FINAL REPORT

SERDP Workshop on Acoustic Detection and Classification of Munitions in the Underwater Environment

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Acronyms

ATR Automated Target Recognition
APL Applied Physics Laboratory
AUC Area-Under-the-Curve
AUV Autonomous Underwater Vehicle
BOSS Buried Object Scanning Sonar
EPA Environmental Protection Agency
COTS Commercial Off The Shelf
DMM Discarded Military Munitions
DOD Department of Defense
EMI Electro-Magnetic Interference
EO Electro-optic
ESTCP Environmental Security Technology Certification Program
GUI Graphical User Interface
IDA Institute for Defense Analyses
IVS Independent Verification Strip
MCM Mine CounterMeasures
MEC Munitions and Explosives of Concern
MR Munitions Response
MRS Munitions Response Site
NATO North Atlantic Treaty Organization
NSWC-PCD Naval Surface Warfare Center - Panama City Division
ONR Office of Naval Research
PA Preliminary Assessment
Pcc Probability of Correct Classification
Pd Probability of Detection
QA/QC Quality Assurance/Quality Control
R&D Research and Development
RA Remedial Action operation
RI Remedial Investigation
ROC Receiver Operating Characteristic
RTK Real Time Kinematic
SAS Synthetic Aperture Sonar
SERDP Strategic Environmental Research and Development Program
SI Site Inspection
SON Statement of Need
UnMES Underwater Munitions Expert System
USACE U.S. Army Corps of Engineers
USBL Ultra Short Base Line
USV Unmanned Surface Vehicles
UXO Unexploded Ordnance
Acknowledgements

The Strategic Environmental Research and Development Program (SERDP) and Noblis Inc. hosted an underwater acoustic workshop on 22-23 August 2017 at the Noblis facility in Reston, Virginia. The purpose of the workshop was to evaluate the progress made in development of acoustic techniques to detect and classify munitions in the underwater environment and to outline a path for future research. The 24 workshop attendees represented a number of government, private, and academic institutions. SERDP greatly appreciates their participation in this workshop.

The strategy for achieving the workshop objectives was developed by the workshop coordinating committee: Dan Sternlicht (Naval Surface Warfare Center, Panama City Detachment), Kevin Williams (Applied Physics Laboratory, University of Washington), Mike Richardson (Institute for Defense Analyses and SERDP), and Herb Nelson (SERDP). Members of the organizing committee also compiled and wrote much of the final report.

We would also like thank Noblis Inc. (Jeffrey Marqusee, Chief Scientist) for their excellent facilities and enthusiastic support for the workshop. Michael Book of Noblis Inc. provided much of the organizational support, took extensive notes during the workshop, and formatted the workshop final report. The Strategic Environmental Research and Development Program (SERDP), Dr. Herb Nelson, Director, provided financial support for the workshop.
Executive Summary

The Strategic Environmental Research and Development Program (SERDP) hosted an Acoustics workshop on 22-23 August, 2017, at the Noblis facility in Reston, Virginia. The purpose of the workshop was to evaluate recent progress made in development of acoustics sensing and processing, and platform development to detect and classify underwater munitions and to recommend future R&D initiatives. Previous workshops [1, 2] held in 2007 and 2013 formed the backdrop for this 2017 workshop.

The workshop began with an overview of state of the art as of 2013 [1]. Following that overview, Office of Naval Research (ONR) program managers presented a review of their current focus areas and programs in Mine Countermeasures (MCM). Further insight into both the MCM and munitions remediation efforts of the Navy was gained via a presentation by NSWC-PCD. Finally, a generic description of the restoration process was presented by the United States Army Corps of Engineers (USACE). Figure 1 is an example of this restoration process. Of particular importance in this process is the Remedial Investigation (RI) step. The performance needed at this step became a point of reference as the workshop proceeded. In general terms, a probability of detection and correct classification of 0.9 (i.e., the Area Under the Receiver Operating Characteristic (ROC) Curve (AUC)) and a geolocation uncertainty of 5 meters for munitions buried up to 0.5 meters in a sand sediment was proposed (and later discussed with both the EPA and the USACE) as acceptable at the RI level and a convenient metric for discussions. The performance needed at the Remedial Action (RA) step will likely be significantly more stringent (e.g., geolocation to less than 1 m and a false alarm rate of 0.)

Figure 1 – Generic restoration process.
The bulk of the workshop was organized around breakout sessions. These sessions took up the subjects of sensors, detection and classification, and deployment platform requirements in sequence. Results from those breakout sessions were then reported to and discussed by the larger group.

From a sensor standpoint the previous separation into high and low frequency sensors [1] was deemed as not as informative as organizing discussions around the data and data products that are derived from the sensors in question, e.g., both low and high frequency sonars have been used for imaging and for examining the frequency angle response of an object. The participants agreed that sensor behaviors at all frequencies are now understood well enough that system (sensor/processing/platform) alternatives can be built and the performance tested.

There are still research questions at the physics level of munitions acoustic behavior at various levels of burial, in complex environments, and when clutter is near-by. Discussions of performance, as embodied in detection and classification algorithms, highlighted the need to estimate/demonstrate performance as a function of environmental conditions and clutter density as well as the need for both stationary and mobile test beds. The physics/performance questions led to the conclusion that modeling will continue to play an important role and will need further development since experiments will never test the entire space within which fielded systems will be required to operate.

Finally, platform requirement discussions indicated that both autonomous underwater vehicles (AUVs) and tow body solutions can meet the R1 navigation requirements in deeper water (> 5m water depth) scenarios and each has advantages and disadvantages. In shallower water, Unmanned Surface Vehicles (USVs) are a viable solution but acoustics sensors may be replaced or augmented by EMI or magnetics sensors. This combination of modalities is also possible in deeper water scenarios but the area coverage rates disparities would need to be taken into account. The general conclusion was that the best choice of platform would be a case-by-case decision.

1.0 Introduction and Objectives of the Workshop

The workshop brought together phenomenology, sensor, and munitions response specialists. The first goal was to review the current state-of-the-art in acoustic technologies for munitions response. Next, to examine state-of-the-art and emerging technologies in the context of what constitutes a successful underwater munitions response survey, as discussed in [3]. Finally, considering current capabilities and gaps, technology thrusts and Munitions Response (MR) requirements, identify R&D needs in development of acoustic sensors, platforms, and concepts of employment that will lead to the wide-area mapping and remediation of underwater sites contaminated with military munitions.

Discussion topics included: projecting future advances in technologies, as well as capability gaps that may still not be addressed; identifying environmental limitations for underwater sensors; identifying mixed modality and system-of-systems approaches to munitions mapping; predicting future operator needs. Together these discussions were aimed at laying the groundwork for determining performance and cost projections that will assist in establishing the "knee" in the performance vs. cost curve.

2.0 Summary of Progress of the SERDP/ESTCP Underwater Munitions Response Program

In 2007 SERDP and ESTCP held a workshop “on Technology Needs for the Characterization, Management, and Remediation of Military Munitions in Underwater Environments” [2]. That workshop established 10 overarching issues and technology specific requirements for underwater
remediation of munitions as having the highest priority. SERDP/ESTCP Statements of Needs (SONs) from 2007 to 2013 were guided by those issues and technology needs. From 2013 to 2017 the subset of those needs associated with acoustics systems, and the progress made on those needs described in the 2013 workshop, were used to guide acoustic-related SONs. Past and present SERDP and ESTCP projects can be viewed at the internet site given in [4].

The seven highest priority items of relevance for acoustics systems from the 2007 workshop and their current status were discussed as part of the present workshop. A summary of that status is given in the paragraphs below.

**Characterize the acoustic response of munitions and typical bottom clutter.** A major focus has been the response of munitions in the low frequency, high bandwidth arena (1-50 kHz), in part because of their utility in detecting buried munitions. Ocean experiments using rail or AUV systems have been carried out on dozens of objects including research targets (spheres, cylinders), munitions, and man-made and natural clutter in both sandy and muddy environments. A portion of that data is available as public release [5]. Larger sets of data are available under more restricted distribution. Modeling capability has continued to advance through the use of both finite element and physical acoustics modeling and model/data comparisons [6-18] have demonstrated the high-fidelity capability of that modeling.

High frequency systems (above 50 kHz) were deemed as a mature technology for the detection and classification of proud and partly buried munitions by the 2013 workshop with the associated acoustic response consisting of highlights and shadows [19-21]. However, more recent experiments have indicated that elastic response of munitions is detectable at these frequencies. Furthermore, low frequency SAS systems can be used to form images. These facts have ramifications on how to view the state of the art and the future processing of data to derive data products for classification use.

**Improve methods for discrimination and classification.** In addition to target physics efforts, the work in [13, 14, 16, 18] also examine the classification capability of low frequency acoustics. Probabilities of correct classification sufficient to satisfy RI needs have been obtained for munitions in simple ocean environments. The Pcc requirements for RA will undoubtedly be higher and may require deriving additional target information from new data products. As acoustic sensor data is examined in new ways, the goal will be to improve the associated Pd and Pcc.

**Combine sensor modalities for improved classification and false alarm reduction.** As the majority of underwater munitions are buried, combining localization, shape and backscatter from acoustics with localization and ferrous properties from magnetic gradiometers has been shown to significantly improve detection/classification rates and reduce false alarm rates [3, 22-24]. For RI this is especially relevant as magnetic gradiometers can detect and localize buried ferrous objects and provide classification features, and have range potential complementary to sub-bottom imaging sonars like the BOSS. At these stand-off ranges active EO comes into play, and for RA the use of EMI is warranted [3].

**Combine existing sensor and navigation technologies.** As of 2013 the state of low frequency acoustics was such that sensor studies were needed before system solutions were sought. As of 2016, those studies [8, 13, 14, 16, 17] had moved work forward to the point that system solutions could be funded [25-28]. Within [25] platform and navigational technologies were proposed that together could satisfy RI and RA needs, and also accommodate complementary non-acoustic sensors.
Conduct navigational error analysis. For a tow body solution [25] carried out an error analysis that indicates geolocation accuracies to +/- 2 meters without the use of Ultra Short Base Line (USBL) acoustics systems and +/- 1 meter with them. Similar analyses for AUVs have indicated errors that are small enough to meet at least RI requirements.

Establish test beds for evaluation of sensor technologies. Design studies are being funded by SERDP to examine test site locations and test bed deployment strategies [29, 30].

Evaluate munitions mobility in the underwater environment. Current status as of the end of 2015 is summarized in [31]. At the center of this effort is the development of a probabilistic expert system to predict burial, migration, and re-emergence of munitions in coastal, estuarine, freshwater, and riverine environments. Planning for demonstrations of munitions burial and mobility modeling in the underwater environments is in the very early stages of development.

3.0 State of the Art: Underwater Acoustics Detection and Classification of Munitions

3.1 Sensors

Though the categorization of sensors into high and low frequency sonars is still useful, the lines have blurred as the research has demonstrated the ability of low frequency sonar to generate images through SAS processing and target responses from high frequency systems have indicated the presence of elastic responses. Participants noted the unifying concept within several regimes (e.g., radar and sonar) of the data taken with any sensor being a sample of a region of wavenumber space [32, 33] (wavenumber is typically defined as radial frequency divided by speed of sound for sonar or light for radar). Then an image is simply formed by one type of processing of that wavenumber information and a frequency/angle target response (structural acoustics or acoustic color) comes from another type of processing of the same data. Imaging and acoustic color are only two of many “spaces” to use. Other types of processing are sure to make different types of information more readily available and should be subject to continued research. The subsections below discuss the most common “data products” used to date – imaging and structural acoustics.

Imaging

In general terms, high frequency imaging sonars create 2D images of the water/sediment interface and proud targets while low frequency imaging sonars can create either 2D images of the interface and proud targets or 3D images of the sub-bottom and buried targets.

High frequency imaging, as a data product, is a mature technology and many commercial sonars exist that can be integrated into a system strategy. These include both side scan with or without SAS (including interferometry sonars that use phase information to determine height “images”) and multi-beam [1, 3]. Low frequency 2D imaging using SAS has also seen extended development [3, 34]. Low frequency 3D imaging is less well developed, at least for munitions remediation [22, 34], and ongoing SERDP projects [26-28] are working to tailor systems to the buried munitions problem. Development of imaging sonar at both low and high frequencies is sufficiently mature that integration into system solutions and demonstrations of capabilities are warranted [25-28].
Structural acoustics

For high frequency commercial systems, a significant concern in producing other data products such as acoustic color has been the issues of getting to raw data as well as overall calibration of the system. Working with commercial manufacturers that allow access to the raw data solves the first issue, access to calibration facilities then solves the second issue. This COTS solution is preferable to “home-grown” systems in most cases. Once calibrated, the data from these high frequency systems can be processed to obtain both image and acoustic color data products. Analyses of this type on 100-200 kHz data have demonstrated that elastic effects are present in munition-sized objects.

For low frequency sonars, extensive effort has been put into both experiments and development of analysis techniques to obtain both 2D images and acoustic color [6-15]. For the case of 3D imaging of buried targets the BOSS system has been used [3, 22]. Deriving acoustic color from BOSS data [34] has been hampered by beampattern effects caused by deployment platforms as well as the challenges of: creating data templates that are consistent with variations in object and radiometric geometries, across-track resolution cells that increase as a function range; the poorly known loading effects of sediment as a function of burial depth; and effects of sediment refraction on the two-way beam patterns. Compensating for both beampatterns and the above sensitivities for BOSS, as well as other classes of sediment volume imaging sonars, is a subject of ongoing development.

Alternate data products and classification features derived from high and low frequency data still need development and testing [21, 35]. Also, the optimal configuration of the sonars may require more research. Trade-offs in bandwidth, beamwidth, and number and arrangement of sensors are among the configuration studies that should be carried out. Participants agreed, however, that development of sonar at both low and high frequencies is sufficiently mature that integration into system solutions and demonstrations of capabilities using various platform solutions are warranted [25-28].

3.2 Detection & Classification

High frequency highlight/shadow classification can be adapted from MCM work on proud objects [19-21]. However, participants noted that MCM automated target recognition (ATR) algorithms may produce high false alarm rates due to munitions fouling and corrosion. Thus, other modalities are needed. One option is to combine both high and low frequency systems [28]; another is to combine with non-acoustic sensors [3, 22-24]

Classification studies [13, 16, 18, 36] have indicated viability, at a RI level, of classification based on acoustic color in simple ocean environments and well separated targets. However, high clutter environments promise to be a challenge. Classification studies using data from a recent experiment [37] will help quantify both the reduced performance as a function of the mean munition/clutter separation distance and, hopefully, suggest mitigation strategies.

Recent performance estimation efforts for ONR have demonstrated the sensitivity of performance to grazing angle of training and testing data, that angle being in turn controlled by sediment sound speed. A more general discussion of environmental sensitivity continues to highlight the need to estimate/demonstrate performance as a function of environmental conditions and clutter density as well as the need for proper test bed design.
3.3 Platform Requirements

As noted in [1, section 6.0] the operational realities in munitions remediation sets constraints that are different than those of MCM operations. These constraints include size, shape, coverage rates, overtness, and autonomy. In both cases, however, there is still a need to geolocate the object of concern and, at least in the case of SAS, to know element positions to a fraction of a wavelength.

Assuming an acceptable geolocation uncertainty at the RI stage of around 5 meters, Unmanned Surface Vehicles (USVs) in shallow water and tow bodies or AUVs in deeper water should be viable solutions. In the case of USVs, positioning of the surface platform to 10’s of cm is possible using Real-time kinematic (RTK) satellite navigation. Direct mounting of sonar system to the USV along with the acoustic time of flight data should allow equivalent geolocation error of the munition. As one moves to the tow body solution the fall back of the tow body relative to the associated surface ship increases the munitions geolocation error. However, with USBL systems analysis has shown [25] that, with typical tow body cable lengths (200 m or less), geolocation to an uncertainty of less than 1 m is possible. Finally, once the platform is decoupled from the surface as in the case of AUVs, one needs to rely on high quality inertial navigation with periodic resurfacing. With present technology, it should be possible to meet the 5m uncertainty criterion of RI though the higher precision geolocation needs for RA are not possible at present. Ongoing development in both platforms and navigation should allow improvements in geolocation without SERDP/ESTCP investment.

A more stringent positioning requirement is set when SAS is used in processing data. In the end, element locations need to be determined to a fraction of the acoustic wavelength. Though hardware solutions to this need are often impossible, autofocusing development over the past several years has produced techniques that are very effective in compensating for random and rapidly oscillating navigation and jitter errors [38].

Each platform solution will have its own pros and cons and the appropriate platform will be a case-by-case decision. For example, AUVs have a higher initial cost than a tow body solution but can have a lower day-to-day cost during operations. On the other hand, a tow body system offers real time access to data allowing assessment and alteration of operational strategy as needed, strap on sensors with low integration cycles, surface based power and data handling, and lower in-water costs and risks. Finally, a USV can operate in shallower waters than either a tow body or AUV.

3.4 Environmental Factors

Performance estimations using both real and model data indicate sensitivity to environment. This implies the need for environmental characterization at Munitions Response Sites (MRSs). Initially, historical information on water depth, bathymetry, ecology, hazards to navigation etc. is useful for determining SI requirements. During the SI process, better bathymetry measurement along with measurement of sediment mean properties (e.g., sound speed, density, layering), water/sediment interface roughness, and assessment of clutter density allow better subsequent mission planning for the RI stage. Alternatively, determining these parameters at the initial stages of the RI was discussed as an option. Regardless, SERDP has funded efforts to use acoustics to infer for sediment properties [39]. Acoustic data provides the added benefit of providing information on the spatial variability of sediment properties. Participants also discussed the possibility of using the same sonars for environmental characterization and munitions remediation. The viability of this strategy needs further research.
4.0 Enabling Developments

Several discussions revolved around both developments of direct use to acoustics researchers and ones that will help set and define the stage in which platform systems will be demonstrated. In the subsections below several of these developments are summarized.

4.1 Datasets Available

Results from both a test pond facility (PONDEX09, PONDEX10) and an open ocean experiment (TREX13) are available at a public dropbox site. Data consist of calibrated cross range/time scattering data from various simple shapes and munitions targets at nine different orientations as well as angle/frequency acoustic templates for those targets. The frequency range of the data is 3-30 kHz. All data were collected using a rail system. Source and receiver were at a height above the bottom of 3.8 meters. Included in the data package is a simple GUI that allows the user to initially view the data.

4.2 Munitions Mobility, Burial, and Reemergence Studies

Central to underwater munitions response (MR) program is the development of a probabilistic expert system to predict burial, migration, and re-emergence of munitions in coastal, estuarine, freshwater, and riverine environments [31]. Development of the Underwater Munitions Expert System (UnMES) is supported by field, laboratory, and modeling studies. The objectives of the field and laboratory studies are to develop physics-based, force-balance models, focusing on a first-order approximation with empirically determined parameters (seafloor and hydrodynamic) that predict dominant patterns of munitions distribution and behavior. Predictions of munitions distribution and potential movement provide decision makers with first order decision and long-term site management strategies for munitions remediation and provide a subsequent guide to the types of sensors and deployment strategies needed for munitions detection and classification in the RI and RA phases of munitions remediation. Acoustic-sediment classification, in turn, provides data of sediment properties and distribution central to predicting munitions behavior.

4.3 Testbed Characteristics, Requirements and Timelines

A summary of the side meeting and roundtable discussion on test bed requirements held at the 2011 SERDP/ESTCP Symposium was provided (see Appendix D). Since that meeting, SERDP has called for proposals on the development of test bed concepts where acoustic, optical, magnetic, and electromagnetic detection and classification technologies can be tested and compared. Based on recent development of sensors and sensor systems test beds are needed sooner than later.

In the 2011 test bed meeting, it was concluded that a mobile, re-deployable, test bed concept is preferable and more cost effective to the development of permanent single or multiple test beds. Participants in the present workshop suggested that an initial test bed strategy that includes both an extensive stationary bed and a simpler, easy-to-deploy, mobile test bed might be required. It is possible that these two strategies represent the end-points of a temporal spectrum and are technically very similar. These test beds will allow experimentation in the variety of environments that munitions remediation is required and allow development, testing, and comparison of the variety of acoustic, optical, magnetic, and electromagnetic detection and classification technologies for munitions remediation. This is consistent with current SERDP acoustic projects [29, 30].
Test bed issues that still need to be addressed include: 1) the types, sizes, number, distribution, and physical characteristics of representative munitions and clutter, 2) methods to deploy targets (positional accuracy and burial), 3) environmental characterization required for the test beds, 4) types of environments to be simulated, and 5) mobility and/or permanence of test beds. It is possible that a universal test bed type will not be appropriate for all sensor, sensor system, platforms, and remediation requirements. The cost benefit ratio of various test bed development strategies has not been addressed but it is obvious that costs can be greatly reduced if the test beds can be used for multiple sensor and platform types at the same time. A second side meeting on test bed requirements was held at the November 2017 SERDP/ESTCP Symposium where test bed requirements and strategies were discussed.

4.4 Utility of Fusing Multiple Modalities from Acoustic and Non-Acoustic Sensors

Acoustics is only one potentially useful modality in munitions remediation efforts [1, 3]. Improved classification performance has been demonstrated by combining a magnetic gradiometer and acoustic images from the BOSS sonar [22]. How to best combine the capabilities of different modalities is a subject in need of further research. Questions include: how does the method of combining modalities change with water depth? How does the difference in standoff distance and therefore area coverage rate play in to combining modalities? What are the platform requirement conflicts between modalities? Given conflicts, is it better to field different modalities on different platforms and do multiple passes? Will these multiple modality strategies be needed as we strive to meet RA requirements? Monitoring the lessons learned from previous and current MR site investigations carried out by the U.S. and NATO Navy laboratories [3, 23, 24] will be instrumental in addressing these questions.

5.0 Underwater Munitions Response Sites

At present, sufficient information on the types of munitions and environments are not available for most potential munition remediation sites. This includes both general summaries of the overall problem (which environmental types, depths, sediment types, munitions types are most important) and site-specific data needed for planning. The Preliminary Assessment (PA) and Site Inspections (SI) are not adequate to provide data on munitions types and distribution or on environmental characteristics needed for UnMES or to provide information needed to design the RI phase of underwater UXO remediation. The research community needs more and better data in order to focus future research directions.

Underwater Munitions Response Sites vary greatly from site to site, as well as within the sites themselves. MRS projects exist in rivers, lakes, estuaries, bays, swamps, ports and open ocean. They have bottom-type characteristics that can include sand, mud, gravel, sea grass, and corals. They can extend throughout the littoral zone to open ocean. Some include flooded valleys or basins that were dry land when used by the DoD. Underwater MRS sites can also be complicated by time of year restrictions, which preclude various operations that might interfere with marine mammals, migratory birds, turtles, and other protected and threatened species and their habitats. A consequence of such restrictions is the need to correctly identify UXO and DMM from among inert munitions items to minimize impacts and damages to existing marine environments. Another reason for the need to correctly identify UXO and DMM from among inert munitions items is to minimize remediation costs; current production rates for munitions response in water are very slow, often require highly trained, UXO-certified dive teams, and are very costly.
6.0 Operator Needs

There are two levels of MRS operators: decision makers and data acquisition/interpretation teams. Decision makers require as much information as is reasonably obtainable to answer key questions and address core needs, including:

1. Are munitions present at this Munitions Response Site (MRS), and if so about how many?
2. Are Munitions and Explosives of Concern (MEC) constrained to this MRS location or are some of them migrating, and if so, to where or in which direction?
3. If no munitions are present in the MRS, is it because the site was never used, or because all the UXO or DMM have moved, and if so, where are they now?
4. Are the MEC partially/entirely proud or fully buried, and if so, how deep?
5. What forcing mechanisms are required to mobilize the MEC?
6. Can we easily classify the MEC from all the surrounding clutter and natural features?
7. What are the water depth profiles for the areas where MEC are present?
8. Rapidly deployable and retrievable positioning systems/markers to verify survey coverage and to provide accurate locations and resolution capabilities within datasets are required. This should include an easily deployable underwater version of the geophysical system verification process (IVS and blind seeding) that are used at land sites
9. Complete sensor function tests for sonars that are much more quantifiable than something like "a rub test"
10. Improved and thoroughly documented Automated Target Recognition (ATR) algorithms
11. QA/QC processes similar to land sites such as line repeatability to demonstrate target detection in various passes of the sensor with accurate/consistent size and position estimates
12. A multi-sensor approach to address corroded targets and targets encrusted with marine growth.

Project team members who collect and interpret data to answer the above questions have the following needs:

1. Tools to efficiently illustrate and convey the findings from complex, high-volume datasets
2. Detection technologies with high probabilities of detection and moderate to high data acquisition rates (i.e. high coverage)
3. Classification technologies with high Pd and low false positive rates
4. Methods to easily and accurately interpret detection data and classify targets
5. Navigation methods that can provide reasonably accurate target locations (e.g. +/-5m) with good performance (e.g. Pd ~.85) for Remedial Investigation/Wide Area Assessment projects.
6. Navigation methods that can provide very accurate target locations (e.g. +/-0.25m) with good very performance (e.g. Pd ~1) for Remedial Action projects
7. Tools to provide rigorous quality control over all the processes and procedures used.

It is important to note real-time, or even near-real-time interpretation/classification is not a need. MR projects generally operate on time-scales of months to year/years.
7.0 Underwater Acoustics Detection and Classification of munitions – the way ahead.

The previous sections have summarized workshop participant’s discussions on progress, and state-of-the-art, in the use of acoustics for underwater munitions remediation (MR). Those participants also pointed to remaining R&D and demonstration efforts that can serve to organize the way ahead in a similar manner to the previous workshops [1,2]. Below, areas for further effort are divided into R&D (SERDP) efforts and demonstration (ESTCP) efforts. They are organized around the session subjects of sensors, detection and classification, and platform requirements.

7.1 SERDP

Sensors

1. Improve models to handle more complicated environments and munitions geometries including munitions in the vicinity of clutter so that munitions’ acoustic response can be simulated at a high fidelity to augment data from experiment and demonstration efforts. Incorporate ability to model the benefit of non-acoustic sensors such as EO, magnetics, and EMI.

2. Use model and experiment data in efforts aimed at performance estimation and RI/RA planning.

3. Continue development of sensors/processing to assess the environmental conditions that affect the detection and classification performance. Examine the potential for using sonars designed for munitions remediation to carry out environmental assessment.

Detection and classification

1. Develop processing for 3D low frequency sonar to produce additional data products for use in classification. Both modeling and previous experimental results (e.g., BOSS) can be used as a starting point. As part of this effort carryout configuration studies, e.g., trade-offs in bandwidth, beamwidth, and number and arrangement of sensors.

2. Use imaging, acoustic color and new data products from both high and low frequency systems to further develop feature extraction and classification algorithms with an eye toward platforms being fielded in ongoing and future ESTCP efforts. Quantify their performance. Include contributions of EO and magnetics for RI; EO and EMI for RA.

Platform requirements

1. Examine the trade-offs and strategies for combining modalities in one or multiple platforms. Quantify the performance enhancements possible with different strategies.

2. Project concepts of employment and associated cost benefits of using towed and unmanned vehicles in the predominant environments expected to be encountered for RI and RA missions.
7.2 ESTCP

Sensors

1. Tailor and enhance COTS sonars to better address the munitions problem, e.g., increased bandwidth and controllable beamwidth in LF systems.

Detection and classification

1. Integrate both standard (i.e., shadow/highlight) and new classifiers into systems to be demonstrated.

Platform requirements

1. Develop both mobile and stationary test beds for demonstrations.

2. Carry out demonstration efforts using alternative platform/sensor-combination solutions.

3. Evaluate navigation and positioning systems for detection, classification and remediation operations.
8.0 References


5. Public release data available at:
   https://www.dropbox.com/sh/ozdx1nmdvip01f6/AACTwnVv_qnLHSNloacVZOSaa?dl=0
   https://www.dropbox.com/sh/5d7w6zpzr576azu/AAA2sSorpsrIfh0Oi4HSRJI3a?dl=0


29. S. Tomich, SERDP project MR-2735, “Preliminary design study of Munitions Response Underwater Test Site,” active project.

30. N. Khadr, SERDP project MR-2736, “A preliminary design study of a re-deployable underwater test bed,” active project.


35. L. Owsley, SERDP project MR-2649, “Elastic Target Modeling for Physics-Based Automatic Classification,” active project.


Appendix A: Final Agenda

SERDP Acoustics Workshop Agenda

**Noblis**  
2002 Edmund Halley Road  
Reston, VA 20190

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<th>Time</th>
<th>Session</th>
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<tr>
<td>0800</td>
<td>Meet and Greet</td>
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<td>0830</td>
<td>Introduction to Workshop and SERDP Objectives</td>
<td>Herb Nelson, SERDP</td>
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<td>0840</td>
<td>Introduction of Participants</td>
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<tr>
<td>0850</td>
<td>Summary of the First SERDP &amp; ESTCP Acoustics Workshop</td>
<td>Kevin Williams, APL University of Washington</td>
</tr>
<tr>
<td>0920</td>
<td>ONR’s Acoustic Mine Detection and Classification Efforts</td>
<td>Kyle Becker, Office of Naval Research</td>
</tr>
<tr>
<td>0940</td>
<td>MCM at NSWC-PCD</td>
<td>Dan Sternlicht, Naval Surface Warfare Center</td>
</tr>
<tr>
<td>1000</td>
<td>Description of Generic UXO Remediation Operations with an Emphasis on</td>
<td>Andy Schwartz, U.S. Army Corps of Engineers</td>
</tr>
<tr>
<td></td>
<td>the Role of UXO Detection and Classification; Update on Underwater</td>
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<tr>
<td></td>
<td>Munitions Sites</td>
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</tr>
<tr>
<td>1020</td>
<td>Break</td>
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<tr>
<td>1040</td>
<td>Breakout Session I Discussions</td>
<td>Breakout Groups</td>
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<td></td>
<td>1) High-Frequency Acoustic Imaging Sensors and Systems: State-of-the-</td>
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<td>Art, Research Issues and Capability Gaps, Limitations, and Future</td>
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<td>Possibilities</td>
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<td>2) Low-Frequency Structural Acoustic Sensors and Systems: State-of-the-</td>
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<td>Art, Research Issues and Capability Gaps, Limitations, and Future</td>
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<tr>
<td>1200</td>
<td>Lunch</td>
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<tr>
<td>1300</td>
<td>Summary and Discussion from Breakout Groups; Evaluate Progress since</td>
<td>Session Chairs</td>
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<tr>
<td></td>
<td>last Workshop</td>
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<tr>
<td>1400</td>
<td>Breakout Session II Discussions</td>
<td>Breakout Groups</td>
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<td></td>
<td>1) Evaluation of Detection and Classification Algorithms</td>
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<tr>
<td></td>
<td>• What level of performance can be expected in different</td>
<td></td>
</tr>
<tr>
<td></td>
<td>environments and for different types of munitions?</td>
<td></td>
</tr>
<tr>
<td></td>
<td>• How much will clutter or noise degrade sensor performance?</td>
<td></td>
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</table>
- Are robust target discriminators possible for all types of UXO and in all environments?

2) Optimal Platform Requirements, State-of-the-Art, and Navigation from the Surf Zone to 40m Water Depths

1600 Breakout Groups’ Summary and Discussion of Classification Algorithms and Platforms  
Session Chairs

1700 Adjourn

---

**Wednesday, 23 August 2017**

<table>
<thead>
<tr>
<th>Time</th>
<th>Session</th>
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<tbody>
<tr>
<td>0800</td>
<td>Reflections from Day 1</td>
<td>Herb Nelson, SERDP</td>
</tr>
<tr>
<td>0830</td>
<td>General Group Discussion</td>
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</table>
- The requirements for acoustic detection and classification for UXO remediation  
- Predicting future operator needs  
- Performance and cost projections  
- Develop a set of operational metrics and concepts of operations for underwater UXO remediation. |
| 0930  | How Does the Environment Affect Sonar Performance and What Environmental Factors are the Most Critical to Understand and Predict Performance? | |
| 1000  | Update on the Status of the Availability of Acoustic Data Sets | |
| 1015  | Break | |
| 1030  | General Group Discussion |  
- Limitations of Current Systems Given Operating Environments and UXO Characteristics.  
- Can Future Systems Overcome These Limitations? |
| 1100  | Testbed Characteristics and Requirements and Timelines for ESTCP Demonstrations | |
| 1120  | Evaluation of the Acoustics Munitions Response Roadmap: the way forward | |
| 1140  | Final Comments and Direction for Workshop Report | |
| 1200  | Adjourn/Lunch | |
| 1300  | Coordinating Group Provides an Outline for a Summary Draft of the Workshop Results and Conclusions | |
| 1600  | Adjourn Coordinating Group | |
Appendix B: List of Attendees

<table>
<thead>
<tr>
<th>First Name</th>
<th>Last Name</th>
<th>Organization</th>
<th>Email</th>
</tr>
</thead>
<tbody>
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<td>U.S. Army Corp of Engineers</td>
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<td>University of Washington</td>
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FINAL REPORT

SERDP/Office of Naval Research Workshop on Acoustic Detection and Classification of UXO in the Underwater Environment

September, 2013
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<tr>
<th>Acronym</th>
<th>Description</th>
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<tr>
<td>APL-UW</td>
<td>Applied Physics Laboratory, University of Washington</td>
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<tr>
<td>ATG</td>
<td>Air-to-Ground</td>
</tr>
<tr>
<td>ATR</td>
<td>Automated Target Recognition</td>
</tr>
<tr>
<td>AUC</td>
<td>Area-Under-the-Curve</td>
</tr>
<tr>
<td>AUV</td>
<td>Autonomous Underwater Vehicle</td>
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<tr>
<td>BUD</td>
<td>Berkeley Unexploded Ordnance Discriminator</td>
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<td>BOSS</td>
<td>Buried Object Scanning Sonar</td>
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<td>BRAC</td>
<td>Base Realignment and Closure</td>
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<td>CAD/CAC</td>
<td>Computer Aided Detection and Classification</td>
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<tr>
<td>CERCLA</td>
<td>Comprehensive Environmental Response, Compensation, and Liability Act</td>
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<tr>
<td>CMRE</td>
<td>Centre for Maritime Research and Experimentation</td>
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<tr>
<td>CSAS</td>
<td>Circular Synthetic Aperture Sonar</td>
</tr>
<tr>
<td>DOD</td>
<td>Department of Defense</td>
</tr>
<tr>
<td>EM(I)</td>
<td>Electromagnetic (Induction)</td>
</tr>
<tr>
<td>EOD</td>
<td>Explosive Ordnance Disposal</td>
</tr>
<tr>
<td>ER,N</td>
<td>Environmental Response, Navy</td>
</tr>
<tr>
<td>ESTCP</td>
<td>Environmental Security Technology Certification Program</td>
</tr>
<tr>
<td>FE(M)</td>
<td>Finite Element Model</td>
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<tr>
<td>FSNSD</td>
<td>Former Seattle Naval Supply Depot</td>
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<td>FUDS</td>
<td>Formerly Used Defense Sites</td>
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<tr>
<td>FWG</td>
<td>Forschungsanstalt der Bundeswehr fur Wasserschall und Geophysik (Federal Armed Services Underwater Acoustics and Marine Geophysics Research Institute in Kiel Germany)</td>
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<td>HLS</td>
<td>Heat, Light, and Sound Research, Inc.</td>
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<tr>
<td>iSSAM</td>
<td>Intersection in Signal Processing, Acoustic, and ATR for Maritime applications (an ONR workshop)</td>
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<td>LIA</td>
<td>Live Impact Area</td>
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<tr>
<td>LSG</td>
<td>Laser Scalar Gradiometer</td>
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</table>
PMA  Production and Manufacturing Area
MBUD  Marine version of BUD
MC  Munitions Constituents
MCM  Mine Countermeasures
MEC  Munitions and Explosives of Concern
MLLW  Mean Lower Low Water
MR  Munitions Response
MRP  Munitions Response Program
MRS  Munitions Response Site
MTA  Marine Towed Array
MUDSS  Mobile Underwater Debris Survey System
NAS  Naval Air Station
NAVFAC  Naval Facilities Engineering Command
NOAA  National Oceanic and Atmospheric Administration
NRL  Naval Research Laboratory
NSWC-PCD  Naval Surface Warfare Center Panama City Division
ONR  Office of Naval Research
Pd  Probability of Detection
REMUS  Remote Environmental Monitoring Units
ROC  Receiver Operating Characteristic
ROV  Remotely Operated Vehicle
RTG  Real-time Tracking Gradiometer
RVM  Relevance Vector Machine
SAS  Synthetic Aperture Sonar
SSA  South Shore Area
SSAM  Small Synthetic Aperture Minehunter
SERDP  Strategic Environmental Research and Development Program
SON  Statement of Need
TNO  Netherlands Organisation for Applied Scientific Research
USACE  U.S. Army Corps of Engineers
UXO  Unexploded Ordnance
VNTR  Vieques Naval Training Range
WSU  Washington State University
ACKNOWLEDGEMENTS

The Strategic Environmental Research and Development Program (SERDP) hosted a workshop on “Acoustic Detection and Classification of Unexploded Ordnance (UXO) in the Underwater Environment” on 16-17 July, 2013, at the Fort Myer Community Center in Arlington, Virginia. The purpose of the workshop was to evaluate the progress made in development of acoustic techniques to detect and classify UXO in the underwater environment and to outline a path for future research. The 38 workshop attendees represented 20 institutions and six countries. Their participation in this workshop is greatly appreciated.

The strategy for achieving the workshop objectives was developed by the workshop coordinating committee: Herb Nelson (SERDP), Mike Richardson (Institute for Defense Analyses and SERDP), Kevin Williams (Applied Physics Laboratory, University of Washington), Bryan Harre and Steve Hurff (Naval Facilities Engineering Command), and Jason Stack and Kyle Becker (Office of Naval Research). This report was written and compiled by the members of the organizing committee along with Dan Sternlicht (Naval Surface Warfare Center, Panama City Division), Larry Mayer (Center for Coastal and Ocean Mapping, University of New Hampshire), and Andrew Schwartz (U.S. Army Corps of Engineers).

We would also like to thank Jamey Westerman at Fort Myer Community Center for the excellent facilities and cooperation in hosting the workshop. Much of the organization of the workshop, development of the website, and formatting of the workshop report was done by Daniel Ruedy of HydroGeoLogic, Inc. This workshop was supported by SERDP, Dr. Anne Andrews, Acting Director.
EXECUTIVE SUMMARY

The Strategic Environmental Research and Development Program (SERDP) hosted a workshop on “Acoustic Detection and Classification of Unexploded Ordnance (UXO) in the Underwater Environment” on 16-17 July, 2013, at the Fort Myer Community Center in Arlington, Virginia. The purpose of the workshop was to evaluate the progress made in development of acoustic techniques to detect and classify UXO in the underwater environment and to outline a path for future research. The 38 workshop attendees represented 20 institutions and six countries. Program managers, research scientists, system developers, and remediation managers were in attendance.

The workshop began with introductory presentations and white papers on previous and current UXO remediation and mine clearance work supported by SERDP, the Environmental Security Technology Certification Program (ESTCP) and the Office of Naval Research (ONR). This included a summary of the highly successful SERDP/ESTCP Munitions Response detection, classification, and remediation research program, the past and present Munitions Response underwater research program, and ONR’s mine detection and classification programs. This was followed by presentations on the inventory of underwater Munitions Response sites and a description of the Department of Defense’s (DOD) munitions response program. The last two presentations included a review of the science and technology of high- and low-frequency acoustic detection and classification, research needs, and future possibilities. Breakout groups developed perspectives on current state of underwater UXO research, directions for the future, and future system requirements.

This report summarizes the introductory presentations and discussions. We include details on some example underwater munitions sites and a listing of the similarities and differences between UXO detection and classification and mine countermeasures for use by sensor and system developers. Finally, we propose a roadmap for the continued development and demonstration of acoustic sensors and systems for munitions response. Included as appendices to this report are the meeting agenda, a list of participants, a summary of a 2010 SERDP side meeting on acoustics detection and classification of underwater UXO, and underwater acoustic related publications from the SERDP munitions response program.

Acoustic systems have inherent advantages over magnetic and electromagnetic induction (EMI) sensors including much greater areal coverage rates and fewer platform design issues. However, these acoustic systems may not be as effective in water depths less than 3-5 m. In these shallow water environments, magnetic and EMI systems deployed using benthic crawlers or unmanned surface vehicles (USVs) may offer better detection and classification probabilities with roughly the same areal coverage rates. A quantitative analysis of UXO remediation requirements across the full spectrum of Formerly Used Defense Site (FUDS), Base Realignment and Closure (BRAC), and active sites is not available at present. We assume that a sufficient requirement for detection and classification of proud and buried UXO in waters deeper than 3-5 m exists.

Operational and platform requirements may be substantially different between mine clearance and UXO remediation. Therefore, SERDP has a major push to develop acoustic sensors, systems, and platforms that are optimized for the UXO remediation. The level of maturity of high-frequency imaging systems is much greater than for lower-frequency systems that exploit
both scattering and structural acoustic properties of UXO. As a consequence, SERDP-supported research should concentrate on these lower-frequency systems that are designed to detect and classify buried UXO. Many of the commercially-available higher-frequency sonar systems may be ready for ESTCP demonstration.

The research emphasis for the lower frequency systems, especially synthetic aperture sonar (SAS), should, for now, remain at the sensor level. Physics-based acoustic research has progressed from conceptual models, laboratory tank testing, pond experiments, to well-controlled field tests. The next experiments should include the deployment of sensors on towed, remotely-operated vehicle (ROV), autonomous underwater vehicle (AUV), or autonomous surface vehicle platforms.

Simulations are required to develop a library of UXO signatures and environments that can be used for template matching and the environmental factors that can influence the matching. Physics-based algorithms should be developed to exploit acoustic color (intensity in frequency and target aspect angle space) plots.
1.0 INTRODUCTION AND OBJECTIVES OF THE WORKSHOP

The Strategic Environmental Research and Development Program (SERDP) hosted a workshop on “Acoustic Detection and Classification of Unexploded Ordnance (UXO) in the Underwater Environment” on 16-17 July, 2013, at the Fort Myer Community Center in Arlington, Virginia. The purpose of the workshop was to evaluate the progress made in development of acoustic techniques to detect and classify UXO in the underwater environment and to outline a path for future research. Topics addressed included both high- and low-acoustic frequencies; imaging techniques and structural acoustic approaches; and focused on detection and classification of proud, partially buried, and fully buried UXO. The strategy for achieving the workshop objectives was developed by the workshop coordinating committee: Herb Nelson (SERDP), Mike Richardson (Institute for Defense Analyses and SERDP), Kevin Williams (Applied Physics Laboratory, University of Washington [APL-UW]), Bryan Harre and Steve Hurff (Naval Facilities Engineering Command [NAVFAC]), and Jason Stack and Kyle Becker (Office of Naval Research [ONR]). The strong presence of ONR program managers and ONR-supported scientists reflect the similar acoustic research issues encountered with mine clearance and UXO remediation. The presence of numerous scientists from Europe demonstrates the international importance of UXO remediation. This report was compiled and written by the members of the organizing committee along with Dan Sternlicht (Naval Surface Warfare Center, Panama City Division [NSWC PCD]), Larry Mayer (Center for Coastal and Ocean Mapping, University of New Hampshire), and Andrew Schwartz (U.S. Army Corps of Engineers [USACE]). The workshop agenda is included as Appendix A and a list of attendees is included as Appendix B.

Many active and former military installations have artillery and bombing ranges and training areas that include adjacent water environments such as ponds, lakes, rivers, estuaries, and coastal ocean areas. At other sites, training and testing areas were deliberately situated in water environments. Disposal and accidents have also generated munitions contamination in the coastal and inland waters throughout the United States. The USACE has identified more than 400 underwater Formerly Used Defense Sites (FUDS) that are potentially contaminated with munitions. The Navy Munitions Response Program (MRP) currently has an additional 57 closed (i.e., Base Realignment and Closure [BRAC]) and active (i.e., Environmental Response, Navy [ER,N]) sites potentially contaminated with munitions. These areas are in shallow water (0-120 feet) where the munitions can pose a threat to human health and the environment. Some of these sites date back to the 18th century and others were used as recently as this decade. Current areal estimates of munitions in underwater environments exceed 10 million acres. Deeper water areas are known to contain munitions from disposal activities that took place through the early 1970s. Munitions may migrate in the underwater environment and it is not uncommon for munitions to wash onshore during storm events. Dredging projects frequently encounter munitions. Both the USACE and the Navy’s Munitions Response Program (through NAVFAC) are charged with managing the remediation of these underwater UXO and require the best technologies to detect, classify, and remediate these munitions.

SERDP and ESTCP’s Munitions Response (MR) program supports the development and demonstration of innovative technologies that can characterize, remediate, and manage sites affected by military munitions found at terrestrial and underwater sites (http://www.serdp.org/Program-Areas/Munitions-Response). SERDP’s success in development
of advanced terrestrial UXO electromagnetic classification systems potentially reduces the need to excavate 70% of detected clutter on terrestrial sites thus greatly reducing the potential remediation costs (which allows more area to be cleaned with fixed budgets) and lessening the environmental impact of the remediation. The land-based UXO munitions remediation program currently supports live site demonstrations of these advanced technologies through funding from ESTCP. The emphasis of the SERDP Munitions Response program has therefore shifted to the very challenging underwater environment. Is there a similar “silver bullet” that can greatly reduce the costs of underwater UXO remediation? Of the 72 current and past underwater munitions (MR) projects supported by SERDP/ESTCP, 28 are related to acoustic detection and classification, 27 are related to electromagnetic induction (EMI) or magnetic detection and classification, eight are related to UXO migration or burial, five to optical detection and classification, five to in situ remediation, two to remediation management and performance models, and three to platforms. Most of these projects were conceived after the “SERDP and ESTCP Workshop on Technology Needs for the Characterization, Management, and Remediation of Military Munitions in Underwater Environment” held in October 2007 (http://www.serdp.org/Program-Areas/Munitions-Response/Underwater-Environments). The 2013 workshop was restricted to the evaluation of progress made in development of acoustic techniques to detect and classify UXO in the underwater environment and to outline a path for future direction. Future workshops will be devoted to electromagnetic and magnetic detection and classification of UXO and UXO migration and burial.

The 2013 workshop began with introductory presentations and white papers (see Appendix A) on previous and current UXO remediation and mine clearance work supported by SERDP, ESTCP, and ONR. This included a summary of the highly successful SERDP/ESTCP land-based remediation program, the past and present Munitions Response underwater research program, and ONR’s mine detection and classification programs. This was followed by presentations on the inventory of underwater UXO remediation sites and a description of the Congressional mandated UXO munitions response program. The last two presentations included a review the science and technology of high- and low-frequency acoustic detection and classification, research needs, and future possibilities. Breakout groups developed perspectives on the current state of underwater UXO research, directions for the future, and future system requirements. This report summarizes the results of the workshop, provides direction for future acoustic remediation efforts, and can be used as a guide for future proposals.
2.0 SUMMARY OF PROGRESS OF THE SERDP/ESTCP UNDERWATER MUNITIONS RESPONSE PROGRAM

Most of the underwater munitions response (MR) projects supported by SERDP/ESTCP are related to acoustic, optical, magnetic, and electromagnetic detection and classification of UXO. A more recent emphasis has been directed toward the prediction of UXO burial, migration, and re-emergence. Some earlier projects investigated methods of in situ remediation and underwater platforms. A description of all past and current underwater munitions response (MR) projects including links to interim and final project reports can be found at (http://www.serdp.org/Program-Areas/Munitions-Response/Underwater-Environments). All but the first 10-12 of these projects were influenced by the SERDP and ESTCP Workshop on Technology Needs for the Characterization, Management, and Remediation of Military Munitions in Underwater Environments. The final report from that workshop recommended 10 areas of overarching issues and technology requirements that had the highest priority for future SERDP research and ESTCP demonstrations. These include:

1. Develop a comprehensive inventory of munitions response sites in the underwater environment.
2. Establish test beds for evaluation of sensor technologies.
3. Evaluate munitions mobility in the underwater environment.
4. Characterize the acoustic response of munitions and typical bottom clutter.
5. Combine existing sensor and navigation technologies.
6. Investigate the role of chemical and laser line scan sensors.
7. Explore munitions indicators that can be exploited for wide area surveys.
8. Improve detection of smaller munitions items by electromagnetic (EM) and magnetic systems.
9. Conduct navigational error analysis.

Recent SERDP/ESTCP Statements of Need (SONs) have emphasized development of sensors that can detect and classify buried UXO (areas 4, 6, 8, and 10) which are relevant to wide area and detailed UXO surveys. It is felt that issues associated with underwater platforms (areas 5 and 9) and the establishment of test beds (area 2) would follow sensor development. Prediction of UXO burial, migration, and re-emergence (area 3) supports the development of sensor performance models and UXO risk analyses. It is felt that development of a comprehensive inventory of munitions response sites (area 1) is not a research issue (see section 5). Research supporting the exploitation of munitions indicators (area 7) has not specifically been supported but is related to the development of sensors and sensor systems. In this section we will describe the progress SERDP/ESTCP researchers have made in the areas listed above.
**Test Beds:** Project-specific test beds have been established to evaluate acoustic, magnetic, electromagnetic, and optical sensor designs and demonstrate commercial and military systems. However, no consistent set of test bed requirements have been established similar to those associated with terrestrial UXO remediation demonstrations. Underwater navigation issues, inadequate ground truth for the types and location of UXO, lack of test evaluation strips, and lack of environmental ground truth have all hampered the evaluation of sensors and sensor systems used to detect and classify underwater UXO. A sidebar meeting held at the 2011 SERDP Symposium established the following underwater test bed requirements. A mobile, re-deployable test bed concept is preferable and more cost effective than permanent single or multiple test beds. The location, orientation, and depth of UXO and clutter should be well known. Environmental conditions that affect the operational effectiveness of acoustic, optical, magnetic, and electromagnetic detection and classification sensor systems are time dependent and should be characterized before, during, and after experiments or demonstrations. These include at a minimum: sediment type, bathymetry, water clarity, hydrodynamic conditions (waves and currents), and clutter. The test beds should provide a consistent, quantifiable set of conditions to allow comparison between sensors and sensor systems during individual experiments and between the results of experiments conducted at different sites and at different times. Deployment and maintenance of such a mobile, re-deployable test bed should be led by a team not associated with the UXO detection and classification sensor systems that are being evaluated.

**UXO Burial and Mobility:** Because of its obvious importance, research related to UXO burial, mobility, and re-exposure has recently become a priority for SERDP/ESTCP. In contrast to terrestrial sites, the underwater environment is dynamic and UXO often do not stay in place. That greatly complicates risk assessment, detection and classification, and subsequent remediation efforts. The burial state also complicates prediction of UXO corrosion and the fate and transport of explosive and chemical contaminants. UXO burial and migration models include physics-based impact and scour models, engineering type empirically-driven models, and probabilistic Bayesian network models (so-called expert system). These models, many developed under ONR’s Mine Burial Program, are being modified and validated for the variety of UXO types and environments of importance for UXO remediation. Ongoing SERDP projects include laboratory and field experiments, development and validation of burial, migration, and re-emergence models, and an integration of these models with in situ sediment characterization from acoustic measurements, historical sediment databases and hydrodynamic databases, and models. The goal is development of probabilistic models that can predict both the short- and long-term behavior and resultant distribution of UXO at underwater remediation sites.

**Acoustic Sensors and Systems:** SERDP has supported development and/or evaluation of three classes of acoustic sensors: commercial systems, bottom mine detection systems designed for naval applications, and wide band synthetic aperture sensors well-suited for UXO detection and classification. Demonstrations of commercial systems (MHz imaging, kHz side scan imaging, narrow and wideband subbottom profilers, multibeam bathymetric sonar, and high- and low-frequency synthetic aperture sonar [SAS] systems) have been only partially successful. Most of the commercial sonar systems demonstrated to date are high frequency and can only be used for detection of proud targets. The lower-frequency commercial systems that are capable of detecting buried targets are used primarily for imaging. Sonar systems designed for detection and classification of naval mines have been developed for military applications. These sonar systems, deployed on autonomous vehicles and actively navigated towfish, include various versions of the
Buried Object Scanning Sonar (BOSS), a scanning synthetic aperture system capable of imaging buried targets; side scan imaging sonar systems; very high frequency imaging sonar systems; and high- and low-frequency SAS systems. Automated target recognition (ATR) methods are being developed for systems like BOSS based on data collected in laboratory tanks, outdoor facilities, and in highly controlled field experiments. These data are being supplemented by acoustic simulations. Operational and platform requirements are potentially much different between mine clearance and detection and classification of munitions (see section 5). Therefore, SERDP has a major push to develop acoustic sensors, systems, and platforms that are optimized for the UXO remediation. Characterizing the acoustic response of munitions in underwater environments is an essential first step. The signatures of munitions vary depending upon 1) munitions type and size; 2) if it is fully intact; distorted, or broken into munitions-related scrap; 3) internal structure; and 4) if it is buried, partially buried, or proud. Research emphasis has centered on wideband synthetic aperture sonar technology at steep grazing angles (above critical) where the full spectrum of frequency and target aspect angles is used to develop acoustic color plots (e.g., BOSS). These acoustic color plots include a target response from higher-frequency scattering (primarily sensitive to target shape) and lower-frequency structural acoustics. SERDP has supported a progressive range of research starting with modeling and basic tank tests with closely controlled variables. This research has suggested that sufficient information is available in acoustic color plots to supplement the classification process for buried UXO. These experiments have been followed by controlled open water data experiments with a variety of UXO and clutter targets to validate these conclusions and develop a library of UXO acoustic signatures. Simulations are also being run to provide a physical understanding of the target signatures; expand the library of acoustic signatures over the acoustic, target, environmental target space; and provide data to develop UXO detection and classification algorithms. It is anticipated that these controlled experiments will be followed by experiments using surface towed or remote underwater vehicles.

**Combine Existing Sensor and Navigation Technologies**: Prototype MCM mine detection systems, developed with support from ONR and NSWC PCD, have been tested to determine if they would be effective in detection of proud and buried UXO typically found in the marine environment. These systems include the Mobile Underwater Debris Survey System (MUDSS) and Small Synthetic Aperture Minehunter (SSAMI and II). Sensors included various versions of BOSS, optical systems, active and passive EM sensors, including a passive fluxgate magnetic sensor, the Real-time Tracking Gradiometer (RTG), laser scalar gradiometer (LSG) and an active EM GEM-3 array. The BOSS synthetic aperture system was the most successful in imaging buried objects in coarse bottom sand, and with the most recent version and advanced signal processing is able to detect larger buried UXO and provide general size and shape information for buried UXO. Optical systems were limited by water clarity and were only able to detect proud targets. Navigation issues and poor ground truth limited evaluation of data fusion approaches to UXO classification. Several projects have investigated (both field studies and theoretical modeling) the combined use of magnetic and electromagnetic sensors typically used in terrestrial studies. The most successful of these, the Marine Towed Array (MTA), comprised a towed wing containing eight cesium vapor total field magnetometers and an array of EM61 EMI sensors. A number of surveys were successfully completed using the magnetometers, but reliability problems plagued the EMI sensors, negating their usefulness. However, as a class, these towed systems typically suffered interference from platform and environmental noise, navigation uncertainties, and differences in detection distances (the fall-off rate of signals from
EMI systems is much greater than for magnetic systems). It was the conclusion of both the acoustics and geophysical working groups during sidebar meetings at the 2010 SERDP/ESTCP Symposium, that although detection/classification systems that combine acoustics, passive magnetics, active EMI, and possibly optics may be needed, research and demonstrations on individual systems should take precedence. The capabilities of each sensor type need to be understood and optimized before combining modalities. It is quite possible that optimal acoustic, magnetic, EMI, and optical sensor designs may not be operationally compatible on the same platform.

**Optics-Related Sensors and Systems:** SERDP/ESTCP has supported demonstrations of optical systems, including video cameras and laser line scanners, with very limited success. This lack of success does not mean optical sensors will not be part of the sensor tool kit used for UXO remediation. The development of full three-dimensional (3-D) mapping and mosaicing of video images combined with ATR algorithms may provide a valuable tool for UXO detection and classification in areas where UXO are proud and the water visibility is good. These tend to be shallow water areas with high recreation potential such as coral reefs.

**Electromagnetic (EM) and Magnetic Systems:** Current underwater geophysical surveys for UXO are primarily limited to passive magnetic arrays towed from surface vessels or part of integrated multi-sensor remotely-operated vehicles (ROVs). These systems have been shown to detect larger UXO and along with accurate positioning data provide seafloor magnetic contour maps. Some systems such as the MTA have demonstrated the capability of providing accurate data inversions yielding target parameters, including location, size, and depth but accurate classification has not been reported. The biggest issues are stand-off distances (1-2 m from the seafloor for magnetics and preferably closer for EMI), navigation, and noise from the platform. Most of the demonstrations of these passive magnetic systems have lacked the adequate ground truth to evaluate system performance. Active EMI systems similar to the advanced EMI systems used at terrestrial sites are still in the development stages. The differences between land-based and marine systems have not been exploited or fully understood. Modeling and simulations suggest that for EMI sensors, which operate from 100 μs (10 kHz) to 25 ms (40 Hz), seawater has negligible effects on the performance of these next-generation EMI sensors and advanced EMI classification models. SERDP is currently supporting fundamental research and modeling needed to understand the physics of geophysical sensing (electromagnetic, magnetic, and electrical) in the marine environment. These include the effects of a conductive media (seawater) on sensor performance, signal interactions with sea surface and seafloor, and platform interference. These all affect optimal sensor array configurations, maximum stand-off (detection) distances, navigation requirements, platform stability requirements, and ultimately the effectiveness of advanced classification modeling. Based on experimental data and modeling, EMI technology will probably be restricted to cued classification of UXO; whereas magnetic sensors may be used for wide-area and detailed surveys. SERDP is currently supporting the development and evaluation of prototype marine versions of advanced EMI sensor systems such as the 2x2 MetalMapper, a sled version of BUD (MBUD), a frequency-domain digital EMI array mounted on a commercial mid-sized ROV, and a EMI sensor based on both electric (E) and magnetic (B) field sources. SERDP is also supporting the development of a new underwater handheld metal detector based on an array of low-power, miniature, total-field atomic magnetometers.
In Situ Remediation: One of the last phases of UXO remediation is the removal of UXO threats from the environment. The standard method is to use explosives trained divers. This is both dangerous and a costly method of UXO remediation. ESTCP has supported demonstrations of other methods to remediate UXO with limited success. These include generation of bubble curtains to reduce the pressure effects of UXO blow-in-place, wide-mesh screen to capture UXO during dredging operations, and collection of buried UXO using a coffer dam with a large electromagnet. SERDP is currently supporting a co-robotic (human operator in partnership with a robot) manipulator for the removal of underwater UXO using a ROV.
3.0 STATE OF THE ART: UNDERWATER ACOUSTICS DETECTION AND CLASSIFICATION OF UXO

The last two presentations of Day 1 of the 2013 SERDP workshop included a review of the science and technology of high- and low-frequency acoustic detection and classification. Topics included data acquisition, modeling, signal processing, and target classification. ONR supported a similar workshop directed towards MCM applications in December 2012 (International Workshop on Intersection in Signal processing, Acoustics, and ATR for Maritime applications [iSAAM]).

The two breakout groups from this workshop developed perspectives on the current state of underwater UXO research, directions for the future, and future system requirements. In this section we provide a summary of discussions from those breakout groups related to the state of the art for underwater detection and classification of UXO. The emphasis for the high-frequency acoustic systems is imaging targets and the seafloor; whereas the emphasis for the low-frequency acoustic systems is detection and classification of buried targets. The low-frequency sonar systems take advantage of both shape-related backscattering and structural acoustic responses of UXO. We purposely did not define what is meant by high, mid, and low frequency, allowing some overlap in the breakout group discussions.

3.1 Mid- to High-Frequency Acoustics (Image based detection/classification)

The current state-of-the-art for acoustic imaging systems is summarized in Table 3-1, which includes a mix of commercial off-the-shelf systems and prototype MCM systems designed and optimized for mine clearance. The Buried Object Scanning Sonar (BOSS), originally developed by Dr. Steve Schock, is a SAS system that can image proud, partially buried, and larger buried mines and UXO. The naval versions of BOSS have been demonstrated for UXO wide area surveys by NSWC-PCD and are part of a suite of sensors deployed with AUVs, such as Bluefin 12 and REMUS-600. There are multiple versions of BOSS that vary with frequency and bandwidth, and number, orientation, and spacing of receivers. BOSS has shown considerable success in detection of proud and buried UXO and can provide information on size, shape, depth, and orientation of larger UXO. Development of higher resolution, 3-D versions of BOSS, and the development of circular synthetic aperture sonar (CSAS) image processing show great promise for classification of larger buried UXO and detection and possibility classification of smaller UXO. Research issues include those related to navigation, platform stability, mult Path in shallow water, multi-element design, multi-aspect data collection, signal processing, and target classification (automated target recognition in MCM). It is important to optimize the SAS design, signal processing, and target detection and classification algorithms with platform characteristics and operational requirements. As a rule of thumb, detection resolution requires a minimum of 3x3 pixels on the target and classification requires at least 9x9 pixels on target.

A number of very high-frequency sector scan imaging sonar systems are commercially available. These systems have resolutions that approach that of optical systems and are capable of detecting and classifying UXO that are proud or perhaps partly buried. Side scan and multibeam sonar systems designed for seafloor visualization, classification, and bathymetric surveys are also widely available and may be useful for UXO wide area surveys. Commercial single beam subbottom profiling sonar systems are ubiquitous and can, depending on frequency, be used for
geophysical studies, sediment classification, and navigation. Because of their narrow track width and low-resolution, these types of single beam systems will play a very limited role in UXO remediation. Low-frequency parametric sonar systems may have a role in the detection of larger, deeply buried UXO. Steerable parametric sonar systems have demonstrated the capability to detect buried pipelines and cables with diameters as small as 3 cm to depths up to 5 m. Swath widths up to 10° are possible.

SERDP is currently supporting the development of physics-based algorithms for sediment classification from high-frequency (150-450 kHz) multibeam sonar systems (Reson Seabat 7125). If successful, these sonar systems should be able to provide sediment characterization needed for UXO wide area surveys. These high-resolution, wide-track width data should be far superior to the single beam downward-looking acoustic sediment classification systems commercially available.

Table 3-1. High Frequency – State of the Art

<table>
<thead>
<tr>
<th>Detection Resolution Requirements: 3x3 pixels on targets</th>
<th>Classification Resolution Requirements: 9x9 pixels on targets</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Categorizing State of the Art in Acoustic Sensing</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Scan Mode</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Sonar System (e.g)</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Op. Freq. Range</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Resol.</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Op. Alt. (m)</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Swath Width</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Det. Limits (Burial State)</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Class. Limits (Obj size)</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Commercial Examples</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Down-looking (high grazing angle)</strong></td>
<td></td>
</tr>
<tr>
<td>Multi-beam (Reson 7125)</td>
<td>400-455kHz</td>
</tr>
<tr>
<td>1/2°, e.g. 5cm x 2cm</td>
<td>&gt;3m</td>
</tr>
<tr>
<td>30°</td>
<td>Proud</td>
</tr>
<tr>
<td>Medium to Large dependent on range</td>
<td>Blueview, Didson</td>
</tr>
<tr>
<td>Buried Object Scanning Sonar</td>
<td>5-20kHz</td>
</tr>
<tr>
<td>&gt;5cm³</td>
<td>&gt;3m</td>
</tr>
<tr>
<td>15m</td>
<td>Proud/Buried</td>
</tr>
<tr>
<td>Buried Medium</td>
<td>EdgeTech</td>
</tr>
<tr>
<td>Parametric (INNOMAR SES-2000)</td>
<td>5-80kHz</td>
</tr>
<tr>
<td>1°</td>
<td>&gt;3m</td>
</tr>
<tr>
<td>-</td>
<td>Proud/Buried</td>
</tr>
<tr>
<td>Buried Large</td>
<td>DRUMS (Guigne International)</td>
</tr>
<tr>
<td><strong>Side-looking (low grazing angle)</strong></td>
<td></td>
</tr>
<tr>
<td>Mid-freq SAS</td>
<td>&gt;10kHz</td>
</tr>
<tr>
<td>5cm x 5cm</td>
<td>&gt;5m</td>
</tr>
<tr>
<td>&gt;100m</td>
<td>Proud/Buried</td>
</tr>
<tr>
<td>Med. Objects</td>
<td>Kongsberg HISAS, AST PROSAS</td>
</tr>
<tr>
<td>High-freq SAS</td>
<td>&gt;60kHz</td>
</tr>
<tr>
<td>2cm x 2cm</td>
<td>&gt;5m</td>
</tr>
<tr>
<td>&gt;100m</td>
<td>Proud</td>
</tr>
<tr>
<td>Small Obj.</td>
<td>Kongsberg HISAS, AST PROSAS</td>
</tr>
<tr>
<td>High-freq SSS (Klein 5000)</td>
<td>500kHz</td>
</tr>
<tr>
<td>Range dependent</td>
<td>&gt;3m</td>
</tr>
<tr>
<td>&gt;100m</td>
<td>Proud</td>
</tr>
<tr>
<td>Small to Large dependent on range</td>
<td>Edgetech</td>
</tr>
</tbody>
</table>

| **Notes**                                               |                                                               |
| Most sensor types mountable across multiple platform types (ship hull/boom, towfish, self-propelled vehicle). High-frequency SAS requires high platform stability. Parametric sonars can require significant power for operation. Classification performance improves with the addition of orthogonal sensors: Magnetic Gradiometer, Camera, or Electro-Optics. Potential operational cost savings using ATR (PMA or embedded) and advanced autonomy. |

3.2 Low- to Mid-Frequency Acoustics (Structural acoustics based detection/classification)

Use of structural acoustic response to detect and classify mines and UXO is a relatively recent effort as compared to acoustic imaging. The advantage from a detection standpoint is that the
lower frequencies used result in increased penetration into the sediment above the critical angle, thus providing an increased ability to detect and classify buried objects.

3.2.1 Data Acquisition Efforts in the United States

There have been efforts by NSWC, NRL, and APL-UW to collect data on proud, partially buried, and buried UXO under well-controlled conditions. These controlled data acquisition efforts have been carried out in test pools and ponds that have sand sediment on the bottom. The references given in the modeling section below include data/model comparisons using some of this data. These same groups have moved recently to ocean experiments. The sediment at the location of the recent ocean experiments is sand. Ocean experiments currently planned for Fiscal Year 2014 will be carried out in muddy sediment.

Some of the data taken by NSWC and APL-UW in a large test pond using rail-mounted sensors is available as public release. Inquiries can be made to the SERDP office directly for copies of these data (see section 9 for more details). The data includes scattered returns from several UXO and natural items at a large number of look angles.

3.2.2 Data Acquisition Efforts in Europe

Data acquisition efforts by the Netherlands Organisation for Applied Scientific Research (TNO), Federal Armed Services Underwater Acoustics and Marine Geophysics Research Institute (FWG), and Centre for Maritime Research and Experimentation (CMRE) in ocean/harbor environments have begun, with several new efforts being anticipated in the next few years. TNO is working in collaboration with the European Defense Agency. They will be fielding their low frequency acoustic system as well as a magnetometer as part of that collaborative effort; a joint sea trial is anticipated in 2015. They have already acquired data using a hull mounted low-frequency system and have shown success in detecting objects in muddy sediments. FWG has been testing a variety of acoustic systems, including low-frequency systems, and are anticipating the first sea trials in October 2013. They will be joining with CMRE as part of a Joint Research Program in the next few years. Part of the FWG strategy is to compare different systems to decide site-specific optimal sensors and combinations of sensors. CMRE efforts have been aimed primarily at MCM systems and have focused on assuring UUV utilization of the MCM sensors to be fielded. CMRE now has a rail system in operation in a shallow water ocean environment with a silt bottom.

3.2.3 Modeling - United States

Combinations of FE and various propagation models have been developed that have high fidelity when compared to results from controlled experiments. At this point, all models use a combination of FE methods to handle scattering in the near vicinity of the target and then various propagation models to determine scattered pressure at the location of the receivers. NSWC, NRL, and HLS all have modeling capabilities developed entirely within the United States. Results from these models have been compared to data (Ref. 1-3) and used in classification studies (Ref. 3)
3.2.4 Modeling – United States/Europe collaboration

APL-UW, Washington State University (WSU), and TNO have been collaborating on model development with a similar philosophy to the U.S.-only efforts, i.e., combining FE modeling local to the target with various physical acoustics models to handle propagation to the receiver (Ref. 1,2,4-6). APL-UW has developed a propagation modeling technique (Ref. 4) that can be combined with FE results and increase the overall computation speeds by a factor of 1000 with small loss in fidelity compared to test pond data, at least from one simple metric of probability of correct classification using template matching. The fidelity of these modeling techniques, as well as those of the previous section, relative to this and other metrics needs to be quantified using ocean data.

3.2.5 Signal Processing

A technique to isolate individual targets using initial SAS processing has been developed (Ref. 7). Using this technique, the acoustic response of targets with cross range separations as little as 1 m can be recovered. The data from test pond experiments (Section 3.2.1) have been used individually and summed to examine the classification characteristics of simple relevance vector machine classification schemes using acoustic template matching. These studies have produced ROC curves with Area-Under-the-Curve (AUC) of about 0.84 using experimentally derived templates and 0.8 using model templates. Alternative RVM analyses using data acquired in a test pool have also shown the model-derived scattering to be of sufficient fidelity to allow classification (Ref. 3). Carrying out similar studies using ocean data is the next step.

Finding better ways to use the acoustic response in classification (e.g., finding and using robust features derived from the acoustic templates) is a current area of research. Incorporating this information into ATR algorithms should increase efficiency of detection/classification efforts.

3.2.6 Summary/Discussion

Workshop participants identified several topics that need to be addressed next based on the current state of the art:

- What are the tradeoffs of speed/fidelity, and how much fidelity is enough? We have not identified the metrics needed to answer this.
- For acoustic color, the predominant classification technique is template matching.
  - Is template matching good enough, the best, or appropriate?
  - Is template matching not the operational answer, but good enough to ask the experimental questions?
  - If it is, how to generate the libraries / templates that can take into account a wide range of variations of parameters and geometries?
- How to extract useful features from acoustic color data?
- Need to explore the regions where elastic sediment modeling might be required.
There was significant discussion of the similarities and differences of the MCM and UXO problem. A summary of much of that discussion can be found in section 6 below. One important point from these discussions is that the sensors being used and the classification schemes used on the resulting data will have considerable overlap even if the systems on which the sensors are deployed may be different. Thus, leveraging MCM and UXO similarities in this regard will continue to be a benefit to both.

4.0 THE WAY AHEAD AND PROPOSED TIMELINE

The SERDP munitions response (MR) program has supported 28 projects related to acoustic detection and classification of UXO in the underwater environment. Much of the current portfolio is directed towards detection and classification of buried UXO using lower-frequency (1-50 kHz) SAS. Given that over 70% of UXO (Ref. 9) are probably buried this seems like a wise decision. Acoustic systems have inherent advantages over magnetic and electro-magnetic induction sensors including much greater areal coverage rates and fewer platform design issues. However, these acoustic systems may not be as effective in water depths less than 3-5 m. In these shallow water environments, magnetic and EMI systems deployed using benthic crawlers may offer better detection and classification probabilities with roughly the same areal coverage rates. In spite of the detailed description of UXO remediation efforts at four sites, given in the next section, a quantitative analysis of UXO remediation requirements across the full spectrum of FUDS, BRAC, and active sites is not available. At present, we will assume that a sufficient requirement for detection and classification of proud and buried UXO waters deeper than 3-5 m exists.

Operational and platform requirements may be substantially different between mine clearance and UXO remediation (see section 5). Therefore, SERDP has a major push to develop acoustic sensors, systems, and platforms that are optimized for the UXO remediation. Based on group discussion the level of maturity of high-frequency imaging systems is much greater than for lower frequency systems that exploit both shape-related scattering and structural acoustic properties of UXO. As a consequence, SERDP supported research should concentrate on these lower frequency systems which are designed to detect and classify buried UXO. Many of the commercially-available, higher-frequency sonar systems may be ready for ESTCP demonstration.

The hardware and signal processing for high-frequency imaging sonar systems, such as side-scan, sector scanning, and multibeam sonar systems is well developed and probably more than adequate for UXO remediation. The research emphasis for these systems should be directed towards detection and classification algorithms. This includes the effects of the environment on target scattering, signal processing and classification. The use of calibrated systems for assessing actual target strength should be encouraged. Test beds need to be developed to provide performance predictions for a variety of UXO and environments.

The research emphasis for the lower-frequency systems, especially SAS, should, for now, remain at the sensor level. Physics-based acoustic research has progressed from conceptual models, laboratory tank testing, and pond experiments to well-controlled field tests. This research has suggested that sufficient information is available in acoustic color plots to develop classification algorithms for buried UXO. The controlled open water experiments have been conducted with a
variety of UXO and clutter targets to validate these conclusions and develop a library of UXO acoustic signatures. The next experiments should include the deployment of sensors on towed, ROV, or AUV platforms in environments where UXO remediation is required. Simulations are required to develop a library of UXO signatures and environments that can be used for template matching. Physics-based algorithms should be developed to exploit acoustic color (intensity in frequency and target aspect angle space) plots. The next step should be platform/sensor integration, testing in well-developed test beds, and demonstration at live sites. UXO remediation may require that multiple sensor modalities be used at many sites. However, capabilities of each sensor type needs to be understood and optimized before combining modalities. It is quite possible that optimal acoustic, magnetic, EMI, and optical sensor designs may not be operationally compatible on the same platform.

**SERDP/ESTCP Underwater Acoustic Munitions Response Roadmap**

- Controlled open water experiments: 2013, 2014
- Platform/acoustic integration; 2015
- Integration testing: 2016
- Mobile test bed development: 2015, 2016, 2017
- Live site demonstrations: 2017, 2018, etc
5.0 UNDERWATER MUNITIONS RESPONSE SITES

As mentioned in the introduction, most underwater munitions response sites are managed by the Navy and USACE. There are over 450 sites across the United States identified as having potential contamination with underwater munitions. In this section, we present a brief outline of the CERCLA process, list the criteria used by the Navy for including sites in the Munitions Response Program and give examples of four broad classes of sites from both programs.

5.1 Munitions Response and CERCLA

In most cases, munitions response projects are carried out following the CERCLA process. A simplified work flow is shown in Figure 5-1.

![Figure 5-1. The CERCLA process as applied to munitions response](image)

The major steps in this process include:

- Preliminary Assessment/Site Inspection: Investigations of site conditions.
- Remedial Investigation/Feasibility Study: Determines the nature and extent of contamination. Assesses the treatability of site contamination and evaluates the potential performance and cost of treatment technologies.
- Record of Decision: Documents the cleanup alternative chosen for the site.
- Remedial Design/Remedial Action: Preparation and implementation of plans and specifications for applying the remedy.
- Response Complete: The remediation has been completed.

5.2 Current Navy Policy for Inclusion of Underwater Sites into the Navy’s MRP

The Navy’s MRP addresses response actions at munitions response sites (MRSs). The Navy uses the following criteria for inclusion of water sites into the Munitions Response Program.

Shallow water areas where munitions releases are known or suspected to have occurred and where:

- Navy actions are responsible for the release
- The munitions are covered by water no deeper than 120 feet
- The site is not:
  - Part of, or associated with, a designated operational range (terrestrial or water range)
  - A designated water disposal site
  - A Formerly Used Defense Site
  - A result of combat operations
  - A maritime wreck
  - An artificial reef

The Navy considers munitions located in waters between high and low tides terrestrial.
5.3 Examples of Underwater Munitions Response (MR) Areas

Underwater munitions response areas encompass a large variety of conditions and munitions profiles but a number of them fall into several broad categories. Four example areas are detailed below to serve as a guide for developers of sensors, analysis methodologies, and systems.

5.3.1 Former Mare Island Naval Shipyard (Navy)

Mare Island Naval Shipyard was closed as part of the BRAC process. Mare Island Naval Shipyard has four underwater MRSs. The MEC contamination at Mare Island Naval Shipyard is related to the accidental or intentional disposal into the water from Navy piers and along the shoreline. The site descriptions at Mare Island Naval Shipyard are as follows:

**Fleet Reserve Piers** – These piers were used for storage of the Reserve Fleet post World War II (WWII) on the Napa River. The site has a water depth of up to 30 feet with a silty bottom and low visibility in the water. The site is suspected to have MEC because of the timeframe and potential wartime use.

**Berths 2&3** - Berths on the Napa River were used by EOD Mobile Unit 9. The MRS has a water depth of up to 10 m with a silty bottom and low visibility in the water. The MRS is suspected of having MEC because of the adjacent land use by an EOD boat unit.

**Ammunition Production and Manufacturing Area (PMA) Offshore/Mare Island Strait** – This MRS is an offshore area adjacent to the Ammunition Production and Manufacturing Area (PMA) which includes shallow areas as well as areas as deep as 30 feet. The MRS boundary is from the shoreline to areas around the current and former piers. The Mare Island Strait connects the Napa River to San Pablo Bay and is a low visibility area used by commercial and recreational boat traffic. The MRS is suspected of having MEC because of the land based munitions operations and pier use from the 1850s until the 1990s. Additionally, MEC has been found on the land adjacent to the MRS and at certain locations along the shoreline.

**South Shore Area (SSA) Offshore/Carquinez Strait** - This site is the offshore area adjacent to the South Shore Area which supported the PMA. It includes the shallow areas as well as areas as deep as 10 m from the shoreline to around the current and former piers. The Carquinez Strait connects the Sacramento River to San Pablo Bay and is a low visibility area used by commercial and recreational boat traffic. The MRS is suspected of having MEC because of the land-based munitions operations and pier use from the 1850s until the 1990s. Additionally, MEC has been found on the land adjacent to the MRS and at certain locations along the shoreline.

5.3.2 Former Vieques Naval Training Range (Navy) & Culebra Water Ranges (USACE)

The former Vieques Naval Training Range (VNTR) is situated in the eastern half of the Island of Vieques, and is bordered on the west by the community of Isabel Segunda, to the north by Vieques Sound, and to the south by the Caribbean Sea. Culebra Island is located approximately 17 miles east of Puerto Rico and approximately 9 miles northeast of Vieques.

The former VNTR consists of approximately 14,500 acres. The Navy has owned portions of Vieques since 1941, when land was purchased for use as an ammunitions storage facility in support of WWII training requirements. Although the island of Culebra was the focal point for
naval gunfire in the 1960s and early 1970s, the development of facilities on the eastern end of Vieques was undertaken in 1964, when a gunnery range was established in the live impact area (LIA). The Atlantic Fleet’s ships, aircraft, and Marine forces carried out training in all aspects of Naval gunfire support, ATG ordnance delivery, air-to-surface mine delivery, amphibious landings, small-arms fire, artillery and tank fire, and combat engineering. The records indicate there were off-shore munitions hits. The VNTR was closed in 2003 and is now designated the Vieques National Wildlife Refuge. The majority of the area is off limits to the public due to the presence of MEC.

Limited surveys of MEC have been conducted in two offshore areas. The physical areas are Bahia Icacos, and Bahia Salinas. Depths in Bahia Icacos are between 1 and 5 m, and up to 7 m. Fourteen soundings were taken in Bahia Salinas and the deepest portion of the bay (6-7 m) is a narrow channel between two shoal areas. The central portion of the bay is approximately 5 m. The total area going out to 30 m depth limit is approximately 9000 acres.

The National Oceanic and Atmospheric Administration (NOAA) completed an “An Ecological Characterization of the Marine Resources of Vieques, Puerto Rico” in 2010. The following table and text summarizes the bottom types for the entire island of Vieques

<table>
<thead>
<tr>
<th>Major Structure</th>
<th>Area (km²)</th>
<th>Percent Area</th>
<th>Detailed Structure</th>
<th>Area (km²)</th>
<th>Percent Area</th>
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<tbody>
<tr>
<td>Coral Reef and Hardbottom</td>
<td>119.56</td>
<td>33.44</td>
<td>Rock/Boulder</td>
<td>1.38</td>
<td>0.39</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>Aggregate Reef</td>
<td>13.79</td>
<td>3.86</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>Individual Patch Reef</td>
<td>6.46</td>
<td>1.81</td>
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<td></td>
<td></td>
<td></td>
<td>Aggregated Patch Reef</td>
<td>1.91</td>
<td>0.54</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Spur and Groove</td>
<td>0.02</td>
<td>0.01</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Pavement</td>
<td>39.37</td>
<td>11.01</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Pavement with Sand Channels</td>
<td>5.98</td>
<td>1.67</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Reef Rubble</td>
<td>17.53</td>
<td>4.90</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Rhodoliths</td>
<td>33.11</td>
<td>9.26</td>
</tr>
<tr>
<td>Unconsolidated Sediment</td>
<td>237.95</td>
<td>66.56</td>
<td>Sand</td>
<td>220.39</td>
<td>61.64</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Mud</td>
<td>7.88</td>
<td>2.20</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>Sand with Scattered Coral and Rock</td>
<td>9.69</td>
<td>2.71</td>
</tr>
<tr>
<td>Other Delineations (land excluded)</td>
<td>0.05</td>
<td>0.01</td>
<td>Artificial</td>
<td>0.05</td>
<td>0.01</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>357.56</strong></td>
<td><strong>100.00</strong></td>
<td></td>
<td><strong>357.56</strong></td>
<td><strong>100.00</strong></td>
</tr>
</tbody>
</table>

The composition and extent of bottom structure and biological cover around Vieques varies over space. The area north-northwest of Vieques is dominated by sand with submerged aquatic
vegetation, interspersed by numerous patch reefs. Moving east from Isabel Segunda, a system of shallow Lagoons and Reef Flats extend from shore, bordered seaward by a line of Pavement and Aggregate Reef. A large area of Rhodoliths dominated by algae cover sits offshore in the deeper water. The formation of Pavement and Aggregate Reef extends around the eastern tip of the island to the south side, where it is more extensive than on the north. Two linear systems of Pavement and Aggregate Reef are present on the south coast; one close to shore, while another is further offshore along the shelf edge. The large area lying between these two reef systems southeast of Vieques is a depression approaching 30 m in depth that was primarily mapped as Reef Rubble. Biological cover types include Seagrass, Algae, Mangrove and Coral.

The Department of Defense used the island of Culebra and adjacent islands and cays to train troops for combat and, although DOD ceased activities in the mid-1970s, military munitions remain on the islands and surrounding waters. Of the 13 MRSs on Culebra, at least six have an underwater component.

The water depths and bottom characteristics on Culebra are similar to those on Vieques. For example, in MRS 09 both mud and sand bottoms were observed with sand being the majority and in MRS 13 sand was the predominant cover. In both of these MRSs, areas of colonized and uncolonized hard bottom and coral reef were observed. In MRS 09, depths range from 0 to 20 feet while in MRS 13 the maximum depth is 50 feet.

5.3.3 NAS Patuxent River UXO 0001 (Navy)

NAS Patuxent River is located in St. Mary’s County in southern Maryland, approximately 65 miles southeast of Washington, D.C., at the confluence of the Patuxent River and the Chesapeake Bay. The Patuxent River supports naval aviation operations by researching, developing, testing, and evaluating aircraft, aircraft components, and related products.

The Historic Munitions Disposal Area (UXO 0001) is located south of the former seaplane basin known as the Chesapeake Basin along the southeastern base boundary. The seaplane basin was constructed in the Chesapeake Bay in 1942, and consists of northern and southern seawalls. A stream known as Pine Hill Run flows along the southeastern boundary of NAS Patuxent River. Pine Hill Run empties into the Chesapeake Bay.

From approximately 1954 to 1974, NAS Patuxent River personnel discarded a variety of excess munitions, both live and inert, into the Chesapeake Bay. At that time, it was a standard safety practice to dispose of old munitions into open water. This practice was halted at NAS Patuxent River in 1974.

The Historic Munitions Disposal Area includes the known disposal area along the seawalls of the Chesapeake Basin and a former pier that was located on base property a few hundred feet south of the basin, as well as a portion of the privately owned beach south of the installation fence that is part of the Cedar Cove subdivision. The privately owned beach is separated from the NAS Patuxent River to the north by Pine Hill Run, which drains into the Chesapeake Bay. The adjacent residential community, Cedar Cove, has approximately 200 homes. Currently, the beach is used for recreational activities by community residents.
Disposed military units were reportedly discarded into the Chesapeake Bay from two locations at NAS Patuxent River:

- Along the seawalls of the former seaplane basin that extend approximately 700 feet into the Chesapeake Bay. Based on the locations where discarded munitions have been recovered during past efforts, the majority of the munitions were discarded inside the seaplane basin.
- A pier, located approximately 350 feet south of the former seaplane basin and extending about 50 feet into the bay, which no longer exists.

Over time, the munitions items disposed into the water were moved by tides and currents and eventually some items started washing up on the shoreline both within and beyond the base boundary near where the items were originally discarded. The primary potential source of concern at the site is MEC resulting from historical disposal operations at NAS Patuxent River immediately to the north. MEC may be present beneath the land surface, on the sediment surface, or in the sediment subsurface.

Figure 5-2. NAS Patuxent River
Historic Munitions Disposal Area - It should be noted that most of UXO 0001 has depths of 3 ft or less. The water is turbid, with poor water clarity. This area is also subject to significant
erosion due to normal wave and storm actions. One tropical storm removed 2 ft of sand from the beach, resulting in redeposition off-shore. Following these storm events, a number of non-MEC metallic objects have been noted as emerging from the waterfront where they were apparently used as improvised rip-rap or fill. These items appear similar in shape and size to MEC (fence posts/pipes/concrete with rebar). The dynamic nature of the site, coupled with limited sensing depth with magnetometry and EMI makes site investigation challenging.

5.3.4 Former Seattle Naval Supply Depot (USACE)

The former Seattle Naval Supply Depot (FSNSD) is located along the Puget Sound in King County, WA, approximately 3 miles northwest of downtown Seattle at the present day Terminal 91 site. The survey area of interest is classified as being in open water surrounding each of the piers or under the overhang of a pier (approximately 60 ft). These are constructed on fill material connected to an upland area at the north of each pier. The west, south, and east perimeter of each pier includes concrete and treated wood pilings and a supported dock area approximately 80 to 85 ft wide. They are fitted with a combined timber/steel pier fender piling system.

The bathymetry of the FSNSD is diverse going from zero feet Mean Lower Low Water (MLLW) underneath the piers down to greater than 60 ft in the deepest sections of the site. Water depths average 30 feet between the piers and between the Pier 90 and the land. At the end of the piers, there is a steep drop off from 10 feet to greater than 60 feet.

In 1942, and 1943, the U.S. Navy acquired the property through condemnation, which in total consisted of 242.97 acres for use as bulk fuel and material storage, and as a marine terminal for naval vessels to support WWII. It was during this period that Discarded Military Munitions items from naval vessels were deposited on sub tidal areas surrounding the piers. Port of Seattle divers recovered a sign labeled “Safety Orders for 3 Inch Guns” from the seafloor in 2010. One section of the sign instructed sailors to throw potentially damaged or defective 3-inch rounds overboard. Based on the findings it was assumed that sailors jettisoned munitions, and munitions-related items overboard as a housekeeping process and to speed the resupply process. No specific records of these events have been found, and it appears that this was an infrequent occurrence rather than a routine procedure. No evidence suggests that any live fire exercises occurred at the site, and all munitions found to date have been unfired and unarmed.
6.0 OVERLAP BETWEEN UXO AND MCM TECHNOLOGY

The common underwater munitions requirements and research issues between SERDP’s underwater Munitions Response program and ONR’s Mine Countermeasures, Ocean Acoustics and Littoral Geosciences and Optics programs relate to sensor system design (acoustic, magnetic, electromagnetic, and optical) for target detection and classification including; underwater platform design and navigation, target physics, sediment acoustics, signal processing, data fusion, simulations and modeling, and automated detection and classification. Other common research issues are related to: 1) object (UXO and mines) seafloor-hydrodynamic interactions including burial, migration and reemergence; 2) environmental characterization; and 3) the physical remediation or neutralization of targets. Nowhere is this overlap more obvious than in fields related to the acoustic detection and classification of bottom mines and UXO in the underwater environment. The result has been jointly supported by investigators, modeling and simulations, and laboratory and open ocean experiments. This is especially true for the research issues associated with detection and classification of buried mines and UXO. Acoustic systems designed specifically for mine clearance and a variety of commercial systems have been demonstrated for UXO detection and classification. These acoustic systems include 1) side scan, multibeam, synthetic aperture, high resolution imaging, and parametric sonar systems with frequencies from kHz to MHz; 2) high-frequency imaging to low-frequency systems that exploit imaging and structural acoustics; 3) wide band and single frequency; and 4) wide and narrow beam systems. In spite of this overlap in basic and applied acoustic research issues, there are a number of differences in mine clearance and UXO remediation that must be considered for the final design and operation of UXO systems for wide area and detailed surveys of UXO- contaminated areas. These include the following:

- Success is driven by speed of operations for MCM versus costs of operations and ecological impacts for UXO remediation, human risk is a factor for both but with differing metrics.
- The MCM vision is for a single networked autonomous system including single-pass, real-time detection, classification, identification, and neutralization of mines with automated fusion of data and mission planning. The UXO remediation is a multi-phased, linear, congressionally-mandated legal process that includes preliminary assessment, site inspection, and a remedial investigation/feasibility study leading to a remedial action phase agreed upon by all stakeholders and follow-on, long-term maintenance phase if deemed necessary.
- Mines are cleared for military operations (e.g., operational areas, beach assess). UXO are cleared to provide for civilian safety (e.g., fisheries, diving, cable and pipeline laying, offshore wind farms, port safety).
- Many operational constraints for mine detection, classification, and clearance systems need not apply to UXO remediation systems. These constraints include size, shape, coverage rates, overtness, and autonomy.
- UXO remediation at land sites has been held to an extremely high standard by State and federal regulators. Requirements for probability of detection and classification (Pdc) may be much higher for UXO remediation than for MCM Mine clearance.
- Mine clearance (MCM) is sometimes clandestine; whereas, UXO remediation is always a public process.
• MCM operations, results, and data products are sometimes classified. UXO remediation and SERDP research and ESTCP demonstrations must be unclassified.

• MCM operations are conducted by the military; whereas, UXO remediation will predominately be conducted by contractors. The initial costs of UXO detection and classification systems must be included in the overall remediation costs.

• UXO may have been in the environment for many decades before remediation efforts are begun and may be impacted by their environment (corroded, covered in growth, etc). MCM operations are most often conducted on more recently deployed mines.

• UXO are generally magnetic cylinders which are detectable by magnetic and EMI sensors. Mines can be made of non-metallic materials designed to be undetectable by magnetic and EMI sensors. Some mine shapes are designed to deter acoustic detection (stealth).

• UXO are generally cylindrical and range in diameter from 20 mm to 155 mm or greater. Shallow water mines can be small and are often squat cylinders; offshore mines are larger and have a great range of shapes (e.g., larger cylinders, Manta, Rockan).

• Mines have triggers (tactile, acoustic, pressure, magnetic); whereas, most UXO were meant to explode on impact. Mines are inherently more dangerous to military operations and to the public. A cost effective and safe option for underwater UXO remediation may be to leave UXO in place with occasional monitoring if the UXO can be shown to be unlikely to come in contact with the public.

• Mines can be cleared by influence sweeping but influence sweeping will not detonate UXO.

• MCM threats include bottom, moored (in volume, near surface), and freely drifting (surface) mines; whereas, UXO remediation typically concerns only bottom ordnance.

• In MCM, the specific minehunting environments (sites) are not known until the adversary chooses when and where to actually lay the mines.

• MCM detection and classification operations can cause explosions; whereas, UXO detection and classification operations (wide area and detailed surveys) are specifically designed not to cause explosions. Physical remediation of both mines and UXO is hazardous, especially to divers.

• UXO will probably be buried and often biological fouled and chemically corroded more than mines given the longer time left in the environment. The biofouling and corrosion may change the UXO target characteristics with time. UXO (especially smaller UXO) will probably be more mobile than mines in shallow water.

• UXO found in water depths deeper than 120 ft are of lesser interest to SERDP’s MR research program. Deep-water UXO that contain energetic material are not considered a great threat to the public. Mine clearance requirements can extend into waters much deeper than 30 m.

• Large stockpiles of chemical and biological munitions were dumped in deep water prior to 1972, when international treaty restrictions ended that practice. Ecological risk assessments from these munitions are of great national interest but out of the scope of SERDP’s MR or the Navy’s mine warfare programs.
• Higher probability of detection (Pd) requirements for UXO suggest that short range, above critical angle detection acoustic strategies should be emphasized. Longer range below critical angle detection of mines may be required during MCM operations.

• Detection and classification of mines by ATR algorithms are often preferred given the short-term operational requirements. Computer aided detection and classification (CAD/CAC) that includes operators will probably be the norm given the higher Pdc requirements and greater time available for UXO remediation.

• Future MCM operations will substantially involve unmanned vehicles (airborne sensors, AUVs, ROVs) whereas UXO detection and classification can be done with towed or hull-mounted sensors or benthic crawlers. The chance of UXO detonation during munitions response is much less than during mine clearance operations.

• Towed or hull-mounted sensors can eliminate much of the navigation uncertainty associated with underwater AUVs and ROVs.
7.0 WHAT KINDS OF SYSTEMS AND PLATFORMS CAN WE EXPECT?

High-frequency acoustic imaging techniques are more advanced compared to lower-frequency techniques that exploit the structural acoustic character of UXO. As such, research advances in these higher frequency systems is more incremental and evolving in character. The numerous applications of high-frequency acoustic imaging systems have led to the commercialization of sensors, platforms and basic signal processing techniques. The main research issues for these high-frequency imaging systems relate to the development of robust classification and identification algorithms. The effects of the environment of target physics (scattering), signal processing, and classification need to be understood. As many as 70% of intact UXO in the underwater environment are buried. Therefore low-frequency acoustic systems, that are less attenuated, are being developed for detection and classification of these buried UXO. Low-frequency (1-50 kHz) SAS uses a combination of imaging and structural acoustics to detect and classify UXO. The sensors, signal processing, classification algorithms, and platforms requirements are in the early stages of development with regard to UXO remediation. SERDP should continue development of these types of sensors, systems, and associated platforms.

Previous side-bar meetings associated with magnetic, electromagnetic, and acoustic methods for detection and classification of underwater UXO suggest that sensor development should precede system and platform development and demonstration, especially those platforms with combined modalities. That is especially true for the lower frequency acoustic systems. Systems or platforms designed for mine clearance may not be appropriate for UXO remediation. Acoustic sensors, systems, and platforms should be optimized for UXO remediation across the full spectrum of UXO types, sites and environments. It is doubtful that a single acoustic sensor type or platform type is appropriate for all UXO types, sites or, environments. High-frequency towed or hull-mounted acoustic systems such as side-scan or multibeam sonar may be ideal for wide area surveys of UXO found proud on coral reefs or other hard bottoms; whereas a lower- frequency SAS mounted on an AUV or towed vehicle may be needed for detection of UXO buried in mud or sand. Many acoustic systems may not be appropriate for water depths shallower than 3 m, where issues associated with multipath, narrow beam widths, navigation and positioning with waves and currents may limit performance. In these shallow depths magnetic and EMI systems that crawl or are towed across the bottom may be more effective.
8.0 OTHER ENABLING TECHNOLOGIES

In addition to sensor systems, of which the acoustic sensors which were the subject of this workshop are one example, several other technologies will be required for an underwater munitions response. As discussed above, acoustic sensors can be mounted below the hull of boats, on autonomous or remotely-operated vehicles, or towed behind either. Geophysical sensors are more susceptible to metallic interference so the hull-mount option is likely not appropriate for these sensors. As the capabilities and limitations of each class of sensor are better defined, SERDP will be devoting an increasing fraction of its budget to deployment issues such as these.

For any sensor modality, analysis algorithms are required to enable detection of UXO and discrimination of the targets of interest from clutter and fragments. These algorithms may be based on a single sensor modality or, as we progress in our understanding of the individual sensors, a combination of sensor modalities each of which brings its own strengths to the job. The ultimate goal is to achieve a probability of detection and correct classification of 1.0 while minimizing the number of clutter items and munitions fragments classified as UXO.

Modeling capabilities for munitions migration and burial will be an important component of munitions response. Having a good estimate of the fraction of UXO that are proud versus buried will allow site managers to use imaging methods (acoustic or optical) to quickly estimate the extent of contamination at a site. These same models will allow the site manager to determine if another survey or a remedial action is required after extreme weather events at the site.

In a remedial action, the detected UXO must be removed from the site or treated. In some environments, this can be accomplished simply by blowing the UXO in place using an auxiliary charge attached to the item by divers. In other, more sensitive environments, intentional detonations would cause unacceptable harm to nearby flora and fauna and other methods will be required. If the UXO specialists conducting the remediation judge that the UXO is safe to move, it can be moved to the beach or a nearby barge for disposal. If not, methods to render the object safe by removing the explosive potential in an environmentally-benign manner are required.

Finally, every underwater munitions response action is likely to make use of mission planning software. Each site will have its own unique environmental conditions that will influence the choice of sensor or sensors and deployment methods. The clutter to be encountered will have some commonality among sites but will also include site-specific items such as crab pots in coastal bays and rivers and coral outcroppings in sub-tropical waters. High-quality mission planning software can guide the site manager through the decision required to identify an effective detection, classification, and, if required, removal scenario.
9.0 ACOUSTIC DATA SETS AVAILABLE

Recent field and laboratory acoustic experiments have developed a significant number of well-characterized acoustic responses from both free-field, proud and buried UXO. Most, if not all, the sediments were fine to medium sand. Data were collected at lower frequencies (1-50 kHz) and include multiple target aspect angles. These data together with FEM simulations provide the beginnings of a lower-frequency UXO acoustics library. As additional data sets become available, this list will be updated.

For access to these data, please contact the SERDP Program Manager for Munitions Response (571-372-6400, mr@serdp-estcp.org).

A subset of PONDEX09 and PONDEX10 data have been made available by NSWC, PCD.
10.0 REFERENCES


APPENDIX A: FINAL AGENDA

SERDP/ONR Workshop on Acoustic Detection and Classification of UXO in the Underwater Environment – July 16 and 17, 2013

Fort Myer
214 McNair Rd, Building 407 Joint Base Myer-Henderson Hall
Arlington, VA 22211

Tuesday July 16, 2013

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<td>Anne Andrews, SERDP</td>
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<td>Mike Richardson, SERDP/IDA</td>
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<td>Presentation: SERDP/ESTCP Support for Land-Based UXO Remediation</td>
<td>Herb Nelson, SERDP</td>
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<td>Presentation: SERDP’s Past and Present Underwater Munitions Response Program</td>
<td>Mike Richardson, SERDP/IDA</td>
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<td>Presentation: ONR’s Acoustic Mine Detection and Classification Efforts and Summary of ONR’s iSSAM Workshop</td>
<td>Kyle Becker, ONR</td>
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<tr>
<td>1020</td>
<td>Presentation: Navy Underwater Munitions Response Sites Overview</td>
<td>Bryan Harre, NAVFAC</td>
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<td>1040</td>
<td>Presentation: Use of MCM Sensors for UXO Detection and Classification</td>
<td>Steve Hurff, NAVFAC</td>
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<td>1130</td>
<td>Presentation: Low-Frequency Acoustic Detection and Classification of Underwater UXO – State-of-the-Art, Research Needs, and Future Possibilities</td>
<td>Kevin Williams, APL-UW</td>
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<tr>
<td>1200</td>
<td>Lunch</td>
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<td>1300</td>
<td>General Group Discussion: Goals and Structure of the Workshop</td>
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<td>1330</td>
<td>Breakout Group Sessions</td>
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<td>Group 1: State-of-the-Art for High-Frequency Acoustic Detection and Classification of Underwater UXO and Assessment of the Progress of SERDP’s Acoustics Program</td>
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<td>Group 2: State-of-the-Art for Low-Frequency Acoustic Detection and Classification of Underwater UXO and Assessment of the Progress of SERDP’s Acoustics Program</td>
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<tr>
<td>1600</td>
<td>General Discussion Based on Breakout Group Reports</td>
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<td>1700</td>
<td>Adjourn for the day</td>
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SERDP/ONR Workshop on Acoustic Detection and Classification of UXO in the Underwater Environment
Wednesday July 17, 2013

0800 Morning Networking Session

0830 Reflection on the first day

0900 General Group Discussion: Requirements for Acoustic Detection and Classification of UXO. Development of a Set of Operational Metrics and Concepts of Operations for Underwater UXO Remediation

1000 Breakout Group Sessions

Group 1: Acoustic Detection

1. What are the limitations of acoustic systems given the performance metrics and operational scenarios?

2. What level of performance can be expected in different environments and for different types of munitions?

3. How much will clutter or noise degrade sensor performance?

4. Are robust target discriminators possible for all types of UXO and in all environments?

5. How does the environment affect sonar performance and what environmental factors are the most critical to understand and predict performance?

1130 General Group Discussion: Limitations of Current Systems Given Operating Environments and UXO Characteristics

1230 Lunch

1300 General Group Discussion: The Way Ahead

1. What are the optimal configurations for sonar hardware, platforms, and signal processing?

2. Are these systems available commercially, can they be adapted from evolving MCM systems, or are new systems required that are developed from the ground up?

3. How do we maximize performance of these acoustic systems?

4. What are the recommendations for future SERDP projects and ESTCP demonstrations?

1500 Final Comments and Direction for Workshop Report

1600 Adjourn
APPENDIX B: LIST OF ATTENDEES

Dr. Ahmad Abawi, HLS Research, abawi@hlsresearch.com
Dr. Anne Andrews, SERDP Office, anne.m.andrews10.civ@mail.mil
Dr. Kyle Becker, Office of Naval Research, kyle.becker1@navy.mil
Mr. Daniel Brown, Applied Research Laboratory – Penn State, dcb19@psu.edu
Dr. Joseph Bucaro, Exct, Inc., joseph.bucaro.ctr@nrl.navy.mil
Dr. Shelley Cazares, Institute for Defense Analyses, scazares@ida.org
Mr. Dan Cook, Georgia Tech Research Institute, dan.cook@gti.gatech.edu
Mr. John Dubberly, Naval Research Laboratory, john.dubberly@nrlssc.navy.mil
Mr. Ira Ekhaus, BAE Systems, ira.ekhaus@baesystems.com
Dr. John Fawcett, DRDC Atlantic, john.fawcett@drdc-rddc.gc.ca
Dr. Warren Fox, Centre for Maritime Research and Experimentation, foxw@cmre.nato.int
Mr. Jeff Hoel, NAVFAC, jeffrey.hoel@navy.mil
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Dr. Herb Nelson, SERDP Office, herbert.h.nelson10.civ@mail.mil
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Dr. Mike Richardson, SERDP and IDA, Mike.richardson@bellsouth.net
Mr. Daniel Ruedy, SERDP Support Office, druedy@hgl.com
Dr. Bill Sanders, Naval Research Laboratory, wsanders@nrlssc.navy.mil
Mr. Andrew Schwartz, U.S. Army Corps of Engineers, andrew.b.schwartz@us.army.mil
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Dr. Daniel Sternlicht, Naval Surface Warfare Center, daniel.sternlicht@navy.mil
Dr. Jason Summers, Applied Research in Acoustics LLC, jason.e.summers@ariacoustics.com
Mr. Michael Tuley, Institute for Defense Analyses, mtuley@ida.org
Dr. Peter Weichman, BAE Systems, peter.weichman@baesystems.com
Dr. Kevin Williams, APL University of Washington, williams@apl.washington.edu
Dr. Preston Wilson, The University of Texas at Austin, pswilson@mail.utexas.edu
APPENDIX C: SERDP SIDE BAR MEETING ON UNDERWATER UXO: ACOUSTICS DISCUSSIONS AND RECOMMENDATIONS (DECEMBER 2, 2010)

Overview

The goal presented to the acoustics group, at least as we interpreted it, was: (1) to assess the present status of SERDP acoustics efforts relative to the vision put forth in the 2007 workshop; and given that assessment (2) to make recommendations on the way forward over the next several years.

This summary, which distills those discussions and presents recommendations, comprises three sections. Section I is mainly an extraction of relevant portions of the 2007 workshop report. Section II summarizes the current status of SERDP acoustics research relative to the recommendations in Section I. Section III presents recommendations for research directions over the next several years.

Section I: Initial recommendations from 2007 workshop

The two critical needs and recommendations within the 2007 workshop report that are especially relevant to the discussions of the acoustics group are reproduced here for convenience and labeled R1 and R2 for later reference:

R1. “Munitions detection capabilities of well established and emerging sonar and other acoustic systems need to be researched and documented. Characterizing the acoustic response of munitions in underwater environments is an essential first step. The signatures of munitions vary depending upon 1) munitions type and size, 2) if it is fully intact, distorted or broken into munitions-related scrap, 3) if it is filled or empty, and 4) if it is buried, partially buried or proud. Creating a signature library would be a useful tool to record this information, which would be particularly useful for structural acoustic techniques. A progressive range of research starting with modeling and basic tank tests with closely controlled variables was suggested. This would be followed by controlled open water data collections and real site demonstrations that would provide further insight as increasing site variables are introduced.”

R2. “… detection of munitions on the seafloor would provide clear evidence that munitions activity occurred in the vicinity. The location of concentrated proud items can help guide site management decisions or plan future remedial investigations. There are several existing and emerging sensors that have the ability to detect proud items. These technologies have not been developed specifically for munitions detection and their performance in detecting proud and partially buried munitions needs to be verified through field demonstrations. Research should investigate a range of munitions and their associated sizes to assess current capabilities.”

Section II: Current status relative to those recommendations

The group started with an initial discussion of where the SERDP program stands relative to R1. The presentations during this year’s SERDP workshop showed considerable progress on this
topic within the modeling and tank experiment arena. Thus the initial phase of R1 is well underway. Issues that remain regarding modeling and tank experiments in R1 include the impact on detection and identification of munitions’ distortion and target burial. The latter includes both sediment loading effects and variations in target pitch angle. It was felt that in addition to resolving these issues to some extent, the next steps should involve controlled open water data collections.

As research has progressed relative to R1, it has become more evident that the probability of detection (Pd) requirements sought by SERDP (Pd very close or equal to 1 for buried UXO) preclude the type of large coverage rate, shallow angle detection (often called sub-critical angle detection), strategies sometimes used in the related Navy mine countermeasure (MCM) problem. Given this requirement, it is felt that as research moves to marine environments, short range, above critical angle detection strategies should be the primary area of focus, at least relative to the evolution of R1. (Further discussion below, relative to R2, incorporates shallow angle detection).

The group felt that, as the research effort moves to the field (ocean, bays, etc), it is important to develop a set of operational metrics and concepts of operation that can form a background for the engineering developments that will eventually transition to operational systems. Examples of topics where concrete metrics are needed include: burial depths for which targets need to be detected and variation of this metric with target size; what $P_{dc}/P_{fa}$ values will be considered acceptable and how this might vary with site usage; and timeline requirements for detection/classification operations.

The group anticipates that the $P_{dc}/P_{fa}$ metrics may eventually point to the need for systems that combine acoustics with other modalities such as passive magnetic or active electromagnetic systems. We feel, however, that each of these modalities should carry out research that quantifies/optimizes its capabilities separately as a precursor to integration of modalities.

Though the Pd's for R1 efforts involving buried UXO dictate steep angle strategies, the use of acoustics to detect proud UXO (applicable for both R1 and R2) implies less stringent requirements. Using the R1-focused low frequency sonars for addressing R2 motivates shallow angle (long range) examination of proud UXO with these sonars.

Also for R2, sidescan, sector scan and multi-beam sonars, which can work effectively on proud or partially buried targets, may allow evidence that munitions activity occurred in the vicinity. The group was not aware of demonstrations to this end; however there has been significant use of these types of sonars in preliminary environmental assessments in support of magnetics and electromagnetic demonstrations.

We feel there are gains to be made in further research using these types of high resolution sonars. This research should be field experiment/demonstration oriented. Particular areas of research that should be considered include the following: 1) assessing UXO mobility and burial using sector scan sonars, 2) using the traditional hundreds of KHz sonar systems to derive absolute acoustic scattering strength and invert for sediment material and interface properties, 3) using the new
generation of sidescan and multibeam sonars that operate at Mega-Hertz (MHz) frequencies to image small, proud UXO during wide area surveys.

It is important to note that the Navy has ongoing efforts related to the MCM equivalent to R1 and R2. Continued coordination with those efforts where possible could be advantageous to both the MCM and UXO problems.

Section III: Recommendations going forward

Given our perception of the current status as presented in the previous section, our recommendations are that:

1. A set of operational metrics and concepts of operation should be developed as part of the SERDP program so that progress toward operational system(s) can be both motivated and monitored and design of these same systems can be carried out.

2. The experimental portion of UXO-related acoustic research related to R1 should focus on well-controlled shallow water field experiments. Here the principal issues involve characterization of munitions responses in these environments regarding types and sizes, physical condition, and burial condition as well as characterization of the nature of interfering clutter returns. Within this context we can see the utility of both short-term (one to two week) experiments focused on R1 and longer term (several week to several month) experiments that combine the research aimed at both R1 and acoustic monitoring in support of UXO mobility and burial.

3. Since it is a given that experiments cannot be carried out under all the environmental conditions that will be present during UXO operations, modeling efforts in support of the experimental program should be continued. The model results need to be compared to experimental results within the context of both target echo response and classifier learning. One goal would be the ability to assess system performance relative to Pdc/Pfa metrics.

4. Research should be carried out aimed at: a) deriving further environmental information from the acoustic systems used in support of magnetic and electromagnetic demonstrations, and b) using higher frequency versions of these same types of systems in wide area surveys for proud UXO.

5. In the long term, system strategies that combine modalities (acoustic, magnetic, electromagnetic) may be needed. However, in research and demonstrations to this end, the capabilities of each sensor type needs to be separately understood, optimized as a precursor to combining modalities. Doing so will allow quantitative assessments of improvement to Pdc/Pfa allowed by combining modalities (where it may not be possible to use each modality in its optimal configuration).

Section IV: Participants:

Dale Bibee (Naval Research Laboratory, SSC)
Joe Bucaro (Naval Research Laboratory, DC)
Brian Houston (Naval Research Laboratory, DC)
Steve Kargl (Applied Physics Laboratory, University of Washington)
Lai, Yi-San
Leasko, Robert
Lim, Ray
Panetta, Paul
Jason Stack (ONR)
Tantum, Stacy
Kevin Williams (Applied Physics Laboratory, University of Washington)
APPENDIX D: LIST OF PUBLICATIONS FROM SERDP/ESTCP-SUPPORTED MR UNDERWATER ACOUSTICS PROGRAM


Appendix D: Side Meeting and Roundtable Test Bed Discussion at the 2011 SERDP/ESTCP Symposium

Date: December 2, 2011: 1300-1500
Attendance: about 25 participants (see attached list)
Object: Develop the need, potential locations, and requirements for future test beds for SERDP projects and demonstration sites for ESCTP projects (see attached agenda).
Summary:

1) Mike Tuley and Andy Schwartz provided an excellent overview of land-based munitions test beds including the Aberdeen Proving Ground (APG) and the Yuma Proving Ground (YPG). These sites were cleared and seeded with known munitions and artificial characteristic clutter. These test beds reduced cost by providing a common site to compare and quantify sensor system performance and to ensure unbiased and accurate performance scoring.

2) It was unanimously decided that similar underwater munitions tests beds were required where acoustic, optical, magnetic, and electromagnetic detection and classification technologies can be tested and compared.

3) Given the range of environments (near-shore coastal, off-shore oceanic, estuarine, swamps, rivers, and lakes), water depths, and sediment types, a variety of test bed locations are required. Marine sites are the first priority.

4) Test beds should include 5-7 typical munitions types with a minimum of 100 munitions seeded for each experiment. Typical munitions include items ranging in diameter from 25 mm to 155 mm. Clutter items should also seeded among the munitions. Every effort should be made to exclude non-seeded items.

5) Test beds should be large enough to accommodate towed, AUV and UUV systems.

6) The location of all munitions and clutter should be known within 25-50 cm (horizontal). The orientation and state of burial of each item should be characterized before and after each experiment. Additional characterization, perhaps continuous, should be made if any movement of the munitions is suspected.

7) In addition to characterization of the munitions, environmental conditions that affect the operational effectiveness of acoustic, optical, magnetic, and electromagnetic detection and classification sensors and system should be characterized. These include at a minimum: sediment type, bathymetry, water clarity, hydrodynamic conditions (waves and currents), and clutter.

8) Techniques for burial and recovery of munitions and clutter, especially in sandy environments, are needed. Some sort of remote robotic system would be preferred compared to the labor intensive diver approach. This approach should provide the precise navigation and orientation/burial listed in item # 6.

9) Approaches to marking, tracking, requiring and maintaining in place munitions and other targets of interest should be developed that do not interfere with sensor performance.

10) General issues associated with permitting need to be addressed.
11) The test beds should provide a consistent, quantifiable set of conditions to allow comparison between sensors and sensor systems during individual experiments and between the results of experiments conducted at different sites and at different times.

12) It was concluded that a mobile, re-deployable, test bed concept is preferable and more cost effective to the development of permanent single or multiple test beds. This will allow experimentation in the variety of environments that munitions remediation is required and allow development, testing and comparison of the variety of acoustic, optical, magnetic, and electromagnetic detection and classification technologies that might be developed for munitions remediation. This approach also eliminates the costly maintenance of munitions test beds where both clutter and munitions are subject to extensive mobility and changes in burial state and where test bed environmental conditions are constantly changing often to the detriment of the experimental goals (i.e., low visibility for optical systems; buried or lost munitions).

13) Deployment and maintenance of such a mobile, re-deployable test bed by a team not associated with munitions detection and classification sensor systems would provide a consistent, unbiased approach to evaluate and compare those sensor systems.

List of 2011 Participants

Drs. Kevin Williams, Stephen Kargl, and Todd Hefner all of APL-UW
Dr. Joseph Bucaro NRL-DC
Dr. Gerald D'Spain or Dr. Scott Jenkins SIO
Drs. Gregory Schultz and Fridon Shubtidze, Sky
Dr. Dean Keiswetter, SAIC
Mr. Andrew Schwartz, USACOE
Mr. John Kloski, SRI
Drs. Raymond Lim,
Ms. Kelly Enriquez, USACOE
Dr. Jesse McNinch, U.S. Army Engineer Research and Development Center
Mr. Richard Funk, Tetra Tech
Mr Ryan Steigerwait, Weston
Drs. Joe Calantoni, Dale Bibe, and Andrea Abelev, NRL