ESTCP
Cost and Performance Report

(MR-201001)

Clutter Identification Using Electromagnetic Survey Data

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ACRONYMS AND ABBREVIATIONS

ASCII	American Standard Code for Information Interchange
EMI	electromagnetic induction
ESTCP	Environmental Security Technology Certification Program
GPS	Global Positioning System
Ha	hectare
IEEE	Institute of Electrical and Electronics Engineers
IVS	Instrument Verification Strip
MP	man-portable
MR	Munitions Response
ms	millisecond
µs	microsecond
MTADS	Multi-sensor Towed Array Detection System
NMEA	National Marine Electronics Association
NRL	Naval Research Laboratory
QC	Quality Control
ROC	receiver operating characteristic
RTK	Real Time Kinematic
Rx	receiver
SAIC	Science Applications International Corporation
SERDP	Strategic Environmental Research and Development Program
TEM	transient electromagnetic
TEMTADS	Time-domain Electro-Magnetic MTADS
TOI	target of interest
Tx	transmit(ter)
USACE	U.S. Army Corps of Engineers
UXO	unexploded ordnance

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EXECUTIVE SUMMARY

BACKGROUND

Attempts to identify buried objects using conventional geophysical survey data have produced uniformly unsatisfactory results. The problem is that classification based on dipole inversion of mapped survey data is intolerant of even centimeter-scale positioning errors in the data, and the technology for geo-location of survey data cannot provide the required positioning accuracy. As originally envisioned, this project sought to demonstrate improved procedures for target classification with EM61 survey data using schemes that are tolerant of the positioning errors. Several procedures were tested with EM61 data from the ESTCP Classification Demonstration at the former Camp Beale in California. They showed no improvement in classification performance over the results using standard processing techniques. Consequently, the project was re-directed to consider classification performance using survey-mode data collected using an advanced man-portable (MP) electromagnetic induction (EMI) sensor array recently developed by the Chemistry Division of the Naval Research Laboratory and SAIC.

The MP system uses a cart mounted 2x2 array of EMI sensors with tri-axial receiver cubes. The success of the MP system for cued target identification in the Camp Beale demonstration was the primary motivating factor for adapting the system for dynamic or survey mode operation in this project.

OBJECTIVE

The objective of this demonstration was to validate the performance of the MP system used in dynamic survey mode in a blind test at a live munitions response (MR) site. Performance metrics include production rate, detection performance, percentage of targets classified using survey data and classification performance.

RESULTS

The demonstration was part of the ESTCP Live Site Demonstration at the former Spencer Artillery Range, Tennessee during May 2012. The dynamic test area covered 0.5 hectare (Ha) of open field. The classification was conducted for 339 unknown anomalies detected within the Dynamic Area. Approximately 70% of the detected anomalies could be classified from the dynamic data alone. Using a combination of results from dynamic data and cued data, 100% of the identified UXO were correctly classified and the number of necessary digs could be reduced by at least 75%.

IMPLEMENTATION ISSUES

The objective of this project was to demonstrate a UXO classification process that made use of dynamic mode data collection with an advanced EMI sensor. The data collected with these systems can be used both for anomaly detection and for classification on a significant fraction of the detected anomalies, limiting the number of anomalies requiring further investigation in cued mode.

Another ongoing goal of this and other projects is to transition these technologies from being research prototypes to use in the industrial community where appropriate. The mechanics of collecting classification-grade advanced EMI cued data with these systems have been shown to be fairly routine in the research community. As part of the ESTCP Munitions Response Live Site Demonstrations, industrial partners have been exposed to the MP system and the associated data collection and processing procedures. The success of this effort will be evaluated on an ongoing basis through the Live Site demonstrations. In the past, analysis of data from these systems has been somewhat of a specialty, requiring specific software and knowledge to proficiently conduct. The successful transition of the processing and analysis procedures for MP data to the Geosoft Oasis montaj environment provides a clear pathway forward.

1.0 INTRODUCTION

1.1 BACKGROUND

The characterization and remediation activities conducted at Department of Defense sites contaminated with unexploded ordnance (UXO) traditionally use geophysical sensors, such as the Geonics EM61, but results are often unsatisfactory and are too expensive. This is due in part to the inability of that sensor technology to distinguish between UXO and non-hazardous clutter. Field experience cited by the U.S. Army Corps of Engineers (USACE) is that less than 1% or 2% of the items excavated at a site are UXO [1].

Attempts to identify buried objects using conventional geophysical survey data have produced uniformly unsatisfactory results. The problem is that classification based on dipole inversion of mapped survey data is intolerant of even centimeter-scale positioning errors in the data, and the technology for geo-location of survey data cannot provide the required positioning accuracy [2, 3, 4, 5, 6]. As originally envisioned, this project sought to demonstrate improved procedures for target classification with EM61 survey data using schemes that are tolerant of the positioning errors. Several procedures were tested with EM61 data from the Environmental Security Technology Certification Program (ESTCP) Classification Demonstration at the former Camp Beale in California [7]. They showed no improvement in classification performance over the results using standard processing techniques [7]. Consequently, the project was re-directed to consider classification performance using survey-mode data collected using an advanced man-portable (MP) electromagnetic induction (EMI) sensor array recently developed by the Chemistry Division of the Naval Research Laboratory (NRL) and Science Applications International Corporation (SAIC).

NRL and SAIC have participated in several programs funded by the Strategic Environmental Research and Development Program (SERDP) and ESTCP, whose goal has been to enhance the classification ability of the Multi-sensor Towed Array Detection System (MTADS). The NRL Time-domain Electromagnetic MTADS (TEMTADS) vehicle towed 5x5 array incorporated an advanced EMI sensor specifically designed for UXO classification [8].

This technology was transitioned to smaller systems for deployment in more confined areas in ESTCP Projects MR-200807 and 200909 [9]. The MP system was constructed as a 2x2 array of upgraded sensors based on those from the original TEMTADS, but with tri-axial receiver cubes. The success of the MP system for cued target identification in the Camp Beale demonstration [7] was the primary motivating factor for adapting the system for dynamic or survey mode operation in this project.

1.2 OBJECTIVES OF THE PROJECT

The objective of this demonstration was to validate the performance of the MP system used in dynamic mode through blind testing at a live site. The dynamic MP system results from the ESTCP Munitions Response (MR) Live Site Demonstration at the former Spencer Artillery Range, located in Spencer, Tennessee in May 2012 are presented in this document. To limit the repetition of information, study- and site-specific information that are presented elsewhere, such

as in the ESTCP Live Site Demonstrations Plan [10], are noted and not repeated in this document.

The MP system was evaluated in terms of classification performance (false alarm rejection) and appropriateness for fielding (production rate, etc.). Specifics are provided in Section 3.0.

1.3 REGULATORY DRIVERS

Stakeholder acceptance of the use of classification techniques on real sites will require demonstration that these techniques can be deployed efficiently and with high probability of discrimination. Demonstration at live sites with extensive ground-truth validation will facilitate regulatory acceptance of the UXO classification technology and methodology.

2.0 TECHNOLOGY

2.1 TECHNOLOGY DESCRIPTION

The MP system comprises a square array of four transmit (Tx)/receiver (Rx) coil pairs mounted on a cart. The transmit coils are wound around the outer portion of 35 cm square Styrofoam forms. The three-axis receiver cubes are wound on 8 cm wooden blocks. Figure 1 (left) shows a new coil under construction. Figure 1 (right) shows the MP cart with Global Positioning System (GPS) antenna. The transient electromagnetic (TEM) and data acquisition electronics are in the backpack worn by the MP cart operator. Data acquisition is controlled by the tablet computer carried by the person walking beside the operator.

Figure 1. Left: Individual TEMTADS/3D EMI sensor with 3 axis receiver under construction, Right: Man-portable TEM array with GPS antenna.

For dynamic survey mode operation we used a decay time (and corresponding transmitter on time) of 2.77 milliseconds (ms). A base time period of 33 ms was used so that three repeats per transmit waveform can be averaged. Gate width was set at 20%, resulting in 19 time gates with center times ranging from 25 microseconds (µs) to 2.5 ms.

2.2 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

The MP system was originally designed to offer similar cued-mode production rates to those seen for larger, vehicular-towed advanced EMI sensors, while also making it possible to operate in difficult terrain and treed areas that the larger systems cannot access. With the upgraded TEMTADS/3D sensors, similar performance was achieved with similar classification-grade data quality. The MP array is 80 cm on a side and mounted on a MP cart. Terrain where the vegetation or topography interferes with passage of a cart of that size will not be amenable to the use of the system.

There is a limiting anomaly density above which the response of individual targets cannot be separated individually. Relatively small sensors were chosen for this array to help mitigate this problem but cannot eliminate it completely. Recent developments, including solvers designed for classification in multiple-object scenarios, such as SAIC's multi-target solver [11], are being evaluated and their performance characteristics in cluttered environments determined.

In dynamic mode, the MP system offers higher data density and correspondingly finer resolution of targets than is typically seen for systems with larger transmitter and receiver coils, such as the iconic Geonics EM61-MK2, although depths of detection and signal-to-noise ratios are comparable between the EM61-MK2 and the MP system. However, this rich data set comes at a productivity cost. A complete transmit cycle of the MP system in dynamic mode has a repetition rate of 7.5 Hz. Systems with few transmitters can cycle faster, resulting in higher along-track data density. Recent advances in smart, or dipole-based, target picking indicate that the additional richness of data collected with the advanced sensors, if used to its full potential, could improve detection performance beyond that of traditional technologies.

3.0 PERFORMANCE OBJECTIVES

Performance objectives for the demonstration are summarized in Table 1. They provide a basis for evaluating the performance and costs of the demonstrated technology.

Production rate was determined by the area covered during a 10 hour work day. This includes required setup, calibration, data download and shut down activities as well as down time for lunch, etc. The goal was a production rate of at least 1 acre/day. The only full day of data collection was May 8. Data collection (including Instrument Verification Strip [IVS]) ran from 9:25AM to 6:08PM. During that time 156 survey data lines were collected, which is 77% of the 202 total survey lines used to cover the 1.3 acre dynamic survey area. Figuring 1¼ hours for setup and shut down activities, this corresponds to an area coverage rate of 1 acre/day.

The system must be capable of detecting the targets of interest (TOI). Seed items (inert munitions and pipe sections) buried at the site were used to evaluate detection performance. The objective was considered to be met if 100% of the seeded items were detected within a halo of 60 cm. At the completion of the dynamic survey of the Dynamic Area, a target list was produced using the criteria outlined in Section 6.2. As this was the first live-site demonstration of this sensor in this mode of operation, a data analyst manually evaluated each target selection. The resulting target list was submitted to the Program Office for evaluation by the USACE, Huntsville. One seed item was missed by the data analyst even though the data for that location met the selection criteria. A root-cause-analysis determined the threshold exceedance for the late time gate was not well-formed and discarded by the data analyst. With the aggressive schedule required for this demonstration, fatigue and time pressure on the data analyst played an additional role. In future demonstrations, an automated version of the target picking process will be used and will prevent this type of error.

Our goal is to significantly reduce the number of anomalies that must be revisited for classification. Substantial cost savings can be realized when a significant percentage of the anomalies can be classified using the survey data. The objective was considered met if 50% of the anomalies could be classified using the survey data. Of the 339 anomalies, 232 (68%) were classified using only the survey data. Cued data were requested for the other 107 anomalies.

The goal of classification is to significantly reduce the number of unnecessary clutter digs without leaving any TOI in the ground. The metric for the final objective was the percentage of clutter anomalies that were correctly classified with all TOI correctly classified. The data analyst set a “stop-dig” threshold at 94 total digs, which captured all 23 of the TOI (Pd = 1.0) in the Dynamic Area. Of the 316 clutter items in the Dynamic Area, 70 (22%) would have been dug at this “stop-dig” threshold, corresponding to a 78% reduction in clutter digs.

Table 1. Performance results for this demonstration.

Performance Objective	Metric	Data Required	Success Criteria	Success? (Yes/No)
Production rate	Area per unit time	Survey data	1 acre/day	Yes
Detection of all TOI	Percent of seeded items detected	Location of seeded items Anomaly list	100% of seeded items detected within a 60 cm halo	No
Classification performance (survey mode)	Percent detected targets classified with survey data	Dynamic inversion fit quality	50% anomalies classified using survey data	Yes
Classification Performance (overall)	Percent clutter rejected at 100% TOI correctly identified	Dig list and ground truth	75% clutter rejection	Yes

4.0 SITE DESCRIPTION

The information in this section is extracted from the ESTCP Live Site Demonstrations Plan [10].

4.1 SITE SELECTION

This site was chosen by ESTCP in their series of sites for demonstration of the classification process. The first site in the series, former Camp Sibert in Alabama, had only one TOI and item "size" was an effective discriminant. A hillside range at the former Camp San Luis Obispo in California was selected as the second demonstration location because of the wider mix of munitions, including 60 mm, 81 mm, and 4.2-in mortars and 2.36-in rockets. Three additional munitions types were discovered during the course of the demonstration. The third site chosen was the former Camp Butner in North Carolina. This site is contaminated with items as small as 37 mm projectiles, adding yet another layer of complexity to the process. Additional sites were included to provide opportunities to demonstrate the capabilities and limitations of the classification process on a variety of site conditions.

The Spencer Range was selected for demonstration because it is more heavily wooded than prior demonstrations and is thought to contain a wide mixture of munitions. These two features increase the site's complexity and both characteristics are likely to be encountered on production sites. A 1.3 acre open area of the site was chosen for the dynamic survey demonstrations.

4.2 SITE HISTORY

In 1941, construction began on the 30,618 acre Spencer Artillery Range and documentation identifies the establishment of two impact areas: Jakes Mountain (5,060 acres) and Bald Knob (2,090 acres). Troop training took place until September 1944, by which time Army ground forces had either departed or were under orders to depart. Subsequent arrangements were made for Dyersburg Army Air Field to use the Spencer Artillery Range as an air-to-ground gunnery range. The land reverted back to the original 25 leaseholders in the summer of 1946. Several surface decontamination sweeps were completed on portions of the former range in the 1950s. Since that time, numerous tracts of land have been sold and/or subdivided, significantly increasing the number of property owners from the original 25 to several hundred landowners today.

4.3 MUNITIONS CONTAMINATION

The suspected munitions at this site include: 37 mm projectiles, 75 mm projectiles, 76 mm projectiles, 105 mm projectiles and 155 mm projectiles. In close proximity to the particular site of this demonstration, 37 mm and 155 mm projectiles were observed during the Remedial Investigation as well as large quantities of unidentified munitions debris.

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5.0 TEST DESIGN

5.1 CONCEPTUAL EXPERIMENTAL DESIGN

The dynamic MP system survey, which is the focus of this report, was part of a larger TEMTADS family demonstration, as discussed in Reference [12]. The basic idea was to:

1. Conduct a geophysical survey of the Spencer Dynamic Area using the MP system,
2. Select anomalies from the mapped survey data consistent with expected signal levels for TOI,
3. Classify as many anomalies as possible using the survey data, and
4. Use static cued data collected with the MP system to classify the remaining anomalies.

A dig list based on the classification data would then be submitted to the ESTCP Program for scoring to determine classification performance.

5.2 SITE PREPARATION

The Dynamic Area was recently harvested of trees. To prepare the area for the survey, tree stumps were ground and remaining vegetation removed. All visible metal objects were removed from the surface at the final selected demonstration site.

At a live site, such as this, the ratio of clutter to TOI is such that only a small number of TOI may be found; far from enough to determine any demonstrator's classification performance with acceptable confidence bounds. To avoid this problem, the site was seeded by the ESTCP Program Office with enough TOI to ensure reasonable statistics.

5.3 SYSTEM SPECIFICATIONS

The MP system has four of the TEMTADS/3D EMI sensors described in Section 2.1 arranged in a 2x2, 80 cm square array. The array is deployed on a wheeled cart fabricated from polyvinyl chloride plastic and G-10 fiberglass as shown in Figure 1 (right). The sensor ride height is 20 cm. The MP system can be operated in two modes: dynamic (or survey) mode and cued mode. In dynamic mode, a GPS antenna and (optionally) an inertial measurement unit are mounted above the TEM array.

The transmitter electronics and the data acquisition computer are mounted in the operator backpack. The EM3D software package, a variant of the software used for the Geometrics MetalMapper, provides dynamic data acquisition functionality. Each transmitter is fired in a sequence. The received signal is recorded for all Rx channels for each transmit cycle. The transmit pulse waveform duration is 33 ms in dynamic mode. While it is possible to record the entire decay transient at 2 μs sample spacing, it was found that binning the data into time gates simplifies the analysis and provides additional signal averaging without significant loss of temporal resolution in the transient decays [13]. In dynamic mode, the data are binned into 19

logarithmically spaced time gates. The data are recorded in a binary format as a single file with multiple data points (one data point per Tx cycle).

The data acquisition computer is mounted in the backpack and is controlled by a second operator using a tablet PC with a Institute of Electrical and Electronics Engineers (IEEE) 802.11g wireless link to the data acquisition computer. The second operator also manages field notes and team orienteering functions. Data collection with the MP system at the former Spencer Artillery Range, TN is shown in Figure 1 (right).

Positioning is provided using cm-level Real Time Kinematic (RTK) GPS receivers. To achieve cm-level precision, a fixed reference base station is placed on an established first-order survey control point near the survey area. The base station transmits corrections to the GPS rover at 1 Hz via a radio link (450 MHz). The rover GPS receiver receives corrections from the fixed base station. This corrected position is reported at 10-20 Hz using a vendor-specific National Marine Electronics Association (NMEA)-0183 message format (e.g., $PTNL, GGK). The RTK receiver is mounted above the array center on a tripod.

5.4 CALIBRATION ACTIVITIES

The system is calibrated by comparing the measured response to a standard 4-inch diameter aluminum ball with the expected response calculated using standard EMI theory [14].

5.5 DATA COLLECTION PROCEDURES

The Dynamic Area was a 1.3 acre section of the Spencer Range demonstration site. Geophysical surveys of the Dynamic Area were conducted with the MP system and a Geonics EM61. The Program Office selected a total of 339 anomalies from the combined surveys as potential TOI. Of these, 23 were TOI and 316 were clutter. Performance of the system response was monitored on a twice-daily basis using the onsite IVS.

The sensor spacing for the TEM array is fixed at 40 cm in both along- and cross-track directions by design. In dynamic mode, a complete Tx cycle (sequentially firing each of the four transmitters) occurs every 0.13 s (7.5 Hz). At a walking speed of ~1 m/s this corresponds to 7.5 complete Tx cycles per meter. Survey lines are spaced every 40 cm.

Data were stored electronically as collected on the data acquisition computer hard drive. Approximately every survey hour, the collected data were copied onto removable media and transferred to the data analyst for quality control (QC) and subsequent analysis. The data were moved onto the data analyst’s computer and the media was recycled. Raw data and analysis results were backed up from the data analyst’s computer to external hard disks daily. These results were archived on an internal file server at NRL or SAIC at the end of the survey.

At the conclusion of data collection activities, all anomalies on the master anomaly list assembled by the Program Office were excavated. Each item encountered was identified, photographed, its depth measured, its location determined using cm-level GPS, and the item removed if possible. This ground truth information was used to validate the objectives listed in Section 3.0.

6.0 DATA ANALYSIS AND PRODUCTS

6.1 PRE-PROCESSING

Prior to detection and classification processing the data were normalized by transmit current, edited to remove noise spikes, and leveled using a median filter.

6.2 TARGET SELECTION FOR DETECTION

An anomaly detection procedure similar to the one described in Reference 15 was used for the MP system dynamic survey data. As this was the first outing of the MP system in dynamic mode, a data analyst made each anomaly selection rather than an automated peak picker routine. The anomaly detection criteria were unchanged. A preliminary detection threshold was selected based on physical models of the systems response to the expected TOI. The site-specific background signal levels were considered as well. Anomalies were picked from mapped data. The mapped data from the Dynamic Area are shown in Figure 2. The data presented are monostatic response from each sensor at the tenth usable time gate, 1.024 ms.

The ESTCP Demonstration Plan for the former Spencer Artillery Range demonstration set an objective of detecting 37 mm projectiles to a burial depth of 34 cm [10]. To establish a detection threshold for this objective with the MP system operating in dynamic survey mode, a series of forward model cases were run using the polarizabilities of known 37 mm projectiles and actual, measured survey track positions from our test field. In dynamic survey mode, the earliest usable time gates are in the 0.1 to 0.2 ms range. Therefore, the first time gate considered in the forward model cases was 0.135 ms. The weakest responses are 37 mm projectiles oriented horizontally.

A forward model was run with a fixed object depth of 34 cm, but over a range of object – survey tracks separations and a range of object azimuth orientations. The results indicated that the expected peak signals for the 37 mm projectile are found within the range of 1.6 to 2.1 mV/A at 0.135 ms. Based on these modeling results, a pre-demonstration, conservative detection level of 1.8 mV/A was selected for the MP system dynamic survey.

After the data were collected and reviewed, it was determined that the last time gate (of 10 used for analysis) was a better choice for target picking. The response from small, thin-walled items has had a chance to decay away while the response from a 37 mm projectile still remained sufficiently above background for target picking. The same model referenced above was used to determine the proper threshold of the 10th time gate and was found to be 0.18 mV/A. Therefore, a decision was made to use the 10th time gate for initial selection and the 1st time gate with the corresponding model prediction in the range of 1.6 to 2.1 mV/A threshold to confirm our picks. This threshold is within the range stipulated in the original plan. If a peak passed the threshold at both time gates, it was added to the target list.

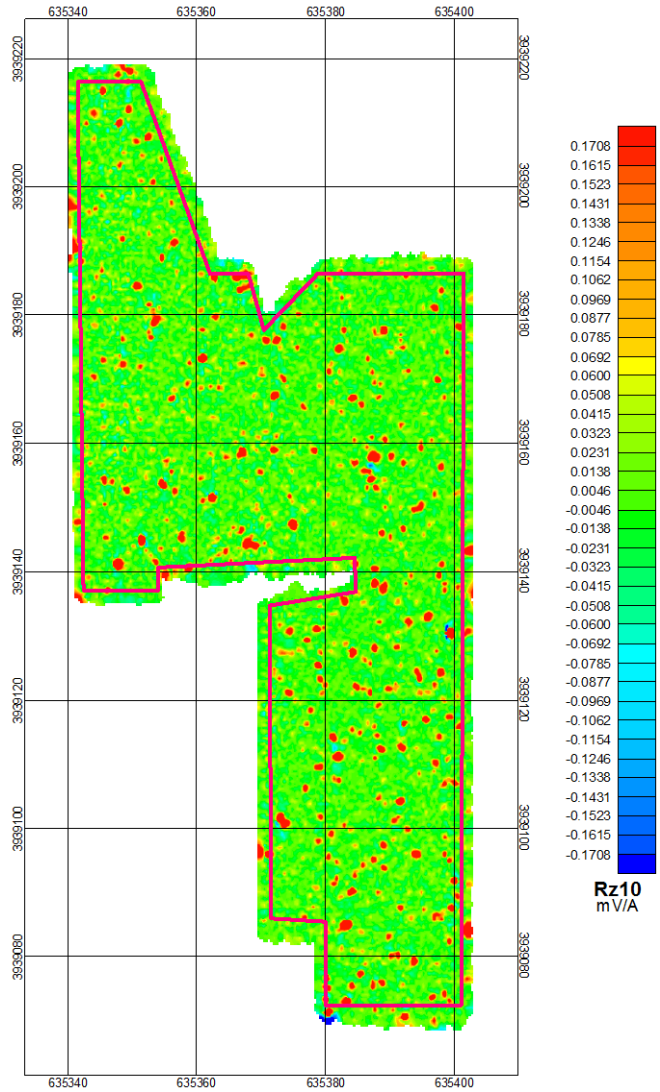

Figure 2. Located and leveled dynamic data (1.024 ms) from the MP system for the dynamic area at the former Spencer Artillery Range, TN.

6.3 PARAMETER ESTIMATION

The raw signature data from TEMTADS sensors reflect details of the sensor/target geometry as well as inherent EMI response characteristics of the targets themselves. In order to separate out the intrinsic target response properties from sensor/target geometry effects, the team inverted the signature data to estimate principal axis magnetic polarizabilities for the targets. The TEMTADS data are inverted using the standard induced dipole response model wherein the effect of eddy currents set up in the target by the primary field is represented by a set of three orthogonal magnetic dipoles at the target location [16].

Given a set of measurements of the target response with varying geometries or “look angles” at the target, the data can be inverted to determine the local (X,Y,Z) location of the target, the

orientation of its principal axes (ϕ,θ,ψ), and the principal axis polarizabilities (β_1,β_2,β_3). The basic idea is to search out the set of nine parameters ($X,Y,Z,\phi,\theta,\psi,\beta_1,\beta_2,\beta_3$) that minimizes the difference between the measured responses and those calculated using the dipole response model.

6.4 CLASSIFIER AND TRAINING

Target classification is based on a library matching procedure wherein the results of a dipole inversion of the TEM array data are compared to principal axis polarizabilities drawn from a library of known signatures. The match is based on three criteria: the amplitude of the primary polarizability, and the ratio of the second and third polarizabilities to the first. The team computed match metrics, each of which runs from 0 (terrible match) to 1 (perfect match).

The experience with these sensors has been that principal polarizabilities determined from in-air measurements are indistinguishable from those determined from measurements taken over buried targets. The team has an extensive collection of inert military munitions collected from many sources, which were measured at the home facility using the TEMTADS family of sensors mounted on a test stand. The team also assembled a fairly extensive polarizability database for clutter items recovered from several different sites. These data collections were used as training data for establishing UXO/clutter discrimination boundaries on the library match metrics.

6.5 DATA PRODUCT SPECIFICATIONS

Provided to the ESTCP Program Office as deliverables were: the Dynamic Area survey data, test pit data for the site-specific TOIs, and data from the daily IVS surveys. All data are provided leveled and current-corrected in American Standard Code for Information Interchange (ASCII) file formats. For the test pit and IVS data, the raw data files are also provided. See Reference 12 for further detailed data product specifications.

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7.0 PERFORMANCE ASSESSMENT

7.1 PRODUCTION RATE

Time stamped survey data files were used to determine the survey production rate. The data collection rate is the product of lane spacing and average along-track speed. The lane spacing for the MP survey was 0.4 m and the average survey speed was 0.95 m/s, resulting in a data collection rate of 0.38 m^2/s. This was ~80% of the EM61 data collection rate in the Spencer Dynamic Area, which had 0.5 m line spacing and an average survey speed of 1.1 m/s. It amounts to 0.35 acre/hour.

The actual area coverage or production rate for a 10 hour day factors in required setup, calibration, data download and shut down activities, as well as down time for lunch, etc. May 8 was the only full day of data collection. Data collection (including IVS) ran from 9:25AM to 6:08PM. During that time, 156 survey data lines were collected, which is 77% of the 202 total survey lines used to cover the 1.3 acre dynamic survey area. Figuring in 1¼ hours for setup and shut down activities, this corresponds to an area coverage rate of 1 acre/day, which amounts to only about 30% of the data collection rate.

At a line spacing of 40 cm, one pair of receiver cubes for each survey line passes roughly over the same path as a pair of receiver cubes from the survey line on either side. In more recent demonstrations, this spacing has been increased to 60 cm, improving the production rate. For very small targets, such as 20mm projectiles, the original spacing is still recommended.

7.2 ANOMALY DETECTION

At the completion of the dynamic survey of the Dynamic Area, a target list was produced using the criteria outlined in Section 6.2. As this was the first live-site demonstration of this sensor in this mode of operation, a data analyst manually evaluated each target selection. The resulting target list was submitted to the Program Office for evaluation by the USACE, Huntsville. One seed item was missed by the data analyst even though the data coverage at that location was good and the sensor readings met the selection criteria. A root-cause-analysis determined the threshold exceedance for the late time gate was not well-formed and discarded by the data analyst (see Figure 3). Additionally, the centroids of the peaks at the early and late time gates did not line up well. With the aggressive schedule required for this demonstration, fatigue and time pressure on the data analyst played a role in this failure. In future demonstrations, an automated version of the target picking process will be used and will prevent this type of error.

7.3 SURVEY MODE CLASSIFICATION

Based on the techniques described in Section 6.0, the dynamic data set collected at the former Spencer Artillery Range Dynamic Area in May 2012 was used to generate an anomaly list. The union of this list and the anomaly list from the EM61-MK2 survey conducted by URS Corporation personnel in April 2012 was used to generate an overall anomaly list for the Dynamic Area. Dipole inversion to determine target parameters for classification was attempted using the survey data for all 339 anomalies on this target list. Classifiable target parameters were

able to be extracted for 232 (68%) of the anomalies. Cued data were requested for the other 107 anomalies.

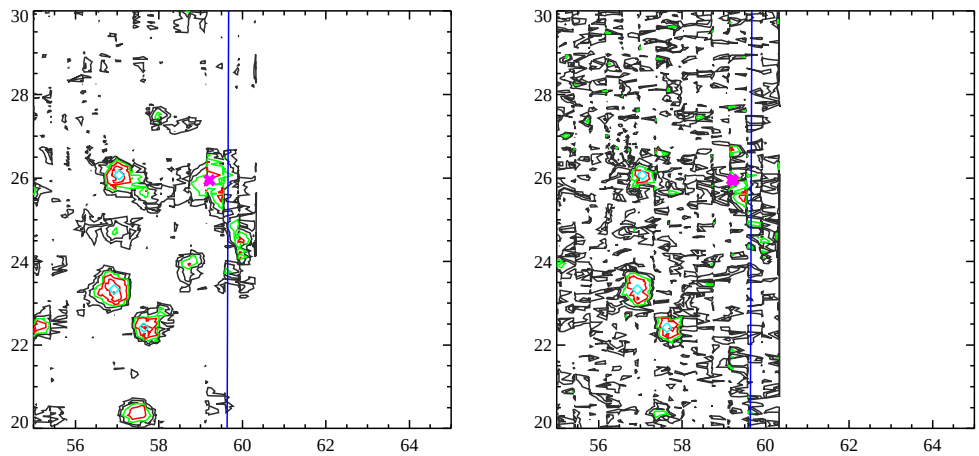

Figure 3. Data contour plots for the early selection time gate (0.137 ms, left) and the late selection time gate (1.024 ms, right). Position is given in local coordinates (meters).

7.4 CLUTTER REJECTION

Once data analysis was complete, a ranked dig list was prepared and submitted to ESTCP for scoring. The results of the classification process are presented in Figure 4 in the form of a receiver operating characteristic (ROC) curve. The ground truth for 18 anomalies was requested for training. These are shown by the black section of the ROC. The data analyst set a "stop-dig" threshold at 94 total digs (end of red portion of ROC), which captured all 23 of the TOI (P_d = 1.0) in the Dynamic Area. The remaining anomalies (green portion) were classified as likely clutter. Of the 316 clutter items in the Dynamic Area, 70 (22%) would have been dug at the "stop-dig" threshold, corresponding to a 78% reduction in clutter digs.

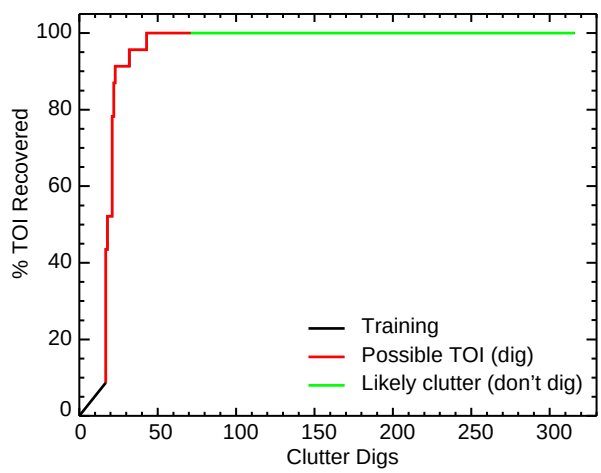

Figure 4. TEMTADS MP 2x2 Cart Dynamic/Cued Classification Results for the former Spencer Artillery Range, TN. Classification performed by SAIC.

8.0 COST ASSESSMENT

8.1 COST MODEL

The cost elements tracked for this demonstration are detailed in Table 2. The cost elements are based on a model recently developed for cost estimation for the MP system at Camp Beale in 2011 [17]. The model assumes a two-person field crew and one data analyst. While the MP system is not currently commercially available, an estimated daily rental rate is provided for comparison to other technologies. The rental rate is based, in part, on the costs of items purchased in prototype quantities (single units) and would presumably decrease significantly if the items were procured at production quantity levels. The data analysis level of effort included in the dynamic mode model is based on projections of the production rate that will be achievable with UX-Analyze and not the actual production rate achieved in this first demonstration.

8.2 COST DRIVERS

Two factors are expected to be strong drivers of cost for this technology as demonstrated. First is the daily production rate (number of anomalies for cued mode, number of acres for dynamic mode). Higher productivity in data collection equates to more anomalies investigated for a given period of time in the field. The second factor is the time required for conducting data QC and analysis. This time can be significantly higher than for other, more traditional methods and could become a cost driver due to the time involvement. The data analysts must be trained to handle the more complex, and richer, data sets properly. The thoughtful use of available automation techniques with operator QC support can moderate this effect.

8.3 COST BENEFIT

The main benefit to using a UXO classification process is cost-related. The ability to reduce the number of non-hazardous items that have to be dug or have to be dug as presumptively-hazardous items directly reduces the cost of a remediation effort. The additional information for anomaly classification provided by these sensor systems provides additional information for the purposes of anomaly classification. If there is buy-in from the stakeholders to use these techniques, this information can be used to reduce costs. Successful implementation of dynamic mode surveying has the potential for further cost reduction by limiting the number of trips to a given area required.

Table 2. TEMTADS MP 2x2 cart dynamic mode tracked costs.

Cost Element	Data Tracked	Cost
Data Collection Costs		
Pre/Post Survey Activities	Component costs and integration costs • Spares and repairs	 $3500
	Cost to pack the array and equipment, mobilize to the site, and return • Personnel required to pack • Packing hours • Personnel to mobilize • Mobilization hours • Transportation costs	$12,450 1 16 3 8 $7250
	Cost to assemble the system, perform initial calibration tests • Personnel required • Hours required	$780 3 2
Survey Costs	Unit cost per acre investigated. This will be calculated as daily survey costs divided by the number of acres investigated per day. • Equipment Rental (day) • Daily calibration (hours) • Survey personnel required • Survey hours per day • Daily equipment break-down and storage (hours)	**$3375/acre** $190 0.5 2 8 0.5
Processing Costs		**$2340/acre**
Preprocessing	Time required to perform standard data clean up and to merge the location and geophysical data.	7.5 hr/acre
Target Picking	Time required to extract and QC anomaly pick locations from survey data	0.5 hr/acre
Parameter Estimation	Time required to extract parameters for all anomalies.	2 min/anomaly 300 anom (typ.)

9.0 IMPLEMENTATION ISSUES

The primary goal of this project was to demonstrate a UXO classification process that made use of dynamic mode data collection with advanced EMI sensors. The data collected with these systems can be used both for anomaly detection and for classification on a significant fraction of the detected anomalies, limiting the number of anomalies requiring cued mode investigation.

At a line spacing of 40 cm, one pair of receiver cubes for each survey line passes roughly over the same path as a pair of receiver cubes from the survey line on either side. In more recent demonstrations, this spacing has been increased to 60 cm, improving the production rate. For very small targets, such as 20mm projectiles, the original spacing is still recommended.

Another ongoing goal has been to transition these technologies from being research prototypes to use in the industrial community where appropriate. The mechanics of collecting classification-grade advanced EMI cued data with these systems have been shown to be fairly routine in the research community. As part of the ESTCP MR Live Site Demonstrations, industrial partners have been exposed to the MP system and the associated data collection and processing procedures. The success of this effort will be evaluated on an ongoing basis through the Live Site demonstrations. In the past, analysis of data from these systems has been somewhat of a specialty, requiring specific software and knowledge to proficiently conduct. The successful transition of the TEMTADS data QC/analysis process to the Geosoft Oasis montaj environment provides a clear pathway for resolving these issues. A final implementation issue is that a clear path to making the MP system commercially available has not been identified yet. Discussions with various groups along these lines are ongoing.

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