EXECUTIVE SUMMARY

Underwater Advanced Time Domain Electromagnetic System

ESTCP Project MR-201313

SEPTEMBER 2019

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1.0 INTRODUCTION

1.1 BACKGROUND

This document has been prepared under Environmental Security Technology Certification Program (ESTCP) Project MR-201313, titled "Underwater Advanced Time-Domain Electromagnetic System," to present the results of the saltwater demonstration (Demonstration), the second planned field evaluation of the system developed as part of this project. The Demonstration took place May 14-17, 2018 at the U.S. Army Corps of Engineers (USACE) Field Research Facility (FRF) in Duck, N.C.

1.2 OBJECTIVE OF THE DEMONSTRATION

The overall objective of MR-201313 is to design, build, and demonstrate an underwater advanced time-domain electromagnetic (TEM) system for cued classification of munitions in the underwater environment. The phased approach consists of initial design and modeling (Phase 1 – completed), engineering design and construction (Phase 2 – completed), underwater evaluation of the system in a freshwater pond (Phase 3 – completed), and demonstration of the system at a saltwater site (Phase 4 – addressed in this document).

1.3 REGULATORY DRIVERS

Not applicable.

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2.0 PERFORMANCE OBJECTIVES

Table 1 contains a summary of the qualitative and quantitative Performance Objectives identified for the Demonstration, including the performance objective, the associated metric by which to measure success, the data required to evaluate the metric, and the minimum acceptable criteria. The qualitative metrics generally pertain to ease of maneuverability, measured by feedback from the divers. The primarily goal of the quantitative performance objectives was to evaluate data quality parameters through each stage of classification (i.e., raw data, modelling fit, library matching, and predicted location relative to the sensor), as is done with advanced EMI data from terrestrial sensors. Secondarily, the performance objectives provided valuable information with regards to the sensors limitations to illuminate small, deeply buried, and laterally offset items.

Table 1. Performance Objectives

Performance Objective	Metric	Data Required	Success Criteria	Results
Quantitative Performance Objectives				
Start-of-project free-air classification	Proper classification for each test item	Dipole inversion parameter values and polarizabilities for each test item from at least one Tx/Rx element	>0.8 fit coherence (using UX-Analyze fit coherence calculation) UX Analyze classification metric >0.9 (library match correlation) <25% difference between calculated and library reference polarizabilities	
Daily sensor response repeatability	Standard response for each tested Tx/Rx element to a known target in a known location.	At start and end of each day the EM system is used, amplitudes from standard item at same distance and orientation for each Tx/Rx element while EM system is at known underwater background location.	≤ 20% Root-Mean-Squared (RMS) variation in amplitude.	Daily Sensor Function Tests show that for functioning data channels the response amplitude variation is <20%.
Daily classification repeatability	Proper classification for each test item	At start and end of each day EM system is used, response curve of test item placed in at least one location within 0.8m of the center of the array	Proper classification with item ≤0.8m of the center of the array >0.8 fit coherence (using UX-Analyze fit coherence calculation). UX Analyze classification metric >0.9 (library match correlation) <25% difference between calculated and site-specific, free-air reference polarizabilities	Properly classified with aluminum sphere <0.8m from center of array. Range of fit coherences: 0.900 – 0.997 Range of library fit metrics: 0.969 – 0.996 Range of percent differences: 10.6 – 19.3
Classification can be achieved if item is within 0.8m of the center of the array in an underwater conductive environment.	Classification is possible if item is within 0.8m of the center of the array.	Response curve of metallic object placed at multiple locations within 0.8m of the center of the array.	Proper classification with item ≤0.8m of the center of the array.	Except for the 20mm) projectile, all targets were classified properly up to 0.65m from the center of the array. Only the Small ISO and 20mm projectile failed to achieve a fit metric >0.9 at any offset from the center of the array.

Table 1. Performance Objectives (Continued)

Performance Objective	Metric	Data Required	Success Criteria	Results
Data quality supports inversion to determine target parameters.	Modeled response match observed responses for each test item	Fit coherence from inversion.	>0.8 fit coherence (using UX-Analyze fit coherence calculation).	All but one of the targets with SNR >30 have fit coherence >0.8. No 20mm projectile test item measurement had a reliable fit coherence >0.8.
Target polarizabilities and classification results from data collected in saltwater match corresponding library polarizabilities.	Target polarizabilities for each test item match library responses.	Dipole inversion parameter values and polarizabilities for known test items.	UX Analyze classification metric >0.9 (library match correlation) <25% difference between calculated and library reference polarizabilities	46 of 66 targets (69%) have <25% difference between calculated and library reference polarizabilities. 40 of 66 targets (60%) have UXA library match metric >0.9. 36 of 66 targets (54%) meet both library match criteria. *For targets with SNR >30:* 45 of 53 targets (84%) have <25% difference between calculated and library reference polarizabilities 39 of 53 targets (73%) have UXA library match metric >0.9 35 of 53 targets (66%) meet both library match criteria
Qualitative Performance Objectives				
Sensor can be sufficiently maneuvered in dynamic underwater environment by divers such that the divers' safety is not compromised.	Divers are comfortable that their safety will not be compromised maneuvering the system.	Verbal feedback from divers.	Divers indicate they are comfortable that their safety is not compromised.	The system was lowered 7m to the Test Area using the LARC-mounted davit. Two divers safely moved system laterally (40m across Test Area) during fair weather conditions (wave heights < 1.5m) without aid of weights or lift bags.

Table 1. Performance Objectives (Continued)

Performance Objective	Metric	Data Required	Success Criteria	Results
Sensor can be sufficiently maneuvered in dynamic underwater environment by divers such that the system can be placed satisfactorily on the desired cue location to collect classification data.	Divers are able to effectively and efficiently maneuver the system to the desired cue location.	Verbal feedback from divers. Time to move system between cue locations.	Divers indicate they are able to effectively and efficiently maneuver the system to the desired cue location and collect data that pass all Quantitative Performance Objectives. Time required to move system between cue locations is less than 10 minutes.	Divers effectively and efficiently maneuvered system through Test Area. A clear data collection plan and two-way communication eliminated any issue of incorrect diver positioning or incomplete data collection. Divers moved system between Test Area cued locations in an average of 1 minute each.
Continued validation that system is sufficiently waterproofed. (Note: This was initially demonstrated in the freshwater pond but will continue to be closely monitored.)	No indications that water has leaked into system components.	Data collected by system and visual observation.	Data do not indicate water has entered system components.	System is sufficiently waterproofed. After two days of field deployment in saltwater conditions, some corrosion was observed on the electronics cannister, but not at a level which could compromise its integrity over a reasonable operational lifespan of the system.
Calibration method can be used both topside and in an underwater conductive environment.	Baseline response plots are similar to response in water and on land.	Data collected by system and visual observation.	Response plots of system are reasonably similar to baseline plots – qualitative measurement.	With the exception of monostatic Ht-Hr Z-axis response, all sensor function test results for the aluminum ball were consistent and acceptable, whether data were collected in free-air or in saltwater.

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3.0 TECHNOLOGY DESCRIPTION

3.1 TECHNOLOGY DESCRIPTION

The Underwater Advanced Time-Domain Electromagnetic System designed, constructed, and demonstrated at a freshwater facility under this project has been described in detail in prior documents, titled *Modeling for Underwater Advanced Time-Domain Electromagnetic System* (June 2014), *Underwater Advanced Time-Domain Electromagnetic System Design* (July 2015), and *System Performance Report* (March 2017). A diagram of the system, as tested in the freshwater pond, is provided as **Figure 1**. A photograph of the system is provided as **Figure 2**.

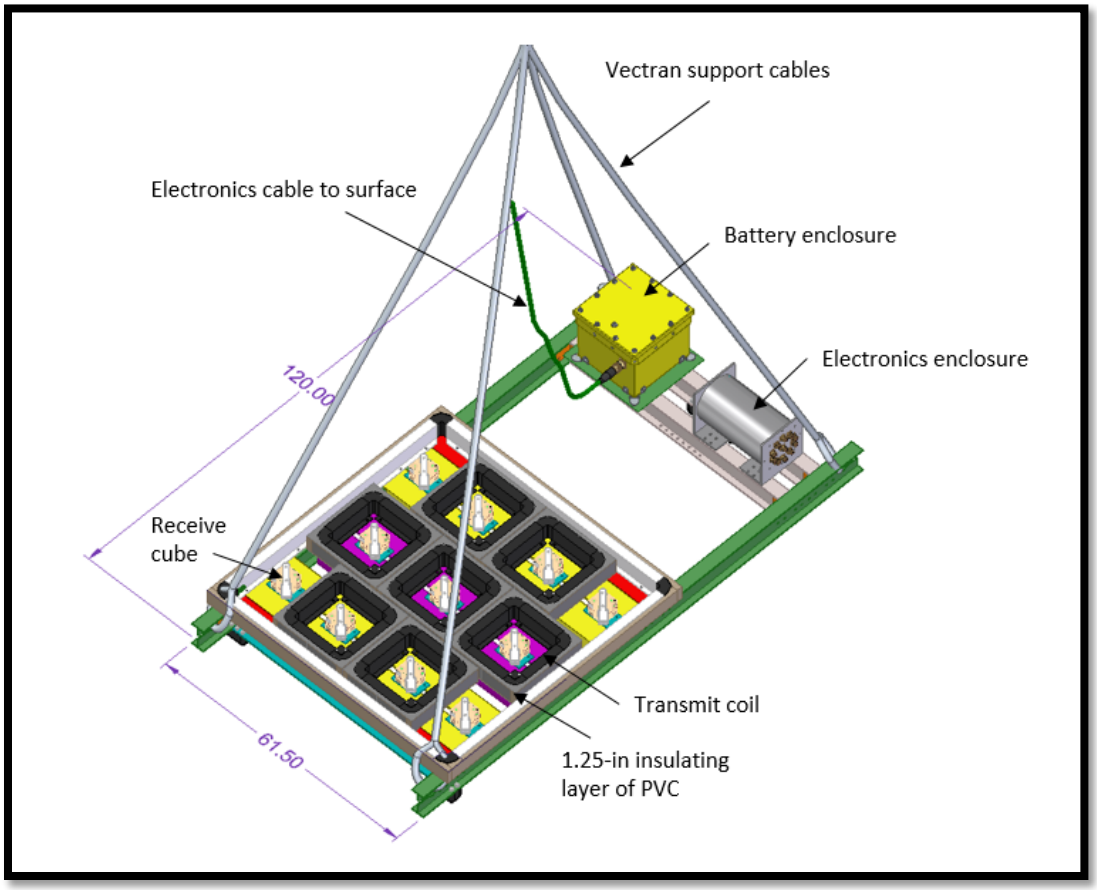

Figure 1. Underwater Advanced Time-Domain Electromagnetic System

Measurements are in inches.

Figure 2. Photograph of the Underwater Advanced Time-Domain Electromagnetic System

Figure 3 presents a diagram identifying transmitter (Tx) and receiver (Rx) locations and nomenclature. The array consists of eleven, 10-centimeter (cm) three-axis receive cubes, denoted by the cube identifier and an "r" indicating "receiver" (i.e., Ar-Kr), seven 40-cm square transmit coils, denoted by the cube identifier and a "t" indicating "transmitter" (i.e., At-Gt), and an outer 1.56-meter (m) square transmit coil (Ht). The resulting total number of data channels is 264. The raw sampling interval is 0.004 milliseconds (ms) and the recorded data are logarithmically averaged over 5 percent windows, resulting in 99 logarithmically spaced decay times ranging from 0.05 ms to 8.124 ms. One hundred measurements are averaged for each recorded measurement.

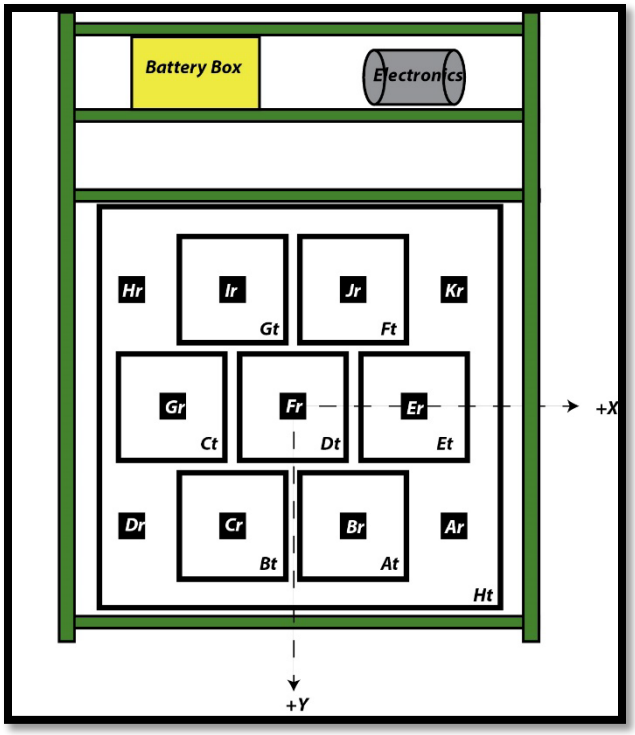

Figure 3. Transmitter and Receiver Locations and Nomenclature

3.2 TECHNOLOGY DEVELOPMENT

As summarized in previous documents under ESTCP Project MR-201313, the EM system was developed across three phases prior to the Saltwater Demonstration (Phase 4). Figure 4 – Figure 7 present products and processes from the previous three phases, and Final Reports for these phases are included as appendices to this report:

- Phase 1: Initial Design and Modeling – Modeling for Underwater Advanced Time-Domain Electromagnetic System White Paper, June 2014 (Final Demonstration Report Appendix B)
- Phase 2: Engineering Design and Construction – Underwater Advanced Time-Domain Electromagnetic System Design, July 2015 (Final Demonstration Report Appendix C)
- Phase 3: Freshwater Evaluation – System Performance Report, March 2017 (Final Demonstration Report Appendix D)

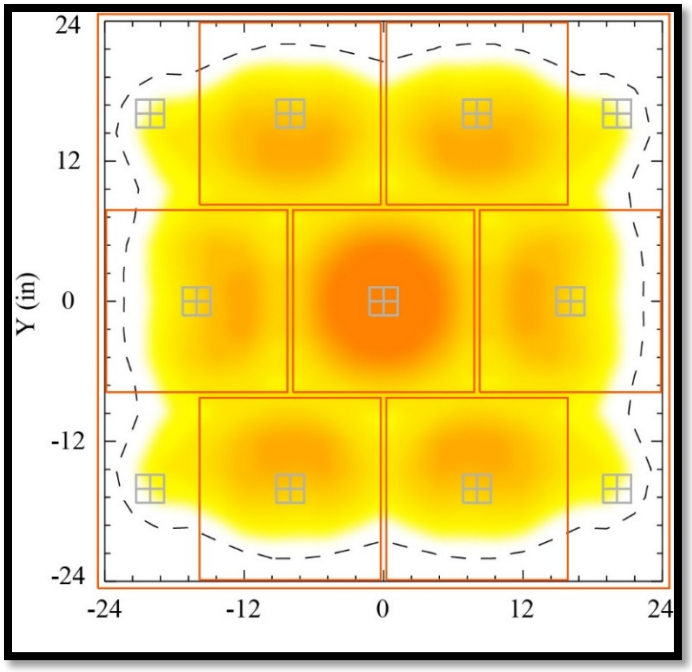

Figure 4. **Phase 1 Modeling Results Indicating Sensor Sensitivity Based on EM Array Concept**

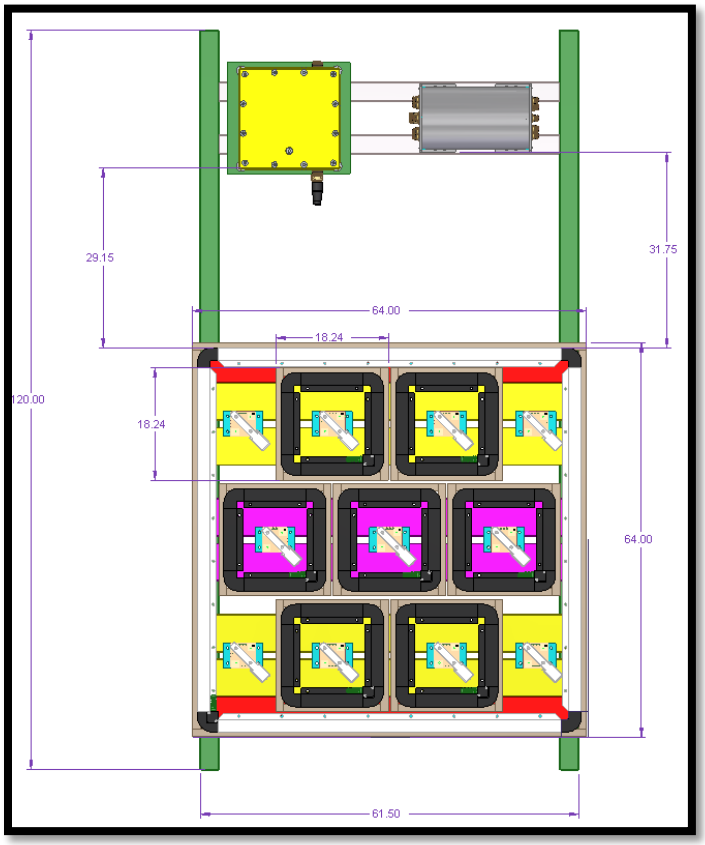

Figure 5. **Phase 2 Engineering and Design Drawing of EM System**

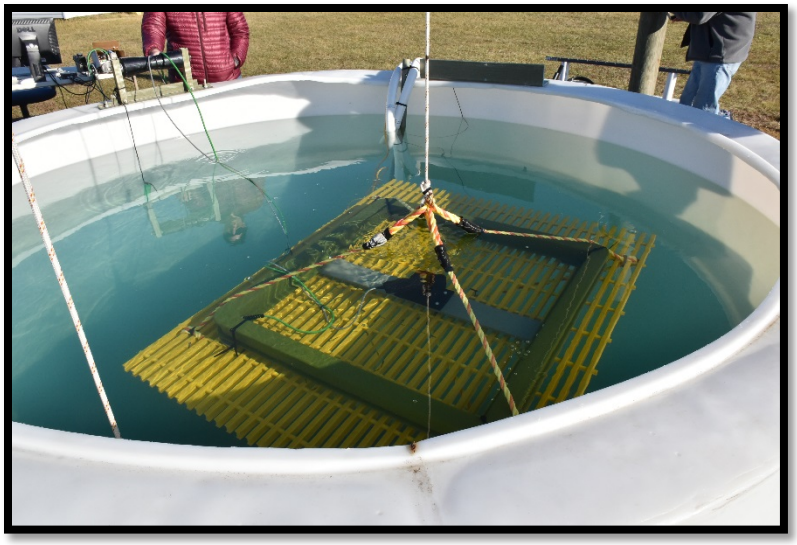

Figure 6. Phase 3 Dunk Test Prior to Freshwater Evaluation

Figure 7. Phase 3 Freshwater Evaluation

3.3 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

The ability to classify EM sources in a dynamic and shallow saltwater environment has the advantages of 1) reducing costs and safety risks, 2) expanding the range of AGC-suitable environments, and 3) improving data quality processing for underwater Munitions Response actions. However, the current EM system configuration is limited by its inability to navigate and collect positional data. The EM system's large form factor, itself a design criterion due to the lack of positional data, is another limitation that may be improved by integrating positional data. The array's large form factor also limits its maneuverability.

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4.0 PERFORMANCE ASSESSMENT

Similar to the 2016 Freshwater Demonstration at Panama City, background-subtracted target data were inverted to estimate target polarizabilities using the UX-Analyze dipole fit algorithm. Malfunctioning data channels (Et, Ft, and Ht transmitter data and Jr receiver Z-axis) were not included, and the first 18 timegates (t < 0.132 ms) were not used. The calculated polarizabilities were compared with free-air polarizabilities using the UX-Analyze classification algorithm.

Table 2 presents all Saltwater Demonstration Test Area results for the eleven test items, including:

- Inverted offsets (X, Y, and Z) from center of EM system;
- Signal to Noise Ratio (SNR);
- Fit Coherence;
- Library Match (underwater cued measurement data match to free-air cued library data);

The effects of test item size and test item location may be seen in the results. Larger test items and test items closer to the center of the EM system array generally had higher fit coherence and library match metrics. Test item location #4 (at the outer edge corner of the EM system array) had the lowest average fit coherence and library match metrics for all items (0.863 and 0.581, respectively). Positioning uncertainty of EM system to the emplaced test item applies to all test item locations.

Table 2. Test Area Results - Quantitative Performance Summary

Test Item	Range of Saltwater Demonstration Results			
	SNR	Fit Coherence	Offset (m)	Library Match
105mm Projectile	616 - 1871	0.985 - 0.999	0.47 - 0.82	0.92 - 0.99
Large ISO	306 - 767	0.988 - 0.998	0.46 - 0.93	0.80 - 0.99
Medium ISO	137 - 483	0.964 - 0.999	0.21 - 0.96	0.69 - 0.98
105mm HEAT	118 - 1308	0.984 - 0.997	0.20 - 1.07	0.57 - 0.99
2.75in Rocket	79 - 1448	0.937 - 0.995	0.12 - 1.04	0.84 - 0.95
60mm Mortar	70 - 282	0.980 - 0.999	0.29 - 0.96	0.87 - 0.95
Aluminum Rod	26 - 193	0.766 - 0.991	0.10 - 2.19	0.06 - 0.99
81mm Mortar	25 - 408	0.945 - 0.996	0.31 - 1.15	0.88 - 0.96
37mm Projectile	18 - 95	0.916 - 0.991	0.20 - 1.25	0.08 - 0.97
20mm Projectile	12 - 24	0.164 - 0.885	0.04 - 8.05	0
Small ISO	9 - 53	0.862 - 0.976	0.28 - 1.40	0 - 0.89

To maintain some consistency with performance of the standard TEMTADS 2x2 and Metal Mapper (which have 48 data channels), the tabulated SNR is the average over the strongest 48 channels in the EM system. 58 of the 66 target measurements (88%) have fit coherence >0.8. This is suspected to be a signal to noise issue. 53 of 53 (100%) measurements with SNR > 30 have fit coherence >0.8. Only 40 of the targets (61%) have a library match metric >0.9. Restricted to targets with SNR >30, the percentage of targets with library match metric increases to 74% (39 of 53). There is no indication that having the array in seawater affects its classification performance. By way of example, **Figure 8** shows 60mm polarizabilities measured in seawater (symbols) and the corresponding free-air library polarizabilities. For this target the SNR is 162, the fit coherence is 0.9989, and the library match metric is 0.95.

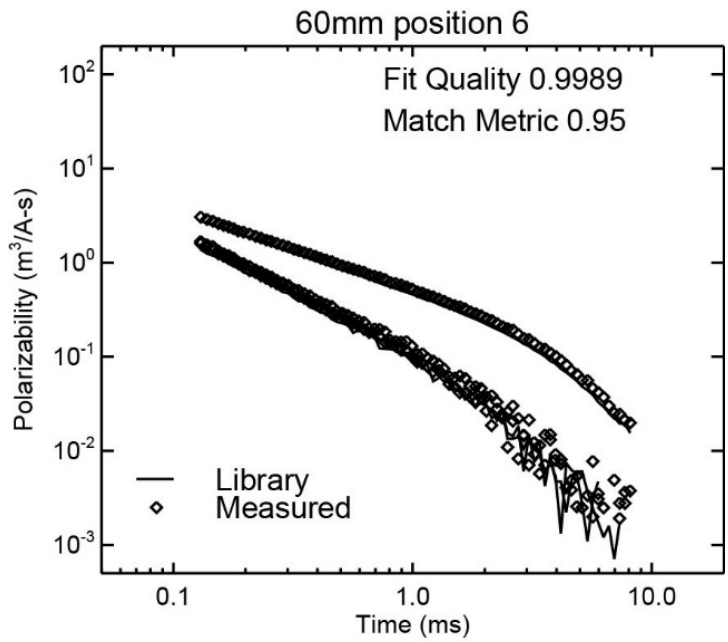

Figure 8. 60mm Polarizabilities Measured in Seawater Compared to In-air (library) Polarizabilities.

5.0 COST ASSESSMENT

No Cost Assessment was performed for the Saltwater Demonstration. Any cost assessment for production use of the EM system would have limited accuracy and usefulness due to the short duration of the Saltwater Demonstration and the overall goal of MR-201313. Additionally, certain costs did not apply to the demonstration (e.g., deployment vessels), or were not included in the demonstration (e.g., EOD-qualified divers and intrusive operations).

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6.0 IMPLEMENTATION ISSUES

The underwater EM system demonstrated is custom-built by Geometrics. The hardware and software are based on the commercially-available Metal Mapper. Though the demonstration was successful, no subsequent demonstrations are planned to progress the EM system from a prototype to commercially available equipment.

Data collection times and transit times between cued data collection locations are minimal compared to the time required to launch and recover the EM system. Improvements to deployment methods will improve overall efficiency, production rates, and cost effectiveness.

Vessel navigation and dive operations for underwater cued AGC data collection are significantly different from traditional underwater geophysical operations (e.g., DGM), and require specialized skills and equipment. For example, real time data review is best implemented with continuous communication between a topside Data Team and the Dive Team.

Divers must be able to safely transport the EM system between cued data collection locations, typically in low visibility settings. The size and weight of the EM system in its current configuration requires two divers to transport with both hands. Reducing the number of transmitters and receivers in the EM system array is possible and would reduce its dimensions and drag but would also reduce the effective footprint of the cued data collection and the 'positioning error budget' for effectively illuminating the subsurface item. This may be a permissible reduction in EM system performance if positional data are incorporated into cued AGC data collection.

The Lighter, Amphibious Resupply, Cargo (LARCs) used in the Saltwater Demonstration are larger than necessary and are the property of USACE FRF. Smaller vessels can deploy the current EM system and vessel requirements must be considered for future underwater EM systems. Commercially-available vessels (e.g., pontoon boat) could be used or modified to launch and recover the EM system.

The finite lengths of the divers' surface supplied air umbilical cords and the EM system's data cables limit the workable configurations between the two LARCs, the divers, and the topside data acquisition computer. The distance between the LARCs must be far enough to prevent collision, but less than the length of the umbilical cord so that the divers can assist with launch and recovery. The data acquisition computer, whether on a vessel or fixed (e.g., on the FRF pier during this demonstration), must be close enough to the divers and EM system to not stretch or break the data cable (currently 70m). This may be improved by placing the data acquisition computer on a vessel.