SERDP/ESTCP MUNITIONS RESPONSE PROGRAM: UNDERWATER REMEDIATION OF UNEXPLODED ORDNANCE (UXO)

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Abstract: *The US Department of Defense Strategic Environmental Research and Development Program (SERDP) and Environmental Security Technology Certification Program (ESTCP) Munitions Response program supports the development and demonstration of innovative technologies to characterize, remediate, and scientifically manage sites affected by military munitions, including unexploded ordnance (UXO) and discarded military munitions. Twenty year's work on terrestrial sites has resulted in a substantial decrease in remediation costs through the development of advanced geophysical sensors and signal-processing methodologies that allow detection and classification of buried UXO. The geophysical inversion of data from electromagnetic induction sensors allows separation of harmless subsurface scrap from dangerous buried UXO, thus reducing costs and improving the effectiveness of UXO remediation on the wide variety of contaminated Department of Defense sites. The Munitions Response program is now focused on reducing costs and improving effectiveness of UXO remediation in the underwater environment. The first stage of this effort was the development and evaluation of underwater sensors (acoustic, magnetic, electromagnetic, and optical) and platforms (remotely operated vehicle, autonomous underwater vehicle, towed, bottom crawler, and airborne) required to detect and classify UXO found in a variety of underwater sites. Field and laboratory studies of UXO behavior are being used to develop a probabilistic expert system model to predict burial, migration, and re-emergence of UXO in coastal, estuarine, freshwater, and riverine environments. Development of new technologies for physical removal or in situ remediation of UXO are also emphasized. The next step includes the development of standardized underwater UXO demonstration sites to test and evaluate the sensors and platforms that are designed to detect and classify underwater UXO. In this paper, we will summarize progress and provide a vision for cost-effective and efficient remediation of underwater UXO.*

Keywords: *munitions remediation, target classification, burial and migration*

1. INTRODUCTION

The Strategic Environmental Research and Development Program (SERDP) and the Environmental Security Technology Certification Program (ESTCP) are the Department of Defense's environmental research programs, harnessing the latest science and technology to improve environmental performance, reduce costs, and enhance and sustain mission capabilities at DoD facilities. Five programs areas (https://serdp-estcp.org/Program-Areas) support technologies (1) to improve energy efficiency, increase the use of renewable energy, and enhance water conservation on DoD installations; (2) to characterize, perform risk assessments, remediate, and manage contaminants in soil, sediments, and water; (3) to advance DoD’s management of its natural and cultural resources; (4) to reduce, control, and understand the sources of waste and emissions in the manufacturing, maintenance, and use of weapons systems and platforms; and (5) that can characterize, remediate, and scientifically manage sites affected by military munitions on US lands and underwater.

Program support for UXO remediation (item 5) at terrestrial sites is nearing completion with the demonstration of advanced geophysical systems and signal-processing methodologies proved to detect and classify buried UXO. This allows separation of harmless subsurface scrap from dangerous buried UXO, reducing the number of costly UXO digs, thus improving the effectiveness of UXO remediation found on the wide variety of contaminated sites. The Munitions Response (MR) program has now turned its support to improving remediation of underwater UXO found in ponds, lakes, rivers, estuaries, and coastal areas out to depths of 30 meters. The main areas of this effort include development of systems to detect and classify UXO during wide-area assessment and detailed surveys, UXO recovery and disposal, munitions burial and mobility, and phenomenology associated with characteristics of munitions and site environmental conditions. These technologies are intended to support Defense Environmental Restoration Program remediation of sites contaminated by munitions which is conducted following the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) process (Fig. 1). The US Army Corps of Engineers and the US Navy have identified over 450 formerly used and active underwater defense sites, totaling more than 10 million acres in US coastal and territorial waters, potentially contaminated with munitions (SERDP-ESTCP, 2010).

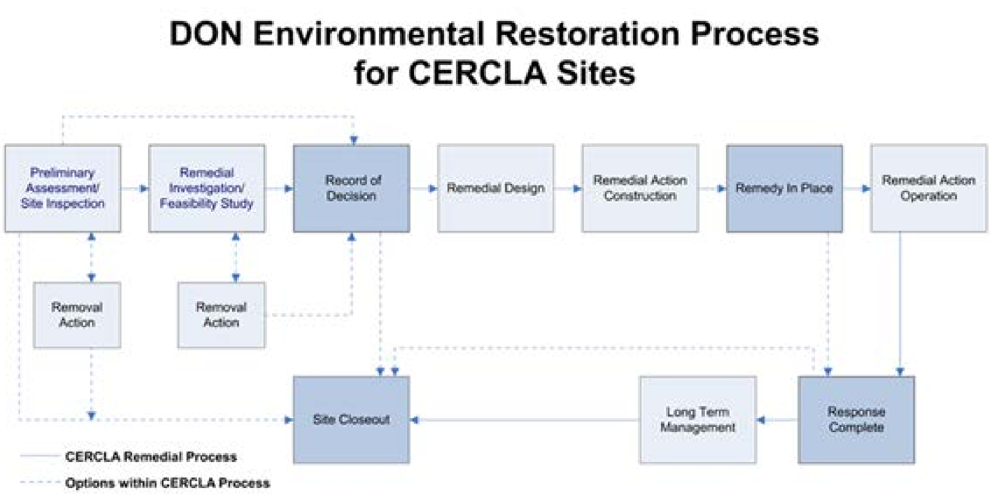

Figure 1 – Generic UXO restoration process covered under the Dept. of Navy (DON) Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA).

2. SENSORS AND PLATFORMS

Given the wide variety of environments (coastal, estuarine, freshwater, and riverine), water depths and bottom types, munitions types, and hydrodynamic conditions, a single sensor modality or platform type is probably inadequate to accommodate requirements at all possible underwater remediation sites. A wide range of options for systems (sensors and platforms) to detect and classify UXO is therefore being investigated. Sensor modalities include high- and low-frequency acoustic sensors, various magnetic sensors, optical systems including LIDAR and traditional still and video camera systems, and cued and single-pass electromagnetic sensor combinations. Platforms include autonomous underwater vehicles (AUVs), remotely operated vehicles (ROVs), towed systems, surface systems, crawlers, and airborne platforms. Sensors including optical (LIDAR, still and video cameras) are limited to proud targets in clear waters. High-frequency acoustic sensors (side-scan and multibeam sonars) are primarily limited to proud targets without water clarity restrictions. Active electromagnetic induction (EMI) and passive magnetic sensors as well as lower frequency acoustic sensors can all be used to detect buried targets but with much different standoff or coverage rates. Towed or AUV platforms may be optimal for waters deeper than about 5 meters; bottom crawlers and surface and airborne platforms are most appropriate for shallow water. Given the maturity of optical and high-frequency imaging sensors to detect and classify proud targets, SERDP has concentrated support on magnetic, EMI, and lower frequency acoustic sensors designed to detect and classify buried targets.

2.1.1. Magnetic and EMI Sensors and Platforms

Both passive magnetic and active electromagnetic systems are being developed for the underwater environments. Potential magnetic and electromagnetic technologies include modified advanced systems proven for terrestrial UXO classification, systems developed for mine countermeasures (MCM) operations, and purpose-built systems specific for underwater UXO remediation. Magnetometers have greater standoff detection ranges (up to 5 meters) and are better suited for larger scale surveys; the shorter detection ranges (1–3 meters) for active electromagnetic systems restrict use to smaller areas (smaller coverage rates) or for cued classification.

Some of the magnetic systems developed or demonstrated under SERDP-ESTCP include towed magnetic arrays such as the Marine Towed Array (Kieswetter, MR-200324) and the Marine Gradient Array (Funk, MR-200808); hand-held diver-operated systems (Prouty, MR-2104); AUV-based laser scalar gradiometers (Angle, MR-201612); drone-based wide-area survey for hard-to-access very shallow underwater sites (Schultz, MR-19-5212); and commercially available AUV-based systems such as Geometrics G-880 total field magnetometer (Trembanis, MR-2730; Steigerwalt, MR-201002). Recent advances in magnetic sensors include miniaturization, improved sensitivity, lower power requirements, and lower cost. Platform magnetic interference and precise navigation and positioning continue to be technology issues.

The advanced EMI sensors and signal processing (inversions) developed for land-based UXO classification dominate the development of underwater EMI systems. The main logistical difficulties in using EMI technology in the marine environment include waterproofing all receiver and transmitter loops and electronics for a conductive environment, designing the optimal transmitter coils and receiver cubes configurations, and providing appropriate platform support and navigation and positioning for operation in a dynamic (e.g., wave and currents) and GPS-denied environment. The geophysical inversions (dipolar polarizations) of UXO electromagnetic responses seem unaffected by biofouling or corrosion (Steinhurst, MR-2500). Numerical (Billings, MR-2412; Shuditidze, MR-2728) and field studies (Saville, MR-201313; Schultz, MR201233; Gasperikova, MR-2321; Bell, MR-2409) have demonstrated that the inversion and classification techniques (library matching, statistical classification methods) developed in the terrestrial setting are in principle adaptable to the underwater setting. The influence of eddy current response due to currents generated in the target and the galvanic coupling of currents through the body (the current channeling response) may affect the scattered field from a metallic target, but typically only at very early times and for large receiver-to-object offsets (Billings, MR19-1261). The effects of background subtraction from a highly variable seafloor (e.g., vertical gradients and horizontal variability) is still an ongoing research issue.

2.2.2 Acoustic Sensors and Platforms

Acoustics offer increased standoff distances relative to magnetic and EMI detection and classification systems. This in turn offers both increased area coverage and deployment-system safety advantages (by maintaining a larger altitude relative to the sediment), thus making acoustics an attractive technology. For munitions that are at least partly proud of the sediment, commercially available high-frequency systems such as multi-beam and side scan have the resolutions needed to detect and classify munitions. Detecting and classifying buried munitions, however, offers a larger challenge. The frequency dependence of the attenuation of sound in sediments motivates use of low frequencies while the resolutions important for classification drives the solution to high frequencies or large apertures. The solution being pursued by multiple SERDP researcher groups (Houston, MR-201714; Brown, MR-2545; Williams, MR18-5004; Sara, MR-2752) is to combine broadband, low-frequency acoustic systems with real cross-track and synthetic along-track processing. The along-track processing requires motion compensation to meet synthetic aperture sonar positioning requirements. Recent developments in motion compensation (Marston and Plotnick, 2015; Gao et al., 2014) have been shown to be successful under challenging conditions. Data from low-frequency, broadband systems allow us to examine munition response in a variety of two-dimensional spaces, for example, time-angle, wavenumber, frequency-angle, and *x–y* (image). Fig. 2 shows an example for a 2-foot-long, 1-foot-diameter aluminum cylinder from a SERDP-sponsored effort in the Gulf of Mexico (Kargl, MR-2231).

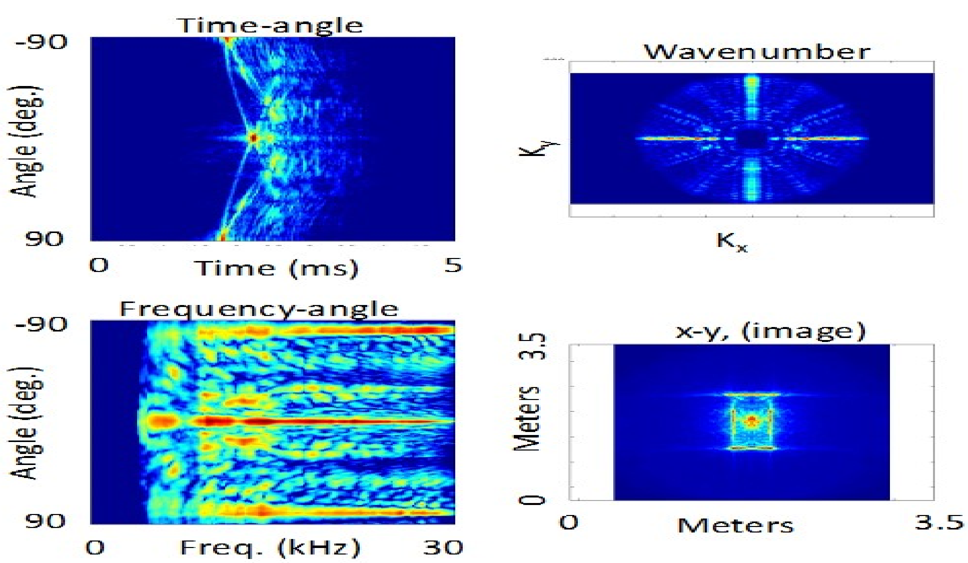

Figure 2. Possible two-dimensional spaces derivable from data acquired on a low-frequency, broadband system.

Different spaces in Fig. 2 offer easy access to different types of munitions information. From a classification standpoint, the ability to operate in a variety of spaces allows development of more discriminating feature sets. The maturity of these low-frequency sensors is to the point that ESTCP efforts to quantify their capabilities using ground-truthed test beds are now underway using three different deployment platforms. One effort (Houston, MR-201714) is fielding an AUV; the second, a surface-vessel-mounted system (Brown, MR-2545); and the third, a towbody mounted sensor suite (Williams, MR18-5005). In concert with these system developments, efforts aimed at developing test beds are in progress (Tomich, MR-2735; Khadr, MR-2736). Regardless of the system, an essential component is the ability to geolocate any object classified as a munition to a resolution sufficient for remediation. Fig. 1 is an example of the restoration process. Of particular importance in this process is the remedial investigation (RI) step. For RI, an area under the curve of 0.9 with as yet unspecified correct classification and false-alarm rates has been given as a starting point. Also for the RI, the goal is a geolocation uncertainty of less than 5 meters for munitions buried up to 0.5 meters in a sand sediment. The performance needed at the remedial action (RA) step will be significantly more stringent (e.g., geolocation to less than 1 meter and a false-negative rate of 0). SERDP and ESTCP researchers have previously used a variety of navigation and positioning methodologies, including high-quality inertial navigation modules onboard AUVs, real-time kinematic (RTK) GPS systems in concert with ultra-short-baseline and long-baseline systems for towbodies, and RTK GPS-only strategies for surface vessel deployments. These commercially available navigation sensors, in concert with the current generation geographic information system mapping technologies, should allow the geolocation requirements of the RI phase of remediation to be fulfilled. Efforts over the next few years will establish the limits of current strategies and their capability relative to RA requirements.

3. BURIAL AND MOBILITY MODELING OF MUNITIONS

Underwater environments represent areas where munitions are much more susceptible to mobility, burial, and re-exposure than terrestrial environments. A wide range of contaminated underwater environments exists, including rivers, lakes, estuaries, and coastal beaches. Each location has different wave and circulation patterns that drive sediment erosion and deposition, which are directly linked to burial, mobility, and re-exposure processes. Likewise, the bottom type can include soft clays or muds, sandy sediments, large cobbles, or coral reefs. Heterogeneous bottom types (or mixtures) are also prevalent, complicating models for burial and mobility. The wide range of boundary and forcing conditions that exist across underwater environments adds complexity to the problem. The need to assess and manage risk associated with each underwater site necessitates the development of robust predictive models. Predictive models require detailed observations for verification and validation. One of the goals of the burial and mobility modeling aspect of the SERDP MR program is to develop predictive models to quantify the behavior of the distribution of munitions contamination present at an underwater site. It is believed that these predictive models must be probabilistic in nature such that they not only make predictions, but also simultaneously estimate the uncertainty of the predictions.

Burial and mobility modeling of munitions in underwater environments will play an essential role in the management of contaminated sites from the initial wide-area assessment phase through any eventual remediation phase that may occur (Fig. 1). Consequently, the critical inputs for burial and mobility modeling must be determined. The inputs must be well characterized at each site, and due to the ephemeral nature of the environments, some inputs will require continuous monitoring such as meteorological and atmospheric forcing. We anticipate that site management will always begin by characterizing the necessary environmental inputs for burial and mobility modeling, which in turn also overlap with the necessary inputs to assess sensor performance before deploying assets for detection and classification. The initial environmental characterization would be followed by site surveys to detect and classify munitions (i.e., quantify contamination). After initial mapping of munitions contamination is performed and UXO deemed hazards remediated, models for the meteorological and atmospheric forcing and probabilistic prediction of burial and mobility can be employed to determine if UXO not initially remediated could become be a hazard to the public because of re-emergence or mobility. If UXO is deeply buried and predicted to remain in place, a manage-in-place strategy of would appear to be the safest and least costly option. The chosen sequence of events will compose a concept for operations that will be focused on making predictions over the relatively short term, such as storm events and seasonal changes (intra-annual variability), as opposed to making predictions over multi-annual to multi-decadal time scales. The focus on predictions of intra-annual variability, starting with individual storm events, will provide a practical method for long-term site management.

The portfolio of projects funded by the SERDP MR program focused on burial and mobility modeling of munitions in the underwater environment ranges from the theoretical to the experimental. One category of projects is focused on the development of analytical and numerical models to predict the behavior of munitions in the natural environment. The portfolio represents a hierarchal approach that includes the effect of local processes by utilizing analytical models that predict scour burial processes (e.g., Friedrichs et al., 2016) and detailed numerical simulations (e.g., Rennie et al., 2017) that investigate the physics of liquefaction adjacent to munitions. Results from local models are combined with laboratory experiments for scour burial (e.g., Rennie, MR-2227) and the initiation of munitions mobility (e.g., Wu et al., 2019) in the development of an expert system based on Bayes theorem for predicting the statistics of phenomenology (Rennie, MR-2227), which is analogous to an existing expert system for mine burial (Rennie et al., 2007). The difficulty in implementing such an expert system lies in the inherit time dependence of the problem in which daily meteorology continually evolves the local hydrodynamics. Consequently, coupled Earth system models for predicting the local hydrodynamics are being utilized to drive the expert system (Palmsten, MR-2733).

Results from field experiments are necessary for verification and validation of the modeling systems for predicting munitions burial and mobility in underwater environments. Several ongoing and previous projects under the MR program portfolio have focused on gathering time-series observations of burial and mobility processes (e.g., Calantoni, MR-2320) through the development of technologies for determining the location and state of burial of munitions (e.g., Traykovski and Austin, MR-2319). In addition, high spatial and temporal resolution measurements of the relevant boundary layer processes (e.g., wave height and direction, current profiles, suspended sediment concentrations, and sediment erosion and deposition) have been recorded simultaneously while monitoring the burial and mobility of surrogate munitions. Unlike previous investigations that have provided before-and-after snapshots of munitions mobility (Wilson et al., MM-0417), more recent experiments have provided long time-series observations of munitions phenomenology.

The development of so-called smart surrogate munitions has provided a valuable tool to improve our understanding of munitions phenomenology. Smart surrogates contain embedded, self-logging sensors that allow monitoring of the state of munitions with high temporal resolution. A wide range of internal sensors has been placed inside of surrogate munitions, including miniature inertial motion units, Wi-Fi tags, shock sensors, photocells, pressure sensors, and data loggers (Puleo, MR-2503). While embedding sensors, care was taken to maintain the properties of size, shape, density, center of gravity, and moments of inertia of the munitions that the smart surrogates represent. The capability provided by smart surrogates becomes particularly significant in the harsh, shallow water environment of the inner surf zone and swash zones of the beach. In these areas, foam on the water surface, along with intermittently high concentrations of bubbles and sediment in the water column, makes it exceedingly difficult to remotely sense the behavior of munitions using traditional optic and acoustic techniques.

4. REMEDIATION AND NEUTRALIZATION TECHNOLOGIES

Underwater munitions may require cost-effective, safe, and environmentally acceptable remediation techniques if leave-in-place options are unacceptable. Current practices employ divers for manual retrieval of targets, a dangerous and costly practice, or blow-in-place procedures, which produce shock-wave pressures and acoustic noise from bubble formation/collapse that are detrimental to marine life. SERDP-ESTCP has supported a variety of alternate neutralization procedures designed to be less dangerous and environmentally acceptable. These include the use of bubble currents to reduce the shock-wave and acoustic pressures generated from blow-in-place practices; covering UXO with geotextile bags to eliminate contact with the public and reduce the effects of potential detonations; robust underwater caisson-like structures to contain explosive impacts; development of blast-barge technology where munitions are brought to the surface and exploded in blast-restricting containers; dredging equipment modifications that detect and remove munitions from the dredged material; and designing robotic techniques to remove munitions from the seafloor, eliminating the need for divers.

More recent development of in situ methods to neutralize energetics contained in munitions includes using a high-pressure water jet to cut access holes into the body of the munition casing and wash out the internal explosive, which is then captured in bags for later analysis and disposal (Schmit, MR18-5116); development of an explosively generated plasma tool to cut holes in munitions via a plasma ablation process and generate high-temperature chemical decomposition that results in rapid deflagration of energetics without detonation (Douglas, MR-201611); and evaluation of an underwater electrochemical remediation system that uses an ablative chemical drilling method to drill access holes in munitions and electrochemical processes to transform nitro-containing explosives into stable compounds that can easily be removed (Jo, MR18-146). The long-term goal of these systems is to develop safe, cost-effective methods to remove or render inert the energetics from underwater UXO without leakage or detonation. But it has been shown that working in a dynamic underwater environment, especially using tethered ROV or independent AUV robotic platforms, is more difficult than operating in easily controlled laboratory settings.

5. STANDARDIZED UNDERWATER UXO DEMONSTRATION SITES

A workshop on the development of standardized underwater UXO demonstration sites ("test beds") was held during the SERDP and ESTCP 2018 Symposium (https://serdp-estcp.org/News-and-Events/Conferences-Workshops/Past-MR-Workshops/Underwater-UXO-Test-Bed-Workshop-Nov-2018). The objectives of this workshop were to establish the requirements, framework, protocols, responsibilities, and timelines for development of a series of sites that can be used to test, evaluate, and demonstrate acoustic, magnetic, EMI, and optical systems designed to detect and classify underwater UXO. Test-bed site locations will be based on a combination of environments representative of sites and munitions slated for near-term remediation (surrogate environments) and test-bed sites appropriate for systems and sensors that are ready for demonstration. Based on these criteria, a rather benign (easy) deeper area (5–20 meters) free of native UXO with both sandy and muddy sediments would provide the best location for the development of the initial test bed. That area should contain large football-field-sized areas with little spatial and temporal variation in sediment properties. Targets of interest should be easily buried and exhibit little or no mobility. Based on lessons learned, a second location in shallow water (e.g., beach area) might provide a second test bed. Test beds in vegetative areas, at gravelly sites, and on coral habitats can follow as needed. The workshop report provides a list of environmental measurements (e.g., currents, waves, water column, bathymetry, meteorological, and sediment type, properties, and layering), numbers and types on munitions and clutter, and geo-positioning and orientation requirements for buried and proud targets of interest. Still to be determined are methods of emplacement of UXO and clutter, methods to determine location and orientation of UXO during demonstrations, and demonstration scoring requirements.

6. THE WAY FORWARD

The success of the terrestrial SERDP-ESTCP programs in reducing cost and improving the safety of UXO remediation via development of electromagnetic classification of UXO provides lofty goals for a similarity structured underwater program. Three technology improvements can greatly reduce costs and improve safety of underwater UXO remediation: development of probabilistic models to predict the behaviour (burial, migration and re-emergence) of UXO in the dynamic environment; improved UXO classification technologies, especially for buried UXO; and development of in situ methods to neutralize UXO without explosion or contaminating the environment with energetics or energetic residues. Significant developments in all three areas have been realized with ongoing SERDP-ESTCP–supported programs.

In addition to these three areas of technological advancement, technologies to measure and model environmental factors are being supported by SERDP. The behaviour of UXO depends on sediment type, water depth, and the dynamics of the overlying water column. Along with a knowledge of the types and spatial distribution of munitions, these environmental conditions provide the necessary inputs to predict UXO behaviour. Sediment and water column properties also provide important inputs to determine what types of platforms and sensors are most appropriate for UXO detection and classification in the wide range of contaminated underwater environments that require remediation.

7. REFERENCES

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