EXECUTIVE SUMMARY

Continued Discrimination Demonstration Using Advanced EMI Models at Live UXO Sites: Data Quality Assessment and Residual Risk Mitigation in Real Time

ESTCP Project MR-201227

APRIL 2018

Distribution Statement A
This document has been cleared for public release

ESTCP

Page Intentionally Left Blank

This report was prepared under contract to the Department of Defense Environmental Security Technology Certification Program (ESTCP). The publication of this report does not indicate endorsement by the Department of Defense, nor should the contents be construed as reflecting the official policy or position of the Department of Defense. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the Department of Defense.

Page Intentionally Left Blank

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing this collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number. **PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.**

1. REPORT DATE *(DD-MM-YYYY)*
31-03-2017

2. REPORT TYPE
ESTCP Executive Summary

3. DATES COVERED *(From - To)*
30 April 2012 – 31 March 2017

4. TITLE AND SUBTITLE

Continued Discrimination Demonstration Using Advanced EMI Models at Live UXO Sites: Data Quality Assessment and Residual Risk Mitigation in Real Time

5a. CONTRACT NUMBER
W912HQ-12-C-0056

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

Dr. Fridon Shubitidze

5d. PROJECT NUMBER
MR-201227

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

White River Technologies, Inc.
1242 Chestnut Street
Newton, MA 02464

8. PERFORMING ORGANIZATION REPORT NUMBER

MR-201227

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Environmental Security Technology Certification Program
4800 Mark Center Drive, Suite 17D03,Alexandria, VA 22350-3605

10. SPONSOR/MONITOR'S ACRONYM(S)
ESTCP

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
MR-201227

12. DISTRIBUTION / AVAILABILITY STATEMENT

13. SUPPLEMENTARY NOTES

14. ABSTRACT

This project demonstrated the capability of advanced electromagnetic induction (EMI) models to perform discrimination of unexploded ordnance (UXO) at live sites; to achieve a high probability of UXO discrimination in situations involving widespread clutter; to minimize the number of false positives in such cases; to identify all UXO with high confidence; to assess the quality of the data; and to provide a robust dig threshold that will minimize the risk to regulators. Specific technical objectives were to:

1. Use advanced physics-based EMI models to extract robust features that will allow reliable classification when starting from dynamic or cued EMI sensor data. Establish the validity and limitations of these advanced models, taking into account the number of objects in a given cell, their size and material heterogeneity, the geology, and the level of background noise.
2. Combine the advanced models with a statistical model-based approach to select robust classification feature vectors for a specific live UXO site that can reliably and effectively discriminate hazardous targets of interest (TOI) from nonhazardous items.
3. Deploy advanced EMI and statistical signal processing tools to assess EMI data quality onsite and provide a robust dig-threshold point; as a last step, use the different targets' extracted extrinsic parameters to mitigate the residual risk due to UXO and to increase the confidence of regulators at the site.

15. SUBJECT TERMS
Electromagnetic Induction, EMI, UXO, Classification, Dynamic Classification,

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**	SAR	10	Fridon Shubitidze
UCLASS	UNCLASS	UNCLASS			**19b. TELEPHONE NUMBER** *(include area code)* (603) 727-9673

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39.18

Page Intentionally Left Blank

EXECUTIVE SUMMARY

Unexploded ordnance (UXO) Live Site classification demonstrations described in this report were conducted in fulfilment of Environmental Security Technology Certification Program (ESTCP) Project MR-201227, "Continued Discrimination Demonstration Using Advanced EMI Models at Live UXO Sites: Data Quality Assessment and Residual Risk Mitigation in Real Time." This project was executed as part of the 2012 ESTCP solicitation, "Military Munitions Detection, Classification, and Remediation: *Classification Technologies.*"

The primary objectives of Project MR-201227 were to:

1. Implement and demonstrate robust procedures and approaches for advanced electromagnetic induction (EMI) sensor data pre-processing, inversion, and sub-surface target classification;
2. Assess quantitatively the quality and utility of advanced EMI sensor data in terms of geologic and background noise effects, and the use of multi-object inversion algorithms to de-couple the EMI response of targets in the presence of high-density metal contamination;
3. Validate processing technology based on extracted intrinsic (effective dipole polarizability) and extrinsic (location) target parameters from measured data, and identify robust classification features in order to distinguish UXO targets from non-hazardous objects; and
4. Fully characterize the discrimination abilities and limitations of the advanced models with regard to the number of objects, target size, and material heterogeneity, geology, and background noise.

UXO classification procedures consist of the following sequential steps: background corrections; data inversion; target detection/picking; to include target feature parameter estimation; ranking; training; and classification, i.e., separating UXO from non-hazardous anomalies. Under this project, our team developed and tested a user-friendly software package for advanced EMI sensor data pre-processing, inversion, and classification. The software package, which supports both cued and dynamic survey datasets, allows the efficient execution of the following procedures:

a. **Background correction:** During this process, each EMI dataset is first normalized by a corresponding transmit (Tx) current. Next, in the case of cued datasets, background data files are selected for a process of subtracting background levels from the original EMI anomaly dataset. In the case of dynamic survey datasets, a median filter approach is employed for removing background noise from target signals.

b. **Data inversion:** After background EMI levels have been applied and corrupted channels removed, combined Orthogonal Normalized Volume Magnetic Source (ONVMS) and Differential Evolution (DE) algorithms are applied to the anomaly datasets using a multiple source inversion approach. The intrinsic and extrinsic parameters of the targets are then extracted and used for ranking.

c. **Targets picking using survey dataset:** Once background levels are removed from the survey data, two approaches are used to pick targets for cued interrogations: (1) The traditional method utilizes signal amplitudes on a two-dimensional (2D) map and identifies peaks of signals above a prescribed threshold level; and (2) a semi-supervised

Gaussian clustering process clusters the inverted extrinsic (source locations) parameters into a three-dimensional (3D) space and identifies targets using cluster centers.

d. **Ranking:** This process uses extracted intrinsic classification features of the targets, such as total ONVMS-effective polarizabilities (via one, two, and three sources) to rank anomalies.

e. **Training:** Typically, target classification feature parameters are clustered and site-specific training target lists are used to support final classification. Specifically, these training data are used to assess background noise levels, validate inversion results, confirm preliminary target ranking results, and (more importantly) determine an optimal "Stop-Dig" point that optimizes classification performance. The Stop-Dig point is established through evaluation of training data derived from "uncertain anomalies," which are located between targets of interest (TOIs) and those targets that are definitively classified as clutter in the preliminary ranked list.

f. **Classification:** Once the ground truth is obtained from the training targets, all anomalies are classified as TOI or clutter, and the optimal Stop-Dig point is defined.

During the course of Project MR-201227, our team processed multiple datasets collected at the following 11 ESTCP UXO Live Site demonstrations:

1. Spencer Range, TN;
2. Camp Edwards Massachusetts Military Reservation (MMR), MA;
3. Camp Ellis, IL;
4. Fort Rucker, AL;
5. New Boston Air Force Station (AFS), NH;
6. Southwestern Proving Ground (SWPG), AR;
7. Waikoloa Maneuver Area (WMA), HI;
8. Andersen Air Force Base (AFB), Guam;
9. Castner Range, Fort Bliss, TX;
10. West Mesa, NM; and
11. Fort Ord, CA.

Data from these sites were collected using several advanced EMI sensors, such as the MetalMapper (MM), 5x5 Time-domain Electromagnetic Multi-sensor Towed Array Detection System (TEMTADS), 2x2 TEMTADS, Man-Portable Vector (MPV), Berkeley UXO Discriminator (BUD), and One-Pass Time-Domain EMI Array (OPTEMA). All data were analyzed using new UXO classification processes based on advanced EMI models (such as ONVMS, Joint Diagonalization [JD]), and DE techniques). The following steps were followed:

1. Data were pre-processed using a multi-static response (MSR) data matrix eigenvalue approach.
2. For each anomaly, extrinsic features (locations and orientations) and intrinsic features (total ONVMS, i.e., effective polarizabilities) were calculated using a combined ONVMS-DE algorithm for one, two, and three sources.

3. The extracted total ONVMS results were clustered using the target attributes of both size and decay and custom training lists were created.

The main goal of these studies was to determine applicability and limitations of the advanced EMI data inversion and classification technology for UXO detection and classification at UXO Live Sites. To assess effectiveness of the technology, the following five main performance criteria were set: (1) identify all seed items and native TOIs with 99% confidence; (2) minimize the number of false negatives, i.e., maximize correct classification of non-TOI; (3) establish the Stop-Dig threshold point where 100% of munitions are correctly identified; (4) minimize the number of anomalies that cannot be analyzed, and (5) accurately estimate subsurface target intrinsic and extrinsic parameters.

Classification Results for Cued Datasets: Advanced EMI classification technology was applied to all cued datasets collected from the 11 UXO Live Sites. During data analysis and classification, for each anomaly, advanced EMI sensor data were inverted and the targets intrinsic (total ONVMS, i.e., size, shape, and material properties) and extrinsic (location, depth, orientation) parameters were estimated. The intrinsic parameters were used for classification, and ranked Dig lists were generated for each dataset independently and were submitted to ESTCP for scoring. All classification results were scored against intrusive results generated by the Institute for Defense Analyses (IDA) as a third party. The scored results were used to assess the five performance criteria and to determine pros and cons of the advanced classification technology for subsurface target detection and classification at UXO Live Sites.

The number of non-TOI targets that could be left in ground with high confidence using the advanced EMI discrimination technology were compared to the total number of false targets that would be present if the technology were absent. The objective was considered to have been met if the method eliminated at least 75% of targets that did not correspond to a TOI in the discrimination step. The independently scored results for all 11 sites are summarized in Table 1. The results show that the main objective—to rank all TOIs as "Dig" at the Stop-Dig point while reducing false alarms by >75%—was met for the majority of sites. The objective was not met for a few sites due to density of anomalies and sensor-to-target separation distances, insufficient data quality, magnetic soil, and inaccurately documenting the intrusive results. However, in all cases, the classification approach was able to rank >98% of TOI correctly as "Dig."

Table 1. Classification performance results for 11 UXO Live Sites.

ESTCP Demo #	Site	Dataset	Efficiency at Stop-Dig Point	Rate At Stop-Dig Point	Rate with All TOI Classified	TOIs Incorrectly Classified
1	Spencer Range, TN Open Area	MM	100%	90%	93%	0
		5x5 TEMTADS	100%	92%	95%	0
	Spencer Range, TN Dynamic Area	MM	100%	86%	90%	0
		2x2 TEMTADS	100%	90%	94%	0
		MPV	100%	75%	78%	0
	Spencer Range, TN Wooded Area	2x2 TEMTADS	98.6%	91%	26.25%	1
		MPV	98.6%	86%	41%	1
2	MMR, MA	MM	99%	76%	67%	1
		2x2 TEMTADS	100%	75%	78%	0
3	Camp Ellis, IL	MM	98%	88%	82.5%	1
		2x2 TEMTADS	97%	84%	63%	1

ESTCP Demo #	Site	Dataset	Efficiency at Stop-Dig Point	Rate At Stop-Dig Point	Rate with All TOI Classified	TOIs Incorrectly Classified
4	Fort Rucker, AL	MM	100%	45%	57%	0
5	New Boston AFS, NH	2x2 TEMTADS	100%	20%	44%	0
6	SWPG, AR	MM	100%	94%	96%	0
		2x2 TEMTADS	100%	92.5%	98%	0
7	WMA, HI	MM	98%	78%	51%	2
8	Andersen AFB, Guam	2x2 TEMTADS	100%	91%	92%	0
9	Castner Range, Ft. Bliss, TX	2x2 TEMTADS	100%	90%	94%	0
10	West Mesa, NM	MM	100%	87%	92%	0
11	Fort Ord, CA TOI-1	MM	100%	90%	94%	0
	Fort Ord, CA, TOI or 2	MM	99.25%	76%	47%	3

Color codes:

- Objective was met. All TOIs were classified as "Dig" at the Stop-Dig point while reducing false alarms by >75% of TOIs.
- Objective was NOT met. All TOIs were classified as "Dig" at the Stop-Dig point; however, due to the high ratio of the number of TOIs to the number of clutter items on the site, the classification was declared non-sufficient.
- Objective was NOT met. 98.6% of TOIs were classified as "Dig" at the Stop-Dig point. Missed classifications were due to the number of target and sensor-to-target separation distances.
- Objective was NOT met. There was insufficient data for the library item.
- Objective was NOT met. This was partially due to insufficient data quality, magnetic soil, and inaccurately documenting the intrusive results.

In addition, the independently-scored classification results for all sites showed that the classification approach was able to deliver better results than other approaches. Specifically, for very challenging sites such as for MMR, MA, Fort Bliss, TX, WMA, HI, and Ford Ord, CA, the approach was able to classify all seeded items as well as site-specific 20-millimeter (mm), 25mm, 35mm, and 40mm projectiles. For example, during the Fort Bliss, TX, demonstration, 92% of all clutter items were identified as "No-Dig," whereas Team 1 and Team 2, who processed the same datasets, identified only 13% and 19% of clutter as "No- Dig," respectively. The comparison between cost savings achieved by our team using the advanced classification approach, and the approaches used by Team 1 and Team 2, are shown in Figure 1. The cost savings was calculated as $125 x the number of clutter items after the last TOI dig. Similar results were achieved for the MMR, MA, and WMA, HI UXO Live Sites. The results show that our advanced classification technology provides the greatest savings among the classification approaches.

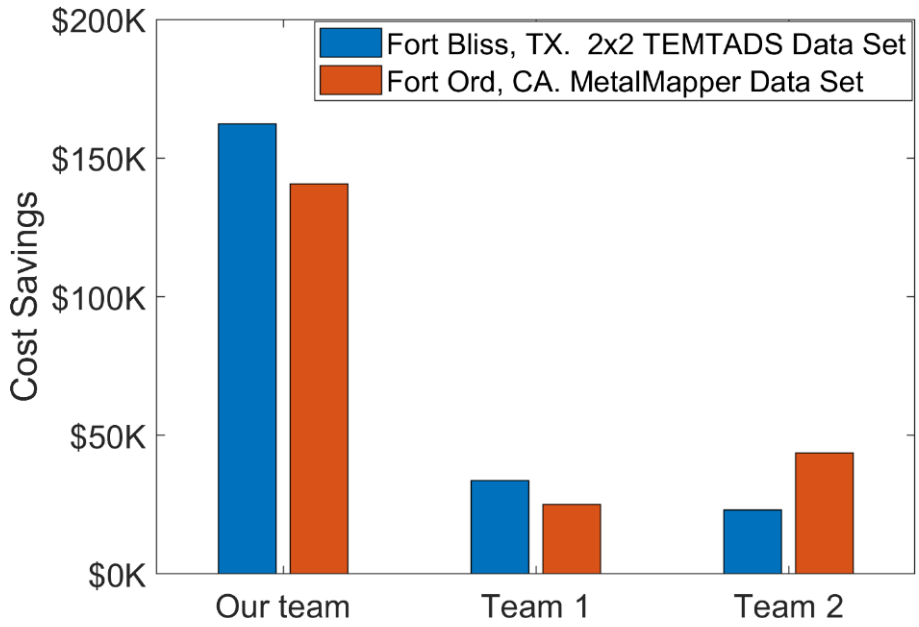

Figure 1. Cost savings achieved by teams at Fort Bliss, TX, and Fort Ord, CA, UXO Live Sites.

Extracting accurate intrinsic and extrinsic parameters of subsurface targets is one of the main products that our data pre-processing and inversion algorithms provide for the mapping and classification subsurface anomalies. Overall, the success of classification directly depends on how accurately these parameters are estimated. For all studies reported in this project, the following criteria were set: the target intrinsic parameters could vary within $\pm$10%, the extracted *x*-*y* location could vary within $\pm$10 centimeters (cm), and the depth could vary within $\pm$5 cm. This objective was successfully met for all datasets collected from the 11 demonstration sites.

Dynamic Data Processing and Classification: Our approach for processing dynamic datasets is based on orthogonal methods such as the JD and ONVMS techniques, which were originally developed for cued data processing and target classification. These methods have also been successfully applied to dynamic datasets collected during the Camp Hale, CO, Live Site classification demonstration.

Comparisons of the data collected in dynamic survey mode and stationary cued mode reveal that dynamic data is not significantly inferior to cued data in terms of the information that can be extracted and exploited for target classification. Our analysis has shown that when advanced models are applied to dynamic datasets, anomalies can be completely characterized and classified, and the number of cued measurements required for complete target classification across a site can be eliminated or significantly reduced.

Comparisons between predicted target locations, estimated by using the target picking/classification algorithm and actual target locations, measured intrusively have shown that our advanced models map the subsurface targets accurately and provide significantly improved anomaly selection compared to a simple thresholding or dipole inversions/matched filter approach. These results are particularly apparent in areas with medium or high-density concentrations of metallic clutter. In addition, the applied advanced EMI models classified each TOI very accurately

from multiple dynamic data points, demonstrating the robustness of the dynamic modeling and analysis methods.

Conclusions: In this project, the advanced EMI data inversion and classification technology was demonstrated at 11 ESTCP UXO Live Sites for identifying all TOI and eliminating >75% of the clutter. The technology was applied to cued and dynamic datasets collected by the next generation EMI sensors, e.g., MM, 5x5 and 2x2 TEMTADS, MPV, BUD, and OPTEMA. The demonstrations showed that for most sites, the advanced classification technology identified all TOI while correctly classifying 75%–92% of the clutter at specified Stop-Dig points. However, there were a few sites where the algorithm did not correctly classify one or more TOI due to insufficient data quality, magnetic soil, or inaccurately documenting the intrusive results. These results illustrate the importance of well-defined data collection procedures and accounting for magnetic soil responses during intrusive investigations. A comparison of the classification results for different sensors showed that the sensors perform equally well when data are analyzed using the advanced EMI models. Similar conclusions are reached when comparing the classification results from cued and dynamic EMI survey datasets. The choice of which sensor to deploy and which survey deployment mode is used on a site can therefore be driven by cost and system efficiency given site-specific survey terrain.

Acronyms

AFB	Air Force Base
AFS	Air Force Station
BUD	Berkeley UXO Discriminator
cm	centimeter(s)
DE	Differential Evolution
EMI	electromagnetic induction
ESTCP	Environmental Security Technology Certification Program
JD	Joint Diagonalization
MM	MetalMapper
mm	millimeter(s)
MMR	Massachusetts Military Reservation
MPV	Man-Portable Vector
ONVMS	Orthogonal Normalized Volume Magnetic Source
OPTEMA	One-Pass Time-Domain EMI Array
SWPG	Southwestern Proving Ground
TEMTADS	Time-domain Electromagnetic Multi-sensor Towed Array Detection System
TOI	target of interest
UXO	unexploded ordnance
WMA	Waikoloa Maneuver Area