EXECUTIVE SUMMARY

Tensor Invariant Processing of Multistatic EMI Data for Target Classification

ESTCP Project MR-201310

JUNE 2018

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ACRONYMS AND ABBREVIATIONS

EMI	electromagnetic induction
ESTCP	Environmental Security Technology Certification Program
IDA	Institute for Defense Analyses
mm	millimeter
ROC	Receiver Operating Characteristic
SERDP	Strategic Environmental Research and Development Program
SNR	signal-to-noise ratio
SWPG	Southwestern Proving Ground
TEMTADS	Transient Electromagnetic Multisensor Towed Array Detection System
TOI	target of interest
UXO	unexploded ordnance

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1.0 INTRODUCTION

Department of Defense sites contaminated with unexploded ordnance (UXO) use 1990s and early-21st-century technology to conduct characterization and remediation activities. These technologies are costly and often yield unsatisfactory results due in part to the inability of the technologies to distinguish between UXO and non-hazardous items. Field experience has shown that when using the old technology, > 90% of objects excavated during remediation are non-hazardous clutter.

The Strategic Environmental Research and Development Program (SERDP) and Environmental Security Technology Certification Program (ESTCP) have developed and tested several purpose-built, multi-axis electromagnetic induction (EMI) sensor array systems for classifying buried objects at munitions response sites. SERDP and ESTCP have also invested in developing new processing procedures optimized for this new generation of EMI sensors. The demonstrations summarized here serve to evaluate the performance of some of these procedures.

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2.0 OBJECTIVE

The objective of the demonstrations is to demonstrate the detection classification performance of the procedures developed in SERDP projects MR-1658, MR-1711, and MR-2100 using data collected with the man-portable Transient Electromagnetic Multisensor Towed Array Detection System (TEMTADS) at several munitions response sites: the former Southwestern Proving Ground (SWPG) near Hope, Arkansas; the closed Castner Range at Fort Bliss, Texas; the former Camp Hale in Colorado, and the former Camp Beale in California.

Detection is based on applying the standard dipole inversion model as a filter over the entire survey site. Locations where the model fits the measured data well are target locations. Classification decisions are based on two parameters easily calculated from magnetic polarizabilities of unknown targets and targets of interest (TOIs). The parameters are measures of the mismatch between the strength and the shape of the respective polarizability curves.

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3.0 TECHNOLOGY DESCRIPTION

Principal axis polarizabilities are the basis for classification and are calculated from the EMI data collected over a target using a signal-to-noise ratio (SNR) weighted inversion algorithm. Figure 1 shows principal axis polarizabilities for two different objects: a 57-millimeter (mm) projectile (left) and a horseshoe (right) encountered at the Remington Woods site in Bridgeport, Connecticut. The objects are similar in size but have very different shapes. Taken together, the sets of three principal axis polarizabilities are quite different for the two objects.

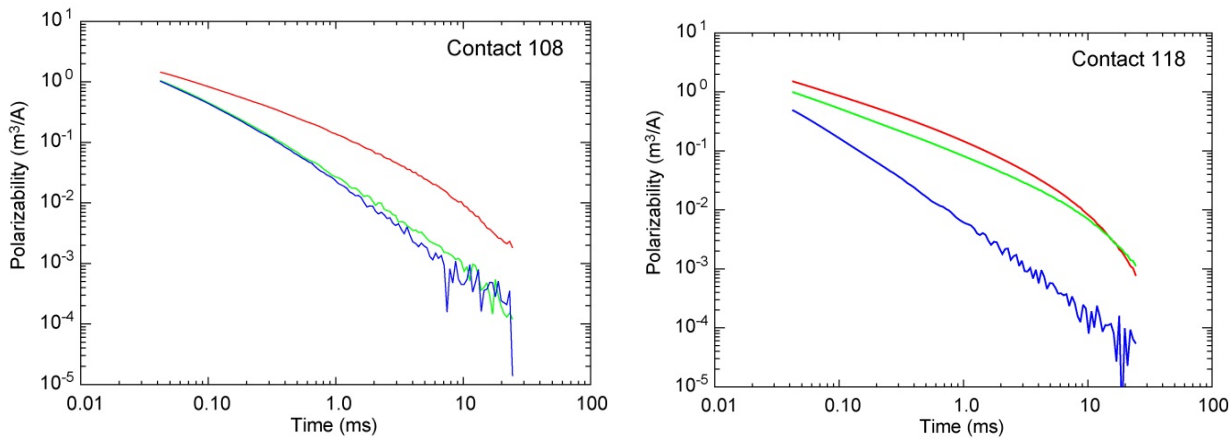

Figure 1. Principal Axis Polarizabilities for a 57mm Projectile (left) and a Horseshoe (right).

Classification exploits the object differences. Classification is a matter of deciding whether the object's polarizabilities are munitions-like or clutter-like. Library matching methods employing various procedures to compare polarizabilities of unknown targets with those of TOI items are commonly used for classification. The methods used by the demonstration exploit the fact that an object's polarizability tensor $\beta_{ij}(t) = V\alpha_{ij}(t)$ is a product of two factors: the volume (V) of the object and a tensor $\alpha_{ij}(t)$ whose eigenvalues $\alpha_i(t)$, i = 1, 2, 3 are determined by the shape and composition of the object. Confronted with an unknown target, its apparent size and EMI "shape" is compared with the sizes and shapes of the TOI.

Given the set (spanning three axes and N time gates) of principal axis polarizabilities β_0 for a TOI and the set of principal axis polarizabilities β for an unknown target, a size ratio s is calculated as

$$s = median\left(\frac{\sqrt[3]{\beta}}{\sqrt[3]{\beta_0}}\right)$$

where the median is taken over all axes, and time gates for the polarizabilities are above some threshold level that reflects the expected inversion noise. If a significant fraction (typically 25–50%) of the available polarizability terms are below this threshold, then the target is put in the "can't analyze" category. The size ratio is defined in terms of the cube root of polarizability because polarizability scales with target volume (linear dimensions cubed).

The size mismatch parameter Δ_{size} is defined as

$$\Delta_{size} = log(s)$$

which is equal to zero if the EMI sizes of the target and the reference TOI are the same. The shape mismatch parameter Δ_{shape} is determined by comparing the unknown target's polarizability with the reference polarizability scaled by the size ratio

$$\Delta_{shape} = \frac{\sum\left|\sqrt[3]{\beta} - s\sqrt[3]{\beta_0}\right|}{\sum\sqrt[3]{\beta}}$$

in which the sums are over all terms with β above the noise level. Optionally, the three principal axis polarizabilities can be assigned different weights W_i in calculating the shape mismatch. For each target, size and shape mismatch parameters are calculated for each TOI. By combining the size and shape mismatch parameters, a net TOI mismatch parameter can be defined as

$$TOI\ Mismatch = \min_{TOI}\left\{|\Delta_{size}| + k\ log(\Delta_{shape})\right\}.$$

Parameter value $k \approx 0.3$ gives the best classification performance. Low values of the TOI mismatch indicate a good match to both the size and the shape of the TOI. Minimizing the parameter over the set of TOI finds the best match to any TOI.

The TOI mismatch parameter typically runs between about -1 and 1, with TOI having the lowest values (best match of target polarizability strength and decay curve shapes to library polarizabilities) and clutter having the highest values (poor match to TOI polarizabilities). Figure 2 shows the distributions of the size and shape parameters (top plot) and the cumulative distribution of the net TOI mismatch (middle plot) for the man-portable TEMTADS array at the Camp Beale classification demonstration. Values for targets identified as TOI using the post-test ground truth are plotted in red and those for clutter items in blue.

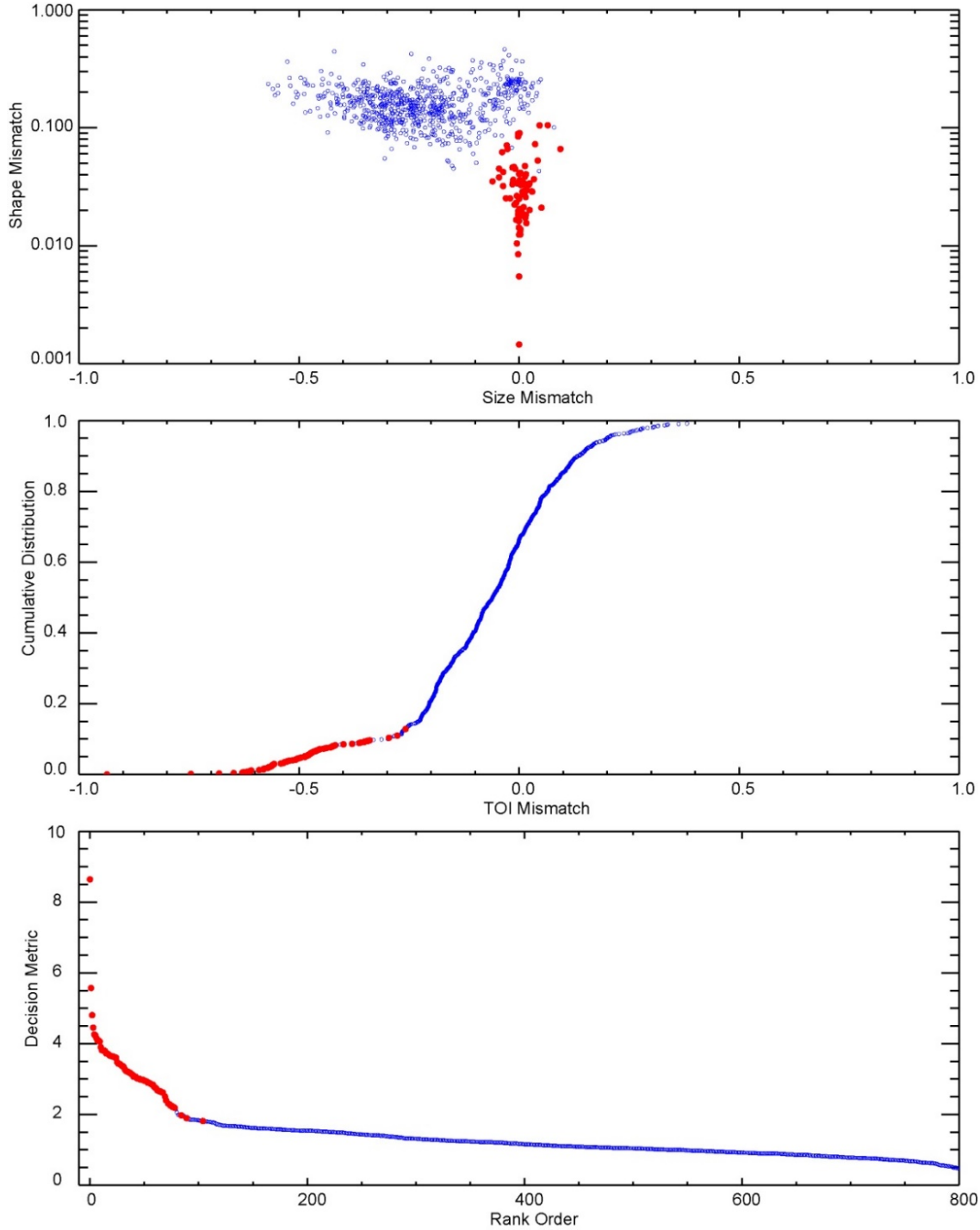

Figure 2. Classification Parameter Distributions for Camp Beale Man-portable TEMTADS Array Demonstration.

Top: scatter plot of size and shape mismatch parameters. Middle: cumulative distribution of net TOI mismatch. Bottom: decision metric values rank ordered from most like TOI to least like TOI. Values for TOI items plotted in red, clutter items in blue.

Classification is based on thresholding a decision metric related to the TOI mismatch. For the sake of consistency with conventions used by other demonstrators (i.e., that TOI have large values of the decision metric and clutter items have small values), the decision metric is defined as 1 over the antilog of the TOI mismatch, which works out to be

$$Decision\ Metric = \max_{TOI}\left\{\min\left(s, \frac{1}{s}\right)\left(\Delta_{shape}\right)^{-k}\right\}.$$

The first term in the curly brackets (s or s^{1}, whichever is smaller) equals 1 when the EMI size of the target matches the TOI. Otherwise, the value of the decision metric is reduced by the extent that the target size differs from the TOI size. The second term is larger when the polarizability shapes match well and smaller when they do not. The bottom plot in the figure shows the decision metric values rank ordered from most like TOI to least like TOI. Again, TOI values are shown in red and clutter values in blue. There is a distinct bend or slope break in the distribution going from TOI to clutter, followed by a gradual decline through the clutter items. Similar patterns are shown in the decision metric distributions obtained by re-processing data from other ESTCP Classification Pilot Program Live Site Demonstrations, leading to the conclusion that with good quality control, the stop-dig threshold may be set at the end of the slope break. As a practical matter, the threshold has to be set low enough to capture those TOI that for some reason do not match the library specimens as well as most, and so setting the stop-dig point tends to be more of an art than a science.

4.0 PERFORMANCE ASSESSMENT

Overall performance in the ESTCP classification demonstrations is summarized by the Receiver Operating Characteristic (ROC) curve. This is a plot of the number of TOI items recovered as a function of the number of clutter digs performed. Results for the SWPG demonstration were excellent. The ROC curve for the SWPG demonstration produced as part of the Institute for Defense Analyses (IDA) scoring report is shown below (Figure 3). The dashed portion corresponds to the anomalies selected for training data and the blue dot is the stop-dig point. At the stop-dig threshold, all TOI were correctly identified, and 18 clutter items had been marked for digging, leaving 474 clutter items (96.3%). The performance for the Fort Bliss and Camp Hale demonstrations was significantly poorer due to inadequate training data. Had the TOI library included examples of the difficult targets, the performance would have approached that demonstrated with the SWPG data.

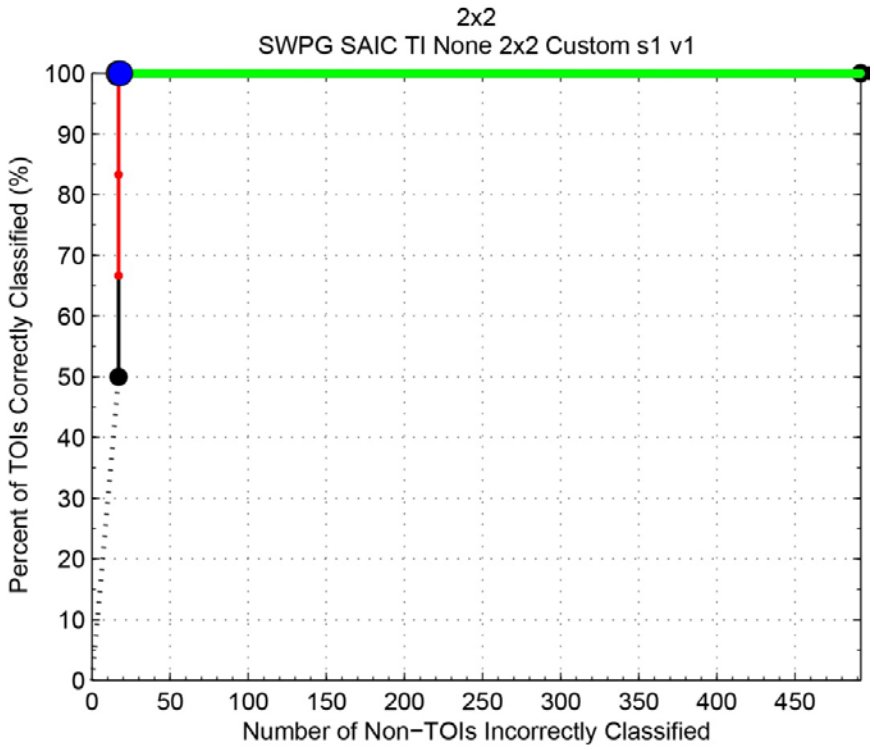

Figure 3. ROC for the SWPG Demonstration.

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5.0 COST ASSESSMENT

These were demonstrations of data processing techniques and cost assessments are not included in the Final Report.

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6.0 IMPLEMENTATION ISSUES

The basic implementation issues noted for the demonstration were the lack of adequate training data and an incomplete TOI library. Performance at Fort Bliss would have been significantly improved had the target library included an example of one of the legacy 37mm rounds found at the site. In addition, some munitions items (e.g., the 40mm illumination round found at Camp Hale) have polarizabilities, which are very similar to those of munitions debris such as fins and fuzes. If such items are present, then the goal of significant reduction in clutter digs while identifying all TOI can be compromised.