ESTCP

DEMONSTRATION REPORT

# TEMTADS 2x2 Classification Former Camp Hale, CO

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This report describes advanced geophysical classification (AGC) processing of Time Domain Electromagnetic Multi-Sensor Towed Array Detection System (TEMTADS) 2x2 time-domain electromagnetic data collected at the Former Camp Hale, CO. TEMTADS data were used for both detection and classification at Area 1 of the East Valley Munitions site. Based on earlier studies, the primary target of concern was the 60 mm mortar. A "two-pass" classification approach was implemented. Dynamic, full coverage TEMTADS 2x2 survey data would detect anomalies and identify high likelihood TOI and screen anomalies that were unlikely to be from TOI. A follow-up cued, static survey would provide higher signal-to-noise ratio (SNR) data for classifying anomalies that were not labelled as either a high probability TOI or non-TOI with the dynamic data.

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# Executive Summary

This report describes advanced geophysical classification (AGC) processing of Time Domain Electromagnetic Multi-Sensor Towed Array Detection System (TEMTADS) 2x2 time-domain electromagnetic data collected at the Former Camp Hale, CO. TEMTADS data were used for both detection and classification at Area 1 of the East Valley Munitions site. Based on earlier studies, the primary target of concern was the 60 mm mortar. A "two-pass" classification approach was implemented. Dynamic, full coverage TEMTADS 2x2 survey data would detect anomalies and identify high likelihood TOI and screen anomalies that were unlikely to be from TOI. A follow-up cued, static survey would provide higher signal-to-noise ratio (SNR) data for classifying anomalies that were not labelled as either a high probability TOI or non-TOI with the dynamic data.

Using a peak detection algorithm on the gridded image data, anomalies were selected using a detection threshold based on a 60 mm mortar at a depth of 60 cm. An Informed Source Selection (ISS) strategy was agreed upon during a meeting between BTG, ESTCP, URS Corp, and Colorado State representatives. A high target density region at the center of the MRS would be designated as "Mag and Dig". Any high probably TOI (e.g., 60 mm, QC seeds) or high probably non-TOI would not be cued. In particular, shallow dipole sources smaller than a 0.50 cal and well modelled (high data fit) would be screened. We note that 0.50 cal and fuses were not considered TOI for this site. At the request of Colorado State representatives, several of the high probably TOI found in the dynamic data analysis were also included for cued analysis. The ISS process resulted in 1791 anomalies being cued and 1883 anomalies being analyzed using dynamic data only.

For the cued targets, static interrogation data were collected and inverted for dipole model parameters. The estimated dipole parameters were then used as an input to a library-matching based classification approach. Analysts were allowed 100 "training" or "analyst calibration digs". These anomalies were chosen using cluster analysis, matches to a large ordnance library containing all polarizabilities available, and visual inspection by the analyst (e.g., polarizabilities not in the library but were UXO-like). Analyst calibration digs resulted in finding 3 TOI: a pair of 81 mm M56 mortars and a 40 mm illumination round cartridge.

Classification was applied to the 1791 cued anomalies. Classification was also applied to dynamic data anomalies that were not cued, in order to identify any high-confidence TOI that were not cued. The decision statistic was based on the fit to polarizabilities in the ordnance library, and the stop-dig point was determined by visual inspection by the analysts, and verified using polarizability fits from the test pit measurements (which included a horizontal 60mm mortar at a depth 60cm) and from fits of TOI in the training data (i.e., QC seeds and the deeper 81 mm mortar). The final classification diglist resulted

in only one non-seed TOI being found: an M83 60mm Illumination M65 series mortar. The cued classification diglist had 157 digs. The dynamic data diglist had 70 digs. All QC Seeds were found.

There was a total of 155 QA/Verification digs. To test the stop-dig point, 50 non-TOI were required after the final TOI of each list (60 digs). Digs were required to test the screening of anomalies that were labelled as small or 0.50 cal (44 digs). A selection of larger targets beyond the stop dig point were dug (15 digs). Finally, a random selection of anomalies was chosen by the ESTCP program office (36 digs). No TOI were found with these digs.

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## Acronyms

| | |
|---|---|
| AGC | Advanced Geophysical Classification |
| cm | Centimeter |
| BTG | Black Tusk Geophysics |
| CSV | Comma Separated Variable |
| DOD | Department of Defense |
| ESTCP | Environmental Security Technology Certification Program |
| FUDS | Formerly Used Defense Site |
| ISO | Industry Standard Object |
| m | Meter |
| mm | Millimeter |
| ms | Millisecond |
| MEC | Munitions and Explosives of Concern |
| QA | Quality Assurance |
| QC | Quality Control |
| RCA | Root-Cause Analysis |
| RF | Recovery Field |
| ROC | Receiver Operating Characteristic |
| s | Second |
| SNR | Signal-to-Noise Ratio |
| TEM | Time domain Electromagnetic |
| TEMTADS | Time Domain Electromagnetic Multi-Sensor Towed Array Detection System |
| TOI | Target of Interest |
| UXO | Unexploded Ordnance |

# 1 Introduction

The former Camp Hale Formerly Used Defense Site (FUDS) is located near Leadville, Colorado. An Environmental Security Technology Certification Program (ESTCP) demonstration was carried out at East Fork Valley Munitions Response Site on the former Camp Hale site. A 7.8 acre site was chosen for the ESTCP demonstration. The site is a relatively flat, open area onto which the East Fork Eagle River would be diverted. Based on findings of the time critical removal actions (TCRA) performed in 2001 and 2003, the detection objective for the site was defined to be a 60 mm mortar at a depth of 60 cm. There were no full coverage data previously acquired in the area as part of the TCRA.

For the ESTCP study, digital geophysical mapping was performed by the cart-based Time Domain Electromagnetic Multi-Sensor Towed Array Detection System (TEMTADS 2x2). TEMTADS 2x2 data collected by URS Corp (now AECOM) were used to develop a target list of locations for cued interrogation. Approximately 1800 anomalies were subsequently cued with the TEMTADS. This report summarizes the processing carried out by Black Tusk Geophysics (BTG) on TEMTADS 2x2 cued data collected as part of this demonstration.

There are a number of objectives for this project:

(1) *Develop a detection and classification approach that can effectively identify all UXO to their clearance depth*. In particular, we want to efficiently recover a 60 mm mortar up to a depth of 60 cm. This approach would be applied to Area 1 (Figure 1) of the site and, if successful, could be used as part of the cleanup operations to other areas of the East Fork Valley site.

(2) *Follow a plan for Quality Assurance (QA) and verification digs that satisfies all stakeholders*. Development and execution of this plan required stakeholders and managers to have a good understanding of the advanced classification methodology and the different decision points. Communicating the processing steps and decisions required numerous emails and calls with project managers and stakeholders.

(3) *Execute the process as closely as possible to an actual production UXO job*. Although this is an ESTCP project, we wanted to be able to produce target lists and dig-lists quickly, in order to keep geophysical field teams and dig teams working efficiently, and to minimize down time.

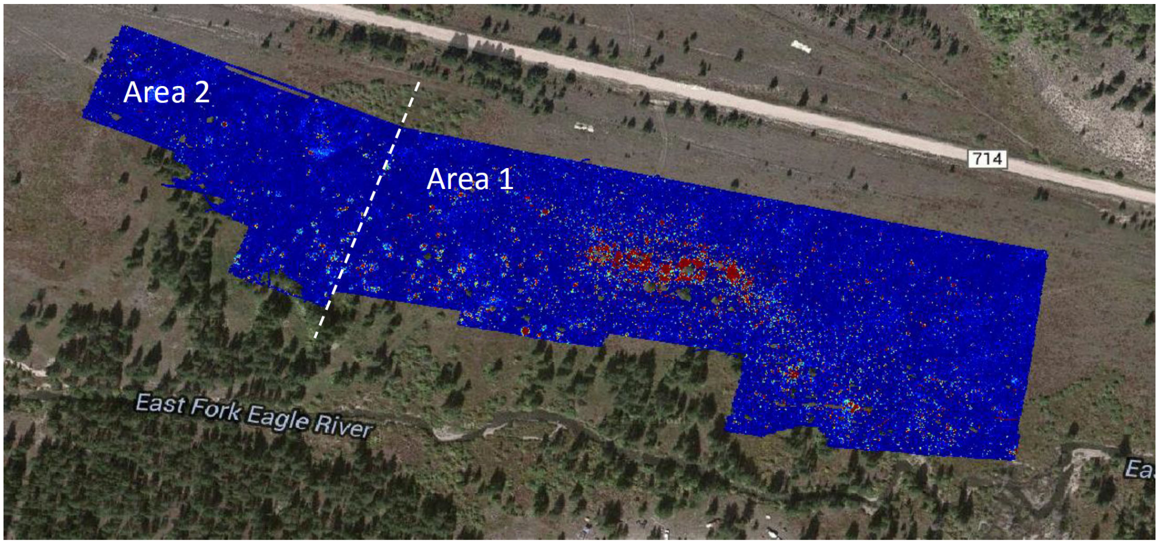



Figure 1. East Fork Valley Munitions Response Site. The area in the image is approximately 530 m across. The work in this report focuses on the data collected in Area 1. Parts of the site to the west of Area 1 (e.g. Area 2) were to be considered for future remediation work.

# 2 Technology description

## 2.1 TEMTADS 2x2

Advanced time-domain electromagnetic sensors have dramatically improved detection and classification of buried MEC. In contrast to commercial mono-static sensors such as the Geonics EM61, the multi-static geometries of next generation time domain electromagnetic sensors provide diverse excitations of a detected target. Multi-component receivers measuring the secondary field of metallic targets over multiple time channels allow for improved discrimination between thick-walled ordnance and thin-walled scrap.

The TEMTADS 2x2 (Figure 2) used for this demonstration is an advanced time domain electromagnetic sensor designed specifically for classification of MEC. The TEMTADS platform includes four transmitter loops and four 3-axis receiver antennas providing 48 independent measurements of the transient secondary magnetic field.

The TEMTADS 2x2 can be deployed in either a dynamic, full coverage mode for creating digital geophysical maps, or in a static, cued interrogation mode for interrogating individual anomalies. In dynamic mode, data are continually recorded on time channels that range from 0.025 to 2.5 ms. In cued mode, data are recorded with the TEMTADS cart stationary above a target. Cued data are recorded on time channels that range from 0.117 to 24.375 ms. In-field inversions of cued soundings help to ensure that the sensor is optimally positioned over each target.

Inversion of cued data using the TEM point-dipole model typically produces well-constrained estimates that can subsequently be input into a classification algorithm.

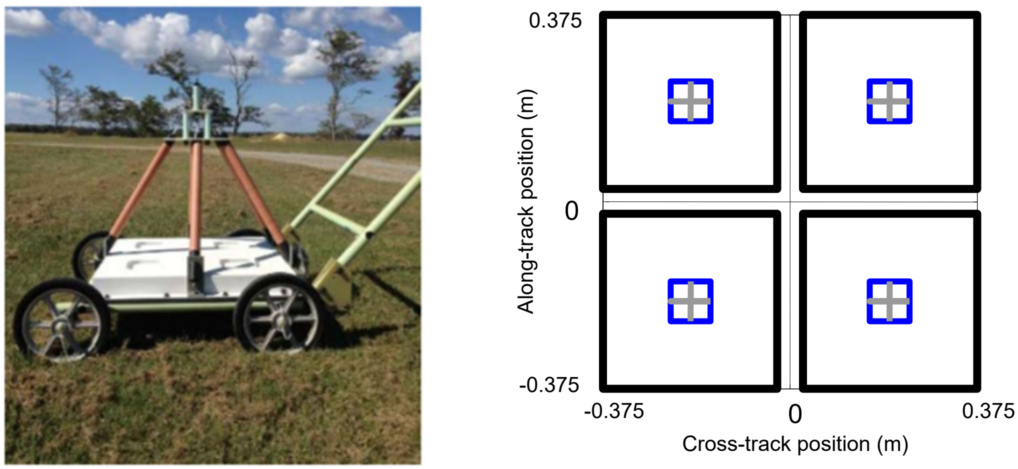



Figure 2. Left: Cued TEMTADS 2x2 array with GPS mount. Right: Sensor geometry showing four transmitters (solid black lines) and concentric 3-axis receivers. Photo credit: TEMTADS 2x2 user manual.

## 2.2 Detection and Classification with Advanced EMI sensors

Target detection using mono-static sensors is usually restricted to identifying anomalies that exceed a pre-defined data amplitude threshold. Data peaks are identified either along transects or off of images of gridded data. With advanced sensors, the dynamic data can be inverted for a dipole model to recover estimates of extrinsic (location, depth, and orientation) and intrinsic (dipole polarizabilities) parameters for each anomaly. Dipole source locations is more accurate than using the peak of a data anomaly for estimating target locations. In addition, properties of the estimated dipole polarizabilities can be used for anomaly screening. This process, known as "informed source selection" ISS, results in a more efficient of cued measurements, since polarizabilities are used to identify data anomalies that can be declared a non-UXO without the need for a cued interrogation measurement.

In cases where dynamic data is not of sufficient quality for classification, anomalies can be further investigated using cued interrogation data acquired over anomalies initially identified in the detection data. These cued interrogations eliminate relative positional errors by acquiring data with a stationary sensor. The multi-static, multi-component geometry of advanced sensors such as the TEMTADS 2x2 allows for reliable target characterization with a single cued sounding.

When inverting cued anomalies, the estimated polarizabilities for each recovered dipole source are matched against a pre-defined library to identify likely targets of interest (TOI) at the site. For this demonstration, all classification processing was carried out using the *UXOLab* software package developed by BTG.

# 3 Detection and Classification at the Former Camp Hale

TEMTADS 2x2 EMI data was used for both detection and classification at Area 1 of the East Valley Munitions site. At the start of the project, a classification strategy was agreed upon at a meeting between BTG, ESTCP, URS Corp, and Colorado State representatives.

The basic approach begins by using dynamic, full coverage TEMTADS 2x2 data to produce a gridded image. This image would then be used to identify regions to be designated as "Mag and Dig" due to high target density. Outside of the "Mag and Dig" area, a peak detection algorithm would be used to locate data anomalies. Each of these anomalies were then inverted for point dipole sources.

The Informed Source Selection (ISS) approach is outlined in Figure 3. Key elements of the screening are:

- *Data Quality:* Any dynamic data anomaly that did not have good fit to a dipole forward model (i.e., low data misfit), or have poor data coverage, or significant elevation variation will have a cued measurement.
- *High probability non-TOI or TOI:* Sources that have a good polarizability fit to a 50 cal or Medium ISO, will not be cued.
- *Deeper sources:* Sources that are deeper than 30 cm and not a good fit to a Medium ISO or 50 cal, will have a cued measurement.
- *Size screening:* Any sources smaller than a 50 cal will not be cued.

Colorado State representatives did not want all of the high probability TOI removed from the cued list. Therefore, we moved a number of sources that were good fit to a medium ISO to the cued list. The cued anomalies were inverted for dipole sources and classified using a library matching approach.

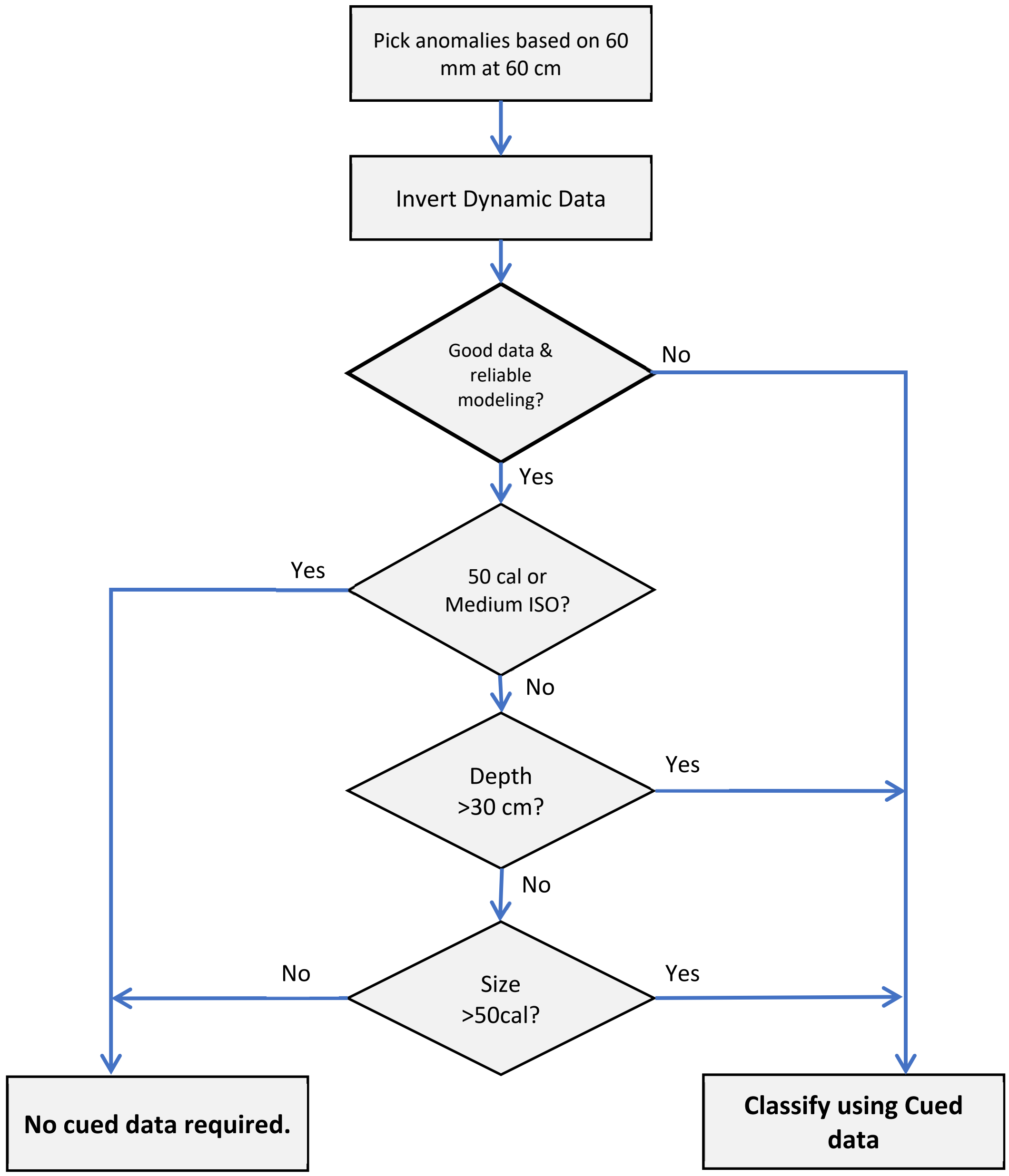



Figure 3. Proposed method for selecting anomalies for cued interrogation.

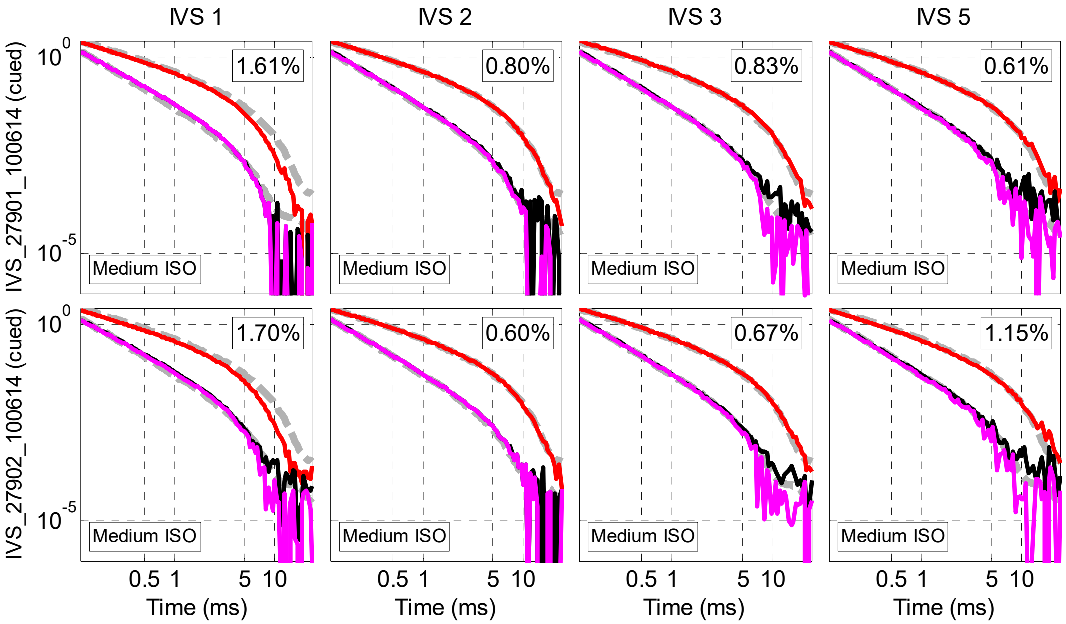
## 3.1 Dynamic TEMTADS 2x2 Processing

Dynamic TEMTADS 2x2 data were acquired by URS Corp/AECOM at the East Fork Valley Munitions site (Figure 4). The East Fork Valley site is flat with only a few trees to obscure GPS satellites. The data processed for classification was from Area 1, which was approximately 7.8 acres. Data were collected using a 0.4 m line spacing. Details of the data collection can be found in the AECOM report submitted to ESTCP *(Demonstration of Advanced Geophysics and Classification Methods on Munitions Response Sites - East Fork Valley Range ComplexFormer Camp Hale,* ESTCP Project MR-201230).

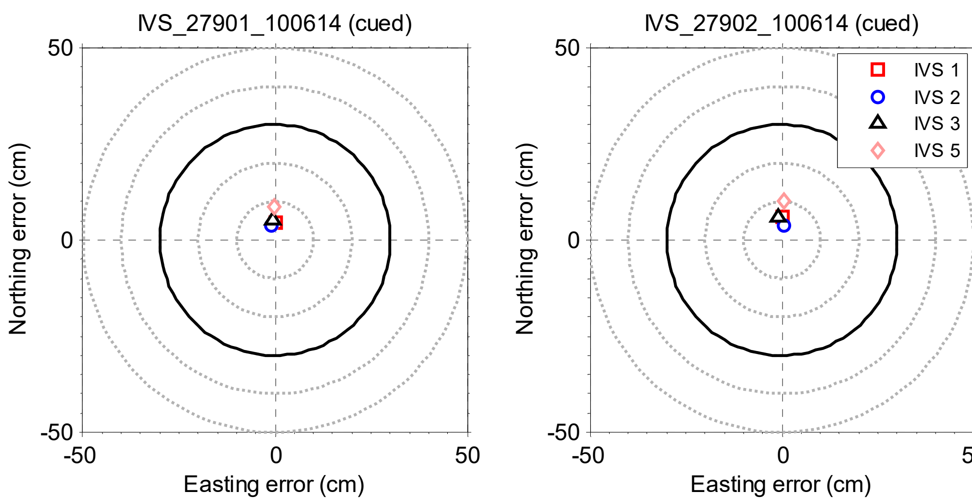
Figure 4. Dynamic TEMTADS data collection

At the end of each day, raw TEMTADS 2x2 TEM file were uploaded to an FTP site. BTG personnel would then download the data, and convert the data to CSV files using the TEM2CSV software provided to us by Dan Steinhurst from Nova Corp. The CSV files would then be imported by UXOLab for quality checks and further processing.

IVS data were collected at the beginning and end of each day. The IVS strip contained 4 emplaced medium ISOs. The IVS data were imported and inverted, and metrics such as the polarizability fit and source location accuracy were tracked by BTG over the course of the project. Figure 5 has example of IVS analysis for cued data. We note that the medium ISO in position "IVS 1" had a slightly faster decay than the other ISOs.




(a) Polarizabilities from morning (top) and afternoon (bottom) IVS measurements




(b) Source location accuracy from morning (left) and afternoon (right) IVS measurements.

Figure 5. Example of daily IVS analysis.

### 3.1.1 Establishing a detection threshold

The detection objective for Area 1, was to detect a 60 mm mortar to a depth of 60 cm. This objective was based on a 60 mm mortar found at a depth of 60 cm at the "Nazi Village" located to the east of the East Valley Munitions site. To determine a target detection threshold, we used the Detection Modeller tool that was developed as part of SERDP project *Decision Support Tools for Munitions Response Performance Prediction and Risk Assessment* (SERDP MR-2226). We used the z-component coaxial data for target picking since this transmitter/receiver geometry has the greatest coupling with the target. Figure 6 contains a plot from the Detection Modeller that shows how the maximum signal strength in the Z-component coaxial data of the TEMTADS varies as a function of the cross-track position of a Medium ISO at a depth of 60 cm. The Medium ISO has approximately the same EMI response as 60 mm mortars. The threshold is shown for time channel 8 (0.214 ms), and for vertical, horizontal along-track, and horizontal cross-track orientations. For a line spacing of 0.4 m, the detection threshold is determined by a horizontal medium ISO oriented along track, and with the cart passing directly above the target. For time channel 8 (0.214 ms), the detection threshold should be at least 0.72 mV/A.

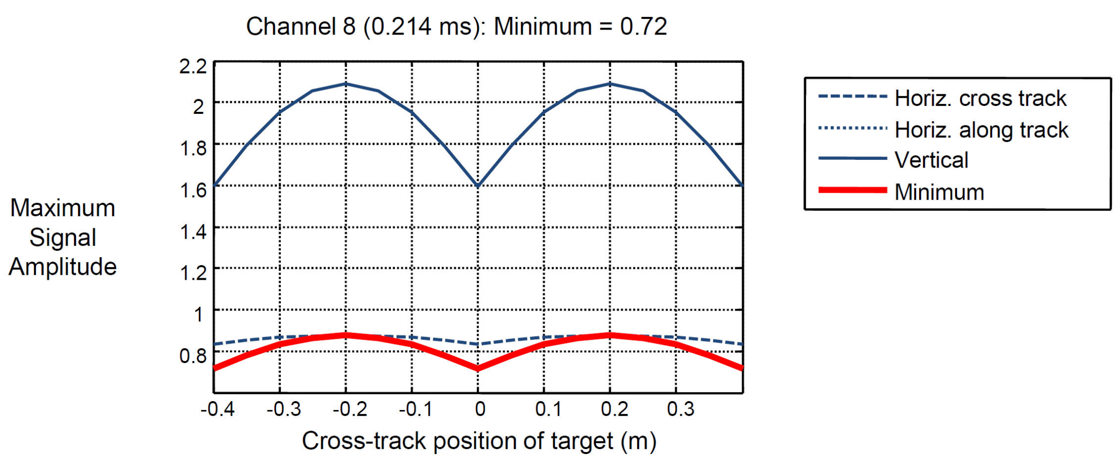
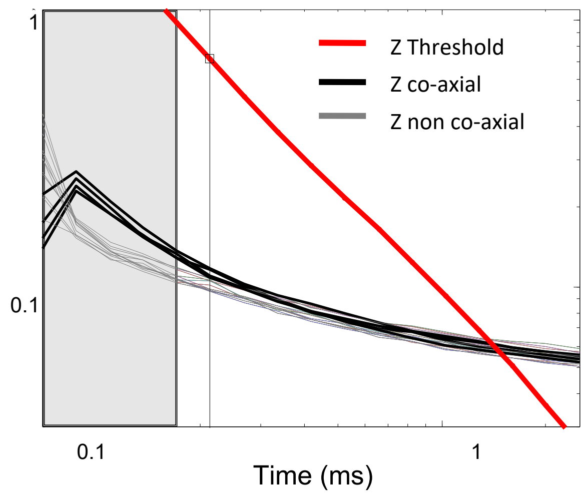
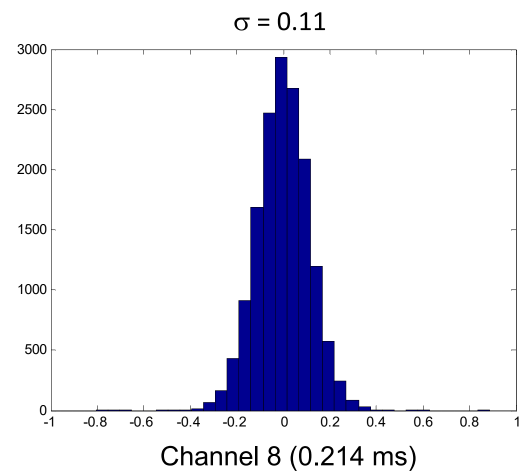



Figure 6. Output from the Detection Modeller software developed in project *Decision Support Tools for Munitions Response Performance Prediction and Risk Assessment* (SERDP MR-2226). For a line spacing of 0.4 m, the detection threshold of the Z-component coaxial data is determined by a horizontal target, oriented along the direction of travel (i.e. along track). For a medium ISO at a depth of 60 cm, the detection threshold is 0.72 mV/A in time channel 8.

In order to select a time channel for detection, we compare detection thresholds to noise levels as a function of time. Noise statistics for z-component data were calculated from a few lines of dynamic data collected on the site. Figure 7(a) compares the standard deviation of the noise to the detection threshold for a medium ISO buried at 60 cm. The threshold for coaxial z-component data is plotted in red, and the standard deviation of the coaxial and non-coaxial z-component data are plotted in black and grey, respectively. The region with the grey box represents a time range that is not included in processing. We see that the difference between the threshold and noise decreases with time. Figure 7(b) plots a histogram of the noise in Channel 8. The 0.72 mV/A threshold exceeds 6 times the standard deviation of 0.11. These results suggest that data from channel 8 would be suitable for detection.




(a) Comparison of threshold and noise




(b) Histogram of noise in Channel 8

Figure 7. Noise analysis results for a TEMTADS 2x2 detecting a medium ISO. On the left, is a comparison of the noise level of the z-component data to the medium ISO threshold. Time channel 8 is shown in as a grey vertical line. On the right is a histogram of the noise from a line of dynamic TEMTADS 2x2 data collected in channel 8.

To verify that a medium ISO at a depth of 60 cm can indeed be detected, test pit measurements were made at a location adjacent to the IVS strip. A single line of dynamic data was acquired over a horizontal medium ISO at 40 and 60 cm. Figure 8 plots the detection channel profiles (i.e., co-axial, z-component data) for both the 40 and 60 cm depth cases (bottom). For both depths, the detection threshold is exceeded. The gridded image for the 60 cm depth case is shown in the top plot. A peak detection algorithm can detect the medium ISO.

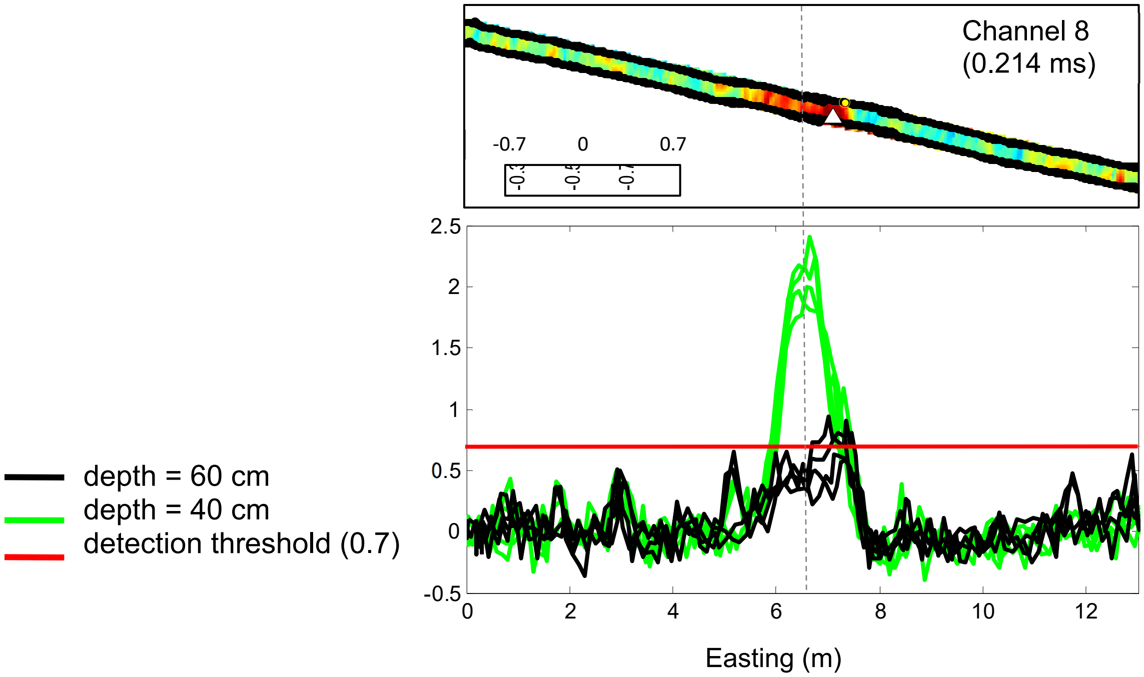
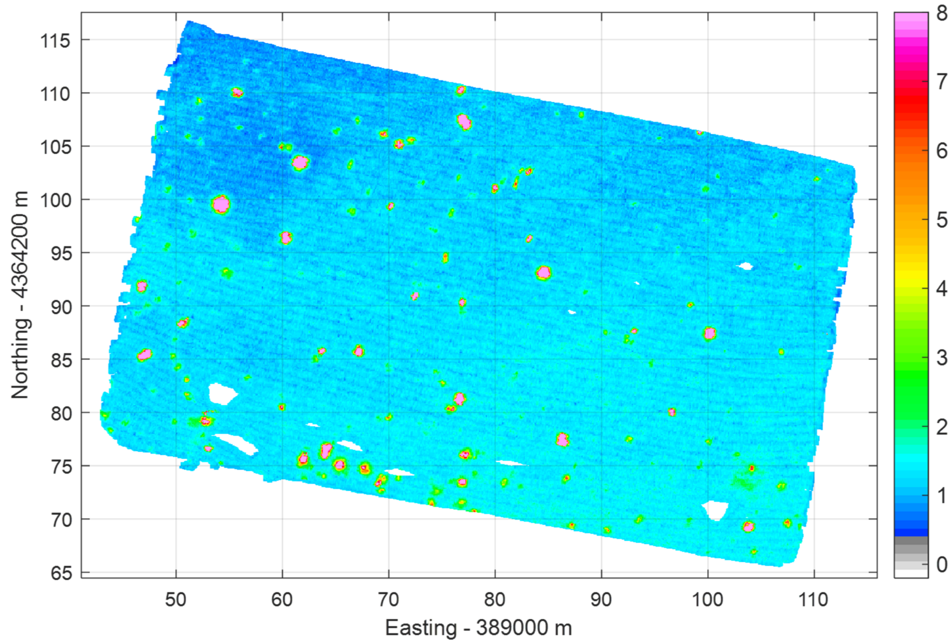



Figure 8. Test pit measurements collected over a horizontal medium ISO. Time channel 8 is plotted. Top: Gridded image for the 60cm depth case. Bottom: profiles for the 40 cm (green) and 60 cm depth (black) cases.

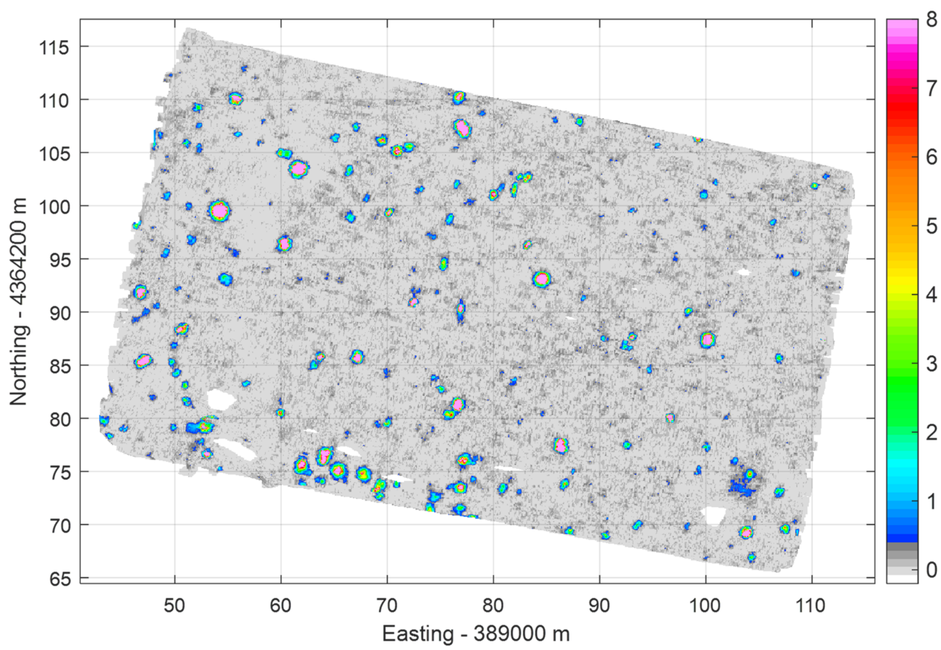
### 3.1.2 Target Picking

The co-axial, z-component data measured at t=0.214ms was used for detection. Prior to gridding an along line de-median filter is used to detrend the data. The filter has a windows width of 101 points which correspond to approximately 10 meters. To reduce filtering artifacts, data within the 10-90 percentile of samples within the filtering window are used for the median calculation. The filtering reduces the effect of the low level of geologic noise in the data (Figure 9).

A pixel size of 0.05 m is used to grid the data. A gridded image of all dynamic data acquired is shown in Figure 10. A peak picking algorithm is used to identify anomalies from the gridded image. We require that a minimum of 3 pixels exceed the 0.72 mV/amp threshold to qualify as a pick. Figure 11 shows the locations of the 3674 picked targets.




(a) Raw data




(b) Filtered data

Figure 9. Example of filtering. Co-axial z-component data are gridded with a 0.05m pixel size.

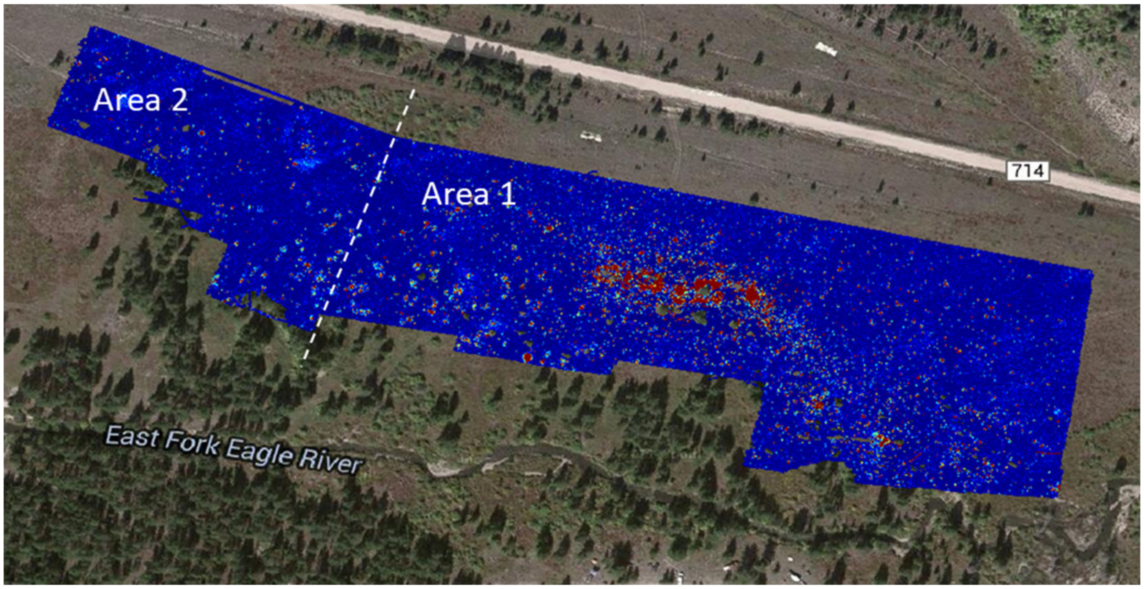



Figure 10. Gridded image of all dynamic data collected as part of this project. Only data in Area 1 were processed and used for classification.

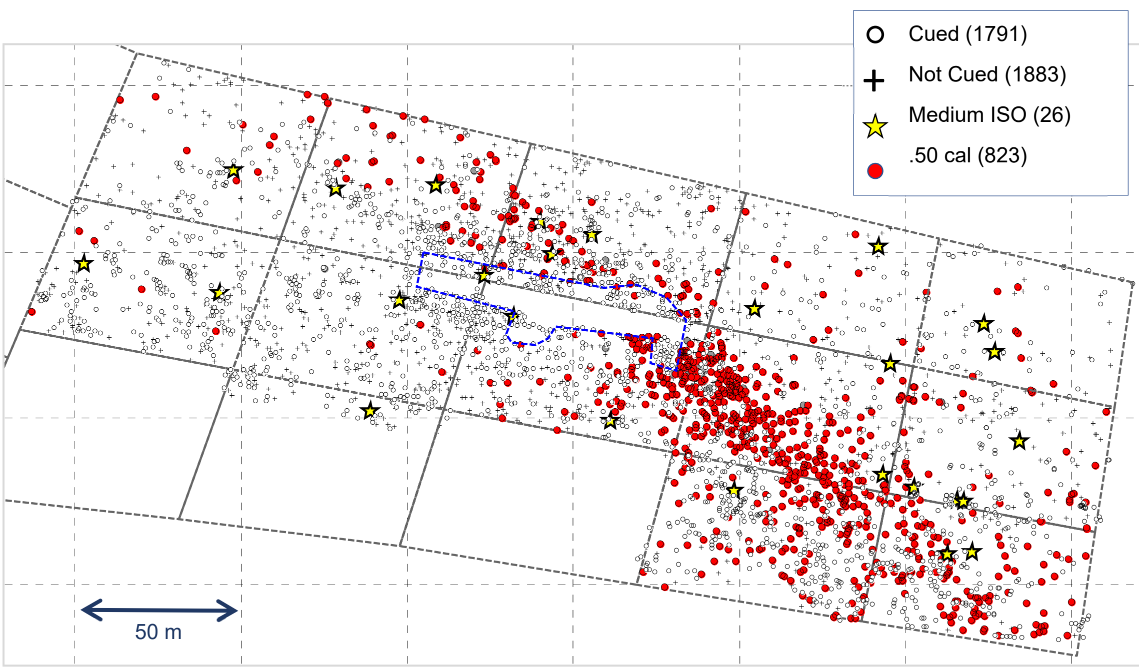



Figure 11. Dynamic data source screening results. During meetings with clients and stakeholders, it was decided to take a conservative approach to screening. Sources designated for a cued anomaly. The dynamic TEMTADS survey identified 3674 potential cued locations. Of these, it was decided that 1791 required a follow-up cued interrogation. Locations of dynamic data sources identified to be from Medium ISO are marked by yellow stars, and sources that appear to be from .50 cals are shown with re circles.

The project team decided that a “Mag and Dig” area should be defined. The initial boundary was defined based on data amplitude. After consultation with the project team, it was suggested to us to be conservative with the definition of the polygon and to draw a simple polygon (for simpler operations for the dig teams). Figure 12 shows the resulting “Mag and Dig” boundary.

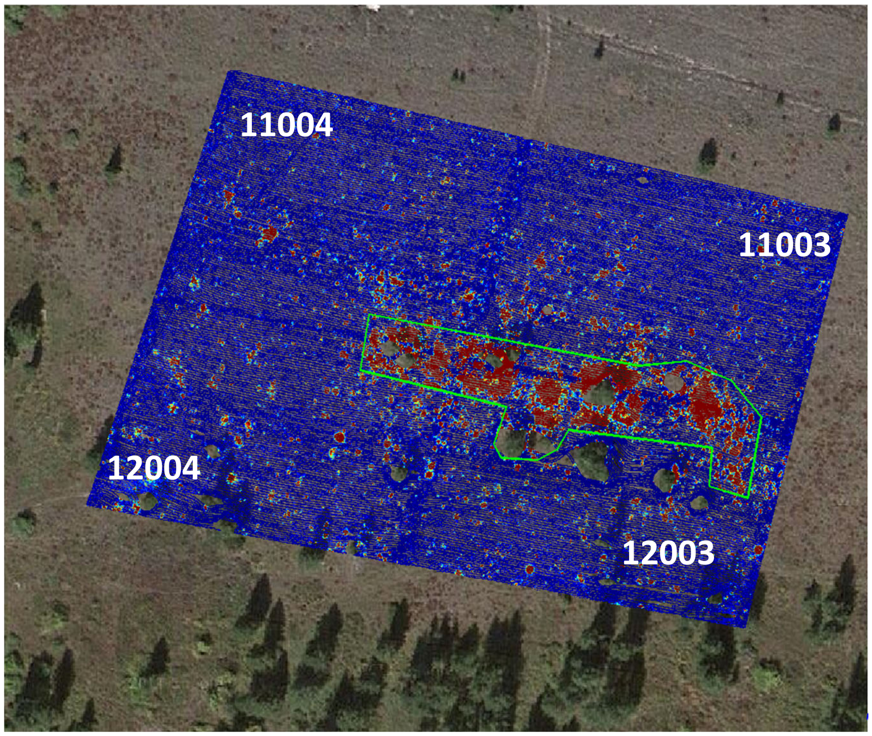



Figure 12. “Mag and Dig” area. The “Mag and Dig” area sat at the center of the Area 1 grids. The polygon was hand drawn, based on the data anomalies.

For each target pick, data within a 0.75m radius circle were inverted using 1 and 2 dipole source models. An example of the types of polarizabilities recovered from inversions are shown in Figure 13. A subset of the data from Figure 9 is shown. For these anomalies, there appears to be a medium ISO, 0.50 cal, 2 examples of fast decaying small scrap, and one example of larger scrap that is larger than a 0.50 cal.

Figure 11 summarizes the results of the Informed Source Selection. The analysis resulted in 1791 anomalies to be cued and 1883 anomalies not cued. The yellow stars indicate the 26 anomalies that had good fits to a Medium ISO. The red dots indicate the 823 anomalies that had a good fit to a 0.50 cal. An example of the sources that were selected as 0.50 cals are shown in Figure 14.

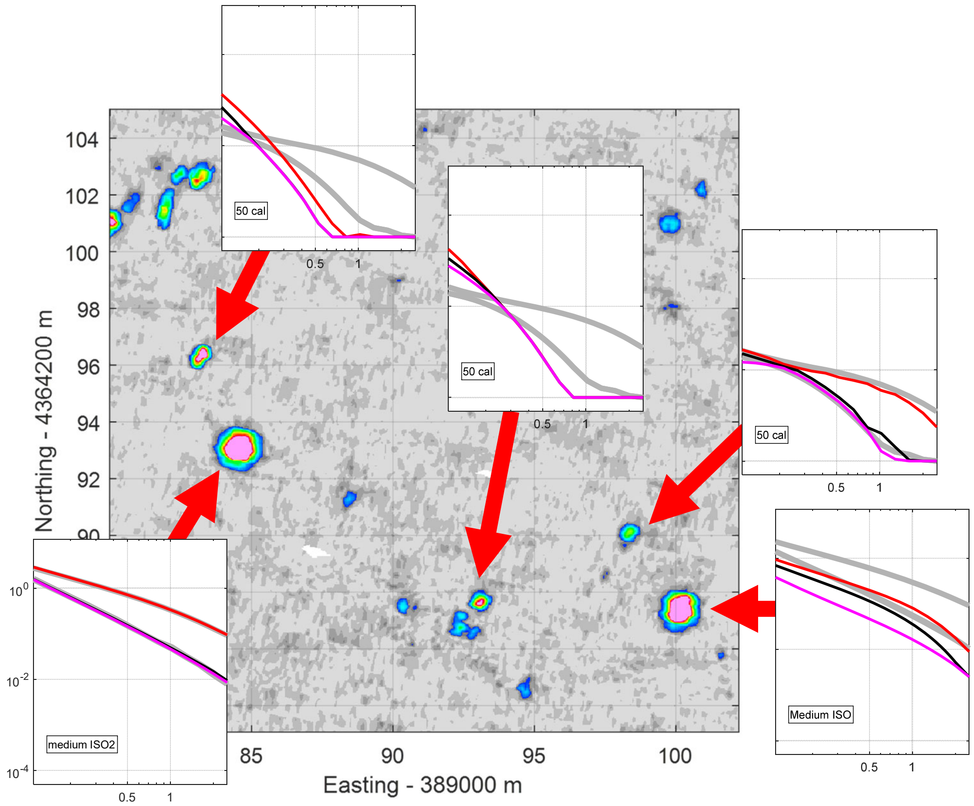



Figure 13. Example of recovered dipole polarizabilities. Examples include a medium ISO, 0.50 cal, small scrap (fast decaying polarizabilities) and larger scrap (bottom right).

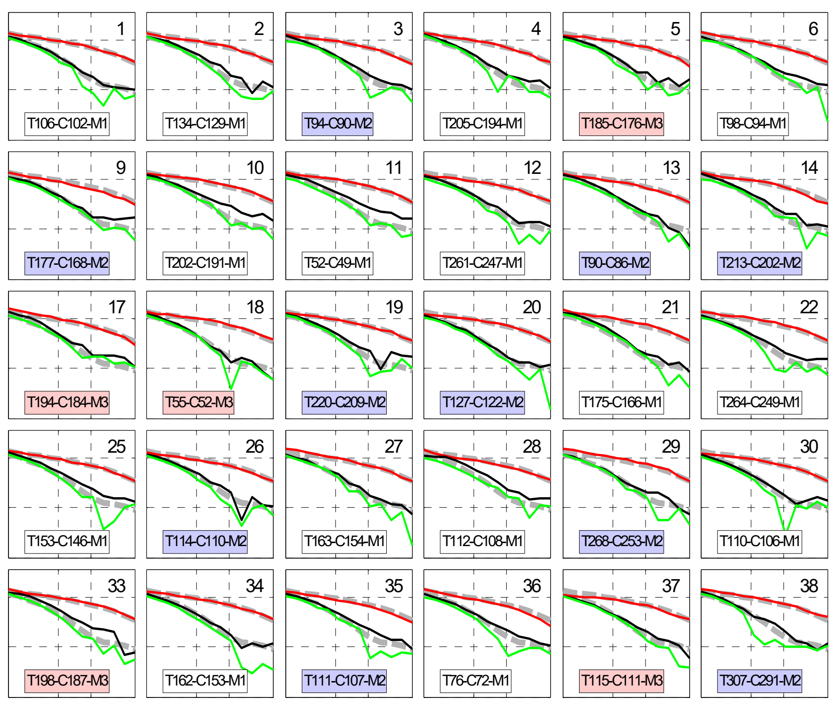



Figure 14. Example of target polarizabilities that match 0.50 cal pols.

# 4 Cued TEMTADS 2x2 Processing

## 4.1 Feature extraction

Cued TEMTADS 2x2 data were acquired in September 2015. CSV files were imported into *UXOLab* for processing. On import *UXOLab* automatically performs background corrections, using the background that was collected closest in time for each anomaly. The data were inverted in *UXOLab* using a sequential inversion approach to estimate target location, depth and primary polarizabilities. Instrument height above the ground was assumed to be 21 cm. Noise standard deviation estimates were based on 135 background measurements. Target location was constrained to lie between ±0.75 m in both X and Y directions relative to the acquisition location. Target depth was constrained to lie between –1.2 and 0 m. The initial optimization for target location identified up to five starting models to input into the subsequent estimation of polarizabilities. We performed three inversions per anomaly, solving for (1) a single dipole source; (2) two dipole sources; and (3) three dipole sources.

Analysis of the data, including visual QC of data and model parameters, selection of training data, and dig list creation, was performed using the *UXOLab* software suite. Visual QC of the data was performed using the *UXOLab* module *QCZilla*, which provides a thorough overview of the observed and predicted data, predicted model parameters, and measures of data/model quality. Predicted polarizabilities were compared to reference polarizabilities compiled from the recent DOD library, our own library compiled from other past ESTCP demonstrations, and the UX-Analyze library.

During data/model QC the primary objectives were to (1) flag high-likelihood TOI anomalies; (2) flag anomalies to be requested as training data; and (3) fail bad models and inversions. Anomalies flagged as high-likelihood TOI were monitored during the dig list creation phase to ensure they were being dug, ideally early in the dig list. Models and inversions were considered to be bad when the inversion failed (i.e., data fit < 0.8), or when the recovered model location(s) were on, or near, an inversion boundary (i.e., significantly outside the footprint of the sensor). In addition, models with an offset >0.7 m from the center of the sensor during acquisition were failed. Models flagged as failed were not used in the classification process. Anomalies with all models from all inversions failed would be classified as "cannot extract reliable parameters" and would be dug. For a given anomaly, if more than one model was passed the classification procedure will consider all passed models and effectively use the one that is "best" based on the classification metric (i.e., reciprocal of polarizability misfit). For anomalies with recollects, the classification procedure will consider all passed models from all measurements of the anomaly and use the one that is "best" based on the classification metric.

## 4.2 Classification

### 4.2.1 Training data selection

Our analysis method is based on polarizability matching with respect to items in an ordnance reference library. To be successful, this approach requires knowledge of the types of ordnance present at the site. The selection of appropriate training data is critical to attain this goal. In general, our training data requests focused on: (1) items whose polarizabilities exhibit UXO-like properties distinct from those of items in our reference library; (2) items with polarizabilities similar to items in our reference library, but with degraded quality; (3) items from a cluster that do not necessarily have UXO-like properties but are from an unknown source; and (4) one-off items.

We used three different methods for selecting training data. During the ongoing daily visual QC of the cued data, the analyst would flag suspicious, UXO-like items (i.e., items with modeled polarizabilities possessing UXO-like properties). Items with polarizabilities substantially different from those in the reference library would be requested as training data.

In addition, we used our custom training data selection tool, *TrainZilla*, to explore feature space and automatically search for clusters of items with self-similar polarizabilities. In *TrainZilla*, the user selects a region in feature space by drawing a polygon, and the program automatically identify clusters of self-similar feature vectors by computing a misfit matrix **M** with elements

$$M_{jk} = \sum_{i=1}^{N} (L^j{}_{total}(t_i) - L^k{}_{total}(t_i))^2$$

where $L^j_{total}$ is the log-transformed total polarizability for the $j^{th}$ feature vector. Feature vectors with mutual misfit less than a user-specified threshold define a cluster in polarizability space. This analysis helps to identify clusters that may not be readily evident in decay-size feature space: e.g., targets with consistent polarizabilities that may be hidden in the "cloud" of non-TOI features. An example of the use of *TrainZilla* at Camp Hale is shown in Figure 15 and Figure 16. This example features a small cluster of items resembling a 20mm projectile found at the New Boston Air Force Station ESTCP live site demonstration project. We asked for training data for three of these items, all of which were small pieces of scrap metal. We subsequently ruled out the presence of 20mm projectiles at Camp Hale. Figure 17 contains examples of two different clusters related to an 81 mm mortar.

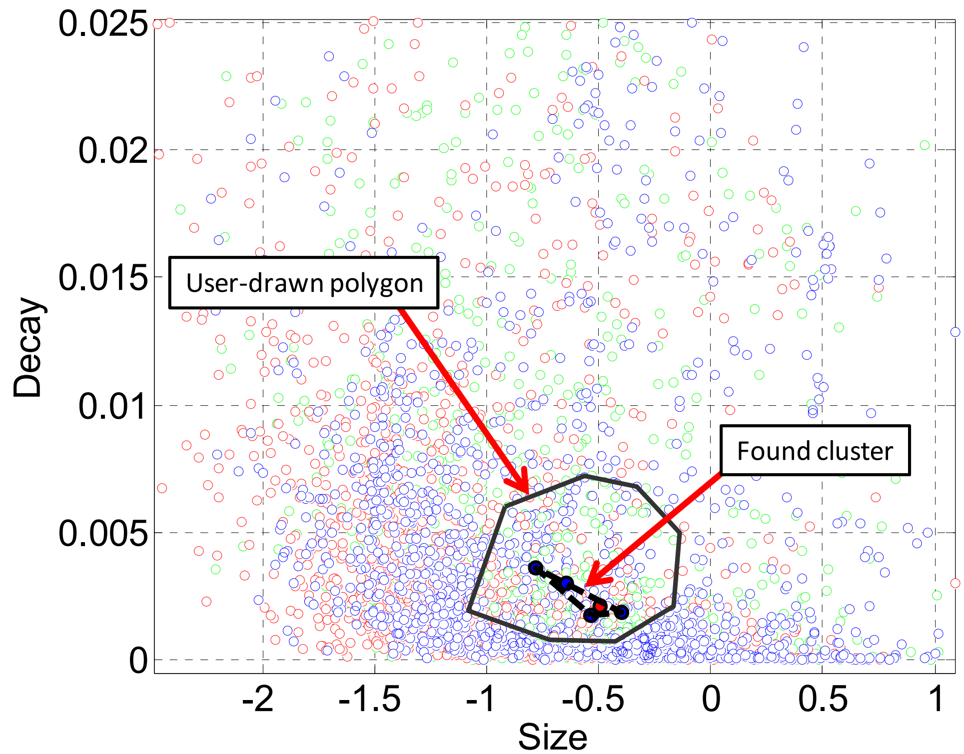



Figure 15. Example of use of the training data selection tool (*TrainZilla*). A polygon (solid black line) is drawn in feature space. Clusters of items with self-similar polarizabilities are automatically found based on the specified cluster search parameters. In this case a cluster comprising 5 features is visible (solid feature symbols encompassed by broken black line). Polarizabilities for the models in this cluster are shown in Figure 16. Colored, open circles represent more than 5000 feature vectors arising from single- and two-object inversions.

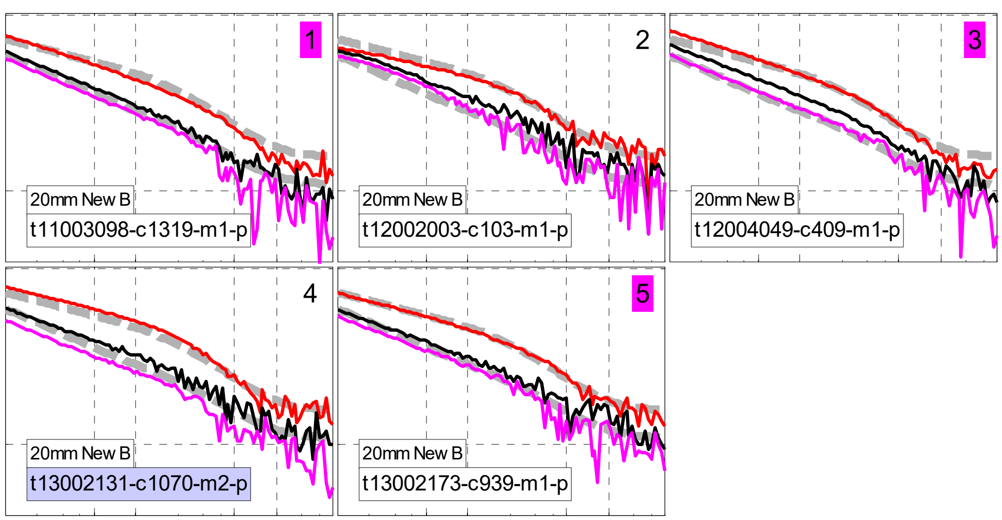
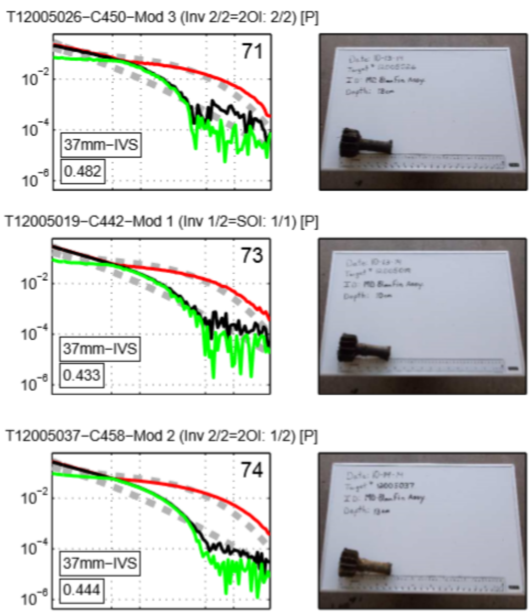
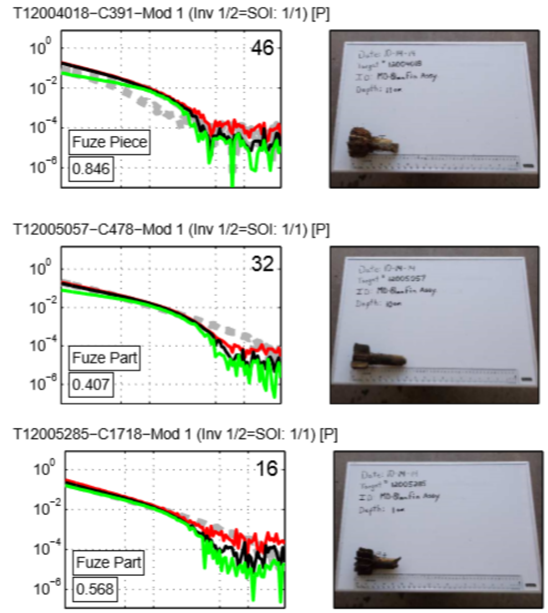



Figure 16. Polarizabilities for the models in the cluster shown in Figure 15. Colored lines are predicted polarizabilities. Broken grey lines are best fitting reference polarizabilities. Target labels are number following "t" in the bottom label of each plot. Training data were requested for the first, third and fifth items (magenta-highlighted index number). All of these turned out to be a small pieces of scrap metal.



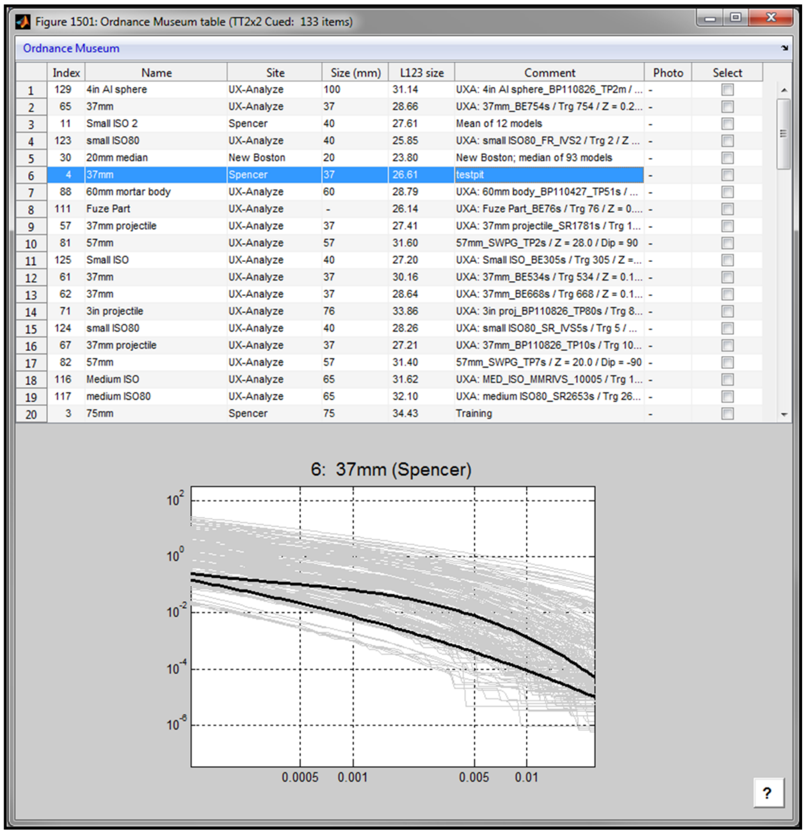

(a) Cluster 81 mm fin assembly




(b) cluster with fin assembly less intact

Figure 17. Examples of clusters related to an 81mm mortar. Multiple 81 mm frag (fin assembly) identified in training due to (a) fin assembly intact, and (b) fin assembly less intact.

Our third approach to selecting training data, geared primarily to finding potential one-off items, was to look for items with polarizabilities that closely match items in a large ordnance library. To do this we used the *UXOLab* module called the *Ordnance Museum* (Figure 18), which, for TEMTADS2x2 cued data, comprises polarizabilities for approximately 130 items (ranging in size from 20mm to 155mm) from past ESTCP live site demonstrations. Approximately 100 of these items were derived from the UX-Analyze polarizability library. With the *Ordnance Museum* we can easily search for models in our dataset with similar polarizabilities to any of the museum items. For Camp Hale we found several items with close matches (polarizability misfit < 0.4 calculated using all three polarizabilities) to *Ordnance Museum* items. In the example shown in Figure 19 eight items were found with good matches to rifle grenade seen at the Fort Rucker ESTCP live site demonstration project. We requested training data for two of these (target labels 11001003 and 12004028). The former was a 40mm illumination round, originally classified as MD, but later classified as a TOI. The polarizabilities of this item were added to our classification reference library. The second item turned out to be frag.




| | Index | Name | Site | Size (mm) | L123 size | Comment | Photo | Select |
|---|---|---|---|---|---|---|---|---|
| 1 | 129 | 4in Al sphere | UX-Analyze | 100 | 31.14 | UXA: 4in Al sphere_BP110826_TP2m / ... | - | |
| 2 | 65 | 37mm | UX-Analyze | 37 | 28.66 | UXA: 37mm_BE754s / Trg 754 / Z = 0.2... | - | |
| 3 | 11 | Small ISO 2 | Spencer | 40 | 27.61 | Mean of 12 models | - | |
| 4 | 123 | small ISO80 | UX-Analyze | 40 | 25.85 | UXA: small ISO80_FR_IVS2 / Trg 2 / Z ... | - | |
| 5 | 30 | 20mm median | New Boston | 20 | 23.80 | New Boston; median of 93 models | - | |
| 6 | 4 | 37mm | Spencer | 37 | 26.61 | testpit | - | |
| 7 | 88 | 60mm mortar body | UX-Analyze | 60 | 28.79 | UXA: 60mm body_BP110427_TP51s / ... | - | |
| 8 | 111 | Fuze Part | UX-Analyze | - | 26.14 | UXA: Fuze Part_BE76s / Trg 76 / Z = 0.... | - | |
| 9 | 57 | 37mm projectile | UX-Analyze | 37 | 27.41 | UXA: 37mm projectile_SR1781s / Trg 1... | - | |
| 10 | 81 | 57mm | UX-Analyze | 57 | 31.60 | 57mm_SWPG_TP2s / Z = 28.0 / Dip = 90 | - | |
| 11 | 125 | Small ISO | UX-Analyze | 40 | 27.20 | UXA: Small ISO_BE305s / Trg 305 / Z =... | - | |
| 12 | 61 | 37mm | UX-Analyze | 37 | 30.16 | UXA: 37mm_BE534s / Trg 534 / Z = 0.1... | - | |
| 13 | 62 | 37mm | UX-Analyze | 37 | 28.64 | UXA: 37mm_BE668s / Trg 668 / Z = 0.1... | - | |
| 14 | 71 | 3in projectile | UX-Analyze | 76 | 33.86 | UXA: 3in proj_BP110826_TP80s / Trg 8... | - | |
| 15 | 124 | small ISO80 | UX-Analyze | 40 | 28.26 | UXA: small ISO80_SR_IVS5s / Trg 5 / ... | - | |
| 16 | 67 | 37mm projectile | UX-Analyze | 37 | 27.21 | UXA: 37mm_BP110826_TP10s / Trg 10... | - | |
| 17 | 82 | 57mm | UX-Analyze | 57 | 31.40 | 57mm_SWPG_TP7s / Z = 20.0 / Dip = -90 | - | |
| 18 | 116 | Medium ISO | UX-Analyze | 65 | 31.62 | UXA: MED_ISO_MMRIVS_10005 / Trg 1... | - | |
| 19 | 117 | medium ISO80 | UX-Analyze | 65 | 32.10 | UXA: medium ISO80_SR2653s / Trg 26... | - | |
| 20 | 3 | 75mm | Spencer | 75 | 34.43 | Training | - | |

Figure 18. *UXOLab Ordnance Museum* interface. This is a library of reference polarizabilities compiled from several ESTCP live site demonstrations. The ordnance museum for TEMTADS2x2 Cued data currently comprises approximately 130 items ranging in size from 20mm to 155mm projectiles.

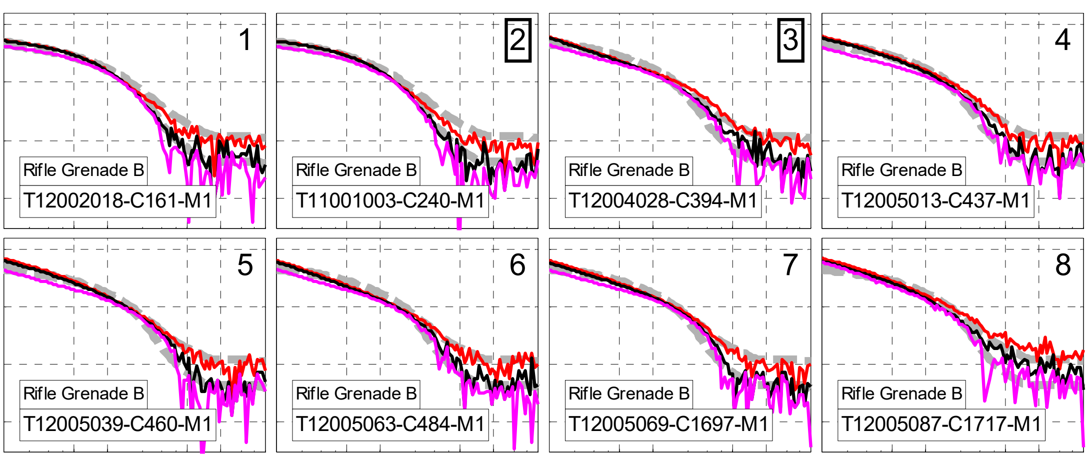



Figure 19. Polarizabilities of eight models with close matches to a Fort Rucker rifle grenade in the *Ordnance Museum*. Anomaly labels are the number following the “T” in each label. We requested training data for items 2 and 3. The first (11001003) was a 40mm illumination round (TOI); the latter (12004028) was frag.

We submitted two training requests for a total of 100 training items spanning all grids (Figure 20). Of the 100 training digs, 83 were cultural debris (scrap metal, nails, bolts, 0.50 caliber projectiles etc.), 14 were munitions debris (frag, fuzes and fuze components), and three were TOI (Figure 21). The latter comprised two 81mm mortars (11005017 and 1200412) and a 40mm illumination round (11001003). Figure 21 shows photos and polarizabilities for the three TOI. The polarizabilities for these items were added to our classification reference library. Based on an analysis of the training data, our ordnance library was reduced to just three distinct items: medium ISO, 81mm mortar, and 40mm illumination round.

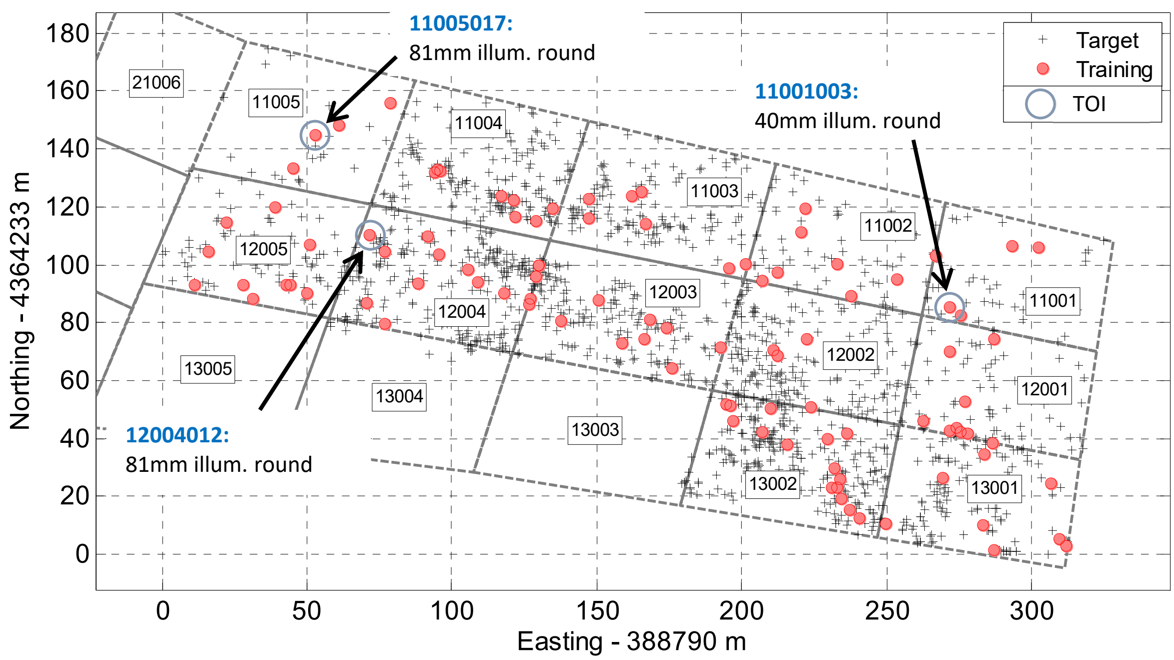



Figure 20. Distribution of the 100 training digs (pink circles). Blue circles show location of the three TOI found in the training digs.

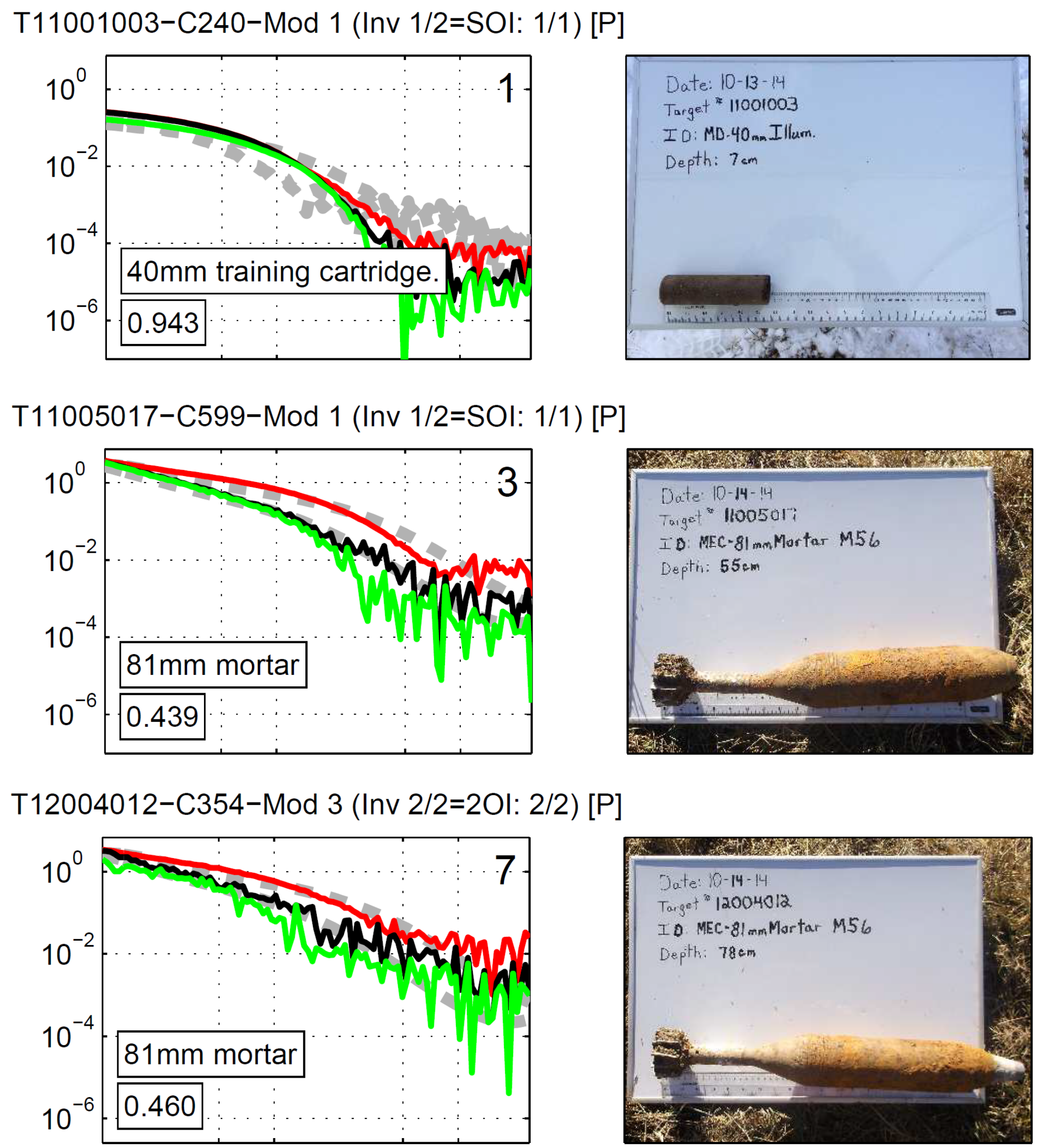



Figure 21. Training data requests that are TOI. Although the 40 mm illumination round was listed as MD, it was decided that it should be considered MEC. The 81 mm M56 Mortars were at depths of 0.55 and 0.78 meters. The estimated depths were 0.53 and 0.68 m, respectively.

### 4.2.2 Classification method: Cued data

The dig list was developed using our visual classification module *DigZilla* (Figure 22). The dig list used a classification approach based on polarizability misfit (to the best fitting library reference item for each model) using all three polarizabilities. Misfits were calculated between the channel 7 (0.16 ms) and channel 75 (5.23 ms). The ordnance library used for our first dig list comprised four items (Figure 23).

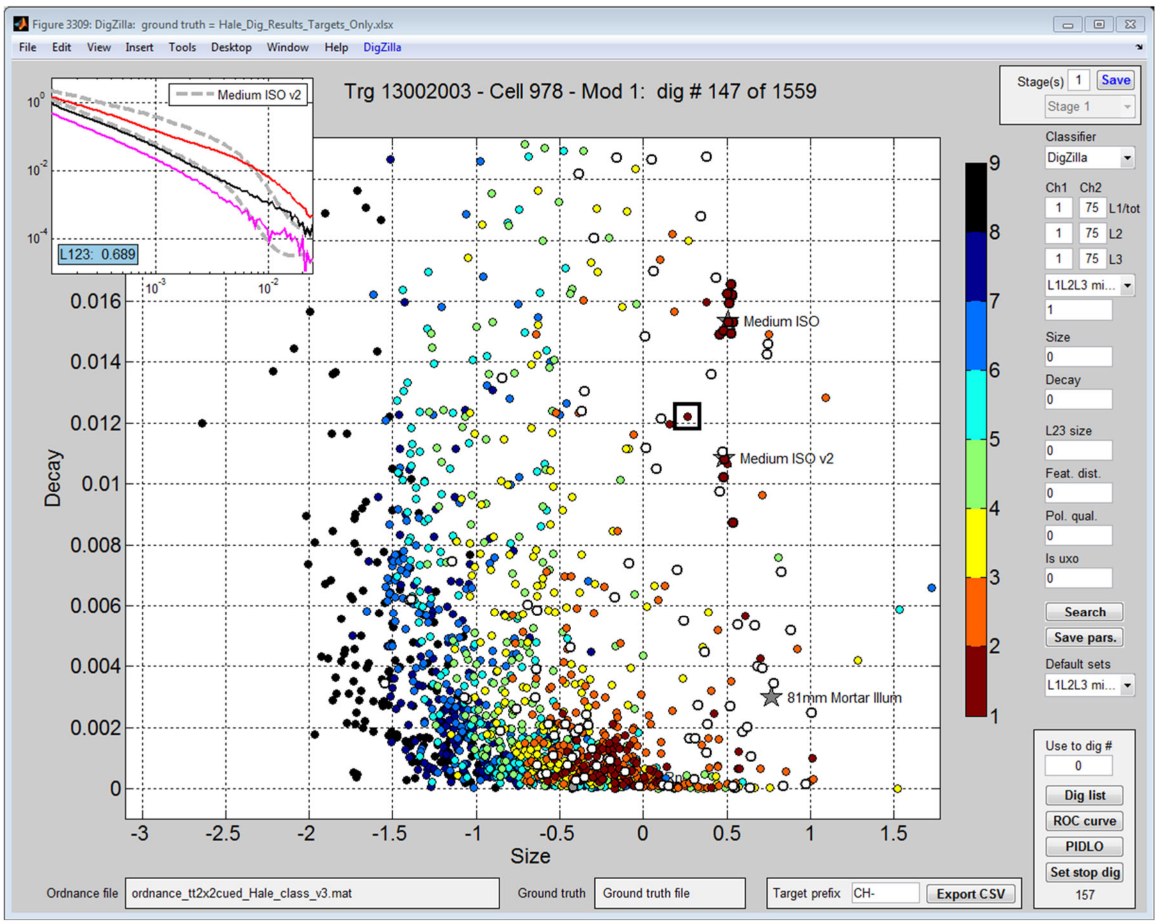



Figure 22. Screen shot of the *UXOLab DigZilla* graphical user interface. Features in the decay versus size feature plot are color coded according to dig list order. White dots are training items. Labeled stars are reference items. Polarizabilities for the currently selected item (black square) are displayed at the top left.

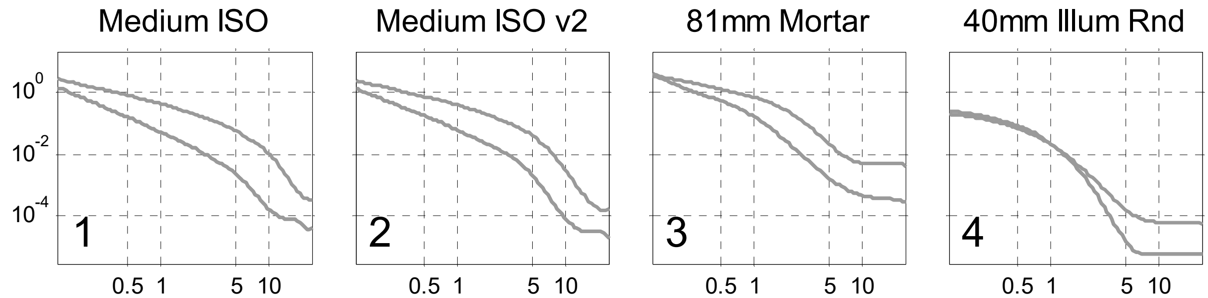



Figure 23. Items in the ordnance reference library used for the dig list.

The decision metric for the dig list is shown in Figure 24. The elbow in the decision metric curve occurs at dig number 140, which is a reasonable first estimate for a stop dig point. We inspected the polarizabilities for all items in dig list order (Figure 25) and set the stop dig point at dig number 157, a slightly more conservative number than that suggested by the decision metric curve.

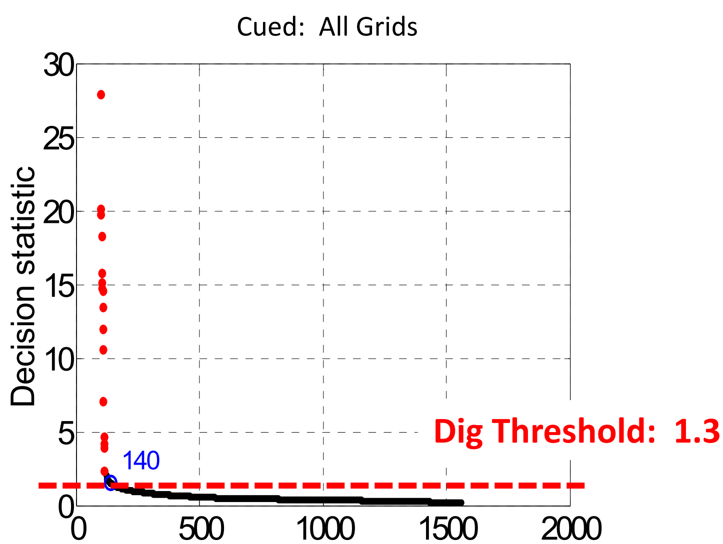



Figure 24. Decision metric plotted against dig number. The x-axis represents dig number. Red dots represent items flagged as likely TOI (medium ISOs) during visual QC of the data. Blue circle at dig number 140 represents the "elbow" of the curve, which can be taken as a rough estimate for a reasonable stop dig point.

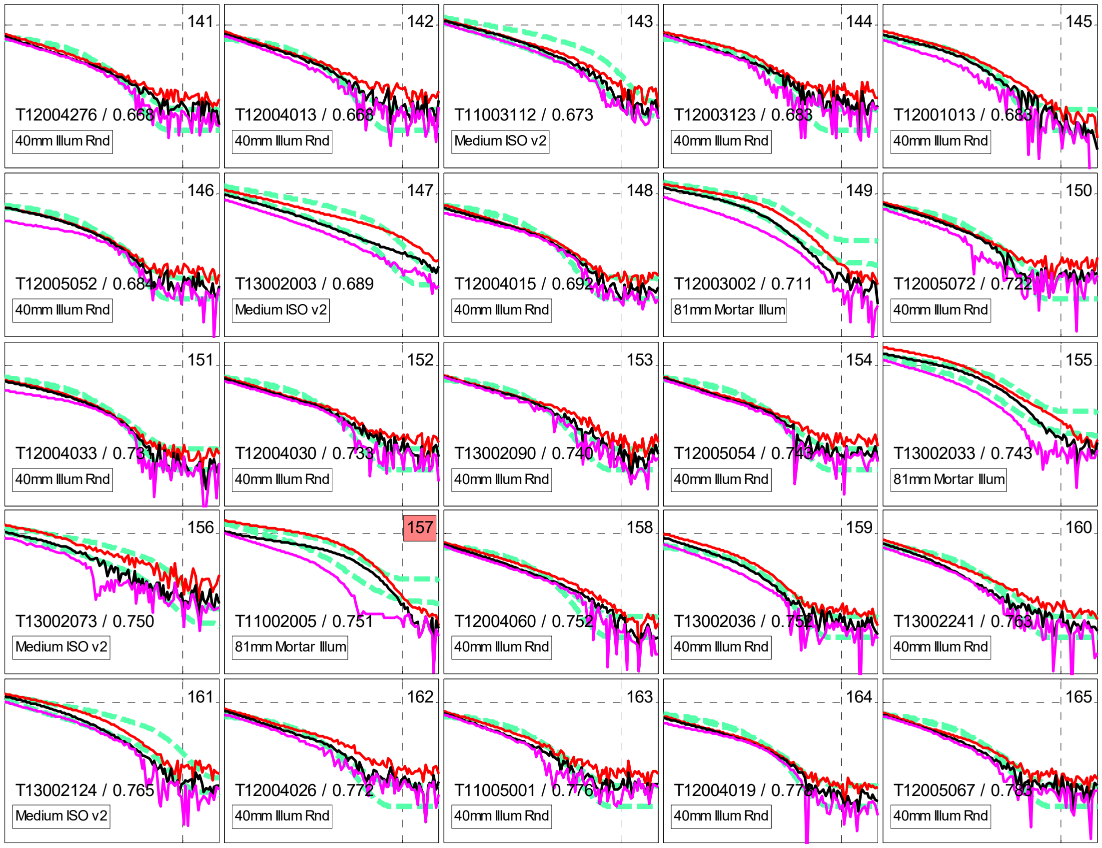


Figure 25. Polarizabilities around in dig list order before and after the stop dig point. Dig numbers are indicated in the top right of each plot. Target labels are the number following the "T" in each label above the label indicating the best matching reference item. The stop dig point (dig number 157) is highlighted in red.

*Analysis of ground truth*

The first twelve digs (digs 102-113), excluding training data and one "cannot analyze" target, were all medium ISO seeds (Figure 26 and Figure 27). The 14th dig (dig 115; target label 11001010; Figure 26) was a 60mm illumination round. Excluding seeds, this was the only TOI found after training. This item was found because it was a good match to the medium ISO reference polarizabilities. To check for the presence of other potential 60mm illumination rounds we added the target 11001010 polarizabilities to our ordnance library and searched the dataset for items with similar polarizabilities. The twelve best fitting items had already been dug in training: all were non-TOI. There were no other good matches in the dataset, from which we concluded that we had found all 60mm illumination rounds.

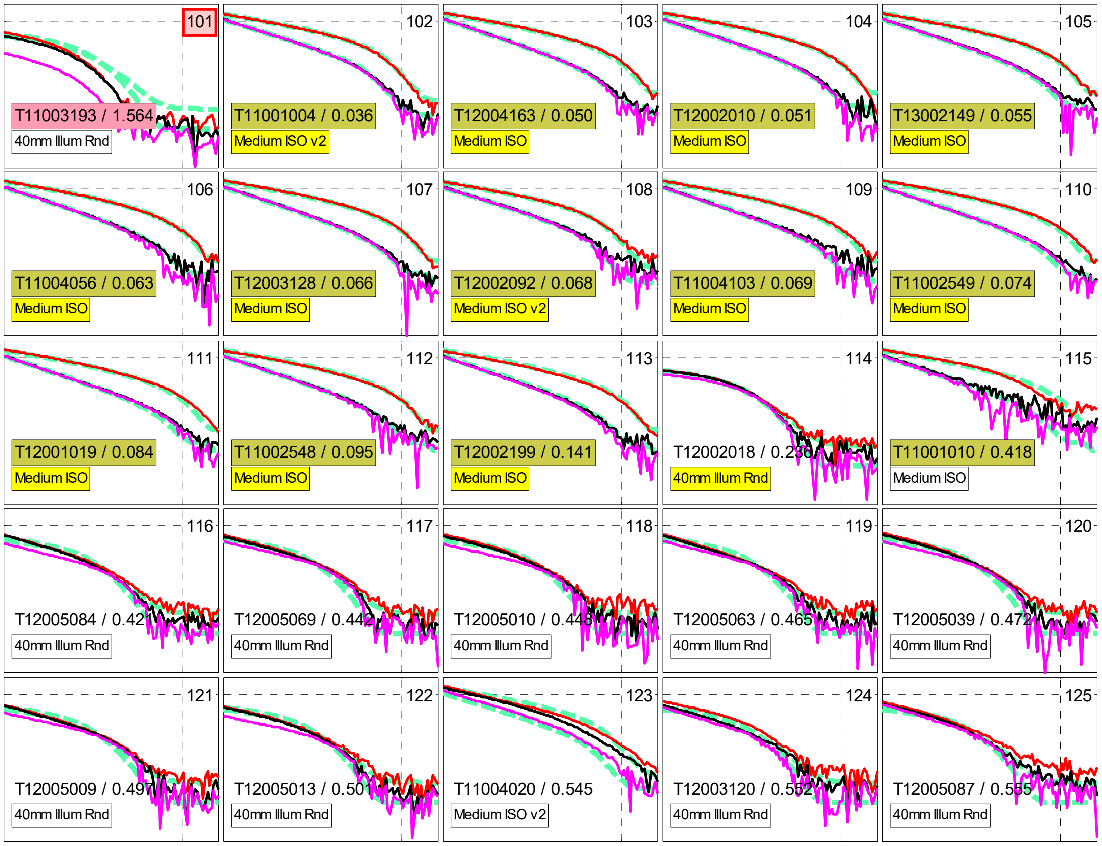



Figure 26. Polarizabilities in dig list order starting at dig number 101. Digs 1-100 were training digs. Dig number 101 was a "cannot analyze" target (poor data fit) which turned out to be a long strand of barb wire on or near the surface. Yellow highlighting of best fitting ordnance label indicates an item flagged as "likely TOI" during visual QC. Yellowish highlighting of the target / misfit label indicates a ground truth TOI. Dig number 114 (target 12002018) was a 40mm flare casing. This object looks identical to the 40mm illumination round (target 11001003), but was considered non-TOI because it did not contain any explosive material.

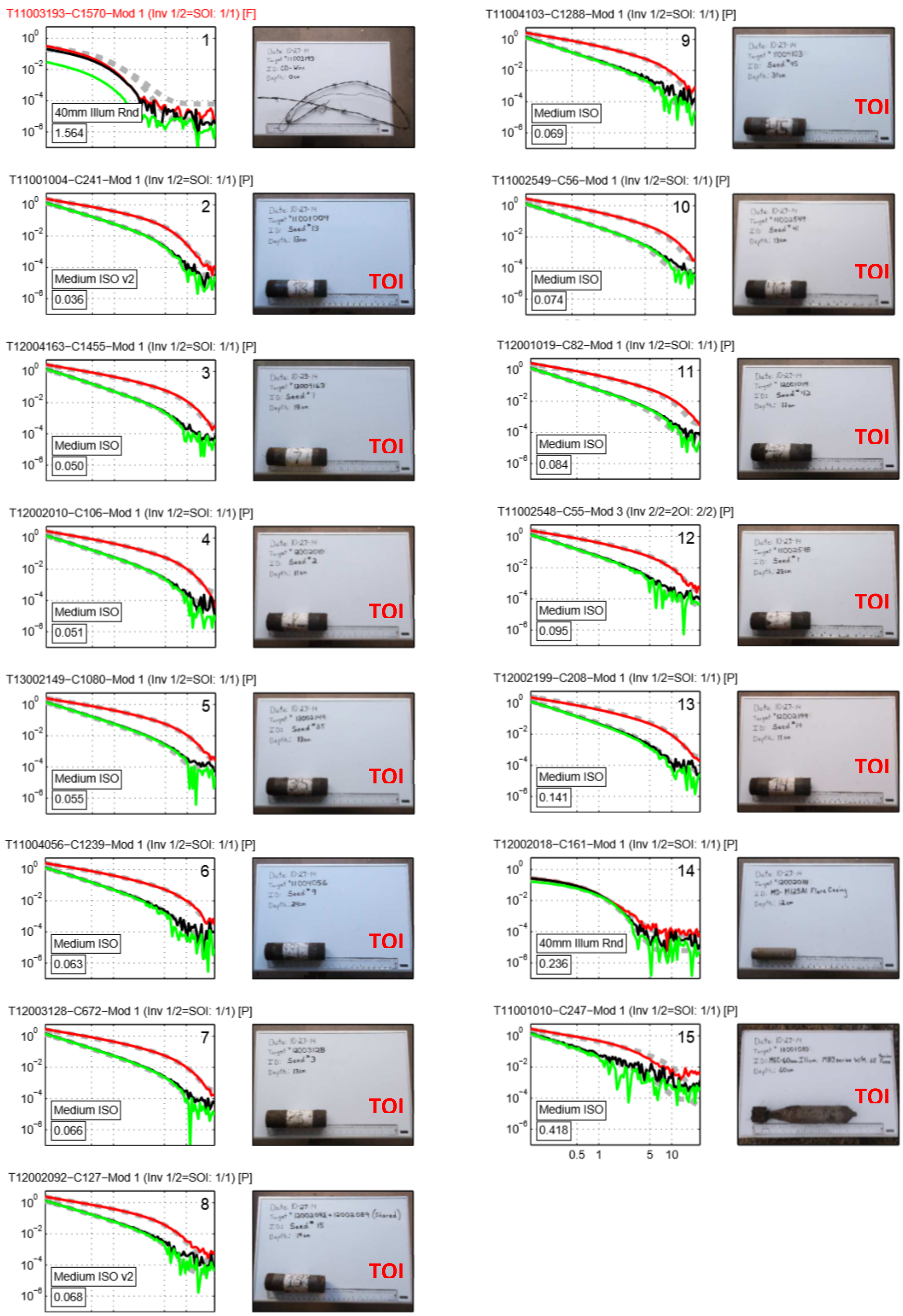
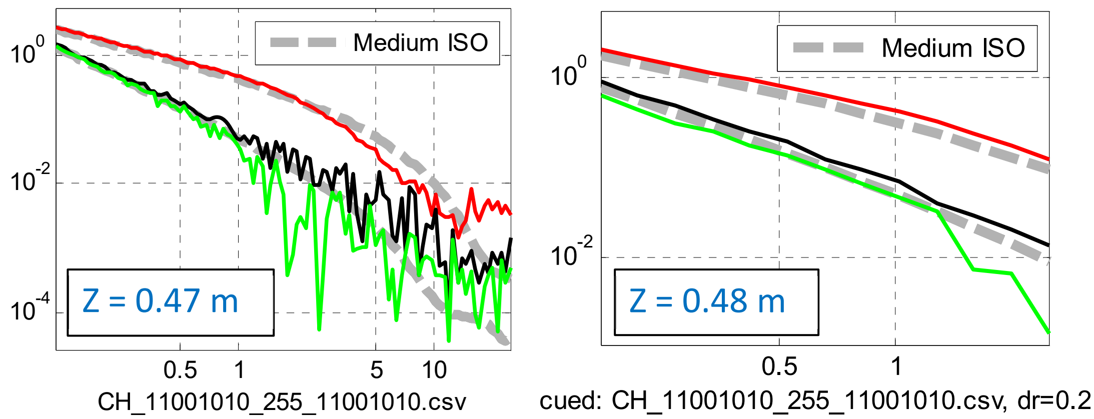



Figure 27. First 15 items (after 100 training digs) in the cued list. Item 14 was not called a TOI since it did not contain any explosive material. The number in the lower left of each plot contains the polarizability misfit. The decision statistic is equal to 1/(polarizability misfit).

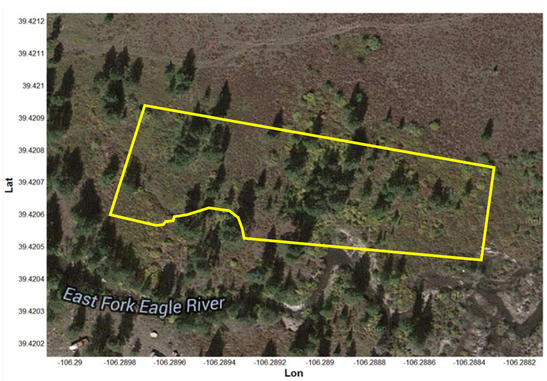

(a) cued polarizabiltiies

(b) dynamic polarizabilities

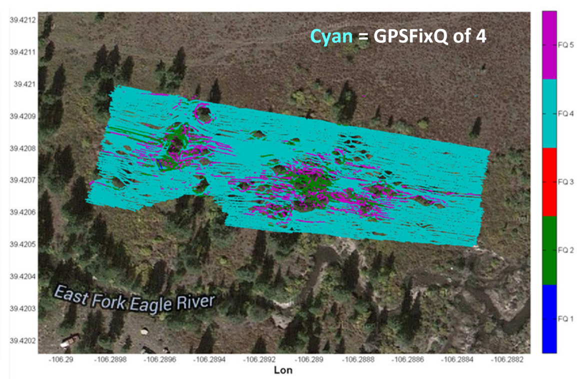
Figure 28. 60 mm illumination round was the only non-seed TOI. CH-11001010 60 mm illumination, M83 series w/PTT fuze, M65 series. Both the cued and dynamic data produced good fits to the target.

### 4.2.3 Classification method: Dynamic data

A ranked, classification diglist was created for anomalies that did not have a cued measurement. Two dynamic diglists were created. A diglist was prepared for the 1100x and 1200x grids, and a second, separate diglist was prepared for the 1300x grids. Figure 20 indicates the labelling convention for the Area 1 grids. The 1300x grids in the Southeast corner of Area 1 had a number of GPS dropouts and had more difficult terrain for the TEMTADS (Figure 29). We chose to create separate diglists because we anticipated that the 13000 anomalies could have poorer data fits due to more difficult surveying conditions. Indeed, there were more cued locations chosen in this region of Area 1.




(a) Outline of the 1300x grids.




(b) GPS Fix values for the 1300x grids

(c) Example of pits and trees in the 1300x grids.

Figure 29. The 1300x grids were processed separately due to possible GPS issues. GPSFixQ values not equal to 4 correlated with gaps and jumps in GPS record. Larger number of cued anomalies acquired in these grids.

The dynamic data classification followed the same steps as the cued data classification. There were no additional training data requested for the dynamic classification. The ordnance library for matching contained the same targets as the cued classification. Similar to the cued classification, the stop dig point was chosen by visual inspection. Although the diglists were created separately, the stop-dig threshold for both diglists was 0.8 (Figure 30).

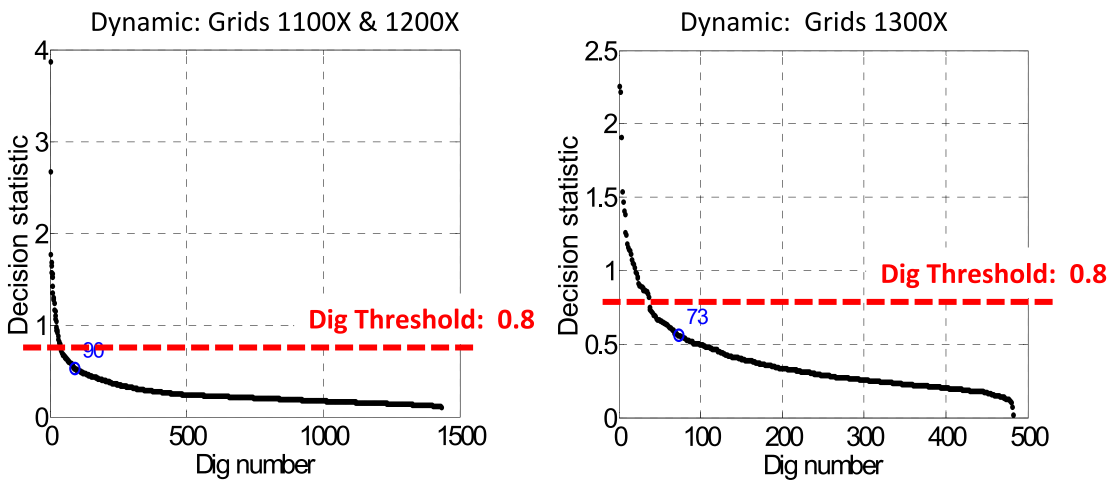



Figure 30. Decision statistic and dig thresholds for the dynamic classification. The blue circle indicates the corner of the L-curve.

Figure 31 shows the ground truth of the first 10 digs of the 1100X and 1200X grids. 4 Medium ISO QC seeds were dug in the first 7 digs. We note that the ground truth for dig 10 is not associated with the dig, but rather it is ground truth is from a nearby anomaly. Figure 32 shows the ground truth for the first 10 digs of the 1300X grids. The first two digs were Medium ISO QC seeds.

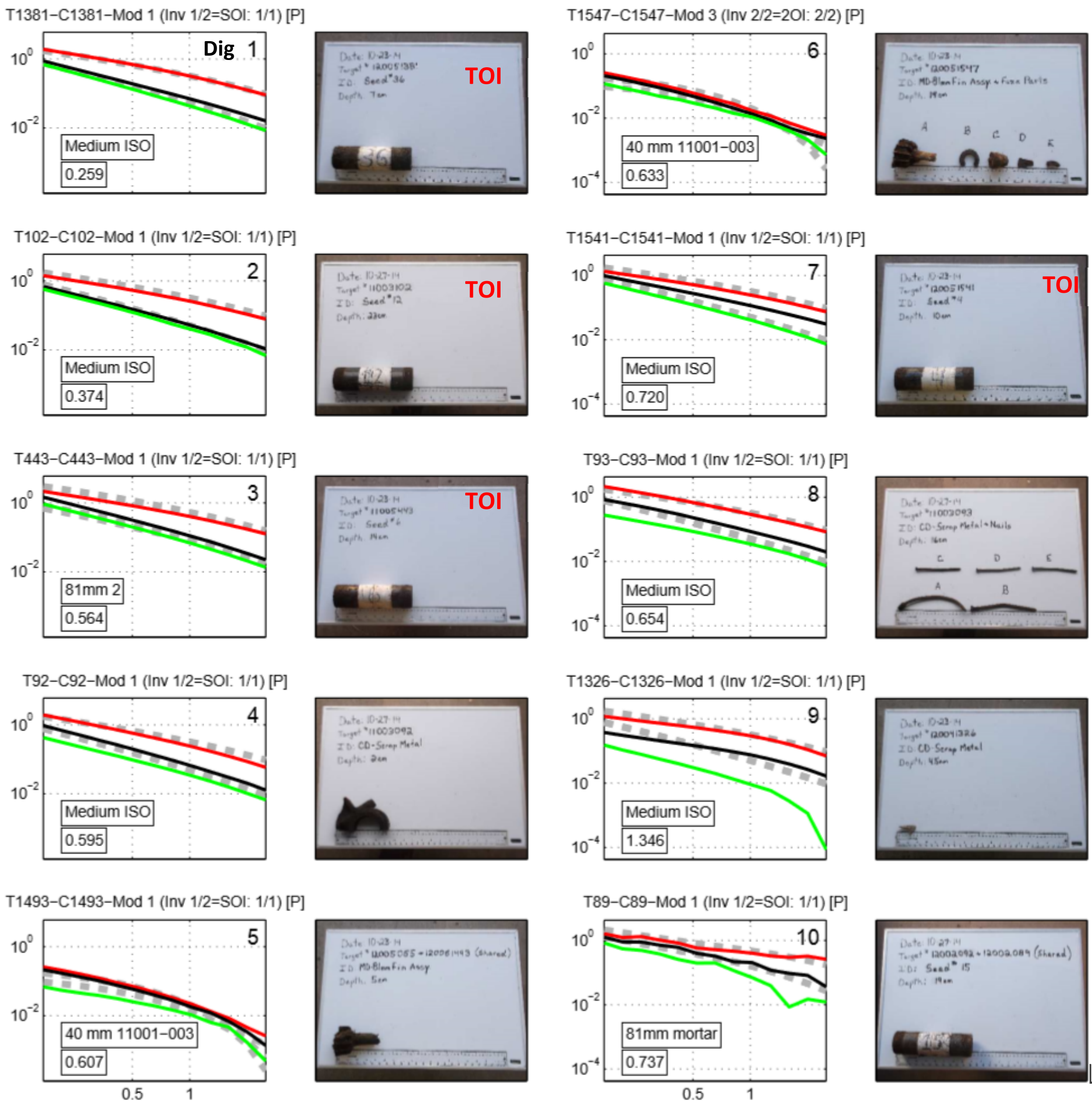



Figure 31. First 10 digs of the diglist for dynamic data from 1100X and 1200X grids. We note that the groundtruth for dig 10 (Medium ISO) does not match the recovered polarizabilities because the ground truth corresponds to a nearby anomaly. The number in the lower left of each plot contains the polarizability misfit.

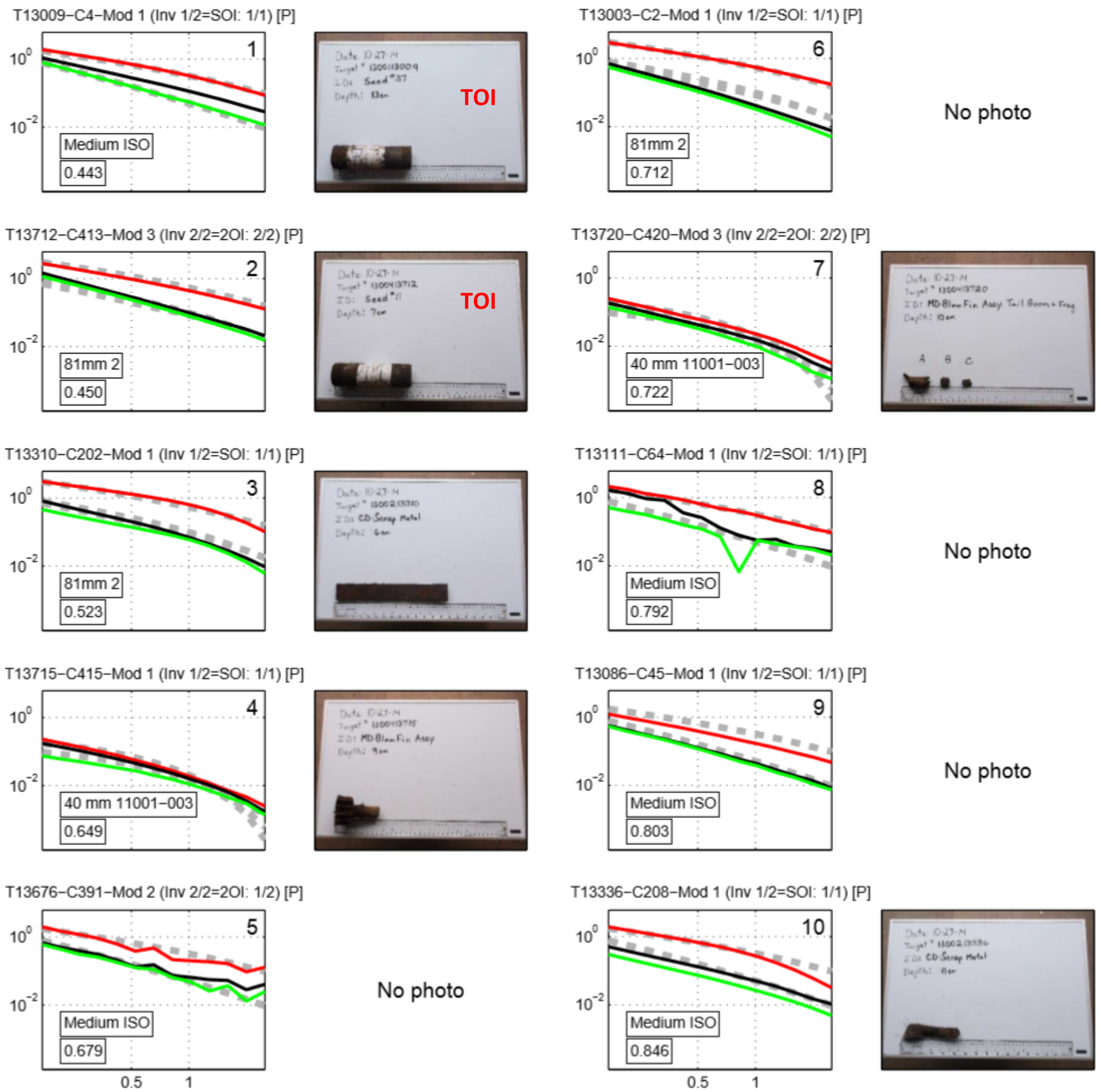



Figure 32. First 10 digs of the 1300X diglist.

### 4.2.4 Diglist summary

Table 1 contains a summary of the diglist performance. From 3674 initial data anomaly selections, the classification process resulted in 327 digs: 100 training digs, 157 digs from analyzing 1791 cued measurements, and 70 digs from analyzing dynamic anomalies. The 327 digs resulted in 22 TOI: 18 QC seeds and 4 native UXO. Table 1 breaks down the number of digs and TOI for each diglist.

Table 1. Summary of diglist performance.

| Diglist | Number of Digs | Number of TOI | Number of digs after final TOI | Decision Statistic Threshold |
|---|---|---|---|---|
| Training/Analyst Calibration Digs | 100 | 3 (2 81 mm mortar, 40 mm illumination) | na | na |
| Cued | 157 | 13 (12 QC seeds, 1 60mm mortar) | 42 | 1.3 |
| Dynamic: Grids 1100X and 1200X | 34 | 4 (all QC seeds) | 23 | 0.8 |
| Dynamic: Grids 1300X | 36 | 2 (all QC seeds) | 25 | 0.8 |

The efficiency of the classification is summarized by the Receiver Operator Characteristic (ROC) curves. The ROC curves for the cued classification are shown in Figure 33 and the ROC curves for the dynamic classification is shown in Figure 34. For each of the diglists, the TOI are found early in the diglist with a number of non-TOI digs (listed in Table 1) prior to the stop dig point to give some confidence in the selection of the decision statistic threshold.

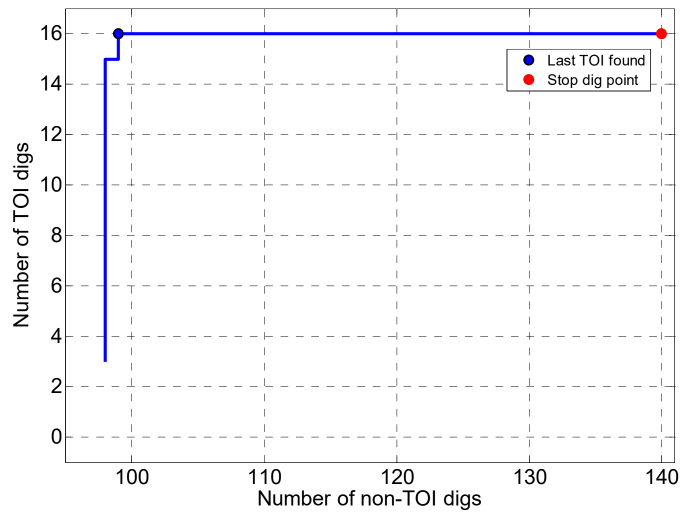
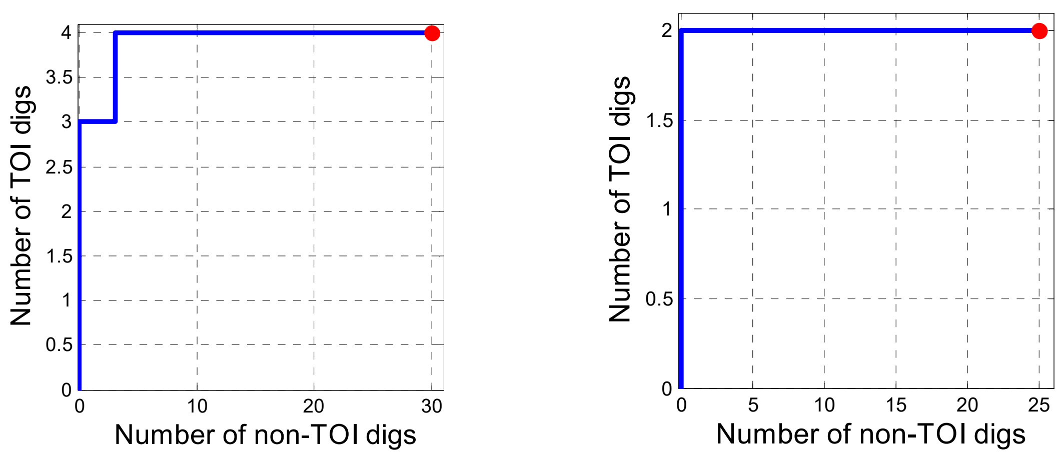



Figure 33. Receiver Operator Characteristic (ROC) curves for cued data classification.




(a) 1100X and 1200X grids

(b) 1300X grids

Figure 34. ROC curves for dynamic data classification. (a) 23 non-TOI anomalies dug after final TOI. (b) 25 non-TOI anomalies dug after final TOI.

### 4.2.5 Analysis of QC Seeds

Following the submission of our diglists, QC seed information for Area 1 was provided to us from AECOM. Table 2 summarizes the seed performance.

There were 18 QC seeds were within the area surveyed by TEMTADS 2x2. All QC seeds were medium ISOs. All seeds were included in the submitted diglists.

The predicted location error for seeds was less than 10 cm. 17 of the 18 seeds had a depth estimate error of 5cm or less. Seed 11 was an outlier, and had a depth estimate error of 12 cm. This seed corresponds to dig 2 in Figure 32. Although the polarizabilities of Seed 11 have the correct shape, the amplitude of the polarizabilities match an 81mm better than a medium ISO. This overestimate of size is consistent with the overestimate in depth.

### 4.2.6 QA/Validation digs

The objective of the validation digs was to ensure that everyone is comfortable that no TOI were left in the ground. The validation digs are designed to test key decisions points during the classification process. Establishing the QA dig strategy was a group effort between the ESTCP Program Office, Colorado State Regulator, AECOM and BTG. The following QA/Validation digs were defined.

1. *Test the stop dig point*: For each of the 3 dig-lists we want to have 50 non-TOI after the final TOI is found. This results in:
    - Cued: 8 additional digs
    - Dynamic 1100x-1200x: 27 digs
    - Dynamic 1300x: 25 digs

2. *Test screening using Dynamic Data:* In order to test the screening, we dig a subset of the anomalies that were screened for being small or 0.50 cal.
    - 44 digs

3. *Dig a selection of larger targets that appear beyond the stop dig point:*
    - 15 digs

4. *Dig a selection of random anomalies:* The ESTCP Program Office randomly chose a selection of anomalies that were not dug.
    - 36 digs

This strategy resulted in a total of 155 QA/Validation digs. No TOI were found with these digs.

Table 2. Summary of Seed Performance

| SEED INFORMATION | | | | | Closest Dig Location | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ID | GRID | Depth (cm) | Easting | Northing | **Target ID:** | **Easting (m)** | **Northing (m)** | **Depth (cm)** | **Grid** | **Dig Stat** | **Diglist** | **xy-offset (m)** | **depth offset (m)** |
| 1 | 11002 | 30 | 389004.62 | 4364332.78 | 11002548 | 389004.63 | 4364332.76 | 26.12 | 11002 | 10.58 | Cued | 0.02 | -0.04 |
| 2 | 12002 | 15 | 389043.36 | 4364282.59 | 12002010 | 389043.35 | 4364282.62 | 15.26 | 12002 | 19.72 | Cued | 0.03 | 0.00 |
| 3 | 12003 | 15 | 388961.39 | 4364298.96 | 12003128 | 388961.39 | 4364298.95 | 14.08 | 12003 | 15.10 | Cued | 0.01 | -0.01 |
| 4 | 12005 | 10 | 388843.78 | 4364337.69 | 1541 | 388843.76 | 4364337.67 | 10.82 | 12005 | 1.56 | Dyn 1100X &1200X | 0.03 | 0.01 |
| 6 | 11005 | 10 | 388847.83 | 4364374.52 | 443 | 388847.83 | 4364374.48 | 15.12 | 11005 | 1.77 | Dyn 1100X &1200X | 0.04 | 0.05 |
| 7 | 12004 | 15 | 388897.88 | 4364335.59 | 12004163 | 388897.88 | 4364335.64 | 14.88 | 12004 | 20.10 | Cued | 0.05 | 0.00 |
| 9 | 11004 | 30 | 388878.75 | 4364369.03 | 11004056 | 388878.67 | 4364369.01 | 26.82 | 11004 | 15.79 | Cued | 0.08 | -0.03 |
| 11 | 13004 | 10 | 388889.11 | 4364302.00 | 13712 | 388889.20 | 4364301.98 | 22.07 | 13004 | 2.22 | Dynamic 1300X | 0.09 | 0.12 |
| 12 | 11003 | 30 | 388955.60 | 4364354.97 | 102 | 388955.66 | 4364354.96 | 27.20 | 11003 | 2.67 | Dyn 1100X &1200X | 0.06 | -0.03 |
| 13 | 11001 | 15 | 389073.73 | 4364328.13 | 11001004 | 389073.74 | 4364328.13 | 13.74 | 11001 | 27.93 | Cued | 0.01 | -0.01 |
| 14 | 12002 | 15 | 389000.58 | 4364288.37 | 12002199 | 389000.54 | 4364288.40 | 16.24 | 12002 | 7.07 | Cued | 0.05 | 0.01 |
| 15 | 12002 | 30 | 389045.41 | 4364316.00 | 12002092 | 389045.40 | 4364316.02 | 29.28 | 12002 | 14.78 | Cued | 0.03 | -0.01 |
| 35 | 13002 | 15 | 389017.29 | 4364270.02 | 13002149 | 389017.25 | 4364270.10 | 15.04 | 13002 | 18.32 | Cued | 0.09 | 0.00 |
| 36 | 12005 | 15 | 388802.92 | 4364346.16 | 1381 | 388802.87 | 4364346.12 | 15.00 | 12005 | 3.87 | Dyn 1100X &1200X | 0.07 | 0.00 |
| 37 | 13001 | 20 | 389062.55 | 4364258.75 | 13009 | 389062.57 | 4364258.82 | 20.52 | 13001 | 2.26 | Dynamic 1300X | 0.07 | 0.01 |
| 41 | 11002 | 15 | 389041.78 | 4364351.53 | 11002549 | 389041.76 | 4364351.55 | 15.07 | 11002 | 13.44 | Cued | 0.03 | 0.00 |
| 42 | 12001 | 15 | 389084.58 | 4364293.04 | 12001019 | 389084.58 | 4364293.00 | 16.16 | 12001 | 11.96 | Cued | 0.04 | 0.01 |
| 45 | 11004 | 30 | 388908.65 | 4364369.94 | 11004103 | 388908.65 | 4364370.00 | 27.65 | 11004 | 14.57 | Cued | 0.06 | -0.02 |

# 5 Conclusions

A “two-pass” classification strategy using dynamic and cued TEMTADS 2x2 data was utilized at Area 1 of the East Valley Munitions site on the Former Camp Hale. The dynamic survey produced 3674 initial data anomaly selections. We adopted a conservative approach to processing the data anomalies. An Informed Source Selection process resulted in 1791 cued measurements. Anomalies that were not cued were classified. The classification process resulted in 100 training digs, 157 digs from cued measurements, 70 digs from dynamic anomalies, and 155 validation digs. All QC seeds were found in the cued and dynamic data classification stage. No TOI were found in the validation digs.

Processing of TEMTADS 2x2 data presented no significant challenges for library matching-based classification. We note that the inversion of dynamic TEMTADS 2x2 data produced good fits to the polarizability library. A more aggressive ISS strategy could have been considered, which would have reduced the number of cued measurements required.