FINAL REPORT

Tensor Invariant Processing of Multistatic EMI Data for Target Classification

Classification Demonstrations:
Former Southwestern Proving Ground - Fort Bliss Camp Hale

ESTCP Project MR-201310

JUNE 2018

Thomas Bell
Leidos

ESTCP

Page Intentionally Left Blank

Page Intentionally Left Blank

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
29-06-2018	ESTCP Final Report	11-06-2013 – 11-06-2018

4. TITLE AND SUBTITLE

Tensor Invariant Processing of Multistatic EMI Data for Target Classification
Classification Demonstrations Southwestern Proving Ground, Fort Bliss and Camp Hale

5a. CONTRACT NUMBER
W912HQ-13-C-0040

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

Thomas Bell

5d. PROJECT NUMBER
MR-201310

5e. TASK NUMBER

5f. WORK UNIT NUMBER

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

Leidos
4001 N. Fairfax Dr.
Arlington, VA 22203

8. PERFORMING ORGANIZATION REPORT NUMBER

MR-201310

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Environmental Security Technology Certification Program
4800 Mark Center Dr
Suite 17D03
Alexandria, VA 22350

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

11. SPONSOR/MONITOR'S REPORT NUMBER(S) MR-201310

12. DISTRIBUTION / AVAILABILITY STATEMENT

Distribution A: Approved for public release; distribution is unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT
This project was to test and evaluate procedures for target detection and classification in the context of the Environmental Security Technology Certification Program (ESTCP) Classification Pilot Program Live Site Demonstrations. The procedures were developed in Strategic Environmental Research and Development (SERDP) projects MR-1658, MR-1711 and MR-2100. Demonstrations were performed using data from ESTCP demonstration projects at the Southwestern Proving Ground, the former Fort Bliss and the former Camp Hale.

15. SUBJECT TERMS
UXO, Munitions Response, Electromagnetic Induction, Detection, Classification

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
					Thomas Bell
a. REPORT	b. ABSTRACT	c. THIS PAGE			19b. TELEPHONE NUMBER *(include area code)*
U	U	U	U	47	(301) 712-7021

Page Intentionally Left Blank

FINAL REPORT

Project: MR-201310

TABLE OF CONTENTS

Page

TABLE OF CONTENTS (Continued)

Page

LIST OF FIGURES

Page

LIST OF TABLES

ACRONYMS AND ABBREVIATIONS

EFV	East Fork Valley
EMI	Electromagnetic Induction
ESTCP	Environmental Security Technology Certification Program
FOM	Figure of Merit
GPS	Global Positioning System
IDA	Institute for Defense Analyses
IMU	Inertial Measurement Unit
ISO	Industry Standard Object (seeded pipe section)
IVS	Instrument Verification Strip
MTADS	Multisensor Towed Array Detection System
MR	Munitions Response
mm	Millimeter
RF	Recovery Field
ROC	Receiver Operating Characteristic
Rx	Receive
SERDP	Strategic Environmental Research and Development Program
SNR	Signal to Noise Ratio
SWPG	Southwestern Proving Ground
TEM	Transient Electromagnetic
TEMTADS	Transient Electromagnetic MTADS
TOI	Targets of Interest
Tx	Transmit
UXO	Unexploded Ordnance

ABSTRACT

INTRODUCTION AND OBJECTIVES

The objective of this project was to test and evaluate procedures for target detection and classification in the context of the Environmental Security Technology Certification Program (ESTCP) Classification Pilot Program Live Site Demonstrations. The procedures were developed in Strategic Environmental Research and Development (SERDP) projects MR-1658, MR-1711 and MR-2100. Demonstrations were performed using data from ESTCP demonstration projects at the Southwestern Proving Ground, the former Fort Bliss, the former Camp Hale, and the former Camp Beale.

TECHNOLOGY DESCRIPTION

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. The parameters are measures of the mismatch between the strength and the shape of the respective polarizability curves.

PERFORMANCE ASSESSMENT

Results for the Southwestern Proving Ground demonstration were excellent. 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 Southwestern Proving Ground data.

IMPLEMENTATION ISSUES

The basic problem is adequate training data and a complete TOI library. Performance at Fort Bliss would have been significantly improved had our target library included an example of one of the legacy 37mm rounds found at the site. This is not the only issue, however. 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.

PUBLICATIONS

Bruce Barrow, “Noise Characteristics and Detection with an Advanced Electromagnetic Induction Sensor Platform for Unexploded Ordnance Surveying,” 26th Symposium on the Application of Geophysics to Engineering and Environmental Problems, Denver, 2013.

EXECUTIVE SUMMARY

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.

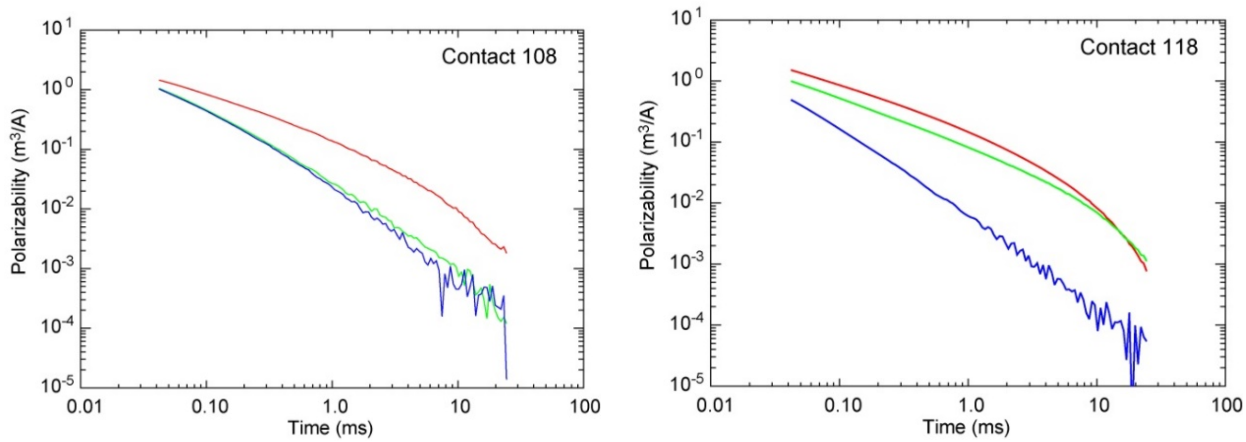
OBJECTIVES

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.

TCEHNOLOGY 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. The figure below 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.



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

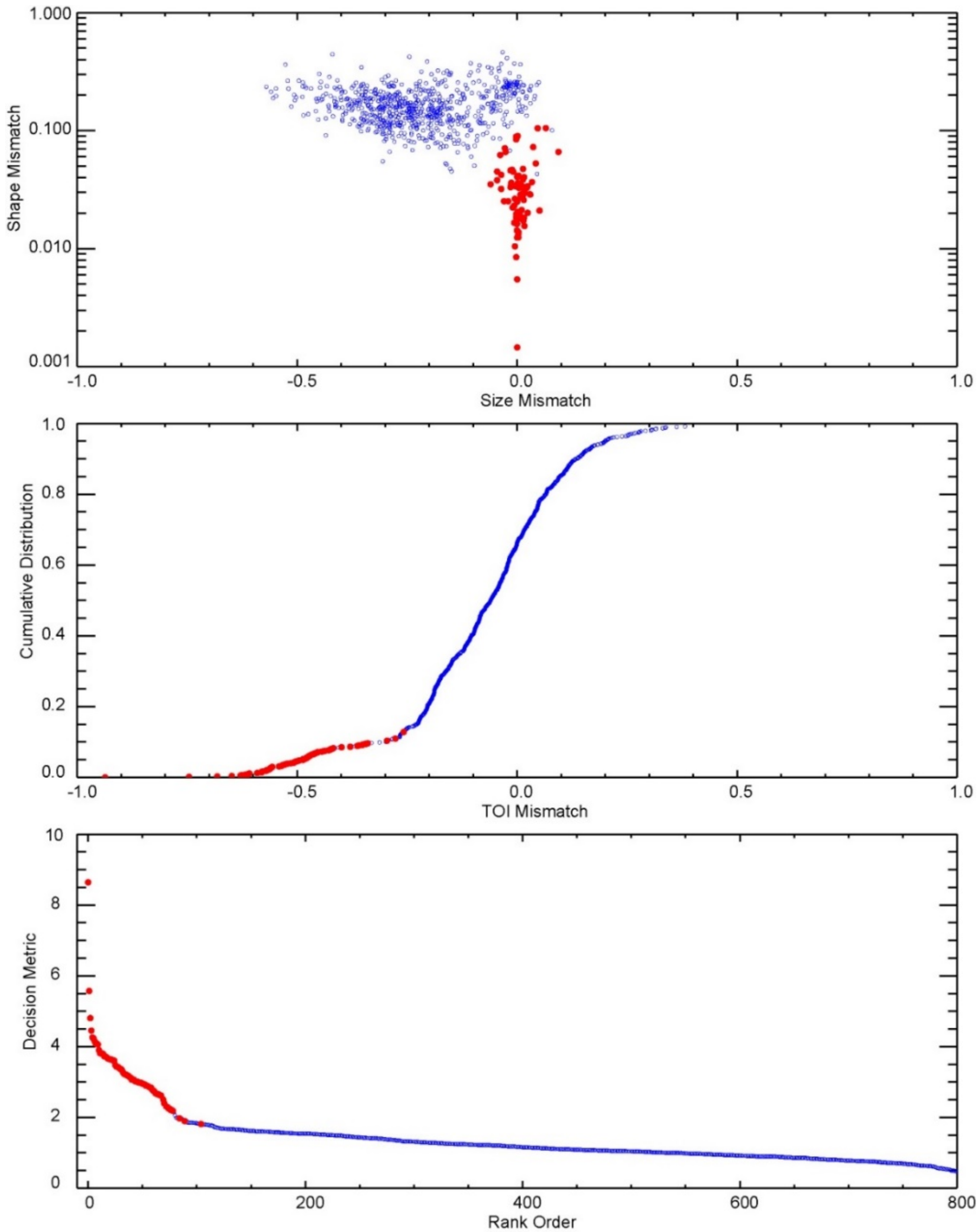
$$\Delta_{shape} = \frac{\sum\left|\sqrt[3]{\beta} - s\sqrt[3]{\beta_0}\right|}{\sum\sqrt[3]{\beta}}$$

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). The figure below 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.



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.

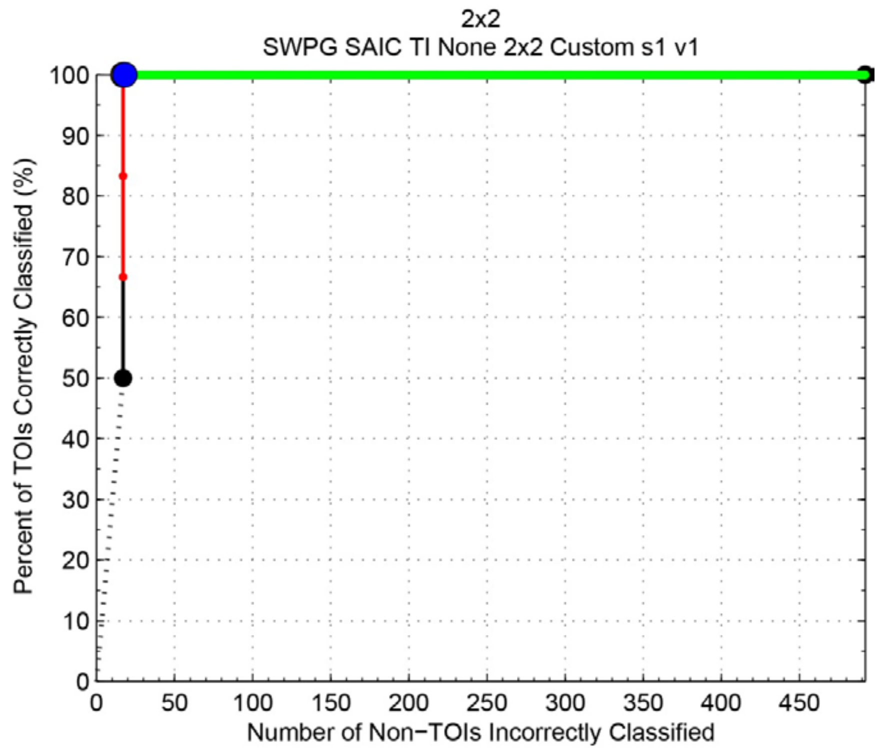
Classification is based on thresholding a decision metric related to the TOI mismatch. For the sake of consistency with conventions used by other demonstrators (i.e., that TOI have large values of the decision metric and clutter items have small values), the decision metric is defined as 1 over the antilog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

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. 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.



ROC for the SWPG Demonstration.

COST ASSESSMENT

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

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.

1.0 INTRODUCTION

The objective of this project is to test and evaluate procedures for target detection and classification in the context of the Environmental Security Technology Certification Program (ESTCP) Classification Pilot Program Live Site Demonstrations. The procedures were developed in Strategic Environmental Research and Development (SERDP) projects MR-1658, MR-1711 and MR-2100 [1, 2, 3]. 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. The parameters are measures of the mismatch between the strength and the shape of the respective polarizability curves.

1.1 BACKGROUND

The characterization and remediation activities conducted at Department of Defense sites contaminated with unexploded ordnance (UXO) using 1990's and early 21st century technology often yield unsatisfactory results and are too expensive. In part, this is due to the inability of that technology to distinguish between UXO and non-hazardous items. Field experience has shown that when using the old technology over 90% of objects excavated during the course of remediation can be non-hazardous clutter.

SERDP and ESTCP have developed and tested several purpose-built multi-axis electromagnetic induction (EMI) sensor array systems for classifying buried objects at munitions response sites. They 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 procedures developed in SERDP projects MR-1658, MR-1711 and MR-2100.

1.2 OBJECTIVE OF THE DEMONSTRATION

The objective of the demonstrations is to demonstrate the detection classification performance of the procedures developed in SERDP projects MR-1711, MR-1658, and MR-2100 using data collected with the man-portable transient EMI (TEM) array (nicknamed "TEMTADS" [4]) at several munitions response sites: the former Southwestern Proving Ground (SWPG) near Hope, Arkansas, the Closed Castner Range at Fort Bliss, TX, and the former Camp Hale, CO. The data collection followed the approach outlined in demonstration plans from Weston Solutions, Inc. [5] and URS Group, Inc. (URS) [6, 7].

1.3 REGULATORY DRIVERS

The ESTCP has assembled an Advisory Group to address the regulatory, programmatic and stakeholder acceptance issues associated with the implementation of classification in the Munitions Response (MR) process. Details can be found in their guide to implementing advanced classification on munitions response sites [8].

Page Intentionally Left Blank

2.0 TECHNOLOGY

The data collection technology and approach are discussed in the Demonstration Plans [5, 6, 7]. The man-portable TEMTADS array was used to collect survey mode data which was then used to identify metallic anomalies within the study area. The survey data were analyzed to produce a list of anomalies considered to have the potential to be targets of interest (TOI). TOI include intact munitions items and pipe sections which simulate the EMI signatures of munitions items and which are implanted at the site for quality control and assurance purposes. The array was then parked the array over each of these anomalies in turn and collected "cued" data to be used for target classification. In the SWPG and Fort Bliss demonstrations we processed the cued data to determine the likelihood that the anomaly is actually due to a TOI. In the Camp Hale demonstration we implemented a physics-based detection algorithm with the survey data to identify and classify potential targets of interest.

The processing and analysis procedures were developed in SERDP projects MR-1658, MR-1711 and MR-2100 for use with the advanced EMI arrays developed by SERDP and ESTCP for target detection and classification. Classification typically involves comparing principal axis polarizabilities calculated from EMI data collected over an unknown target with those of known TOI [8]. The classification algorithm used here exploits the fact that an object's polarizability is a product of two factors: the volume of the object and a tensor whose eigenvalues depend only on the shape and composition of the object. Confronted with an unknown target, we compare its apparent size and EMI "shape" with the sizes and shapes of TOI. Classification is based on thresholding a figure of merit (FOM) parameter that is a weighted sum of parameters quantifying the mismatches in the EMI size and shape of the target relative to the TOI. For multiple TOI, the FOM is minimized over the set of TOI. This basic algorithm is also used in cluster analysis to identify unexpected munitions. In this case each target is compared against all others to find groups which have similar EMI size and shape.

In the conventional approach, cued locations are selected by looking at signal amplitude peaks above some reasonable threshold. This simple detection approach has two disadvantages. First, it only looks at the monostatic sensor channels (T_z-R_z) which typically, but not always, peak at the target's location. Second, the amplitude threshold is usually selected to find a certain TOI down to a maximum depth; this amplitude threshold will also include many small bits of clutter located on the surface. For the Camp Hale demonstration, instead of using signal amplitude we applied the dipole model-based detection filter developed under SERDP project MR-1711. This detection filter uses all transmit/receive channels from an advanced EMI sensor. The filter output peaks at the target's location based on the data's fit to the dipole model. The filter can be set to respond weakly to shallow clutter.

2.1 TECHNOLOGY DESCRIPTION

2.1.1 TEMTADS EMI Sensors

The man-portable TEMTADS array used in the SWPG demonstration consists of four single-axis transmit (Tx) coils and four three-axis receive (Rx) cubes arranged in a 2x2 array of Tx/Rx pairs. The picture on the left in Figure 1 shows one of the large (35 cm square by 8 cm high) Tx coils and one of the 8 cm Rx cubes which fits inside the foam core of the Tx coil.

The middle picture shows three of the Tx/Rx pairs set into the plastic array enclosure. The centers of the Tx/Rx pairs are spaced 40 cm apart. The picture on the right shows the assembled array with its Global Positioning System (GPS) antenna. The array is mounted on a cart with the coils 20 cm above the ground. For the Fort Bliss demonstration the array was mounted on skids which provide 15 cm vertical offset when resting on the ground for cued data collection, and it is suspended from poles for carrying from anomaly-to-anomaly.

Figure 1. Man-Portable TEMTADS Array Used in the SWPG Demonstration.

Currents through the Tx coils illuminate a target in the ground under the array with an alternating bipolar magnetic field (primary field), which excites eddy currents in the target. Figure 2 shows the Tx current waveform for a block time of 0.9 s with nine repeats of the basic bipolar cycle within the block. This was the pattern used for the cued data at SWPG. The Rx coils measure the decay of the secondary magnetic field from the eddy currents during the intervals between the alternating pulses of positive and negative Tx current. The measured responses are averaged over the block after inverting those from the negative current pulses. A sequence of 18 of these blocks was collected over each target and the net responses from the 18 blocks were stacked (averaged) to produce the recorded EMI response for each of the 48 possible Tx/Rx combinations (four transmitters and each of the three axes of the four receivers).

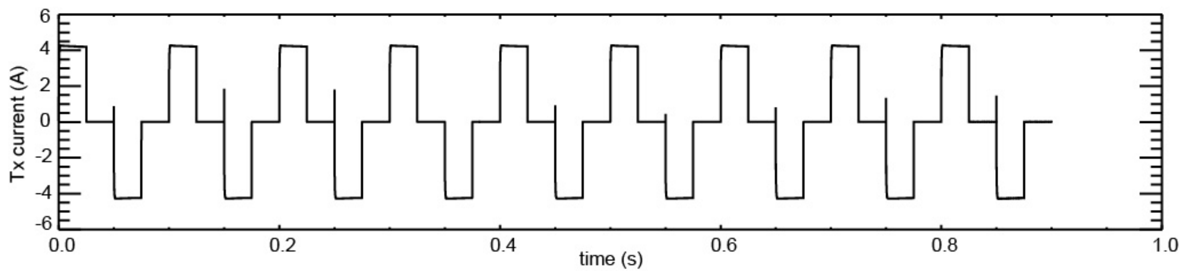


Figure 2. TEMTADS Transmitter Current Waveform.

Secondary field data are recorded for 121 time gates spaced logarithmically out to 25 ms after the primary field cutoff (25 ms is just the time interval between the end of one current pulse and the beginning of the next). Figure 3 is an example of the TEMTADS data collected over a target. Background response has been removed from the signals as described in section 2.1.2 below. Each panel corresponds to a different Tx/Rx pair, and different colors are used to show the responses for the different Rx cube axes. The ordinate (vertical axis) scale is the background-subtracted signal in mV normalized by the peak Tx current and the abscissa (horizontal axis) scale is time gate.

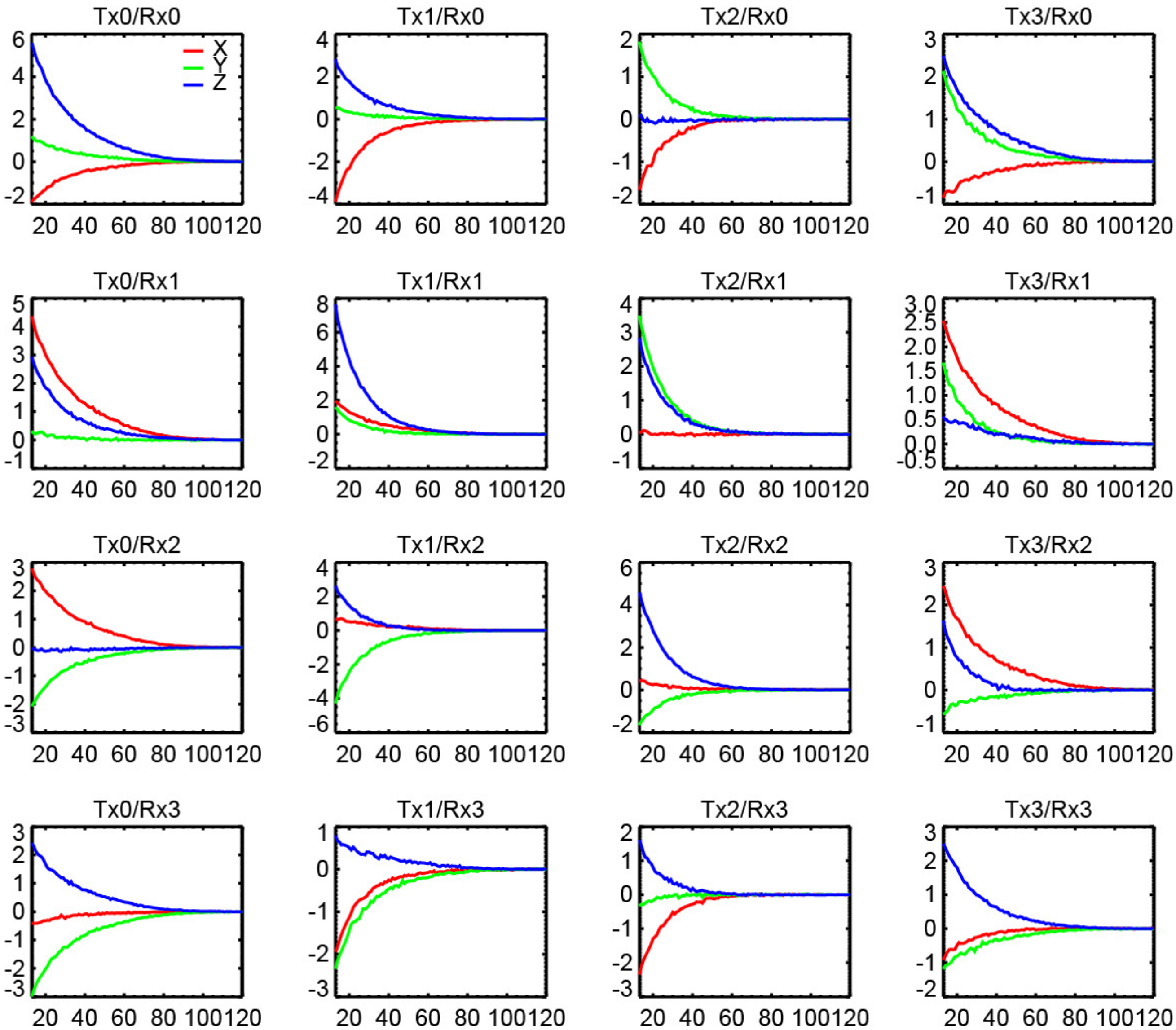


Figure 3. Sample TEMTADS Cued Data Set. Ordinate is Signal in mV Normalized by Tx Current, Abscissa is Time Gate.

The Camp Hale demonstration used dynamic survey mode data. Each coil fires three bipolar pulses over a period of 1/30th of a second. The on/off duration of these pulses is 2.77 milli-seconds. The Rx coils measure the decay of the secondary magnetic field from the eddy currents during the off intervals between the alternating pulses of positive and negative Tx current. The measured responses are averaged over the duration after inverting those from the negative current pulses. The total time to fire all four transmits is 0.133 seconds. Given a platform speed of 0.8 m/s, the sensor moves roughly 0.1 m over this cycle and 0.025 m between each Tx. Figure 4 shows the four Tx current waveforms over a complete block of data.

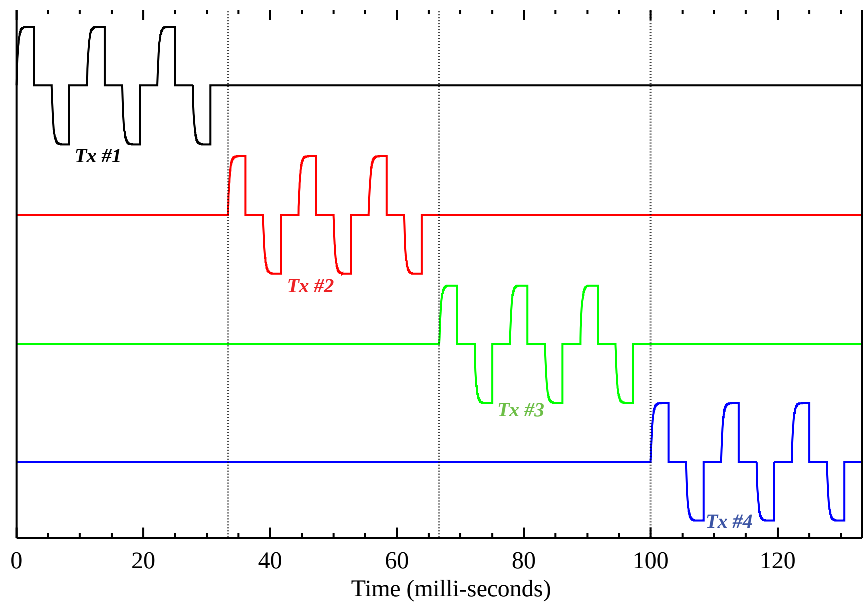


Figure 4. Dynamic TEMTADS Transmitter Current Waveforms Over One Complete Cycle.

Secondary field data are recorded for 19 time gates spaced logarithmically out to 2.77 milli-second after the primary field cutoff. Figure 5 is an example of the TEMTADS data collected as the platform moves over a target. Background response has been removed from the signals as described. Each panel corresponds to a different receive coil component, and different colors indicate which transmit coil is firing. The ordinate (vertical axis) scale is the background-subtracted signal in mV normalized by the peak Tx current and the abscissa (horizontal axis) scale is distance traveled. The data are for a single time gate at 0.137 milli-second after the transmit turn-off.

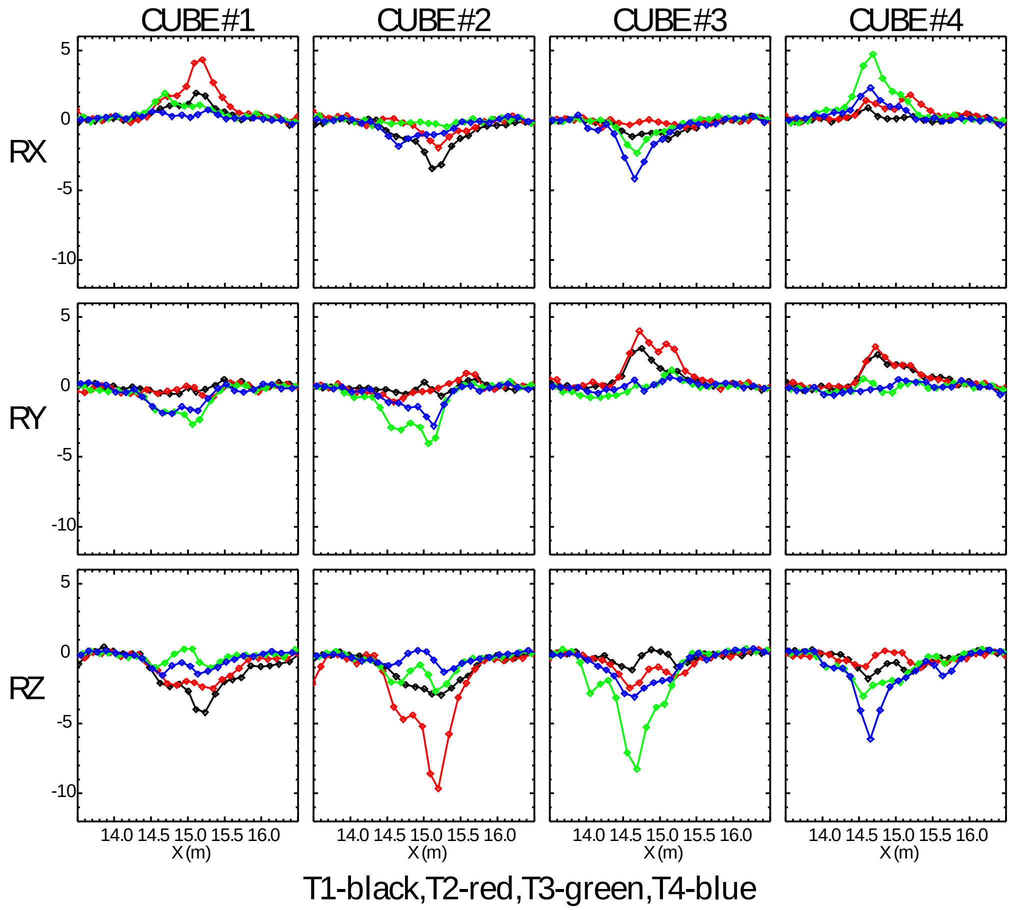


Figure 5. Sample TEMTADS Dynamic Data Set.

Ordinate is signal in mV normalized by Tx current, abscissa is distance traveled in meters. The plot colors indicate which transmit coil is firing.

2.1.2 Processing

As recorded the data include a substantial background response caused primarily by electronic ring-down following the primary field shutoff at the end of each current pulse. This is removed from the data by subtracting background shots taken over nearby, nominally target-free ground. With cued data we skip the first 12 gates because the very early time ring-down effects overwhelm the target response. For the dynamic survey data we skip the first 5.

In dynamic survey mode, along with the EMI sensor data, one GPS record and one inertial measurement unit (IMU) record is collected for each complete transmit cycle. Each sensor has a different data rate, but the current TEMTADS system does not synchronize or adequately time stamp the positioning and EMI data. Current processing assumes the GPS positioning and IMU orientation occurs at the center of the transmit cycle. This results in position timing errors of up to one half of the transmit cycle, 0.133 seconds, or at a platform speed of 1.0 m/s, position errors up to 0.07 m. The orientation information from the IMU is used to map the GPS antenna position to the center of the EMI coils. A platform position and orientation is interpolated for each of the individual transmit coil firing times.

Bad sensor and poor positioning records are edited out. The EMI data are normalized by the peak transmit currents. Background levels are removed from the EMI data. For most of the data this is done by calculating a median level for the data file and subtracting it off. For data over dense target regions, a background region is manually selected and subtracted. Data collected over extremely dense target regions cannot be adequately zeroed.

All of the data files are merged for the entire site and the detection filter is run on this complete data set. Details of the filter can be found in [2]. The filter output is on a regular grid across the site and ranges between 0 and 1 with larger values indicating target locations. Filter peaks are selected as possible target locations. Grid locations with little or no data present are flagged with a null value. These null regions can be flagged as missed. At each filter peak, a window of data is selected and an N-dipole inversion is run with N = 1, 2, 3 and 4. Each inversion results in target locations and polarizations. Repeated locations and bad polarization results are edited out. In moderately dense target regions, higher order N-dipole fits can be run. Extremely dense regions are processed to find TOI, but are flagged as areas where targets are probably being missed. This flagging is done manually based on large continuous areas where the measured signal amplitude and the detection filter output are significantly above the background (6 times RMS noise).

Principal axis polarizabilities are calculated using a signal to noise ratio (SNR) weighted [9] inversion algorithm. The principal axis polarizabilities are the basis for classification. Figure 6 shows principal axis polarizabilities for two quite different objects: a 57 mm projectile (left) and a horseshoe (right) encountered at the Remington Woods site in Bridgeport, CT. The objects are similar in size but have quite different shapes. Taken together the sets of three principal axis polarizabilities are quite different for the two objects.

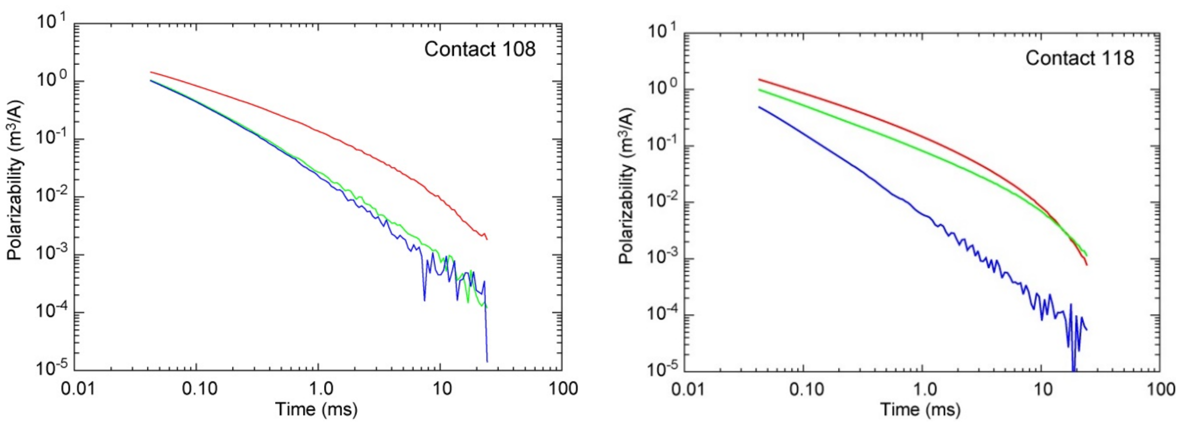


Figure 6. Principal Axis Polarizabilities for a 57 mm Projectile (left) and a Horseshoe (right).

Classification exploits these 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. Ours exploits 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, we compare its apparent size and EMI "shape" 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, we calculate a size ratio s 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 which the polarizabilities are above some threshold level which 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. We define the size ratio 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 we can define a net TOI mismatch parameter as

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

We have found that using a 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 7 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 [3]. Values for targets identified as TOI using the post-test ground truth are plotted in red and those for 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) we define the decision metric as one 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 one 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 Figure 7 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 as we go from TOI to clutter, followed by a gradual decline as we chew through the clutter items. We see similar patterns in the decision metric distributions obtained by re-processing data from other of the ESTCP Classification Pilot Program Live Site Demonstrations, leading us to conclude 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 which for some reason do not match the library specimens as well as most, and so setting the stop-dig point tends to be a bit of an art.

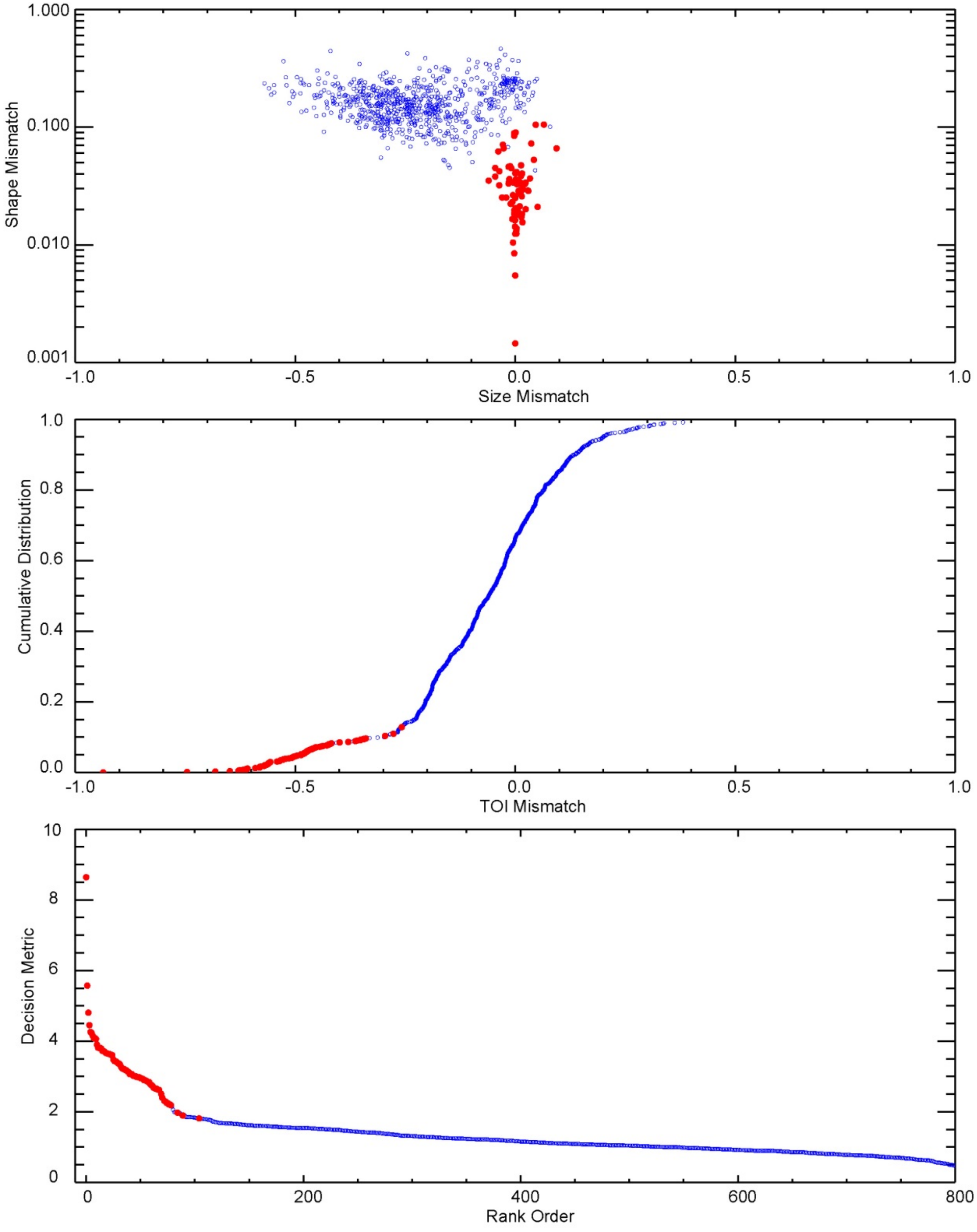


Figure 7. Classification Parameter Distributions for Camp Beale Man-portable TEMTADS Array Demonstration.

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.

2.2 TECHNOLOGY DEVELOPMENT

The development work for this project was done under SERDP projects MR-1658, MR-1711 and MR-2100 and is documented in references [1, 2, 3].

2.3 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

The advantages of this technology are both quantitative and qualitative.

The detection filter improves upon the present signal amplitude approach [2]. It peaks at the target location. It can be set to reduce the response to surface clutter. A filter threshold can be set for a given TOI at desired depth based on the TOI's polarization and the actual measured survey noise.

For the classification approach, re-processing data from the recent Camp Beale demonstration produced a Receiver Operating Characteristic (ROC) which rises more rapidly and hits the 100% TOI recovered level with 50% fewer clutter digs beyond the training set than the ROC from conventional processing. Improved classification performance improves munitions response efficiency. The procedure operates in an intuitive and easily visualized feature space. It is transparent, objective and easily automated. All of this is likely to facilitate transition to production work and ease regulatory acceptance.

We did not encounter any problems in taking the technology from the research phase to the scale of the demonstration. This is a processing demonstration and we had re-processed and classified cued data from the recent Pole Mountain and Camp Beale demonstrations without incident. Prior to the demonstration the detection filter had been tested on dynamic data from the Southwest Proving Ground and Castner Range demonstrations.

3.0 PERFORMANCE OBJECTIVES

The performance objectives for this demonstration are summarized in **Table 1**. The first objective is a detection goal, to locate all TOI to within 0.4 m, and applies to the Camp Hale demonstration only. The rest apply to all three. The classification goals are to correctly identify all TOI as TOI and as many as possible clutter items as clutter. The fourth objective addresses how well we are able to specify the correct stop-dig threshold (i.e. which meets the classification objectives) in advance. The final two objectives refer to target feature extraction.

Table 1. Performance Objectives

Objective	Metric	Data Required	Success Criteria
Maximize correct location of TOI	Distance of target locations from measured ground truth	• Ranked anomaly list • Ground truth	All target locations within 0.40 m of the ground truth
Maximize correct classification of TOI	Number of TOI retained	• Ranked anomaly list • IDA scoring report or ground truth	Correctly classify all TOI
Maximize correct classification of clutter	Number of clutter digs eliminated	• Ranked anomaly list • IDA scoring report or ground truth	Reduction of clutter digs by >85% while retaining all TOI
Specification of stop-dig threshold	Probability of correct TOI classification and number of clutter digs at threshold	• Stop-dig threshold • IDA scoring report or ground truth	Stop-dig threshold to achieve classification objectives
Minimize number of anomalies that cannot be analyzed	Number of anomalies classified as "Can't Analyze"	Target parameters extracted from data collected over target	Reliable target parameters estimated for >95% of anomalies
Correct estimation of target parameters	Accuracy of estimated target parameters for seed items	Target parameters extracted from data collected over seeds	• Size mismatch within ±0.10 • Shape mismatch <0.2

Page Intentionally Left Blank

4.0 SITE DESCRIPTION

The SWPG demonstration site is located within Recovery Field (RF) 15 of the former Southwestern Proving Ground in the southwestern corner of Arkansas. RF 15 is in open farmland and is relatively even grade across the site. Known and suspected munitions types in RF 15 include 20mm, 37mm, 40mm, 57mm, 75mm, 76mm, 90mm, 105mm and 155mm projectiles and 81mm mortars.

The Fort Bliss demonstration site is a 5-acre parcel of the Closed Castner Range Munitions Response Site (MRS) in Fort Bliss, TX. Fort Bliss is located in three counties, Dona Ana and Otero counties in New Mexico and El Paso County in Texas. The installation encompasses approximately 1.1 million acres. The Closed Castner Range MRS on Fort Bliss is located within El Paso, Texas, between U.S. Highway 54 and the Franklin Mountains State Park and is approximately 15 miles south of the border with New Mexico. The MRS is now 7,007 acres, after acreage east of U.S. Highway 54 was transferred to non-DoD entities. The site contains medium and large caliber projectiles (including high explosives [HE], fragmentation, target practice), mortars, pyrotechnics, illumination flares, grenades, and small arms.

The East Fork Valley (EFV) Range Complex within the Former Camp Hale, Colorado and is located on 382 acres in the White River National Forest approximately 10 miles south of Red Cliff and 18 miles north of Leadville off U.S. Highway 24. Eagle Valley was the primary area of Camp Hale first used by the Army for weapons training and later used by the Central Intelligence Agency. Munitions used at Camp Hale include small arms, demolition and bulk explosives, grenades, landmines, rockets, mortars and projectiles ranging in caliber from 37mm to 155mm.

Page Intentionally Left Blank

5.0 TEST DESIGN

5.1 BASIC EXPERIMENTAL DESIGN

The basic experimental designs are described in the Demonstration Plans [5 ,6, 7]. Our demonstration entails analysis of data. For the SWPG demonstration data were collected over nominally 500 anomalies in a roughly 0.16 Ha (0.4 acre) area of RF-15. These data were collected by NAEVA Geophysics personnel. For the Fort Bliss demonstration the cued mode data collection was to consist of surveying static data over no greater than 1,500 anomalies identified by URS from the TEMTADS survey data. In the Camp Hale demonstration URS used the man-portable TEMTADS array to collect survey mode data which was used to identify metallic anomalies within the study area. The survey data were analyzed to produce a list of anomalies considered to have the potential to be targets of TOI. They then parked the array over each of these anomalies in turn and collected "cued" data to be used for target classification. We processed the dynamic survey data to both determine the location of possible metallic anomalies and then calculate the likelihood that the anomaly is actually due to a TOI.

The ESTCP Program Office coordinated data collection activities and provided us with survey and/or cued data over selected anomalies. We processed the data to extract target parameters which were then be passed to our classification routines. After training on data from previous demonstrations, data from the instrument verification strip (IVS) and test pit, and a limited amount of site-specific ground truth, the classification routines were used to produce ranked anomaly lists. We requested ground truth data on 20 targets for training to identify possible unforeseen munitions types. None were found. At the conclusion of this training, we submitted a ranked anomaly list. According to ESTCP instructions, the list is structured such that all anomalies for which training labels were requested are placed at the top of the list. Then, the anomalies for which we were not able to extract meaningful parameters would be listed (we had none). Following these "can't extract reliable parameters" anomalies, the list is ordered from the item we are most confident is TOI through the item we are most confident is not TOI. The dig list was scored by IDA with emphasis on the number of items that are correctly labeled non-hazardous while correctly labeling all TOI. The primary objective of the demonstration is to assess how well we are able to order our ranked anomaly list and specify the threshold separating high confidence clutter from all other items.

5.2 VALIDATION

At the conclusion of data collection activities at SWPG and Fort Bliss, 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.

The Camp Hale demonstration plan specified that at the conclusion of data collection activities, all anomalies on the master anomaly list assembled by the Program Office would be excavated.

Validation was to be based on retrospective analysis using scoring results from the Institute for Defense Analysis (IDA). As it turned out, IDA scoring reports were not available so our results are based on a self-assessment using the available ground truth. Only a small set of the detected anomalies within the survey area were investigated intrusively: there were several thousand potential target locations but only 372 locations were excavated, yielding 632 items.

6.0 DATA ANALYSIS AND PRODUCTS

For target detection the basic data analysis flow is:

1. Bad data (GPS or IMU problems) are dropped and remaining good survey data mapped.

2. The detection filter is run over the mapped data and filter peaks above threshold of 0.2 picked. The threshold of 0.2 corresponds roughly to a 37mm projectile at a depth of 0.30m.

3. At each detection filter peak N=1, 2 and 3 dipole fits are run on fixed windows of data.

4. The analyst picks spots to adjust the window and re-run fits with N=1, 2, 3, 4, 5, 6 dipoles. The adjustments accommodate bigger signal footprints, multiple overlapping footprints and indications of signal from a side object (e.g. corresponding to a large deep item dominated by small shallow one).

5. For each N-dipole fit spot, analyst identifies the most consistent fits.
   a. Consistent with Tz-Rz and detection filter footprint
   b. Consistent progression for N=1 to N=2, to N=3 …
   c. Physically sound polarization, non-negative, reasonable shape.

For classification, target parameters (polarizabilities) were extracted using SNR weighted dipole inversion augmented by other relevant processing techniques developed in SERDP projects MR-1658 and MR-2100. Scale/shape factors were calculated using the procedures described in 2.1.2 and targets were classified by choosing the closest match to a library of possible TOI.

Page Intentionally Left Blank

7.0 PERFORMANCE ASSESSMENT

7.1 PERFORMANCE OBJECTIVES

There were six performance objectives (see **Table 1**). The first objective is a detection goal, to locate all TOI to within 0.4 m, and applies to the Camp Hale demonstration only. The rest apply to all three. The classification goals are to correctly identify all TOI as TOI and as many as possible clutter items as clutter. The fourth objective addresses how well we are able to specify the correct stop-dig threshold (i.e. which meets the classification objectives) in advance. The final two objectives refer to target feature extraction. The results are summarized in Table 2. The right-hand column indicates whether or not the performance objective was met for each of the demonstrations: 1. Southwestern Proving Ground, 2. Fort Bliss, 3. Camp Hale. Details are in sections 7.1.1 - 7.1.6.

7.1.1 Detection and Location of TOI

This objective applies to Camp Hale only. The detection goal is to set a “flag” within 0.40 m of all items in the field. Ground truth was available for only a small set of the detected anomalies within the survey area; there were several thousand potential target locations but only 372 locations were excavated. 274 of these were in areas where dynamic data were available and the detection filter could be applied. For 265 of these (97%) the offset between the ground truth target location and a detection filter peak is less than 0.4 m. All of the 21 ground truth TOI in the areas where we had data were matched within 0.4 m by potential target locations in the detection filter output.

7.1.2 Classification: Correct Classification of TOI

The objective was to correctly identify all TOI. For the SWPG and Fort Bliss demonstrations performance evaluation was determined directly from the IDA scoring of our final ranked anomaly (dig) list. IDA scoring reports were not produced for Camp Hale, and we had to use available ground truth for self-assessment.

At SWPG there were six TOI in the cued demonstration area (four 2”x8” seeded pipe sections, one 37mm projectile and one 75mm projectile). All of the TOI were correctly classified as such in the final dig list submitted to ESTCP for scoring by IDA.

There were 39 TOI in the cued demonstration area at Fort Bliss. Eleven of these were not correctly classified as such in the final dig list submitted to ESTCP for scoring by IDA. The ground truth is suspect for two of the missed TOI. The other nine are a group of legacy 37mm projectiles that would have been picked up had we done a better job of selecting training data.

At Camp Hale there were 21 ground truth TOI in the areas where we had data: 17 Medium ISO’s, two 81mm projectiles, one 60mm illumination round and one 40mm illumination round. All but the 40mm round were correctly identified using the MR-201424 Blossom Point library. The library did not include a 40mm illumination round and it was missed by the library-based classification analysis. The principal axis polarizabilities extracted from the data for the missed 40mm round are similar to those of fins and fuzes found at the site.

7.1.3 Classification: Correct Classification of Clutter

The objective was to reduce clutter digs by >85% while retaining all TOI.

At SWPG there were 492 clutter items. At the point where all TOI had been identified only 17 clutter items had been marked for digging, leaving 475 clutter items (96.5%).

There were 1452 clutter items at Fort Bliss. At the point where all TOI had been identified 724 clutter items had been marked for digging, leaving 728 clutter items (50.1%). This was due to our failure to identify a group of legacy 37mm rounds. Had one been included in the training data the last one would have been identified after 91 clutter digs.

At Camp Hale, at the point where all of the TOI in the MR-201424 library were correctly classified 2676 of 2734 possible clutter items (98%) were rejected. With the missed item added to the library the knee of the decision metric curve is broader due to fins and fuzes which match fairly well to the 40mm illumination round. In this case 2060 of the 2734 possible clutter items are rejected (~75%).

7.1.4 Classification: Stop-Dig Threshold

The stop-dig threshold performance objective was met only in the SWPG demonstration. 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 objective was to set the stop-dig threshold so that all TOI were identified and clutter digs had been reduced by >85%. Sections 7.1.2 and 7.1.3 describe the failures for the Fort Bliss and Camp Hale demonstrations.

7.1.5 Feature Extraction: Can't Analyze

This is as much a function of data quality and signal strength relative to noise as it is of the quality of the algorithm used for inverting the data to extract target features (principal axis polarizabilities). The objective was that reliable target parameters would be estimated for >95% of the anomalies, leaving <5% in the "Can't Analyze" category. We did not distinguish between "can't analyze" and "can't extract reliable parameters." Overall the data quality at SWPG and Fort Bliss was very good and it turned out that no targets had to be designated "Can't Analyze" in the final dig list.

For the Camp Hale demonstration we used a criterion of at least three good time gates to calculate shape/scale match to the library. To use all three polarizations in the match, 2734 of 3278 targets (83%) can be used. For a two-polarization match, 3119 of 3278 (95%) can be used. Most of remaining polarizations could be rejected on basic object size, i.e. polarizations are too small to be an object of interest.

7.1.6 Feature Extraction: Target Parameter Estimation

By comparing the target features (polarizabilities) of the seed items one against the other we can get a quantitative measure of the accuracy of the feature extraction process for these data. We use the size and shape mismatch parameters described in section 2.1.2 to compare the polarizabilities of the seed items with each other. The objective specified that the accuracy of target parameters extracted from data collected over the seed items result in <10% variation in the size estimates and <10% shape mismatch relative to the nominal polarizability for the seeded object.

There were four medium ISOs seeded in the cued demonstration area at SWPG. The overall spread in size estimates was 5.5% and the maximum shape mismatch was 3.2%.

At Fort Bliss the overall spread in size estimates for 28 medium ISOs was 0.937 to 1.099, within ±10%. The maximum shape mismatch was 6.5%.

At Camp Hale the size mismatch was within ±0.1 and the shape mismatch was <0.2 for all of the TOI using the MR-201424 Blossom Point library.

Table 2. Performance Results.

The right-hand column indicates whether or not the performance objective was met for each of the demonstrations: 1. Southwestern Proving Ground, 2. Fort Bliss, 3. Camp Hale.

Objective	Metric	Data Required	Success Criteria	Results
Maximize correct location of TOI	Distance of target locations from measured ground truth	• Ranked anomaly list • Ground truth	All target locations within 0.40 m of the ground truth	1. – 2. – 3. Yes
Maximize correct classification of TOI	Number of TOI retained	• Ranked anomaly list • IDA scoring report or ground truth	Correctly classify all TOI	1. Yes 2. No 3. No
Maximize correct classification of clutter	Number of clutter digs eliminated	• Ranked anomaly list • IDA scoring report or ground truth	Reduction of clutter digs by >85% while retaining all TOI	1. Yes 2. No 3. Yes
Specification of stop-dig threshold	Probability of correct TOI classification and number of clutter digs at threshold	• Stop-dig threshold • IDA scoring report or ground truth	Stop-dig threshold to achieve classification objectives	1. Yes 2. No 3. No
Minimize number of anomalies that cannot be analyzed	Number of anomalies classified as "Can't Analyze"	Target parameters extracted from data collected over target	Reliable target parameters estimated for >95% of anomalies	1. Yes 2. Yes 3. Yes
Correct estimation of target parameters	Accuracy of estimated target parameters for seed items	Target parameters extracted from data collected over seeds	• Size mismatch within ±0.10 • Shape mismatch <0.2	1. Yes 2. Yes 3. Yes

7.2 OVERALL PERFORMANCE

Overall performance in the ESTCP classification demonstrations is summarized by the ROC curve. This is a plot of the number of TOI items recovered as a function of the number of clutter digs as we move through the dig list [8]. The ROC curve for the SWPG demonstration produced as part of the IDA scoring report is shown in Figure 8. The dashed portion corresponds to the anomalies selected for training data and the blue dot is our stop-dig point (see section 7.1.4 above). The ROC for the Fort Bliss demonstration is shown in Figure 9. There was no IDA scoring for the Camp Hale demonstration.

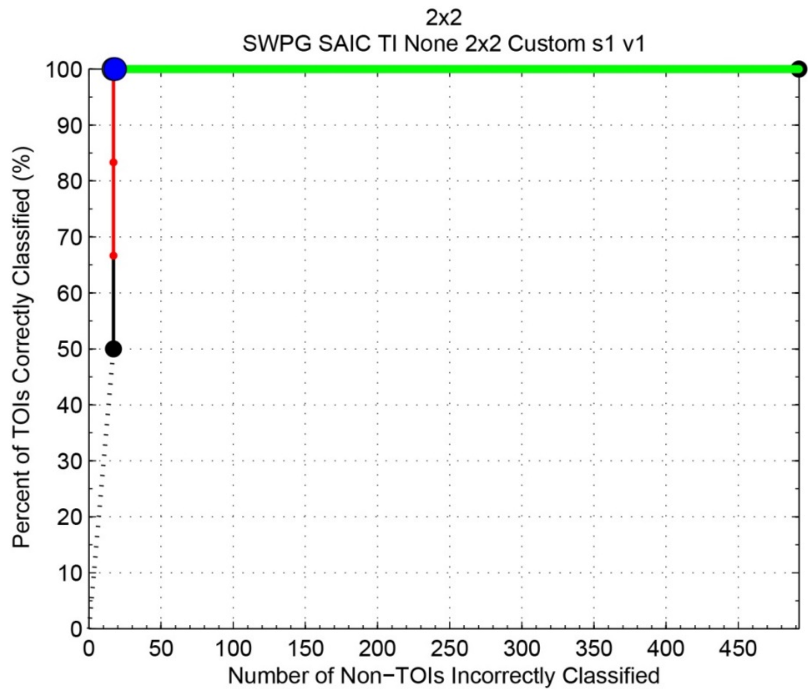


Figure 8. ROC Curve for SWPG Classification Demonstration.

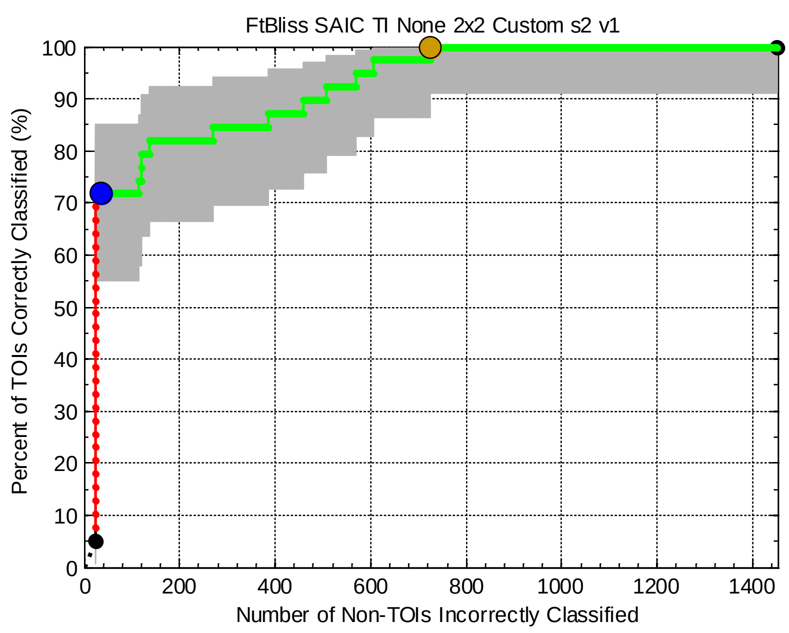


Figure 9. ROC Curve for Fort Bliss Classification Demonstration.

8.0 COST ASSESSMENT

These were simply processing demonstrations and cost assessments are not provided.

Page Intentionally Left Blank

9.0 REFERENCES

1. Thomas Bell, "Magnetic Surface Modes and UXO/Clutter Classification and Discrimination," Final Report SERDP Project MR-1658, December 2011.

2. Thomas H. Bell and Bruce Barrow, “Bulk Magnetization Effects in EMI-Based Classification and Discrimination,” SERDP Project MR-1711 Final Report, March 2015.

3. Thomas Bell, "Tensor Invariant Processing for Munitions/Clutter Classification," Final Report SERDP Project MR-2100, November 2013

4. James B. Kingdon, Bruce J. Barrow, Thomas H. Bell, David C. George, Glenn R. Harbaugh and Daniel A. Steinhurst, "TEMTADS Adjunct Sensor Systems: Hand-held EMI Sensor for Cued UXO Discrimination (ESTCP MR-200807) and Man-Portable EMI Array for UXO Detection and Discrimination (ESTCP MR-200909) Final Report," Naval Research Laboratory Memorandum Report NRL/MR/6110--12-9401, April 5, 2012.

5. ESTCP Project MR-201231 Demonstration Plan, “ESTCP Munitions Response Live Site Demonstrations, Former Southwestern Proving Ground, Arkansas,” Principal Investigator, Ryan Steigerwalt, Weston Solutions, Inc., April 2013.

6. ESTCP project MR-201230 Demonstration Plan, "Demonstration of Advanced Geophysics and Classification Methods on Munitions Response Sites - Closed Castner Range, Fort Bliss, Texas," URS Group, October 2013

7. ESTCP project MR-201230 Demonstration Plan, "Demonstration of Advanced Geophysics and Classification Methods on Munitions Response Sites - East Fork Valley Range Complex, Former Camp Hale, Colorado," August 2014.

8. Anne Andrews and Herb Nelson, "Implementing Advanced Classification on Munitions Response Sites: A Guide to Informed Decision Making For Project Managers, Regulators, and Contractors," ESTCP Final Report, December 2011.

9. Stephen Billings, Laurens Beran and Doug Oldenburg, "Robust Statistics and Regularization for feature Extraction and UXO Discrimination," Final Report, SERDP Project MR-1629, July 2011.

Page Intentionally Left Blank

APPENDIX A POINTS OF CONTACT

Point of Contact (Organization)	Mailing Address	Phone and e-mail	Role in Project
Herb Nelson (ESTCP)	4800 Mark Center Drive, Suite 17D08 Alexandria, VA 22350	Office: 571-372-6400 herb.nelson@nrl.navy.mil	MR Program Manager
Ryan Steigerwalt (Weston Solutions)	1400 Weston Way West Chester, PA, 19380	Office: 267-258-2672 Ryan.Steigerwalt@WestonSolutions.com	Principal Investigator
Brian Junck (Weston Solutions)	1400 Weston Way West Chester, PA, 19380	Office: 610-701-3926 Brian.Junck@WestonSolutions.com	Co-PI
Tom Bell (Leidos)	4001 N. Fairfax Dr., Suite 7132 Arlington, VA 22203	Office: (703) 312-6288 Cell: (301) 712-7021 bellth@leidos.com	Principal Investigator