TECHNICAL REPORT

Live Site Demonstrations - Massachusetts Military Reservation

ESTCP Project MR-201104

SEPTEMBER 2014

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Parsons

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14. ABSTRACT

The project involved the collection and classification of 2,271 cued data points at the Massachusetts Military Reservation using the MetalMapper sensor. Anomaly densities at this project site were considerably and consistently higher than those seen on previous Demonstration Projects, and there is no plan by the Government to relinquish control of the site. With anomaly densities and continued Government control of the site in mind, the goal of this project was the identification and removal of large, explosives-filled munitions (60mm and larger) potentially contributing to groundwater contamination rather than the identification and removal of every munition present. Approximately 90% of the targets of interest (TOI) at the site were correctly classified as TOI, with a 78% reduction in digs. The majority of the missed TOI were 60mm mortar illumination rounds, which proved difficult to differentiate from smaller fragments given their thin-walled construction. The ability of the MetalMapper to significantly reduce excavations on future projects would depend significantly on the importance placed on identifying these specific munitions.

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MetalMapper Sensor; Advanced electromagnetic induction; UXO; Classification; Live Site Demonstration; Massachusetts Military Reservation

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Acronyms

σ	standard deviation
β1, β2, β3	polarizabilities along principal axes of target
BUD	Berkeley UXO Discriminator
CD	cultural debris
CIA	Central Impact Area
cm	centimeter
DAQ	data acquisition computer
EMI	electromagnetic induction
ESTCP	Environmental Security Technology Certification Program
GPS	Global Positioning System
HE	high explosive
HEAT	high-explosive antitank
IAGWSP	Impact Area Groundwater Study Program
IDA	Institute for Defense Analyses
IMU	inertial measurement unit
ISO	industry standard object
IVS	instrument verification strip
MD	munitions debris
MEC	munitions and explosives of concern
mm	millimeter
MMR	Massachusetts Military Reservation
MR	munitions response
N	repeat factor
P_{class}	probability of correct classification
N_{fa}	number of false alarms
OER	Ordnance & Explosives Remediation
QC	quality control
ROC	receiver operating characteristic
RTK	real-time kinematic
T	period
TEMTADS	Time-Domain Electromagnetic Multi-sensor Towed Array Detection System
Tetra Tech	Tetra Tech EC, Inc.
TNT	trinitrotoluene
TOI	targets of interest
USB	universal serial bus
UTM	Universal Transverse Mercator
UXO	unexploded ordnance

EXECUTIVE SUMMARY

This report describes in detail the procedures, methods, and resources Parsons used to complete the demonstration project at the Massachusetts Military Reservation for Environmental Security Technology Certification Program (ESTCP) Munitions Response (MR)-201104 (Evaluation and Discrimination Technologies and Classification Results) and ESTCP MR-201157 (Demonstration of MetalMapper Static Data Acquisition and Data Analysis). The 2011-2012 ESTCP Unexploded Ordnance (UXO) Classification Study, Massachusetts Military Reservation (MMR), was conducted with three primary objectives:

- Test and validate detection and discrimination capabilities of currently available and emerging advanced electromagnetic induction sensors developed specifically for discrimination on real sites under operational conditions.
- Investigate in cooperation with regulators and program managers how classification technologies can be implemented in munitions and explosives of concern (MEC) cleanup operations.
- Identify and remove large target items as they pose the greatest potential for groundwater contamination from the energetic filler in the UXO.

Parsons had two separate teams working on the project under two different ESTCP project numbers, ESTCP 201104 and ESTCP 201157. One team was responsible for site setup, the placement of 30 seed items for use in measuring the capabilities of the MetalMapper advanced electromagnetic induction (EMI) sensor tested during the project, and the intrusive investigation of the 2,287 targets (including seed items) selected for additional investigation with the advanced sensors. The second team was responsible for the cued survey of 2,287 targets with the MetalMapper. These targets were selected from EM61-MK2 data collected by the National Guard Bureau during their Impact Area Groundwater Study Program (IAGWSP), a separate effort from the ESTCP demonstration. EM61-MK2 targets were selected in locations designed to test the capabilities of the MetalMapper with regard to a much higher anomaly density than had been present on previous demonstration sites. The field MetalMapper field collection effort took place over 3 weeks, and the average production rate was 207 points per day.

The MetalMapper is an advanced EMI system developed by Geometrics, Inc., with support from the ESTCP. It has three mutually orthogonal transmit loops in the Z, Y, and X directions and contains seven triaxial receiver antennas inside the Z (bottom) loop, allowing 21 independent measurements of the transient secondary magnetic field. Data were collected statically, such that one data point was collected for each target selected for investigation. The collected data were inverted and analyzed using the UX-Analyze add-on to Geosoft's Oasis montaj software. Once analysis was complete, a theoretical ranked dig list (theoretical because all targets were intrusively investigated regardless of demonstrators' stop-dig points) was submitted for scoring by the Institute for Defense Analyses (IDA).

Dig list scoring was based on the number of targets of interest (TOI) correctly identified as items that should be dug and the number of non-TOI or clutter items that were correctly classified as items that did not need to be intrusively investigated. The intrusive investigation was split into two phases, I and II, and a separate ranked dig list was submitted for each phase. The dig lists submitted were scored against the ground truth set compiled following the intrusive investigations. Comparison of the Phase I dig list with the Phase I ground truth set resulted in

the correct identification of approximately 97% of the TOI recovered in the intrusive investigation (5 of 148 TOI incorrectly classified as clutter) and a reduction in the amount of clutter that would have been dug by approximately 78%. The missed TOI included three items considered too small to be of concern at MMR (only small amounts of energetic filler) and one item with questionable location compared to the MetalMapper collection location. The one item of concern identified as a false negative was a 60-millimeter (mm) mortar illumination round. This single round was not deemed concerning enough to add to the library prior to the compilation of the Phase II list. Comparison of the Phase II dig list to the Phase II ground truth set resulted in the correct identification of 83% of the TOI recovered (20 of 115 TOI incorrectly classified as clutter). Seventeen of the missed TOI were the same illumination round incorrectly identified as non-TOI in the Phase I dig list, indicating that the misclassification of this item could be a more significant problem than anticipated following Phase I. Retrospective analysis of the dataset indicated that these items could be identified as TOI by adding examples to the classification library, but doing so significantly reduced the amount of clutter that could be consistently identified as non-TOI. More consideration should be given to exactly how these specific munitions might impact the groundwater issues at MMR and how many added digs would be necessary to detect them consistently.

1.0 INTRODUCTION

Currently, up to 90 percent of excavation costs on most unexploded ordnance (UXO) / munitions and explosives of concern (MEC) projects are related to removing scrap metal that does not represent an explosive hazard. Significant cost savings could be achieved through the use of geophysical discrimination methods that could reduce the number of excavations required to remove explosive hazards from sites. The objective of this project is to demonstrate the use of advanced electromagnetic induction (EMI) sensors in static data acquisition mode and associated analysis software. To achieve these objectives, a controlled test was conducted at the Massachusetts Military Reservation (MMR).

This is one of a series of the Environmental Security Technology Certification Program (ESTCP) demonstrations of classification technologies for munitions response (MR). This demonstration is designed to evaluate classification methods at a site that is known to contain a mix of munition types. Munitions of interest for this site include 4.2-inch, 60-millimeter (mm), and 81-mm mortars, and 105-mm and 155-mm projectiles.

The objectives at this site are somewhat different from the standard ESTCP classification demonstration. Most MR removal actions are motivated by the explosion risk of the UXO contamination. In this case, although the risk of explosion is present, the site team is additionally concerned about the potential for groundwater contamination from the energetic filler in the UXO. Because of this, all UXO are not considered equal risks; larger projectiles have substantially more filler than small mortars and are therefore a more important target.

1.1 BACKGROUND

The Fiscal Year 2006 defense appropriation contained funding for the "Development of Advanced, Sophisticated Discrimination Technologies for Unexploded Ordnance (UXO) Cleanup." The ESTCP responded by conducting a UXO discrimination study at the former Camp Sibert, Alabama. The results of this first demonstration were very encouraging. The conditions for discrimination were favorable at this site and included a single target of interest (TOI; 4.2-inch mortar) and benign topography and geology. All of the classification approaches demonstrated were correctly identified a sizable fraction of the anomalies as arising from nonhazardous items that could be safely left in the ground. Both commercial and advanced sensors produced very good results. ESTCP chose Camp San Luis Obispo, California, as the site for the second study, which provided greater challenges in topography and a wider mix of TOI. Again, the results were very positive, with increased discrimination of TOI versus nonhazardous items.

In 2010, the third ESTCP study was conducted at the former Camp Butner, North Carolina, which included smaller TOI than either of the previous sites. Great success was achieved in identifying 37-mm projectiles, fuzes, and larger TOI with the advanced sensors. ESTCP sponsored a fourth study in 2011 at the former Camp Beale, California, a site with a wide range of TOI, moderate to steep terrain, and trees. Previous studies included open field pastures; the study area at Camp Beale included medium-density, wooded areas to provide increasing difficulty to test the high standards established in the previous studies. Additionally, the Camp Beale project included the use of smaller, man-portable EMI sensors such as the Naval Research

Laboratory's Time-Domain Electromagnetic Multi-sensor Towed Array Detection System (TEMTADS) 2x2 cart, Lawrence Berkeley National Laboratory's man-portable Berkeley UXO discriminator (BUD), and Sky Research's man-portable vector machine. All of the EMI sensors tested at the former Camp Beale were quite successful in discriminating between TOI and clutter.

The study area at MMR was chosen by ESTCP to test MetalMapper's discrimination capabilities in areas with much higher target densities than were present at previous demonstration sites, and its effectiveness in identifying large target items within high target densities.

1.2 OBJECTIVES OF THE DEMONSTRATION

This approach has the potential to reduce the number of excavations required to effectively remove the explosive safety risk (MEC) at a given site, which would result in significant cost savings related to the closure of formerly used defense sites. The cost savings are expected to be particularly significant at removal action sites. Parsons is currently involved with U.S. Army Corps of Engineers projects at several MEC and recovered chemical warfare materiel sites that could be used for additional testing and refining of the process required for this type of discrimination approach.

1.3 REGULATORY DRIVERS

As part of the cleanup of former Department of Defense sites, buy-in is required from regulatory agencies at the federal, state, and local levels. The advancement in classification sensors and their successful deployment at real-world sites needs to be documented for their use to be accepted by the applicable regulatory agencies. Their acceptance of the use of this technology at sites for which they are ultimately responsible will be particularly important because of the potential for Department of Defense budget cuts to affect the amount of money that will be available for future remedial actions.

2.0 TECHNOLOGY

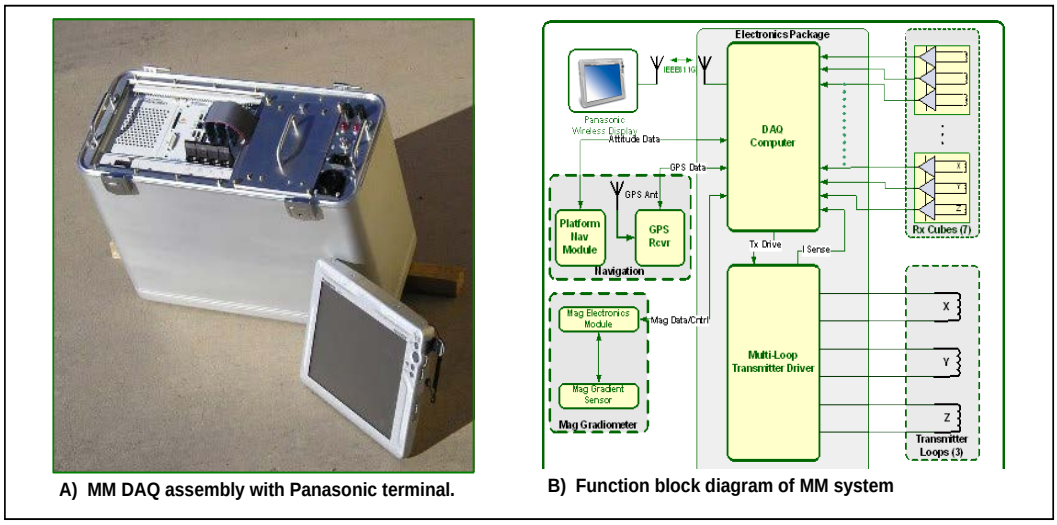
2.1 TECHNOLOGY DESCRIPTION

The MetalMapper is an advanced EMI system developed by Geometrics, Inc., with support from the ESTCP. The MetalMapper draws elements of its design from advanced systems currently being developed by G&G Sciences, Inc. (supported by Naval Sea Systems Command, the Strategic Environmental Research and Development Program, and ESTCP) and by Lawrence Berkeley National Laboratory with support from the Strategic Environmental Research and Development Program and ESTCP. It has three mutually orthogonal transmit loops in the Z, Y, and X directions and contains seven triaxial receiver antennas inside the Z (bottom) loop. Typically, the transmit loops are driven with a classical bipolar pulse-type time domain electromagnetic waveform (i.e., alternating pulse polarity with a 50% duty-cycle). Depending on the survey mode (e.g., Static/Dynamic), the fundamental frequency of transmission can be varied over the range $1.11 \leq f \leq 810$ hertz. The seven receiver antennas allow 21 independent measurements of the transient secondary magnetic field.

The data acquisition computer (DAQ) is built around a commercially available product from National Instruments. The National Instruments DAQ is a full-featured PC running Windows 7. The DAQ, electromagnetic transmitter, and batteries for the system are packaged in an aluminum case that can be mounted on a pack frame, on a separate cart such as a hand truck, or on the survey vehicle such a tractor. The instrumentation package also includes two external modules that provide real-time kinematic (RTK) global positioning system location and platform attitude (i.e., magnetic heading, pitch, and roll) data. These modules are connected to the DAQ through serial RS232C ports. A block diagram of the DAQ system is in Figure 2-1.

The MetalMapper has two modes of data collection: dynamic and static. Data collected in dynamic mode results in data files containing many data samples. Generally speaking, dynamic mode data are collected while the antenna platform is in motion. Static mode data collection is employed for cued surveys. As its name implies, the antenna platform remains static or motionless during the period of data acquisition. Depending on the acquisition parameters (e.g., sample period and stacking parameter) it can take tens of seconds to complete a static measurement. The results of the static measurement are written into a binary data file containing only a single data point representing the average (stacked) result, usually over tens or even hundreds of repetitions of the transmitter's base frequency.

Figure 2-1: Data Acquisition Computer and Functional Block Diagram



A) MM DAQ assembly with Panasonic terminal.

B) Function block diagram of MM system

Data are acquired in time blocks that consist of a fixed number of transmitter cycle "repeats." Both the period (T) and the repeat factor (N) are operator selectable and are varied in multiplicative factors of 3. The MetalMapper also averages an operator-specified number of acquisition blocks (NStacks) together before the acquired data are saved to disk. The decay transients that are received during the off times are stacked (averaged) with appropriate sign changes for positive and negative half cycles. The decays in an individual acquisition block are stacked, and the decays in that block are averaged with other acquisition blocks (assuming the operator has selected NStack greater than one). The resultant data are saved as a data point. A photo of the typical configuration of the instrument used for collecting cued data is shown in Figure 2-2.

Figure 2-2: Antenna Array and Deployment of the MetalMapper at MMR

In its present (third generation) form, the MetalMapper technology has been demonstrated and scored at the Standardized UXO Technology Demonstration sites at the Yuma Proving Ground (blind grid only), Aberdeen Proving Ground (blind grid plus direct fire and indirect fire areas), at Camp San Luis Obispo and Camp Butner in connection with 2009 and 2010 classification studies, and at Camp Beale during 2011 and 2012 live site demonstrations carried out by ESTCP. The performance of the MetalMapper at these sites is documented in formal reports issued by the Aberdeen Test Center and by the various demonstrators who analyzed the data collected at Camp San Luis Obispo, Camp Butner, and Camp Beale.

Naval Research Laboratory staff also used the laboratory's man-portable TEMTADS 2x2x3 array to collect cued data on approximately 1000 anomalies. The TEMTADS system was used to collect data over 300 anomalies collected by the MetalMapper for comparison. The TEMTADS data results are presented in a separate report authored by the Naval Research Laboratory and are not covered in this document.

2.2 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

A few advanced EMI sensors are similar to the MetalMapper in theory, design, and size, with the most comparable being the TEMTADS 5x5 and the full-size BUD. The TEMTADS 5x5 consists of 25 pairs of transmit/receive coils oriented in a 5x5 grid pattern, approximately 2 meters to a side. The BUD consists of three orthogonal transmitters and eight pairs of differenced receivers. These instruments have been part of the ongoing ESTCP classification demonstrations, and similar results have been documented for all three during previous projects. The main advantage of the MetalMapper is that it is currently commercially available, while the other two advanced EMI sensors are generally only used by the organizations that developed them. As discussed in Section 1.1, various man-portable EMI sensors were tested successfully at Camp Beale. As with the TEMTADS 5x5 and the BUD, these sensors are not yet commercially available.

The greatest limitation of the MetalMapper is its size, both of the sensor itself and of the accompanying computer, screen, and cables. The system is designed primarily for use in relatively flat, open fields and cannot currently be used effectively in wooded areas.

3.0 PERFORMANCE OBJECTIVES

This demonstration had three primary performance objectives:

- Evaluating whether classification techniques will work at the MMR site
- Evaluating where classification techniques will work at MMR
- Evaluating the cost effectiveness of classification techniques in the areas at MMR where classification is determined to be effective

The specific performance objectives for this demonstration are summarized in Table 3-1.

3.1 OBJECTIVE: REPEATABILITY OF INSTRUMENT VERIFICATION STRIP MEASUREMENTS

The reliability of the survey data depends on the proper functioning of the survey equipment. This objective concerns the twice-daily confirmation of sensor system performance.

3.1.1 Metric

The metrics for this objective were the distance between the modeled and actual locations of the seed items in the instrument verification strip (IVS) and the classification results for each point collected over an IVS seed.

3.1.2 Data Requirements

Twice daily surveys of the IVS strip were used to judge this objective.

3.1.3 Success Criteria

This objective was met if the modeled X, Y locations of the IVS seed items are within 15 centimeters (cm) of the actual locations, if the depth (Z direction) is within 10 cm of the actual burial depth, and if the seeds items are classified as the correct munition type.

3.2 OBJECTIVE: SUCCESSFUL REACQUISITION OF TARGETS WITH THE METALMAPPER

Data collected directly over target source items should lead to a high probability of detecting the TOI at the site.

3.2.1 Metric

The metric for this objective was the distance between the center of the MetalMapper when cued data are collected and the modeled location of the source item.

3.2.2 Data Requirements

The center of the MetalMapper was determined following pre-processing of the MetalMapper data and was a function of the GPS (Global Positioning System) position measured when the data are collected and the attitude (pitch and roll) of the sensor. The modeled location of the source item was determined following initial inversion of the data.

3.2.3 Success Criteria

The objective was considered to be met if 95% of the collection locations (either original collection locations or re-shots collected due to excessive offsets) are within 40 cm of the modeled locations.

Table 3-1: Performance Objectives for this Demonstration

Performance Objective	Metric	Data Required	Success Criteria
Data Collection Objectives			
Repeatability of IVS measurements	Measured target locations Correct classification of IVS seeds	• Twice-daily IVS data	X, Y < 15 cm (1σ) Z < 10 cm (1σ) IVS seed items identified correctly
Successful reacquisition of targets with MetalMapper	Offset between collection and modeled target locations	• GPS-located collection location • Modeled target location	95% of original or re-shot target locations < 40 cm from modeled locations
Analysis and Classification Objectives			
Maximize correct classification of TOI	Number of TOI retained.	• Prioritized anomaly lists • Scoring reports from IDA	Approach correctly classifies all TOI
Maximize correct classification of non-TOI	Number of false alarms eliminated.	• Prioritized anomaly lists • Scoring reports from IDA	Reduction of false alarms by > 50% while retaining all TOI
Specification of no-dig threshold	Probability of correct classification and number of false alarms at demonstrator operating point.	• Demonstrator - specified threshold • Scoring reports from IDA	Threshold specified by the demonstrator to achieve criteria above
Minimize number of anomalies that cannot be analyzed	Number of anomalies that must be classified as "Unable to Analyze."	• Demonstrator target parameters	Reliable target parameters can be estimated for > 98% of anomalies on each sensor's detection list.
Correct estimation of target parameters	Accuracy of estimated target parameters.	• Demonstrator target parameters • Results of intrusive investigation	X, Y < 15 cm (1σ) Z < 10 cm (1σ)

σ = standard deviation; cm = centimeter(s); GPS = Global Positioning System; IDA = Institute for Defense Analyses IVS = instrument verification strip; TOI = targets of interest

3.3 OBJECTIVE: MAXIMIZE CORRECT CLASSIFICATION OF TARGETS OF INTEREST

One of the two main objectives of this demonstration was to correctly classify all seeded items and any MEC items remaining at the site as TOI. However, while the goal of the project was to identify all remaining TOI correctly, the ESTCP Demonstration Plan (ESTCP, 2012) did note that this was a more stringent requirement than was required based on the cleanup objectives for the site. Because this site is not accessible to the general public and the National Guard has no future plans for the site that would make explosive MEC a particular hazard, the objectives for this site are more focused on removing MEC based on its potential hazard as a groundwater contamination source rather than for the explosive hazard.

3.3.1 Metric

The metric for this objective was the number of items on the MetalMapper anomaly list that can be correctly classified as TOI.

3.3.2 Data Requirements

Following data collection, MetalMapper data was analyzed to create a prioritized dig list, which assigned each target to one of three categories: 1) TOI 2) non-TOI, or 3) Can't Analyze. The targets classified as either TOI or Can't Analyze were considered "dig" targets. Institute for Defense Analyses (IDA) personnel used their scoring algorithms to assess the results.

3.3.3 Success Criteria

The objective was considered to be met if all of the items of interest are correctly labeled as TOI on the prioritized anomaly list. Given the requirement to remove potential sources of groundwater contamination, results for the site were deemed adequate if a large percentage of the large (60 mm and larger) TOI at the site was labeled as TOI on the prioritized anomaly list.

3.4 OBJECTIVE: MAXIMIZE CORRECT CLASSIFICATION OF NON-TARGETS OF INTEREST

This was the second of the two primary measures of the effectiveness of the classification approach. In addition to correctly classifying TOI, the effectiveness of the MetalMapper in discriminating munitions was a function of the degree to which responses that do not correspond to TOI could be eliminated from consideration during the intrusive investigation.

3.4.1 Metric

The metric for this objective was the number of targets on the ranked anomaly list created using the MetalMapper data that could be correctly classified as non-TOI.

3.4.2 Data Requirements

Following data collection, MetalMapper data was analyzed to create a prioritized dig list, which assigned each target to one of three categories: 1) TOI, 2) non-TOI, or 3) Can't Analyze. The targets classified as non-TOI were considered "no dig" or non-TOI targets. IDA personnel used their scoring algorithms to assess the results.

3.4.3 Success Criteria

The objective was considered to be met if more than 50% of the non-TOI items can be correctly labeled as non-TOI while retaining all of the TOI above the dig threshold.

3.5 OBJECTIVE: SPECIFICATION OF NO-DIG THRESHOLD

In a retrospective analysis, as performed in this demonstration, it is possible to tell the true classification capabilities of a classification procedure based solely on the ranked anomaly list submitted. In a real-world scenario, not all targets may be dug, so the success of the approach depended on the ability of an analyst to accurately specify their dig/no-dig threshold.

3.5.1 Metric

The probability of correct classification, P_{class}, and number of false alarms, N_{fa}, at the dig/no dig threshold in the prioritized dig list were the metrics for this objective.

3.5.2 Data Requirements

Following data collection, MetalMapper data was analyzed to create a prioritized dig list, which assigned each target to one of three categories: 1) TOI, 2) non-TOI, or 3) Can't Analyze. The category into which each target was placed determined using a decision statistic to be developed during analysis of the MetalMapper data. The dig/no dig threshold for this project was the decision statistic value that separates targets classified as TOI from those classified as non-TOI. IDA personnel used their scoring algorithms to assess the results.

3.5.3 Success Criteria

The objective was considered to be met if more than 50% of the non-TOI items were correctly labeled as non-TOI while retaining all of the TOI at the specified threshold.

3.6 OBJECTIVE: MINIMIZE NUMBER OF ANOMALIES THAT CANNOT BE ANALYZED

Anomalies for which reliable parameters could not be estimated using the collected MetalMapper data cannot be classified. These anomalies were placed in the dig category, which reduces the effectiveness of the classification process.

3.6.1 Metric

The number of anomalies for which reliable parameters cannot be estimated was the metric for this objective.

3.6.2 Data Requirements

Those targets for which parameters could not be reliably estimated were identified as such on the prioritized dig list submitted following analysis of the MetalMapper data.

3.6.3 Success Criteria

The objective was considered met if reliable parameters can be estimated for > 98% of the targets on the prioritized dig list.

3.7 OBJECTIVE: CORRECT ESTIMATION OF TARGET PARAMETERS

This objective involves the accuracy of the target parameters that are estimated in the first phase of the analysis. Successful classification is only possible if the input features are internally consistent. The obvious way to satisfy this condition is to estimate the various target parameters accurately.

3.7.1 Metric

Accuracy of estimation of target parameters is the metric for this objective.

3.7.2 Data Requirements

Target parameters were provided as part of the final results submission. Parsons compared the submitted modeled source locations to those measured during the intrusive investigation.

3.7.3 Success Criteria

The objective was considered to be met if the estimated X, Y locations are within 15 cm (1 standard deviation [σ]), and the estimated depths are within 10 cm (1σ).

4.0 SITE DESCRIPTION

MMR was chosen as the next in a progression of increasingly more complex 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. The conditions for discrimination were favorable at this site and included a single TOI (4.2-inch mortar) and benign topography and geology. Additional demonstrations were conducted at Camp San Luis Obispo, CA; Camp Butner, NC; the Pole Mountain Target and Maneuver Area, WY; Fort Sill, OK; and Camp Beale, CA. These sites all added complications such as an increased number of munitions types, including smaller munitions generally more difficult to identify from munitions fragments, and/or more difficult topographic (i.e., hills and trees) or geologic (rock outcroppings) conditions.

MMR is an approximately 200,000-acre site in Western Cape Cod, Massachusetts. The seeding and demonstration were conducted in two separate, 3-acre areas (northern and southern) of the Central Impact Area (CIA). MetalMapper data were only collected in the southern area; TEMTADS data were primarily collected in the northern area, although TEMTADS data were also collected over 300 targets in the southern area to provide an overlap with a portion of the MetalMapper targets. An aerial photo of the demonstration area is shown in Figure 4-1. A more specific site description can be found in the *Final Central Impact Area Source Investigation Report* (Tetra Tech EC, Inc. [Tetra Tech], 2011).

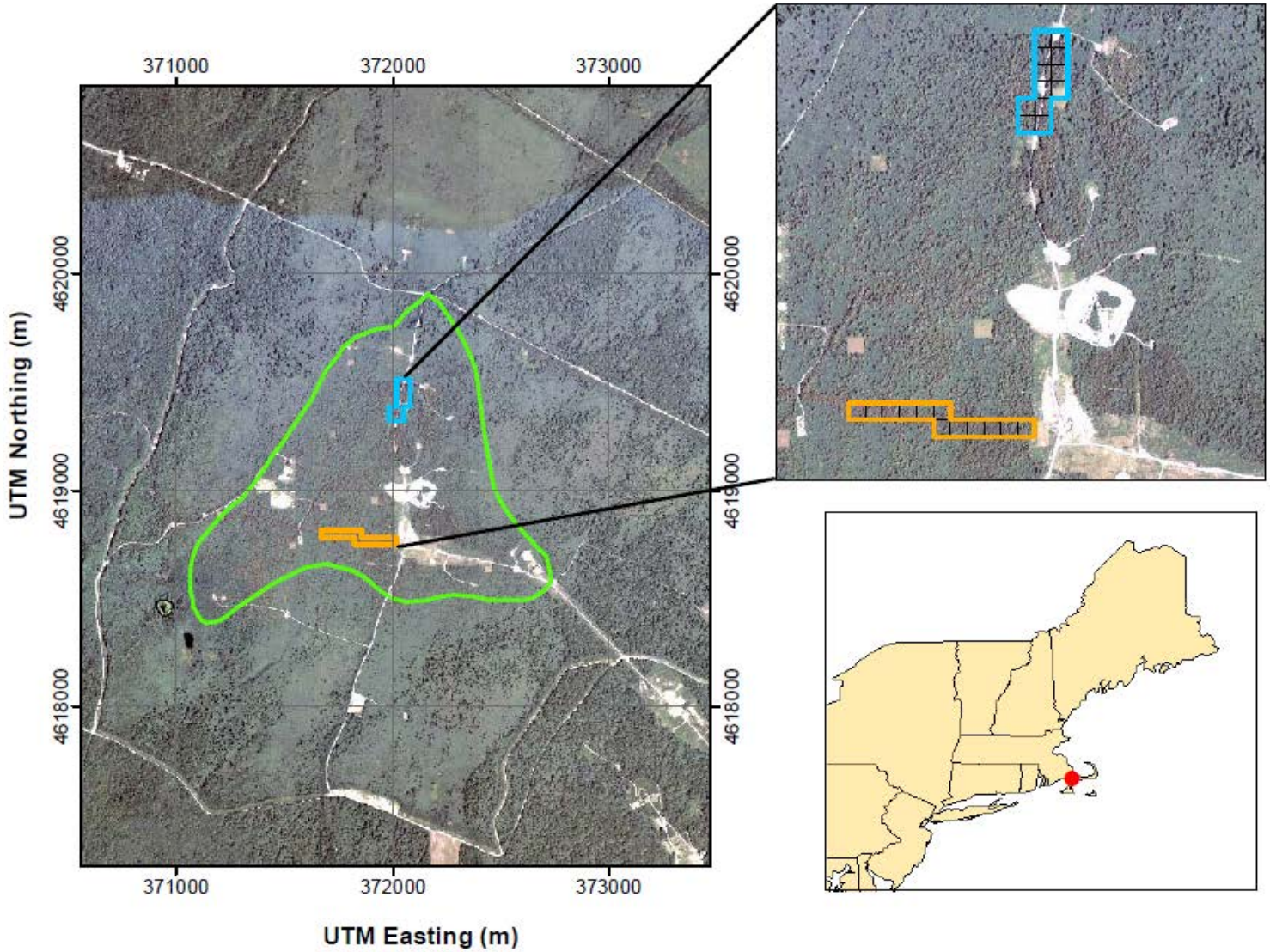
4.1 SITE SELECTION

The study area at MMR was chosen by ESTCP to test the capabilities of the MetalMapper in areas with much higher target densities than were present at previous demonstration sites. In addition, the terrain in this study area was generally much more rugged than that on previous sites, with many large, deep craters and a considerable amount of roughly cut brush. The study area boundaries overlap CIA targets T43, T27, T26, and T1. This location was chosen to incorporate this work as part of the National Guard Bureau's Impact Area Groundwater Study Program (IAGWSP).

4.2 BRIEF SITE HISTORY

Portions of MMR were used by the military beginning in the early 1900s. The CIA has been used as an impact area for artillery and mortars from the late 1930s until 1997. During the late 1940s, the CIA also contained Navy air-to-ground rocket ranges that utilized 2.25-inch rockets. Various types of munitions, including 37-mm, 40-mm, 75-mm, 90-mm, 105-mm, and 155-mm artillery projectiles and 50-mm, 60-mm, 70-mm, 81-mm, 3-inch, and 4.2-inch mortars, have been fired into the CIA. These munitions include high explosive (HE) charges designed to explode upon impact, and practice or "inert" rounds which do not contain an HE charge but may contain a spotting charge designed to emit smoke upon impact.

Figure 4-1: Locations of Two Demonstration Study Areas within Central Impact Area, Massachusetts Military Reservation



The predominant HE charge used in pre-World War II munitions contained TNT (trinitrotoluene). Post-World War II artillery and mortar munitions used Composition B for the HE charge, which is a mixture of cyclotrimethylenetrinitramine and TNT. The low-intensity training round artillery practice projectile was introduced in 1982 to reduce the noise associated with HE explosions, since this noise was a source of complaints from the public abutters. The low-intensity training round includes a spotting charge containing perchlorate. The use of HE artillery projectiles was discontinued in 1989, and the firing of all munitions into the CIA was discontinued in 1997.

HE munitions that did not explode (UXO) or that partially functioned (UXO low order) have accumulated within the CIA during its use. UXO along roadways or at other locations that presented a safety hazard due to human access have historically been blown in place using an explosive donor charge. Blow-in-place operations were also used to clear areas for site investigation under the IAGWSP starting in 1997. Post-blow-in-place soil sampling and removal of soil contaminated by blow-in-place activities have been conducted since 1999 under the IAGWSP.

4.3 MUNITIONS CONTAMINATION

The suspected munitions in the CIA include:

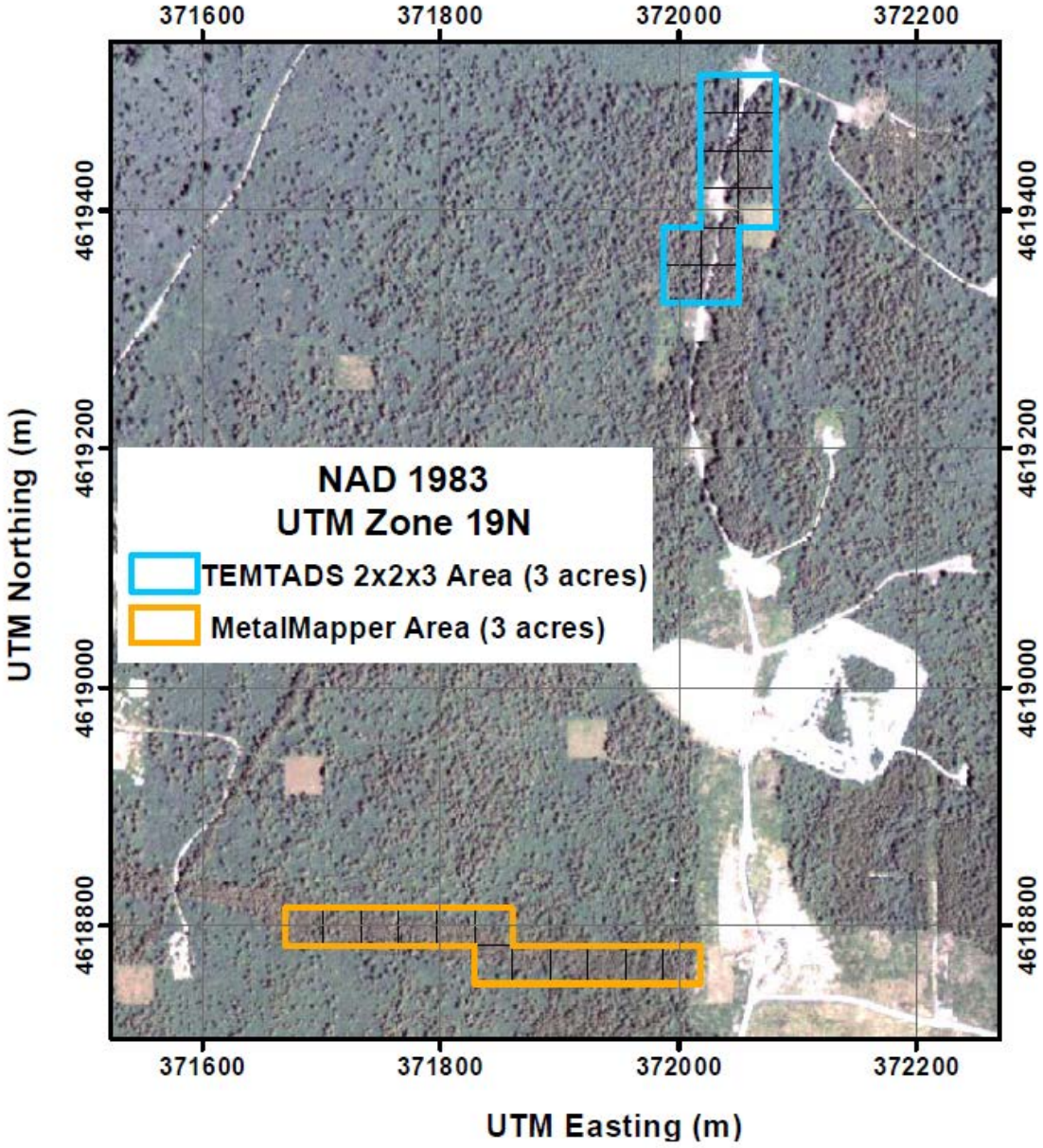
- 5-inch, 7-inch, 8-inch, 14.5-mm, 20-mm, 30-mm, 37-mm, 75-mm, 90-mm, 105-mm, 155-mm, and 175-mm, projectiles
- 60-mm, 81-mm, and 4.2-inch mortars
- 2.36-inch, 2.75-inch, and 3.5-inch rockets
- 57-mm recoilless rifle rounds

The munitions of primary interest for the demonstration area include 4.2-inch mortars, 60-mm mortars, 81-mm mortars, 105-mm projectiles, and 155-mm projectiles. These larger munitions contain a high percentage of the mass of explosives remaining in the CIA.

4.4 SITE CONFIGURATION

The demonstration site consists of two separate, 3-acre locations within the CIA area, surrounding targets T43, T27, T26, and T1. The study used EM61-MK2 data previously collected by Tetra Tech to identify targets for survey by the MetalMapper and TEMTADS and to identify potential locations for seeds items. The demonstration area is shown in Figure 4-2.

Figure 4-2: Demonstration Site Boundaries



Note: Site was cleared for vegetation.

5.0 TEST DESIGN

5.1 CONCEPTUAL EXPERIMENTAL DESIGN

The objective of this program is to demonstrate a method for the use of classification in the MR process. The three key components of this method are collection of high-quality geophysical data and principled selection of anomalous regions in those data; analysis of the selected anomalies using physics-based models to extract target parameters such as size, shape, and materials properties; and the use of those parameters to construct a ranked anomaly list. Each of these components will be handled separately in this program.

The National Guard Bureau coordinated the EM61-MK2 cart survey data collection as part of their ongoing IAGWSP and provided ESTCP with the raw data for this demonstration. ESTCP coordinated preprocessing of the survey data and anomaly selection, to create a master anomaly list.

Parsons was provided the anomaly list from the EM61-MK2 survey . Cued MetalMapper data were collected over all targets on the master anomaly list to extract target parameters. These parameters were passed to a classification routine which, after training on a limited amount of site-specific ground truth, was used to produce a prioritized anomaly list.

Validation digging was then performed for all anomalies on the master anomaly list. The underlying target(s) were uncovered, photographed, located with a cm-level GPS system, and removed. Ground truth data was then requested for classification training, if necessary.

At the conclusion of training, an initial ranked anomaly list was submitted. This list was ordered from the item deemed most likely to be a munition through the item deemed most likely to be not hazardous. It also included the threshold constituting the dig/no dig point in the list. Targets for which meaningful parameters could not be extracted were placed at the top of the list. Dig results from the first round of digging were provided prior to the construction of a final ranked anomaly list, with each anomaly marked dig or no-dig. These final inputs were scored by the IDA with emphasis on the number of items that are correctly labeled nonhazardous while correctly labeling all TOI.

The primary objective of the demonstration was to assess the order of the ranked anomaly list and the ability to specify the threshold separating high confidence clutter from all other items. The secondary objective was to determine the classification performance that could be achieved through a retrospective analysis.

5.2 SITE PREPARATION

5.2.1 Survey of Historical Records

Much of the historical information on this site has been summarized in the *Final Central Impact Area Source Investigation Summary Report* (Tetra Tech, 2011). These reports are posted on the ESTCP ftp server and can be used for reference.

5.2.2 Acquire Site-Specific Information

The demonstration site falls within the CIA. The range has formerly been described as being used for 40-mm grenade, 66-mm light antitank weapon, and 2.36-inch and 3.5-inch rocket weapons system training. These weapons, along with those listed in Section 4.3, were recovered during the remedial investigation and feasibility study or are suspected to be present at the site. Due to the historical usage of this site over many years, it is also likely that other munitions types beyond those listed above may be encountered.

5.2.3 First-Order Navigation Points

It is important that all survey data and validation activities be conducted on a common coordinate system. Therefore, for consistency, Parsons used the control point located at the range control office, which was also used by the previous digital geophysical mapping team and other demonstrators. Because the control point had a full-time base station provided by Tetra Tech, Parsons synchronized to their frequency to create a secondary local station closer to the demonstration areas. The coordinates for base station point are given in Table 5-1.

Table 5-1: Geodetic Control Location

ID	Latitude WGS 84	Longitude WGS 84	Elevation (ft) from Top of Well Casing
LW4468	41 42 30.92394N	070 33 56.81178	186.73

5.2.4 Brush Cutting / Surface Clearance

Significant brush cutting and a surface sweep were performed by Tetra Tech prior to their collection of the EM61-MK2 data used to select targets for the advanced EMI surveys. The main objective of the surface clearance was to ensure that no hazardous items would be encountered prior to the nonintrusive phases in the demonstration area and to remove metallic surface debris from the grids.

5.2.5 Initial EM61-MK2 100% Coverage Survey

A 100% coverage EM61-MK2 survey was performed by Tetra Tech in both the northern and southern survey areas prior to seeding and the collection of advanced EMI data. These surveys were used to guide the seeding plan and to identify targets for the advanced EMI surveys.

5.2.6 Seeding Operation

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 in the investigation area; far from enough to determine classification performance with acceptable confidence bounds. To avoid this problem, the site was seeded with enough TOI to ensure reasonable statistics.

Parsons conducted seeding operations at MMR from June 6, 2012, through June 10, 2012. The seeding operation covered approximately 6 acres in the two sections of the CIA selected for use in the demonstration. The location of each seed item was established with a Trimble R8 RTK GPS system. The project coordinate system was in Universal Transverse Mercator (UTM) Zone

19N, WGS84 coordinates. All seed items, with the exception of medium industry standard objects (ISOs), were received from the Army Research lab in Welcome, Maryland.

Parsons flagged 160 locations with the Trimble R8 RTK GPS system and established anomaly avoidance at each location to ensure a clean area for emplacement. All 160 seed locations were dug to proper size and depth. Digging operations involved both mechanical and manual procedures to meet exact specifications and to minimize burial evidence. Digging operations proved very challenging due to the roots and fallen trees left from the brush cutting. Heavy equipment was used to remove large tree limbs and roots prior to seeding. Each seed hole was dug to meet the azimuth and depth requirements given to Parsons. The dip angle specifications were set to a 45-degree tolerance in which the exact angles was determined by Parsons but measured with a level for documentation. Exact angles above horizontal, below horizontal were recorded. After all the emplacement requirements of depth, inclination, dip angle, length, and location were completed, a photo was taken of the seed item in the burial location. All the emplacement information, along with the seed item and north direction, is visible in the photos.

Seed location holes were not backfilled until final quality control (QC) checks were complete. QC checks consisted of comparing the location with the original designated location; capturing the center location of the emplaced seed item with GPS; and checking the depth, inclination, and dip angle of each seed item. Once these checks were complete, the hole was backfilled with a shovel to prevent any excess movement of the seed items.

Seed items for the MMR demonstration project included 155-mm projectiles, 81-mm projectiles, 105-mm projectiles, 4.2-inch mortars, and medium ISOs. A list of the seed items emplaced for the project is included in Table 5-2.

Table 5-2: Massachusetts Military Reservation Demonstration Seed Items

Seed Item	Total
Medium ISO	20
81 mm	40
4.2-inch mortar	20
105-mm projectile	40
155-mm projectile	40
Total	**160**

5.2.7 Establish an Instrument Verification Strip and Training Pit

A clean area for use as the IVS was identified in an unused sand road immediately adjacent to the connex box used to store the project equipment. The section of road used for the IVS was approximately 6 feet wide and 100 feet long. A list of the seed items placed in the IVS is included in Table 5-3.

Table 5-3: Instrument Verification Strip Seed Items

IVS item	Description	Depth (cm)	Orientation
T-001	Shot put	30	N/A
T-002	155-mm projectile	50	Horizontal
T-003	81-mm mortar	30	Horizontal
T-004	Blank space	N/A	N/A
T-005	Medium ISO	30	Horizontal

5.3 SYSTEM SPECIFICATION

The MetalMapper sensor and data acquisition system are described in detail in Section 2.1. During the demonstration at MMR, the antenna array was placed in a wooden sled attached to the rear three-point hitch of a tractor (Figure 2-2). A Trimble R8 GPS was mounted directly above the sensor array using a wooden tripod, and an inertial measurement unit was attached to the wooden support used to stabilize the X- and Y-direction transmitters, also directly above the center of the array. These instruments streamed positional data constantly, at a rate of approximately 10 hertz, although the stream rate for the GPS was modified throughout the project in an attempt to solve repeated software crashes. The two instruments were connected to the DAQ via USB (universal serial bus) ports, and the incoming data were used both to navigate from point to point and to locate the collected data.

5.4 CALIBRATION ACTIVITIES

5.4.1 Test Pit and Instrument Verification Strip Data Collection

A test pit was constructed at the site before the arrival of the MetalMapper data collection team. The pit was an approximately 6-foot by 3-foot by 4-foot hole that allowed the collection of static MetalMapper data over TOI expected at the site. The test pit data could then be used for comparison with field data collected over unknown targets. Test pit items were generally oriented in four directions relative to the MetalMapper (vertical, 45 degrees along path, horizontal along path, and horizontal perpendicular to the path) at a single depth selected to produce a strong signal-to-noise ratio for each orientation of the test object. TOI placed in the test pit were intact, inert munitions items received from the Army Research lab or recovered at the MMR site during the surface sweep or previous MMR munitions removal projects. MetalMapper data were collected over the following items:

- Medium ISO
- 81-mm mortar
- 4.2-inch mortar
- 105-mm projectile
- 105-mm high-explosive antitank (HEAT) projectile
- 155-mm projectile

In addition to the test pit data, data were collected over the IVS twice daily. The items in the IVS are identified in Table 5-3. All data collected over the IVS strip were inverted in the field as described in Section 6.2 and compared to the MMR target library as described in Section 6.4. Two tests were performed using the IVS data:

- Inverted locations were compared to the known locations for the IVS seed items, with the differences between the modeled and known locations expected to be less than 15 cm X,Y and 10 cm depth; and
- The item identified by the target library comparison was compared to the actual buried item, and it was expected that the identified item matched the TOI with a relatively high confidence (0.7 weighted metric confidence expected in the field). Identified results were considered a match to the IVS seed as long as the sizes of the two items were relatively similar (e.g., medium ISO seed identified as a 60-mm projectile was acceptable, shot put identified as an 81-mm mortar was not).

IVS testing results are detailed in Section 7.1.

5.4.2 Background Data

Given the high density of targets within the survey area, background data could not be collected efficiently within the grids because background locations could not be identified either in the EM61-MK2 data or by maneuvering the MetalMapper in the survey area. Therefore, background data from the IVS strip (location T-004) were used to correct each day's survey data. The background point used to correct data (i.e., morning or afternoon) was determined using the point collected closest in time to the point being corrected. Generally, each IVS point was used to correct approximately half of the points collected each day.

5.5 DATA COLLECTION PROCEDURES

The operator moved the array by lifting the sled, navigating to the vicinity of each selected point using the graphic display on the computer monitor in front of him, and setting the MetalMapper down on the point. Reacquisition of the EM61-MK2 targets selected for cued data collection was accomplished using "dancing arrows" displayed on the monitor. The "dancing arrows" display shows the seven receivers in the array, arranged as they are in the Z-coil, typically with a blue arrow pointing out of each. The arrows point toward the metallic source nearest each of the receivers. Under ideal conditions, there is one source in the vicinity of the selected point, and all of the arrows point inward toward the center of the array. In the case of multiple sources, one or more of the outer arrows may point outward from the array toward another piece of metal. Generally, the operator attempted to position the array such that, at least, the arrows in the three receivers closest the middle of the coil were pointing at each other.

The MetalMapper's single-point or cued-collection mode was used for all data collection at MMR. Once the MetalMapper was positioned correctly above the target, the operator collected a data point using the settings indicated in Table 5-4.

Table 5-4: Acquisition Parameters Used during the Camp Beale Demonstration

Mode	Tx Mode	Hold-Off Time (µs)	Block Period(s)	Rep Fctr	Dec Fctr (%)	Stk Const	Base Freq (Hz)	Decay Time (µs)	No. Gates	Sample Period (s)	Sample Rate (S/s)
Static	ZYX	50	0.9	27	10	10	30	8,333	50	9	N/A

µs = microsecond(s); Hz = hertz; s = second(s); S/s = samples per second

Static targets were identified according to the identification determined for each target picked in the dynamic EM61-MK2 survey. In the case of repeated measurements associated with a single target point, 10,000 was added to the original identification (e.g., the re-shot for 0001 was 10001).

5.5.1 Scale of Demonstration

Parsons' field team collected 2,312 data points during the project for 2,271 targets. Sixteen of the 2,287 targets selected in the EM61-MK2 data could not be collected due to vegetation or terrain. Additional points were re-shots of already collected points due to a high offset between the location of the center of the MetalMapper and the modeled location of a target, points due to a high offset between the location identified in the EM61-MK2 survey and the center of the MetalMapper, and points that may have been incorrectly identified during initial collection. A distance of 40 cm between the array location and the modeled location was considered the greatest acceptable distance between those two points. The greatest acceptable distance between the EM61-MK2 pick and MetalMapper collection point was 73 cm, which was based on the standard USACE measurement quality objective of ½ of the survey line spacing (75 cm for the EM61-MK2 survey) plus 35 cm for allowable offset between seed items and target selection locations. Re-shots were collected for any targets with larger offsets.

5.5.2 Sample Density

One data point was collected per target, as described in Section 5.5; re-shots were collected for targets with modeled locations greater than 40 cm from the collection location or for collection locations farther than 73 cm from the EM61-MK2 pick.

5.5.3 Data Quality Checks

An instrument calibration check was conducted at least twice a day (at the beginning and the end of the field day). These checks ensured that the instrumentation was functional, properly calibrated, and stable.

A final check on the quality of static data was performed after initial inversion was performed using the UX-Analyze module in Oasis montaj. Inverted target locations were compared to data collection locations to determine if offsets between the two are greater than 40 cm. The collection location was also compared to the location of the EM61-MK2 target. Re-shots were collected for targets with collection to modeled locations greater than 40 cm or EM61-MK2 pick to collection locations distances greater than 73 cm.

5.5.4 Data Handling

Data were recorded in binary format as files on the hard disk of the MetalMapper DAQ. These data were offloaded to other media at least once, and sometimes more frequently, per day. The computer's hard disk had enough capacity to store all the data from the entire site, so these data were not erased until they had been thoroughly reviewed and archived. The data file names acquired each day were cataloged (usually on a spreadsheet) and integrated with any notes or comments in the operator's field book. All data ended up on the hard drives of one or more laptop computers used to post-process data. Data were also archived to a data server in the Parsons office.

Raw binary files were preprocessed using the TEM2CSV software package, which outputs "preprocessed and located" data files in a text readable format (.csv). Preprocessing included the location of the point in UTM meters and subtraction of background. Located and background-corrected .csv files were imported into Oasis montaj for further processing and analysis.

5.6 INTRUSIVE PROCEDURES

Intrusive operations were broken down into two phases, I and II. Phase I was performed between July 17, 2012, and August 10, 2012, and included the investigation of all the TEMTADS-only grids in the northern area and a signification portion of the TEMTADS/MetalMapper and MetalMapper-only grids in the southern area. A total of 1,362 targets were investigated during Phase I, including all of the TEMTADS-only targets that could be investigated, all 300 of the combined TEMTADS/MetalMapper targets, and approximately 600 MetalMapper-only targets. The only TEMTADS-only targets not investigated were within the road passing through these grids, and no intrusive operations were performed on or near the road. Phase II of the intrusive investigation took place between May 20, 2013, and June 20, 2013, and included 1,049 of the remaining 1,386 MetalMapper-only targets not investigated during Phase I. The final 337 targets were not excavated due to time constraints at the site. Table 5-5 summarizes the targets investigated and sources recovered by intrusive phase.

Intrusive operations began with site-specific training, which included prepping the staging area for intrusive activities and performing equipment checks. The staging area consisted of a 20-foot-long connex box approximately ¼ mile from the survey area. All Parsons intrusive equipment was stored in the connex and locked at the end of the day. Daily equipment checks included confirming GPS accuracy over known monuments, EM61-MK2 static tests, and handheld analog instruments calibrations.

All excavated anomalies, excluding the seed items, were placed in a sandbag and stored in the connex. MEC items discovered during the intrusive operations were flagged and Tetra Tech was notified immediately. Parsons' intrusive team worked with Tetra Tech UXO personnel throughout the project on protocols involving MEC and overall safety. Parsons also kept daily communications with range control and the U.S. Army Corp of Engineers on the schedule of the impact areas and planned accordingly to work around live firing operations. Phase II intrusive operations were conducted in a similar manner to the Phase I operations, except that the recovered items from each target location were not bagged and stored separately.

Table 5-5: Intrusive Phase Summary

Intrusive Phase	Southern Grids Targets Investigated	Southern Grids Sources Recovered	Northern Grids Targets Investigated	Northern Grids Sources Recovered
Phase I	901	2,789	431	1,227
Phase II	1,049	5,109	0	0

Personnel on site to conduct the intrusive operation included only Parsons with Tetra Tech supporting demo operations on a separate contract. The field team consisted of seven Parsons personnel. Parsons' site safety and health manager and site manager conducted daily site safety briefings, as appropriate.

5.6.1 Equipment

The equipment used during the MMR intrusive activities included the following:

- Schonstedt Magnetic Locator (Model GA-52Cx)
- Whites Metal detector
- EM61-MK2
- Trimble R8 GPS system
- Digital level
- Miscellaneous hand tools
- Digital cameras

5.6.2 Field Procedures

Reacquisition of all targets was conducted using the Trimble R8 GPS system. The GPS base station was set up on survey monument established using the Tetra Tech base station. Parsons flagged all target locations with a plastic pin flag marked with the target identification and EM61-MK2 pre-value. The depth estimations determined the initial approach to every target. To preserve the azimuth and inclination of the anomalies, the digging of all targets began with skinning the surface manually by hand. Azimuth data reflected magnetic north; inclination was determined using a digital level and readings reflected positive or negative from horizontal. Location data captured by GPS was used to document the center mass and elevation of each item. A photograph was collected of the item with written dig result data on a whiteboard. An EM61-MK2 unit was used to scan the location to confirm the absence of all metallic items from that target location.

The Parsons team leader who orchestrated the movements of the different tasks associated with the information-gathering process recorded all documentation on a dig sheet. The intrusive operations consisted of two intrusive teams: a heavy-equipment team and a hand-dig team, based on the depth and difficulty of the excavation. As the two teams excavated the anomalies, other Parsons personnel helped with the documentation and GPS tasks.

Munitions debris (MD) and cultural debris (CD) scrap collected from target locations was stored in labeled burlap sandbags with the pin flag. Large 155-mm projectiles were stored in a designated area determined by Tetra Tech. Parsons' senior UXO and site safety officer worked with Tetra Tech to transfer the certified MD scrap to a holding location used by Tetra Tech as part of their ongoing project. All seed items recovered from intrusive operations were stored in a secure area and prepared for final shipment.

All target locations were backfilled after completion of the excavation. After the final anomalies were excavated and backfilled, Parsons conducted a walkthrough and confirmed that all holes were filled and no trash was left.

Excavation data collected by the intrusive team was digitally downloaded to a database and reviewed daily. The daily information required the target ID to be connected with intrusive documentation, photo, and GPS coordinates. Assessment of each target item required the coordinates to match the original location and the picture to match the documented findings. Photographs of the intrusive operation are shown in Figure 5-1.

5.7 INTRUSIVE RESULTS

5.7.1 Phase I Results

During the Phase I intrusive operation, Parsons investigated 1,376 anomalies. These included all of the anomalies in the northern area except for those in or near the road, and 895 in the southern area. On average, 86 digs were completed per day, based on 16 intrusive days. Given multiple items recovered from the majority of the anomaly locations, more than 4,000 sources were removed during the investigation. Most of the MD encountered consisted of large pieces of munitions fragments and empty projectiles. The results of the Phase I intrusive investigation are summarized in Table 5-6.

5.7.2 Phase II Results

Parsons investigated 1,049 anomalies in the southern area during the Phase II investigation. As with the Phase I effort, multiple items were recovered from most of the intrusive locations, and more than 5,000 sources were removed during the investigation. On average, 53 digs were completed per day, based on 20 intrusive days. There were some location issues during the Phase I intrusive investigation due to the proximity of sources to each other and the large number of items pulled from each hole, so more care was taken to reduce the number of holes open at one time during Phase II. This was likely the cause of the discrepancy between the dig rates for the two phases. The results of the Phase II intrusive investigation are summarized in Table 5-6.

Figure 5-1: Intrusive Operation Photos

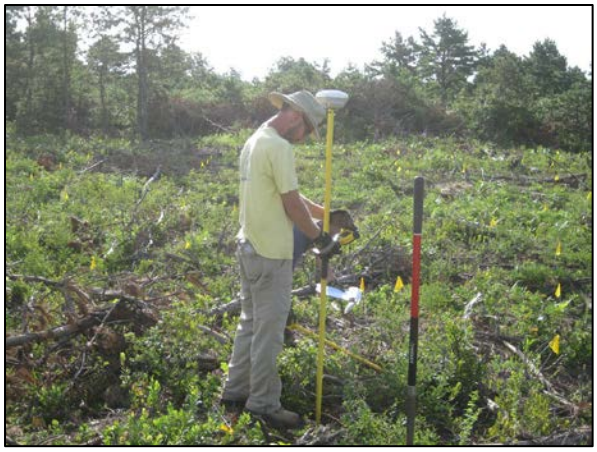


Table 5-6: Intrusive Results

Type	Targets	
Northern Area	**Phase I**	
Targets of interest (munitions and explosives of concern, material potentially presenting an explosive hazard, seed, intact round identified as munitions debris)	26	
Munitions debris	1,129	
Other debris	72	
No contact	0	
Southern Area	**Phase I**	**Phase II**
Targets of interest (munitions and explosives of concern, material potentially presenting an explosive hazard, seed, intact round identified as munitions debris)	126	115
Munitions debris	2,647	4,977
Other debris	13	16
No contact	3	1

5.8 MUNITIONS DEBRIS SCRAP

MD and CD scrap recovered from the demonstration area at MMR were provided to the onsite environmental contractor. The MD/CD scrap filled six 55-gallon drums, all with locks and numbered custody seals. Disposition of the recovered MD was performed by the onsite environmental contractor. Recovered seed items not taken from onsite stockpiles of MD at the beginning of the project were returned to Glen Harbaugh at the Army Research Lab.

6.0 DATA ANALYSIS AND PRODUCTS

The MetalMapper was used to collect static data over 2,271 of the 2,287 targets identified at MMR based on EM61-MK2 data. Sixteen targets were not collected because they were either in the woods or on top of a berm and were inaccessible to the MetalMapper. The processing and analysis steps that were used to generate a dig/no dig decision for each target are described below.

6.1 PREPROCESSING

Raw MetalMapper data are collected and stored as .tem files. The MetalMapper acquisition software uses a convention for assigning a unique name to each data file without the need to manually enter the name. The operator supplies a prefix for the root name of the file (e.g., "Static"). The acquisition software then automatically appends a five-character numerical index to the filename prefix to form a unique root name for the data file (e.g., Static00001). The index is automatically incremented after the file has been successfully written. Although the target identification is not used as the file name in the .tem file, the Target identification is stored in the file according to name of the target highlighted on the MetalMapper screen during collection.

Preprocessing of the .tem files was accomplished using TEM2CSV, a program specifically developed for this purpose. TEM2CSV subtracted the site background from the data point using a background file specified by the user, converted the points from the geographic coordinate system used for collection to the UTM Zone 19N coordinate system used for processing, and exported the resulting data to a .csv file that could be imported into The UX-Analyze package in Geosoft's Oasis montaj software. The exported .csv file name contained both the collection identification and the Target identification (e.g., 1651_Static00001_1651). Preprocessing was typically completed in batches based on time to account for differing background data. At MMR, the survey area contained so much subsurface metal that no background locations readily accessible for frequent re-survey could be identified in the EM61-MK2 data. Therefore, data collected at the background IVS point (IVS-04) in the morning and afternoon were used to correct all of the survey data. Unless there appeared to be a problem with a particular background file, data were tied to the nearest background point in time.

6.2 PARAMETER ESTIMATION

All MetalMapper data points were inverted using UX-Analyze to determine a number of modeled parameters for each target. These parameters included the location, size, and orientation of the source object; the polarizability of each axis of the object; and information regarding the quality of the data and the relative match between the inverted data and the expected model.

All target inversion was initially performed using the UX-Analyze batch processing mode with the multiple object solver enabled. Targets for which multiple objects were identified using the multiple object solver were re-inverted using the batch processor without the multiple object solver enabled. In these cases, the single object and multiple object results were compared to determine which method returned a result more indicative of TOI. Although the multiple object result may have approximated the expected model to a higher degree, the result more indicative of potential TOI was used for target ranking to be conservative. As discussed further in Section 6.4.1, initial dig list results suggested that the UX-Analyze multiple object solver in version 7.5

of Oasis Montaj did not separate out multiple objects effectively enough for some of the targets at MMR. As a result, all of the data were re-inverted using the updated solver in Oasis Montaj version 7.5 T1. The main difference between the two solvers was the number of results obtained for each target. The old solver returned only one result using one algorithm to determine whether various point clouds were modeled as single or multiple objects. The version in the T1 build returned up to four results for each target using four different algorithms to organize point clouds into various combinations of single or multiple objects.

6.3 CLASSIFIER AND TRAINING

6.3.1 Confidence Metrics

The polarization curves developed for each target were compared to a library of known polarization curves compiled using test stand data and test pit data from MMR. The items in the MMR comparison library were limited to the larger TOI expected at the MMR site: 60-mm, 81-mm, and 4.2-inch mortars and 105- and 155-mm projectiles. Examples of various types of these items were used (e.g., 105-mm projectile and 105-mm HEAT round), but items not expected at the site, such as bombs, were not included. Additionally, given the primary goal of the demonstration (i.e., the identification of large MEC items contain relatively large amounts of explosive), smaller MEC such as 40-mm grenades were not included in the library even though they were known to be present on site. An initial comparison between the measured targets and the library data was performed using a weighted confidence metric for the three primary polarizabilities (size: 1, shape 1: 0.5, shape 2: 0.5). During this comparison, the four results from the multiple object solver were compared to the library, and the one with the highest confidence metric was selected for use with that target. If the result selected was not the one already in the target database, the database result was replaced. All further confidence metrics were generated using the multiple object result selected during the weighted metric comparison. In addition to the weighted confidence metric generated during the initial comparison of the results to the library, three more metrics were generated for each target:

1) three-curve metric - size: 1, shape 1: 1, shape 2: 1
2) two-curve metric - size: 1, shape 1: 1, shape 2: 0
3) one-curve metric - size: 1, shape 1:0, shape 2:0

As a first step each target was examined by looking at a figure showing the two closest matches for the weighted, two-curve, and one-curve comparisons to the library. Results were generally grouped into one of five categories:

1) All three polarizability curves ($\beta1$, $\beta2$, $\beta3$) were usable
2) Only two of the curves ($\beta1$, $\beta2$) were usable
3) Only $\beta1$ was usable
4) No usable curves, but it was determined unlikely that there was a target large enough to be TOI in the acquisition location
5) Can’t analyze (no usable curves, and it was considered likely that the curves were unusable despite the existence of a source potentially large enough to be TOI)

The difference between targets deemed likely to have a source potentially related to TOI (can’t analyze) and those with unusable curves due to a small or nonexistent source was typically determined based on the modeled location of the source relative to the collection point and the signal strength calculated for the target in question. If the source was modeled within 40 cm of

the collection location and the signal strength was less than 20, the target was considered likely to be a no contact. The assumption was that the targets with signal amplitudes higher than 20 were considered potentially large objects for which the data might be poor. In addition, the field team recorded notes in their logbook for all targets that could not be found near the picked location using the MetalMapper's dancing arrows. Targets with such notes were removed from consideration as can't analyze targets.

6.3.2 Training Data

Training data selection for MMR began with a comparison of the library data to the survey data using two decay (time gates 8-32 and 8-43) versus size feature space plots (Figures 6-1 and 6-2). A preliminary threshold separating targets possibly representing TOI and targets more likely to be clutter was indentified on each plot based on the location of the library data on the plots. The threshold was set at 0.035 for the 8–32 decay plot and at 0.0045 for the 8–43 decay plot. The initial training data request for MMR was composed of 25 targets selected for their similarity to ordnance based on the library match and on their location within the space plots. All of the targets selected had weighted confidence metrics greater than 0.575, two-curve metrics greater than 0.700, and one-curve metrics greater than 0.800, suggesting a reasonably good match to library TOI. Unlike other sites in the live site demonstration program, a large percentage of the targets at the site fit these criteria. Therefore, many of the training data selections were made to see if targets with relatively strong matches to the library data could be filtered out based on decay. Many of the selected targets were those for which the decay for gates 8–32 was above the 0.035 threshold but the decay for gates 8–43 was below the 0.004 threshold, or vice versa. Additional consideration was given to whether there appeared to be any clusters of targets below either of the thresholds.

Only two of the requested targets were TOI (Figures 6-1 and 6-2), both relatively large-sized targets within the dataset. In addition, both were below the gates 8–32 decay threshold and one was below the gates 8–43 threshold. These results suggested that the use of these thresholds as definitive cutoffs between likely TOI and likely non-TOI was more applicable for smaller sources than it was for larger sources.

6.3.3 Decision Statistic

Classification for the MMR project was accomplished using three of the confidence metrics generated for each target during the comparison to the library data, the weighted metric, the two-curve metric, and the one-curve metric, the feature space plots, and to varying degrees, the decay thresholds. Two Stage 1 classifiers were developed for the MMR data. One used only the 0.035 threshold for the time gates 8–32 decay to a limited degree; the other used the thresholds for both sets of decay values. Two lists were used because the 0.0045 threshold for the gates 8–43 decay appeared to remove a relatively large number of targets plotted near some of the library data. Given the location of these targets on the space plot, it was felt that keeping them on at least one list was a conservative approach that needed to be considered for this site. The more conservative approach used the following classifiers:

- **Priority -1**: Training data
- **Priority 0**: Can't analyze

Figure 6-1: Feature Space Plot (Decay 8-32) Used for Training Data Selection

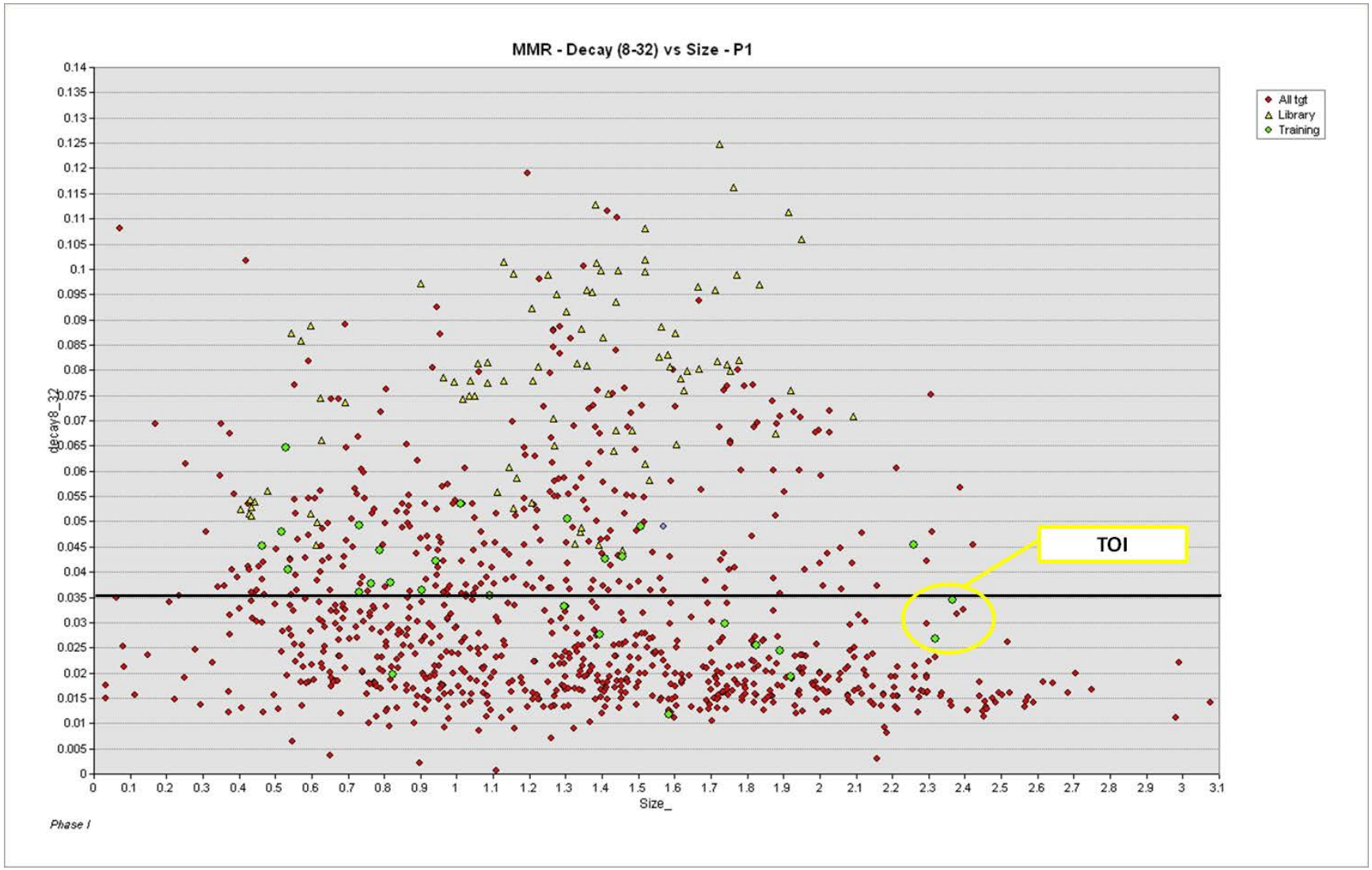
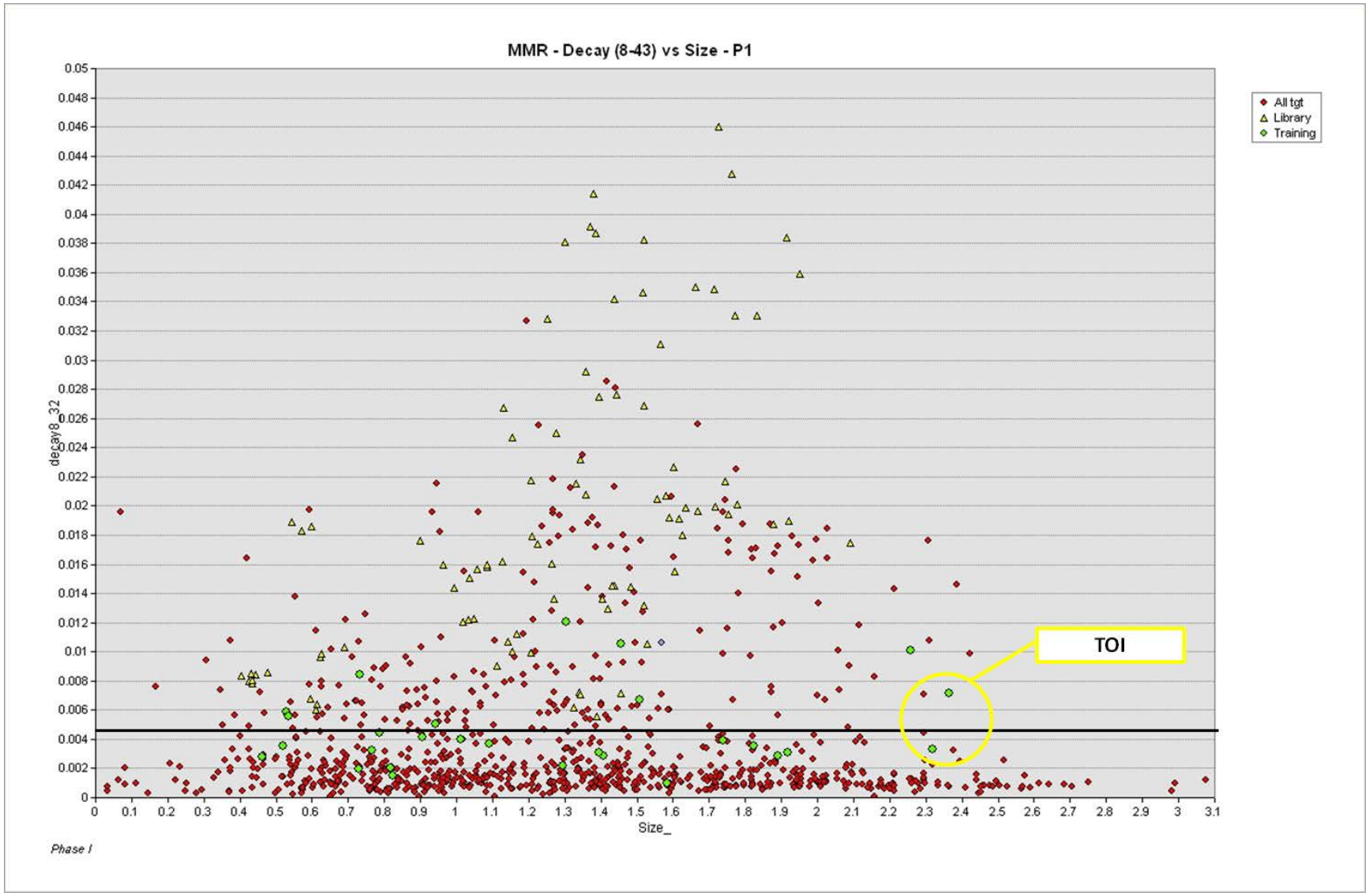


Figure 6-2: Feature Space Plot (Decay 8-43) Used for Training Data Selection



- **Priority 1 (Category 1)** – The following are all true:
  Weighted confidence metric > 0.575;
  two-curve confidence metric > 0.7;
  one-curve confidence metric > 0.8; and
  decay (gates 8-32) > 0.035
- **Priority 2 (Category 1)**:
  Targets classified using only two-curve or one-curve matches and targets with noisy data that were relatively close to being Priority 1 targets.
- **Priority 3 (Category 2 digs)** – The following are all true:
  Weighted confidence metric > 0.8;
  two-curve confidence metric > 0.7;
  one-curve confidence metric > 0.8; and
  decay (gates 8-32) < 0.035
- **Priority 4 (Category 2 non-digs)** – The following are all true:
  Weighted confidence metric between 0.575 and 0.8;
  two-curve confidence metric > 0.7;
  one-curve confidence metric > 0.8; and
  decay (gates 8-32) < 0.035
- **Priority 5 (Category 1)**:
  Targets not meeting the above criteria

This approach did not discard any relatively good matches to the library data based on gate 8–43 decay and classified the better-matching targets below the gate 8–32 decay as "can't decide" digs. The more aggressive approach used the following classifier:

- **Priority -1**: Training data
- **Priority 0**: Can't analyze
- **Priority 1 (Category 1) - The following are all true:**
  Weighted confidence metric > 0.575;
  two-curve confidence metric > 0.7;
  one-curve confidence metric > 0.8; and
  decay (gates 8-32) > 0.035 **or** decay (gates 8-43) > 0.0045 **or** targets added by the analyst based on space plot location
- **Priority 2 (Category 1)**:
  Targets classified using only two-curve or one-curve matches and targets with noisy data that were relatively close to being Priority 1 targets
- **Priority 3 (Category 2 digs)**:
  Either decay value below Priority 1 threshold, but space plot location potentially indicative of TOI. However, location or curve appearance not indicative enough of TOI for immediate addition to Priority 1. Cat 2 digs/non-digs at discretion of analyst.
- **Priority 4 (Category 2 non-digs)** – The following are all true:
  Either decay value below Priority 1 threshold, but space plot location potentially indicative of TOI. However, location or curve appearance not indicative enough of TOI for immediate addition to Priority 1. Cat 2 digs/non-digs at discretion of analyst.
- **Priority 5 (Category 1)**:
  Targets not meeting the above criteria

The decision statistic used to rank the targets for both classifiers was calculated as 5 - priority + weighted confidence metric. The decision statistic was then sorted from high to low to order the targets on the dig lists.

6.4 DATA PRODUCTS

6.4.1 Stage 1 Phase I Dig Lists

The Stage 1 dig list containing only the targets investigated during the Phase I digs was submitted with the following parameters:

- Training Data: 25 items selected as described in Section 6.3.2 (same for both dig lists).
- Can't Analyze: 14 targets that could not be collected; the data for all collected points were deemed usable (same for both dig lists).
- Likely TOI (Category 1): Decision statistic greater than 3.0.
- Can't Decide (Category 2 Digs): Decision statistic between 2.0 and 3.0.
- Can't Decide (Category 2 Non-Digs): Decision statistic between 1.0 and 2.0.
- Likely Clutter (Category 3): Decision statistic less than 1.

The Stage 1 dig lists were only compared to the project seed items identified as "QC seeds." Due to the differing strategies used for classification, the results with respect to the seed items were different for the two lists submitted. The results for each are detailed below.

<u>UXAnalyze1</u>

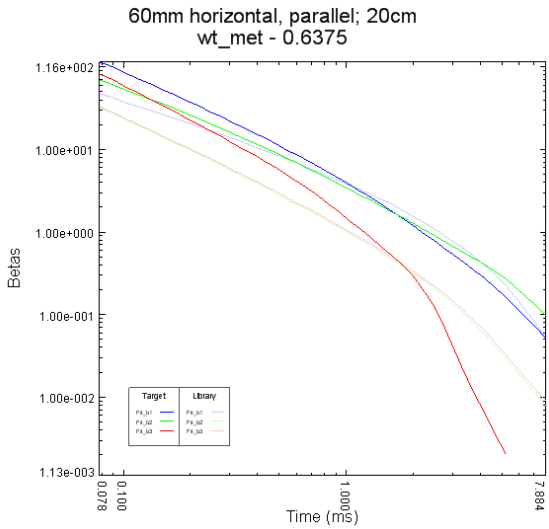
The UXAnalyze1 dig list was the more aggressive of the two lists submitted, and five QC seeds were missed. Analysis of why the seeds were missed was going to be performed following analysis of the more conservative list, but the misses on the more conservative list (discussed below) indicated that further analysis of a more aggressive list would be pointless. Therefore, the analyst did not look at which seeds were missed on this list, simply noting that it performed worse than the more conservative list.

<u>UXAnalyze2</u>

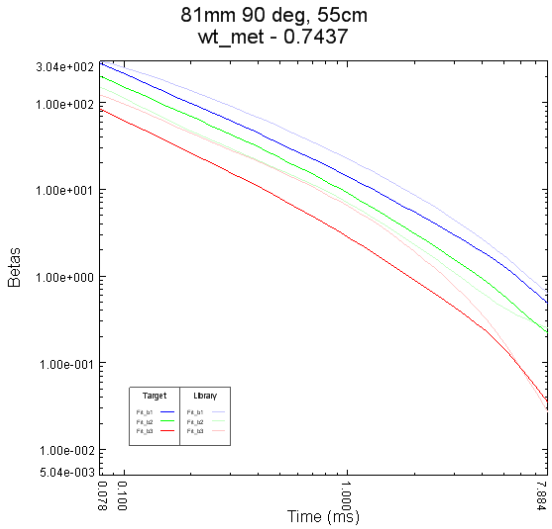
The UXAnalyze2 dig list was the more conservative of the two lists submitted. Comparison with the list of QC seeds indicated that three seeds would have gone un-dug based on the Stage 1 list: CE-1698 and CE-1918, both intact 81-mm mortars, and CE-2180, a 155-mm projectile. The polarization curves for these three items are shown in Figures 6-3A, B, and C.

Figure 6-3: Polarization Curves for Missed Quality Control Seeds

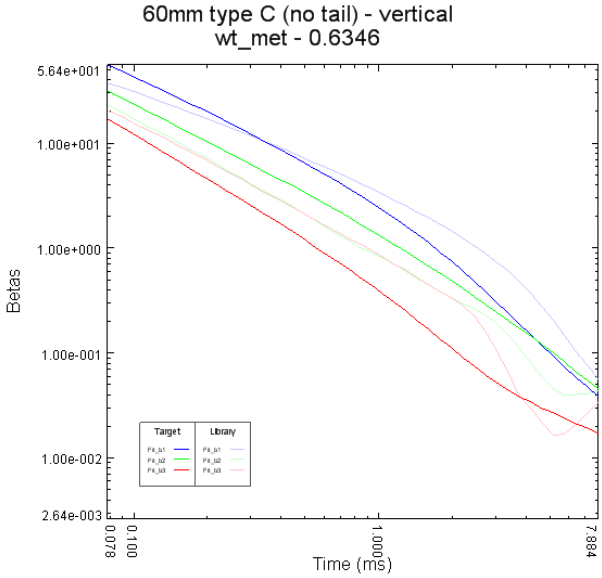
A: CE-1698 (81 mm)



B: CE-1918 (81 mm)



C: **CE-2180 (155 mm)**



As shown in the figures, none of these three items looks particularly ordnance-like based on the curves. CE-1698 and -1918, in particular, look more plate-like than cylindrical. All three were below the 0.035 decay threshold used for this list, and CE-1918 was the only one of the three that had confidence metrics above all three of the weighted, two-curve, and one-curve thresholds. It was felt that modifying the classifier to identify these three targets as items that needed to be intrusively investigated would be worthless because so many targets would have to be added as digs that the MetalMapper survey would not end up saving money over a traditional dig-everything approach. The suspected reason for the non-library-matching results was the inability of the multiple-object solver used to successfully separate out all of the sources contributing to the received signal for these seeds. The result was two (or more) different sources looking like a single plate-like object rather than an 81-mm mortar and frag. Because a new version of

UX-Analyze containing a more advanced multiple object solver had been developed since the initial target inversions were performed, it was decided that the new solver should be tested on the MMR dataset. Revised results for the three missed seeds are shown in Figures 6-4A, B, and C.

While the results don't look significantly better for all items — particularly CE-1698 and -2180, which still look a bit plate-like — the metrics, both with respect to confidence and decay, increased to the point that these targets would now be included as digs using the former classifier. Therefore, the entire dataset was re-inverted using the new multiple object solver. Rather than trying to update the old dig lists with new confidence metrics, the classification process was restarted using the re-inverted data. The training data and Can't Analyze datasets from the UXAnalyze1 and UXAnalyze2 lists were the used for the new lists, except that the three missed QC seeds from the first dataset were included as training data for the new lists.

6.4.2 Stage 1 Dig Lists – Revised

The classification rules for the re-inverted datasets were the same as the original classification rules with the minor exception of the reduction of the gates 8–43 decay threshold from 0.0045 to 0.0040 for the more aggressive of the two lists.

<u>UXAnalyze3</u>

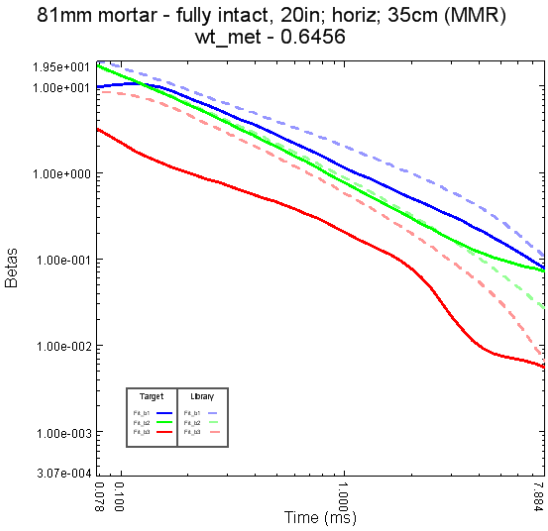
The more conservative classifier from the original inversions was used to compile the UXAnalyze3 dig list. Because it was unknown whether any digs on the first list were classified as likely clutter on this list, it was compared to the QC seed list. No QC seed items were missed.

<u>UXAnalyze4</u>

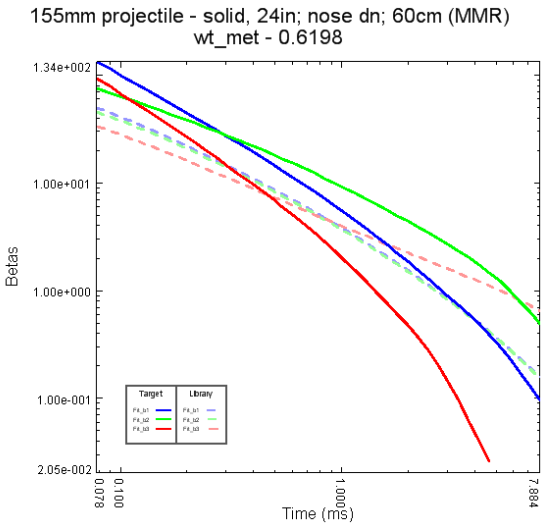
The more aggressive classifier from the original inversions was used to compile the UXAnalyze4 dig list. Comparison with the QC seed list indicated that one seed, CE-2130 (81-mm mortar) was incorrectly identified as likely clutter. Although the confidence metrics for this target were well above the thresholds used as cutoffs for TOI (Figure 6-5), the gates 8–43 decay value was 0.0034, which was below the threshold of 0.004. As a result of the miss, the threshold line for the gates 8–43 decay value was modified as shown in Figure 6-6. Although targets with decays below the original 0.004 threshold were still considered non-digs to begin with, additional consideration was given to adding any that looked like particularly strong matches to TOI, including CE-2130.

Figure 6-4: Revised Polarization Curves for Missed Quality Control Seeds

A: CE-1698 (81 mm)



B: CE-1918 (81 mm)



C: CE-2180 (155 mm)

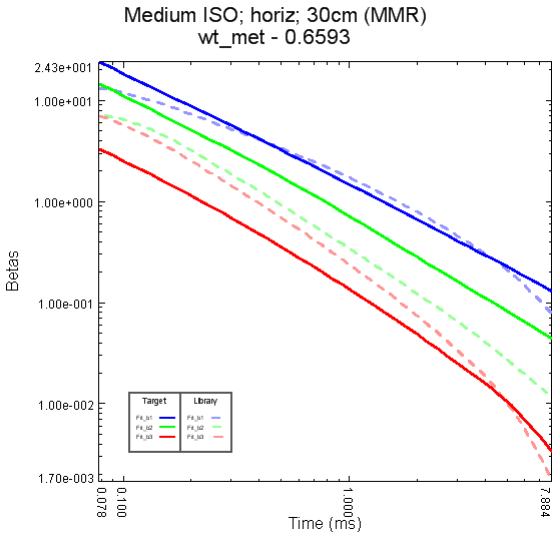
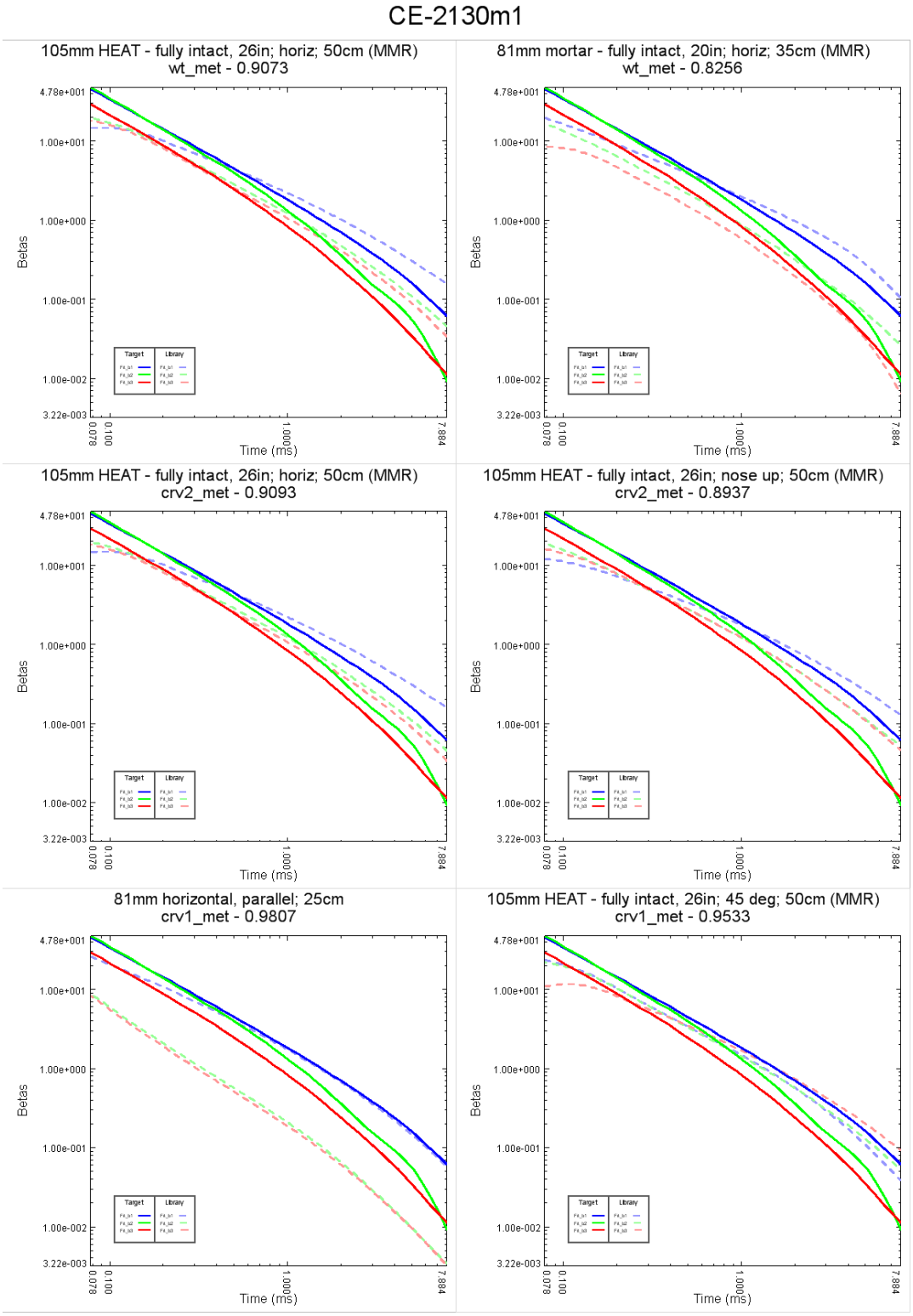
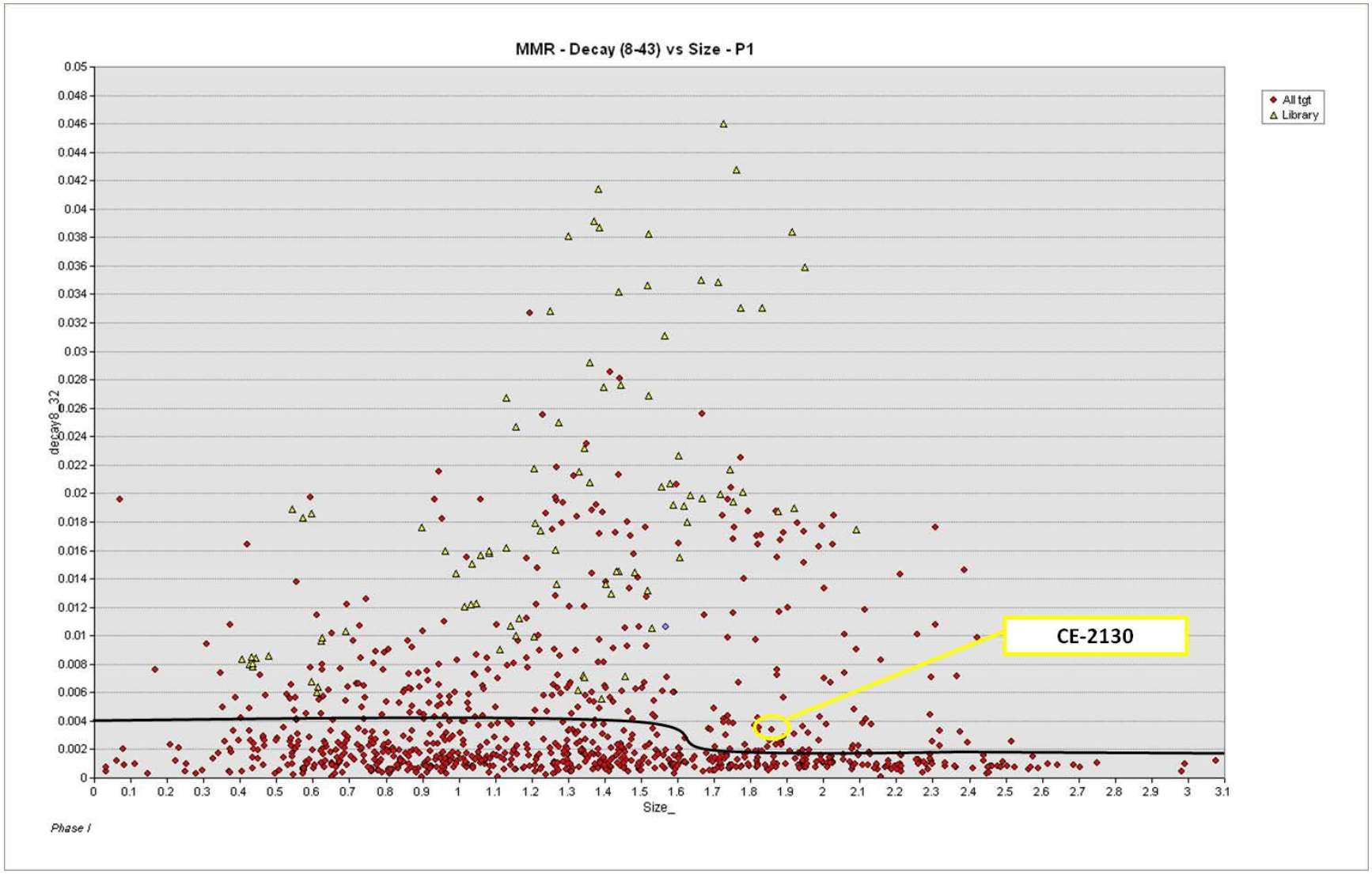


Figure 6-5: Polarization Curves and Confidence Metrics for CE-2130



Top row = weighted metric; middle = 2-curve, bottom = 1-curve

Figure 6-6: Missed Quality Control Seed in Feature Space



6.4.3 Dig List Stage 2

Based on the few misses for either Stage 1 dig list, ground truth, typically delivered after the submission of Stage 2 lists, was delivered based on the targets marked as digs on the Stage 1 dig lists. No major modifications were made to either of the classifiers used for the project. Nine targets were changed from non-digs to digs on the UXAnalyze3 list based on their proximity in feature space to items that were revealed to be TOI in the ground truth. All of these targets had been screened out based on their gate 8–32 decay values in Stage 1. Seven digs were added to the UXAnalyze4 list based either on their proximity to ground truth TOI in the feature space or on the revision of the gates 8–43 decay threshold shown in Figure 6-6. Ground truth for the new digs was returned following the submission of the Stage 2 lists. None of the added digs on either list were TOI.

6.4.4 Dig List Stage 3

None of the targets added to either dig list following Stage 1 were TOI, so there was no reason to modify the classifiers or add any additional targets for Stage 3. Therefore, both lists were compared to the full Phase I ground truth results without any changes to the Stage 2 lists. The final UXAnalyze3 dig list included 373 digs out of a total of 895 Phase I targets (42% dig rate), and the UXAnalyze4 dig list included 309 digs (35% dig rate).

6.4.5 Phase II Dig List

The results of the comparison of the two Phase I dig lists were used to determine the classifier to be used to rank the unexcavated targets remaining at the site following the Phase I intrusive operation. The results, detailed in Section 7, indicated that the TOI detected versus non-TOI removed from consideration as dig targets statistics were better for the UXAnalyze4 classifier. Therefore, this classifier was used to compile the dig list for the Phase II targets.

7.0 PERFORMANCE ASSESSMENT

7.1 OBJECTIVE: REPEATABILITY OF INSTRUMENT VERIFICATION STRIP MEASUREMENTS

One IVS seed item was incorrectly classified (i.e., weighted confidence that the seed item was the seed item or a similarly-sized TOI was less than 0.7) during the project. Because this failure was out of a dataset of 105 IVS items surveyed over the course of the project, the IVS failure rate was slightly less than 1%. The incorrect classification occurred during the afternoon survey of the IVS on June 19, 2012. It is apparent that the data are poor given the lack of a third polarizability curve. Because poor data are collected occasionally with the MetalMapper, the "Can't Analyze" classification has been used to identify targets that must be dug given unusable MetalMapper data. Had this target been in the field rather than in the IVS, it would have been classified as a Can't Analyze and would have been dug.

The standard deviations of the horizontal and vertical differences in location between the actual and modeled locations of the seed items were 4.1 cm and 4.7 cm, respectively. Both are well within the stated goals of 15 cm for the horizontal and 10 cm for the vertical.

7.2 OBJECTIVE: CORRECTLY POSITION METALMAPPER RELATIVE TO SOURCE

The results used for 209 of the 895 Phase I targets had a modeled location greater than 40 cm from the collection location but were judged usable by the analyst based on three factors:

- The target was classified as a TOI despite having a modeled location greater than 40 cm from the collection location;
- The operator noted during collection that there was no source evident at the dynamic target location (based on the dancing arrows display), so data was collected directly on top of the dynamic location to satisfy the requirements of the collection to dynamic target distance data quality objective; or
- The version of the target selected for classification (multiple object solver version of the point selected rather than single object solver version) was more indicative of TOI than a modeled point within 40 cm of the collection location despite being outside the data quality objective radius.

Two hundred thirteen of the 1,392 Phase II targets had a modeled location greater than 40 cm from the collection location for the same reasons.

7.3 CORRECTLY POSITION METALMAPPER RELATIVE TO EM61-MK2 TARGET

One MetalMapper collection point was within 73 cm of every EM61-MK2 target location. Seventeen of the selected results were farther than 73 cm from their dynamic selection locations but were judged usable by the analyst based on the following factors:

- The target was classified as a TOI despite the offset between the collection location and the dynamic target;
- The collected data looked reasonable (i.e., inversion good, no noise) and there were no other dynamic targets within 1.5 meters of the dynamic target in question, signifying that the operator collected data over the intended source; or

- The collection location was outside the dynamic survey area, indicative of a source that was not fully covered by the dynamic survey.

7.4 OBJECTIVE: MAXIMIZE CORRECT CLASSIFICATION OF TARGETS OF INTEREST

7.4.1 Phase I Results

The submitted Stage 3 dig lists were compared to the complete set of the Phase I ground truth data from MMR by the IDA. This comparison identified the same five TOI that would have gone un-dug on both lists:

- CE-1381: 60-mm mortar
- CE-2089: parachute flare
- CE-2128: cartridge
- CE-2141: 155-mm projectile
- CE-2167: 37-mm projectile

Out of the 895 targets classified for Phase I of the MMR project, 148 were considered TOI following the intrusive investigation. Given the five misses, 143 of the 148 TOI (96.6%) at the site were correctly classified as targets that should be dug. Figures 7-1 and 7-2 show the receiver operating characteristic (ROC) curve for the two MMR dig lists.

Figure 7-1: Receiver Operating Characteristic Curve for UXAnalyze3 Dig List

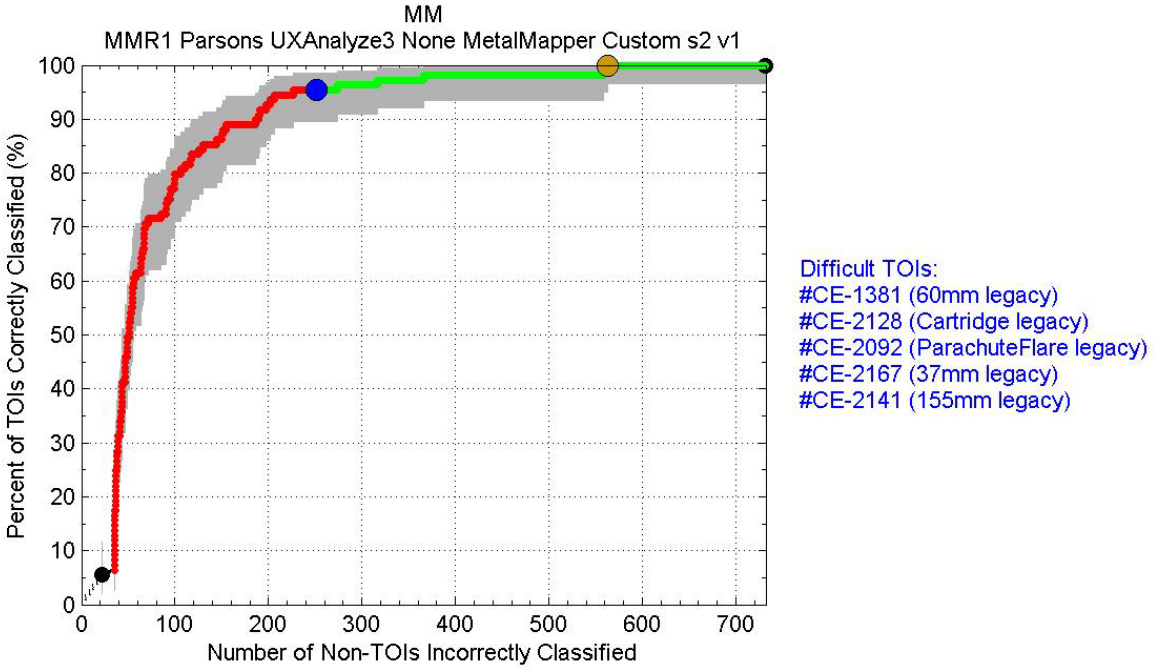
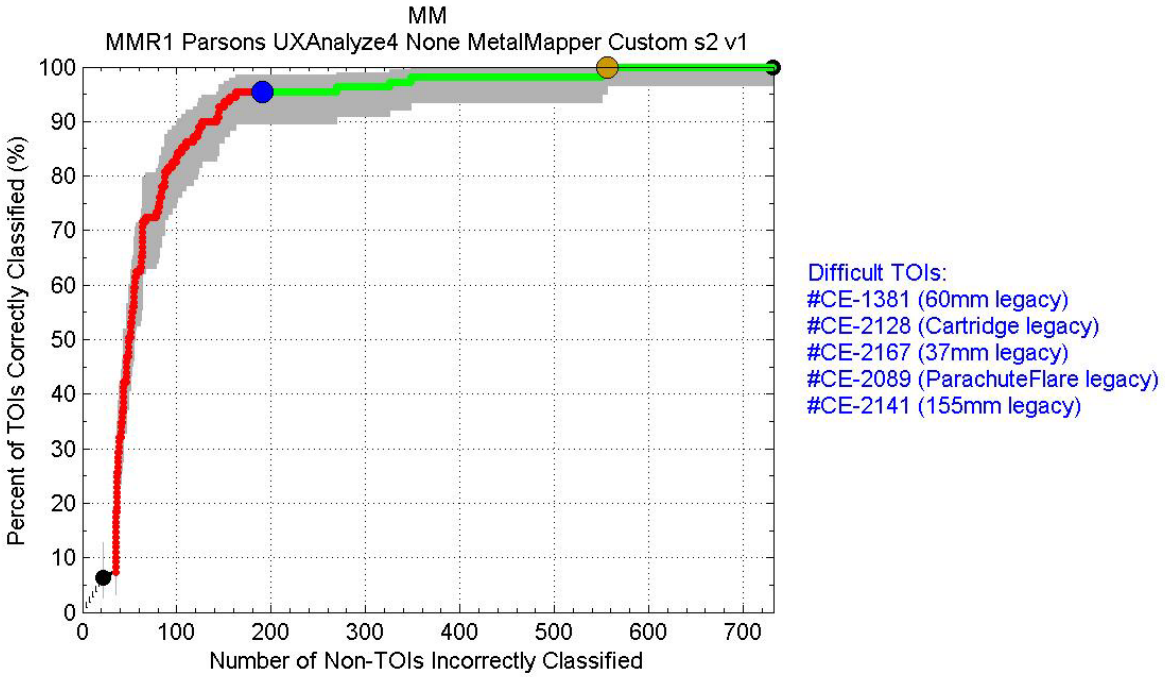


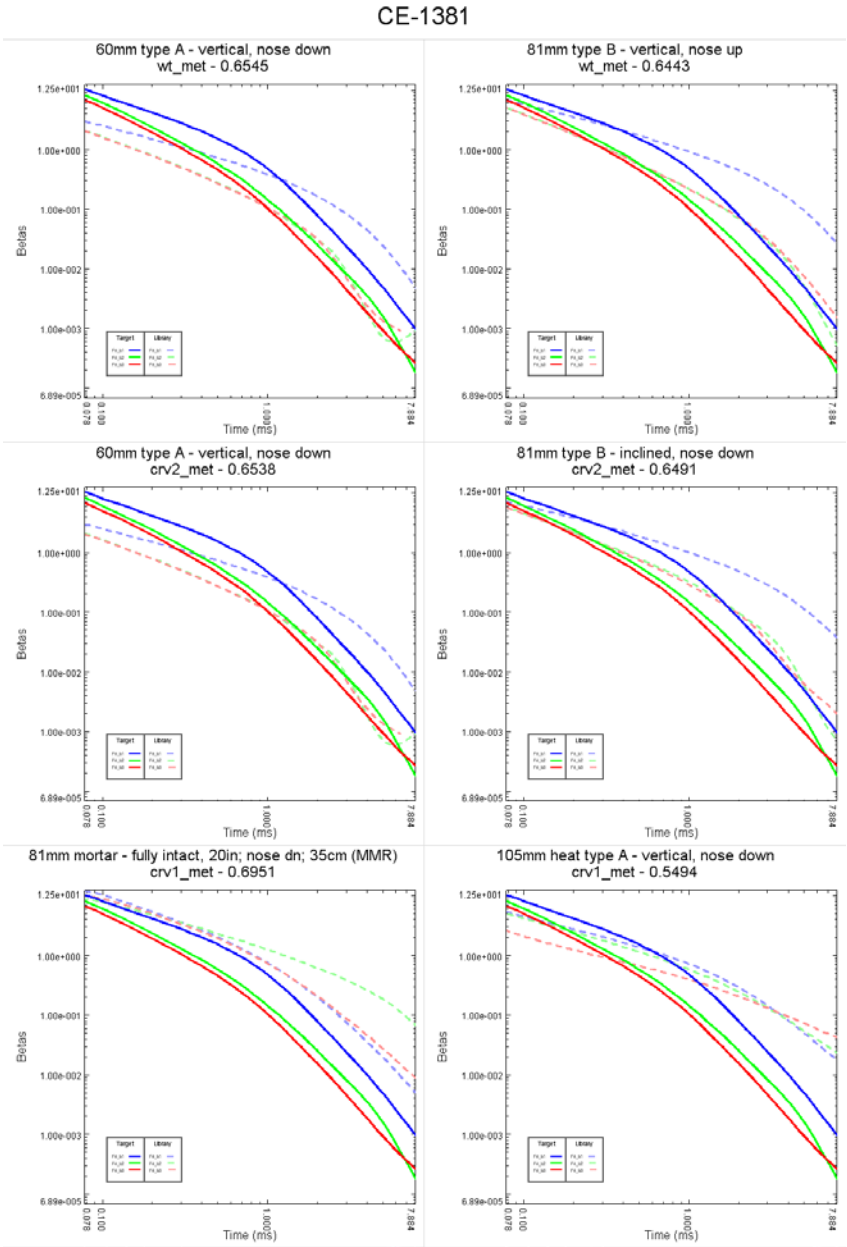
Figure 7-2: Receiver Operating Characteristic Curve for UXAnalyze4 Dig List



Although identified as TOI by the IDA during scoring, three of the five missed items were not considered high-priority removals given the goals of the project (i.e., the identification/removal of large munitions containing the majority of the energetic filler that could contribute to groundwater contamination). Only the 60-mm mortar (CE-1381) and the 155-mm projectile (CE-2141) were identified as munitions of primary interest in the *ESTCP Demonstration Plan* (ESTCP, 2012). CE-1381 was not identified as a TOI based on the two-curve and one-curve confidence metrics, which were both below their respective thresholds of 0.700 and 0.800 (Figure 7-3).

It is suspected that the 60-mm mortar examples in the library did not match the recovered illumination round warhead very well. There were four versions of 60-mm mortar rounds in the library, three of which were in the standard MetalMapper library supplied with UX-Analyze and one of which was from test pit data collected at the former Camp Beale in California. Because there are no pictures of the three versions in the default MetalMapper library, it is unknown how closely they match the one recovered at MMR. However, Figure 7-4 illustrates the differences between the MMR and Camp Beale mortars.

Figure 7-3: Polarization Curves and Confidence Metrics for CE-1381



Top row = weighted metric; middle = two-curve, bottom = one-curve

Figure 7-4: 60-mm Mortar Types

A: MMR **B: Beale Test Pit**

Because there were possibly significant differences between the 60-mm examples in the library and the recovered item, a possible solution to the false negative was adding this item to the library. However, the two decay values calculated for this item (0.019 for time gates 8–32 and 0.0007 for gates 8–43) were low enough that it would have been classified as non-TOI even if the confidence metrics had been higher. Adding this item to the library and modifying the decay thresholds to select it as a target would have added a substantial number of digs to the project. Given the project goal of reducing the amount of energetic material in the subsurface rather than removing every piece of TOI, it was not recommended that these changes be made to identify one specific partial 60-mm mortar round.

The ground truth results for CE-2141, the missed 155-mm projectile, did not include a recovered location. Therefore, it is difficult to make any definitive statements regarding the misclassification of this item as non-TOI. The multiple-object inversion returned two TOI-like results for this item, one that matched an 81-mm mortar with weighted, two-curve, one-curve confidence metrics of 0.73, 0.73, and 0.90, and one that matched a 60-mm mortar with confidence metrics of 0.82, 0.81, and 0.90. Based on the higher confidence metrics and an extremely low gate 8–43 decay value of 0.0009 for the source that matched the 81-mm mortar, the source matching the 60-mm mortar was selected as the result for this target. It was ultimately not selected as a dig based on its decay values (0.020 for time gates 8–32 and 0.0023 for gates 8–43) rather than confidence metrics.

However, because there was no recovery location, it is unclear exactly how close the recovered 155-mm projectile was to either of the modeled results. In addition, the result for CE-2151 suggested that this target was a 105-mm HEAT round that should be dug. The modeled location of this target was approximately 1.2 meters from the recommended dig location for CE-2141. CE-2151 was not intrusively investigated during the Phase I or Phase II intrusive operations, apparently due to a lack of time. It is possible that the 155-mm may actually have been recovered closer to that EM61-MK2 target and been the reason for the “dig” recommendation there. Without more detail about where the 155-mm listed as the results for CE-2141 was actually recovered, it was not recommended that the classifier be modified to detect it.

7.4.2 Phase II Results

The single dig list submitted for Phase II of excavation was compared to the complete set of Phase II ground truth data by Parsons. Of the 1,386 targets remaining uninvestigated following Phase I, only 1,049 were excavated during Phase II due to time constraints at the site.

Twenty of 115 items identified as TOI following the intrusive investigation were incorrectly classified as non-TOI in the Phase II dig list, meaning that only 83% of the TOI were correctly classified as TOI. One of the false negatives was for a 37-mm projectile, which was not considered a high-priority target, as discussed in Section 7.4.1. The other 19 were 60-mm projectiles, 17 of which were the same type of illumination round warhead shown in Figure 7-4A. The other two were fuzed HE rounds, which were again thought to be dissimilar to the 60-mm mortar examples in the classification library. Because so many more illumination rounds were recovered during the Phase II intrusive investigation, three examples of these and one of the HE rounds were added to the classification library, and the full dataset was re-compared to the library. Addition of the illumination round examples to the library resulted in the detection of all of the others using the current classifier (without any decay thresholds). However, the number of digs added to correctly identify these as TOI appears to be huge (more than 700 upon a quick review). A more thorough reclassification effort would need to be performed to determine the exact impact on the dig rate at the site. However, it appears these warheads are quite similar geophysically (smaller size and faster decay than most of the other TOI identified at the site and polarizability curves similar to many of the fragments or fragment pits) to a great deal of the clutter at the site.

7.5 OBJECTIVE: MAXIMIZE CORRECT CLASSIFICATION OF NON-TARGETS OF INTEREST

7.5.1 Phase I Results

The submitted UXAnalyze3 dig list correctly identified 69% (517 of 747) of the clutter as clutter in the dataset, although this did include the misidentification of five TOI as non-TOI. The UXAnalyze4 dig list correctly identified 78% (581 of 747) of the clutter as clutter with the same five missed TOI. As discussed in Section 7.4, no modifications were recommended for either classifier in order to consider these TOI "detected." With no modifications, these percentages could be considered the approximate reductions in clutter digs that would be seen using either of the classifiers.

However, as indicated in Figures 7-5 and 7-6, there were no TOI recovered at the site with a size less than approximately 0.8. It therefore seems reasonable to set a bottom threshold for the size of a target to be considered TOI, as has been done with the two decay values. In the case of the Phase I targets, the removal of any targets with sizes less than 0.65 would have reduced the number of dig targets on the UXAnalyze3 dig list by 44 (75% reduction in clutter digs) and those on the UXAnalyze4 list by 30 (82% reduction in clutter digs). The Phase II dig list for MMR was submitted using this threshold. Future use would likely depend on the results of the Phase II dig list versus seed item comparison.

The dashed lines on both figures are the initial decay thresholds used to separate TOI from likely clutter. Re-addition as potential TOI was strongly considered for any targets above/to the right of the solid lines, with re-addition based on confidence metrics and polarization curve appearance. The TOI below the solid lines on the figures were the five missed items discussed in

Section 7.4, were correctly classified as targets that should be dug based on the use of less than three polarization curves (somewhat poor data), or were sources for which more than one point was collected (i.e., two or more EM61-MK2 targets were picked on the same source). In the case of the sources with more than one EM61-MK2 target, at least one of the MetalMapper points collected in the vicinity was labeled as a dig.

7.5.2 Phase II Results

Prior to the re-comparison of the full dataset to the classification library containing the 60-mm illumination round warheads and the HE mortar example, the Phase II dig list contained 407 digs for 1,392 targets, including the 115 TOI in both numbers. Without the TOI, there were 292 non-TOI digs for 1,277 non-TOI targets, which represented a reduction in non-TOI digs of approximately 77%. As mentioned in Section 7.4.2, a quick re-classification effort indicated that adding the illumination rounds to the library and disregarding the decay thresholds currently used in the classifier would significantly decrease the amount of clutter that could be left in the ground at this site.

7.6 OBJECTIVE: CORRECT SPECIFICATION OF NO-DIG THRESHOLD

7.6.1 Phase I Results

Because items were missed in the comparison of the dig lists to the ground truth set, the no-dig thresholds on the submitted dig lists were set incorrectly. Target CE-1381, the missed 60-mm mortar, was 339 spots below the dig threshold in the UXAnalyze3 dig list and 396 spots below the threshold on the UXAnalyze4 dig list. As indicated in Section 7.4, it seemed that modifying the classifiers to detect this item would result in so many additional digs that the use of the MetalMapper at MMR would not be particularly worthwhile. Given the nature of the problem at MMR (groundwater contamination from energetic material versus explosive hazard), the stop dig thresholds were deemed appropriate for both dig lists.

7.6.2 Phase II Results

The recovery of 17 of the 60-mm illumination round warheads during the Phase II intrusive investigation indicated that they were much more prevalent than indicated by the Phase I investigation. As with the Phase I list, the illumination rounds were relatively low priority within the no-dig section of the ranked dig list. A retrospective analysis of the data performed after adding examples of the illumination rounds to the classification library indicated that they could be identified as TOI using a classifier similar to the one used to compile the Phase I and Phase II dig lists. However, the number of dig targets added to the dig list in order to find these warheads appears to be quite significant if only the confidence metrics used in the classifier are considered. Additional effort would be necessary to perform a full reclassification of the data using the modified library and to determine if additional filters could be developed using size/decay values or other geophysical characteristics to separate the items from much of the clutter at the site.

Figure 7-5: Feature Space Plot (Decay 8–32) Showing Targets of Interest Recovered during Massachusetts Military Reservation Phase I

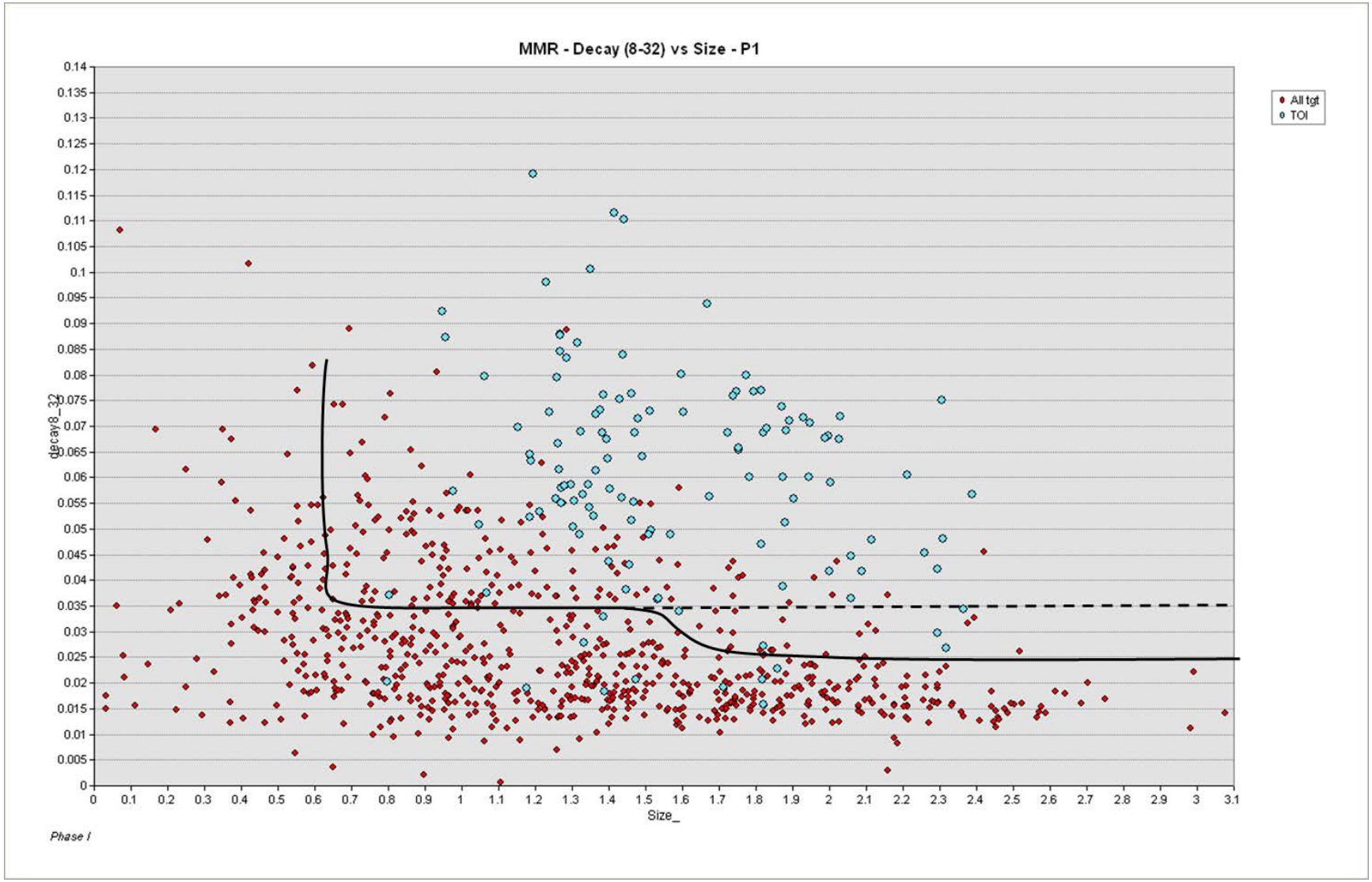
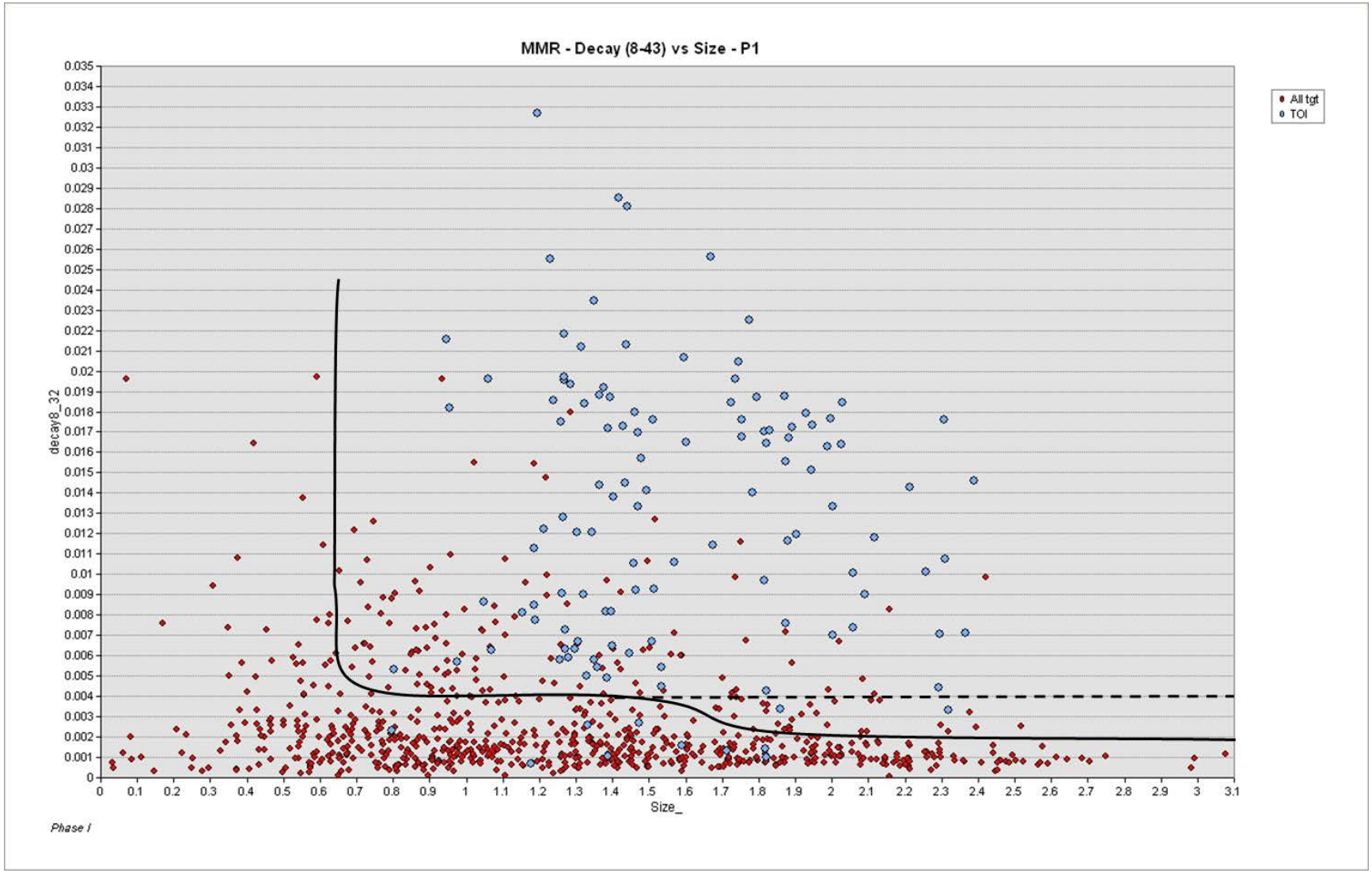


Figure 7-6: Feature Space Plot (Decay 8–43) Showing Targets of Interest Recovered during Massachusetts Military Reservation Phase I



7.7 MINIMIZE NUMBER OF ANOMALIES THAT CANNOT BE ANALYZED

The same 14 targets were classified as Can't Analyze on the dig lists submitted. All 14 were targets that could not be collected due to topography and/or vegetation. All collected points were deemed usable. Because topography is beyond the scope of the field team or data analyst to control, the Can't Analyze rate for this project is considered to be 0%.

7.8 CORRECT ESTIMATION OF TARGET PARAMETERS

The target parameters estimated in this case were the X, Y, and relative Z (depth) coordinates of the targets. Because the goal with this objective is to direct the dig teams to the correct locations for TOI, the comparison of estimated coordinates to actual coordinates was performed only for TOI and for those targets marked as digs in the ranked dig list.

7.8.1 Phase I Results

The success criteria for this performance objective were X, Y offsets for which one standard deviation of the dataset was less than 15 cm and one standard deviation of the depth offset was less than 10 cm. The horizontal offset for the TOI dataset was above the performance objective, with a calculated standard deviation of 28 cm, as was the depth offset, with a calculated standard deviation of 18 cm. The results for all targets marked as digs were similar, with calculated standard deviations of 30 cm for the horizontal offset and 14 cm for the vertical offset. It is assumed that a combination of the high target densities at the site and the relatively large size of the objects being recovered are responsible for the larger-than-expected horizontal offsets. The high target densities could be creating problems for the multiple object solver, which may not be modeling location as effectively as anticipated. The intrusive team also used the same central point as the defined location of the "source" if multiple objects were recovered near one another. Many of the objects recovered during this project were quite large compared to those recovered at other sites, so there may be some discrepancy between the center of mass per the intrusive team and the center of mass per the modeled results, particularly in the case of locations with multiple objects recovered. Finally, the site was covered in craters, stumps, and brush piles. A great deal of the vertical offset, which is quite a bit higher than that seen on previous demonstration sites, may be because the data collection team was often unable to lay the MetalMapper flush with the ground surface.

7.8.2 Phase II Results

The standard deviation for the Phase II TOI horizontal offset was 19 cm, and the standard deviation for the Phase II vertical offset was 11 cm. Both were above the performance objectives, although they were much closer to the objectives than the Phase I data were. It is expected that a greater emphasis put on recording GPS coordinates for each recovered item during Phase II was the reason for the increased accuracy. The horizontal and vertical offsets for the dig targets were both 15 cm for the Phase II intrusive effort.

8.0 COST ASSESSMENT

The cost assessment was split into two groups: MetalMapper costs and conventional intrusive costs. The MetalMapper costs include instruments, surveying, seeding, and analysis costs; the conventional intrusive costs include surface sweep, data collection, and intrusive costs.

8.1 COST MODEL

The cost model for the MMR demonstration includes the total cost of the project and potential savings from the classification process. The total cost includes the seeding operation, MetalMapper operations, processing, and intrusive operation. Estimates for each operation are listed in Table 8-1.

Table 8-1: Details of Costs Tracked

Cost Element	Data Tracked During Demonstration	Estimated Costs
Seeding Costs		
Seed emplacement / initial set up	Costs for surface sweep, seed emplacement, surveying seeds	$45,103
MetalMapper Survey Costs		
Instrument Costs	MetalMapper rental ($500/day; 29 days)	$14,500
	MetalMapper prep fee (project)	$1,000
	MetalMapper shipping (project)	$2,769
	Tractor rental (project)	$1,365
	Tractor mob/demob (project)	$250
	RTK GPS cost ($800/week; 3 weeks)	$2,400
	Shipping (RTK GPS, etc; project)	$324
	Total	**$22,608**
	Per target	**$9.88**
Survey Costs	Field-related labor (two geophysicists), equipment setup, test pit data collection, cued data collection, preprocessing, initial target inversion for quality control checks, non-equipment direct costs (e.g., per diem, hotel, truck rental, fuel)	$46,995
	Per target	**$20.54**
Analysis Costs	All processing and analysis performed following the completion of field activities	$8,626
	Per target	**$3.77**
Intrusive Costs		
Investigations	All costs related to the intrusive investigation	$363,455
	Cost per anomaly to intrusively investigate	$152

Although the MetalMapper used for data collection at MMR was funded by ESTCP, standard rental costs and prep fees were used to determine the cost for the MMR project had Parsons rented the MetalMapper for the duration of the project. Survey and analysis costs were tracked using a task-specific number in Parsons' project controls system. Although production rates were higher on this project than on previous demonstration projects, another reason for the significant drop in MetalMapper survey costs was the addition of a UXO technician to the field team for safety purposes on Parsons' two earlier field projects. Given the full surface sweep performed before this project, the tech was unnecessary at MMR.

The final result of the classification process provides an alternative approach to the final costs of the intrusive operations. The analysis compares costs of using MetalMapper versus digging all anomalies classified as no-digs. The cost model assumes the use of the UXAnalyze4 classifier. As discussed in Section 7.4, this classifier is expected to reduce the number of clutter digs necessary at the site by as much as 82%, although the proven result of 78% for Phase I will be used for the model. The cost of MetalMapper classification and analysis at MMR was $34.19 per target.

The overall cost of excavating the 2,381 Phase I and Phase II anomalies was approximately $363,455 ($152/anomaly). However, this is a factor of the relatively small scale of the demonstration project and the challenging vegetation conditions at this site. As shown in Section 8.3, the MetalMapper would likely prove to be a cost-saving tool on a larger scale project.

8.2 COST DRIVERS

Based on the factors described above, the total per-target cost for the MetalMapper-related work of the MMR project was $34.19. The production rate for the project was 207 targets collected per day, which did not include re-shots as part of the collection. The average production rate prior to the collection of re-shots was 227 targets per day. These seem like achievable rates at this site; therefore, Parsons considers $34.19 per target a reasonable estimation of the costs that would be expected for future projects at MMR.

For the intrusive investigation phase at MMR, Parsons investigated 2,381 anomalies in 36 intrusive days. The average anomalies intrusively investigated per day was 68 anomalies, which was fewer than the estimated 80 anomalies per day planned for the project. The decrease in productivity was almost entirely due to the need to clear multiple sources at each target location. The most common item excavated at MMR was MD (frag).

8.3 COST-BENEFIT

For a production removal action project with 10,000 anomalies selected for investigation, the $34.19/anomaly cost calculated for the demonstration was used for data collection and processing. The intrusive costs is expected to be closer to $100/anomaly. Assuming a 60% reduction in the number of clutter items that could be eliminated from intrusive investigation would yield a potential cost savings based on the following assumptions:

- 10,000 anomalies at $100/anomaly for intrusive investigation equals a cost of $1,000,000.
- Reduction of 6,000 anomalies equals a reduction of $600,000 in excavation costs.

- MetalMapper costs for collecting and analyzing 10,000 anomalies at $34.19/anomaly equals $341,900.
- Total net savings under this scenario equals $258,100 (26%).

9.0 IMPLEMENTATION ISSUES

There were a few notable implementation issues regarding the MMR project:

- The greatest challenge for the intrusive portion of the project was the sheer amount of clutter present at the site. While only relatively large dynamic targets (with regard to instrument response) were selected for follow-on investigation with the advanced EMI sensors, most of the site was littered with smaller fragments that were not picked as cued targets. These fragments made clearing intrusive locations particularly difficult and required quite a bit more time to locate and catalog than on previous projects.
- The MetalMapper data collection went very well for this project. There were few software or hardware issues except for a broken inertial measuring unit (IMU) cable. Because the IMU data were not essential to the collection or processing of the MetalMapper data, the field team carried on without it for about 2 days during collection. It was thought that the data collected without a functioning IMU might show greater offsets to the recovered sources than that collected with the IMU. However, for the 1 day without the IMU with dig results (June 21, 2012; points collected during the partial days without the IMU were not investigated during the Phase I digging) showed little offset difference from the rest of the data. The standard deviation of offsets for June 21 was 29 cm versus 28 cm for all of the Phase I results.
- The only other MetalMapper implementation issues in the field were due to the rough condition of the site (e.g., craters, stumps, fallen trees, brush) leading to slow drive times to the farthest end of the site and the lack of available background point collection locations. The data seem to be of sufficient quality for use in discriminating large TOI from the vast amounts of clutter at the site, but it is unknown how different geophysically the background location at the IVS strip was from the field site.
- The misclassification of some 60-mm illumination round warheads as clutter was the largest issue with the classification portion of the project. These rounds appear to be much more geophysically similar to much of the clutter at the site (relatively small size and fast decay) than they are to the larger TOI present and even to thicker-walled 60-mm mortars. It appears that attempting to consistently classify them as TOI would add a significant number of clutter digs to any intrusive investigation. It may be worth considering their potential impact at the site with regard to the overriding groundwater concerns to determine whether adding digs to recover them is worthwhile.

10.0 REFERENCES

ESTCP, 2012. *Demonstration Plan: Live Site Demonstration, Massachusetts Military Reservation*. June.

Tetra Tech EC, Inc. (Tetra Tech), 2011. *Final Central Impact Area Source Investigation Report*.