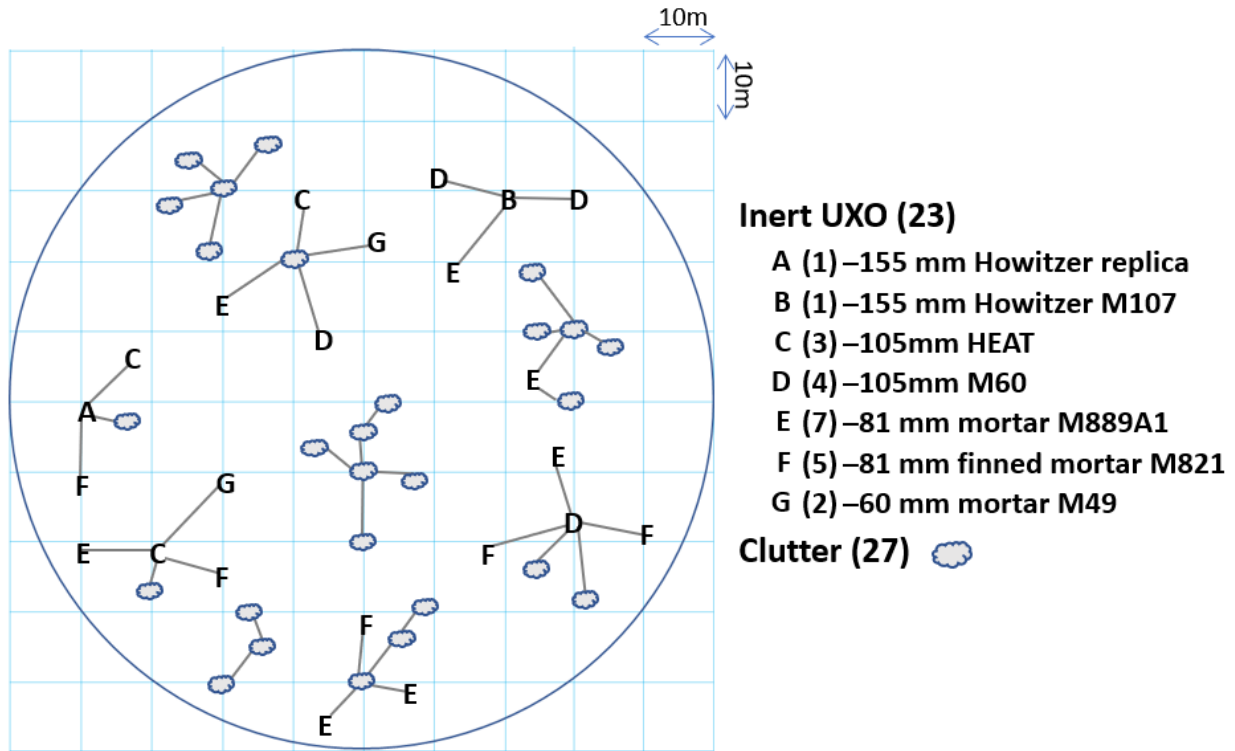


Figure 5. Conceptual design of the 2021 blind site showing the planned location of targets in a 100 m diameter test grid. Letters (A–G) identify the target types on the right with corresponding locations in the grid. The number of each target type is in parentheses ().

4.0 Testbed Operations

PNNL testbed operations in 2021 involved geolocation technology comparisons, target preparation, emplacement, ground-truthing, and recovery. PNNL provided logistical support for visiting technology demonstrators and other SERDP collaborators working in Sequim Bay. PNNL collected relevant environmental data before, during, and after the technology demonstrations.

4.1 Target Geolocation

4.1.1 Target Geolocation System Comparison

In 2021, PNNL continued identifying the most cost-efficient and practical diver-assisted underwater target geolocation technology system for testbed operations in Sequim Bay. PNNL conducted trials to evaluate geolocation performance for accuracy, precision, and efficiency in late spring and summer, prior to target emplacement. The trials site design consisted of three screw anchors set in an area between and west of the UltraTEMA-4 and MuST calibration lines (Figure 2). Divers deployed the screw anchors in a triangular configuration separated by 9–18 m.

During May and June three technologies and methods were used to collect geolocation data at the screw anchors. Four surveys were carried out with each technology at different times to provide a range of environmental conditions and 12 total position solutions for each screw anchor. The three different systems used for the comparison were (1) a real-time kinematic (RTK)-GPS surface buoy tethered to divers at the bottom (Woodruff et al. 2021), (2) and Applied Acoustics Vector Navigation (VNav™) acoustic system, and (3) an iXblue GAPS™ USBL. The GPS surface buoy system was similar to the one used for target geolocation in 2020, with a significant upgrade to a RTK-GPS base station and rover from Emlid (model Reach RS2™ receivers).

The VNav™ acoustic system consisted of a vessel-mounted transceiver and three remote beacons that were lashed to the screw anchors and unable to move in the current. The system required integration with the RTK-GPS system for accurate transceiver location surface position input within several centimeters. Measured offsets from the RTK-GPS receiver mounted on the roof of the PNNL vessel wheelhouse to the submerged VNav™ transceiver were input into the VNav™ system. To generate an accurate geolocation solution, the VNav™ system calculates a least-squares minimization from multiple acoustic ranges between the transceiver and beacon in a 360° halo surrounding the target. Each quadrant requires approximately 30 ranges for a total of 120 ranges per geolocation solution and with 1 ping every 5 seconds, vessel speeds of 1–2 knots, and survey circles on the order of 50 m diameter, each geolocation solution required 10–15 minutes of survey time.

The GAPS™ USBL system also included a vessel-mounted transceiver submerged 1 m below the boat's keel, three remote beacons lashed to the screw anchors and RTK-GPS integration. Unlike the VNav™, the GAPS™ relies on an internal high-grade inertial motion unit, compass, and a four-element internal transceiver array to generate single range geolocation solutions. The advanced GAPS™ USBL calculates 3-D geolocation positions from phase delays in the received acoustic ping replies from the individual beacons and can track and locate multiple beacons at the same time. During the GAPS™ surveys, the ping rate was also set at 1 ping

every 5 seconds as allowed under PNNL permit authorizations, and 50–60 points were taken as the vessel made one complete 50 m diameter circle around the targets in roughly 7–8 minutes.

Both the VNav™ and GAPS™ acoustic geolocation systems performed well and within the tolerance expected (accuracy <1m, Figure 6), but some operational requirements set them apart as viable options for the Sequim Bay test bed. The VNav™ system provides a solution at a lower upfront cost (\$20K VNav™ system + 10 beacons @ \$5K each, total system approximately \$70K), but surveys require two dives to place a set of 10 beacons over targets, recover them, and place them over the next set of 10 targets. In between dives, the vessel performs the acoustic geolocation effort that takes twice the time as the GAPS™. The VNav™ system would require more diver time and thus higher overall cost to geolocate targets accurately.

Although more expensive with an approximate cost of \$200K, the GAPS™ system provides real-time beacon tracking and geolocation solutions from diver-held beacons. As divers move through an area, multiple beacons can be tracked, allowing ground-truthing in a single diver-assisted effort. The GAPS™ system can provide a long-term, cost-efficient, and highly accurate geolocation approach for test bed operations.

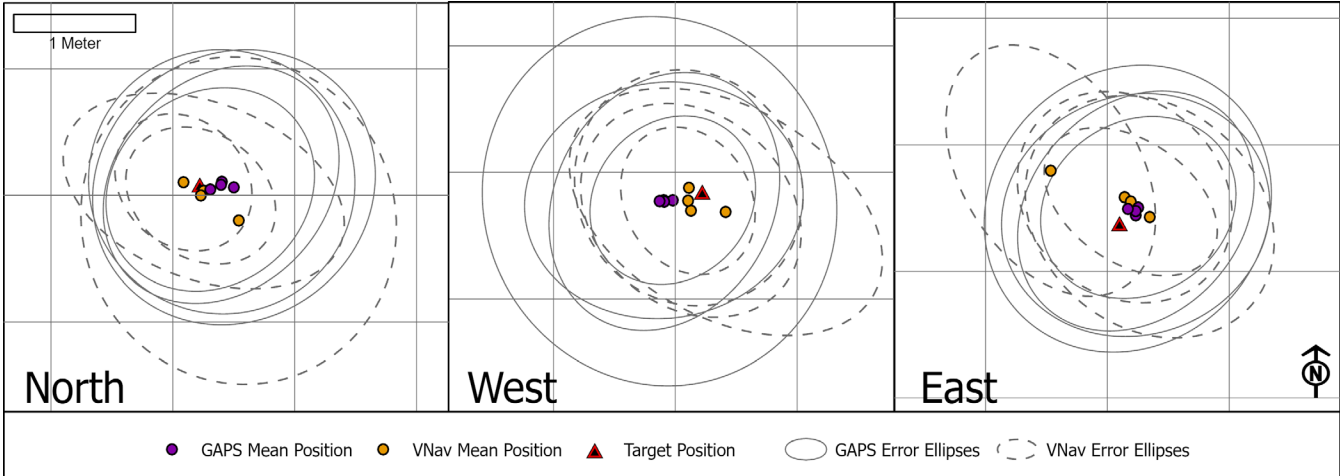


Figure 6. Results from geolocation system trials at three screw anchor positions in the testbed. The red outlined triangles indicate the GPS surface buoy position taken as the ground-truth position for the screw anchors. Four survey points from each technology are shown in blue and orange, and the error ellipses defined by the scatter in the solutions are shown as thin dashed and solid lines.

4.1.2 Geolocation System Used for 2021 Operations

After identifying a USBL system as the best technology for target geolocation in Sequim Bay, PNNL leased an Applied Acoustics EasyTrak™ USBL similar to the system used in 2020, with several additional upgrades, including RTK-GPS input and a high-grade gyro compass system. The iXblue GAPS™ USBL system used in the geolocation trials was not available for lease during operations. Several initial check-out geolocation surveys at the trials area revealed high scatter in the positions (5–6 m) beyond the <1 m tolerance expected for the system. Troubleshooting with the vendor showed intermittent performance improvements, but after nearly 2 weeks of testing, the EasyTrak™ system was deemed to have a hardware malfunction and was returned to the vendor with no lease costs incurred to the project. After consultation

with the SERDP/ESTCP program office, a decision was made to collect geolocation ground-truth data using the Global Navigation Satellite System (GNSS) surface buoy method used in 2019–2020.

The GNSS surface buoy method requires calm winds and limited tidal currents to provide accurate geolocation for targets on the seafloor (Woodruff et al. 2021). Because of these limitations, ground-truthing dives were scheduled around daytime slack tidal windows that were evaluated for wind prior to deployment. These challenges resulted in a large number of canceled dives, extending the ground-truth data out 10 weeks after the UltraTEMA-4 system demonstration—well beyond the planned 2-3 weeks. Issues with the RTK base station correction for the new Emlid system required a change to the Trimble GNSS receiver used in 2020, which required post-process kinematic corrections. The issue with the Emlid base correction has since been resolved and that system is reporting horizontal errors on the order of 1–2 cm. GNSS buoy surveys collected with the Trimble system were immediately post-process kinematic corrected and reviewed for data quality and accuracy to determine if additional dives to revisit targets were necessary. This process provided further confidence for the target geolocations.

4.2 Target Preparation

As in previous years, target tethers were used to ensure proper target placement and recovery, and help the divers navigate under conditions of poor visibility. In an effort to make the tethers more acoustically “invisible” and not affect the target acoustic signatures, previous techniques with improvements were used to connect targets. The baseline of each calibration line was 3/8” (9.5 mm) Everson Proline groundline. This line is sturdy, easy to splice, visible, easy to manipulate underwater, and did not need to be acoustically transparent. The 2 m tether lines attaching targets to the baseline were made of the same type of 1/8” (approximately 3 mm) Amsteel line used in 2020. Instead of the wooden toggles used in 2020 that were visible to the MuST system, Amsteel line was spliced directly to the target to minimize any physical anomalies that could be a cue for the demonstrators.

Each line was attached to the target in the most low-profile manner possible. If there was a ring or hole in the target the line was spliced directly through it (e.g., Figure 7A). Otherwise, the line was tightly spliced around the target as a harness using any depression, width change, and accessories available to help keep the line in place (Figure 7B, C). When the line was wrapped around the target, the splice was tightened using a whipping with waxed thread to take up as much slack as possible (Figure 7B). To attach the target tether to the baseline, 3/4” (19 mm) flat side quick release plastic buckles were used at the baseline to allow quick and positive connections during deployment and recovery (Figure 7D). These buckles were smaller than those used in 2020, and the female side of the buckle clip was attached to the baseline with a zip tie spliced through the weave of the baseline at 5 m intervals. Coded rubber hose washers were also attached to the baseline at tether attachment points to indicate the distance along the baseline for orienting the divers in low visibility (Figure 7D, e.g., 4 washers = 40 m along the baseline). The male side of the clip was spliced to the distal end of the target tether ensuring the clips were as far away from the targets as possible to avoid inference with the acoustic profile of the target.

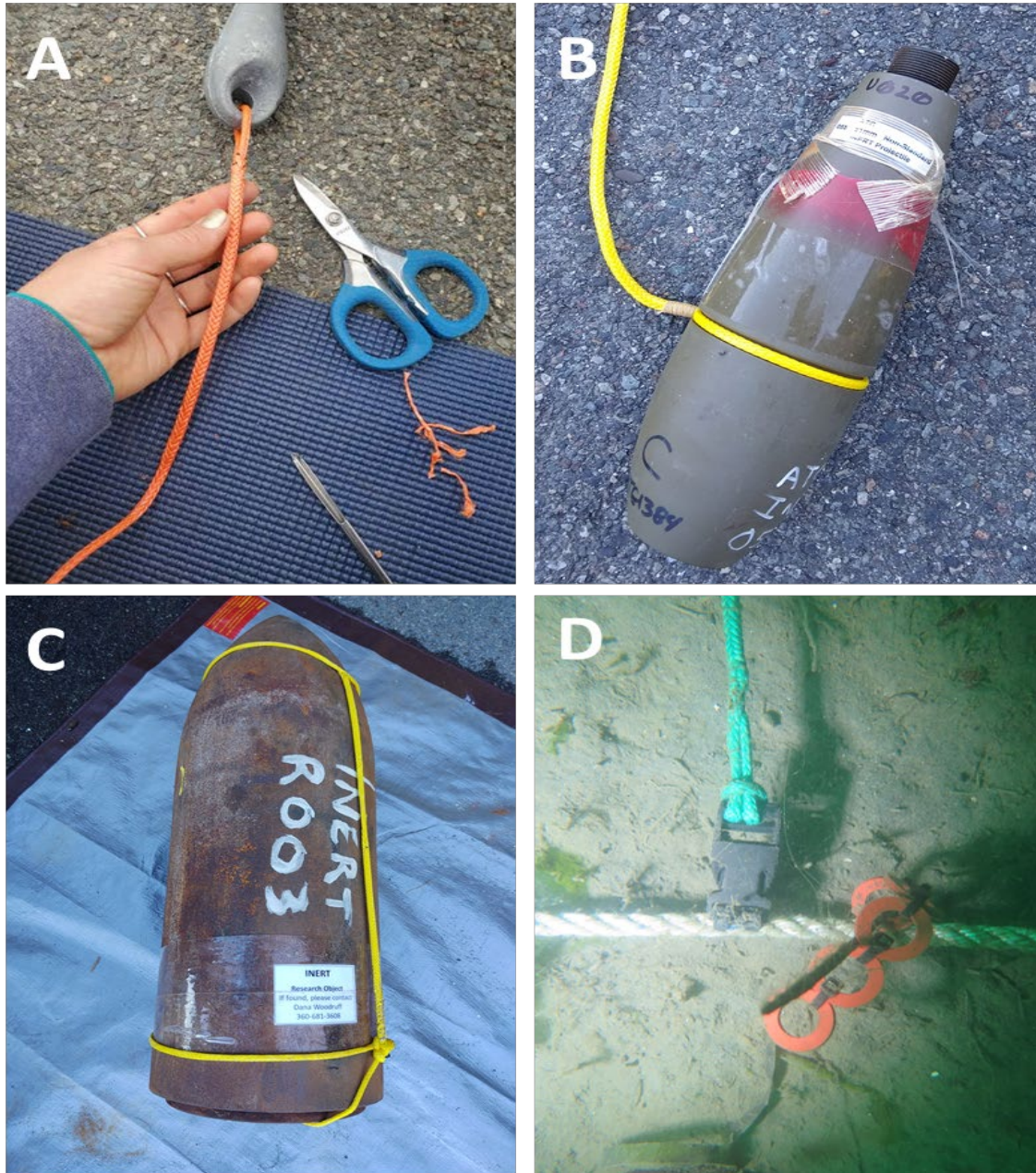


Figure 7. Attachment mechanisms for the target tethers. (A) Tether is spliced directly to the target. (B) Tether is wrapped around the target; note the whipping (tan) on the line at the target to tighten the line. (C) Harness constructed around the target. (D) Side-release clips used to attach the tether line (green) to the baseline (white); note the hose washers used to mark distance along the baseline.

In the blind site, acoustic transparency of the tethers was a high priority to avoid cues for target locations. Therefore, the Amsteel line was used for all the lines in the blind site. Tethers were of various lengths, depending on the layout of the cluster, and were spliced directly to the targets in the same manner as those at the calibration site. The distal end of the tether was left free for divers to tie to the center target in each cluster (Figure 8A). No clips, buckles, or thicker lines were used in the blind site, thereby minimizing acoustic cues or interference.

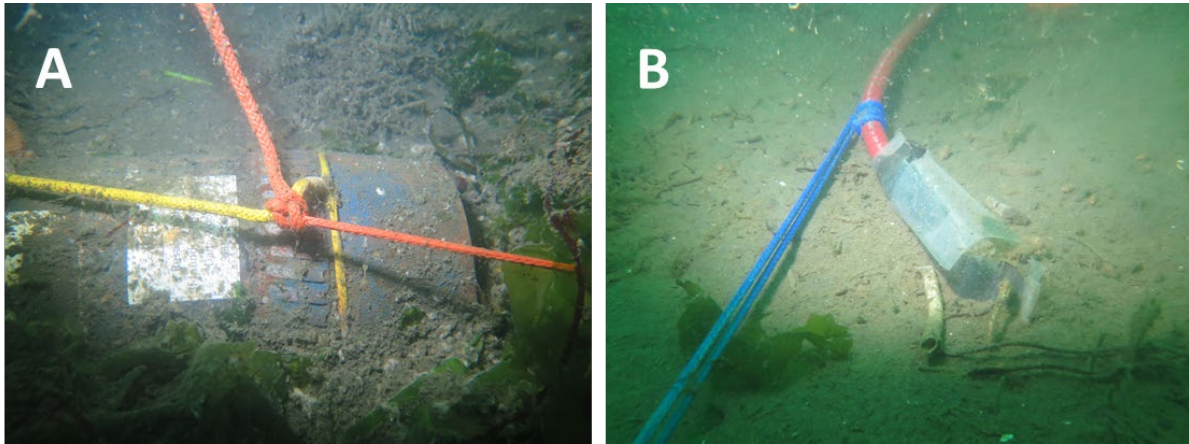


Figure 8. Additional low-profile attachment methods for tethers. (A) Orange tether tied to yellow harness in one of the blind site clusters. (B) Prussik knot used to attach the potted cable end to a tether.

4.3 Target Emplacement

PNNL divers placed targets using the same methods as previous years with slight modifications. Prior to each dive, a set of targets was identified according to the deployment plan, marked with a unique identifier so divers could place it in the correct location on the seafloor. A weighted downline was deployed at each pre-determined deployment site using the vessel GPS and was marked at the surface with a large buoy. The targets were then either deployed from the vessel as the anchor for the downline or were attached individually or in bags to the deployed downline using a carabiner and slid down to the seafloor (Figure 9). The divers descended the same downline and placed the targets according to the planned layout.

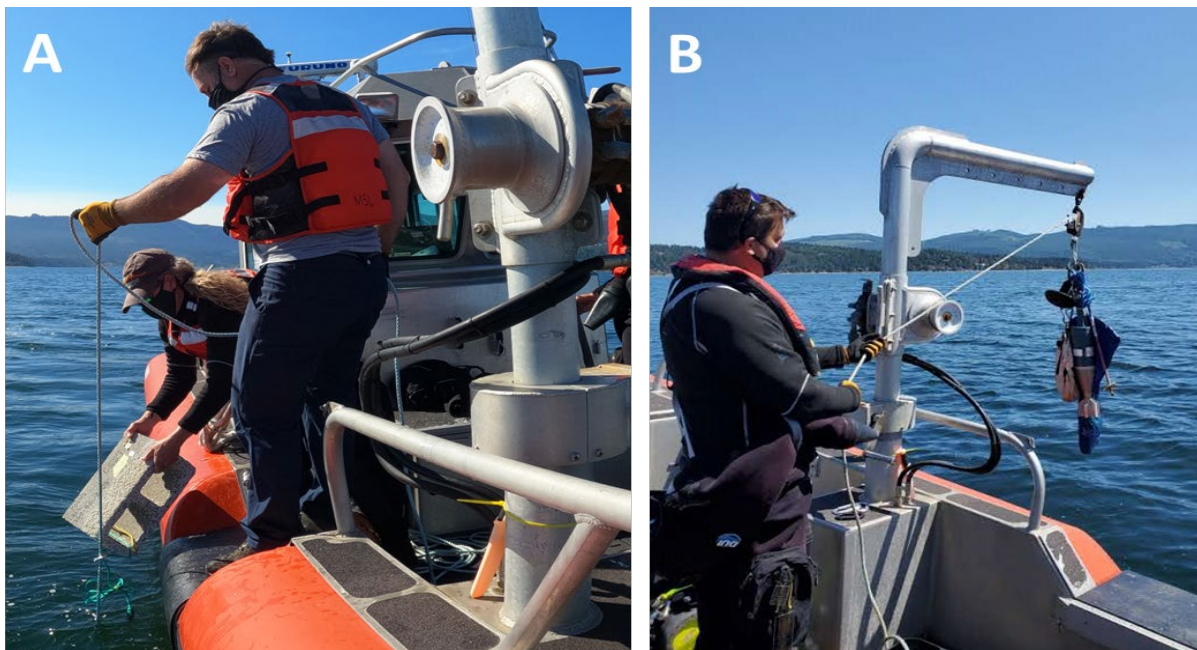


Figure 9. Dropping targets to a calibration line, using an anchored downline and carabiner (A) and dropping all targets with the downline to a blind site cluster (B).

4.3.1 Calibration Sites

The two calibration lines were deployed this year using similar methods. A downline was dropped at the western GPS point of each calibration line. Divers descended and installed a helical screw anchor in the seafloor to act as an anchor point for the baselines. The divers then swam a compass bearing to deploy the rest of the baseline along the seafloor. Baselines were premeasured so the divers could deploy the length of the baseline, pull it tight, and then install a second screw anchor at the eastern end. Another downline with a surface buoy was then attached to the eastern end of the calibration lines so the divers could use either end of the baselines for ascents, descents, and deploying targets from the vessel.

Half the targets were dropped on each end of the baselines to minimize the swimming required. The divers disconnected each target from the downline and swam along the baseline to the appropriate position for attachment of each target. Labels on the targets, markings on the baselines, and the communications with the boat ensured proper positioning. Once the target was at the appropriate position along the baseline, the end of the tether was clipped into the buckle on the baseline and the target was swum perpendicular to the baseline to the full extent of the tether (i.e., 2 m). The second diver held the baseline so it would not be deflected and to make sure the swimmer was perpendicular to the line.

4.3.2 MuST Calibration Line

At the western end of the MuST calibration line, a set of different test line types (Section 3.4.1, Figure 3) were attached in series (bearing west) to the end of the baseline. A shackle connected each 10 m length of line to the next and another screw anchor was set to anchor the western end of the last 10 m section of line. On the main body of the baseline, several targets were buried by hand by the divers. Once all targets and test lines were deployed, the screw anchors were removed.

4.3.3 EMI Calibration Line

The EMI calibration line also had a 10 m long section of insulated copper wire attached to each end (Section 3.4.2, Figure 4). The length of wire cable was attached to the screw anchors with an Amsteel tether (Figure 8B). The end of the cable was staked down with a large plastic ground stake to keep it in place without interfering with the magnetic signature of the wire.

4.3.4 Blind Site

The blind site was not set up along a baseline like the calibration sites but was instead deployed in clusters. Targets were grouped into 10 clusters consisting of two to five smaller targets tethered radially around a central heavier target. During deployments, the targets for each cluster were attached to the anchored downline that was placed at the position of the center target. Divers then descended the downline, located each radial target, tied the free end to the harness or ring on the center target with a two half-hitch knot, and pulled the target to the full extent of the tether line in a pre-determined compass bearing.

The working depths of the testbed limited the dive to approximately 25–30 minutes of bottom time. The blind site targets were deployed in 10 dives (i.e., one per cluster), the MuST calibration line was deployed in seven dives, and the EMI calibration line was deployed in four dives. An additional three dives were used to document the sites with photographs and videos. All deployments were conducted between mid-July and the end of August 2021.

4.4 Target Ground-Truthing

A full suite of descriptive information was recorded for each target (UXO and clutter items) during the ground-truth data collection. Descriptions included the following information:

- 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
- coordinates of the fiducial point of each emplaced target in Universal Transverse Mercator units to two decimal points, and latitude/longitude (WGS 84) to seven decimal points
- burial depth of each target to the top center (within 5 cm)
- azimuth (orientation) of each target (within 10°, magnetic north)
- inclination (tilt) of each target (within 5° from horizontal), + is nose up, - is nose down
- other diver observations (e.g., biofouling, tether status—taut, loose, disconnected).

Similar to last year, the inclination of the target was estimated from the perceived centerline of the target if there was no obvious edge (e.g., a crab trap has an obvious edge but the curved sides of the finned mortar do not). To measure buried targets, the target was unburied enough to find the upper edge, which was used to estimate the centerline.

Ground-truth information collected for both calibration sites are shown in Table 4. Ground-truth information for the MuST line was collected on six dives between September 1 and 17. Ground-truth information was collected on nine dives from the EMI calibration line between August 26 and September 21 with two additional geolocation confirmation dives in November and December.

Table 4. Ground-truth information collected by divers from the MuST calibration site, and the EMI calibration site.

	Date	PNNL ID	Target Type	Description	Target Burial	Burial Depth	Diver Compass Orientation (deg magnetic)	Tilt (deg) ^(a)
MuST Calibration Line	9/16/21	R003	Replica	155 mm Howitzer replica	proud		315	2.5
	9/16/21	R001	Replica	155 mm Howitzer replica	full	15 cm	NA	NA
	9/16/21	C007	Clutter	Cement Block	proud		320	5
	9/16/21	U206	UXO	105 mm HEAT	full	5 cm	310	NA
	9/16/21	U018	UXO	105 mm HEAT	proud		140	-10
	9/17/21	U002	UXO	155 mm Howitzer projectile M107	partial	1/2 buried	30	-2
	9/17/21	U012	UXO	155 mm Howitzer projectile M107	full	>15cm deep	300*	NA
	9/17/21	U213	UXO	81 mm mortar M821	partial	1/4 buried	330	-8
	9/17/21	C006	Clutter	Scuba tank	proud		325	4
	9/17/21	U204	UXO	105 mm projectile M60	proud		350	2
	9/17/21	U008	UXO	105 mm projectile M60	full	>15cm deep	310*	NA

Date	PNNL ID	Target Type	Description	Target Burial	Burial Depth	Diver Compass Orientation (deg magnetic)	Tilt (deg) ^(a)
9/17/21	U226	UXO	81 mm mortar M889A1	proud		350	-2
9/20/21	U230	UXO	40 mm mortar L70	partial	1/2 buried	350	-3
9/20/21	C004	Clutter	Anchor	proud	flukes 2/3 covered	0	25
9/20/21	U229	UXO	60 mm mortar M49	partial	1/2 buried	190	-4
9/20/21	I001	ISO Pipe	Medium ISO pipe 8"	partial	1/2 buried	55	4
9/20/21	I002	ISO Pipe	Medium ISO pipe 8"	proud		340	2
9/20/21	I003	ISO Pipe	Medium ISO pipe 8"	partial	10cm exposed	vertical	2 N
9/20/21	I004	ISO Pipe	Medium ISO pipe 8"	proud		30	2
9/20/21	I005	ISO Pipe	Medium ISO pipe 8"	proud		310	0
9/20/21	I006	ISO Pipe	Medium ISO pipe 8"	partial	11cm exposed	vertical	0
9/20/21	I007	ISO Pipe	Large ISO pipe 12"	proud		30	5
9/20/21	I008	ISO Pipe	Large ISO pipe 12"	proud		330	0
9/20/21	I009	ISO Pipe	Large ISO pipe 12"	partial	20cm exposed	vertical	1
9/20/21	I010	ISO Pipe	Large ISO pipe 12"	partial	1/4 buried	60	4
9/20/21	I011	ISO Pipe	Large ISO pipe 12"	proud		330	-2
9/21/21	I012	ISO Pipe	Large ISO pipe 12"	partial	15cm exposed	vertical	6 SW

(a) tilt + = nose up, - = nose down.

Ground-truth information for the blind site was collected by divers during 17 dives from all targets (inert UXO and clutter) shortly after the demonstrations were complete (October to early December 2021). Table 5 includes ground-truth information for the 23 inert UXO emplaced at the blind site. Appendix A lists the geolocation information and target type for all items emplaced at the blind site (inert UXO, clutter, replicas).

Table 5. Ground-truth information collected by divers from inert and replica UXO targets at the blind site. Clutter items are not shown.

Cluster	Date	PNNL ID	Target Type	Description	Target Burial	Burial Depth	Diver Compass Orientation (deg magnetic)	Tilt (deg)
1	11/22/21	U007	UXO	105 mm projectile M60	partial		220	10
1	11/22/21	U210	UXO	81 mm mortar M821	proud		due South	0
1	11/22/21	U224	UXO	81 mm mortar M889A1	proud		250	-10
1	11/22/21	U211	UXO	81 mm mortar M821	proud		230	-3
2	11/30/21	U209	UXO	81 mm mortar M821	proud		330	5
2	11/30/21	U223	UXO	81 mm mortar M889A1	partial	1/4 buried	90	-10
2	11/30/21	U222	UXO	81 mm mortar M889A1	partial	1/2 buried	110	-10
4	10/15/21	U016	UXO	105 mm HEAT	partial	1/2 buried	270	-8
4	10/15/21	U225	UXO	81 mm mortar M889A1	proud		190	10

Cluster	Date	PNNL ID	Target Type	Description	Target Burial	Burial Depth	Diver Compass Orientation (deg magnetic)	Tilt (deg)
4	10/15/21	U228	UXO	60 mm mortar M49	buried		300	-25
4	10/15/21	U212	UXO	81 mm mortar M821	partial	3/4 buried	30	-15
5	12/10/21	R002	Replica	155 mm Howitzer replica	proud		350	3
5	12/10/21	U006	UXO	81 mm mortar M821	proud		200	2
5	12/10/21	U014	UXO	105 mm HEAT	proud		280	-5
7	11/19/21	U001	UXO	155 mm Howitzer	partial	1/2 buried	230	3
7	11/19/21	U010	UXO	105 mm projectile M60	partial	3/4 buried	160	10
7	11/19/21	U011	UXO	105 mm projectile M60	partial	1/2 buried	180	15
7	11/19/21	U020	UXO	81 mm mortar M889A1	partial	1/4 buried	200	-10
8	10/19/21	U003	UXO	105 mm HEAT	partial	3/4 buried	NA	NA
8	10/19/21	U227	UXO	60 mm mortar M49	proud		260	4
8	10/19/21	U009	UXO	105 mm projectile M60	partial	1/2 buried	270	10
8	10/19/21	U019	UXO	81 mm mortar M889A1	partial	1/2 buried	NA	10
10	12/3/21	U015	UXO	81 mm mortar M889A1	partial		30	0

Figure 10 shows the final placement of inert UXO and clutter items in the blind site. This target field was used for a formal demonstration of the MuST in late September 2021 (Section 4.5). While the design of the blind site target field called for at least a > 9 m separation between UXO and UXO, and a >3 m separation between UXO and clutter (Section 3.4.3), several nearest neighbor distances ranged from 5–9 m between UXOs and from 2.4–3 m between UXO and clutter items.

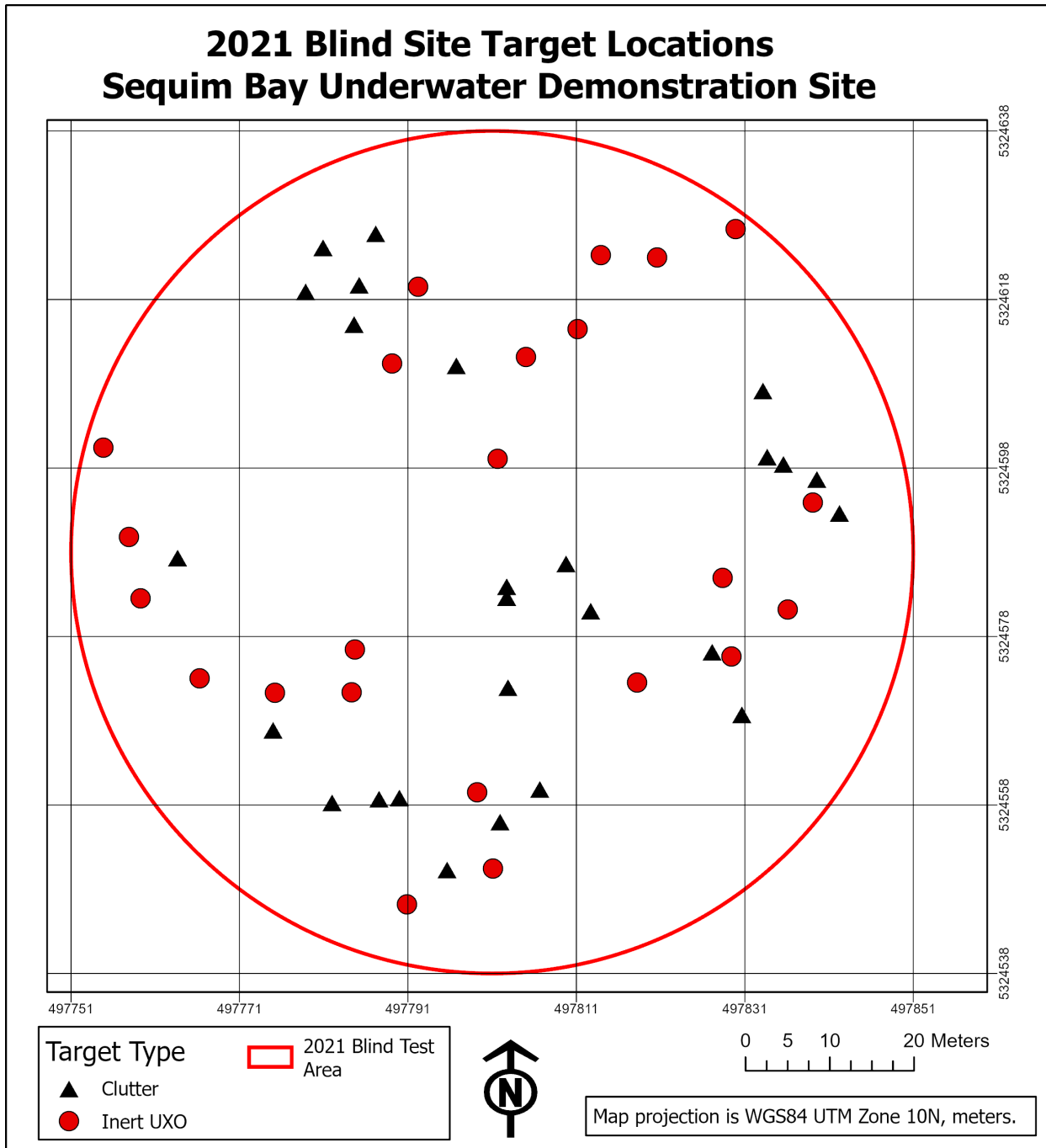


Figure 10. Location of the 2021 target locations at the blind site, including 23 UXO and 27 clutter items.

4.5 Technology Developers and Collaborators

4.5.1 Formal Demonstration of APL-UW MuST Technology

The APL-UW team conducted their first formal demonstration of the MuST in Sequim Bay between September 27 and October 1, 2021, supported by their research vessel *R/V Jack Robertson*. Logistical support from PNNL-Sequim was provided as needed to the APL-UW staff during the demonstration. Prior to the demonstration, position and ground-truth information was provided for each target along the MuST calibration line (Figure 3), and a list of target types that were present in the calibration line and could be present in the blind site (Table 3). No other information was provided to them regarding the blind site (i.e., number of targets or clutter items, position information).

4.5.2 Engineering Test of Black Tusk/Tetra Tech UltraTEMA-4

The Black Tusk Geophysics/TetraTech team conducted their first engineering/shakedown test of the UltraTEMA-4 technology in Sequim Bay on October 4–8, supported by the *R/V Ugle Duckling*. PNNL-Sequim staff provided logistical support as needed. Prior to the demonstration, position and ground-truth information was provided to the team for each target along the EMI calibration line (Table 4), as well as all targets along the MuST calibration line. Although this was not a formally scored demonstration, no additional information was provided regarding the blind site in order to provide the opportunity for an informal demonstration of their platform over a target field. A PNNL marine mammal observer was onboard the *R/V Ugle Duckling* during operation of their towed platform.

4.5.3 Geotechnical Survey

During the week of October 25, 2021, Dr. Nina Stark (Virginia Tech) conducted a sediment survey in Sequim Bay to assess the shear strength and pore pressure response of sediments. Three types of technologies were deployed: (1) a PFFP (BlueDrop by BlueCDesigns) was deployed in the upper meter of sediment to collect soil density information; (2) a ponar sediment grab sampler was used to collect surface sediments at selected sites; and (3) a gravity core sampler (10 cm in diameter, 80 cm in length). The 76 station locations are shown in Figure 11. PNNL vessels (*R/V Strait Science*, *R/V Desdemona*) and crew supported the Virginia Tech crew during all field operations.

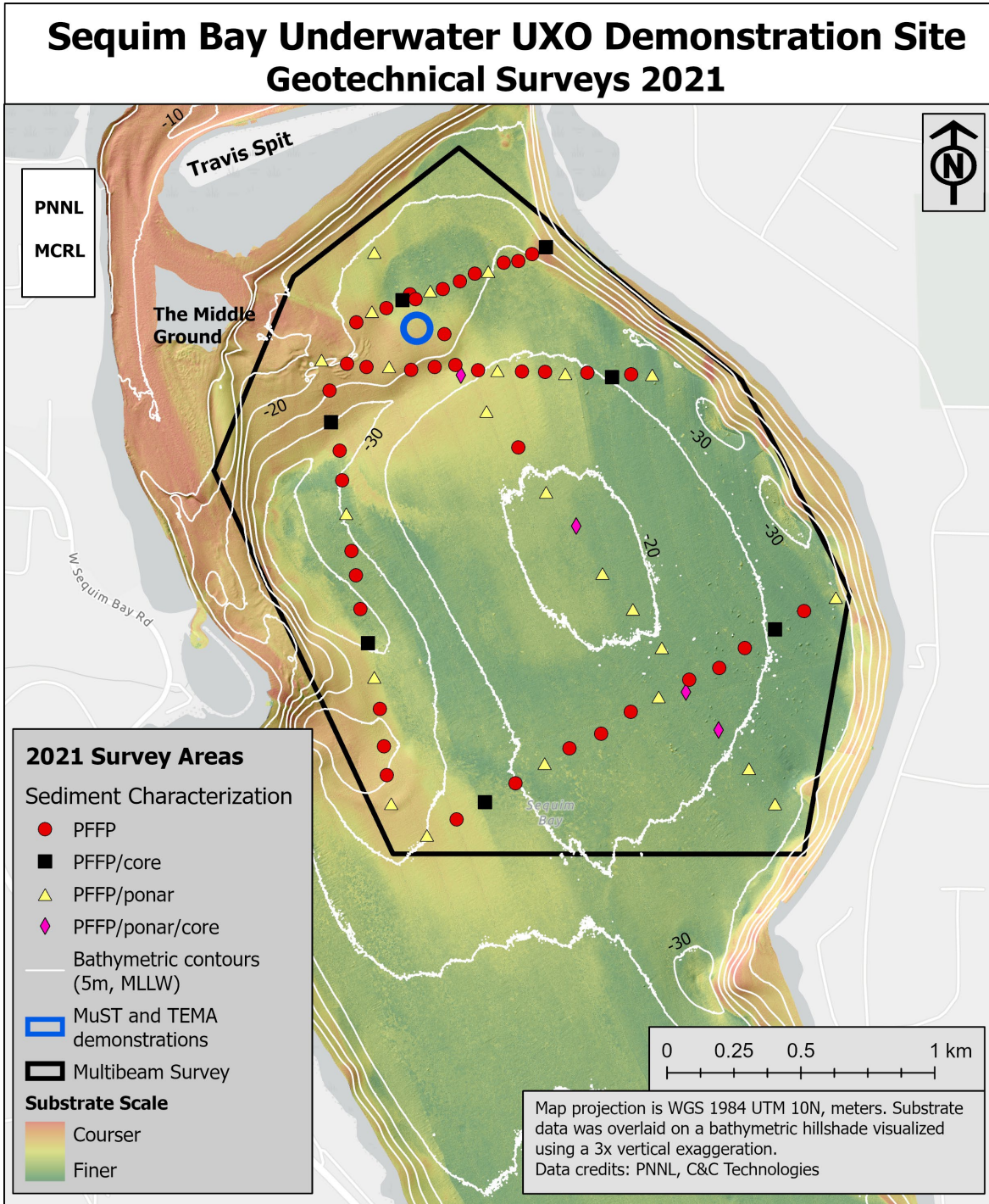


Figure 11. Station locations of sediment collection information within Sequim Bay for the portable free-fall penetrometer, gravity core, and ponar grab sampler.

4.5.4 Multibeam Survey

As part of SERDP project MR18-1406, *Demonstration of Physics-based Inversions of Multibeam Echosounder for Sediment Properties*, APL-UW (Hefner-PI) conducted a multibeam sonar survey between November 16 and 20, 2021. The survey was conducted by the *R/V Robertson* using a Teledyne RESON T-50 multibeam echosounder. The area surveyed is shown in Figure 11 (black polygon) and data were collected in collaboration with the Virginia Tech team (Section 4.5.3).

4.6 Target Recovery

Target recoveries were conducted in the same manner as in 2020 and 2021. After the target characterization and geolocation were completed, the divers attached buoyed uplines to each target for retrieval. This was done for individual targets if they were large, heavy, or a farther distance from other targets. Multiple smaller targets were brought to a common location and attached to the same upline to be lifted to the surface. The vessel would then go to each upline buoy and lift the targets to the surface either by hand or using the hydraulic davit.

Target retrieval was conducted between mid-December and the beginning of February. The blind site clusters required 12 dives, the EMI calibration line required 2 dives, and the MuST calibration line required 10 dives.

4.7 Environmental Characterization

4.7.1 Environmental Data Collection

Quantitative and qualitative environmental measurements and observations were collected during the field season at the calibration site and blind site. An environmental data collection log sheet was developed in consultation with IDA's scoring team to identify the environmental observations that best inform both ground-truth data collection activities and demonstrator technology performance. The latter would also assist in performance comparisons of UXO remediation technologies in different testbed environments and project sites. Environmental data logged during each vessel operation included the following:

- tidal stage (slack high, ebb, slack low, flood)
- average/gust wind speed (hand-held anemometer) and direction
- air temperature
- conductivity, temperature, depth (CTD) profiles using a Sontek Castaway™ CTD – also provides salinity and sound speed
- secchi depth – turbidity
- wind wave height (qualitative)
- precipitation and cloud cover (qualitative).

In addition to data collection from the PNNL vessel during daily activities, an ADCP was deployed between the blind and calibration sites to record water current velocities. A Nortek ECO™ ADCP measured water column speed and direction every 4 minutes from October 15, 2021, to November 14, 2021. The ADCP was suspended 1 m from the seafloor and recorded

10,687 samples in three layers below the surface at 11.3 m, 14.9 m, and 18.5 m depths. Hydrostatic pressure, temperature, and tilt were also measured by the ADCP.

4.7.2 5.9.2 Data Summaries

The 48 CTD profiles are summarized in Figure 12. Mean levels for variables at each depth are shown as bold lines, and the range of values is highlighted. Variability was greatest in the top 5 m of the water column, caused by mixing from winds, freshwater input from precipitation, and solar surface warming and cooling. Mean profiles from the CTD measurements show little variation with depth, yet individual profile measurements could vary substantially.

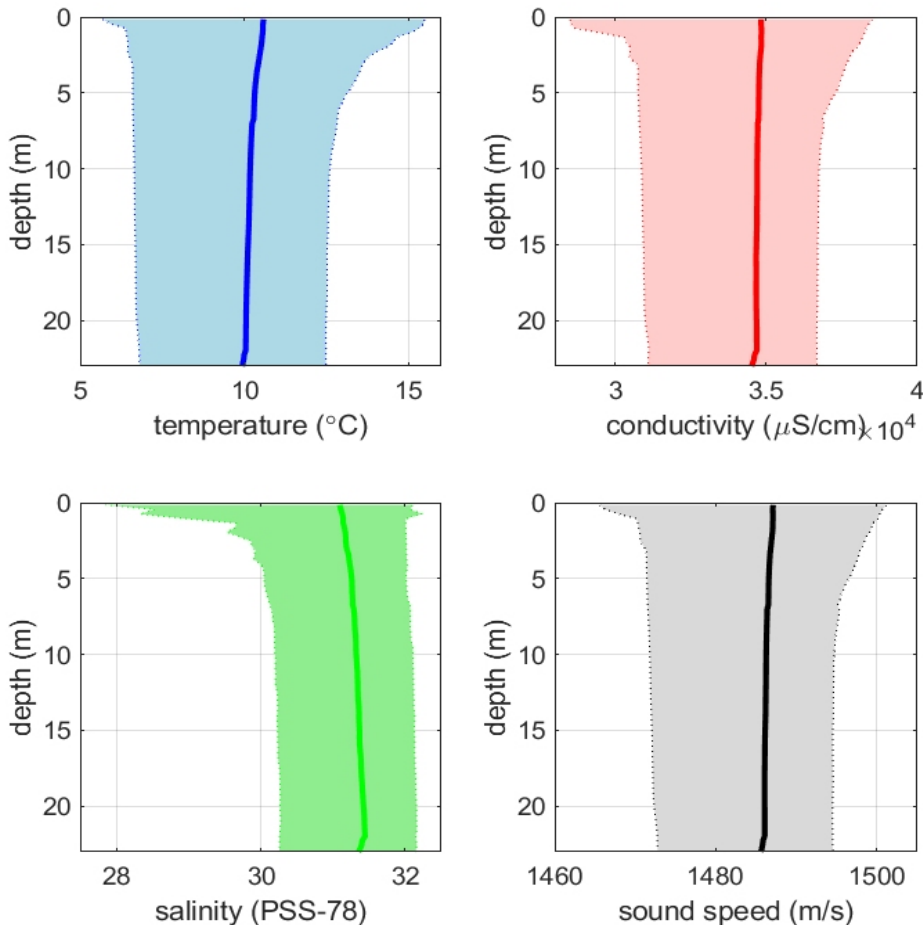
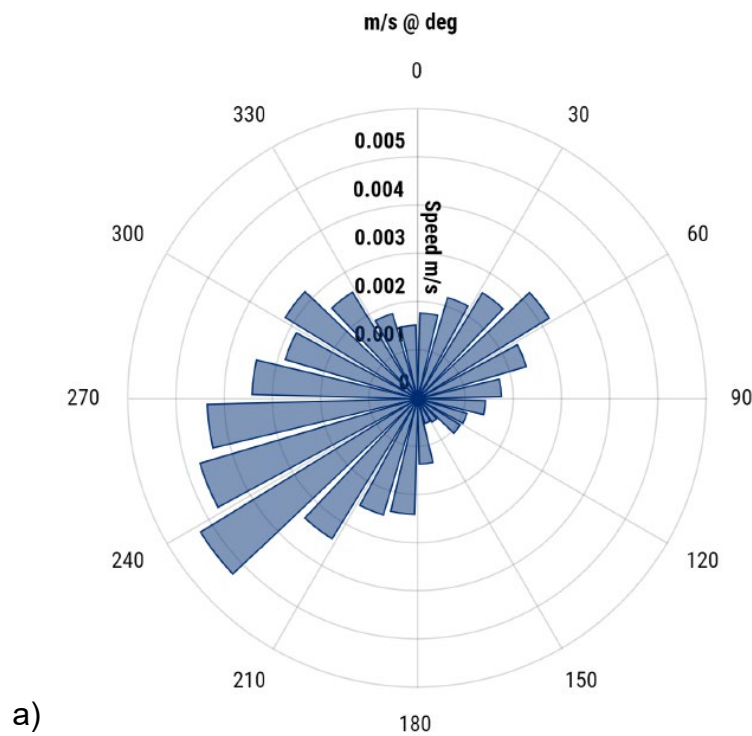


Figure 12. Clockwise from top left: temperature, conductivity, sound speed and salinity versus depth summary plots from 48 individual CTD casts in the Sequim Bay test bed in 2021. Bold lines show mean values with shading representing the range of values.

The month of data collected by the ADCP showed the mean flow was generally strongest and most frequently observed coming from the southwest (Figure 13). This pattern is observed most strongly in the upper water column; near the seafloor at 18.46 m the mean flow speed is more symmetric between ebb and flood tides moving in the southwest and northeast directions. The maximum current speeds and directions (Figure 14) show that flows coming from the northeast are strongest, opposite of the dominant mean current speed and direction. The maximums are associated with peak flows during the larger excursions of the spring/neap tidal cycle. Summary statistics are given in Table 6.

Table 6. Summary statistics of current speeds and directions at three depth layers (upper = 11.3 m, middle = 14.9 m, lower = 18.5 m) measured by the ADCP in the Sequim Bay testbed during October 15, 2021–November 14, 2021.

		Upper	Middle	Lower	Unit
Speed	Mean	0.06	0.05	0.05	m/s
	Max	0.77	0.73	0.66	m/s
	Min	0.00	0.00	0.00	m/s
	Std. dev	0.05	0.05	0.05	m/s
	Mean	Max	Min	Std. dev	Unit
Temperature	9.9	16.8	9.6	0.2	°C
Pressure	20.9	22.1	0.0	0.8	m
Tilt	1.2	16.0	0.7	0.2	deg



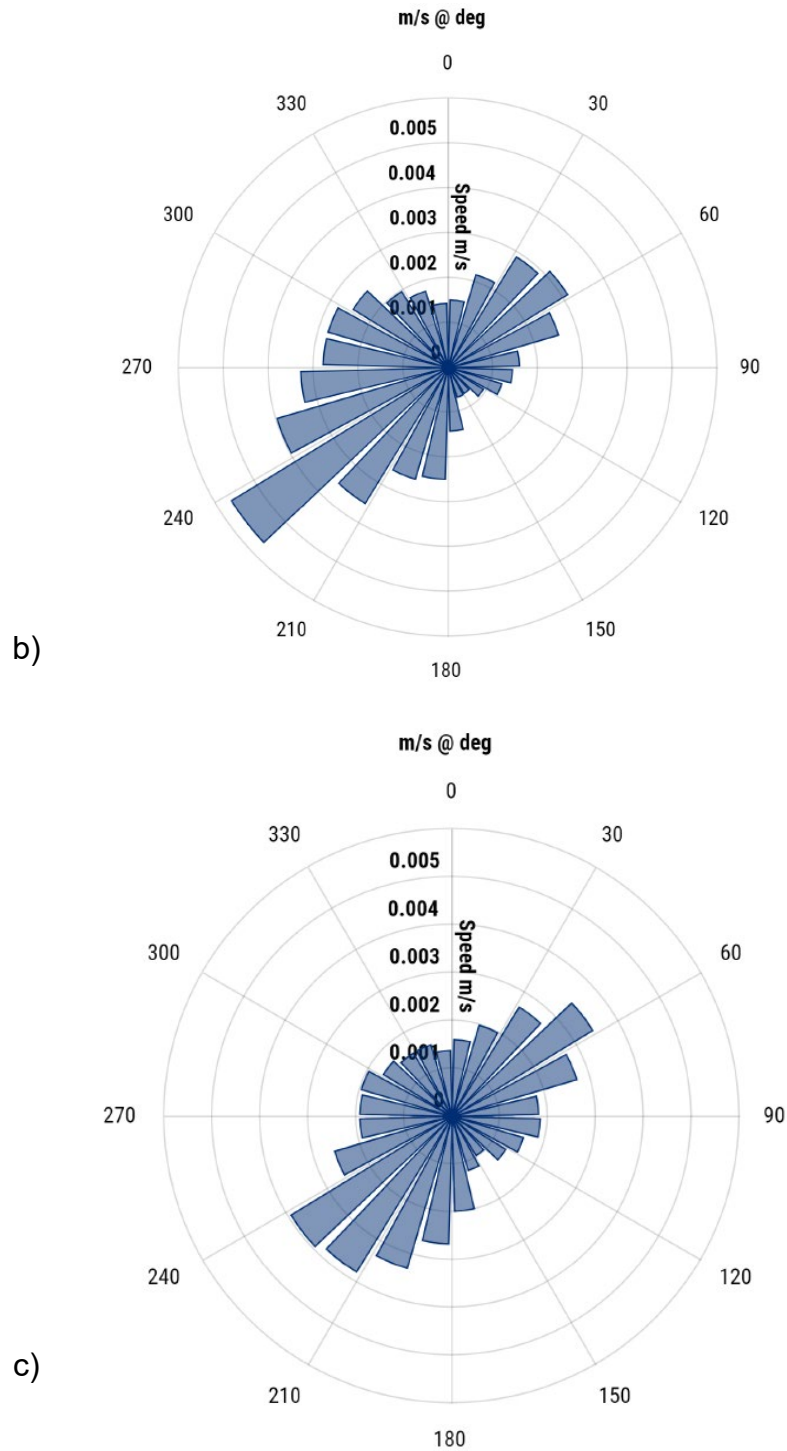
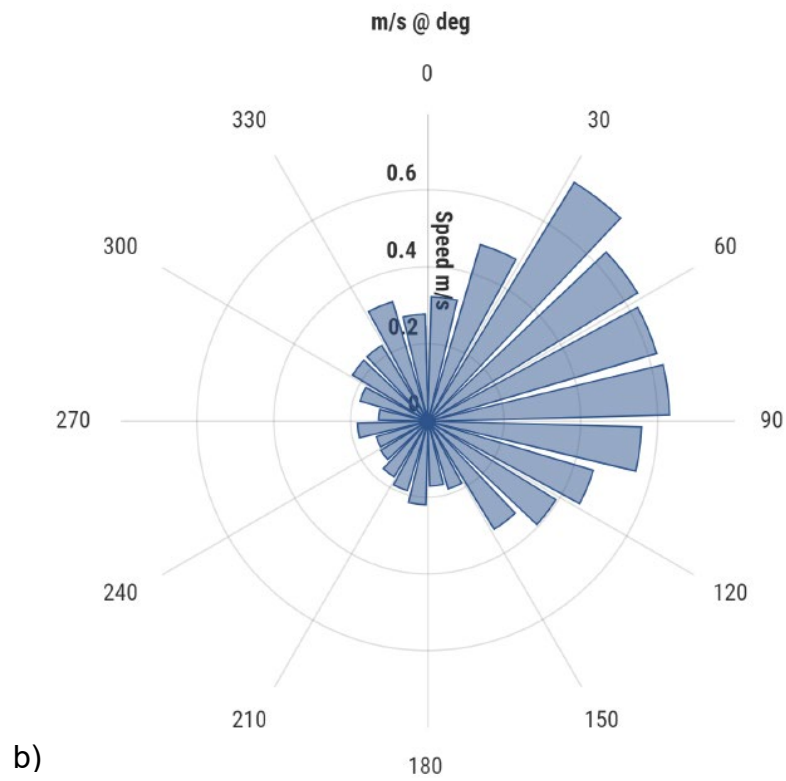
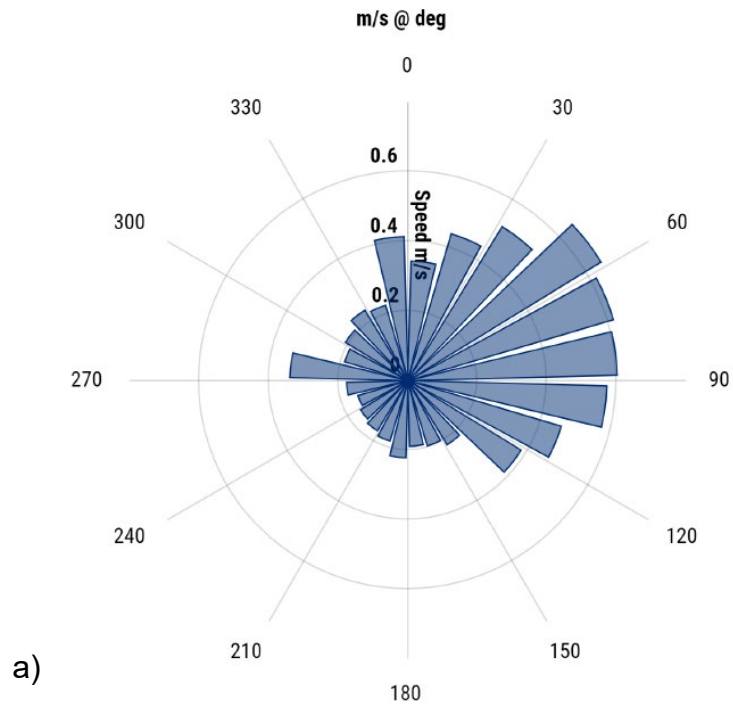


Figure 13. Polar histogram plots of the mean current speed and direction at each of the three depths: a) upper 11.3 m, b) middle 14.9 m, and c) lower 18.5 m.



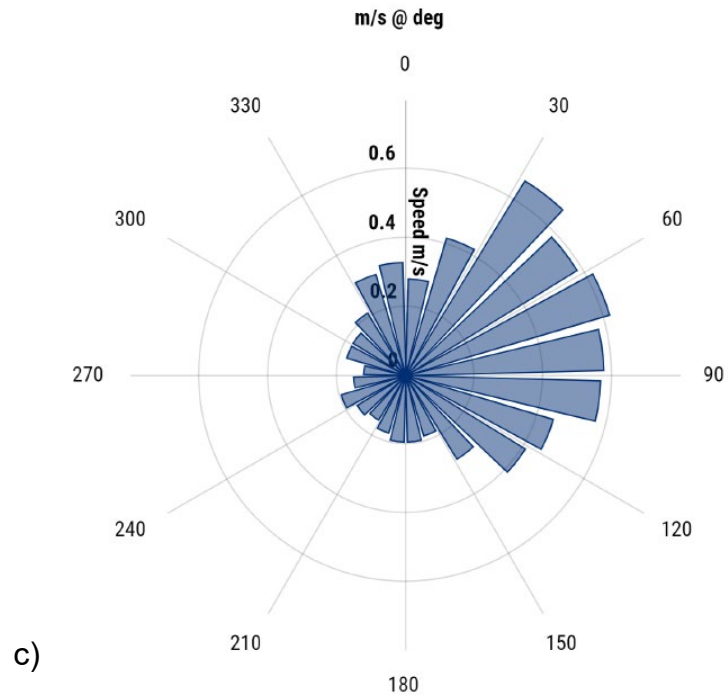
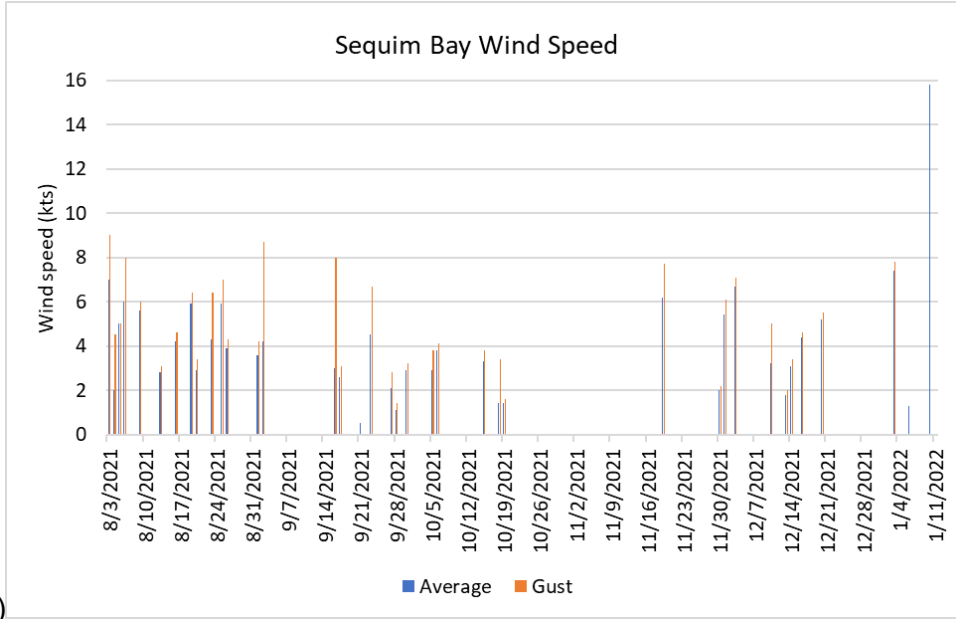
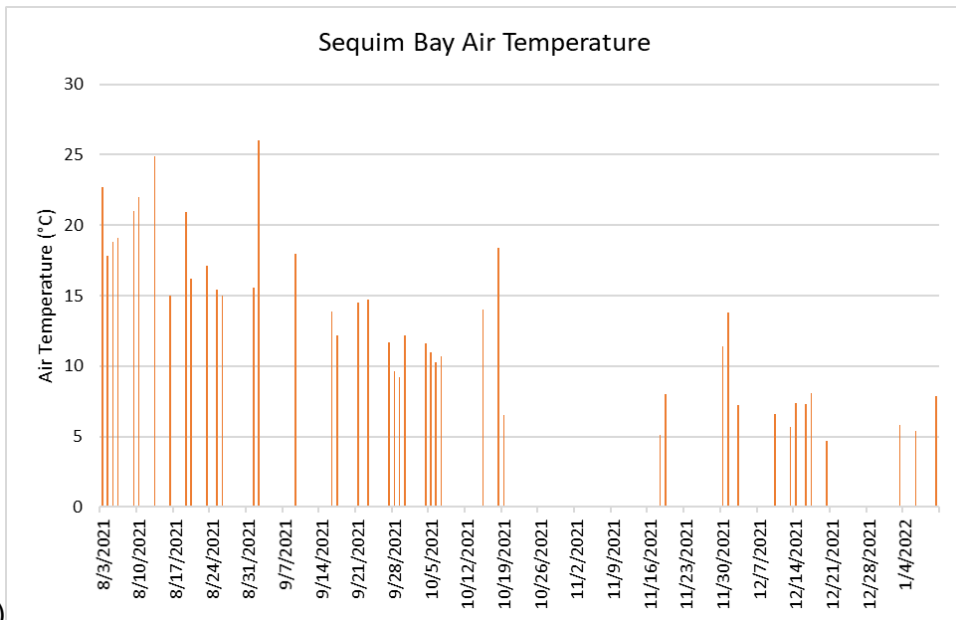


Figure 14. Polar histogram plots of the maximum current speed and direction at each of the three depths. a) upper 11.3 m, b) middle 14.9 m, and c) lower 18.5 m.

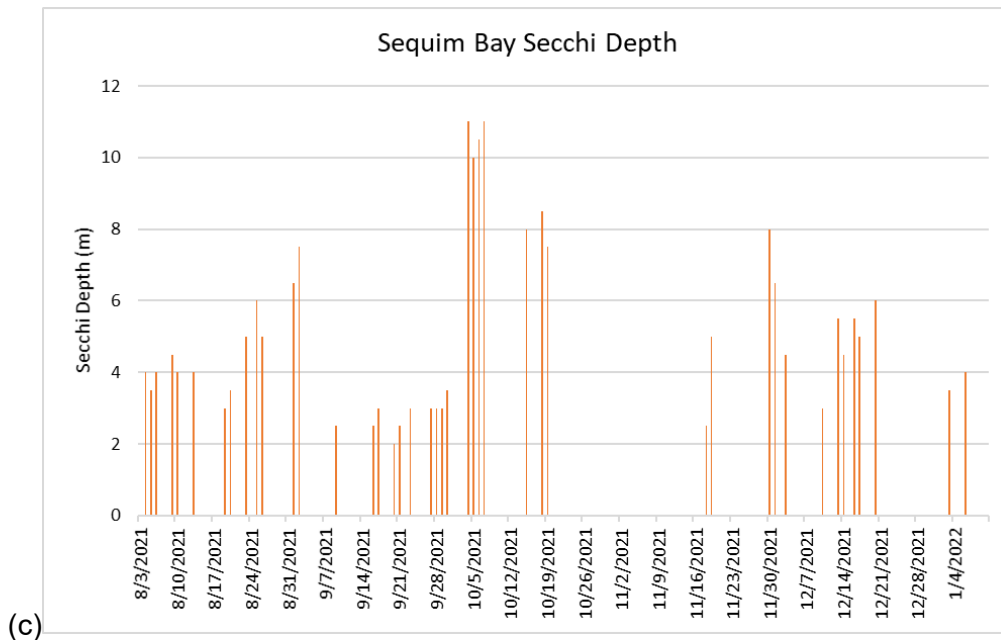
Recorded average wind speeds and gusts were mostly below 10 kts, indicative of the calm conditions required to perform the GPS buoy ground-truth data collection efforts (Figure 15a). Air temperatures declined steadily from $\sim 20^{\circ}\text{C}$ to just above 5°C during August–January (Figure 15b) and secchi depths (Figure 15c) indicate significant changes in turbidity and visibility near the surface with a peak in visibility observed in early October.



(a)



(b)



(c) Figure 15. Environmental data collected during PNNL vessel operations between August 2021 and January 2022, including (a) wind speed (kts), (b) air temperature (°C), and (c) secchi depth (m).

4.8 Time and Effort Summary

The time and effort required to conduct a successful demonstration is considerable. The initial phase of planning, permitting, test bed design and coordination with technology developers occurred over a nine-month window prior to field demonstrations. Securing permit authorizations for work in the test bed required less time for activities conducted in previous years (e.g. MuST survey), however new activities (e.g. geotechnical survey) required more time, with the total time spanning about 6 months (Table 3).

The field operations, including diver support, are a critical component of the Sequim Bay test bed demonstrations requiring extensive effort. The working depths of the test bed limit the bottom time for divers to approximately 25-30 minutes per dive. For this year’s test bed design 21 dives were required to place 77 tethered targets in prescribed locations at the blind and calibration sites. Target placement occurred 1-2 months prior to the demonstrations.

Dive operations for ground-truth data collection (i.e. accurate target geolocation and metadata collection) required an additional 32 dives. Originally planned as a 2-4 week operation prior to and between demonstrations, these were extended through December. Switching from the USBL system to the GNSS surface buoy method added constraints to scheduling since this method requires light winds and low tidal current to provide accuracy of target location on the seafloor. Limited weather windows in the fall and winter also extended the timeline. Finally, target retrieval required 24 dives between mid-December 2021 and early February 2022.

The overall time and effort required was more extensive than previous years, noting that the number of targets placed in 2021 (77) was almost three times the number placed in 2020 (30). Lessons learned and future directions are discussed below.

5.0 Lessons Learned and Next Steps

Despite continued challenges related to COVID-19, the FY 2021 field operations were executed successfully with expanded scope. Planning with the SERDP/ESTCP program office, and early discussions with APL-UW, Black Tusk Geophysics/Tetra Tech, Virginia Tech, and IDA resulted in two successful technology demonstrations, including a formally scored test of the MuST system and an engineering test of the UltraTEMA-4. The testbed operations this year included a significant expansion of the target field that incorporated several new types of munitions and clutter objects, modified blind site design, tether improvements, geolocation technology evaluations, and permitting for hosting two new technologies in the testbed (UltraTEMA-4 and Virginia Tech's PFFP). The lessons learned from FY 2021 will inform future testbed operations and technology deployments. Challenges as well as potential paths forward are listed below. Adaptive management and flexibility, especially with respect to remediation system developers' varying requirements and target grid layouts, are recognized as being essential moving forward.

- Target selection and handling. Several new inert UXO items and a much wider variety of clutter objects were used in the testbed in 2021, some of which proved to be more challenging to work with than anticipated. For instance, a minnow trap was used as a clutter item. Each time the divers visited the minnow trap it was in a different position and had moved on the seafloor. It was too light and mobile during larger tidal exchanges and not suitable for use as a clutter object. The divers reported that smaller and lighter weight inert UXO items are easier to deploy and retrieve, but they also have a greater chance of moving in the bottom currents experienced during larger tides and therefore may require emplacement in the sediment to reduce their mobility. Several weeks of time are required for the design and splicing of the tethers for attachment to the targets in a way that makes the tethers difficult to detect by the demonstrator technologies. This will be required each year as the design of the blind site layout changes. The 1/8" Amsteel line was the line of choice for tether splicing and handling by the divers underwater. Several targets—namely the APL-UW Howitzer replicas—were particularly challenging due to significant weight and a lack of tether attachment points. Because no holes or attachments can be added to the replicas, APL-UW suggested that for future tests they could provide a sling that would remain on the replicas during deployments and would aid in deployment/recovery operations.
- Target Field and Site Design. In FY 2021 targets were placed a short distance on either side of a linear baseline in two lanes at the calibration site; one for each developer. This design was successful from the test bed operator and both technology demonstrators' perspectives and may be repeated in future years.
- Scheduling and Planning. Understanding which developers and technologies will be hosted far in advance is necessary for successful demonstrations. The target field design preferences of the SERDP Program office and scoring team should be determined well before the field season (e.g., spring for fall testing). Information regarding the number and types of targets, minimum spacing between targets, and testing area size should be confirmed during the early planning stages. The timing for diver operations to set up and deploy the targets in the testbed, ground-truth data collection, and technology demonstration testing occurring within a condensed time period is optimized by having early knowledge of the site design preferences. This also promotes longer time periods (e.g., at least 30 days) between target deployment and testing to allow for sediment disturbances to "heal," reducing the deployment footprint.

- Permitting. In 2021 the UltraTEMA-4 system and the PFFP were newly permitted for use in the test bed. This was possible due to the early and thorough communication between the research teams and PNNL for permit authorization, and this practice highlights the need for early engagement in future years as new technologies are hosted. Technologies new to the Sequim Bay testbed require longer review periods for permit approval.
- Fishing and Crabbing Activity. 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 or create a hazard for expensive research equipment being towed behind the vessel. 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 shortly beforehand (e.g., tribal fisheries). Late September and early October has generally been relatively quiet with respect to fisheries, although 2021 was an exception; an unforeseen crab fishery opening coincided with the engineering test of the UltraTEMA-4. Active engagement and education between PNNL with fishery managers before demonstration testing may help alleviate some of the fishing pressure around the testbed. Still, this is recognized as being an unpredictable and potential hazard for research vessel operators and technology demonstrators.
- Target Geolocation System. The >20 m working depth of the test areas continued to present logistical challenges related to bottom time limitations for the dive team. The geolocation system trials performed in May/June identified the iXblue GAPS™ USBL system for geopositioning as a solution for reducing the number of dives and bottom time to complete testbed operations in comparison to other methods limited by tidal currents and weather. The challenges and lessons learned from the 2021 geolocation system trials and testbed operations highlight the need for the advanced technology provided by the iXblue GAPS™ USBL in future years. iXblue underwater geolocation and tracking systems are recommended and in use by several SERDP/ESTCP developers (UltraTEMA-4, MuST) and provide an efficient and accurate method for geolocation ground-truthing of targets in the Sequim Bay testbed. With the GAPS™, PNNL will be better poised to collect timely geolocation ground-information for technology demonstrations in the future.

6.0 References

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Appendix A

Geolocation information for the 2021 blind site targets in the Sequim Bay underwater test bed.

ClusterID	Type	PNNL ID	Description	Easting ^(a)	Northing ^(b)	Latitude ^(c)	Longitude ^(d)
1	clutter	C018	dive weight belt	497827.57	5324576.48	48.0744588	-123.0291648
1	clutter	C033	pulley	497831.10	5324569.06	48.0743920	-123.0291174
1	UXO	U007	105 mm projectile M60	497829.86	5324575.82	48.0744529	-123.0291340
1	UXO	U210	81 mm mortar M821	497818.69	5324572.72	48.0744250	-123.0292840
1	UXO	U211	81 mm mortar M821	497836.53	5324581.42	48.0745033	-123.0290446
1	UXO	U224	81 mm mortar M889A1	497828.84	5324585.15	48.0745368	-123.0291478
2	clutter	C011	large screw anchor	497796.10	5324550.63	48.0742262	-123.0295872
2	clutter	C026	metal sign	497807.10	5324560.20	48.0743123	-123.0294395
2	clutter	C029	square crab trap	497802.38	5324556.32	48.0742774	-123.0295028
2	UXO	U209	81 mm mortar M821	497799.65	5324559.73	48.0743080	-123.0295395
2	UXO	U222	81 mm mortar M889A1	497791.34	5324546.39	48.0741880	-123.0296510
2	UXO	U223	81 mm mortar M889A1	497801.56	5324550.65	48.0742264	-123.0295138
3	clutter	C013	radar reflector	497790.43	5324559.18	48.0743031	-123.0296634
3	clutter	C016	small grapnel anchor	497782.44	5324558.60	48.0742978	-123.0297706
3	clutter	C030	chain	497788.01	5324559.04	48.0743018	-123.0296958
4	clutter	C012	small screw anchor	497775.43	5324567.21	48.0743753	-123.0298647
4	UXO	U016	105 mm HEAT	497775.68	5324571.55	48.0744143	-123.0298614
4	UXO	U212	81 mm mortar M821	497784.78	5324571.56	48.0744144	-123.0297392
4	UXO	U225	81 mm mortar M889A1	497766.69	5324573.24	48.0744295	-123.0299821
4	UXO	U228	60 mm mortar M49	497785.18	5324576.66	48.0744603	-123.0297338
5	clutter	C202	range scrap metal	497764.09	5324587.66	48.0745592	-123.0300171

ClusterID	Type	PNNL ID	Description	Easting ^(a)	Northing ^(b)	Latitude ^(c)	Longitude ^(d)
5	replica	R002	155 mm Howitzer replica	497758.33	5324589.99	48.0745802	-123.0300945
5	UXO	U006	81 mm mortar M821	497759.70	5324582.72	48.0745147	-123.0300760
5	UXO	U014	105 mm HEAT	497755.27	5324600.64	48.0746760	-123.0301355
6	clutter	C005	SCUBA tank	497803.18	5324582.97	48.0745172	-123.0294923
6	clutter	C022	large instrument bracket	497810.22	5324586.97	48.0745531	-123.0293978
6	clutter	C024	boat propeller	497803.33	5324572.27	48.0744209	-123.0294902
6	clutter	C025	boat ladder	497813.14	5324581.36	48.0745027	-123.0293585
6	clutter	C200	range scrap metal	497803.17	5324584.26	48.0745287	-123.0294924
7	UXO	U001	155 mm Howitzer M107	497821.04	5324623.21	48.0748792	-123.0292528
7	UXO	U010	105 mm projectile M60	497814.34	5324623.50	48.0748818	-123.0293427
7	UXO	U011	105 mm projectile M60	497830.37	5324626.54	48.0749092	-123.0291274
7	UXO	U020	81 mm mortar M889A1	497811.59	5324614.72	48.0748028	-123.0293796
8	clutter	C008	cement block	497797.19	5324610.48	48.0747646	-123.0295728
8	UXO	U003	105 mm HEAT	497792.69	5324619.73	48.0748479	-123.0296333
8	UXO	U009	105 mm projectile M60	497802.12	5324599.28	48.0746639	-123.0295066
8	UXO	U019	81 mm mortar M889A1	497789.58	5324610.59	48.0747656	-123.0296750
8	UXO	U227	60 mm mortar M49	497805.45	5324611.38	48.0747727	-123.0294619
9	clutter	C003	bruce anchor	497785.65	5324620.04	48.0748506	-123.0297278
9	clutter	C010	boat hook	497785.05	5324615.38	48.0748087	-123.0297358
9	clutter	C015	large grapnel anchor	497781.37	5324624.49	48.0748906	-123.0297853
9	clutter	C032	wheel	497787.62	5324626.15	48.0749056	-123.0297014
9	clutter	C203	range scrap metal	497779.30	5324619.26	48.0748435	-123.0298131
10	clutter	C014	large bruce anchor	497836.03	5324598.78	48.0746595	-123.0290513
10	clutter	C027	steel pipe	497842.69	5324592.97	48.0746072	-123.0289620

ClusterID	Type	PNNL ID	Description	Easting^(a)	Northing^(b)	Latitude^(c)	Longitude^(d)
10	clutter	C028	square crab trap	497840.00	5324596.99	48.0746434	-123.0289980
10	clutter	C031	lawn chair	497834.10	5324599.64	48.0746673	-123.0290772
10	clutter	C201	range scrap metal	497833.60	5324607.49	48.0747378	-123.0290840
10	UXO	U015	81 mm mortar M889A1	497839.54	5324594.12	48.0746175	-123.0290041
(a) Easting	Mean X-coordinate projected to WGS84 UTM Zone 10N, meters						
(b) Northing	Mean Y-coordinate projected to WGS84 UTM Zone 10N, meters						
(c) Latitude	Mean Y-coordinate un-projected to WGS84 UTM Zone 10N, meters						
(d) Longitude	Mean X-coordinate un-projected to WGS84 UTM Zone 10N, meters						

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