DEMONSTRATION REPORT

Demonstration of Advanced Geophysics and Classification Technologies on Munitions Response Sites

Former Spencer Artillery Range
Van Buren County, Tennessee

ESTCP Project MR-201161

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14. ABSTRACT
This document serves as the Environmental Security Technology Certification Program (ESTCP) Demonstration Report for the Demonstration of Advanced Geophysics and Classification Technologies on the Former Spencer Artillery Range Munitions Response Site (MRS). This project is one in a series of projects funded by ESTCP to test the effectiveness of advanced geophysical sensors and physics-based data analysis tools for anomaly classification.

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ACRONYMS

ANN	Artificial Neural Network
ASCII	American Standard Code for Information Interchange
CERCLA	Comprehensive Environmental Response, Compensation, and Liability Act
DERP	Defense Environmental Restoration Program
DGM	Digital Geophysical Mapping
DoD	Department of Defense
EMI	Electromagnetic Induction
ESTCP	Environmental Security Technology Certification Program
GPS	Global Positioning System
GSV	Geophysical System Verification
IDA	Institute for Defense Analyses
ISO	Industry Standard Object
IVS	Instrument Verification Strip
LFO/MFO	Least Favorable Orientation/Most Favorable Orientation
LM	Library Matching
MDAS	Material Documented As Safe
MEC	Munitions and Explosives of Concern
MM	MetalMapper
MMRP	Military Munitions Response Program
MPPEH	Material Potentially Presenting an Explosive Hazard
MRS	Munitions Response Site
mV	Millivolts
NCP	National Oil and Hazardous Substances Pollution Contingency Plan
Nfa	Number of False Alarms
NRL	Naval Research Laboratory
Pclass	Probability of Correct Classification of TOI
PMTMA	Pole Mountain Training and Maneuver Area
QAPP	Quality Assurance Project Plan
QC	Quality Control
RTK	Real Time Kinematic
RTS	Robotic Total Station
SARA	Superfund Amendments and Reauthorization Act
SEG	Society of Exploration Geophysicists
TEMTADS	Time-domain Electromagnetic Multi-sensor Towed Array Detection System
TOI	Target of Interest
URS	URS Group, Inc.
USACE	U.S. Army Corps of Engineers
UTM	Universal Transverse Mercator
UXO	Unexploded Ordnance

1.0 INTRODUCTION

The project purpose is to use traditional (e.g., EM61-MK2) and advanced geophysical sensors [e.g., Time-domain Electromagnetic Multi-sensor Towed Array Detection System (TEMTADS) and MetalMapper (MM)] and advanced data analysis methods in a production environment to characterize approximately 9.24 acres of the Former Spencer Artillery Range Munitions Response Site (MRS), Van Buren County, Tennessee.

This document serves as the Environmental Security Technology Certification Program (ESTCP) Demonstration Report for the Demonstration of Advanced Geophysics and Classification Technologies on approximately 9.24 acres of the MRS, in Van Buren County, Tennessee. This project is one in a series of projects funded by ESTCP to test the effectiveness of advanced geophysical sensors and physics-based data analysis tools for anomaly classification.

1.1 BACKGROUND

ESTCP contracted URS Group, Inc. (URS) to conduct site preparation activities, including a baseline subsurface anomaly density survey using electromagnetic induction (EMI) geophysical data with the EM61-MK2 in a single-sensor cart configuration. Additionally, URS conducted a second EM61-MK2 survey after seeds were emplaced and utilized advanced EMI sensors (i.e., TEMTADS 2x2 and MM) in both dynamic survey mode to map 1.23 acres (dynamic area) and cued mode to investigate individual anomalies. TEMTADS 2x2 was used in cued mode over 689 anomalies in the 3.73 acre wooded area and 340 anomalies in the 1.23 acre dynamic area. MM was used in cued mode to investigate 1,444 anomalies in both the open area (4.28 acres) and dynamic area. URS processed and demonstrated the use and performance of advanced anomaly classification methods using the MM data.

1.2 OBJECTIVE OF THE DEMONSTRATION

Digital geophysical mapping (DGM) of former military ranges results in the identification and location of subsurface anomalies at a site. Typically, very small fractions of these anomalies are munitions and explosives of concern (MEC). The majority of these anomalies are harmless metallic objects (e.g., munitions fragments, small arms projectiles, range-related debris, or cultural debris). ESTCP and other collaborators have developed advanced EMI sensors and geophysical data processing methods that have proven effective at classifying subsurface metallic objects as either targets of interest (TOI) (i.e., objects having the size, shape, and wall thickness associated with MEC) or non-targets of interest (non-TOI) (i.e., harmless scrap metal). This demonstration serves to:

- Demonstrate the cost and performance of these sensors and methods on increasingly challenging MRSs,
- Train Military Munitions Response Program (MMRP) contractors on the application of these sensors and methods to facilitate technology transfer and industry-wide adoption, and
- Identify opportunities for potential improvement of the sensors and classification methods.

1.3 REGULATORY DRIVER

The ESTCP Live Site Demonstrations are executed under the guidance of the Department of Defense (DoD) MMRP, which is a portion of the Defense Environmental Restoration Program (DERP). DERP is the DoD program to execute environmental response consistent with the provisions of the Comprehensive Environmental Response, Compensation, and Liability Act of 1980 (CERCLA) as amended by the Superfund Amendments and Reauthorization Act of 1986 (SARA); the National Oil and Hazardous Substances Pollution Contingency Plan (NCP) (40 Code of Federal Regulations 300); and Executive Order 12580, Superfund Implementation.

2.0 TECHNOLOGY

2.1 TECHNOLOGY DESCRIPTION

A Geonics EM61-MK2 was paired with a Trimble R8 Real Time Kinematic (RTK) Global Positioning System (GPS) (in open areas) and a Trimble S6 Robotic Total Station (RTS) (in wooded areas) to conduct the DGM survey of the demonstration site. The Geometrics MM and the Naval Research Laboratory (NRL) TEMTADS 2x2 array were used in dynamic survey mode to detect anomalies. Anomalies were identified and subsequently analyzed in cued mode using both the MM and TEMTADS. The outputs from MM were analyzed to classify anomalies as TOI or non-TOI using Library Matching (LM), parameter thresholds, and data mining techniques, including clustering and Artificial Neural Network (ANN)-based classifiers. URS used several software applications, including Geosoft's Oasis Montaj UX-Analyze extension, Sigma Plot, Weka (data mining software), and Geosoft scripts developed by URS.

2.1.1 Digital Geophysical Mapping

The baseline DGM survey was performed using a Geonics EM61-MK2, paired with a Trimble R8 RTK GPS, Trimble S6 RTS, and an Allegro CX field computer. The EM61-MK2 system consisted of a 1.0 m by 0.5 m coil containing both a transmitter and receiver antenna. The lower coil was located 42 cm above the ground surface for optimal data collection using the standard wheel mode. Cross-line spacing during the survey was maintained by establishing flagged grids and using ropes and measuring tapes as guides.

2.1.2 Advanced Geophysical Data Collection

2.1.2.1 Dynamic Survey Mode

The MM system and the TEMTADS 2x2 array were demonstrated in dynamic survey mode in a 1.23 acre area (the dynamic area). The purpose was to identify, locate, and potentially classify anomalies and then return in cued mode to each anomaly and compare the responses. The MM was mounted on a front-end loader bucket mounted on a tractor, with the monitor attached to the tractor hood. TEMTADS is a self-contained man-portable cart-mounted system. Positioning for both systems was provided by an RTK GPS mounted above the center of the array.

2.1.2.2 Cued Mode

The MM system was demonstrated in cued mode on 1,104 anomalies in the open area and on 340 anomalies in the dynamic area. The TEMTADS 2x2 array was used for cued interrogation of 689 anomalies in the wooded area and 340 anomalies in the dynamic area.

2.1.3 Anomaly Classification Methods

URS applied three classification methodologies to classify anomalies as TOI and non-TOI from the MM cued mode data. Anomalies were classified into two categories:

- Category 0: Cannot analyze (not used)
- Category 1: Likely TOI
- Category 2: Cannot decide (not used)
- Category 3: Likely non-TOI

The Geosoft UX-Analyze software package was used to process and invert the data for polarizability. Inversion results were classified using LM and data mining tools, including classifier and clustering algorithms augmented by visual review of the data. Initially three ranked anomaly lists were submitted. The first list was based on several ANN, the second list utilized a simple threshold on a series of parameters (SIMPLE), and the third list used LM tools. After QC failures resulting from undetected seed items were identified, a failure analysis was performed and only the ANN and LM lists were resubmitted.

Details of the classification methodology are described in Section 6.

2.2 TECHNOLOGY DEVELOPMENT

Learning algorithms used for data mining are commonly divided into two categories, classifiers and clustering. Classifiers use labeled data (training data) where the classification is known to "learn" what parameter values are associated with the target class. Clustering algorithms work with labeled or unlabeled data by associating these data into clusters based on proximity within the parameter space.

A critical step to any data mining approach is the selection of appropriate parameters to describe the data. Typical datasets contain large amounts of redundant information that may degrade the performance of data mining algorithms. Conversely, an inadequate parameter set that does not fully capture the information available in the original data degrades classification performance. URS built upon existing parameterization approaches (Smith and Lee 2002) by also using polynomial curve fitting to further parameterize the dataset.

URS used classifier and clustering algorithms combined with visual review of the data independently so that the clustering algorithms could be used as a check of the classifier results. The selected classifier algorithm, the ANN tool MultilayerPerceptron, was used to perform an initial classification, subject to the limitations of the training data. The use of ANN to discriminate between TOI and non-TOI has been established by previous investigators (Geometrics 2010; Szidarovsky, Poulton, and MacInnes 2008). However, classifier algorithms risk overtraining, where the results are specific only to training data examples and are not capable of recognizing the more general class to which the training data examples belong.

Clustering also risks overtraining (i.e., every dataset member is defined as a cluster), but this can be addressed by limiting the number of clusters that can be defined via an input parameter for the algorithm. Clustering is also independent of any training dataset, and can be used to identify data gaps that need to be filled within the training dataset by identifying clusters that are not represented in the training data. Clustering algorithms and visual review were used to identify potential gaps within the training data, and were used to identify situations where the classifier had overtrained and only selected a portion of a cluster rather than the entire cluster, as appropriate. Clustering and visual review were used as a QC check on both the completeness of the training data and on the classifier algorithm results to help avoid overtraining.

2.3 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

2.3.1 Dynamic Data Collection with Advanced Geophysical Sensor Arrays

The ability to collect a single dataset that allows munitions response project teams to identify and distinguish individual anomalies and to subsequently classify each anomaly as a TOI [presumably Unexploded Ordnance (UXO)] or non-TOI (presumably harmless scrap) would dramatically decrease the total cost of munitions responses. It will also expedite munitions response schedules. Advanced geophysical sensor arrays will also more precisely locate target anomalies, improving geophysical survey quality in cluttered areas and reducing data management challenges related to linking geophysical anomalies with subsurface anomaly sources. Dynamic data collection with advanced sensors is typically slower and more costly than equivalent EM61 surveys.

2.3.2 Library Matching

LM tools, currently integrated within the UX-Analyze package, are conceptually easy to grasp and relatively easy to utilize. Existing response libraries consist primarily of single-source inversion results, and not multi-source inversion responses. Due to the presence of numerous multi-source responses at the Former Spencer Artillery Range, URS developed a custom library containing only multi-source inversion results. Some TOI were found to have better library matches to non-TOI items than TOI items, which required a visual review to identify which items with primary non-TOI matches had strong TOI matches as well.

2.3.3 Threshold Classification

Threshold classification is very easy to implement and is equivalent to the current methods for selection of EM61 anomalies for intrusive investigation. It works very well in datasets like Pole Mountain Training and Maneuver Area (PMTMA) where all TOI were found within well-defined ranges of parameter values, but does not work if TOI that do not fit easily defined parameter ranges are present.

2.3.4 Artificial Neural Network

ANN-based approaches have proven successful in eliminating 80% or more clutter from dig lists in multiple ESTCP demonstrations. However, the ANN approach is highly dependent on the quality and quantity of training data, and typically is site specific.

3.0 PERFORMANCE OBJECTIVES

Performance objectives for the demonstration, provided in Table 1, serve as a basis for the evaluation of the performance and costs of the demonstrated technology. These objectives are for the baseline EM61-MK2 data collection, MM and TEMTADS dynamic data collection, MM and TEMTADS cued data collection, and the MM data analysis and classification.

Table 1. Quantitative Performance Objectives for this Demonstration

Performance Objective	Metric	Data Required	Success Criteria
Data Collection Objectives			
Along-line measurement spacing	Point-to-point spacing from dataset	Mapped survey data	*EM61 cart:* 90% <15 cm along-line spacing *TEMTADS:* 90% <25 cm along-line spacing *MM:* 90% <15 cm along-line spacing
Complete coverage of the demonstration site	Footprint coverage	Mapped survey data	≥85% coverage at 0.5 m line spacing and ≥98% coverage at 0.75-m line spacing (open area only) calculated using UXProcess Footprint Coverage QC Tool
Repeatability of IVS measurements	Amplitude of EM anomaly Measured target locations	Twice-daily instrument verification strip survey data	*EM61 cart:* amplitudes ±25% down-track location ±25 cm *Advanced Sensors Survey:* amplitudes ±10% down-track location ±10 cm *Advanced Sensors Cued:* Polarizabilities ±10%
Cued interrogation of anomalies	Instrument position	Cued mode data	*MM:* 100% of anomalies where the center of the instrument is positioned within 40 cm of actual target location *TEMTADS 2x2:* 100% of anomalies where the center of the instrument is positioned within 40 cm of actual target location
Detection of all targets of interest (TOI)	Percentage of detected seeded items	Location of seeded items and anomaly list	100% of seeded items detected with 60 cm halo
Analysis and Classification Objectives			
Maximize correct classification of TOI	Percentage of TOI placed in Category 1	Prioritized anomaly lists and dig results	Correctly classify 100% of TOI
Maximize correct classification of non-TOI	Percentage of correctly classified non-TOI	Prioritized anomaly lists and dig results	>75% of non-TOI classified in Category 3 while retaining all TOI
Specification of no-dig threshold	Percentage of TOI placed in Categories 1 or 2 and percentage of non-TOI placed in Category 3	Prioritized anomaly lists and dig results	Threshold specified to achieve criteria above
Minimize number of anomalies that cannot be analyzed	Percentage of anomalies classified as Category 0	Inverted MM and TEMTADS cued mode data and prioritized anomaly dig list	Reliable target parameters can be estimated for >95% of anomalies on each sensor's detection list

Performance Objective	Metric	Data Required	Success Criteria
Correct estimation of target parameters	Accuracy of estimated target parameters for seed items	Estimated and actual parameters [polarizabilities, XY locations, and depths (Z)] for seed items	Polarizabilities ±20% X, Y <15 cm (or 1 σ) Z <10 cm (or 1 σ)

3.1 OBJECTIVE: ALONG-LINE MEASUREMENT SPACING

The reliability of the survey data depends on the extent of coverage of the site. This objective concerns the ability to collect data with acceptable along-line measurement spacing.

3.1.1 Metric

The metrics for this objective are the percentage of data points within an acceptable along-line spacing.

3.1.2 Data Requirements

A mapped data file will be used to judge the success of this objective.

3.1.3 Success Criteria

This objective is considered to be met for the EM61 cart if at least 90% of the mapped data points are within 15 cm along the survey line from their neighboring points. For the TEMTADS, at least 90% of the mapped data points must be spaced no more than 25 cm along the survey line. For the MM, at least 90% of the mapped data points must be spaced no more than 15 cm along the survey line.

3.2 OBJECTIVE: COMPLETE COVERAGE OF THE DEMONSTRATION SITE

The reliability of the survey data depends on the extent of coverage of the site. This objective concerns the ability to completely survey the site and obtain valid data.

3.2.1 Metric

The metric for this objective is the footprint coverage as measured by the UXProcess Footprint Coverage QC tool.

3.2.2 Data Requirements

A mapped data file will be used to judge the success of this objective.

3.2.3 Success Criteria

This objective is considered to be met if the survey achieved at least 85% coverage at 0.5-m line spacing and 98% at 0.75-m line spacing (open field area only) calculated using the UXProcess Footprint Coverage QC tool.

3.3 OBJECTIVE: REPEATABILITY OF INSTRUMENT VERIFICATION STRIP MEASUREMENTS

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

3.3.1 Metric

The metrics for this objective are the amplitude and down-track position of the maxima for the EM61 cart and advanced sensors in survey mode and the standard deviation of the polarizabilities for the advanced sensors in cued mode obtained from each of the twice-daily surveys of the instrument verification strip (IVS).

3.3.2 Data Requirements

The data will be used to judge this objective.

3.3.3 Success Criteria

This objective is considered to be met for the EM61 cart if the measured amplitudes for each object are within 25% of the mean and the down-track position of the anomaly is within 25 cm of the known location. The objective is considered met for the advanced sensors in survey mode if the measured amplitudes for each object are within 10% of the mean and the down-track position of the anomaly is within 10 cm of the known location. The objective is considered met for the advanced sensors in cued mode if the standard deviation of the estimated polarizabilities is within 10% of the mean.

3.4 OBJECTIVE: CUED INTERROGATION OF ANOMALIES

The reliability of cued mode data depends on acceptable instrument positioning during data collection in relation to the actual anomaly location.

3.4.1 Metric

The metric for this objective is the percentage of anomalies that are within the acceptable distance of the center of the instrument during data collection from the actual target location.

3.4.2 Data Requirements

URS provided the ESTCP Program Office with the location of the center of the instrument for each cued anomaly interrogated. The Program Office reviewed the offsets for the QC seeds and provided feedback to the demonstrator if their instrument was not within the acceptable distance.

3.4.3 Success Criteria

The objective is considered to be met if the center of the instrument is positioned within the following distance of the actual anomaly location for 100% of the cued anomalies: MM – 40 cm and TEMTADS 2x2 – 40 cm.

3.5 OBJECTIVE: DETECTION OF ALL TARGETS OF INTEREST

Quality data should lead to a high probability of detecting TOI at the site.

3.5.1 Metric

The metric for this objective is the percentage of seed items that are detected using the specified anomaly selection threshold.

3.5.2 Data Requirements

URS prepared an anomaly list. Institute for Defense Analysis (IDA) personnel scored the detection probability of the seeded items.

3.5.3 Success Criteria

The objective is considered to be met if 100% of the seeded items are detected within a halo of 60 cm.

3.6 OBJECTIVE: MAXIMIZE CORRECT CLASSIFICATION OF TARGETS OF INTEREST

This is one of the two primary measures of the effectiveness of the classification approach. By collecting high-quality data and analyzing those data with advanced parameter estimation and classification algorithms URS expected to be able to classify the targets with high efficiency. This objective concerns the component of the classification problem that involves correct classification of TOI.

3.6.1 Metric

The metric for this objective is the number of items on the anomaly list for a particular sensor that can be correctly classified as TOI by each classification approach.

3.6.2 Data Requirements

URS prepared a ranked anomaly list for the targets on the sensor anomaly list. IDA personnel used scoring algorithms to assess the results.

3.6.3 Success Criteria

The objective is considered to be met if all of the TOI are correctly labeled as TOI on the ranked anomaly list.

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

This is the second of the two primary measures of the effectiveness of the classification approach. By collecting high-quality data and analyzing those data with advanced parameter estimation and classification algorithms URS expected to be able to classify the targets with high efficiency. This objective concerns the component of the classification problem that involves false alarm reduction.

3.7.1 Metric

The metric for this objective is the percentage of non-TOI items that are correctly classified as non-TOI by each classification approach.

3.7.2 Data Requirements

URS prepared a ranked anomaly list for the targets on the sensor anomaly list. IDA personnel used scoring algorithms to assess the results.

3.7.3 Success Criteria

The objective is considered to be met if more than 75% of the non-TOI items can be correctly labeled as non-TOI while retaining all the TOI on the dig list.

3.8 OBJECTIVE: SPECIFICATION OF NO-DIG THRESHOLD

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

3.8.1 Metric

The probability of correct classification of TOI (Pclass) and number of false alarms (Nfa) at the demonstrator-specified threshold are the metrics for this objective.

3.8.2 Data Requirements

URS prepared a ranked anomaly list with a dig/no-dig threshold indicated. IDA personnel used scoring algorithms to assess the results.

3.8.3 Success Criteria

The objective is considered to be met if URS sets a dig/no-dig threshold that results in more than 75% of the non-TOI items being correctly labeled as non-TOI, while correctly identifying all the TOI.

3.9 OBJECTIVE: MINIMIZE NUMBER OF ANOMALIES THAT CANNOT BE ANALYZED

Anomalies for which reliable parameters cannot be estimated cannot be classified by the classifier. These anomalies must be considered TOI and reduce the effectiveness of the classification process.

3.9.1 Metric

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

3.9.2 Data Requirements

URS provided a list of all parameters as part of the results submission, along with a list of those anomalies for which parameters could not be reliably estimated.

3.9.3 Success Criteria

The objective is considered to be met if reliable parameters can be estimated for greater than 95% of the anomalies on each sensor anomaly list.

3.10 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.

3.10.1 Metric

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

3.10.2 Data Requirements

Each analyst in demonstration reports compared estimated parameters for the seed items to those expected.

3.10.3 Success Criteria

The objective is considered to be met if the estimated polarizabilities are within ± 20%, the estimated X, Y locations are within 15 cm (1 σ), and the estimated depths (Z) are within 10 cm (1 σ).

4.0 SITE DESCRIPTION

4.1 SITE SELECTION

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

This site was selected for demonstration because it is more heavily wooded than prior demonstrations and was thought to contain a wide variety of munitions. These two features increase the site's complexity, and both characteristics are likely to be encountered on production sites. The tree cover poses a navigation challenge by increasing the difficulty of obtaining accurate GPS readings.

4.2 SITE HISTORY

In 1941, U.S. Army Corps of Engineers (USACE) constructed Spencer Range to serve as the main artillery range for Camp Forrest in Tullahoma, Tennessee. A December 1941 report describes the construction of two impact ranges onsite, Jakes Mountain and Bald Knob (USACE 2001). In 1944, Dyersburg Army Air Field used the area as an air-to-ground gunnery range. Small arms, 37mm anti-aircraft guns, field and heavy artillery, mortars, anti-tank rockets, and target rockets are known to have been used in training on the site. The land reverted to the original leaseholders in the summer of 1946. Several surface clearance sweeps were completed on portions of the former range during the 1950s. The land has since been subdivided and sold, significantly increasing the number of property owners to several hundred. Figure 1 is a location map of the Former Spencer Artillery Range demonstration area. The 5-acre demonstration site is within MRS-01, which is within the Jakes Mountain Impact Area (see Figure 2). MRS-01 is privately owned and is currently used for hunting and logging. The landscape is primarily heavily wooded. The predominant vegetation in the area is forests of coniferous and deciduous trees with pervasive undergrowth. Loblolly pines were replanted on the site after surface and clear-cutting activities (EODT 2007).

4.3 SITE GEOLOGY

The Former Spencer Artillery Range is underlain by Pennsylvanian era sandstone, shale, siltstone, and conglomerate. The rocks in this area consist of Pennsylvanian marine deposits of sandstone, shale, coal, and limestone. Bedrock is observed at the surface in some areas of the site. Where covered with soil, depth to bedrock generally ranges from approximately 2 ft to 6 ft below ground surface (USACE 2001). The soil types on site include the Gilpin silt loam, Hartsells loam, Lonewood silt loam, and Udorthents-Mine Pits complex.

4.4 MUNITIONS CONTAMINATION

The MRS contains several munitions types, including 37mm, 75mm, 76mm, 105mm, and 155mm projectiles. The Remedial Investigation reported an average anomaly density of the MRS to be approximately 131 anomalies/acre (USACE 2011a, 2011b).

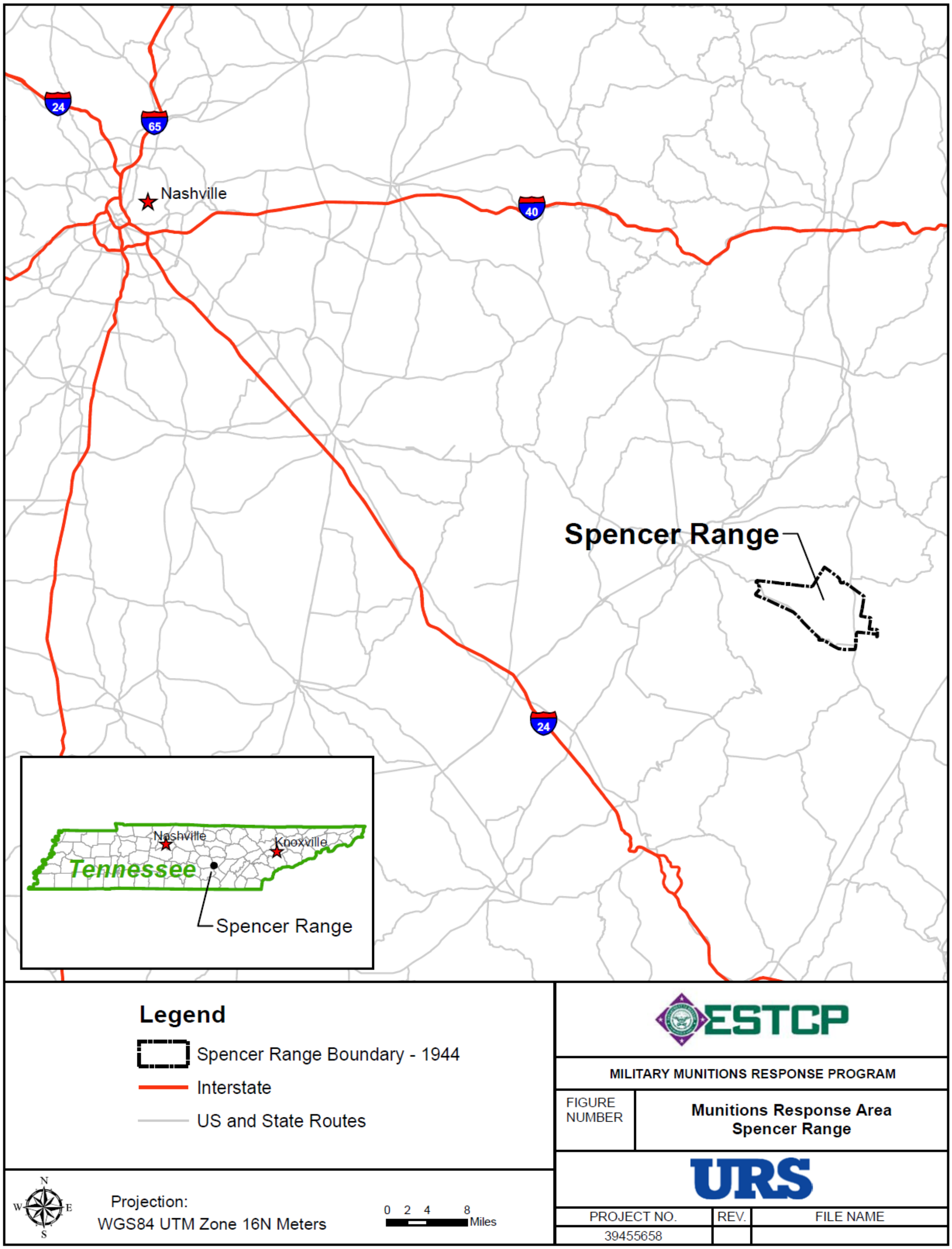

Figure 1. ESTCP Former Spencer Artillery Range Demonstration Site Location Map

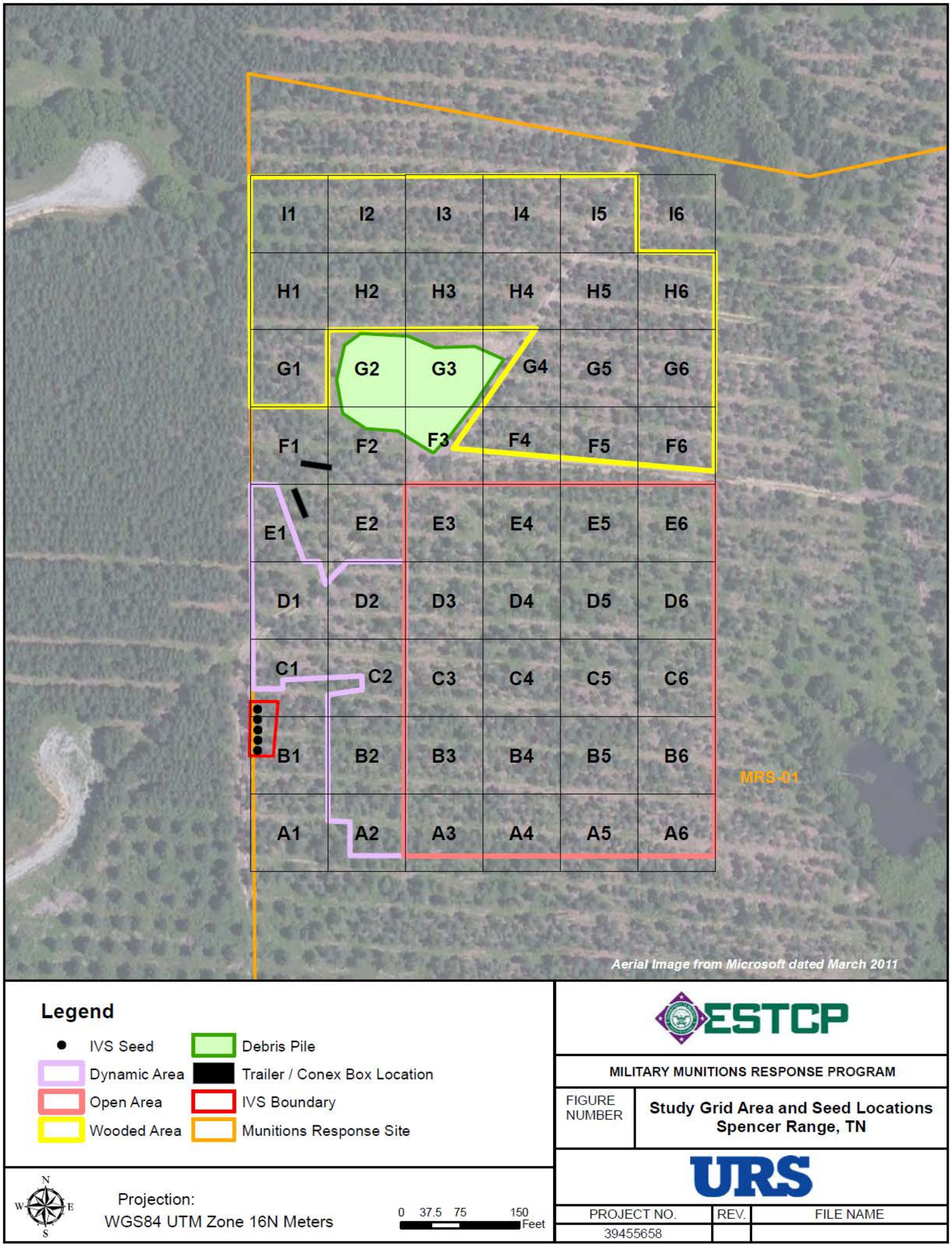

Figure 2. ESTCP Former Spencer Artillery Range Demonstration Site

Note that the open area and dynamic area were recently cleared of trees, which is not reflected in the aerial photo in Figure 2. Current vegetation conditions are shown in Figure 3 through Figure 5.

Figure 3. Vegetation Conditions in the Wooded Area

Figure 4. Vegetation Conditions in the Open Area (Pre-Grubbing)

Figure 5. Vegetation Conditions in the Open Area (Post-Grubbing)

5.0 TEST DESIGN

URS had three roles in this project:

- Overall site management (e.g., site preparation, DGM, and validation digging),
- Advanced instrument data collection and processing, and
- Advanced instrument data analysis and anomaly classification.

During site preparation activities, URS seeded the demonstration site and conducted baseline DGM with an EM61-MK2. URS collected both dynamic and cued mode data using two advanced geophysical sensor arrays (TEMTADS 2x2 and MM). URS geophysicists classified anomalies using the MM data. URS subsequently performed intrusive investigation of all anomalies to validate all demonstrators' classification results. This section discusses the activities that were executed by URS in support of this project.

5.1 CONCEPTUAL EXPERIMENTAL DESIGN

- **Demonstration/Work Plan Development**: URS prepared a site-specific MEC Quality Assurance Project Plan (QAPP) in lieu of a traditional work plan for the Former Spencer Artillery Range demonstration project (ESTCP 2012).
- **Site Preparation**: URS performed a surface sweep, removed ground vegetation (including grinding stumps), and emplaced 175 inert seed items in the 9.24-acre demonstration site. URS also installed an IVS.
- **Geophysical Data Collection**: URS surveyed approximately 9.24 acres using a cart-mounted EM-61 with a line spacing of 0.5 m. Data were processed, targets selected, and data submitted to the ESTCP Program Office.
- **TEMTADS 2x2 Data Collection**: URS surveyed (dynamic mode) 1.23 acres with the cart-mounted TEMTADS 2x2 in the dynamic area. URS also collected cued mode data over 689 targets in the wooded area and 340 targets in the dynamic area.
- **MM Data Collection**: URS surveyed (dynamic mode) 1.23 acres with the tractor-mounted MM in the dynamic area. URS also collected cued mode data over 340 targets in the dynamic area and 1,104 targets in the open area.
- **MM Data Processing**: URS used the Geosoft UX-Analyze software package to process and invert the MM data.
- **MM Data Analysis and Classification**: URS used the inversion results for each of the targets to classify them using LM and data mining tools, including classifier and clustering algorithms augmented by visual review of the data.
- **Intrusive Investigation**: URS intrusively investigated 2,133 anomalies identified by the ESTCP Program Office. Each anomaly was photographed and attribute information (e.g., nomenclature, size, depth, position, and orientation) was captured and provided to the ESTCP Program Office.

5.2 SITE PREPARATION

To begin the project, the URS Senior UXO Supervisor and field crew conducted a surface sweep to ensure there was no surface MEC within the demonstration site. Once the surface sweep was completed, the field team worked with a subcontracted vendor to grind stumps in the open area and remove underbrush in the wooded area. Once the vegetation was removed, the field team seeded the demonstration site.

A total of 175 targets were emplaced within the demonstration site at the Former Spencer Artillery Range:

- 60 inert 37mm projectiles
- 10 inert 60mm mortars
- 30 inert 75mm projectiles
- 3 inert 105mm projectiles
- 2 inert 155mm projectiles
- 60 industry standard objects (ISOs) (1.5 in. × 4 in. pipe nipples)
- 10 ISOs (2 in. × 8 in. pipe nipples)

The ESTCP Former Spencer Artillery Range MEC QAPP, Worksheet #17, provides a detailed description of the site preparation and seed emplacement locations and procedures. An example of the data collected for each seed item is shown in Figure 6.

Figure 6. Example of Blind Seed Item and Data Recorded

5.3 CALIBRATION ACTIVITIES – INSTRUMENT VERIFICATION STRIP

URS installed and used an IVS to verify the proper operation and functioning of the geophysical equipment used and to measure site noise readings of each instrument before and after each day of field data collection. The IVS was installed and operated consistently with the specifications and descriptions contained in *Geophysical System Verification (GSV): A Physics-Based Alternative to Geophysical Prove Outs for Munitions Response* (ESTCP 2009). The IVS also served to verify that geo-location systems provided accurate sensor location data. ISOs and inert munitions were used as reference seed items. The IVS contained four seed items of the sizes, at the depths, and in the orientations listed in Table 2. A fifth location with no seed item was also included in the IVS. Seed items were placed horizontally, without inclination/declination.

Table 2. Former Spencer Artillery Range Instrument Verification Strip

Item ID	Description	Easting (m)	Northing (m)	Depth (m)	Inclination	Orientation
T-001	Shotput	3939129.12	635344.10	0.30	Not applicable	Not applicable
T-002	37mm inert projectile	3939125.12	635344.18	0.15	Horizontal	Across Track
T-003	75mm inert projectile	3939121.12	635344.30	0.30	Horizontal	Across Track
T-004	Blank space	3939117.14	635344.27	N/A	Not applicable	Not applicable
T-005	1.5 in. x4 in. pipe nipple	3939113.07	635344.21	0.15	Horizontal	Across Track

EM61-MK2 standard response curves and polar displacement plots for the seeded items are located in Appendix B.

5.4 DATA COLLECTION – EM61-MK2 GEOPHYSICAL SURVEY

5.4.1 Sample Density

All data were collected at a sample frequency of 10 Hz to result in less than 15 cm along-line density. Sample density, including cross-line and along-line spacing, results are discussed in Section 7.1 and Section 7.2. For each grid, the team used measuring tapes and PVC pin flags to establish the 0.5 m lane spacing. Twine was laid out in survey direction approximately every 10 lanes to aid in data collection and lane control. The instrument operator performed the survey by walking directly down the lane between flags and back over the flags in alternating passes. This procedure was repeated until the entire grid was surveyed by sequential, alternating passes and allowed for strict control of the spacing between alternating transects. To allow direct comparison between survey files, the survey tape, pin flags, and twine were laid out so that data collection was started and finished with at least one pass inside the adjacent grids on either side of the surveyed grid. After completion of each grid, the field team continued to record data while traversing through the grid and circling each obstacle within the grid (rocks, trees, large shrubs, etc.) that might have resulted in a gap in coverage. To fill gaps identified by the data processor, the field teams returned to the grid where the gap was identified and collected data on a series of transects identified by the data processor. These “gap fill” transects included significant overlap of adjacent data to allow comparison between datasets and to ensure that each gap was completely filled.

5.4.2 Quality Checks

Daily field activities were coordinated during the morning briefing to ensure that the field teams maintained sufficient separation throughout the day to prevent interference between geophysical sensors when needed. After completing the tailgate safety brief, the field teams performed a minimum 15-minute instrument warm-up to allow the EM61 to reach a stable operating temperature to minimize instrument drift. After warm-up, each team proceeded to the IVS where they performed and recorded the following series of QC tests. These tests were also performed in the evening after data collection was complete.

- **Cable Shake/Personnel Test:** This test was performed in a designated area adjacent to the IVS. The operator started the test and another team member proceeded to shake each cable connecting the various elements of the DGM system while the operator monitored for spikes in response or other indicators of a potential problem. The team members and the operator then took turns approaching and backing away from the EM61 sensor to confirm that they did not have significant amounts of metal on their person that could be detected by the instrument.
- **Static Test:** Performed in the same location as the cable shake test, the operator initiated this test and then let the instrument record for a minimum of 1 minute while all possible noise sources were kept away from the system. This test verified that the background instrument and ambient electromagnetic noise were low enough for successful data acquisition.
- **Spike Test:** Performed in the same location as the cable shake test, the operator placed a small ISO in the same location with respect to the instrument coil and let the instrument record for a minimum of 1 minute while all possible noise sources were kept away from the system. This test verified that the instrument delivered consistent responses over metallic objects.
- **Seeded IVS:** This test consisted of sequential alternating passes directly over the seeded IVS. Seed responses were monitored for consistency and location during later data analysis.
- **Background IVS**: This test consisted of sequential alternating passes directly over the background IVS. Responses were monitored for consistency and overall noise levels during later data analysis.

Each QC test was recorded under a file convention starting with the date (MMDD) and followed by a test identifier (CAB for cable shake, STA for static test, IVS for seeded IVS, and BCK for background IVS). This was followed by a 1 to indicate that the test was performed in the morning or a 9 to indicate evening. If the field team identified a problem and needed to repeat a test, this number was sequentially increased to the next whole number (2, 3, etc.) until the QC test was successfully performed and completed. For example, the morning cable shake test on June 23 would be labeled <<0623CAB1>>.

The IVS data were evaluated using a physics-based process in which signal strength and sensor performance were compared to known response curves of four seed items (see Table 2) to verify the DGM system was operating within manufacturer's specifications prior to and throughout site surveys. The Geophysical System Verification (GSV) process is designed to perform initial verification of the proposed DGM systems using an IVS. Positioning and least favorable orientation (LFO)/most favorable orientation (MFO) plots were generated for each survey team for four seed item objects (i.e., shotput, 37mm, 75mm, and 1.5 in. x 4 in. pipe nipple,) and position plots only for the shotput containing data acquired throughout the project. LFO/MFO data should fall between the two curves and positioning data should be within 0.25 m of the ISO location. Plots for the IVS 75mm projectile are displayed in Figures 7 and 8. All IVS tests passed. The remaining IVS plots and data are contained in Appendix B.

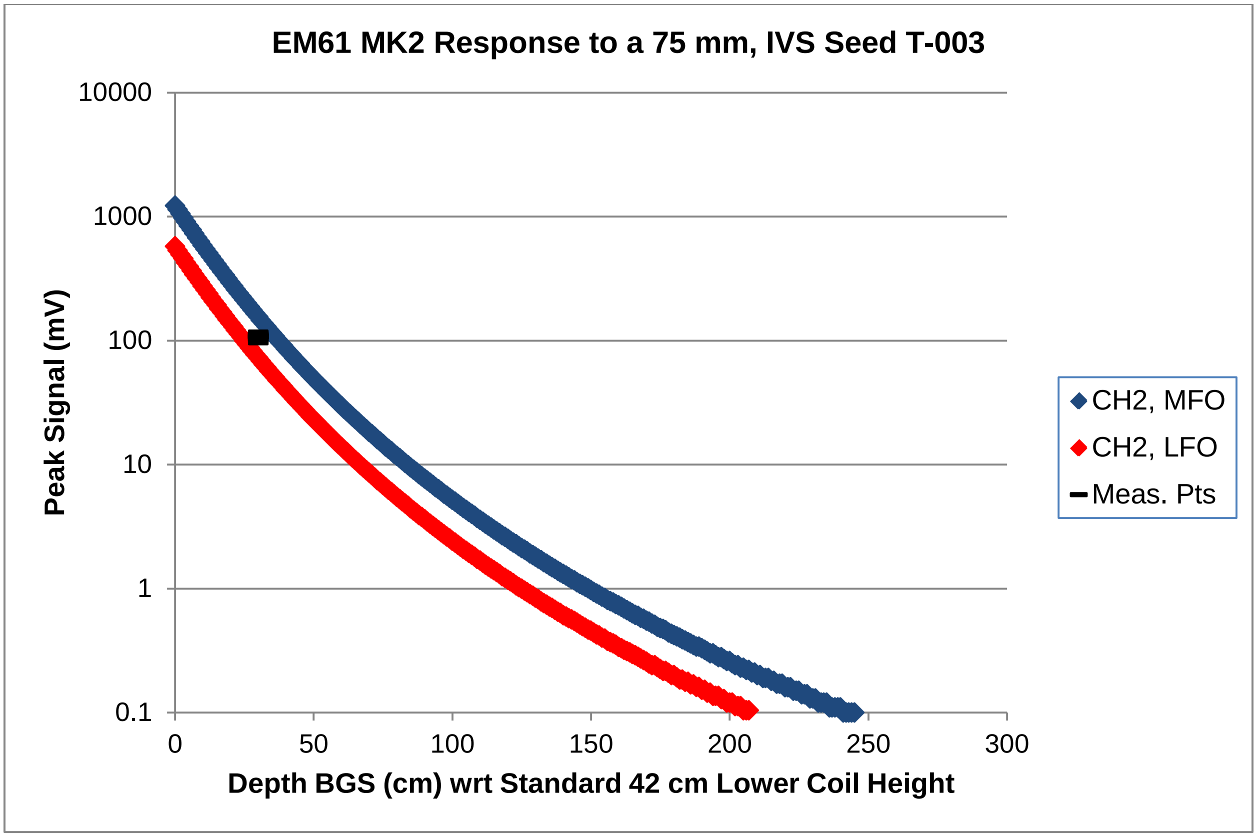

Figure 7. IVS LFO/MFO Plot for the 75mm Projectile Seed Item

5.4.3 Data Summary

For each dataset, the field team created a file using the date and a sequential alphabetic character (A, B, C). For example, the first file collected on June 23 would be <<0623A>>, while the second file collected would be <<0623B>>. Data were collected continuously, including while turning around outside of the survey grid at the end of each pass, with acquisition otherwise paused during interruptions.

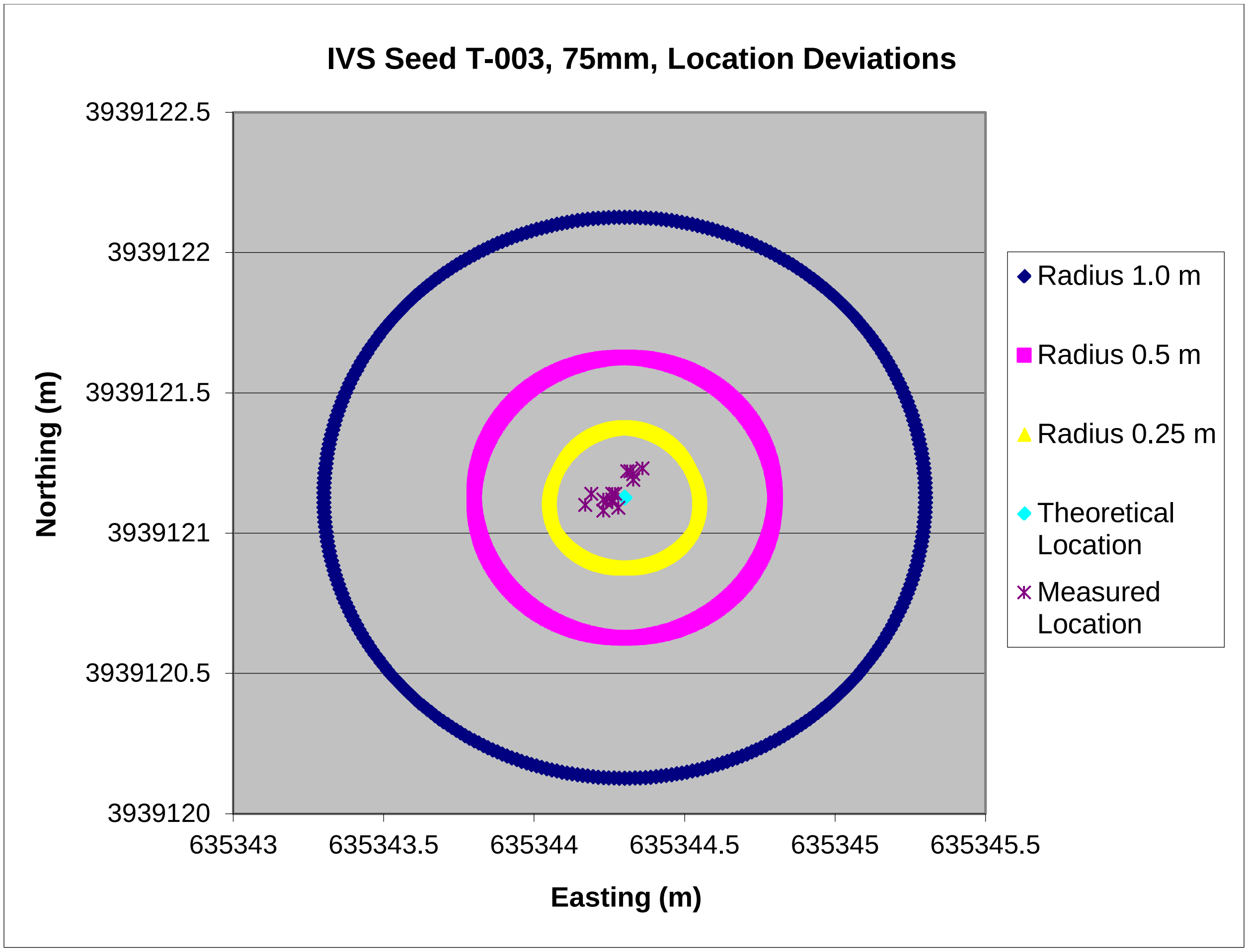

Figure 8. IVS Positioning Plot for the 75mm Projectile Seed Item

EM61 data were recorded into binary file formats with either an .r61 or a .p61 extension. These formats were converted into an intermediate .m61 ASCII format, and then a final .xyz format. Delivered data were organized by data and team, with the files labeled using the conventions previously discussed. Additional delivered data included the final processed data in Geosoft database (.gdb) format. These data are grouped into four rectangular blocks of grids covering the entire site. Additional information about the contents of the files, including the coordinate system and channel descriptions, are captured in the metadata files included in Appendix C, which also contains the deliverable DGM data.

5.5 DATA COLLECTION – ADVANCED SENSORS (TEMTADS AND METALMAPPER) IN DYNAMIC SURVEY MODE

5.5.1 Sample Density

The dynamic survey mode consisted of complete coverage in the designated dynamic area. Figure 9 shows dynamic data collection, with the TEMTADS 2x2, using taut lines to maintain transect spacing. Data were collected along parallel transects with 0.5 m nominal transect spacing; however, it was necessary for some transects to deviate from a straight line path due to obstructions. Sample rate and survey pace were slow enough to ensure down-line spacing of less than 15 cm. Survey position was recorded and logged using an RTK GPS.

Figure 9. Dynamic Data Collection Using the TEMTADS 2x2

5.5.2 Quality Checks

Equipment Warm-Up: Field personnel followed the manufacturer's instructions for a warm-up period prior to data acquisition. Each day prior to data acquisition a series of measurements were taken over a known location, at 5 minute intervals, until two successive measurements demonstrated repeatability.

Static Background Test: A static background test was performed to quantify instrument background readings or electronic drift and to identify any interference spikes. A minimum of 1 minute of static background was collected after instrument warm-up. At the end of each day, 1 minute of static background data was collected.

IVS: Survey personnel collected data over the IVS in each direction in the morning and after the data collection day. They evaluated the response compared to expected theoretic values and the spatial accuracy to established location.

Background Noise Test: Survey personnel collected profile data in each direction in the background noise lane.

Battery Strength Test: At the beginning of the day and periodically throughout use, the survey personnel checked the battery power remaining and replaced batteries as necessary.

Test Pit: Cued responses were collected over a variety of items in multiple orientations and depths in a prepared test pit. These responses served as training examples for classifier routines, and to confirm that the advanced data acquisition systems were functioning as designed by comparing local test pit responses with test pit data collected at other sites.

Six Line Test: Survey teams collected data over the IVS three times at different speeds. The first mapping was performed at normal production pace, the second mapping at a slow pace, and the third mapping at a fast pace.

Verify Configuration and Initialization Files: Prior to any data acquisition, the field team reviewed the configuration and initialization files for the acquisition software. The field team confirmed they had the latest reliable acquisition software, and confirmed they were using the appropriate configuration and initialization files.

5.5.3 Data Summary

Discrete data files were created for each of the following events:

- Static background test;
- Each time the IVS was performed;
- Background noise test;
- When data acquisition started in a new area;
- When the system was powered off and back on, including battery swaps; and
- Each time an issue with the system that could have a significant impact on data quality was identified and corrected (e.g., loose wheel, loose cable, metal caught on system).

Files were named on the field computer using the date in MMDDYY format. A sequential letter was assigned to the files started throughout the day. For May 11, 2012, the first file name was “051112a,” and the second file was “051112b.”

5.6 DATA COLLECTION – ADVANCED SENSORS (TEMTADS AND METALMAPPER) IN CUED MODE

5.6.1 Sample Density

The cued mode data collection consisted of surveying static data over a list of anomalies identified from the EM61 survey. Cued mode data were collected over each identified anomaly, with measurements repeated as necessary due to offsets of the sensor relative to the anomaly source or other data quality issues. Cued mode data were collected directly over the anomaly location as indicated either by the positioning system of the sensor or a reacquired flag location. For anomalies interrogated using the TEMTADS, locations were reacquired and marked based on the RTS or RTK GPS location selected by the data processor and were refined, when necessary, using an EM61.

Figure 10. Cued Data Collection Using the MM

When operating the MM, the data acquisition system software was used to help select a new location based on the preliminary analysis where the software identified the anomaly source location. In these situations, data were collected directly over the anomaly source location if it was within 40 cm of the original selected anomaly location. If it was farther away than 40 cm from the original location, and not within 40 cm of another anomaly location, both the original and new locations were surveyed. The data file associated with the new location was associated with the original anomaly ID and was recorded in the field log as an added point offset from the original location. Figure 10 shows cued data collection with the MM.

5.6.2 Quality Checks

Equipment Warm-Up: Field personnel followed the manufacturer's instructions for a warm-up period prior to data acquisition. Each day prior to data acquisition a series of measurements were taken over a known location, at 5 minute intervals, until two successive measurements demonstrate repeatability.

Static Background Test: A static background test was performed over a fixed location, typically the empty test pit, to quantify response repeatability at the beginning and end of each day.

IVS: Cued responses were collected over each item in the IVS at the beginning and end of each day to demonstrate response repeatability over known sources. These responses were also used as training data for classifier routines.

Battery Strength Test: At the beginning of the day and periodically throughout use, data collection teams checked the battery power remaining and replaced batteries as necessary.

Background Response Measurement: Cued responses were collected at regular intervals at locations where no metallic source was known to be present based on previous DGM data. These locations represent the typical geologic response of the cued mode area. The interval between background response measurements was generally 1 hour but could have been less due to restarting equipment or changing field conditions (i.e., rain).

Test Pit: Cued responses were collected over a variety of items in multiple orientations and depths in the test pit. These responses served as training examples for classifier routines and confirmed that the advanced data acquisition system was functioning as designed by comparing local test pit responses with test pit data collected at other sites.

Verify Configuration and Initialization Files: Prior to any data acquisition, the field team reviewed the configuration and initialization files for the acquisition software. The field teams confirmed they had the latest reliable acquisition software, and confirmed they were using the appropriate configuration and initialization files for the system setup.

5.6.3 Data Summary

Raw MM data were collected and stored as .tem files. The MM 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., “Spn_T”). The acquisition software then automatically appends a 5-character numerical index to the filename prefix to form a unique root name for the data file (e.g., Spn_T00001). The index is automatically incremented after the file has been successfully written. Although the target identification (ID) is not used as the file name in the .tem file, the target ID is stored in the file according to name of the target highlighted on the MM 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 Universal Transverse Mercator (UTM) Zone 16N 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 ID and the target ID (e.g., Spn_T00001_2621). Preprocessing was typically completed in batches representing approximately 1 hour of data collection, with the day split to account for differing background data. Background files were collected approximately every hour during data collection in a predetermined geophysically quiet location within the survey area. Unless there appeared to be a problem with a specific file, data were typically corrected using a background file collected at a similar time and location.

5.7 VALIDATION

5.7.1 Excavation Procedure

Intrusive investigations using "dig and verify" methods were completed in the Former Spencer Artillery Range demonstration site to determine whether the identified targets were MEC, munitions debris, or harmless scrap. The reacquisition navigated to the target location with RTK GPS, then refined and pinpointed the excavation location utilizing an EM61-MK2. The reacquisition team documented the new surface location using RTK GPS and marked it with pin flag for excavation.

A target list was derived from the advanced sensor dynamic data collection and associated data processing/analysis. The target list, in UTM coordinates, was provided to the reacquisition teams in tabular and grid map form on a handheld Trimble GeoXH. Daily functional QC tests were conducted for all reacquisition equipment, including EM61-MK2, magnetometers, and GPS.

Subsurface anomalies were manually excavated in accordance with EM 385-1-97 (USACE 2008). If the intrusive investigation of a target anomaly did not result in a finding (i.e., metallic object), 12 in. below specified depth, and 2 ft from the reacquisition target, URS abandoned the dig location as a "no contact."

5.7.2 Data Recording Procedure

The following data were recorded during intrusive investigation of anomalies.

- **Item Location**: The location of the item was recorded with an RTK GPS to a horizontal precision of 2 cm in Easting and Northing.
- **Depth**: The depth was measured in centimeters using a ruled straight edge from a horizontal guide at ground surface to the approximate center of the metal item.
- **Identification**: The item was described if it could be identified (e.g., 4.2-in. mortar base plate, aluminum can, large bolt, nail).
- **Digital Photograph**: A digital photograph of all metal items found at each anomaly location was taken with the items in front of a background with visible ruled markings in centimeters and the anomaly number.
- **Number of Contacts**: URS recorded the number of discrete metal items (greater than 1 in. in size) found during the investigation of the anomaly location.

When excavating anomalies with more than one metal item, each item was recorded with an identical anomaly number.

5.7.3 Post Clearance

URS bagged all items recovered from each hole in a bag marked with the anomaly number. On completion of each anomaly, the hole was refilled to grade. Material potentially presenting an explosive hazard (MPPEH) was inspected and certified as material documented as safe (MDAS) by qualified UXO technicians. MDAS was shipped to a qualified scrap metal processor for final disposition.

5.7.4 Validation Results

Dig results including detailed descriptions, actual recovered locations, and photographs are provided in the project database included in Appendix D. All the seed items were recovered, and no MEC was recovered during validation. Two MD items required venting with explosive charges to confirm that they did not present an explosive hazard. Figure 11 shows an example of a digital photograph of a recovered metallic anomaly and relevant data.

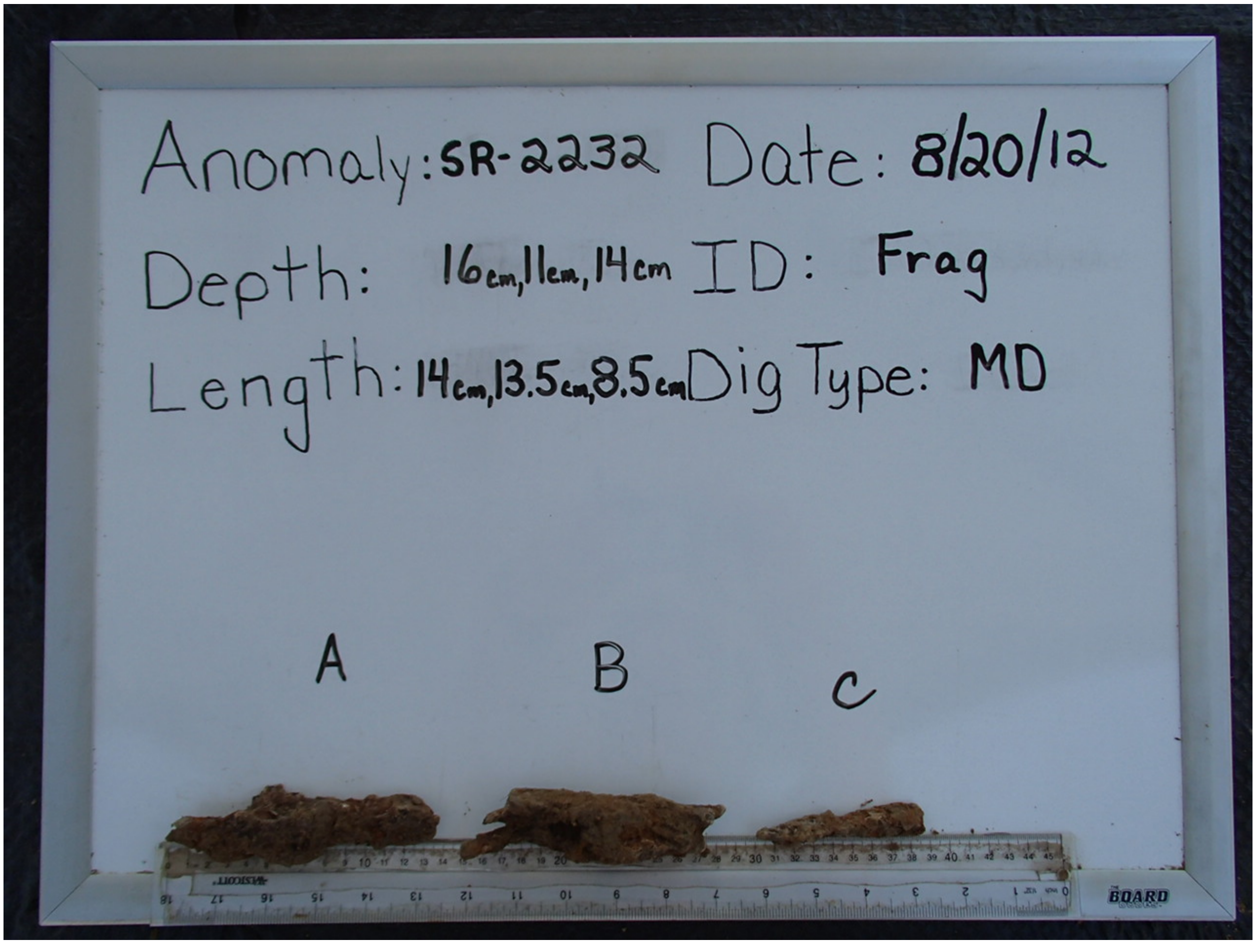

Figure 11. Example of Photo and Relevant Data from Validation Digging

6.0 DATA ANALYSIS AND PRODUCTS

6.1 EM61-MK2 DGM DATA PROCESSING AND INTERPRETATION

6.1.1 Processing

DGM data were corrected and processed using NAV61 and DAT61 software to convert binary files in American Standard Code for Information Interchange (ASCII) format and to interpolate locations for each DGM sample. Oasis Montaj was then used to:

- Convert location data from latitude and longitude to WGS 84 UTM Zone 16, Meters;
- Interpolate DGM samples where vegetation interfered with the RTS system;
- Identify and apply latency corrections;
- Level data to remove instrument drift using an iterative filter that subtracted median values of background noise from the data;
- Grid data using a minimum curvature algorithm;
- Test cross-line and down-line spacing to ensure compliance with project metrics; and
- Identify target responses above the threshold using the Blakley method.

6.1.2 Target Selection for Detection

URS selected anomalies for advanced classification using a target response-based procedure. The threshold was set to detect all 37mm at 34 cm depth (above 4 mV in gate 2 for the EM61-MK2 cart). A subset of anomalies was selected to detect all 37mm at 30 cm depth (above 5.2 mV in gate 2 for the EM61-MK2 cart) and provided to the demonstrators by the ESTCP Program Office. Figure 12 is a plot of the EM61-MK2 production survey processed data. The anomaly distribution is relatively uniform throughout the survey area.

6.2 METALMAPPER DATA PROCESSING AND INTERPRETATION

URS used the Geosoft UX-Analyze software package to process and invert the MM data. Prior to classification, inversion results were reviewed to determine whether data were of sufficient quality to classify the target anomaly source. Both single- and multi-source inversions were reviewed for data quality, to determine whether the inversion fits cohesions were greater the 0.75, and the inverted anomaly source locations were within 0.6 m of the MM location. Inverted results that did not meet these criteria were selected for recollection. If the results were already recollected data, no further attempts were made to collect additional data.

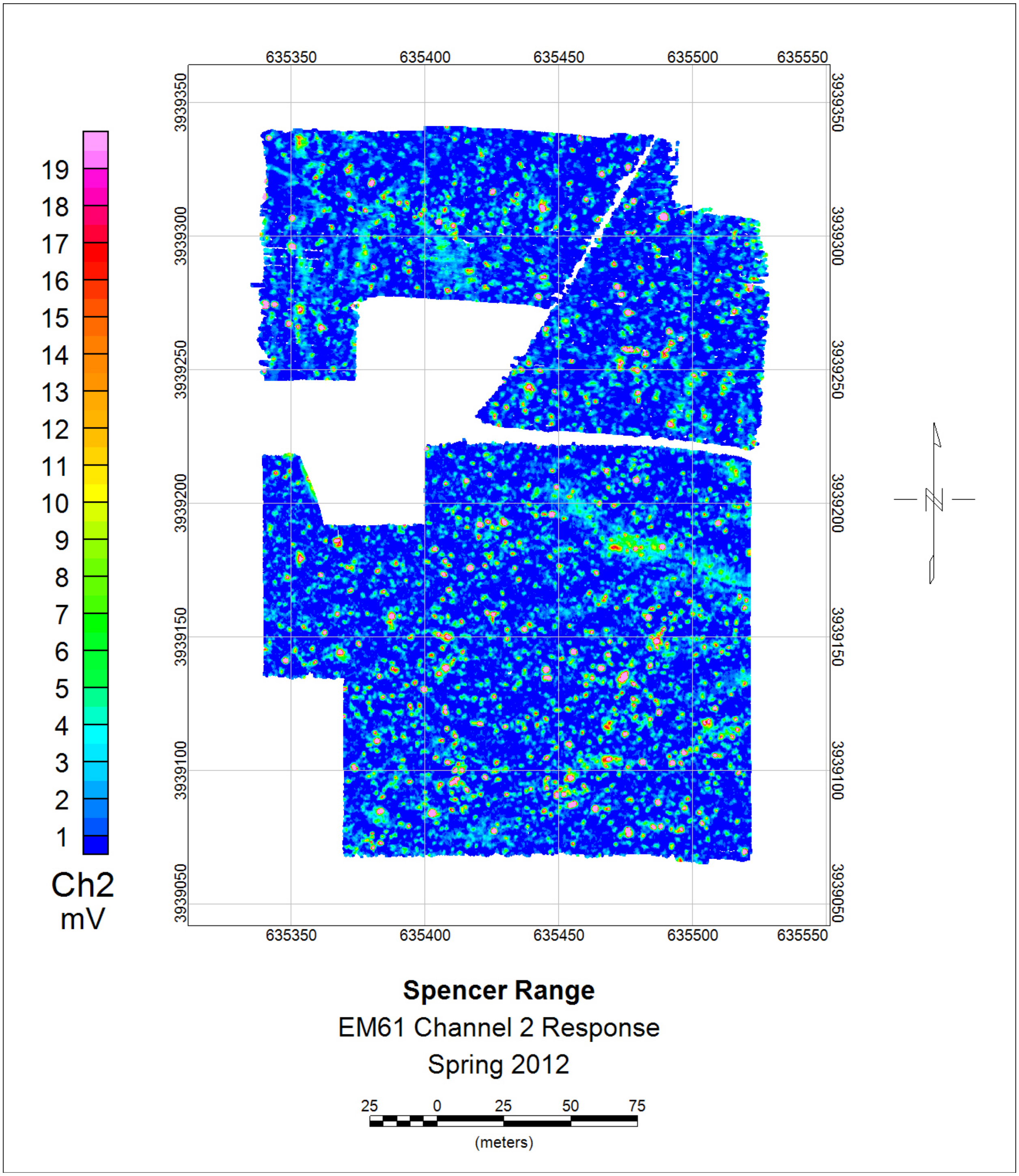

Figure 12. EM61-MK2 Production Data Channel 2 Survey Results

6.2.1 Multi-Source Inversion Selection

All data analysis was performed based on the multi-source inversion with the Geosoft UX-Analyze package. Only multi-source data were used to maintain consistency within each approach. Single- and multi-source inversion results for the same anomaly can vary significantly.

Therefore, comparing a multi-source inversion result with a library item generated from a single-source inversion, or clustering multi- and single-source results, poses issues for data analysis. To remove this potential source of error, all analyses were performed on multi-source inversion results.

6.2.2 Evaluation of Inversion Results

Two parameters output from the UX-Analyze inversion were used to initially determine whether the inversion results were sufficient to perform classification: fit cohesion and estimated horizontal offset of the anomaly source from the center point of the array.

Previous ESTCP MM studies (ESTCP 2010) have established that reliable estimates of position and target size are obtained when the correlation coefficient (√fit cohesion) is greater than 0.80. Previous studies have also demonstrated that, when a target is offset from the MM platform center, the ability of the inversion to adequately extract the principal polarizability curves is compromised. In particular, the minor transient symmetry and ratio values can be affected. Previous efforts have found no adverse effects for horizontal offsets less than 0.5 m, but larger offsets can be affected. Responses with a fit cohesion of less than 0.75 and/or horizontal offsets greater than 0.6 m were flagged for further review by the data analyst and recollected when necessary. Figure 13 shows a histogram of the MM cued mode data for Fit_Coh and Figure 14 shows a histogram of the offset of the MM array from the inverted fit location.

Based on these results, 4 targets out of 1,444 were flagged for further review by the analyst. These flags were noted, in case further discrepancies were later identified associated with these responses, and submitted for analysis.

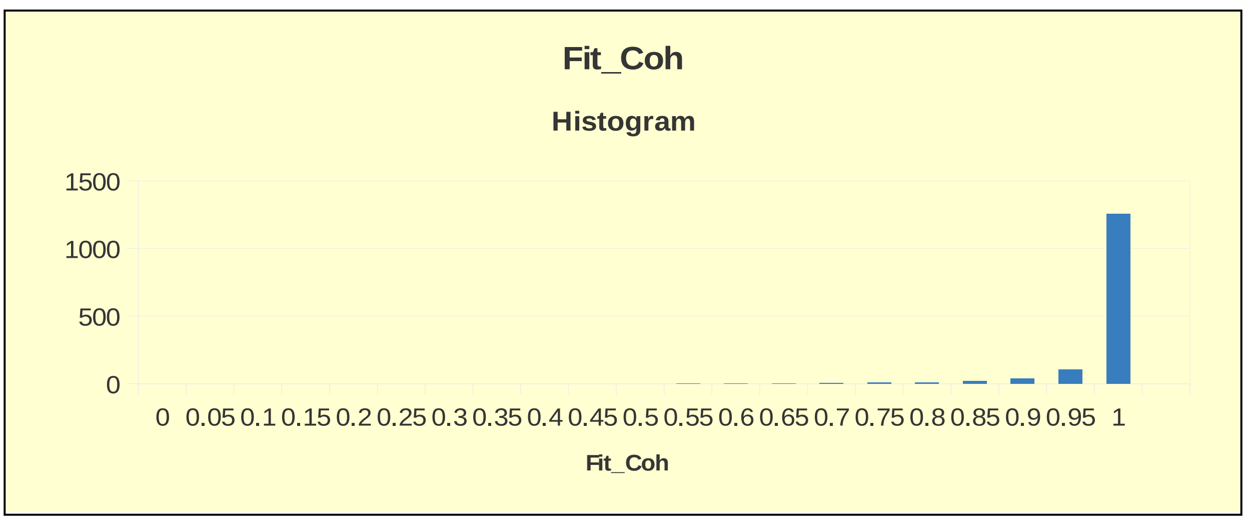

Figure 13. Histogram Showing Fit_Coh Values

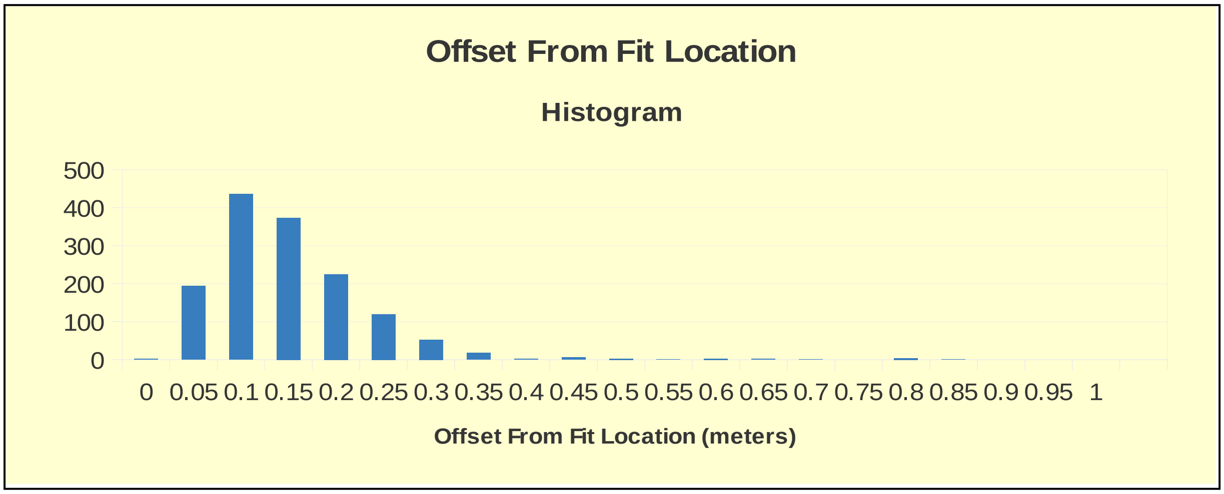

Figure 14. Histogram Showing Array Offset from Fit Location

6.3 METALMAPPER CUED MODE DATA ANALYSIS AND CLASSIFICATION METHODS

Inversion results were classified using LM and data mining tools, including classifier and clustering algorithms, augmented by visual review of the data. Classification was conducted in six steps.

1. Multi-source inversion results and dynamic EM61 data were used to determine whether there were sufficient high-quality data to classify the target anomaly source.
2. Cued inversion results were parameterized into values that characterize the size, time decay, and ratios between polarizability axes.
3. The LM algorithm contained within UX-Analyze, supported by results from the SimpleKMeans clustering algorithm within Weka, was used to develop an initial classification list. A unique library was developed utilizing PMTMA data, Former Spencer Artillery Range IVS and test pit data, and select items within the standard library. The list was visually reviewed to confirm that LM results were reasonable, and used as a basis for selecting training data. LM was also used to predict the anomaly source item type for all the classification lists.
4. Parameters derived from polarizability inversions were analyzed using the MultilayerPerceptron ANN algorithm within Weka, with several runs with different parameters combined into the ANN-ranked anomaly list. This list was updated using additional training data and updated input parameters as a result of a QC failure analysis, and resubmitted.
5. LM results were used to generate the LM ranked anomaly list. This list was updated by creating a new library containing missed QC seed items and matching only to those items. The best fits were moved to the TOI portion of the ranked anomaly list.
6. A threshold-based classifier, SIMPLE, was also developed by inspecting ranges within each parameter that were characteristic of TOI. Although the threshold-based classifier initially performed better than the other two approaches, the failure analysis indicated that with the inclusion of the QC seeds there was sufficient scatter of TOI within the parameter space that threshold-based classifier was discontinued.

6.3.1 Parameter Estimates

URS utilized data mining techniques to develop two target lists. Cued response polarizability inversion results were parameterized into a series of scalar values using two separate approaches. Parameterization of the inversion results was performed to simplify the dataset and make subsequent analysis more efficient. All the Former Spencer Artillery Range and PMTMA inverted cued responses were parameterized to allow use of PMTMA data as training data in the analysis of Former Spencer Artillery Range data.

6.3.1.1 Scalar Moments

The first set of parameters was based on scalar moments of the principal transients as defined by Smith and Lee (2002). These parameters can broadly be categorized into three categories: size, shape, and time (persistence). Size is measured by two different methods of integration known as the zero and first moment: $P_0 = \int \frac{dP}{dt} dt$ and $P_1 = \int t \frac{dP}{dt} dt$ .There are eight size scalars: P_{0x}, P_{0y}, P_{0z}, $I_2(P_0)$, P_{1x}, P_{1y}, P_{1z}, and $I_2(P_1)$, with $I_2(P_0)$ defined as $\sqrt[3]{P_{0x}P_{0y}P_{0z}}$. Shape has six scalars: $P_{0T} = \sqrt{(P_{0y}P_{0z})}$, $P_{0R} = P_{0x}/P_{0T}$, $P_{0E} = (P_{0y} - P_{0z})/P_{0x}$, P_{1T}, P_{1R}, and P_{1E}. Time (persistence) has four scalars: $\tau_x = P_{1x}/P_{0x}$, $\tau_y = P_{1y}/P_{0y}$, $\tau_z = P_{1z}/P_{0z}$, and $\tau_I = I_2(P_1)/ I_2(P_0)$.

The parameters were calculated using scripts developed in Oasis Montaj platform for the analyzable cued data.

6.3.1.2 Curve Fitting

A second set of parameters was calculated using commercially available curve-fitting algorithms within TableCurve2D.

Prior to curve fitting, the natural logarithm was taken of both the time window and the inverted polarizability plot. The fundamental physical relationship between inverted polarizability and time is an exponential decay, and is therefore roughly linear when presented in a logarithmic format. This linear relationship allows for a wider range of functions to realistically model the curves, and results in more robust fits. Because the time windows of the MM are scaled logarithmically, this also presents an even time interval between inverted polarizability values, further aiding the curve fitting.

Initial curve-fitting tests were performed on a subset of 10 representative polarizability curves, which were fit using several thousand different curve-fitting equations. Potential candidates were selected from the pool of available equations and further tested against a subset of 250 representative polarizability curves for robustness of fit across all the curves. Preference was given to functions with the fewest number of independent parameters, in-line with the overall objective, simplifying the dataset through parameterization.

Many of the best fits for the initial polarizability curves were generated using polynomial functions. This has solid theoretical backing. The Weirstrauss approximation theorem states that every continuous function f(x), defined in an interval, can be uniformly approximated by a polynomial function of n degrees. Because of this relationship, polynomial functions of n^{th} order are frequently used in curve fitting. However, while the best fits to any given polarizability curve are likely to be large degree polynomials, larger degree polynomials are expected to be less robust across all curves, due to Runge's phenomenon, which occasionally results in significant oscillations between points on the polarizability curve. This phenomenon is equivalent with over-fitting noise, or the Gibbs phenomenon in Fourier series.

With initial review of the data and consideration of all of these factors, a sixth degree polynomials function:

$$f(x) = a + bx + cx^2 + dx^3 + ex^4 + fx^5 + gx^6$$

was chosen to perform the curve fitting. This function was determined to be complex enough to fit most of the more subtle features present in the polarizability inversions, but simple enough to avoid Runge's phenomenon and to meet the objective of simplifying the data through parameterization. Figure 15 shows an example of curve-fitting inverted polarizabilities using a sixth degree polynomial.

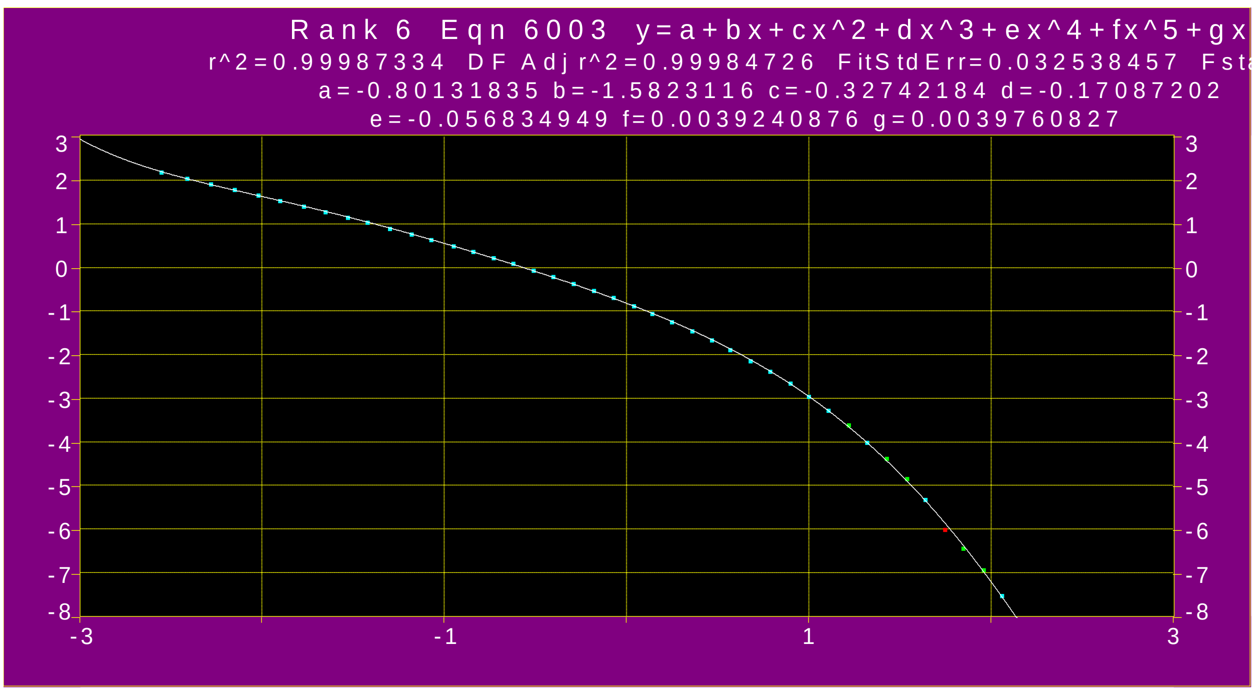

Figure 15. Log-scale Polarizability Plot Showing Sixth Degree Polynomial Curve Fit

Based on this selection, 21 parameters were generated to describe each of the polarizability inversion results, including 7 parameters to describe each of the three polarizability decay curves.

Figure 16 shows various parameters plotted against each other, with known TOI (shown in orange) and known non-TOI (shown in blue). Anomalies with unknown sources are shown by the character M. The clustering of known TOI indicates that these parameter combinations should be useful in classifying unknown anomaly sources as either TOI or non-TOI.

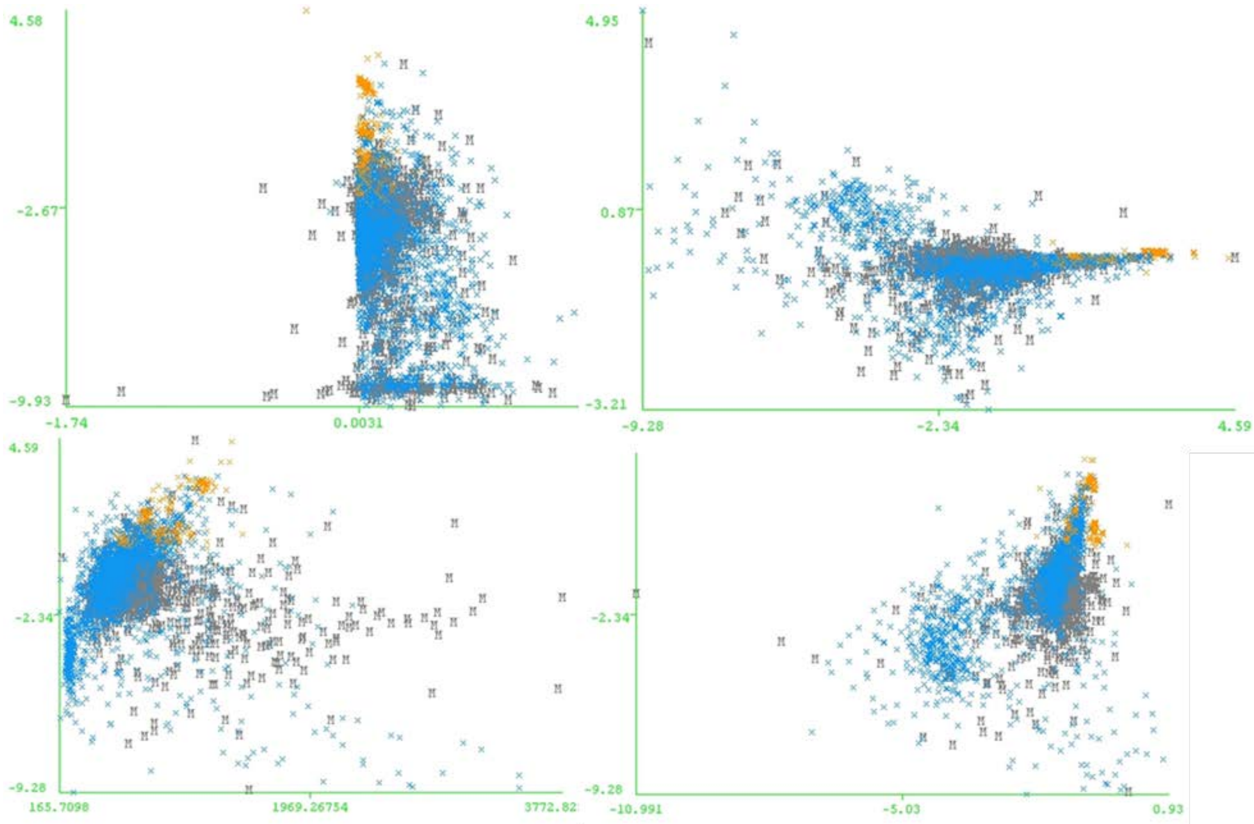

Figure 16. Parameter Plot Showing TOI and non-TOI Distribution

6.3.2 Library Matching

The UX-Analyze LM algorithm was run on all the Former Spencer Artillery Range polarizability responses. The algorithm compares the inverted polarizability with a library of known target polarizability signatures, and generated a fit quality for each item within the library. Usually the best, or primary, fit is used to determine whether the item represents a TOI.

The library provided within UX-Analyze is based on either single-source inversion results or an unknown mix of single- and multi-source inversion results. To ensure standardization to the multi-source inversion results, URS independently developed its own library based on data collected over seed items from PMTMA and test pit combined with IVS data at the Former Spencer Artillery Range. Examples of munitions types not included in either of these demonstrations were copied from the standard library into the URS library, along with a very limited number of clutter items, taking every effort to ensure that as much of the library as possible reflected multi-source rather than single-source inversion results.

LM results indicating a fit quality of better than 80% were considered to be indicative of potential TOI. Potential TOI were extended below this threshold based on analyst discretion. A primary fit to a non-munitions item, and primary fit quality to TOI of less than 80%, were classified as non-TOI.

6.3.2.1 Initial Clustering

In parallel to generating the library matches, several runs were performed using a SimpleKMeans clustering algorithm within the Weka data mining software package. The purpose of this initial analysis was to help select training data examples in combination with the LM. While many data mining techniques require pre-existing labeled (training) data, clustering algorithms can also be used with unlabeled data. They work by associating data into clusters based on proximity within the parameter space.

Clustering also minimizes the risks of overtraining inherent in data mining techniques. Overtraining can be easily accomplished by setting the number of clusters equal to the number of dataset members, but in practice can be readily addressed by limiting the number of clusters that can be defined via an input parameter. Clustering can also be used to identify data gaps that need to be filled within the training dataset by identifying clusters that are not represented in the training data.

The SimpleKMeans algorithm uses a normalized parameter space and allows configuration of how distance is calculated and how many groups are generated. Chebyshev, Euclidian, and Manhattan distance metrics were evaluated and selected for use. Euclidian distances result from a unique, shortest path between two points (the way the crow flies). Manhattan distance is calculated based on the absolute sum of the distances in each coordinate (the distance a taxicab travels following city blocks), and Chebyshev distance is the greatest difference along any coordinate system dimension (the number of moves a king is from another square on the chessboard). The number of clusters was also varied; the best results were typically set around 150 clusters, or about 10% the total number of dataset members.

6.3.2.2 Training Data Selection

Table 3 shows an example spreadsheet of how the clustering and LM results were combined for visual review. Clusters where the large majority of responses were associated with library matched TOI were colored green, and grey where the large majority did not match TOI. Clusters without a clear majority were left white, and responses associated with a library match that went against the clear majority, outliers, were colored red. These charts were used to separate highly likely TOI and highly unlikely TOI from the responses there were uncertain and difficult to classify. A subset of the uncertain and difficult to classify responses was submitted as training data requests.

6.3.2.3 Final Ranked Anomaly List

After incorporating the training data into the LM list, a ranked anomaly list was submitted based on the library match results, with a few nominal responses below the library match threshold of greater than 80% fit quality included based on the responses falling within clusters that were predominantly library matched to TOI.

Table 3. Example of Training Data Selection Table

All Parameters Euclidean Dist. 150 Clusters Spencer Only	All Parameters Manhattan Dist. 150 Clusters	All Parameters Euclidean Dist. 25 Clusters	All Parameters Euclidean Dist. 150 Clusters	URS Library Fit Quality	Match Type	ID
cluster61	cluster39	cluster10	cluster39	0.6769	spn_37mm_Horiz_20cm to center	121
cluster105	cluster54	cluster1	cluster79	0.9635	PM_37mm projectile_id-1029	122
cluster8	cluster39	cluster10	cluster39	0.513	spn_37mm_Horiz_20cm to center	123
cluster12	cluster12	cluster18	cluster12	0.586	spn_37mm_Horiz_20cm to center	124
cluster75	cluster127	cluster15	cluster127	0.5028	Clutter (Barbed wire)	125
cluster48	cluster16	cluster16	cluster16	0.8313	spn_37mm_45degree, nose down_22cm to center	126
cluster99	cluster45	cluster15	cluster56	0.7426	spn_37mm_Horiz_20cm to center	127
cluster62	cluster102	cluster16	cluster102	0.9354	PM_37mm projectile_id-341	128
cluster21	cluster6	cluster6	cluster1	0.9279	PM_Small ISO_id-2184	129
cluster148	cluster146	cluster12	cluster19	0.364	Clutter (Shovel blade - vertical, blade up)	130
cluster127	cluster127	cluster23	cluster119	0.5549	spn_37mm_Horiz_20cm to center	131
cluster49	cluster109	cluster0	cluster109	0.5672	Clutter (Barbed wire)	132
cluster54	cluster79	cluster1	cluster16	0.8717	PM_37mm projectile_id-1029	133
cluster131	cluster43	cluster18	cluster138	0.6481	PM_Small ISO_id-1268	134
cluster55	cluster126	cluster16	cluster126	0.9437	PM_Small ISO_id-1847	135
cluster73	cluster26	cluster22	cluster108	0.4721	PM_57mm projectile_id-1158	136
cluster70	cluster107	cluster3	cluster35	0.9401	PM_60mm mortar_id-1493	137
cluster143	cluster141	cluster18	cluster124	0.6812	spn_37mm_45degree, nose down_22cm to center	138
cluster48	cluster136	cluster23	cluster28	0.5406	spn_37mm_45degree, nose down_22cm to center	139
cluster90	cluster112	cluster10	cluster112	0.4829	PM_Small ISO_id-1079	140
cluster30	cluster147	cluster6	cluster147	0.9034	PM_Small ISO_id-1268	141
cluster33	cluster33	cluster6	cluster33	0.7593	spn_37mm_Horiz_20cm to center	142
cluster45	cluster95	cluster16	cluster63	0.8609	spn_37mm_Horiz_20cm to center	143
cluster6	cluster24	cluster18	cluster124	0.5603	PM_Small ISO_id-2184	144
cluster45	cluster126	cluster16	cluster126	0.9606	PM_Small ISO_id-1584	145
cluster125	cluster125	cluster1	cluster125	0.8936	PM_57mm projectile_id-606	146
cluster95	cluster7	cluster6	cluster7	0.676	PM_Small ISO_id-539	147
cluster125	cluster125	cluster21	cluster125	0.8264	PM_75mm projectile_id-514	148

6.3.2.4 Quality Control Failure Analysis

The LM list failed to identify and target one QC seed in the dynamic area, SR-1502, and two QC seeds in the open area, SR-190 and SR-199.

Anomaly SR-190 and SR-1502 were both associated with small ISO items; SR-190 was associated with a seeded 155mm projectile. Since no 155mm projectile had been included in the initial URS library, a 155mm project response was added and back tested against SR-190. The back test indicated a match of better than 95%. All other matches to either SR-190 or the library 155mm projectile were added as TOI to the LM list.

The other missed items, in particular SR-199, posed a more significant challenge. The decay curves associated with SR-199 do not closely match any of the dozens of other small ISOs recovered from PMTMA and Former Spencer Artillery Range. This is illustrated in Figure 17. The polarizabilities generated by the multi-source solver were nearly an order of magnitude smaller than the single-source inversion results, suggesting a possible issue with the multi-source solver routine within UX-Analyze.

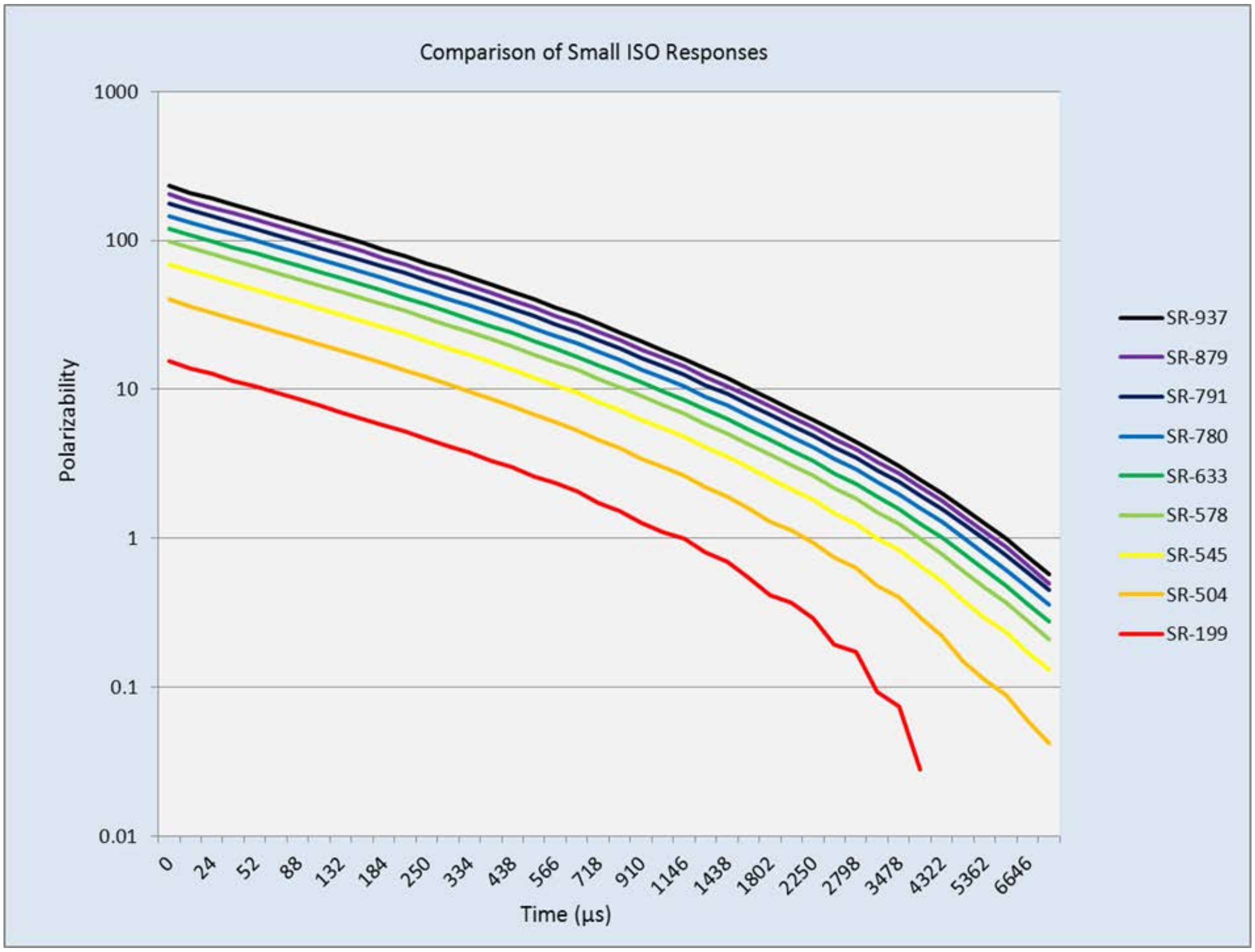

Figure 17. Polarizability Curves for SR-199 and Other Small ISOs

For SR-1502, a small ISO item found with two pieces of munitions debris, the multi-source inversion results show what appears the be two items within the target clouds shown in green in Figure 18, but the inversion only solved for one item (A). The failure to resolve at least two items results in a fit cohesion significantly lower than the fit cohesion of the target clouds.

Based on these issues with the multi-source solver, it was determined that all the Former Spencer Artillery Range data would be re-inverted using a new, Beta, version of the multi-source solver, along with the PMTMA data to maintain consistency within the URS library.

After re-inverting all the Former Spencer Artillery Range data, the URS library was updated with the new results, including the QC seeds. Further testing of the new library revealed that non-TOI responses were sometimes a primary match to responses that also matched the QC seeds at SR-199 and SR-1502 at a level above the greater than 80% fit threshold. A subset library was created containing only SR-199 and SR-1502, along with a select number of clutter items, and the library match was run on only these items to identify responses above the greater than 80% fit threshold. Any responses that matched these two library items were added to the LM list.

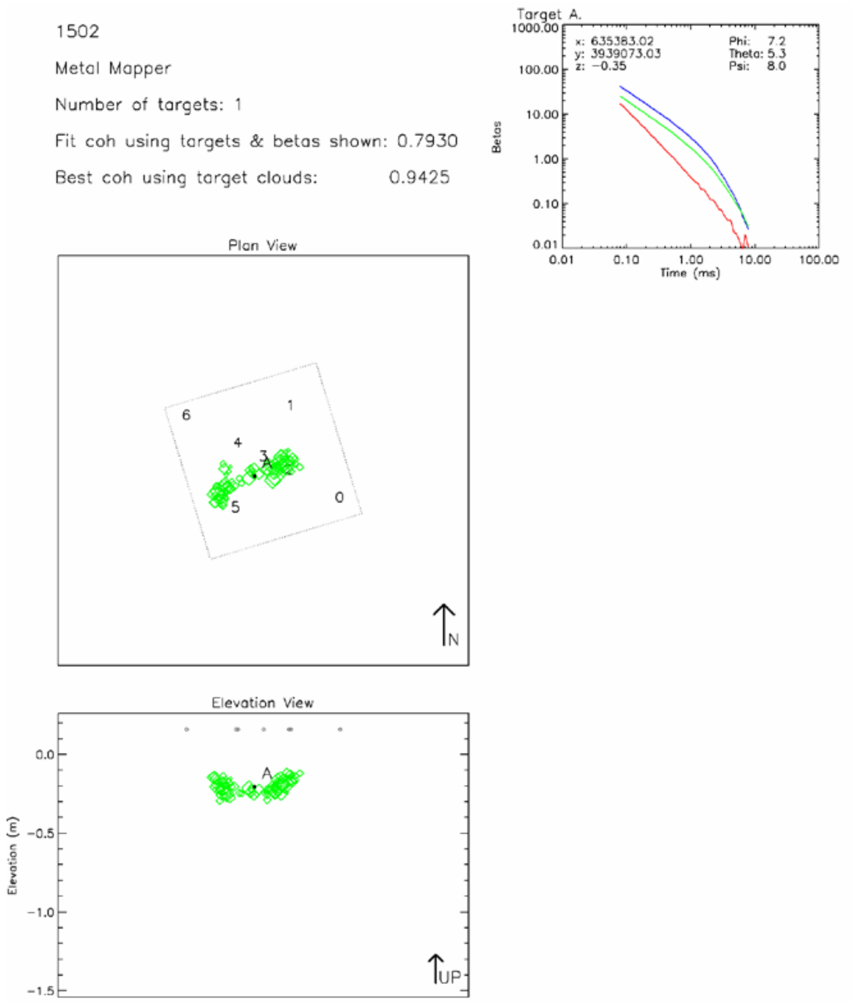

Figure 18. Multi-Source Inversion Result with Inaccurate Single Source

6.3.3 Classifier-Based Classification

The ANN-based classifier algorithm MultiLayerPerceptron within Weka was used to develop the ANN-ranked anomaly list. A training dataset was developed from library data, IVS and test pit data at the Former Spencer Artillery Range, requested training data, and previous demonstration data at PMTMA. The parameters discussed in Section 6.3.1.2 were calculated for all of these datasets. Further analysis was performed to identify and eliminate redundant parameters.

In parallel with the classifier algorithm approach, clustering techniques and visual review of the parameterized data were used to identify disjoint clusters within the parameter space. Cued responses considered or known to be either TOI or non-TOI were included on these plots for visual reference. The clustering techniques and visual review served to confirm relationships identified through the classifier algorithm regions that can be associated with likely TOI or unlikely TOI.

6.3.3.1 Overview of Data Mining Approach

Learning algorithms used for data mining are commonly divided into two categories, classifiers and clustering. Classifiers use labeled data (training data) where the classification is known to "learn" what parameter values are associated with the target class. Clustering algorithms work with labeled or unlabeled data by associating these data into clusters based on proximity within the parameter space.

Classifier and clustering algorithms are complementary and often used together. An example of this is the use of clustering to expand classifier algorithms where training data are limited and/or expensive to obtain (Nigam et al. 1999). First, a classifier is used to identify a set of parameter values associated with the target class using a limited set of training data. Then, clustering is performed on a larger unlabeled dataset. Clusters, which contain members associated by the classifier with the target class, are then determined to be associated with the target class. These clusters, now labeled as part of the target class, are then used as additional training data for a second classifier iteration.

URS used classifier and clustering algorithms combined with visual review of the data independently so that the clustering algorithms could be used as a check of the classifier results. The selected classifier algorithm was used to perform an initial classification, subject to the limitations of the training data. Classifier algorithms risk overtraining, where the results are specific only to training data examples and are not capable of recognizing the more general class to which the training data examples belong.

Clustering also risks overtraining (i.e., every dataset member is defined as a cluster), but this can be addressed by limiting the number of clusters that can be defined via an input parameter for the algorithm. Clustering is also independent of any training dataset, and can be used to identify data gaps that need to be filled within the training dataset by identifying clusters that are not represented in the training data. Clustering algorithms and visual review were used to identify potential gaps within the training data, and were used to identify situations where the classifier has overtrained and only selected a portion of a cluster rather than the entire cluster, as appropriate. In summary, clustering and visual review were used as a QC check on both the completeness of the training data and on the classifier algorithm results to help avoid overtraining.

6.3.3.2 Training and Test Datasets

It is critically important that the training dataset contains a representative sample of the munitions that may be encountered during the demonstration. The training dataset was initially composed of library data, test pit data, requested training data, previous demonstration data from PMTMA, and Former Spencer Artillery Range IVS data. This was later expanded to include QC results data as well.

6.3.3.3 Parameter Evaluation

Principal component analysis was initially used to evaluate the parameter space. Principal component analysis transforms the data matrix through parameter space to a set of linearly uncorrelated variables called principal components, less than or equal to the original number of parameters. In cases with numerous correlated parameters, principal component analysis can simplify the initial dataset, reduce classifier calculation time, and typically improve classifier results (Witten et al. 2011).

Principal component analysis performed on the Former Spencer Artillery Range and PMTMA datasets reduced the initial 39 parameters (18 scalar moments and 21 curve fit parameters) down to 15 principal components. ANN results using the entire parameter set consistently performed better on synthetic test data than ANN results based on the principal components. This is likely due to relative scaling issues between the parameters. However, based on time/budget constraints this issue was not investigated further, and the initial ANN-ranked anomaly list was prepared without using principal component analysis.

After QC results became available, the parameter evaluation process was modified as part of the corrective action. Plots of each parameter versus the known TOI in the entire training dataset were prepared and visually reviewed. Parameters that showed clearly defined ranges for TOI within more widely ranging non-TOI were selected to be included for use in classification, while parameters that showed no clear relationships or ranges of values associated with TOI were removed. The removed parameters consisted of the eight scalar moments related to size, P_{0x}, P_{0y}, P_{0z}, $I_2(P_0)$, P_{1x}, P_{1y}, P_{1z}, $I_2(P_1)$, and two scalar moments related to shape, $P_{0T,\ \text{and}}$ P_{1T}.

The other scalar moments related to shape, all the scalar moments related to time/persistence, and all the curve fit parameters were preserved.

6.3.3.4 Artificial Neural Network Classifier

The MultilayerPerceptron algorithm within Weka, an ANN classifier, was used to analyze the parameters extracted from the polarizability curves. A multi-layer perceptron maps input data into a set of appropriate output, in this case a class. As a mapping operation it functions similarly to inversions, which map data into a series of model parameters, and attempt to minimize a misfit function. It uses the supervised learning technique, backpropagation, which is loosely equivalent to inversions, which generate synthetic data and compare it to the original input data to obtain an error measurement.

ANNs are composed of nodes organized into a series of layers: an input layer with each variable (parameter) represented as a node, an output layer which in this case is simply the class TOI/non-TOI, and a user determined number of hidden layers. Nodes within the hidden layers contain nonlinear activation functions that apply weights to each of the connected inputs. The hidden layer output or class is then compared to a training dataset with known class. The weights are then modified using the gradient decent method to attempt to minimize the error in the next iteration.

Key features of ANN are the quality and quantity of training data where the class is known; the number of hidden layers and nodes within each hidden layer; the size of the step used within the gradient decent, which is often referred to as the learning rate; and the number of iterations performed, referred to as training time.

Figure 19 shows the ANN model used for analysis at the Former Spencer Artillery Range. It contains two hidden layers, the first containing the same number of nodes as the input layer, and the second layer containing half the sum of the input layer and output layer. This configuration was arrived at empirically by comparing the quickness of convergence between various configurations. The training dataset comprised nearly all the previous PMTMA demonstration data and requested training data from the Former Spencer Artillery Range.

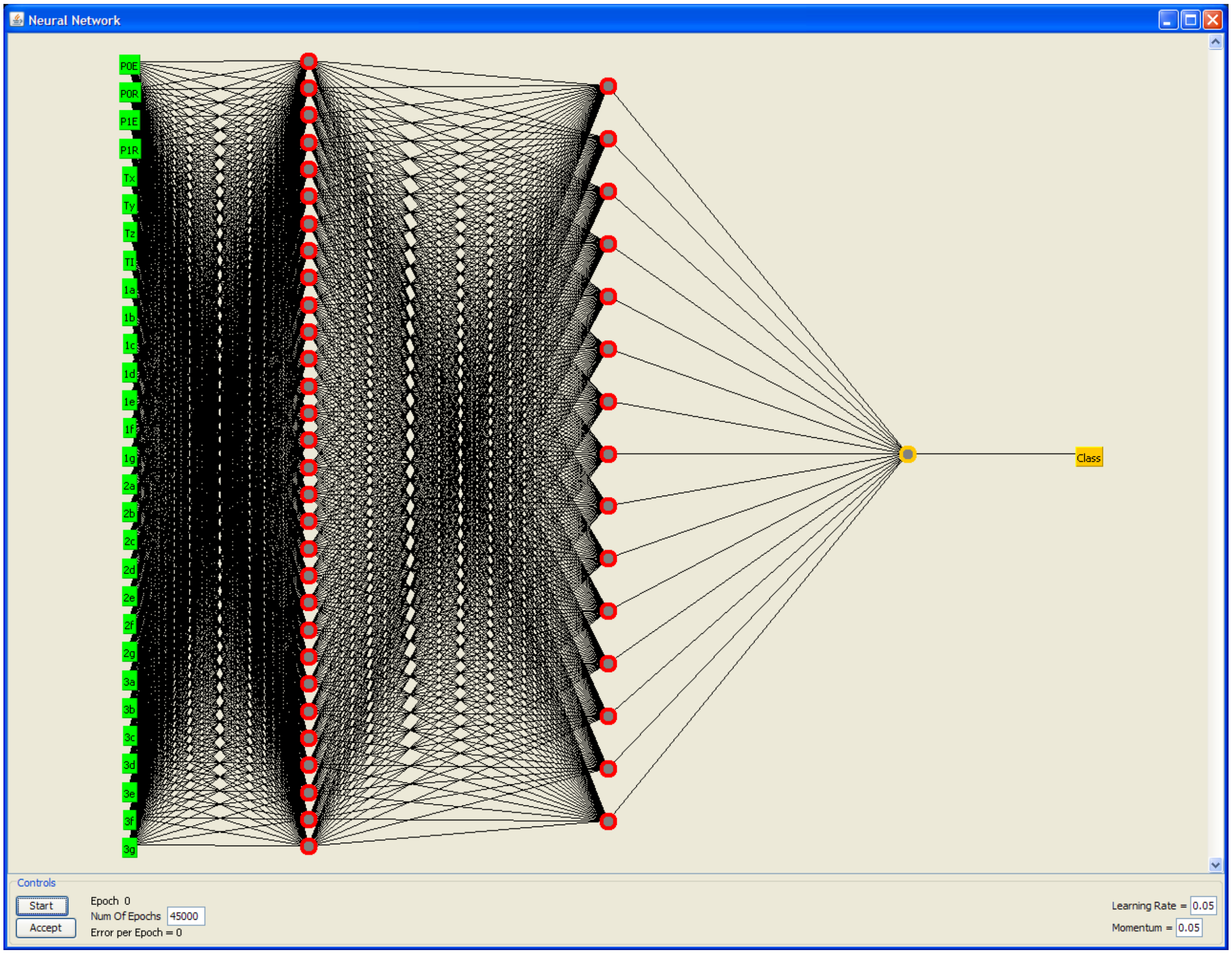

Figure 19. Artificial Neural Network Design with Two Hidden Layers

The ANN-ranked anomaly list failed to identify 13 QC seeds in the dynamic and open areas.

ANNs learn from existing training data, and are therefore highly dependent on the quantity and quality of the training data. They are also prone to overtraining when the training dataset does not contain a range of the target class that fully characterizes the possible items with the target class. To create as large a training set as possible, all the MM data and intrusive investigation results from the previous PMTMA demonstration were incorporated within the training dataset.

Initial inspection of the responses of the undetected seed items revealed that some of the inverted polarizabilities associated with the missed seed items did not match the signatures of the existing training data, both visually, and within the parameter space generated for this analysis. Figure 17 shows the inverted polarizabilities associated with SR-199, a small ISO item, in relation to other small ISO items included within the training dataset.

The variation between responses to seed items at PMTMA and Former Spencer Artillery Range may be a least partially dependent on the increased geologic response at Former Spencer Artillery Range relative to PMTMA. Figure 20 shows examples of inverted polarizabilities using the multi-source solver where the solver is unable to resolve discrete target locations. Instead, the responses are inverted to a distributed cloud of polarizabilities, perhaps indicative of the effects of a distributed source inherent in the geology rather than a discrete metallic source.

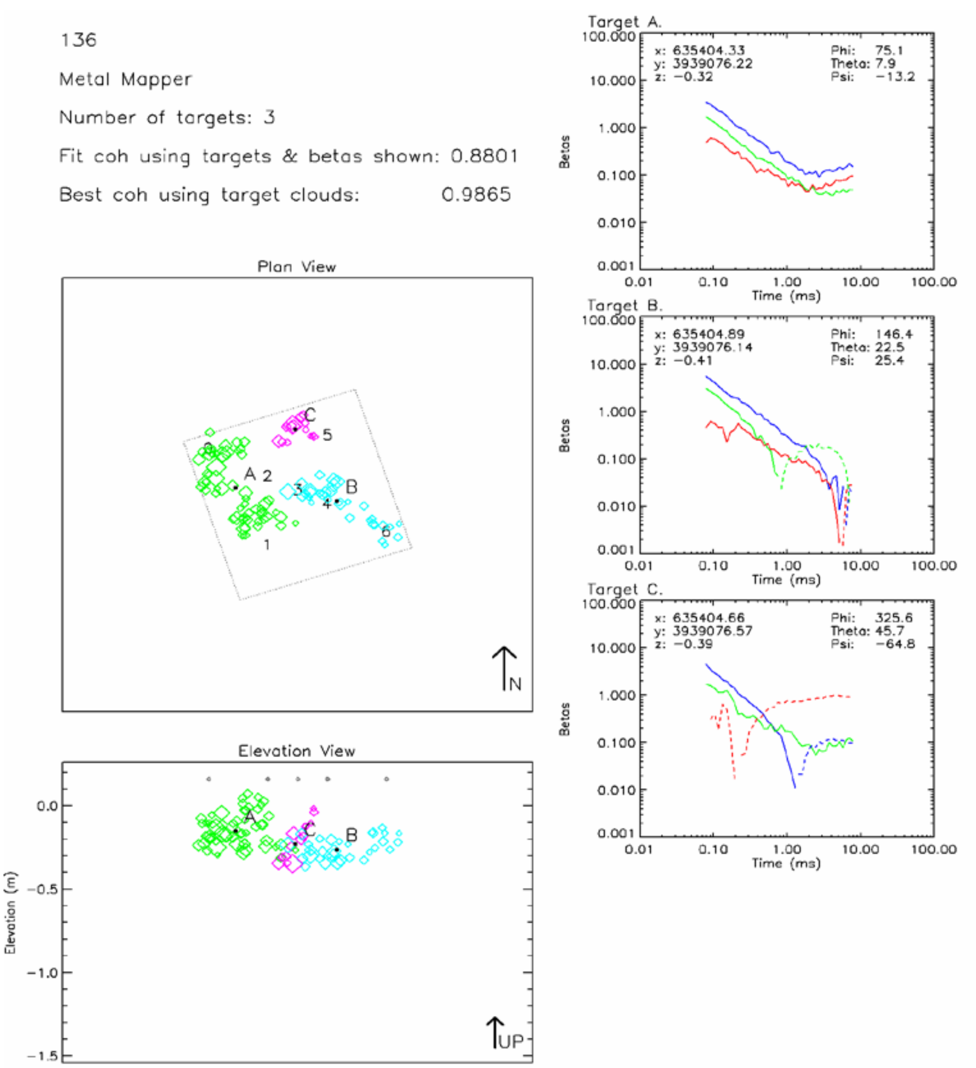

Figure 20. Multi-Source Inversion Result with Likely Geologic Response

A second issue with the ANN was identified within the parameters used for the ANN. It is possible to improve algorithm performance by reducing the learning rate and increasing the training time. In cases where the weights space within the hidden layers is noisy, a learning rate that is too fast can result in iterations within the algorithm that increase rather than decrease the error between predicted and actual class. Effectively the algorithm can no longer find the best path of the lowest error point and instead overshoots in directions that can be heavily influenced by random noise. Solutions deteriorate with each iteration rather than improve. This effect was observed while running the MultilayerPerceptron algorithm within Weka. Reducing the step size while increasing the training time allowed the algorithm to slowly converge on a more precise minimum error point.

As a result of the QC failures, two corrective actions were implemented for the ANN list. The first corrective action was to increase the training dataset by using the QC failure items as part of the training dataset. This helps significantly in utilizing a training dataset more fully representative of the items and geologic conditions present at the Former Spencer Artillery Range. The second corrective action was to significantly reduce the step size within the MultilayerPerceptron algorithm, while increasing the training time. New ANN lists for both the dynamic and open areas were prepared and submitted based on these corrective actions.

6.3.4 Simple Threshold Classification

6.3.4.1 Visual Review

Clustering techniques, as described in Section 6.3.2.1, were combined with visual review of the data to identify groups of targets within feature space. Identified clusters were compared with classifier results and training data to identify clusters that likely represent TOI or non-TOI. Initial clustering results proved to be disappointing, with significant mixing of TOI and non-TOI within individual clusters. Based on these observations, it was determined that a strictly visual approach might be more successful.

Figure 16 includes plots of various parameters compared to known TOI. While reviewing these plots, it became apparent that many of the parameters showed clear separation between values associated with TOI and values not associated with TOI. Based on this observation, a simple series of thresholds was developed for each parameter containing all the known TOI. These thresholds function similarly to the target thresholds used to select geophysical anomalies for advanced sensor interrogation and intrusive investigation. Figure 21 shows an example threshold used for determining whether an anomaly was within the range to be considered TOI.

Anomalies were assigned a rank of either 0 or 1 for a given parameter depending on whether they were in the non-TOI or TOI range, respectively. Ranks for the nine best parameters were combined into a single rank ranging from 0 to 9. For the SIMPLE ranked anomaly list, anomalies of rank 9 were selected as TOI, and all other ranks were selected as non-TOI.

Figure 21. Parameter Plot with Threshold

The SIMPLE ranked anomaly list failed to identify four QC seeds in the dynamic and open areas, equivalent to the LM ranked anomaly list. Despite this apparent equivalence to the significantly more complicated and labor-intensive LM list, further analysis indicated a significant problem within the SIMPLE list.

Figure 22 shows two example plots of parameters compared to the known TOI. Both plots show a significant outlier from the otherwise tightly clustered TOI. The outlier in all three cases is anomaly SR-199.

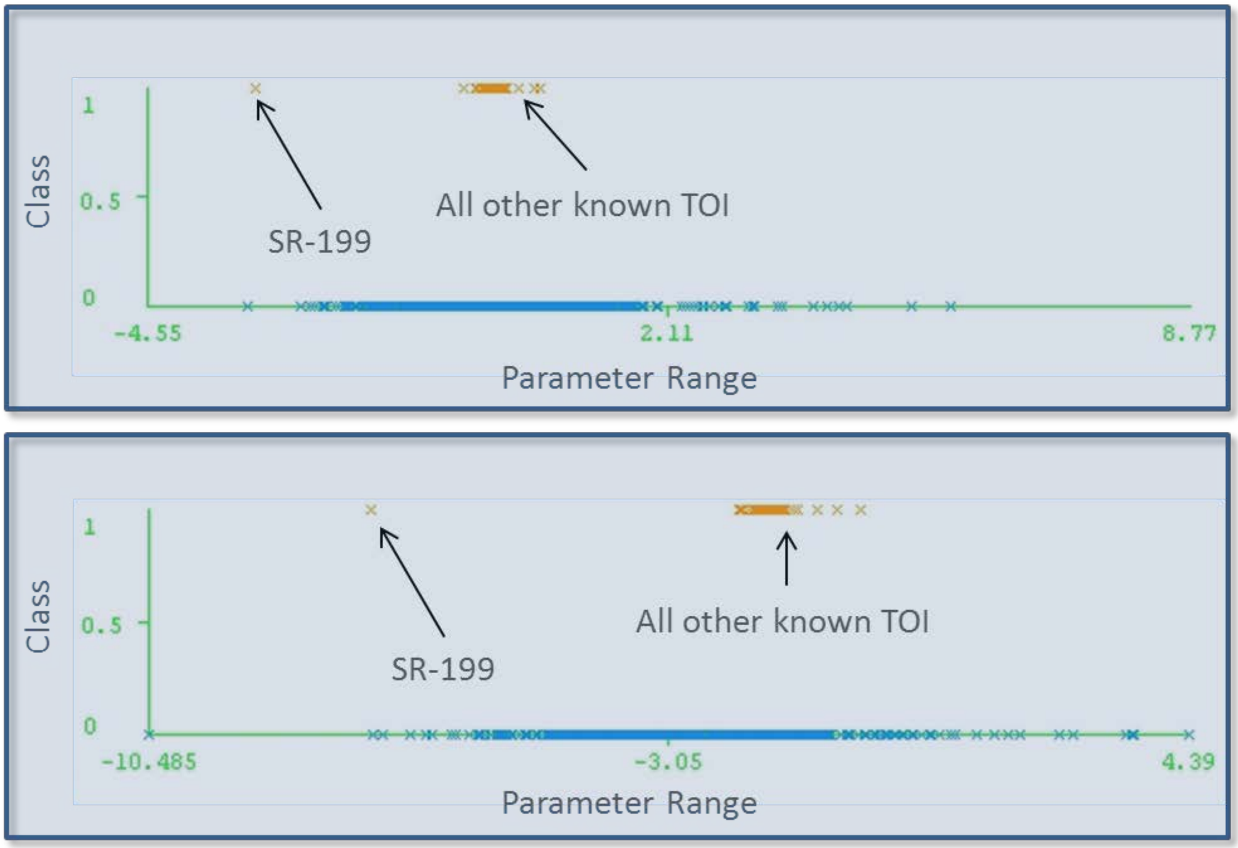

Figure 22. Parameter Plots with SR-199 Outlier

Expanding the range of each parameter so that it is sufficient to include SR-199 results in an anomaly target list containing roughly 50% of the anomalies. While this approach would have been very successful at PMTMA, as the tight clustering of known TOI in Figure 15 and Figure 21 indicate, it is not sufficiently robust for the Former Spencer Artillery Range, and no revised SIMPLE ranked anomaly list was submitted.

6.3.5 Summary

Multiple classification approaches, including LM, ANN, and visual review, were tested. Data were initially reviewed by LM and clustering to identify candidates for requested training data. Data were also parameterized using scalar moments and polynomial curve fitting. Parameterized data were analyzed using ANN to generate a ranked anomaly list and a simple threshold-based ranked anomaly list.

Lists were submitted for comparison to the QC seeds, and QC failure results were incorporated into the LM and ANN lists following corrective action, including revised training data and better selection of parameters within each approach. QC failures indicated that the SIMPLE threshold-based list was not a viable approach for the Former Spencer Artillery Range. Finally, LM results were used to identify the expected type of TOI for each anomaly selected for intrusive investigation.

6.4 Data Products

Table 4 provides the general prioritized target list statistics. The complete prioritized target lists are contained in Appendix E.

Table 4. General Prioritized Target List Statistics

List Name	TOI	TOI Identified (%)	Training Targets	Training Targets (%)	Can't Analyze	Can't Analyze (%)	List Length	List Length (%)	Total Targets
Spencer Open URS LM01	82	99.6%	51	4.6%	0	0%	420	38%	1,104
Spencer Open URS ANN01	82	100%	51	4.6%	0	0%	240	22%	1,104
Spencer Dynamic URS LM01	25	100%	3	0.9%	0	0%	98	29%	340
Spencer Dynamic URS ANN01	25	100%	3	0.9%	0	0%	43	13%	340

Each of the URS prioritized target lists identified all TOI in Category 1, except for one TOI that was identified in Category 2 using the LM method in the open area. See Figures 23 through 26.

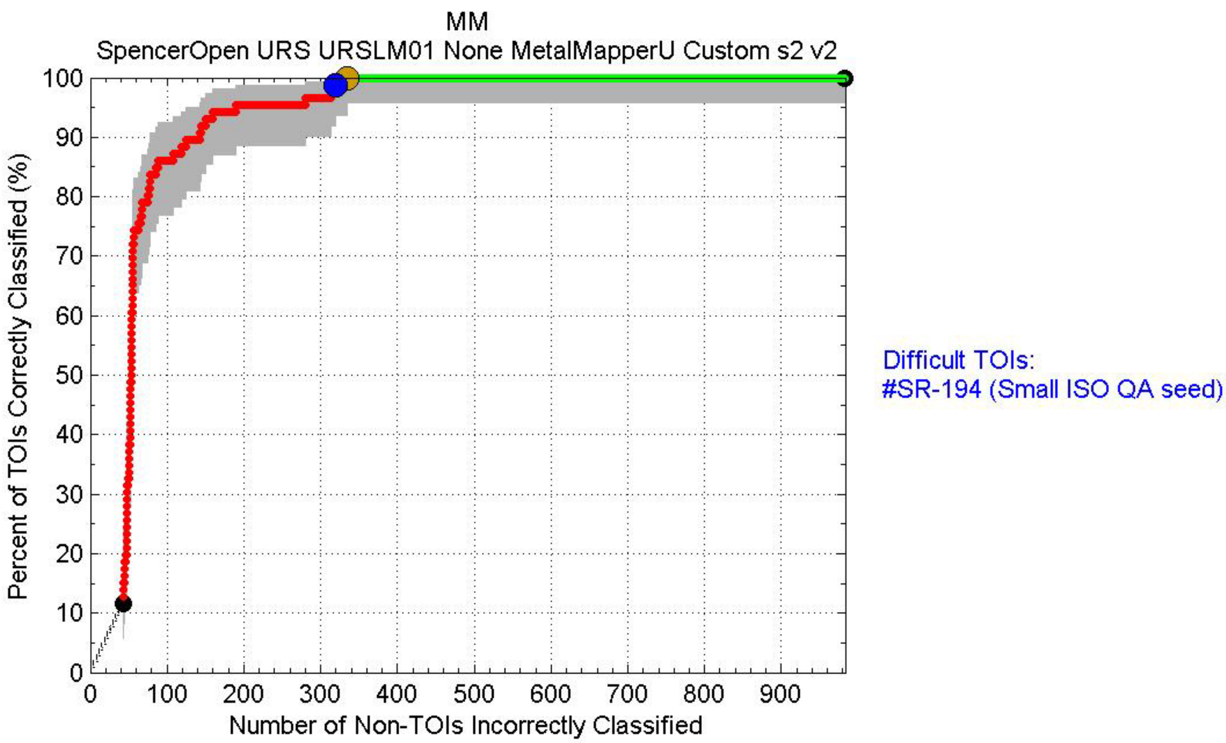

Figure 23. Classification Results Plot for Spencer Open URS LM01

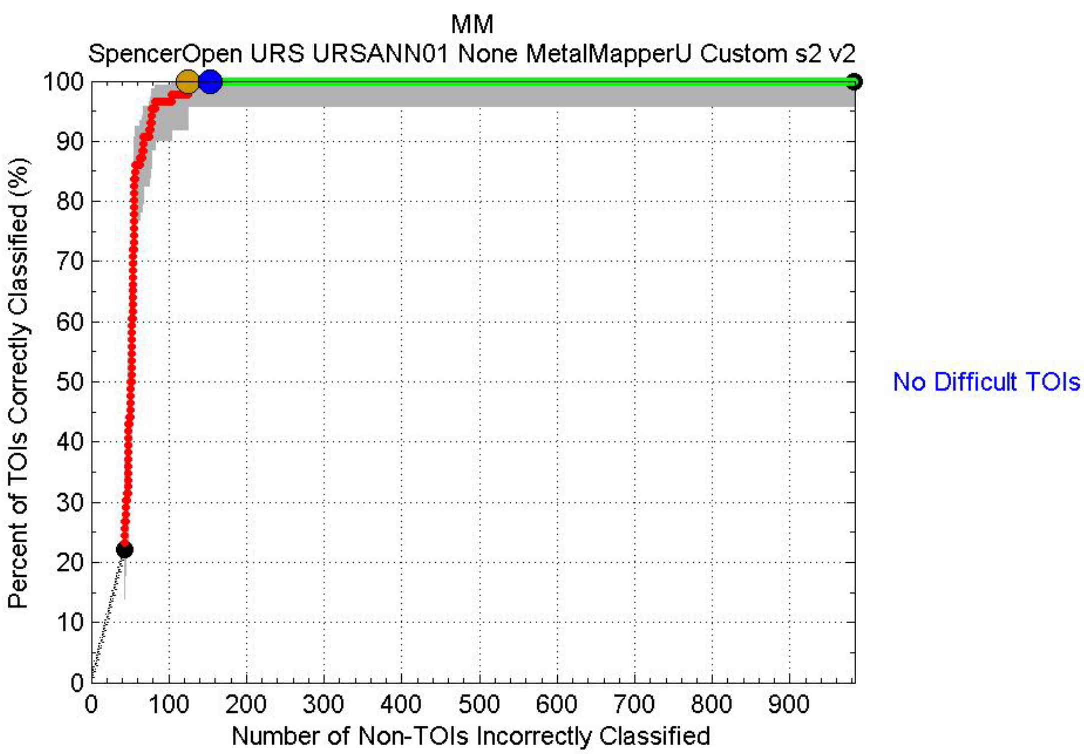

Figure 24. Classification Results Plot for Spencer Open URS ANN01

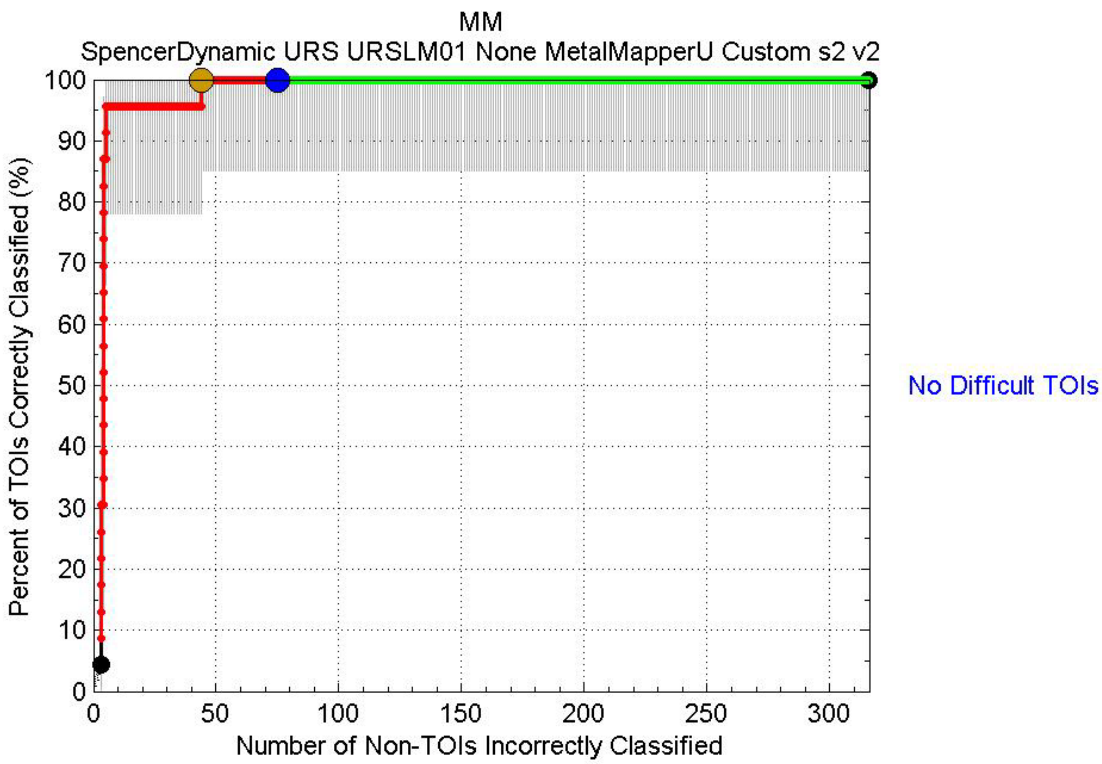

Figure 25. Classification Results Plot for Spencer Dynamic URS LM01

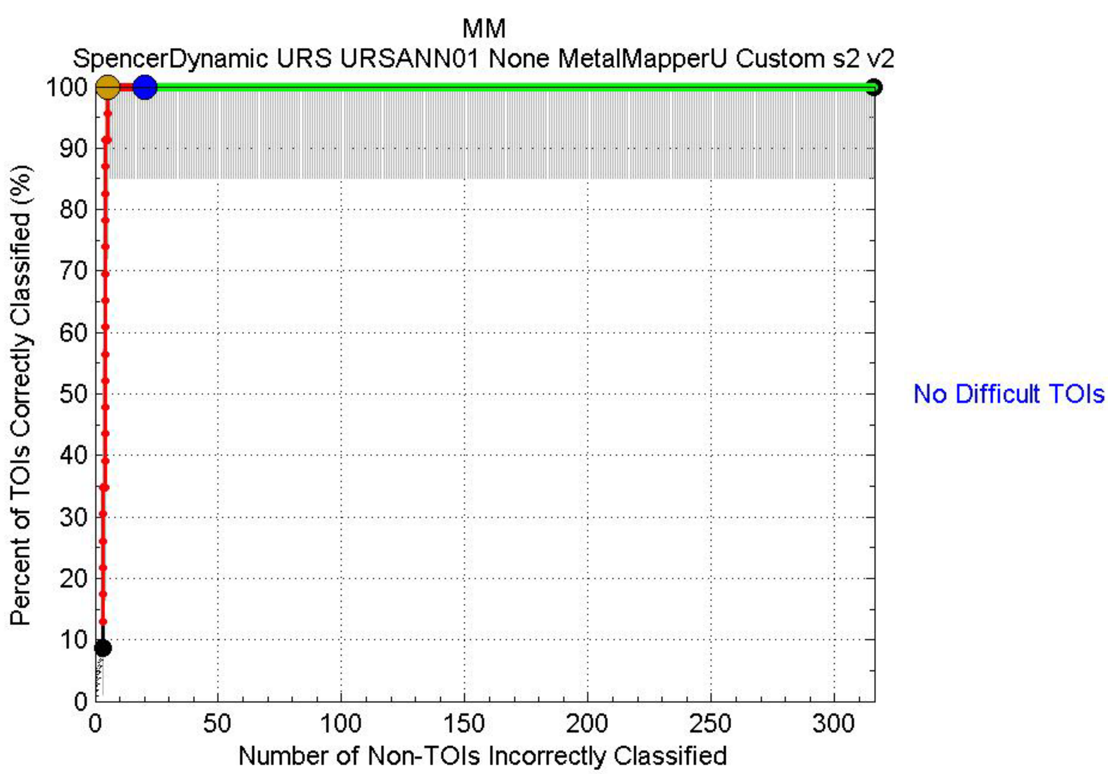

Figure 26. Classification Results Plot for Spencer Dynamic URS ANN01

7.0 PERFORMANCE ASSESSMENT

The performance objectives for this demonstration are summarized in Table 1 and are repeated here as Table 5. The results for each criterion are discussed in the following sections.

Table 5. Quantitative Performance Objectives and Results

Performance Objective	Metric	Data Required	Success Criteria	Results
Data Collection Objectives				
Along-line measurement spacing	Point-to-point spacing from dataset	Mapped survey data	*EM61 cart:* 90% <15 cm along-line spacing	98.2% open area, 97.3% wooded area
			TEMTADS: 98% <15 cm along-line spacing	*Not Assessed*
			MM: 90% <15 cm along-line spacing	*Not Assessed*
Complete coverage of the demonstration site	Footprint coverage	Mapped survey data	≥85% coverage at 0.5 m line spacing and ≥98% coverage at 0.75-m line spacing (open area only) calculated using UXProcess Footprint Coverage QC Tool	99.7% at 0.5 m, 100% at 0.75 m for open areas
Repeatability of IVS measurements	Amplitude of EM anomaly Measured target locations	Twice-daily instrument verification strip survey data	*EM61 cart:* amplitudes ±25% down-track location ±25 cm	Pass (maximum 16%) / Fail for T-005 (see discussion)
			Advanced Sensors Survey: amplitudes ±10% down-track location ±10 cm	*Not Assessed*
			Advanced Sensors Cued: Polarizabilities ±10%	Pass for T-003, fail for other seed items (see discussion)
Cued interrogation of anomalies	Instrument position	Cued mode data	*MM:* 100% of anomalies where the center of the instrument is positioned within 40 cm of actual target location	99.5%
			TEMTADS 2x2: 100% of anomalies where the center of the instrument is positioned within 40 cm of actual target location	*Not Assessed*
Detection of all targets of interest (TOI)	Percentage of detected seeded items	Location of seeded items and anomaly list	100% of seeded items detected with 60 cm halo	100%
Analysis and Classification Objectives				
Maximize correct classification of TOI	Percentage of TOI placed in Category 1	Prioritized anomaly lists and dig results	Correctly classify 100% of TOI	ANN – 100% LM – 99.7%

Performance Objective	Metric	Data Required	Success Criteria	Results
Maximize correct classification of non-TOI	Percentage of correctly classified non-TOI	Prioritized anomaly lists and dig results	>75% of non-TOI classified in Category 3while retaining all TOI	ANN- 87% LM – 69%
Specification of no-dig threshold	Percentage of TOI placed in Categories 1 or 2 and percentage of non-TOI placed in Category 3	Prioritized anomaly lists, and dig results	Threshold specified to achieve criteria above	Achieved by ANN method. Missed last seed with LM method by 15 anomalies
Minimize number of anomalies that cannot be analyzed	Percentage of anomalies classified as Category 0	Inverted MM and TEMTADS cued mode data and prioritized anomaly dig list	Reliable target parameters can be estimated for >95% of anomalies on each sensor's detection list	100%
Correct estimation of target parameters	Accuracy of estimated target parameters for seed items	Estimated and actual parameters [polarizabilities, XY locations, and depths (Z)] for seed items	Polarizabilities ±20% X, Y <15 cm (or 1 σ) Z <10 cm (or 1 σ)	±20% exceeded X, Y < 15 cm, 69% Z < 10 cm, 66%

7.1 OBJECTIVE: ALONG-LINE MEASUREMENT SPACING - RESULTS

URS utilized Geosoft's Oasis Montaj UX-Process Sample Separation analysis module. The separation distance was set to 0.15 m, and the maximum percentage of the data that exceeded that displacement for any submitted dataset was 8.9%, which is less than the 10% criteria. This includes end-of-line points; therefore, the actual percentage is lower than the captured values. The processing log, included in Appendix C, shows the down-line sample separate values captured for each dataset. Data collected on April 20, 2012 (0420g) did not meet this metric due to RTS issues and were not used. URS did not process dynamic data for either of the advanced sensors; therefore results of these performance objectives were not assessed.

7.2 OBJECTIVE: COMPLETE COVERAGE OF THE DEMONSTRATION SITE

URS utilized Geosoft's Oasis Montaj UX-Process Footprint Coverage QC Tool. The processing log included in Appendix C shows the percentage of coverage at 0.5 m and 0.75 m footprint width (see Figures 27 and 28, respectively). Footprint coverage metrics exceeded the coverage standards due to obstacles that are noted in the processing log, including large ruts and trees within the wooded areas. Further details are captured in the daily processing logs.

7.3 OBJECTIVE: REPEATABILITY OF INSTRUMENT VERIFICATION STRIP MEASUREMENTS

The response amplitudes were within acceptable ranges (±25%) for all of the IVS items for the EM61 survey. The locations of peak responses were within acceptable ranges (±25 cm) for all but two IVS locations for T-005. The largest errors were in the direction of travel over the IVS, and likely reflect the difficulty in accurately locating the anomaly source for a double-peak anomaly since T-005 was laid along the direction of travel.

As no advanced sensor dynamic survey data was processed, repeatability of amplitudes and down track location were not assessed for advanced sensors.

Response amplitude for the MM was measured by calculating the zero moment polarizability (P_{0x}) for the primary polarizability of each response within the IVS. The zero moment is effectively an integrated valued representing the area under the polarizability curve. Results for the largest item, Seed T-003 were all within ±10%. Results for the next largest polarizabilities, Seed T-005, were within ±16%. Results for the remaining two seeds (T-001 and T-002) were within ±10% for 80% of the samples, but the outliers were quite large, with a maximum difference of 76%. The source of this variability is not known, but it is relatively rare, and is more significant with the smaller seed items suggesting a relatively constant magnitude of error when the issue occurs. One possible source may be errors in the removal of background responses.

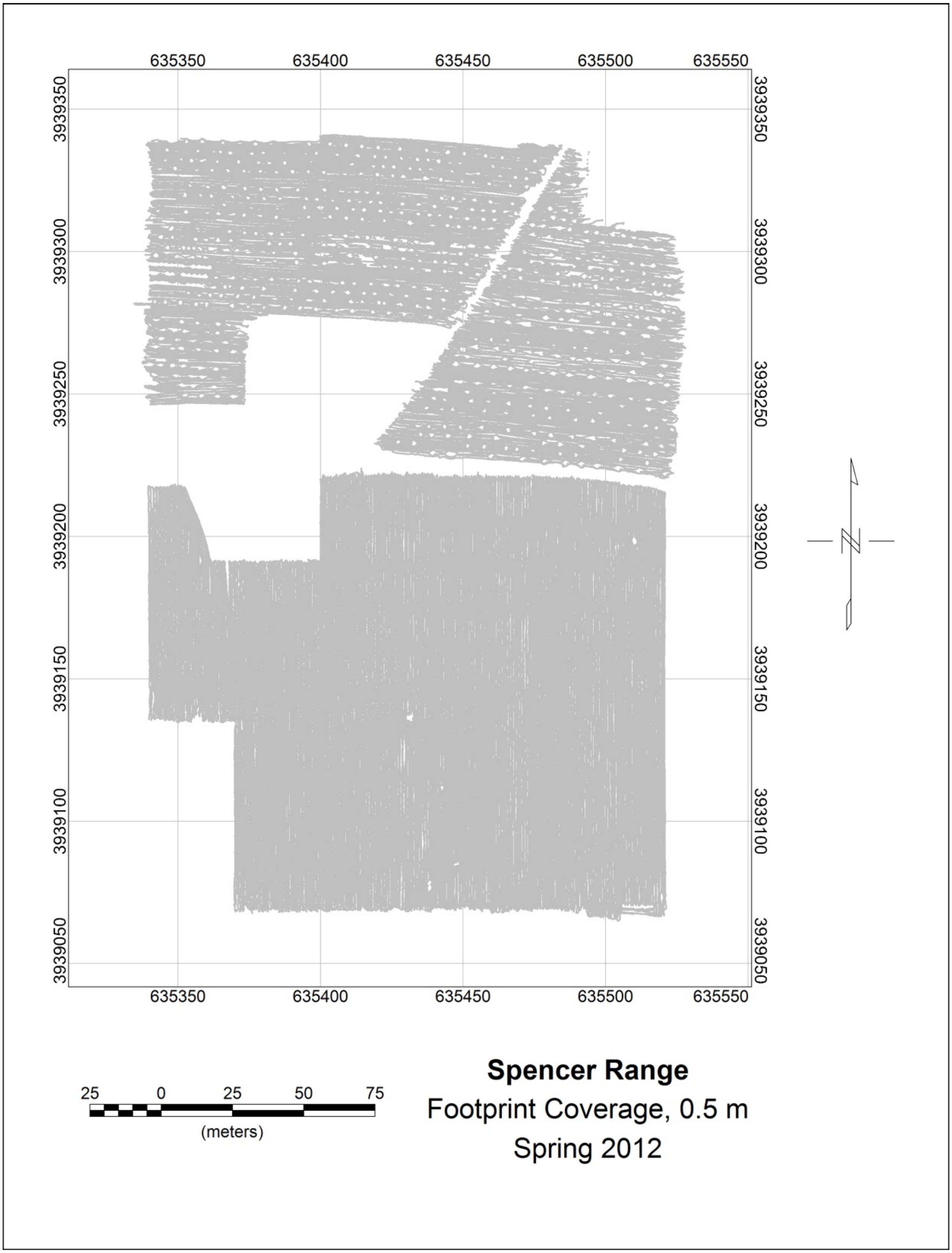

Figure 27. Footprint Coverage Plot Using a Width of 0.5 m

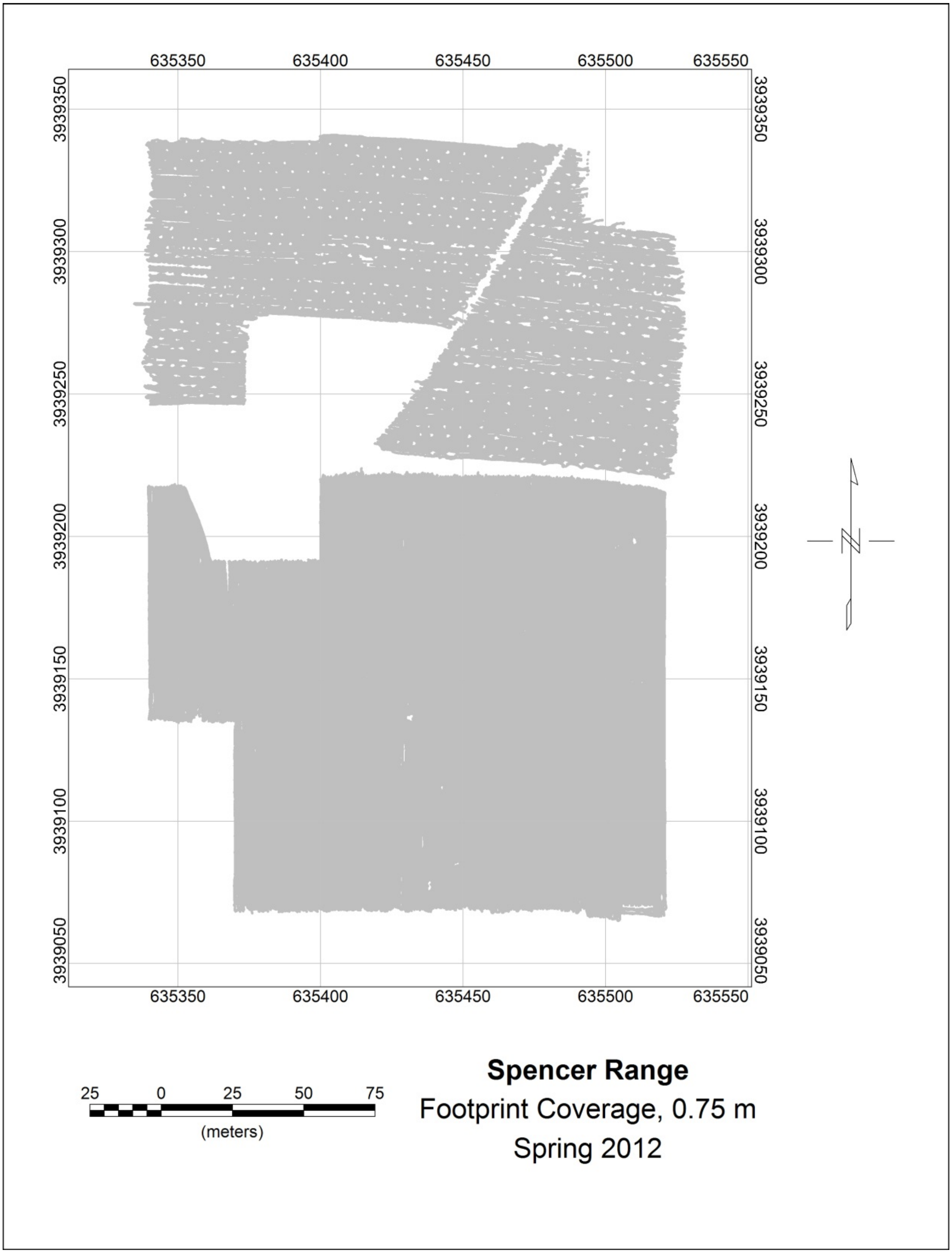

Figure 28. Footprint Coverage Plot Using a Width of 0.75 m

7.4 OBJECTIVE: CUED INTERROGATION OF ANOMALIES

The center of the instrument was positioned within 40 cm of the actual anomaly location for 99.5% of the cued anomalies.

7.5 OBJECTIVE: DETECTION OF ALL TARGETS OF INTEREST

All 175 of the total 175 seed items (see Figure 29) were placed on the delivered target list.

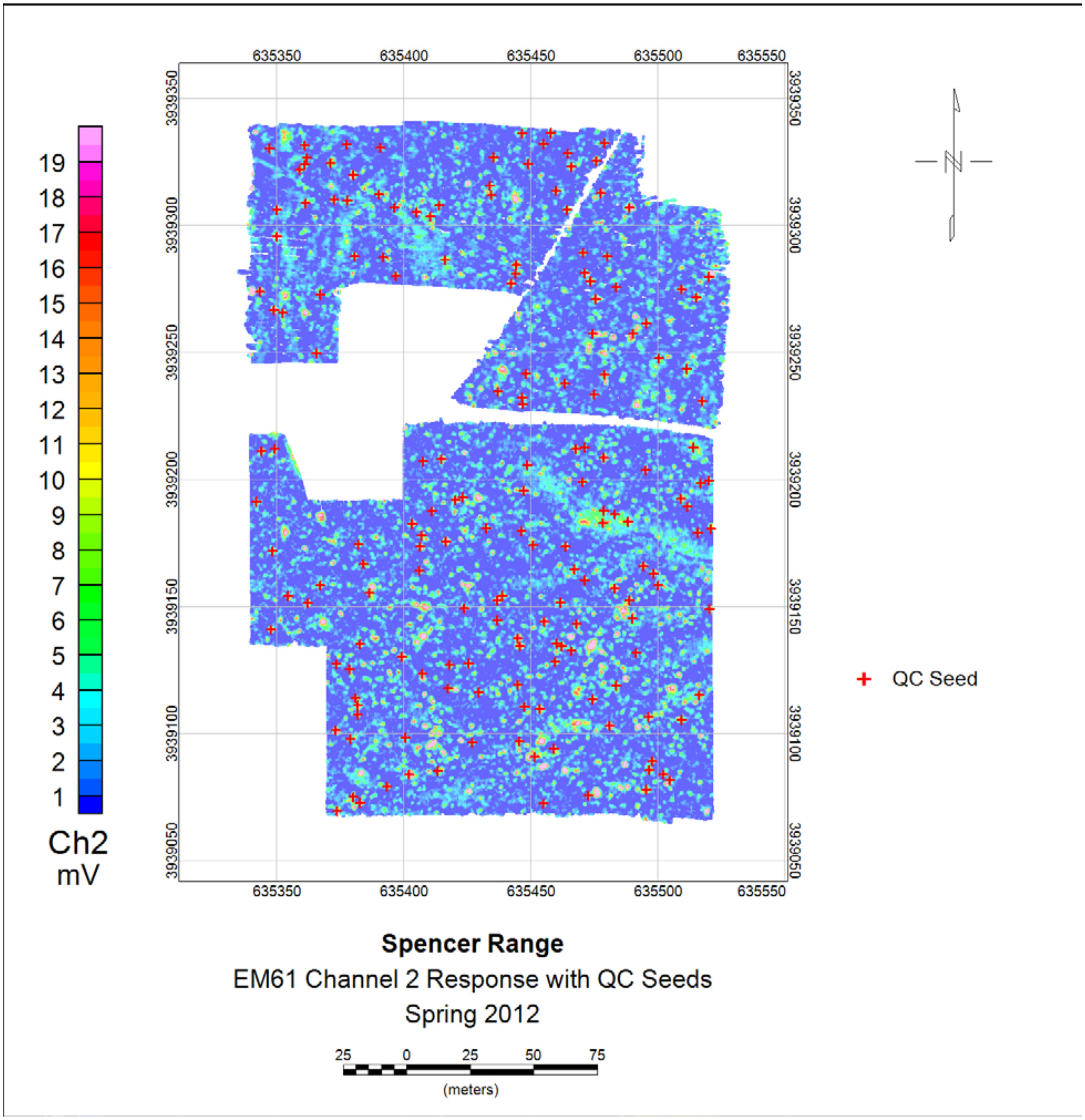

Figure 29. EM61-MK2 Production Data with All 175 QC Seed Items Identified

7.6 OBJECTIVE: MAXIMIZE CORRECT CLASSIFICATION OF TARGETS OF INTEREST

100 percent of the 107 TOI were correctly labeled as TOI on the ANN ranked anomaly list, and 99.7% of the total were correctly labeled TOI on the LM ranked anomaly list.

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

A total of 87% of the non-TOI were correctly classified by the ANN-based approach, and 69% of the non-TOI were correctly classified by the LM-based approach.

7.8 OBJECTIVE: SPECIFICATION OF NO-DIG THRESHOLD

URS sets a dig/no-dig threshold that results in more than 75% of the non-TOI items being correctly labeled as non-TOI, while correctly identifying 100% of the TOI. The LM-based approach failed to identify 1 TOI by choosing a cut-off 15 targeted anomalies prior to where the TOI appeared on the ranked list, an error in the no-dig threshold of roughly 1% of the total targeted anomaly list.

7.9 OBJECTIVE: MINIMIZE NUMBER OF ANOMALIES THAT CANNOT BE ANALYZED

URS was able to effectively classify all targeted anomalies using the parameters generated by the UX-Analyze multi-source inversion.

7.10 OBJECTIVE: CORRECT ESTIMATION OF TARGET PARAMETERS

The objective will be considered to be met if the estimated polarizabilities are within ± 20%, the estimated X, Y locations are within 15 cm (1 σ), and the estimated depths (Z) are within 10 cm (1 σ). As demonstrated in Figure 17, there is over an order of magnitude in variability in small ISO inverted polarizabilities, well beyond the ± 20 polarizability objective. This likely results from difficulties in separating background response from measured signal, possible variations between seed items, effects stemming from the orientation and location of the seed relative to the sensor, and the variability inherent in the instrument and the inversion software.

69% of the inverted horizontal locations were within 15 cm of the recovered item location, 80% were within 40 cm, and 87% were within 60 cm. Some of this variability results from ambiguity between multiple inverted sources and multiple recovered items, recovered items were only matched to the ‘best’ fit to generate these results. Additional error may be added during the process of recovering and locating the anomaly sources.

66% of inverted depths were within 10 cm of the recovered item depth. The mean error was 3 cm too shallow, and the median error was 1 cm too deep. The median indicates that the inversion is typically slightly too deep, but the mean error is positive because there is a wider range of possible values deeper than the inverted depth. Some of this variability results from ambiguity between multiple inverted sources and multiple recovered items, recovered items were only matched to the ‘best’ fit to generate these results. Additional error may be added during the process of recovering and locating the anomaly sources.

It should be noted that although none of these metrics were met, the analysts were still able to achieve up to 100% detection of TOI while removing up to 87% of non-TOI. These standards may not be appropriate for advanced sensor target parameters.

8.0 COST ASSESSMENT

The cost elements traced for this demonstration are detailed in Table 6.

Table 6. Project Costs

Cost Element	Data Tracked During Demonstration	Estimated Costs
Project Planning	Develop project-specific documents: • MEC QAPP • Health & Safety Plan • Data Analysis Plan Kick-off meeting General site setup activities	$42,395
Site Preparation	Set up onsite project area Surface sweep Vegetation removal Initial EM61 data collection (density estimates) Install blind seed items Labor Equipment rental Supplies Travel	$143,171
EM61 Data Collection	2 people (field team) data collection and processing Project Geophysicist Equipment rental Supplies Travel	$64,109
TEMTADS Data Collection	2 people (field team) data collection • Dynamic data collection on 1.23 acres in the dynamic area • Cued data collection on 689 targets in the wooded area and 340 targets in the dynamic area Project Geophysicist Equipment rental (Note: Does not include rental costs for advanced geophysics sensor arrays.) Supplies Travel	$24,198
MM Data Collection	2 people (field team) data collection and processing • Dynamic data collection on 1.23 acres in the dynamic area • Cued data collection on 1,104 targets in the open area and 340 targets in the dynamic area Project Geophysicist Equipment rental (Note: Does not include rental costs for advanced geophysics sensor arrays.) Supplies Travel	$83,473

Cost Element	Data Tracked During Demonstration	Estimated Costs
MM Data Analysis/Classification	Analyzed 1,444 anomalies	29 minutes/anomaly $27/anomaly $39,657
Validation Digging	7 UXO Technicians Number of days Equipment rental Supplies Travel	2,568 anomalies (2,133 targets plus subsurface anomalies found within a 60 cm radius of original target) $143/anomaly $367,155

8.1 COST DRIVERS

The primary cost considerations associated with the selection and broad implementation of advanced geophysics and classification technologies are:

- Cost of data collection with advanced sensor arrays (primarily labor, per diem, and equipment rental);
- Cost of data processing, analysis, and anomaly classification (primarily labor); and
- Cost savings associated with reduction in number of anomalies requiring intrusive investigation (primarily labor, per diem, and equipment rental).

8.2 COST BENEFIT

The primary driver for developing advanced geophysics and classification technologies is to reduce the total cost associated with executing munitions responses. DoD recognizes that a large portion of the munitions response budget is and will be spent excavating and removing harmless metal fragments and non-munitions-related metal from MRSs. The implementation of advanced geophysics and classification has been demonstrated to reduce the total number of anomalies requiring intrusive investigation (i.e., excavation) by 60–90% in demonstration/validation projects. For advanced geophysics and classification to be broadly employed, these technologies must cost less to implement than the intrusive investigations that would be avoided by their implementation.

The equations below approximate the potential cost savings that DoD could realize from the implementation of advance geophysics and classification at the Former Spencer Artillery Range. The equations are based on the limited-scale live site demonstration performed by URS. The equations are based on the implementation of the MM in the open area and dynamic area (i.e., about 5.51 acres) and assume that an initial anomaly list must be established through DGM using an EM61-MK2.[1] It is reasonable to anticipate that cost savings would increase proportional to the area over which classification methods are applied.

[1] This assumption may become invalid if the ongoing live site demonstrations show the ability to correctly classify anomalies based on data collected in survey (dynamic) mode. If it is possible to classify anomalies directly from

Cost savings = (Reduction in Intrusive Investigation Costs) – (Cost of Advanced Geophysical Data Collection + Cost of Data Analysis and Classification)

Reduction in Intrusive Investigation Costs = Cost to Dig All Anomalies - Cost to Dig Anomalies Classified as TOI

8.2.1 Reduction in Intrusive Investigation Costs by Applying Each Classification Method in the Open Area

Cost to Dig All Anomalies in the Open Area = 1,104 anomalies x $143/anomaly = $157,872

Cost to Dig Anomalies Classified as TOI (LM01) = 420 anomalies x $143/anomaly = $60,060

Cost to Dig Anomalies Classified as TOI (ANN01) = 240 anomalies x $143/anomaly = $34,320

Reduction in Intrusive Investigation Costs (LM01) = $157,872 – $60,060 = <u>$97,812</u>

Reduction in Intrusive Investigation Costs (ANN01) = $157,872 – $34,320 = <u>$123,552</u>

8.2.2 Reduction in Intrusive Investigation Costs by Applying Each Classification Method in the Dynamic Area

Cost to Dig All Anomalies in the Dynamic Area = 340 anomalies x $143/anomaly = $48,620

Cost to Dig Anomalies Classified as TOI (LM01) = 98 anomalies x $143/anomaly = $14,014

Cost to Dig Anomalies Classified as TOI (ANN01) = 43 anomalies x $143/anomaly = $6,149

Reduction in Intrusive Investigation Costs (LM01) = $48,620 – $14,014 = <u>$34,606</u>

Reduction in Intrusive Investigation Costs (ANN01) = $48,620 – $6,149 = <u>$42,471</u>

8.2.3 Total Cost Reduction by Applying Each Classification Method to Both Dynamic and Open Areas

Cost of Advanced Geophysical Data Collection = $83,473

Cost of Data Analysis and Classification = $39,657

Cost savings = (Reduction in Intrusive Investigation Costs) – (Cost of Advanced Geophysical Data Collection + Cost of Data Analysis and Classification)

Total Cost Reduction for LM01 = ($97,812 + $34,606) – ($83,473 + $39,657)

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survey data, then the costs associated with performing traditional DGM using EM61-MK2 will also be avoided through the implementation of advanced geophysical data collection.

Total Cost Reduction for LM01 = $132,418 – $123,130 = $9,208

Total Cost Reduction for ANN01 = ($123,552 + $42,471) – ($83,473 + $39,657)
Total Cost Reduction for ANN01 = $166,023 – $123,130 = $42,893

URS' application of the MM and the LM classification method has the potential to save the government approximately $9,208 on the relatively small (i.e., about 5.51 acre) area of the Former Spencer Artillery Range MRS.

URS' application of the MM and the ANN classification method has the potential to save the government approximately $42,893 on the relatively small (i.e., about 5.51 acre) area of the Former Spencer Artillery Range MRS.

Assuming that cost savings would increase proportionally to the area over which classification methods are applied, the classification methods demonstrated by URS have the potential to generate the following estimated cost savings.

Site Acreage	LM Savings	LM Savings/Acre	ANN Savings	ANN Savings/Acre
5.51	$ 9,208.00	$ 1,671.14	$ 42,893.00	$ 7,784.57
50	$ 83,557.17	$ 1,671.14	$ 389,228.68	$ 7,784.57
100	$ 167,114.34	$ 1,671.14	$ 778,457.35	$ 7,784.57
200	$ 334,228.68	$ 1,671.14	$ 1,556,914.70	$ 7,784.57
500	$ 835,571.69	$ 1,671.14	$ 3,892,286.75	$ 7,784.57
1000	$ 1,671,143.38	$ 1,671.14	$ 7,784,573.50	$ 7,784.57

9.0 IMPLEMENTATION ISSUES

Advanced geophysical sensors (e.g., TEMTADS and MM) and advanced data analysis methods in a production environment were successfully used to characterize MEC hazards at the Former Spencer Artillery Range demonstration site. Because URS' role in the Live Site Demonstration Program is to evaluate the implementation of these advanced sensors and classification methods from the perspective of a large-scale MMRP production company, URS documented issues/recommendations that will support implementation on an industry-wide scale. Industry-wide fielding of advanced geophysical sensor arrays will benefit from addressing several logistical and deployment-related issues. These issues focus on making the system more market-ready and improving deployment efficiency. The wide-scale use and acceptance of classification methods can be facilitated primarily through documentation of standardized methods, communication and outreach, and reconciling some current policy/guidance inconsistencies. These will serve to make the process more transparent and increase the likelihood of stakeholder acceptance.

9.1 Advanced Geophysical Sensor Arrays

9.1.1 Terrain Limitation

Advanced geophysical sensors typically include multiple coils to illuminate anomalies from multiple directions/angles. Most are large and vehicle-mounted or cart-mounted with very low (i.e., less than 6 in.) clearance. As such these instruments are generally limited to flat terrain with low/no vegetation. Conditions at many MRSs would preclude their use. ESTCP has several ongoing live site demonstrations of man-portable advanced EMI sensors that show promise to expand the portfolio of sites to which advanced geophysics and anomaly classification can apply.

9.1.2 Standard Configuration for MetalMapper

MM acquisition was generally straightforward and proceeded at a quick pace once initial setup hurdles were overcome. Two issues associated with data acquisition using MM are worth noting:

- At the outset of the live site demonstration, the required type of vehicle and mounting configuration for the MM was not clear. Recommend that the vendor communicate:
    - The type (or types) of vehicles that have been successfully used to deploy the array in the past.
    - The required type of three-point hitch. The user would be able to confirm with the vehicle supplier that the tractor has the proper hitch prior to delivery.
    - Vehicle configurations (e.g., counterweighting and mounting locations for monitor/controls) that have been used successfully and safely in the past. (The MM attached to a bucket mounted on the front of a tractor was front heavy and prone to tipping. The Former Spencer Artillery Range site included moderate slopes and numerous ruts left by heavy equipment. When the front wheels of the tractor caught ruts or went down significant slope, it destabilized the tractor and created the potential for a roll-over accident. URS utilized sandbags attached to

the back of the tractor to help stabilize it. In a subsequent field deployment at Camp Ellis, URS designed a system for mounting the MM on a reach lifter, which proved significantly more stable and safe. Figures 30 and 31 show vehicle instability and blocked field of view associated with the initial system mounting configuration. These were subsequently remedied through trial and error.)

- Specifications for Support Equipment/Components: Recommend the vendor develop and deliver a standard set of support equipment for MM, including spare system cables, deep cycle marine batteries, and series battery cables. Also, provide all software and computer system specifications in advance of system delivery (i.e., when system is reserved).

Figure 30. Tractor Instability while Raising MM

Figure 31. Tractor Operator Field of View with MM

9.1.3 Improved Default Display

The URS field crew collected nearly one day of MM data that had to be recollected because of issues with the transmitter. These issues could have been recognized if the field teams had set the acquisition software to automatically display plots after each sounding. Corrective action was implemented to resolve this issue, including the field crew setting up the acquisition software so that response curves would be displayed after each measurement.

9.1.4 Disclaimer Regarding Time-domain Electromagnetic Multi-sensor Towed Array Detection System

The list of recommendations above focuses on MM. One reason is that this system was delivered to the site and the URS field team was primarily responsible for deploying, operating, and troubleshooting the system. TEMTADS, on the other hand, was accompanied by the system developers from NRL. The NRL staff supported the deployment and operation of the TEMTADS and performed troubleshooting and adjustments as needed during data collection. Although this support was very helpful, it was less reflective of a true production setting.

9.2 Anomaly Classification

- Other demonstrators have typically trained directly with the software developers when performing advanced analysis. URS chose to perform analysis independently using tools available within UX-Analyze as well as an approach modified and expanded from previous demonstrations (ESTCP 2011b). This proved to be a valuable learning experience, and will make future training more relevant than it would be without having the direct experience of using these tools independently.

- The library provided with UX-Analyze contains responses generally derived from single-source inversions. These inversion results are often not equivalent to multi-source inversion results, particularly in the amplitude of the inverted polarizabilities. For this reason, it is suggested that single- and multi-source inversion results both be captured in the response libraries.
- URS was unable to identify a straightforward way to automatically select items that were good matches to TOI but did not have a TOI as a primary match. This would significantly speed up the review of LM results, and allow for the inclusion of more non-TOI within the library without the fear that they would make it more difficult to flag potential TOI using LM.

10.0 REFERENCES

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Due to the size and format of the Appendices

They are available upon request only.

You may submit your request in writing to:

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Attention: Document Manager

Appendix B
IVS DATA: EM61-MK2 STANDARD RESPONSE CURVES AND POLAR DISPLACEMENT PLOTS

Appendix C
METADATA FILES AND DGM DATA

Appendix D
DIG RESULTS

Appendix E
PRIORITIZED TARGET LISTS