DEMONSTRATION REPORT

Dipole Discrimination Techniques Applied to Live Sites

TEMTADS 2x2 Classification
Southwest Proving Ground, Arkansas

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14. ABSTRACT

This report describes advanced classification processing of TEMTADS 2x2 time-domain electromagnetic data collected at the Southwest Proving Ground, Arkansas. The initial cued data set consisted of 1950 anomalies, of which 38 did not have cued data acquired within the required offset distance. These 38 targets were, therefore, listed as "can't analyze" and labelled as "dig". Black Tusk Geophysics processed 1912 cued interrogations to recover estimates of intrinsic dipole polarizabilities for detected sources. Quality Control (QC) of the inversion results flagged high-likelihood targets of interest (TOI) anomalies and failed bad models and inversions.

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Executive Summary

This report describes advanced classification processing of TEMTADS 2x2 time-domain electromagnetic data collected at the Southwest Proving Ground, Arkansas. The initial cued data set consisted of 1950 anomalies, of which 38 did not have cued data acquired within the required offset distance. These 38 targets were, therefore, listed as "can't analyze" and labelled as "dig". Black Tusk Geophysics processed 1912 cued interrogations to recover estimates of intrinsic dipole polarizabilities for detected sources. Quality Control (QC) of the inversion results flagged high-likelihood targets of interest (TOI) anomalies and failed bad models and inversions. In addition, estimated polarizabilities were used to identify potential novel TOI at the site via cluster analysis and comparison with a comprehensive polarizability library. Of the 36 anomalies in the training data request, 25 were TOI.

Our classification approach used polarizability matching with a large library (more than 400 items) to generate a prioritized dig list. The greatest potential challenge was the variability in 20 mm projectile polarizabilities at the site, and whether the range of 20 mm polarizabilities would be sufficiently represented in the classification library. Indeed, the first stage classification dig list resulted in a missed 20 mm QC seed due to its polarizabilities not matching a member of the library. For the second stage dig list, the reference library was augmented with the polarizabilities of the missed seed. The second stage dig list identified a 20 mm projectile, whose polarizabilities were also added to the library. A stage 3 dig list was created, that resulted in no additional TOI found. For Quality Assurance (QA) purposes, an additional 100 digs were added, to form the stage 4 dig list. Since no TOI were found in the QA digs, the dig list was then finalized.

All TOI were found before the stop dig point. We designated 248 of 1950 targets (12.7%) for digging and left 1702 items in the ground (87.3%).

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Acronyms

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
SWPG	Southwest Proving Ground
TEMTADS	Time Domain Electromagnetic Multi-Sensor Towed Array Detection System
TOI	Target of Interest
UXO	Unexploded Ordnance

1 Introduction

The Southwestern Proving Grounds (SWPG) Formerly Used Defense Site (FUDS) is located near Hope, Arkansas. An Environmental Security Technology Certification Program (ESTCP) demonstration was carried out at Recovery Field (RF) 15 on the SWPG site. Suspected Munitions and Explosives of Concern (MEC) items at the site include 20 mm, 37 mm, 40 mm, 57 mm, 75 mm, 76 mm, 90 mm, 105 mm, 120 mm, and 155-mm projectiles, and 81 mm mortars.

RF-15 is a relatively flat, open area that is ideal for the deployment of towed advanced detection systems. For the ESTCP study, digital geophysical mapping was performed by the Metal Mapper, One Pass Time domain EM array (OPTEMA) and TEM-8 during August and September 2015. Based on the resulting data, a target list of locations for cued interrogation with was developed. Approximately 1900 anomalies were subsequently cued with the cart-based Time Domain Electromagnetic Multi-Sensor Towed Array Detection System (TEMTADS 2x2). This report summarizes the processing carried out by Black Tusk Geophysics (BTG) on TEMTADS 2x2 cued data collected as part of this demonstration.

2 Technology description

2.1 Detection

Advanced time-domain electromagnetic sensors have dramatically improved classification of buried MEC. In contrast to commercial standard mono-static sensors, 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. Inversion of observed data using the TDEM point-dipole model typically produces well-constrained estimates that can subsequently be input into a classification algorithm.

The TEMTADS 2x2 (Figure 1) used for this demonstration is an advanced time domain electromagnetic sensor designed specifically for classification of MEC. The antenna platform includes four transmitter loops and four 3-axis receiver antennas providing 48 independent measurements of the transient secondary magnetic field.

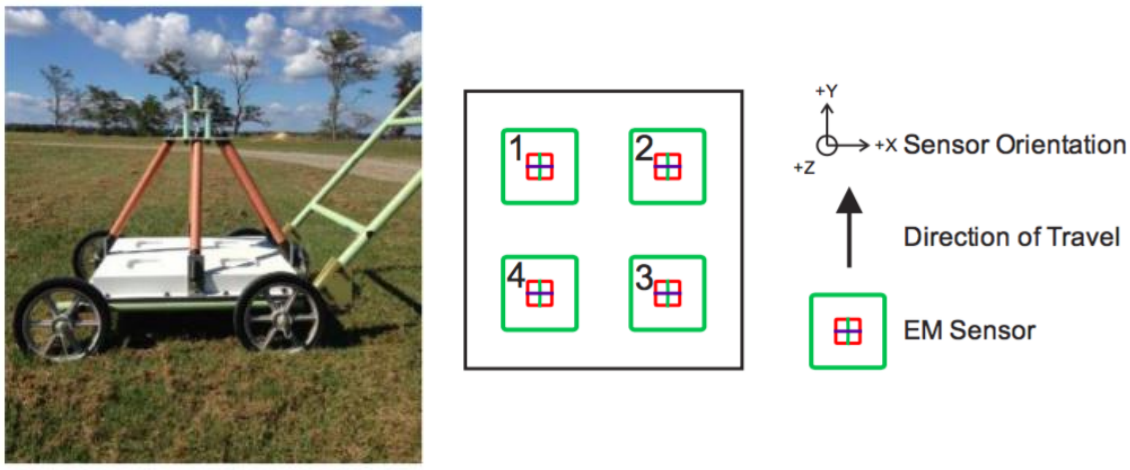


Figure 1. Left: Cued TEMTADS 2x2 array with GPS mount. Right: Sensor geometry showing four transmitters (solid green lines) and concentric 3-axis receivers (red, green, blue lines). Image credits: TEMTADS 2x2 user manual.

2.2 Classification

Target classification is usually carried out 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. In-field inversions of cued soundings help to ensure that the sensor is optimally positioned over each target.

Cued interrogation data are inverted using a dipole model to recover estimates of extrinsic (location, depth, and orientation) and intrinsic (dipole polarizabilities) parameters for each interrogated target. The estimated polarizabilities for each recovered dipole source are then 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 Cued TEMTADS 2x2 Processing

3.1 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. The initial library comprised 398 items with examples of most of the known/suspected munitions type in the SWPG conceptual site model. The library was augmented with polarizabilities based on ground truth from training requests as described below. Each item in the ordnance reference library was assigned a size (diameter) in mm. Each item with a dig decision of "dig" in the submitted dig list was assigned a size category (1 for diameter <50mm; 2 for 50<diameter<=100mm; and 3 for diameter>100mm) based on the ordnance item in the reference library with the best matching primary polarizability (L1).

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; however, in this dataset there no anomalies fell into this category. 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.

The SWPG anomaly list comprised 1950 targets; however 38 of these targets had no data acquired within a distance of 0.4 m. These targets were classified as "cannot extract reliable parameters". Cued data were available for 1912 unique anomalies. Of the 12672 total models (including models from recollects), 11610 were passed and considered in the classification process; 1062 were failed. A total of 36 anomalies were classified as "high likelihood UXO" during QC.

Following the submission of a finalized classification dig list, we received ground truth information to assess performance. We found that, of the 36 anomalies classified as "high likelihood UXO" during our QC process, 25 correspond to TOI. The total number of unique TOI in the TEMTADS 2x2 Cued dataset, excluding shared targets, is 27.

3.2 Classification

3.2.1 Training data selection

Figure 2 shows the distribution of models in decay versus size feature space. The largest concentration of features corresponds to a size that is smaller, and a decay that is faster, than most of the reference features. However, some of the reference features (20mm, small ISO, 37mm) fall in a region of fairly high feature density. This suggests that classification may be challenging due to the similarity in size/decay with a large number of what are most likely scrap items.

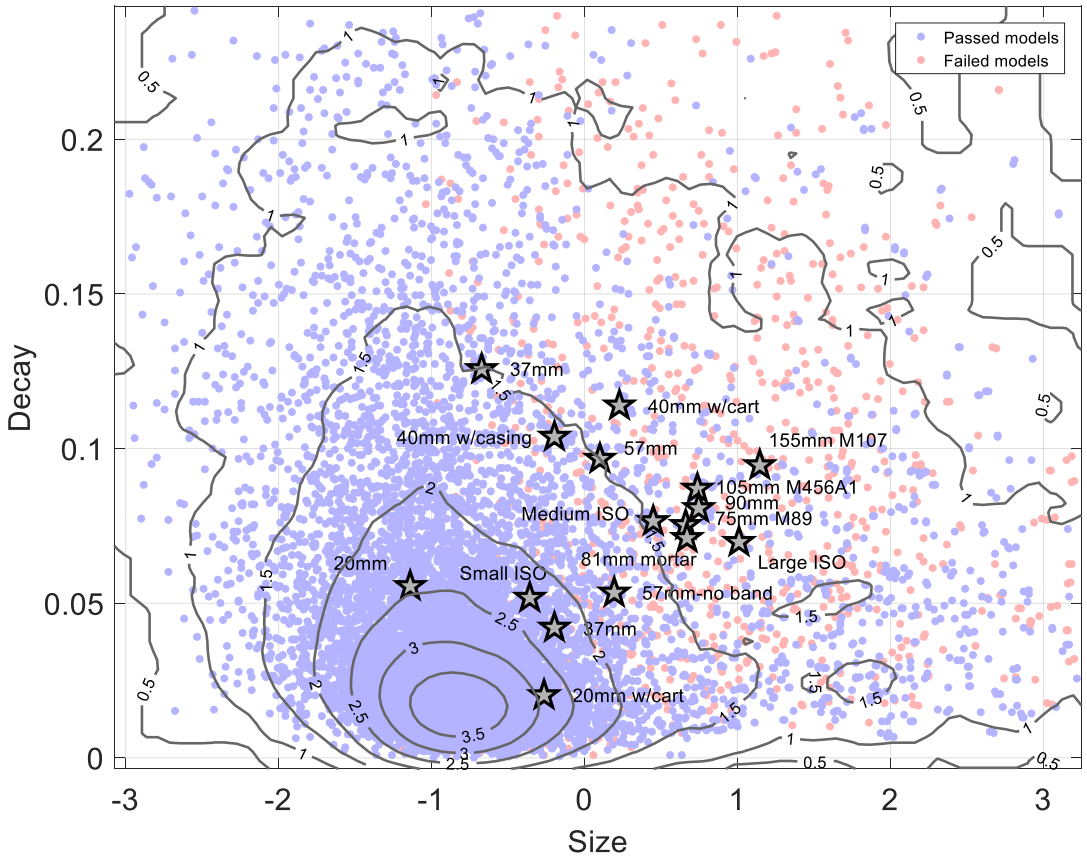


Figure 2. Distribution of models in decay(t4,t56) versus size(t4) feature space, where size(t4) is the total polarizability measured at the 4th time channel (t1=0.136 ms), and decay(t4,t56) is size(t4)/size(t56) where t56=1.977 ms. Some outliers are not shown. Stars represent selected ordnance library reference items ranging in size from 20mm to 155mm. Contours indicate relative density of features.

Our analysis method is based on polarizability matching with respect to ordnance items in a reference library. Our starting reference library included the DOD library and items measured from other projects. While the starting library was large (almost 400 entries), TOI that have not been previously encountered may be present, e.g., different versions or partially intact ordnance. Because of this, it is important to augment the large starting library with measurements of locally occurring TOI, initially through training data requests.

Generally, during visual QC the analyst keeps track of suspicious, UXO-like items (i.e., items with modeled polarizabilities possessing UXO-like properties). Training data for some of these, particularly those with polarizabilities that are somewhat different from the items in the reference library, would be requested. In addition, we used our custom training data selection tool, *General Cluster*, to explore feature space and automatically search for clusters of items with self-similar polarizabilities (Figure 3). Feature vectors with mutual

misfit less than a user-specified threshold define a cluster in polarizability space. This analysis is helpful for identifying 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.

Training data requests typically focus on: (1) items whose polarizabilities exhibit UXO-like properties distinct from those of items in the reference library; (2) items with polarizabilities similar to items in the 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. Figure 4 shows an example cluster from which two training requests were made. Polarizabilities are similar to 20mm reference polarizabilities, but ground truth showed that both correspond to four pieces of small frag.

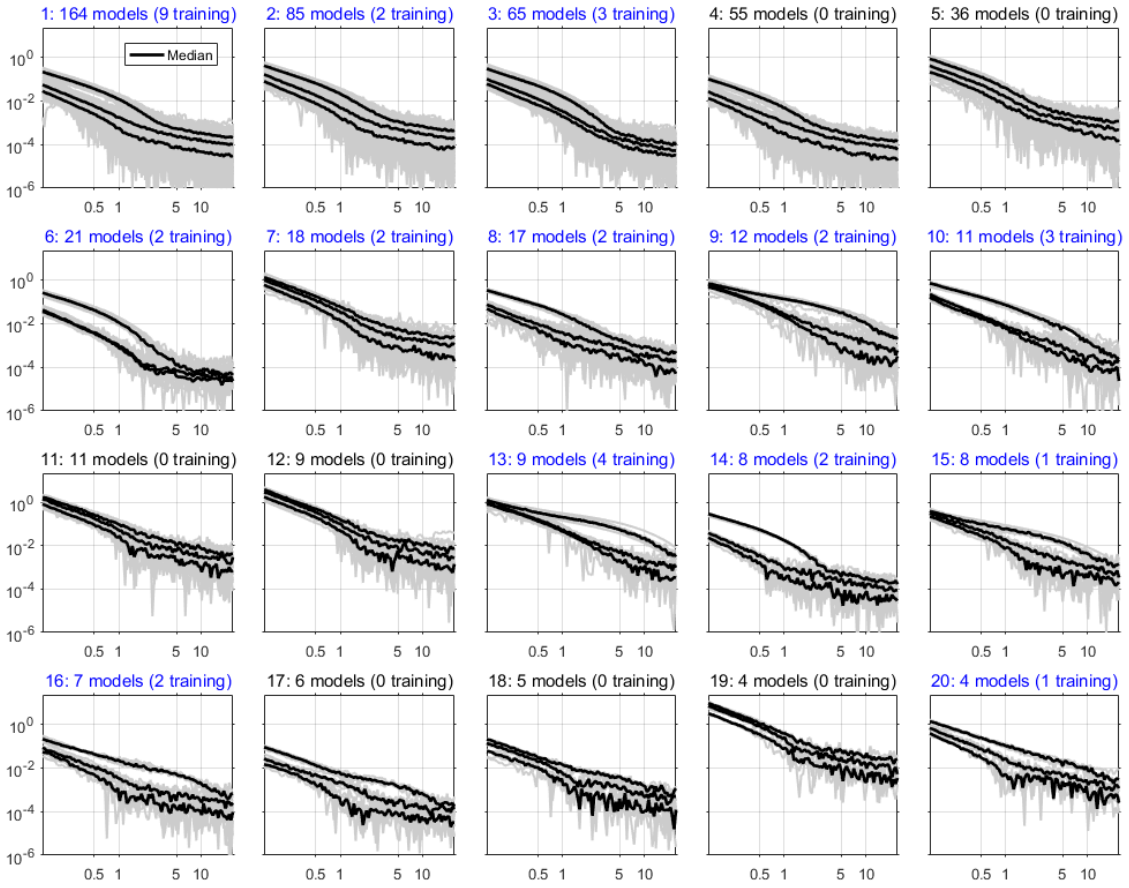


Figure 3. A set of 20 clusters found by *General Cluster*, sorted by number of members in cluster. Grey lines are polarizabilities of all members of a cluster. Black lines are median polarizabilities. Training requests were made for members of clusters with blue titles.

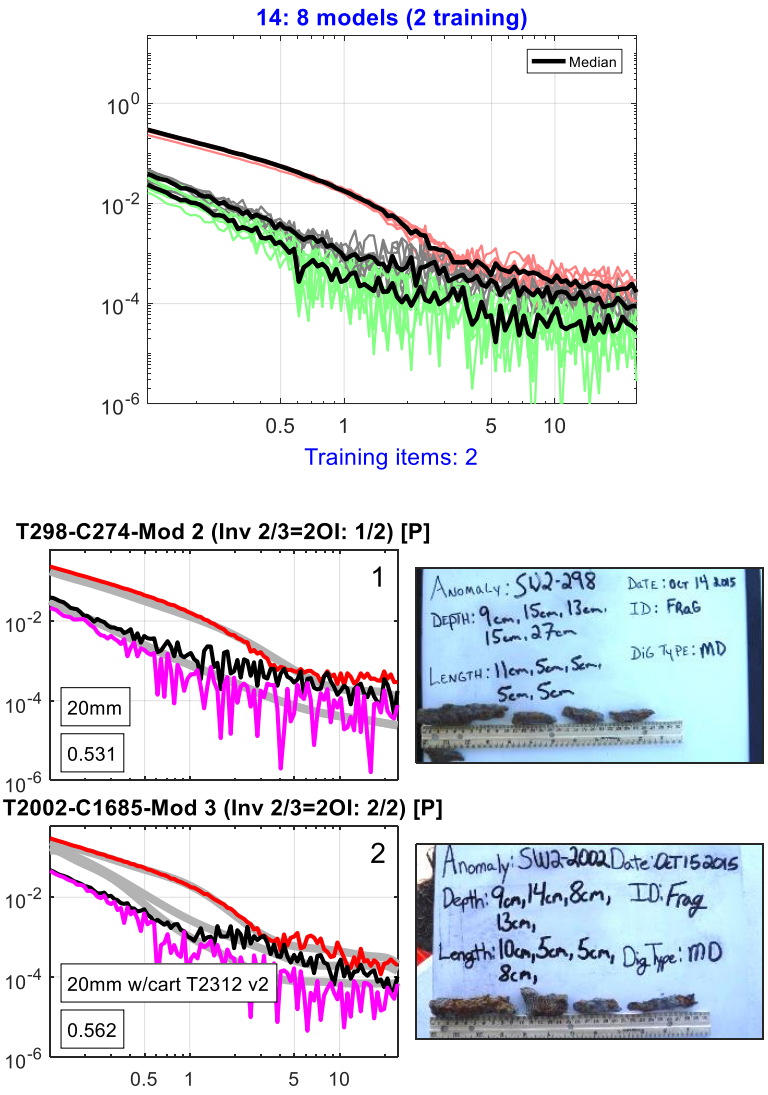


Figure 4. Top: polarizabilities for cluster #14, comprising 8 models. Black lines are median polarizabilities. Middle: Polarizabilities for two items requested as training data plotted against best-fitting reference polarizabilities. Bottom: ground truth photos.

Five training requests were submitted for a total of 44 targets. Of these 11 were TOI Figure 5 comprising six different types of ordnance: 20mm, 37mm, 40mm, 57mm, 75mm, 90mm, plus a small ISO. The remaining 33 training digs were all frag.

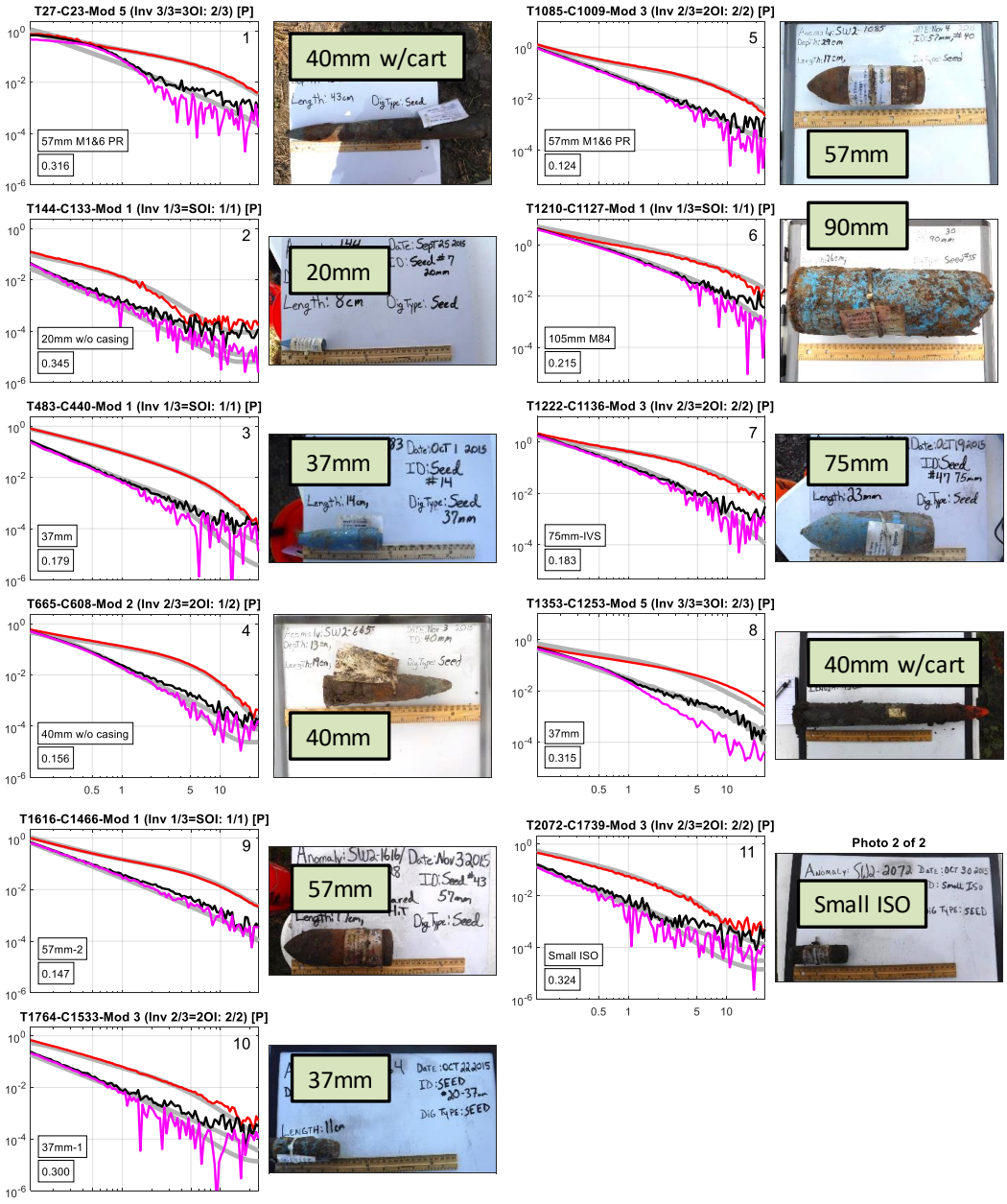


Figure 5. Training requests that were TOI. Eleven of 44 requested items were TOI.

3.2.2 Classification method

Dig lists were developed UXOLab's classification module *DigZilla* (Figure 6), which is integrated with other elements of the *UXOLab* software suite.

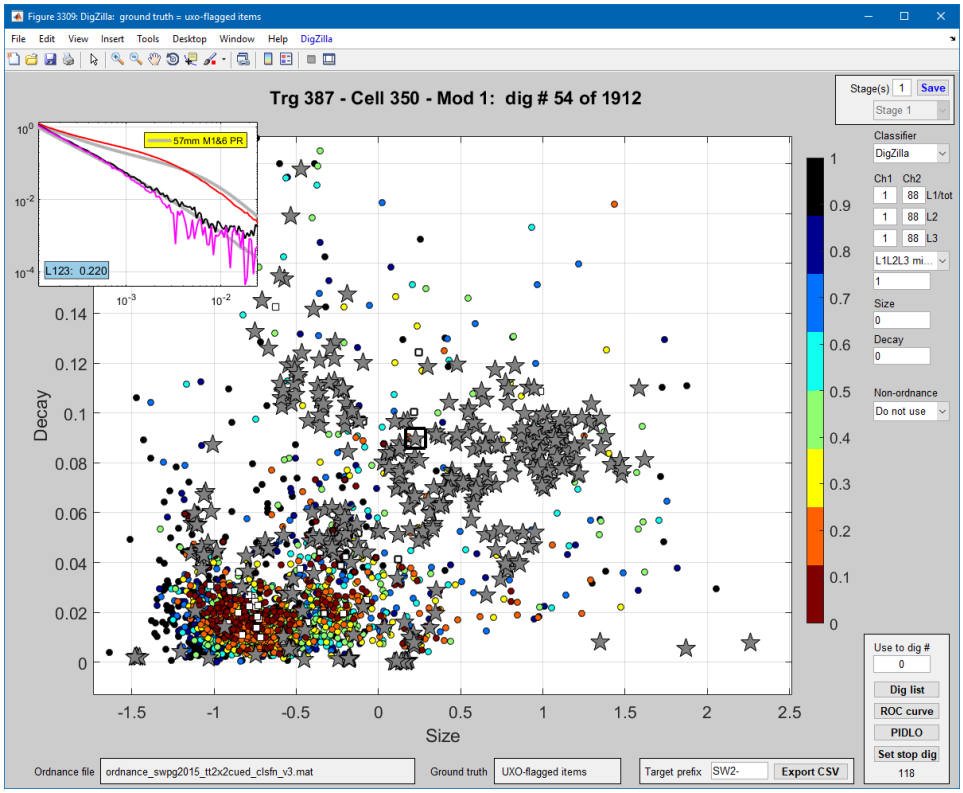


Figure 6. Screen shot of the *UXOLab DigZilla* graphical user interface. Features in the decay versus size feature plot are color coded according to dig list order (red earliest, black latest). White squares are training items. Stars are reference items. Inset polarizabilities at top left are for the currently selected item (black square).

The DigZilla classifier uses polarizability matching to create an ordered dig list. Polarizability misfits with respect to reference items were calculated between the first time channel (0.117 ms) and channels 88 (10.189 ms). The ordnance library used for the initial comprised 417 items. The stop dig point for the stage 1 list was dig number 118 (156 including targets with no data).

The stage 1 dig list missed one QC seeds, resulting in a root-cause analysis (RCA) describing the factors that resulted in the missed seed and procedures taken to ensure that this kind of failure will not occur again. The entire RCA document is included below.

Start of Root Cause Analysis

Root Cause Analysis for missed QC seed at SWPG2

Site: SWPG2 (2015)
Analyst: Black Tusk Geophysics
Data: TT2x2 Cued
Date: March 23, 2017

Our stage 1 dig list missed one QC seed (Table 1 and Figure 7).

Table 1. Missed QC seed information.

Anomaly	Depth (cm)	Identification	Dig Number
SW2-2341	13	20 mm with cartridge	242

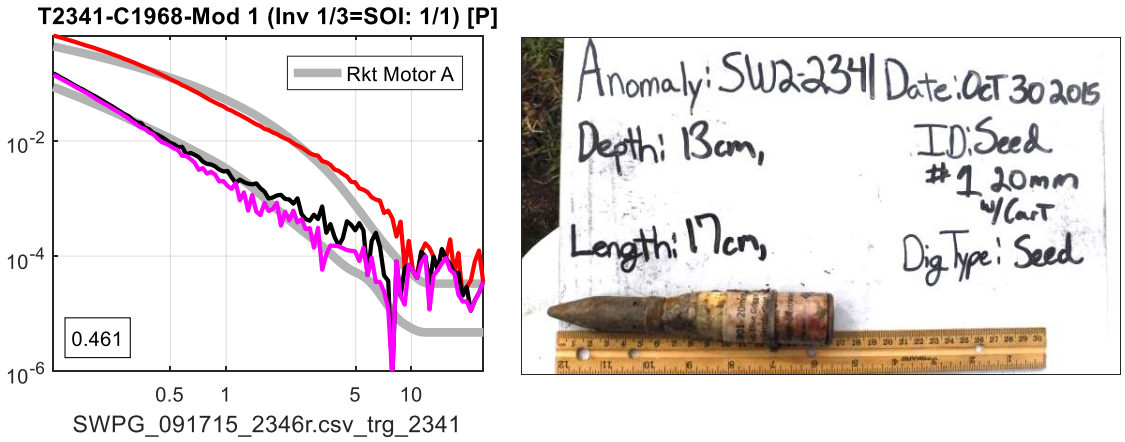


Figure 7. Left: polarizabilities for SW2-2341 (20mm w/cartridge; red, black and magenta lines) relative to polarizabilities for the best fitting reference item in our library (rocket motor; grey lines). Right: ground truth photo of the missed seed.

a. Analysis of the factors that resulted in the misclassification of the missed seed
Our classification method is based on matching polarizabilities with items in an ordnance reference library. The library used for the stage 1 dig list comprised 417 items, including 223 items from the ESTCP TT2x2 24ms library, 94 from the UX-Analyze library, and the remaining items taken from previous ESTCP studies, as well as five items based on training data from this site. Although we used a large library it did not contain an item with polarizabilities sufficiently similar to the missed seed for it to appear earlier on the dig list. As shown in Figure 7, the best matching item is a rocket motor, but the misfit value (0.461) was too large for this item to be classified

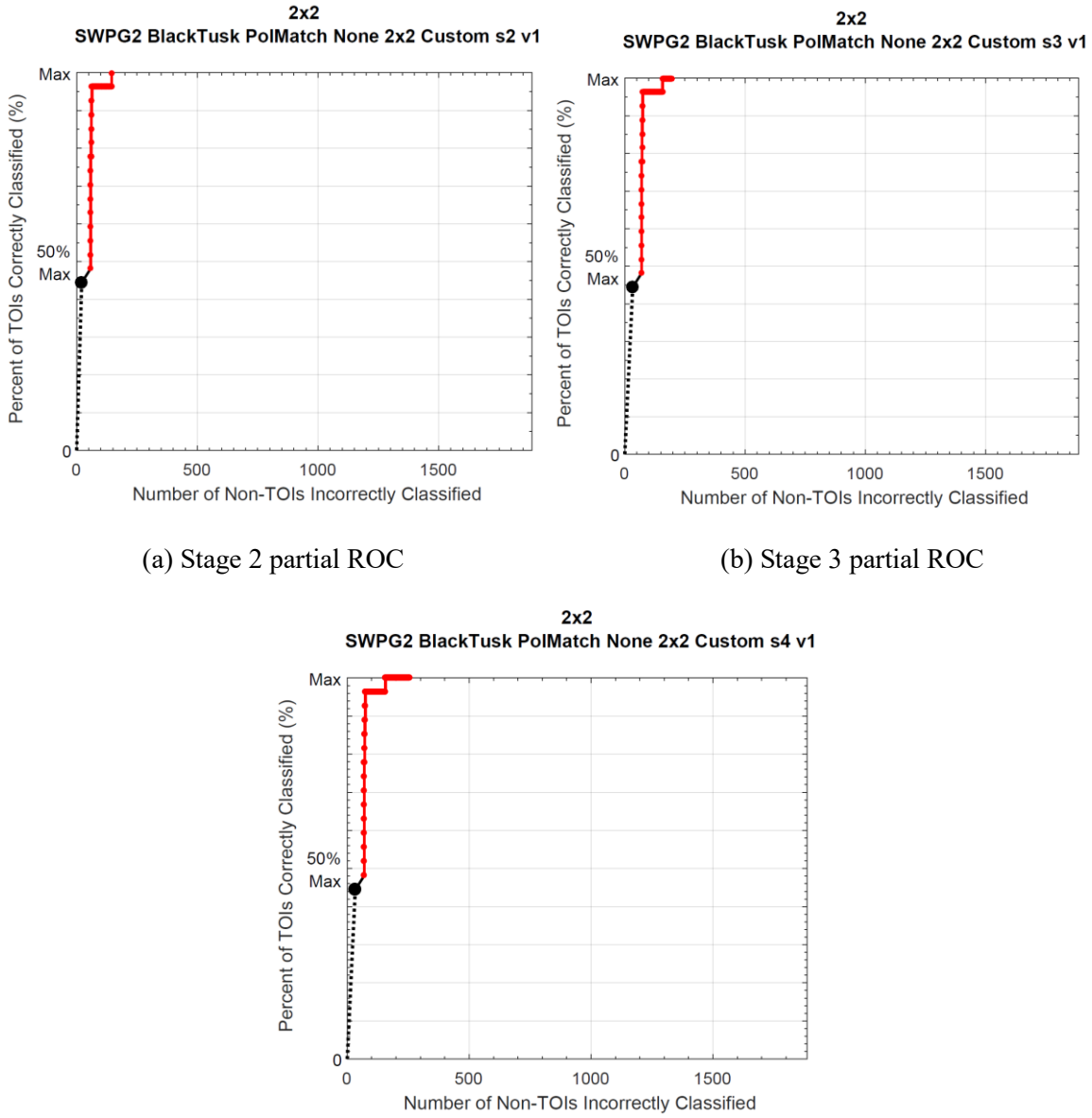
as a dig. In our stage 1 dig list, the stop dig point corresponded to a misfit of 0.425 (i.e., items with misfits less than 0.425 were dug). Additionally, our cluster analysis resulted in 24 clusters, none of which contained target 2341. Therefore, we did not request training data for it based on membership in a cluster. We did however request training data for target SW2-747, which has very similar polarizabilities to the missed seed. Target SW2-747 turned out to be three small pieces of frag.
Summary: the misclassification of this seed was caused by its distinct response relative to items in our large ordnance library.

b. Description of how the analysis procedures have been modified based on the additional information provided
We have created reference polarizabilities based on the missed seed and added these to our reference library. Doing so ensures that items with similar polarizabilities will be dug.

c. Evidence that the modified analysis scheme correctly classifies the missed seeds and can reasonably be expected to correctly classify all remaining TOI.
Adding polarizabilities based on the missed seed to our ordnance reference library ensures that if this item were to be classified (and not treated as a training item) it would occur before our stop dig point (in fact at dig 41, the seventh dig after training digs). The new reference library, augmented with polarizabilities for SW2-2341, also ensures that other items with sufficiently similar polarizabilities will be found.

End of Root Cause Analysis

For the stage 2 dig list, the reference library was augmented with polarizabilities from the missed seed for a total of 418 items. The stop dig point was extended to dig number 136 (174 including targets with no data). The stage 2 partial ROC curve is shown in Figure 8(a). The final dig on this list, target SW2-2312, was a TOI (20mm with cartridge; Figure 9).



(a) Stage 2 partial ROC

(b) Stage 3 partial ROC

(c) Stage 4 partial ROC

Figure 8. Partial ROC curves for different stages. (a) The final dig of stage 2 was a 20 mm TOI was found, which resulted in adding the polarizabilities from that target to the classification library. Classification of remaining anomalies using the modified resulted in no additional TOI (plot (b)). As a QA step, an additional 100 digs were added to the stage 3 list, to form the stage4 list. No additional TOI were found in the stage 4 list, and thus the stage 4 list became the finalized dig list.

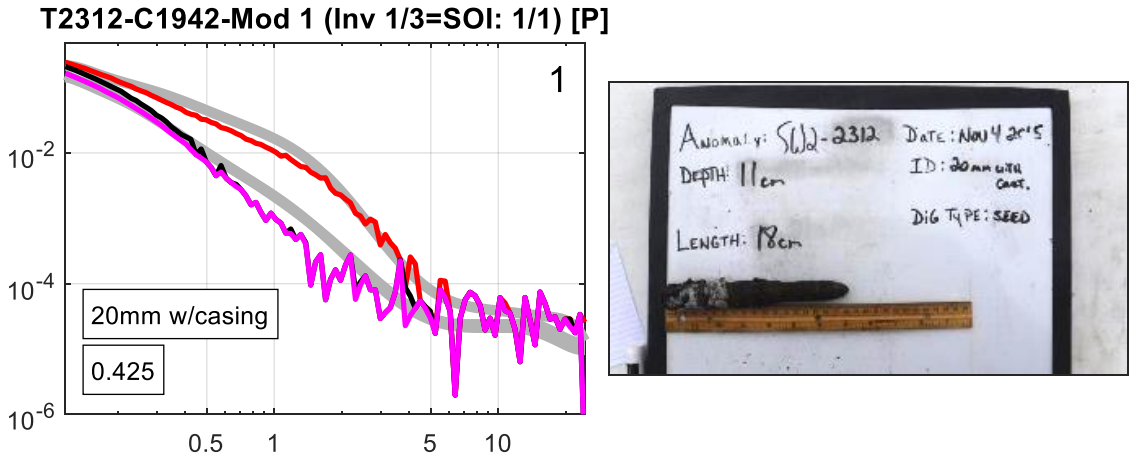


Figure 9. Polarizabilities and ground truth identification of target SW2-2312, the final dig on the stage 2 dig list.

Polarizabilities for SW2-2312 were added the reference library. A search of the dataset revealed only one good match (target 497) to the target SW2-2312 polarizabilities. Training data were requested for this single item which proved to be frag. A stage 3 dig list was created with a stop dig point of 186 (224 including targets with no data). Polarizability matching for the new digs on this list used a reduced set of time channels: 60/42/34 = 2.426/0.967/0.643 ms for the primary, secondary and tertiary polarizabilities, respectively. The shorter window is a conservative measure to ensure that any models with a good match over the shorter range will get dug. The stage 3 dig list found no new TOI (Figure 8(b)).

The stage 3 list was effectively the last list; however, as a quality assurance (QA) check, a stage 4 dig list was submitted with a stop dig point of 248 (286 including targets with no data, Figure 8(c)). This list provides 100 digs beyond the final TOI on the list (target SW2-2312; dig 148). With no additional TOI found, the list was finalized.

The program office did not score the finalized dig list. Instead, the program office provided a file with ground truth (SWPG_Intrusive_Data_6_6_16.xls) such that we could be able to score the dig list. For the TEMTADS 2x2 set of anomalies, there were 27 TOI. All of the TOI were seeded targets, including 20 mm (with and without cartridge), 37 mm, 40 mm, 57 mm, 75 mm, 90 mm, and small ISO.

The final ROC curve is shown in Figure 10, with the final stop dig point indicated by the red dot. All TOI were found before the stop dig point. We dug 248 of 1950 targets (12.7%) and left 1702 items in the ground (87.3%).

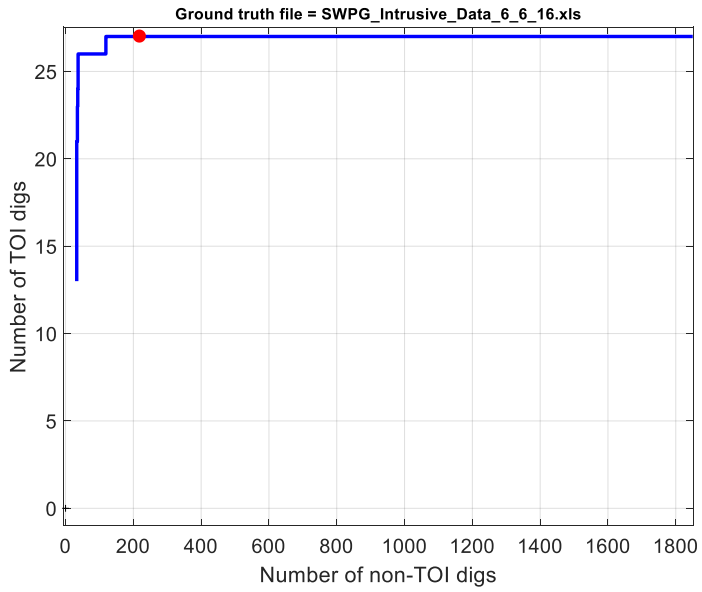


Figure 10. Final scoring for SWPG2. The red dot is stop dig point. No TOI were found after the stop dig point.

4 Conclusions

Processing of TEMTADS 2x2 data collected at the Southwest Proving Grounds presented no significant challenges for library matching-based classification. The greatest potential challenge was the variability in 20 mm projectile polarizabilities at the site, and the possibility that the range of 20 mm polarizabilities would not be sufficiently represented in the classification library.

Our initial polarizability classification library combined the DOD ordnance library developed by ESTCP, a library from UX-Analyze, and a library developed by BTG from previous ESTCP projects. The classification library was augmented by polarizabilities from TOI identified in the training data stage. In addition, a pair of 20 mm projectiles with cartridge found during the classification process were added to the library, since their polarizabilities were sufficiently different from 20 mm projectiles already in the library.

All TOI were found in the stage 1 and 2 dig lists. A stage 3 dig list was developed that used a classification library that included polarizabilities of a 20 mm projectile with cartridge found in the stage 2 list. When no TOI were found in the additional stage 3 digs, a stage 4 list that added 100 QA digs was submitted. The stage 4 list represents the final dig list.

All TOI were detected before the stop dig point. We dug 248 of 1950 targets (12.7%) and left 1702 items in the ground (87.3%).