DEMONSTRATION REPORT

Dipole Discrimination Techniques Applied to Live Sites

MetalMapper Classification
Southwest Proving Ground, Arkansas

ESTCP Project MR-201226

MARCH 2018

Leonard Pasion
Black Tusk Geophysics

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14. ABSTRACT
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.

The SWPG RF-15 site is a relatively flat, open area that is ideal for the deployment of towed advanced detection systems. A vehicular mounted MetalMapper sensor was used to create a digital map of the site (Steigerwalt, 2015). From these data, a set of locations for cued MetalMapper measurements were chosen. The ESTCP program office distributed a MetalMapper cued list and dataset that included 1398 anomalies. This report summarizes the processing carried out by Black Tusk Geophysics (BTG) on MetalMapper cued data.

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Executive Summary

This report describes advanced classification processing of cued MetalMapper data collected at the Southwestern Proving Ground (SWPG), Arkansas. The advanced electromagnetic induction data were acquired by Weston Solutions, Inc in May 2013. Black Tusk Geophysics processed 1398 cued interrogation anomalies to recover estimates of intrinsic dipole polarizabilities for detected sources. Quality Control (QC) of inversion results flagged high- likelihood targets of interest (TOI) anomalies and failed bad models and inversions. Twenty-three anomalies were flagged as "high likelihood UXO" during QC; 17 of these correspond to actual TOI. The total number of unique TOI in the MetalMapper Cued dataset is 17 i.e., all TOI were flagged as high-likelihood TOI during QC.

The estimated polarizabilities were used to identify potential novel TOI at the site, via cluster analysis and comparison with a comprehensive polarizabilities library. Of the 25 anomalies that made up two training data requests, two were TOI. Based on training data and fits to the comprehensive library, a site-specific library was created for classification. The classification approach used polarizability matching with a site-specific library to generate a prioritized dig list. The location of the library items relative to the majority of targets in the decay-amplitude feature space, suggested the SWPG site had limited overlap between TOI and non-TOI items. Separation between TOI and non-TOI suggested that the classification problem might be straightforward. Following the stage 1 dig list, six additional "QC" or "analyst" digs were made to form the stage 2 dig list. These digs represent anomalies beyond the stage 1 stop dig point that appeared TOI-like but whose polarizability fit metric was not high enough to be labelled as "dig". When none of these 6 digs were revealed to be TOI, we requested an additional 6 digs for targets that had fuse-like characteristics. The six additional digs formed a stage 3 dig list, with the additional digs being all frag. The final partial (stage 3) receiver operating characteristic (ROC) curve was fit to a binormal model, to estimate the posterior probability that each target is a TOI. This test suggested that at the 99% confidence level, all TOI had been dug. Therefore, the stage 3 list was designated as our final dig list.

In March 2014, our final dig list was submitted to the program office by the Institute for Defense Analysis (IDA). For the final scoring set of targets, IDA excluded 41 anomalies from the initial set of anomalies, leaving 1357 anomalies in the final list to be scored. The IDA scoring showed that our final dig list found the 17 TOI before the stop dig point at dig number 62; resulting in a False Alarm Rate (FAR) of 3.65 digs per TOI dug. The last TOI was found with dig number 52.

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Acronyms

cm	Centimeter
CSV	Comma Separated Variable
EMI	Electromagnetic Induction
ESTCP	Environmental Security Technology Certification Program
FAR	False Alarm Rate
FUDS	Formerly Used Defense Site
IDA	Institute for Defense Analysis
ISO	Industry Standard Objects
m	Meter
mm	Millimeter
ms	Millisecond
MEC	Munitions and Explosives of Concern
QC	Quality Control
ROC	Receiver Operating Characteristic
RF	Recovery Field
s	Second
TOI	Target of Interest
SWPG	Southwestern Proving Grounds
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.

The SWPG RF-15 site is a relatively flat, open area that is ideal for the deployment of towed advanced detection systems. A vehicular mounted MetalMapper sensor was used to create a digital map of the site (Steigerwalt, 2015). From these data, a set of locations for cued MetalMapper measurements were chosen. The ESTCP program office distributed a MetalMapper cued list and dataset that included 1398 anomalies. This report summarizes the processing carried out by Black Tusk Geophysics (BTG) on MetalMapper cued data.

2 Technology description

2.1 MetalMapper Electromagnetic Induction Sensor

The MetalMapper is a next generation electromagnetic induction (EMI) sensor designed for classification of buried unexploded ordnance (UXO) (Prouty et al., 2011). Three orthogonal transmitter coils provide diverse excitation of buried conductive targets (Figure 1). Seven receiver "cubes" each measure orthogonal components of the induced secondary magnetic field.

The MetalMapper can be deployed for detection surveys that map metallic targets at a site. In this study, the sensor was used for cued interrogations where the array was positioned over targets identified in a previous detection survey and EMI data were collected for classification. When deployed in a static, cued interrogation mode, the MetalMapper records the decay of the secondary field of targets in the time domain up to 7.9 ms.

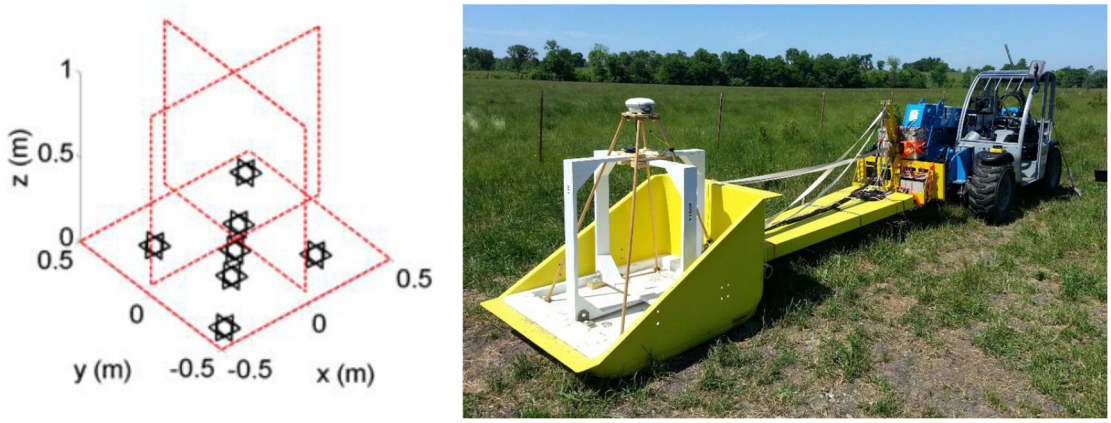


Figure 1. *Left*: MetalMapper sensor geometry. Red dashed lines indicate the three transmitter coils and solid black lines are the 7 3-component, receiver cubes. *Right*: MetalMapper setup for cued collection at SWPG. Image from "*Technical Report: ESTCP Munitions Response Live Site Demonstrations – Former Southwestern Proving Ground, Arkansas, ESTCP Project MR-201231*." (Steigerwalt, 2015).

2.2 Classification

For the processing in this report, target classification was 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 MetalMapper 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. The processing workflows implemented in UXOLab include algorithms developed in previous SERDP (e.g. MR-1637, MR-2226) and ESTCP (e.g. MR-2010004, MR-201226) funded research projects.

3 Cued MetalMapper Processing

3.1 Feature extraction

MetalMapper cued data for all anomalies were received as a set of raw CSV files for both the cued anomaly data and the background measurements. All CSV files were imported into UXOLab. 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 14 cm. Noise standard deviation estimates were not available, so a constant noise value of 1 over all time channels was used. Target location was constrained to lie between ±0.7 m in both X and Y directions relative to the picked location. Target depth was constrained to lie between –1.2 and 0 m. The initial optimization for target location identified up to eight 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. This results in 6 models for each cued measurement.

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 for various ordnance items initially derived from an extensive suite of test pit measurements. The SWPG test pit contained 37mm, 40mm, 57mm, 60mm, 75mm, 81mm, 90mm, 105mm, small and large industry standard objects (ISO), with measurements taken at various depths and orientations. As the analysis proceeded, the library of reference items was augmented with additional items based on ground truth obtained through training data requests and partial ground truth. 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; and (2) 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., the data misfits are large), or when the recovered model location(s) were on, or near, an inversion boundary. Bad models and inversions were identified in a semi-automated manner, e.g. models would be sorted by different measures of polarizability/data quality and the visual QC process would focus on the models with the poorest quality. A number of typical metrics considered during the QC analysis are listed in Beran and Zelt (2015).

With multi-source inversions, it is not uncommon that one of the models is unrealistic (e.g., deep, large in magnitude, sometimes located on or near a horizontal inversion boundary) yet provides the best fit to the reference polarizabilities (e.g., Figure 2). In these cases the model was flagged as failed. Models flagged as failed were not used in the classification process. Anomalies with all models from all inversions failed were classified as "cannot extract reliable parameters"; these anomalies were 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.

The SWPG MetalMapper Cued dataset comprised 1398 unique anomalies. Of the 8388 total models (i.e. 6 models per anomaly), 7256 were passed and used in the classification process; 1132 were failed. Six anomalies were classified as "cannot extract reliable parameters" due to poor data fits. Final ground truth revealed that all were either frag or no contact. Twenty-three anomalies were flagged as "high likelihood UXO" during QC; 17 of these (74%) correspond to actual TOI. The total number of unique TOI in the MetalMapper Cued dataset is 17 i.e., all TOI were flagged as high-likelihood TOI during QC.

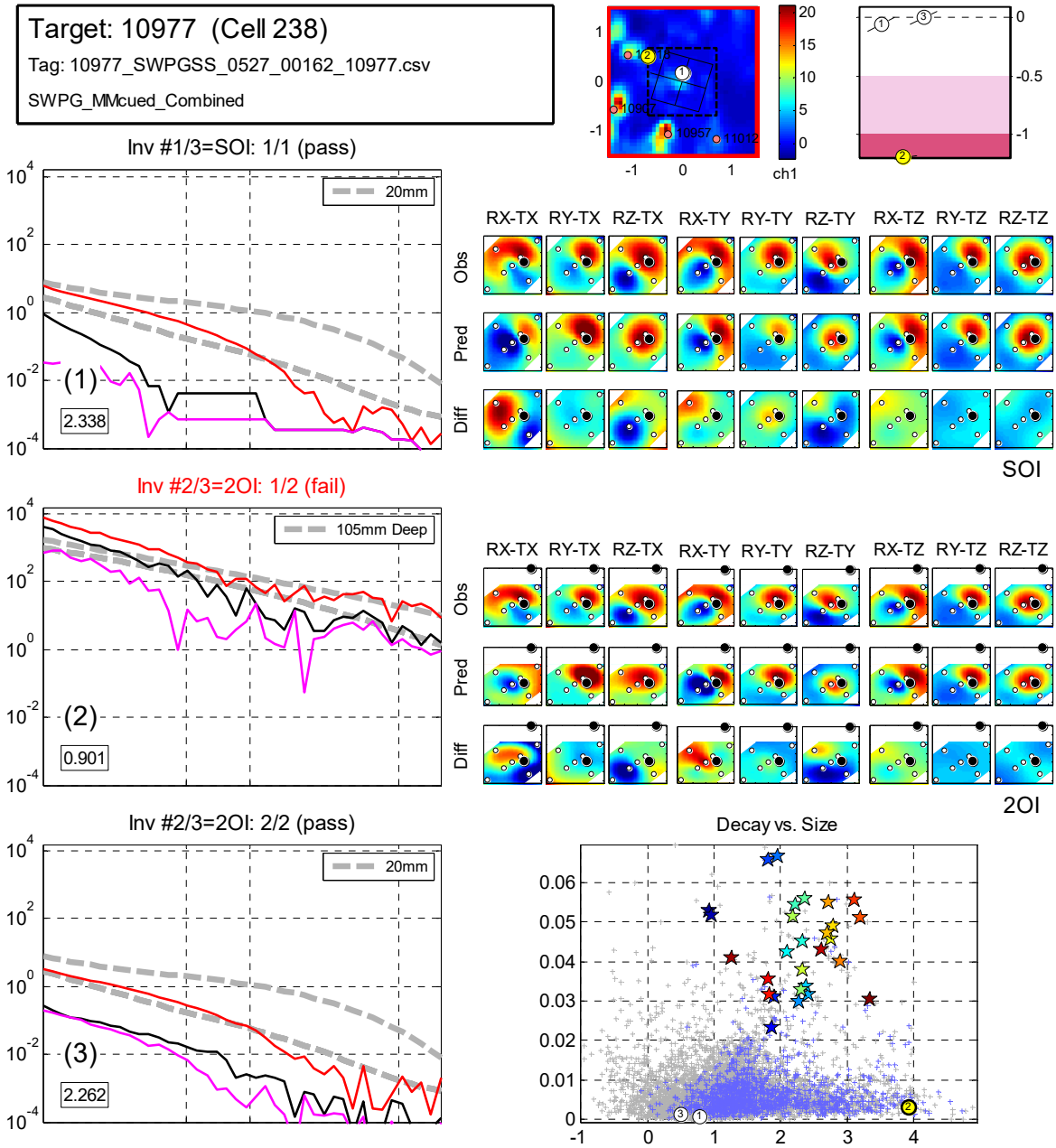


Figure 2. Example of an unrealistic two source inversion model (anomaly 10977; frag?). The first model of the two source inversion (2OI, model 2) provides the best fit (i.e., minimum misfit) to the reference polarizabilities (misfit = 0.901), but the predicted depth of 1.2 m and location beyond the edge of the instrument (i.e., at the vertical and horizontal inversion boundaries), and high amplitude and jittery appearance of the polarizabilities are classic signs that this model is an artifact of the multi-object inversion process. Accordingly, this model was failed during QC. Polarizabilities for single source inversion (SOI) and two source inversion (2OI) are shown at left. Modeled target locations (X-Y and Z) are shown at the top right (gridded EM61 data is displayed behind the X-Y plot). Gridded observed, predicted and residual data for single source and two source inversions are shown below location maps. Decay versus size feature plot is shown in bottom right. Dots are test data; stars are reference items. Numbered circles are models for this anomaly.

3.2 Classification

3.2.1 Training data selection

Figure 3 shows the distribution of models in decay versus size feature space. The separation between the features for reference items and the majority of dataset features suggests, without further information, that the classification difficulty level should not be high for SWPG.

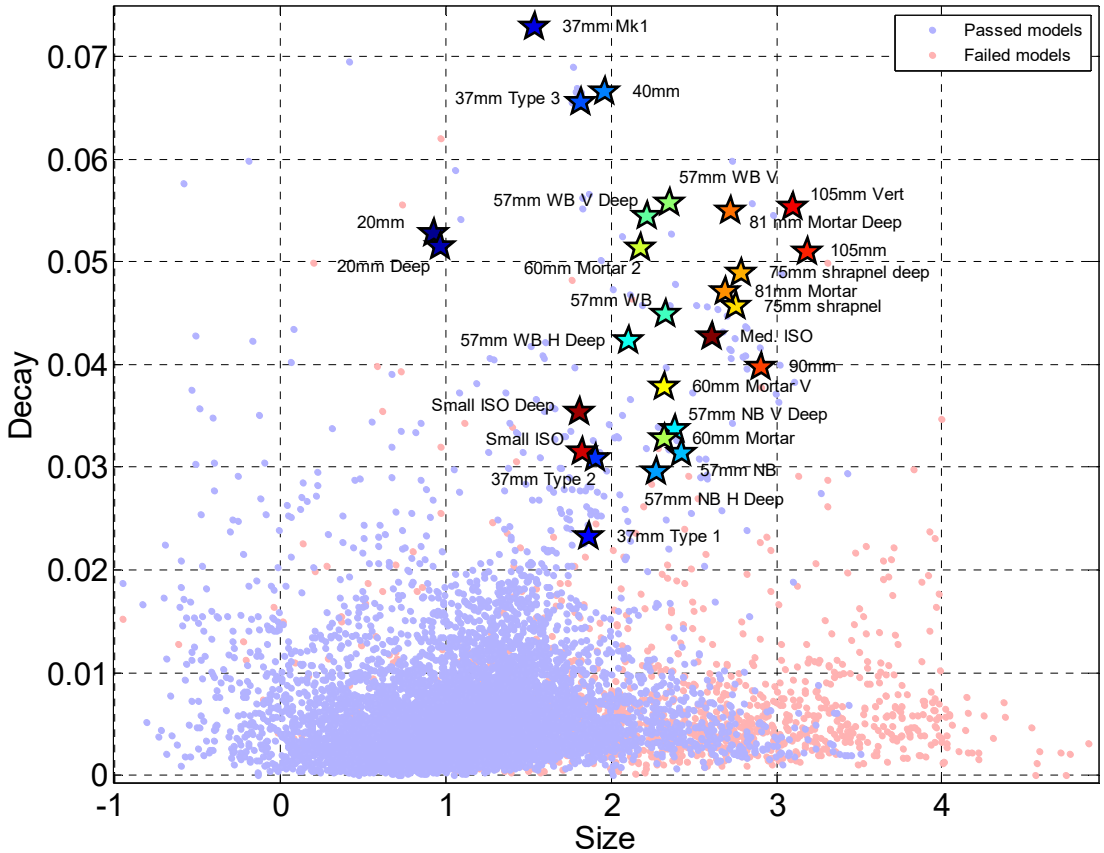


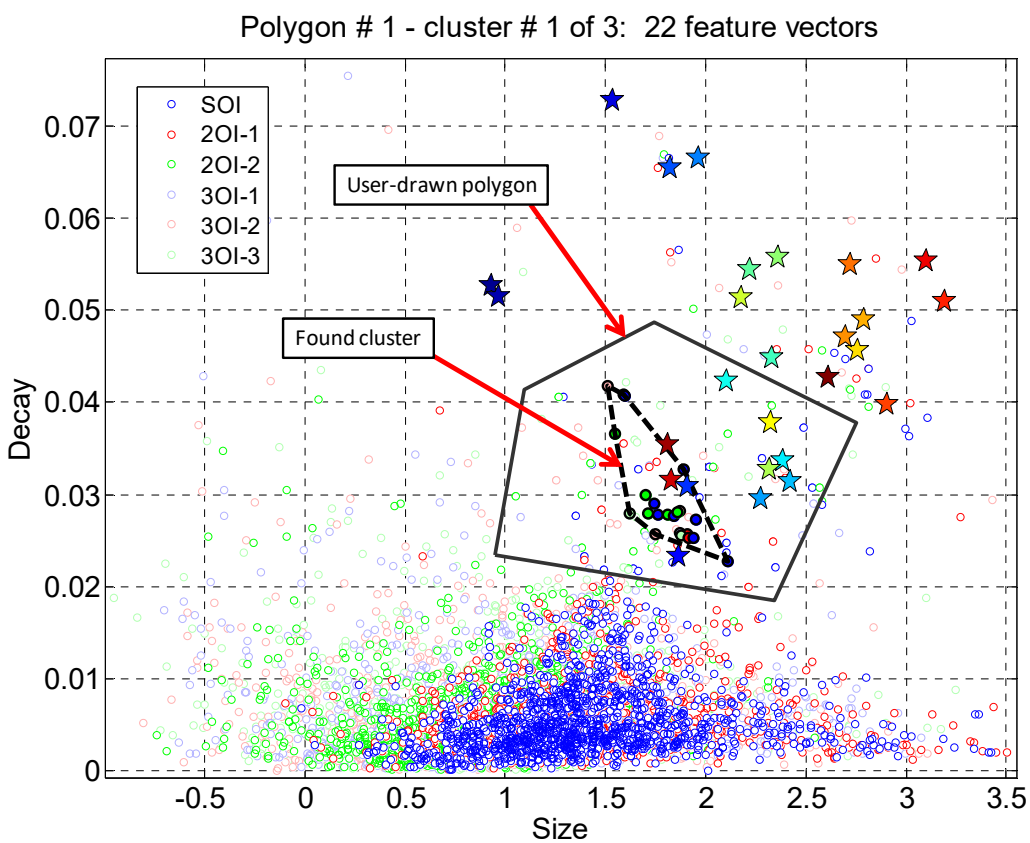
Figure 3. Distribution of models in Decay versus Size feature space. In this plot we define Size as the base 10 logarithm of the total polarizability measured at the first time channel (t1=0.106 ms). We define the Decay as size(t29)/size(t1) where t29=3.006 ms. A few outliers are not shown. Labeled stars represent ordnance library reference items based on test pit measurements.

Our analysis method is based on polarizability matching with respect to ordnance items in a reference library. For this approach to be successful it is important to determine the types of ordnance present at the site. 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 different from the

items in the reference library, would be requested. 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 jth 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. A basic example of the use of *TrainZilla* is shown in Figure 4 and Figure 5.



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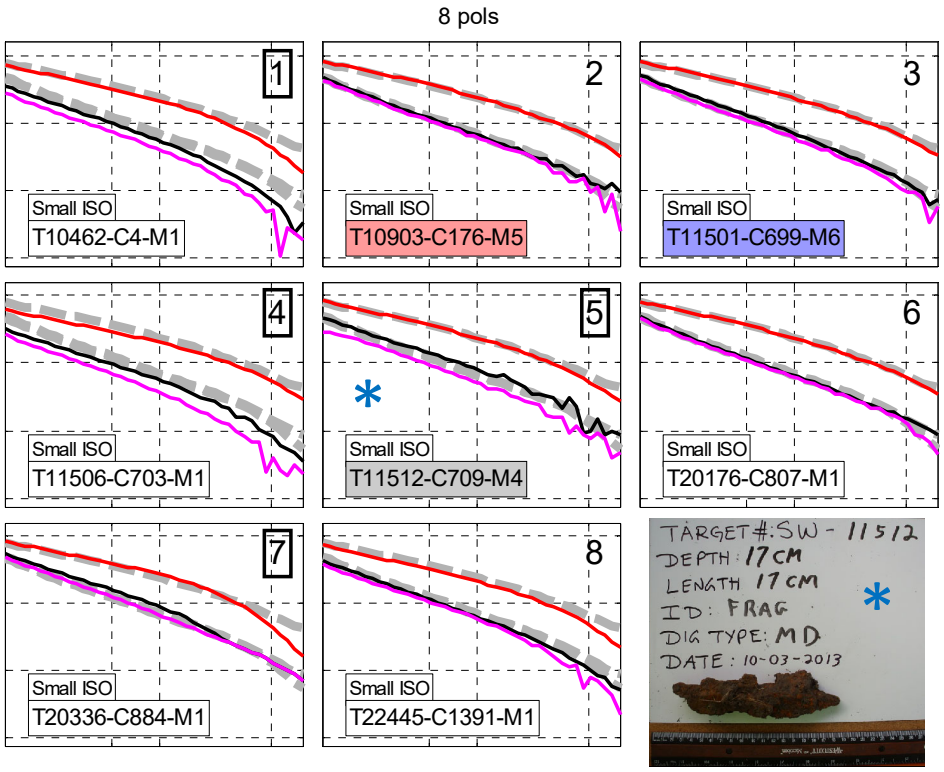


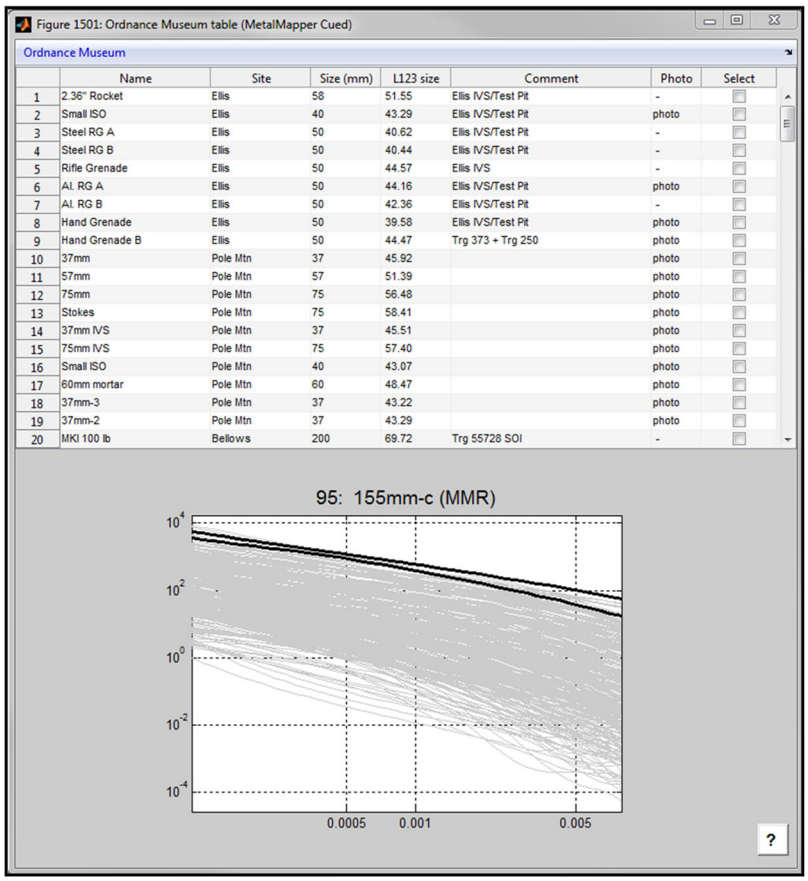
Figure 5. Polarizabilities for some of the models in the cluster shown in Figure 4. Colored lines are predicted polarizabilities. Broken grey lines are best fitting reference polarizabilities. Training data were requested for four items (black box around index number); all of these were non-TOI. The inset photo shows the ground truth for SW-11512 (index number 5) – an approximately ISO-sized piece of frag.

Our training data requests typically focused on: (1) items whose polarizabilities exhibited 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; and (3) one-off items.

An alternative approach to selecting training data, geared primarily to finding potential one-off items, is to look for items with polarizabilities that closely match items in a large ordnance library. We do this with the UXOLab module called the Ordnance Museum (Figure 6), which – at the time of processing these SWPG data – comprised of polarizabilities for approximately 170 items (ranging in size from 20mm to 155mm) from past ESTCP live site demonstrations and other classification projects (Note: that the SWPG MetalMapper cued data were processed prior to the creation of the Munitions Classification Library developed in ESTCP Project MR-201424 (Khadr et al., 2016)). With the Ordnance Museum, we can easily search for models in our dataset with similar polarizabilities to any of the museum items. For SWPG we found several items with close matches (polarizability

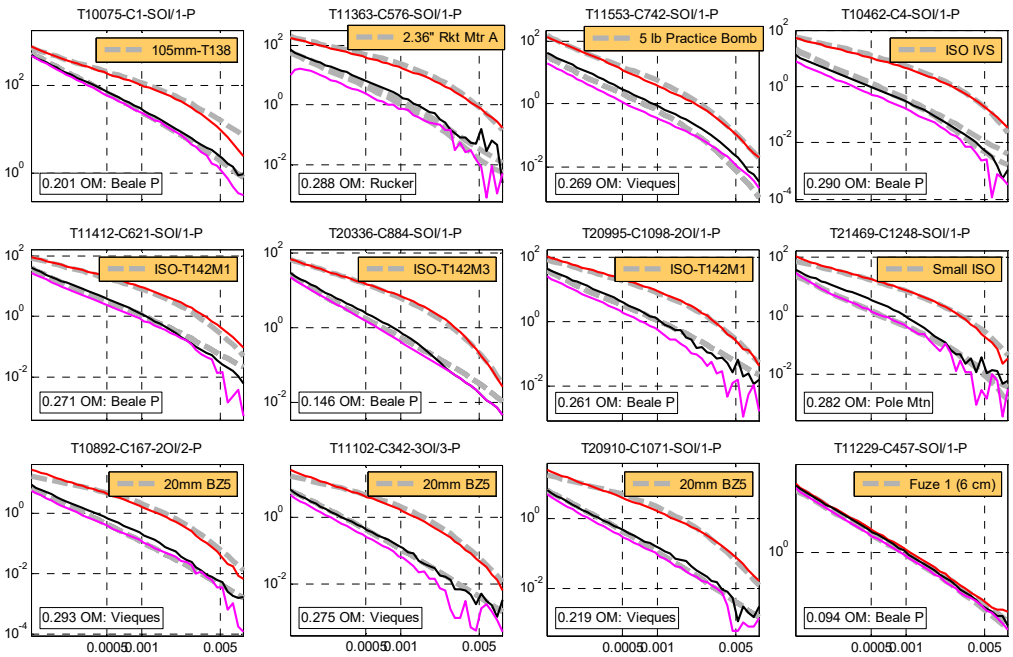
misfit < 0.3 calculated using all three polarizabilities) to Ordnance Museum items. Twelve representative items are shown in Figure 7. We requested training data for all of these items; all were non-TOI.

We submitted two training requests prior to submitting our first dig list for a total of 25 items. The first training request consisted of 22 targets, resulting in only two TOI: SW-10710 (20mm) and SW-1175 (105mm) (Figure 8). One item (SW-11229) was an M43 Fuze (Figure 7; bottom right panel), but this was considered a non-TOI. A second training request consisted of 3 targets, all of which were non-TOI.



	Name	Site	Size (mm)	L123 size	Comment	Photo	Select
1	2.36" Rocket	Ellis	58	51.55	Ellis IVS/Test Pit	-	
2	Small ISO	Ellis	40	43.29	Ellis IVS/Test Pit	photo	
3	Steel RG A	Ellis	50	40.62	Ellis IVS/Test Pit	-	
4	Steel RG B	Ellis	50	40.44	Ellis IVS/Test Pit	-	
5	Rifle Grenade	Ellis	50	44.57	Ellis IVS	-	
6	Al. RG A	Ellis	50	44.16	Ellis IVS/Test Pit	photo	
7	Al. RG B	Ellis	50	42.36	Ellis IVS/Test Pit	-	
8	Hand Grenade	Ellis	50	39.58	Ellis IVS/Test Pit	photo	
9	Hand Grenade B	Ellis	50	44.47	Trg 373 + Trg 250	photo	
10	37mm	Pole Mtn	37	45.92		photo	
11	57mm	Pole Mtn	57	51.39		photo	
12	75mm	Pole Mtn	75	56.48		photo	
13	Stokes	Pole Mtn	75	58.41		photo	
14	37mm IVS	Pole Mtn	37	45.51		photo	
15	75mm IVS	Pole Mtn	75	57.40		photo	
16	Small ISO	Pole Mtn	40	43.07		photo	
17	60mm mortar	Pole Mtn	60	48.47		photo	
18	37mm-3	Pole Mtn	37	43.22		photo	
19	37mm-2	Pole Mtn	37	43.29		photo	
20	MKI 100 lb	Bellows	200	69.72	Trg 55728 SOI	-	

Figure 6. UXOLab Ordnance Museum interface. This is a large library of reference polarizabilities compiled from several ESTCP live site demonstrations, and other projects. The ordnance museum for MetalMapper Cued data currently comprises approximately 170 items ranging in size from 20mm to 155mm projectiles.



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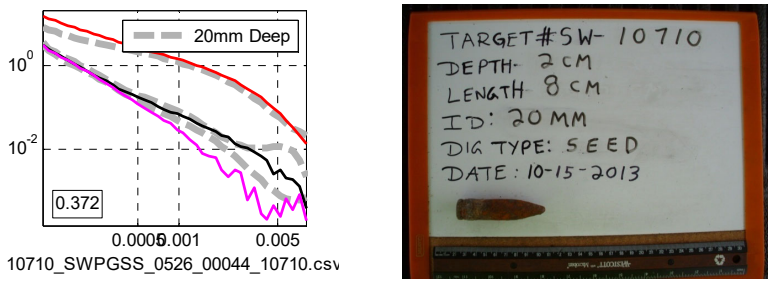
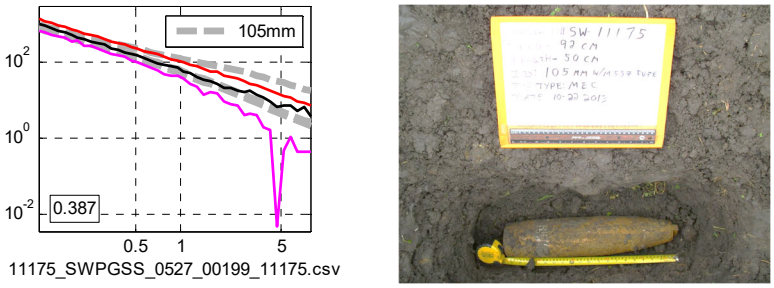


(a) Target 10710: 20 mm seed



(b) Target 11175: 105 mm with M557 fuze.

Figure 8. TOI from the first training data request.

Based on the results from training data process, we eliminated several items from our initial ordnance reference library. For example, a search of the data set suggested that there were no additional 105 mm projectiles within the data, and it was therefore removed from the dataset. The resulting ordnance library used for classification is shown in Figure 9.

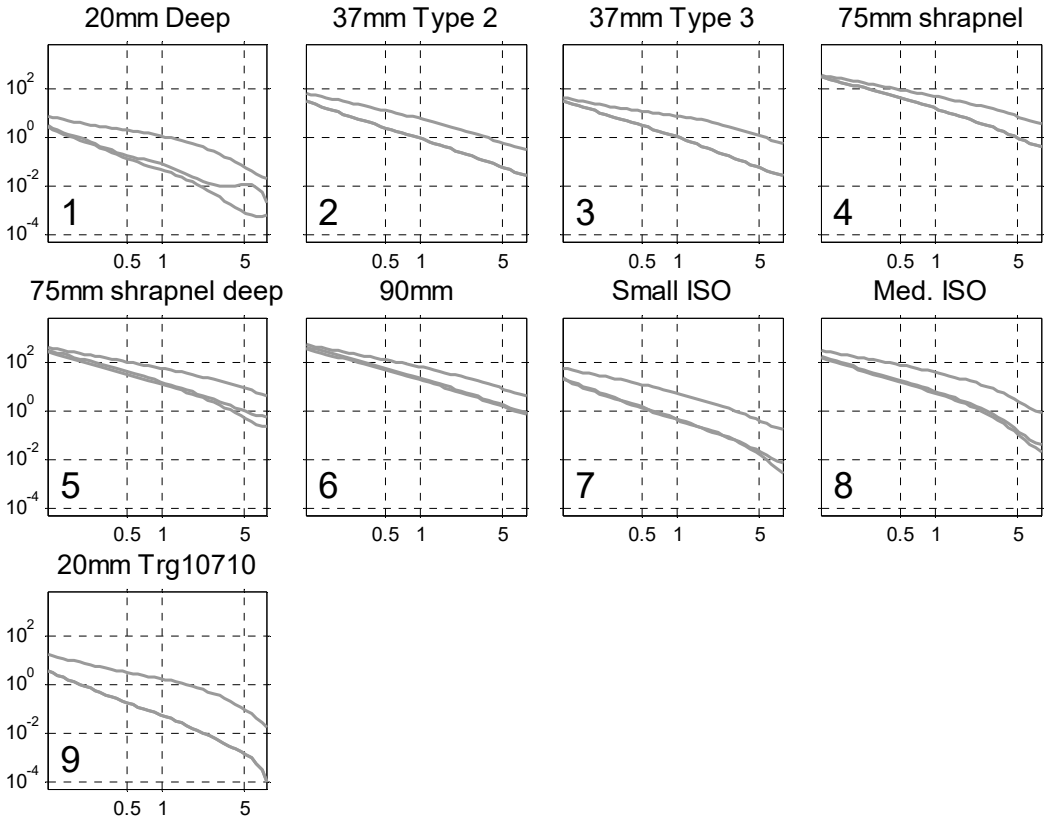


Figure 9. Items in the ordnance reference library used for the stage 1 dig list.

3.2.2 Classification method

Our dig lists were developed using our visual classification software *DigZilla* (Figure 10), which is fully integrated with other elements of the UXOLab software suite. *DigZilla* allows for the creation of multi-stage dig lists with minimal effort, and supports a number of classifiers.

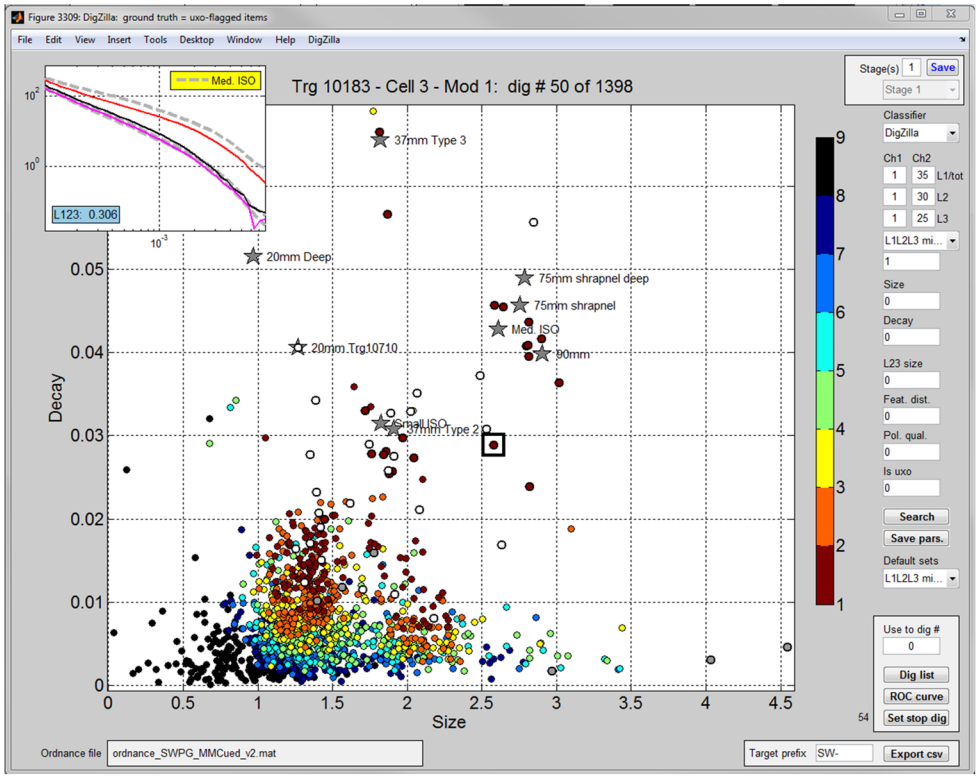
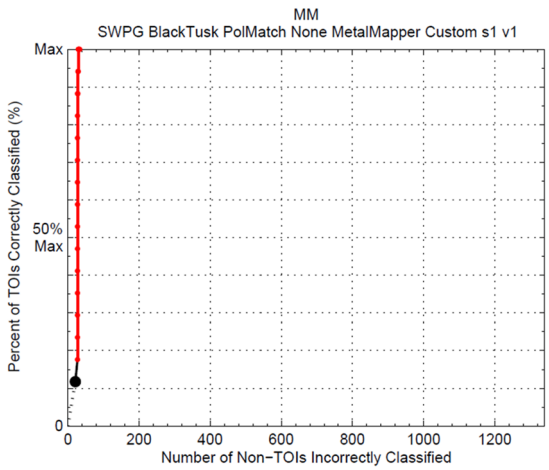


Figure 10. Screen shot of the UXOLab *DigZilla* graphical user interface. Features in the decay versus size feature plot are color coded according to dig list order (red earliest; black latest).

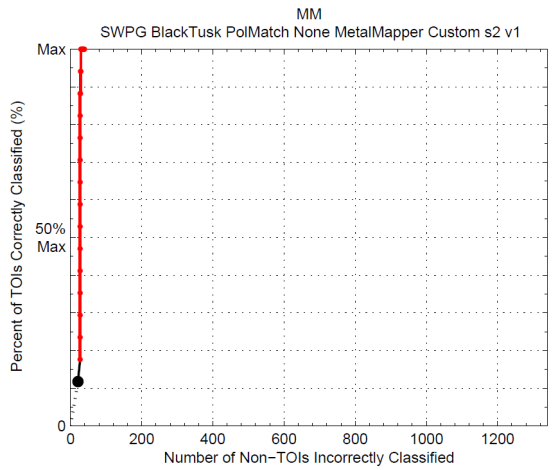
Our initial (stage 1) dig list classified based on polarizability misfit (to best fitting library reference item for each model) using all three polarizabilities. For this stage, and all subsequent stages, misfits for the primary, secondary and tertiary polarizability were calculated between the first time channel and channels 35 (3.78 ms), 30 (2.23 ms) and 25 (1.31 ms), respectively. The maximum time channels to use were determined automatically using a measure of average polarizability reliability. The ordnance library used for our first dig list comprised 9 items. The stop dig point for this list was dig number 54.

The partial ROC curve for the stage 1 dig list (Figure 11(a)) showed that (ignoring training items and items flagged as cannot analyze) almost all of the items dug were TOI. The last five digs were non-TOI.

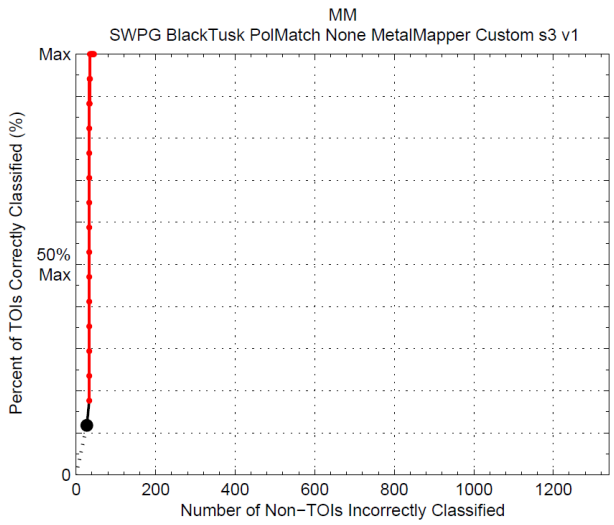
After inspecting the polarizabilities in dig list order, we decided to dig six additional "QC" or "analyst" digs (SW- 20381, 10744, 20203, 11474, 21123 and 20792), to form the stage 2 dig list. The items were chosen by the analyst based on their visual resemblance to reference TOI (although all have relatively large misfits with respect to the best fitting reference item). These items occurred at dig numbers 70, 88, 93, 107, 165 and 183 in the stage 1 dig list. All six of the additional digs were non-TOI (Figure 11(b)).



(a) Stage 1 partial ROC



(b) Stage 2 partial ROC



(c) Stage 3 partial ROC

Figure 11. Partial ROC curves during classification process

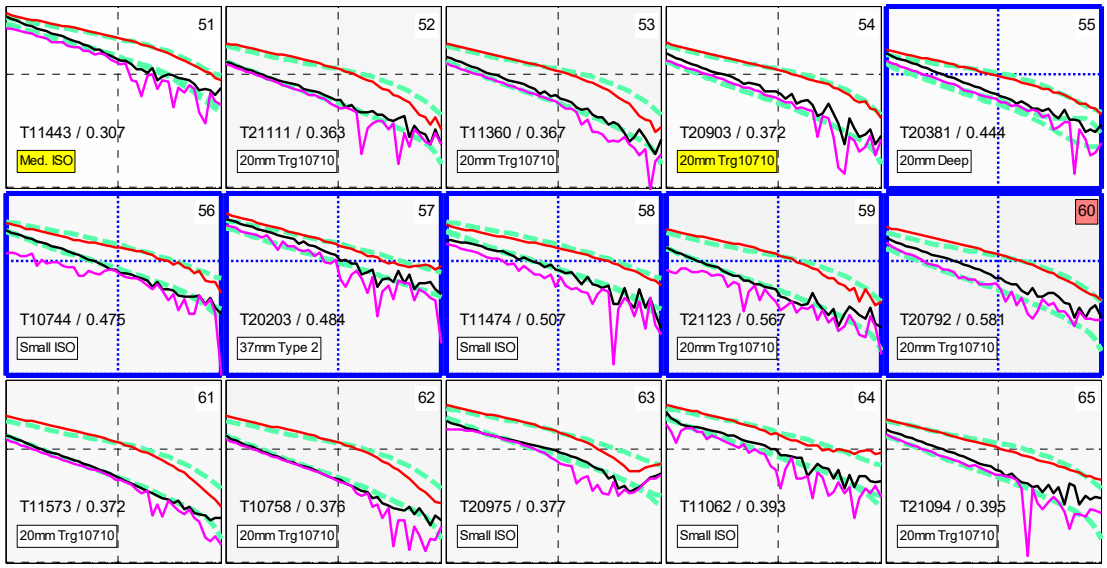


Figure 12. Additional 6 "analyst" or QC digs added to the stage 1 dig list. The stage 1 dig list stopped at dig 54. The stage 2 dig list, with the additional digs highlighted with blue boxes, results in a stop dig point at dig 60. None of these additional digs were of TOI.

We requested additional training data for six items with fuze-like properties (Figure 13). All of these were non-TOI. Re-inspection of the polarizabilities in dig list order suggested that all TOI had been found.

By fitting the final partial (stage 3, Figure 11(c)) ROC curve to a binormal model it is possible to estimate the posterior probability that each target is a UXO (Beran and Zelt, 2014). This test suggested that at the 99% confidence, all TOI have been dug. On this basis, we declared out stage 3 dig list (which looks very similar to the stage 1 dig list in Figure 9) to be our final dig list.

In March 2014, our final dig list was submitted to the program office by the Institute for Defense Analysis (IDA). For final scoring, IDA excluded 41 anomalies from the initial set of anomalies, leaving 1357 anomalies in the final list to be scored. The scoring showed that our final dig list found the 17 TOI before the stop dig point at dig number 62; resulting in a False Alarm Rate (FAR) of 3.65 non-TOI digs per TOI dug. The last TOI was found with dig number 52. The final dig list found all TOI before the stop dig point (Figure 14). We dug 62 non-TOI items to find 17 TOI, which gives a FAR of 3.65 non-TOI digs per TOI dig.

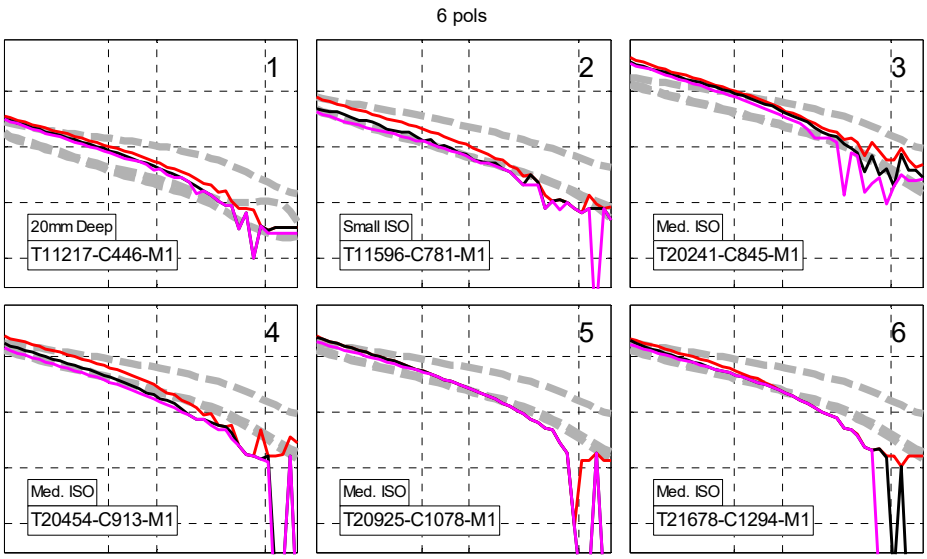


Figure 13. Additional 6 digs with fuze-like properties. The groundtruth revealed that all the targets were non-TOI ("frag").

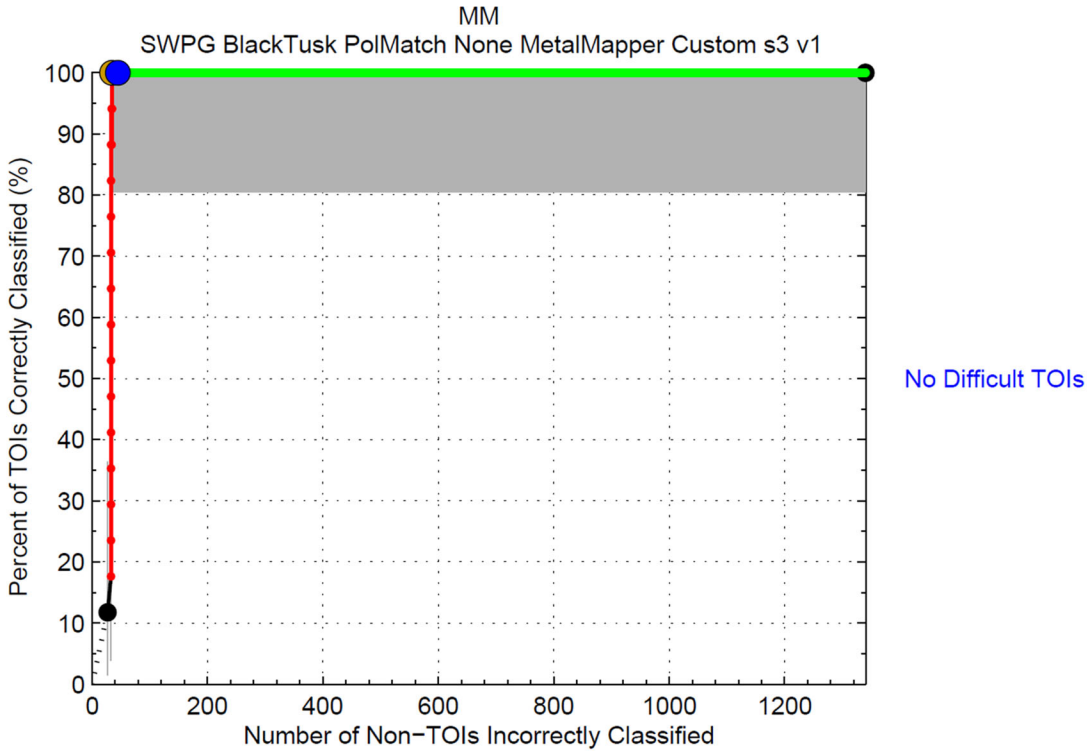


Figure 14. Final ROC curve. All TOI were found before the stop dig point (dig number 62). We dug 10 non-TOI after the last TOI (SW-20602, dig number 52) was found.

4 Conclusions

Processing of cued MetalMapper data collected at SWPG presented no significant challenges for advanced classification. All TOI were readily identified with a minimal number of non-TOI digs using our standard data processing procedures.

5 References

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