DEMONSTRATION REPORT

MetalMapper Survey, Fort Rucker, AL

ESTCP Project MR-201226

MAY 2021

Leonard Pasion
Black Tusk Geophysics

ESTCP

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*	**2. REPORT TYPE**	**3. DATES COVERED** *(From - To)*
05-05-2021	ESTCP Demonstration Report	13-Mar-2013 to 5-May-2021

4. TITLE AND SUBTITLE

MetalMapper Survey, Fort Rucker, AL

5a. CONTRACT NUMBER W912HQ-12-C-0079

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

Leonard Pasion

5d. PROJECT NUMBER MR-201226

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Black Tusk Geophysics
1755 West Broadway
Vancouver, BC
V6J4S5

8. PERFORMING ORGANIZATION REPORT NUMBER

MR-201226

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Environmental Security Technology Certification Program
4800 Mark Center Drive, Suite 16F16
Alexandria, VA 22350-3605

10. SPONSOR/MONITOR'S ACRONYM(S)

ESTCP

11. SPONSOR/MONITOR'S REPORT NUMBER(S) MR-201226

12. DISTRIBUTION / AVAILABILITY STATEMENT

DISTRIBUTION STATEMENT A. Approved for public release: distribution unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

This report describes advanced classification processing of MetalMapper “Classic” time-domain electromagnetic data collected at Fort Rucker, Alabama. The objective of this work was to test a primarily automated library-based classification approach at the Fort Rucker Site. Black Tusk Geophysics (BTG) processed 402 cued interrogations to recover estimates of intrinsic dipole polarizabilities for detected sources. Estimated polarizabilities were used to identify potential novel TOI at the site via cluster analysis and comparison with a comprehensive polarizability library. As groundtruth information was made available via “training” or “analyst calibration” digs, the polarizability library was supplemented with new polarizabilities. The Fort Rucker classification presented significant challenges for the library-based classification approach. The polarizabilities of TOI on site exhibited a high level of variability due to the range of physical condition and state of the TOI encountered. There were several non-TOI items with polarizabilities that were similar to those in the library. In SERDP project MR-2226, a “dataset degree of difficulty” was defined that provides an objective measure of the likely difficulty of classification. The measure of difficulty for Fort Rucker indicates it is essentially the most challenging ESTCP live site of those that were performed between 2011 and 2013 and processed by BTG. The main source of difficulty is the overlap in size-decay space of the majority of non-TOI features with some of the TOI features. i.e., much of the scrap at Fort Rucker has polarizabilities that look like TOI (particularly, rocket motors).

15. SUBJECT TERMS

UXO Classification, electromagnetic induction sensors, geophysical data inversion

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON** Leonard Pasion
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			**19b. TELEPHONE NUMBER** *(include area code)*
UNCLASS	UNCLASS	UNCLASS	UNCLASS	29	604-428-3382

1 Executive Summary

This report describes advanced classification processing of MetalMapper "Classic" time-domain electromagnetic data collected at Fort Rucker, Alabama. The investigation site lies on an area formerly used as an Anti-Tank Rocket and Grenade Range. The area of interest is part of a golf course, with a focus on greens and tee-off areas.

The objective of this work was to test a primarily automated library-based classification approach at the Fort Rucker Site. Black Tusk Geophysics (BTG) processed 402 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 (i.e., non-informative) 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. As groundtruth information was made available via "training" of "analyst calibration" digs, the polarizability library was supplemented with new polarizabilities.

The Fort Rucker classification presented significant challenges for the library-based classification approach. The polarizabilities of TOI on site exhibited a high level of variability due to the range of physical condition and state of the TOI encountered. This resulted in additional polarizabilities being added to the classification library. Also, the decision metric – which is a measure of the polarizability misfit – required a larger threshold to account for the variability. There were several non-TOI items with polarizabilities that were similar to those in the library.

In retrospect, the Fort Rucker demonstration site was not an appropriate site for automated library-based classification. Fifty percent of the targets (201 of 402) at the site were TOI. 167 of the 201 TOI are rocket motors and about 40% of these are multi object scenarios with multiple pieces of frag present. The large amount of frag is bound to result in recovered polarizabilities that in some cases will not be a good match to typical rocket motor polarizabilities. Following the disappointing classification performance, we reassessed and re-tested our multi-source solvers and approach.

In SERDP project MR-2226, a "dataset degree of difficulty" was defined that provides an objective measure of the likely difficulty of classification based on data and model metrics and the reference library used for classification. Our final measure of difficulty for Fort Rucker indicates it is essentially the most challenging ESTCP live site of those that were performed between 2011 and 2013 and processed by BTG. Measures of data and model quality for Fort Rucker are, in fact, relatively good compared to other sites. The main source of difficulty is the overlap in size-decay space of the majority of non-TOI features with some of the TOI features. I.e., much of the scrap at Fort Rucker has polarizabilities that look like TOI (particularly, rocket motors).

2 Table of Contents

1 Executive Summary i

2 Table of Contents ii

3 List of Figures ii

4 List of Tables v

5 Acronyms v

1 Introduction 1

2 Technology description 1

2.1 MetalMapper "Classic" Electromagnetic Induction Sensor 1

2.2 Classification 1

3 Cued MetalMapper Processing 3

3.1 Feature extraction 3

3.2 Classification 4

3.2.1 Training data selection 4

3.2.2 Classification method 7

3.2.3 MetalMapper cued retrospective analysis 14

3 List of Figures

Figure 1. MetalMapper "Classic" sensor geometry. Red dashed lines indicate transmitter coils and solid black lines are receiver cubes 2

Figure 2. Image of the MetalMapper Classic acquiring data at the Fort Rucker site. Image from Cost and Performance report of ESTCP MR-201161 2

Figure 3. Example of an unrealistic 3OI model (anomaly 10068; 2.36" rocket frag). Polarizabilities from SOI (top left), 2OI, (top row; center and right), and 3OI (bottom row). The third model of the 3OI (model 6; lower left) provides the best fit (i.e., minimum misfit) to the reference polarizabilities (misfit = 0.772), but the predicted depth of 0.71 m, location

beyond the footprint of the sensor (on one of the horizontal inversion boundaries), high amplitude and jittery appearance of the polarizabilities, and low model contribution are classic signs that this model is an artifact of the multi-object inversion process. Accordingly, this model was failed during QC. Red, black and magenta lines: predicted polarizabilities. Grey lines: best fitting reference polarizabilities (label at top right of each plot). Number in lower left corner is misfit with respect to the best fitting reference item. Inset map in lower right corner of each plot shows (a) predicted location (dot) relative to center of the sensor (+) and horizontal inversion boundaries (dotted lines); (b) black line inside column on the left indicates predicted depth relative to maximum allowed depth in inversion (1.2 m); and (c) shaded bar along top edge indicates the relative contribution of the model to the predicted data for each inversion. The percent model contribution, predicted depth (Z) in m and offset from the center of the sensor (R) in m are indicated next to each inset map. 4

Figure 4. Distribution of models in decay(t3,t29) versus size(t3) feature space, where size(t3) is the total polarizability measured at the third time channel (t1=0.13 ms), and decay(t1,t29) is size(t3)/size(t29) where t29=2.006 ms. A few outliers are not shown. Labeled stars represent ordnance library reference items used in initial (stage 1) dig list submission. Black dotted line highlights the densest region of feature space, within which fall four of the reference features. 5

Figure 5. 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 23 features from 11 unique targets is visible (solid feature symbols encompassed by broken line). Polarizabilities for some of the models in this cluster are shown in Figure 6. 6

Figure 6. Polarizabilities for some of the models in the cluster shown in Figure 5. Colored lines are predicted polarizabilities. Grey lines are best fitting reference polarizabilities. Training data were requested for the target 100659 (index number 7), which was identified as 3.5" rocket frag (non-TOI). 7

Figure 7. 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). 8

Figure 8. Items in the ordnance reference library used for the stage 1 dig list. The first five items were derived from IVS measurements; the remaining seven were based on training data..... 9

Figure 9. Polarizabilities for three missed rifle grenades (red, black and magenta lines) relative to polarizabilities for the IVS rifle grenade item (broken grey lines). Polarizabilities for all three models are overlain in lower right panel. 10

Figure 10. Polarizabilities for FR-10225. We requested training data for this item, which has polarizabilities similar to the missed TOI, but this one turned out to be frag. Broken grey lines are reference polarizabilities based on the three missed rifle grenade TOI. 11

Figure 11. Top: polarizabilities for two missed hand grenades relative to polarizabilities for the IVS hand grenade item (broken grey lines). Bottom: polarizabilities for both models are overlain. 11

Figure 12. Partial ROC curve for the stage 2 dig list. 12

Figure 13. Partial ROC curve for the stage 3 dig list. Of the 40 digs beyond the stage 2 stop dig point, 17 (42.5%) were TOI. 13

Figure 14. Partial ROC curve for the stage 4 dig list. Of the 9 digs beyond the stage 2 stop dig point, 4 (44.4%) were TOI. 13

Figure 15. ROC curve for the final (stage 5) dig list with list of thirteen missed TOI. 14

Figure 16. Library of seventeen reference ordnance polarizabilities used for classification, sorted approximately from largest to smallest. Some are based on IVS measurements; others are based on ground truth received during the analysis. 15

Figure 17. Predicted polarizabilities (red, black and magenta lines) for FR-10028 and FR-10177 (both Mk 2 practice hand grenade) and polarizabilities of Mk2 hand grenade from our reference library (broken grey lines), which were based on polarizabilities from FR-10548 and 10771. Misfit between predicted and reference polarizabilities calculated using L1, L2 and L3 is shown in the bottom left. 16

Figure 18. Polarizabilities for FR-10028 and FR-10177 (thick black boxes) and other similar models from other anomalies, all compared to the polarizabilities for our reference Mk 2 hand grenade. All of the other models correspond to rocket frag or target debris – none are TOI. Anomaly numbers appear in the label at lower left preceded by "T". 17

Figure 19. Predicted polarizabilities (red, black and magenta lines) for five missed 2.36" rocket motors and polarizabilities of the best fitting 2.36" rocket motor variant from our reference library (broken grey lines). Anomaly numbers appear in the title of each plot preceded by "T".. 18

Figure 20. Predicted polarizabilities (red, black and magenta lines) for two missed 3.5" rocket motors (FR-10553 and FR-10510) and polarizabilities of the best fitting 2.36" rocket motor variant from our reference library (broken grey lines). 19

Figure 21. Predicted polarizabilities (red, black and magenta lines) for nine 3.5" rocket motors obtained from ground truth requests prior to the stage 5 dig list and polarizabilities of the best fitting 2.36" rocket motor variant from our reference library (broken grey lines). 19

Figure 22. Predicted polarizabilities (red, black and magenta lines) for FR-10597 (2.36" rocket) and polarizabilities of the best fitting 2.36" rocket variant from our reference library (broken grey lines). 20

Figure 23. Predicted polarizabilities (red, black and magenta lines) for two missed 2.36" rocket warheads (FR-10284 and FR-10047) and polarizabilities of the Mk 2 hand grenade from our reference library (broken grey lines). 21

Figure 24. Predicted polarizabilities (red, black and magenta lines) for FR-10171, a burial pit comprising 2.36" rocket, 118 2.36" rocket motors and a large amount of target debris, and polarizabilities of the closest matching item from our reference library (2.36" rocket; broken

grey lines). Polarizabilities for two different models are shown (left: single object inversion; right: three object inversion). 21

4 List of Tables

Table 1. List of missed QC seeds. 9

Table 2. List of missed TOI. The stop dig point was dig number 265. 14

5 Acronyms

AL	Alabama
AGC	Advanced Geophysical Classification
BTG	Black Tusk Geophysics
cm	Centimeter
CSV	Comma Separated Variable
ESTCP	Environmental Security Technology Certification Program
IVS	Instrument Verification Strip
m	Meter
mm	Millimeter
ms	Millisecond
MEC	Munitions and Explosives of Concern
MMC	MetalMapper “Classic”
QC	Quality Control
ROC	Receiver Operating Characteristic
s	Second
SOI	Single Object Inversion
2OI	Two Object Inversion
3OI	Three Object Inversion
TOI	Target of Interest
UXO	Unexploded Ordnance

1 Introduction

Fort Rucker is located in Dale County Alabama. An ESTCP munitions response study was carried out on a former anti-tank rocket/grenade range that was later developed and became part of a golf course. During a site inspection, other site visits and previous work, numerous subsurface anomalies were detected and the following munitions items were encountered:

- 2.36-inch and 3.5-inch rocket,
- Rifle grenade,
- M6 series 2.36-inch rockets,
- M9A1 rifle grenades, and
- MK II hand grenade.

Advanced geophysical data collection, mapping and classification was performed for the ESTCP study. URS (MR-201161) collected MetalMapper "Classic" (MMC) data in dynamic and cued mode. Black Tusk Geophysics processed only the cued data, and did not process the dynamic mapping data. This report summarizes the processing carried out by Black Tusk Geophysics on the cued data collected as part of this demonstration.

2 Technology description

2.1 MetalMapper "Classic" Electromagnetic Induction Sensor

The MetalMapper "Classic" (Figure 1) is an advanced geophysical electromagnetic induction (EMI) sensor designed for classification of buried unexploded ordnance (UXO). The MMC has three orthogonal transmitter coils to provide diverse excitation of buried conductive targets. Seven receiver "cubes" each measure orthogonal components of the induced secondary magnetic field.

In this study, the MMC was deployed for both detection surveys that map metallic targets at a site, as well as for cued interrogations where the array was positioned over targets identified in the previous detection survey and EMI data were collected for classification. When deployed in a cued interrogation mode, the instrument measures the EMI over a larger time widow and averages multiple measurements to reduce the noise of the data.

2.2 Classification

Classification with EMI data uses data inversion to fit observed EMI data collected over each target. The forward model is typically parameterized by the target location, orientation and dipole polarizabilities. The polarizabilities provide information about intrinsic target properties including size, shape and material composition. Advanced geophysical classification (AGC) relies on matching estimated polarizabilities with a predefined library to identify likely targets of interest (TOI).

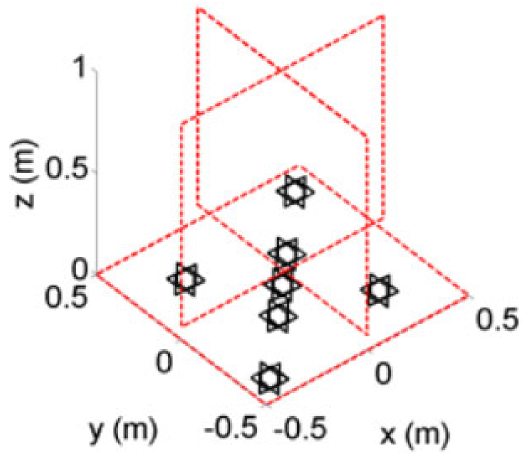

Figure 1. MetalMapper "Classic" sensor geometry. Red dashed lines indicate transmitter coils and solid black lines are receiver cubes.

Figure 2. Image of the MetalMapper Classic acquiring data at the Fort Rucker site. Image from Cost and Performance report of ESTCP MR-201161.

3 Cued MetalMapper Processing

3.1 Feature extraction

MetalMapper “Classic” cued data for all anomalies of the Fort Rucker Proof-of-Principle Area were received as a set of background-corrected CSV files. All CSV files were imported into UXOLab and inverted using a sequential inversion approach to estimate target location, depth and primary polarizabilities. Instrument height above the ground was assumed to be 10 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 five starting models to input into the subsequent estimation of polarizabilities. We performed three inversions per anomaly, solving for (1) a single object (single object inversion: SOI); (2) two objects (2OI); and (3) three objects (3OI).

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 IVS measurements. The Fort Rucker IVS contained a 2.36” rocket, rifle grenade, hand grenade and small and medium ISOs. 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 estimate (mm) based on the size of the best-matching reference item.

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.

With multi-object 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 3). 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.

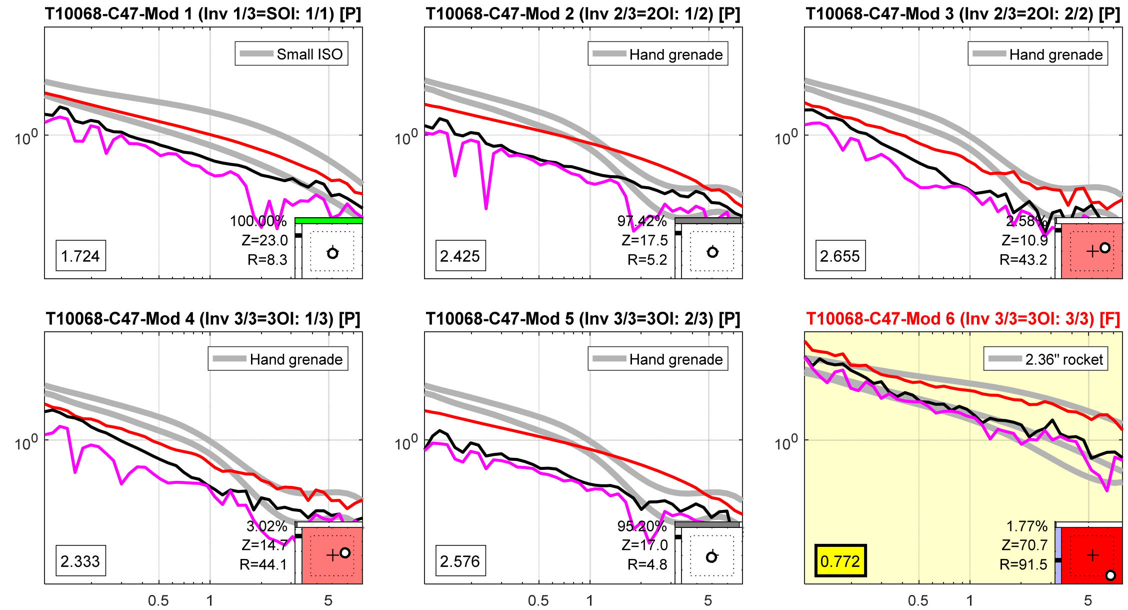

Figure 3. Example of an unrealistic 3OI model (anomaly 10068; 2.36" rocket frag). Polarizabilities from SOI (top left), 2OI, (top row; center and right), and 3OI (bottom row). The third model of the 3OI (model 6; lower left) provides the best fit (i.e., minimum misfit) to the reference polarizabilities (misfit = 0.772), but the predicted depth of 0.71 m, location beyond the footprint of the sensor (on one of the horizontal inversion boundaries), high amplitude and jittery appearance of the polarizabilities, and low model contribution are classic signs that this model is an artifact of the multi-object inversion process. Accordingly, this model was failed during QC. Red, black and magenta lines: predicted polarizabilities. Grey lines: best fitting reference polarizabilities (label at top right of each plot). Number in lower left corner is misfit with respect to the best fitting reference item. Inset map in lower right corner of each plot shows (a) predicted location (dot) relative to center of the sensor (+) and horizontal inversion boundaries (dotted lines); (b) black line inside column on the left indicates predicted depth relative to maximum allowed depth in inversion (1.2 m); and (c) shaded bar along top edge indicates the relative contribution of the model to the predicted data for each inversion. The percent model contribution, predicted depth (Z) in m and offset from the center of the sensor (R) in m are indicated next to each inset map.

The Fort Rucker MMC cued dataset comprised 402 unique anomalies. Of the 2448 total models, 2255 were passed and used in the classification process; 193 were failed. No anomalies were classified as "cannot extract reliable parameters" (i.e., there was at least one passed model for each anomaly). 157 anomalies were flagged as "high likelihood UXO" during QC; 141 of these (90%) correspond to actual TOI. The total number of unique TOI in the MetalMapper Cued dataset is 201.

3.2 Classification

3.2.1 Training data selection

Figure 4 shows the distribution of 2448 models in decay versus size feature space. The overlap of reference features with dataset features, particularly in the densest region of feature space, suggests that, without further information, the classification difficulty level may be high. Indeed, using our "dataset degree of difficulty" measure, which uses data, model and feature space metrics our initial estimate of classification difficulty is "high" (more challenging than other previous live site demonstrations such as Pole Mountain, Beale, Spencer, SWPG, Ellis and Butner.

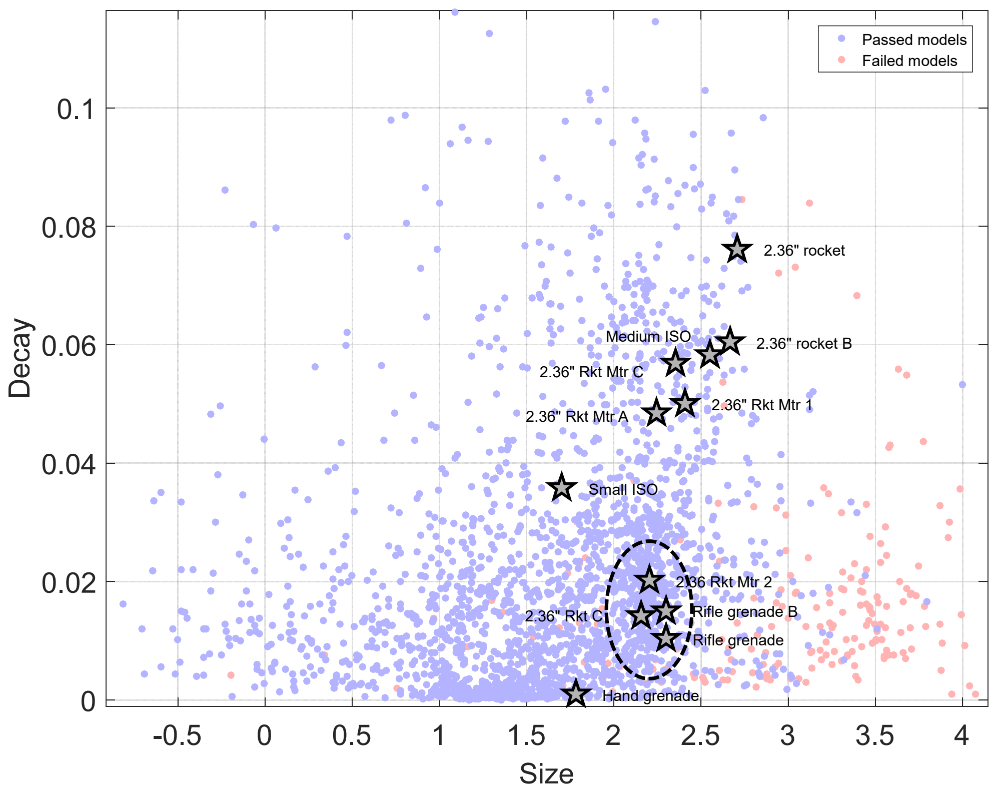

Figure 4. Distribution of models in decay(t3,t29) versus size(t3) feature space, where size(t3) is the total polarizability measured at the third time channel (t1=0.13 ms), and decay(t1,t29) is size(t3)/size(t29) where t29=2.006 ms. A few outliers are not shown. Labeled stars represent ordnance library reference items used in initial (stage 1) dig list submission. Black dotted line highlights the densest region of feature space, within which fall four of the reference features.

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 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. A basic example of the use of *TrainZilla* is shown in Figure 5 and Figure 6.

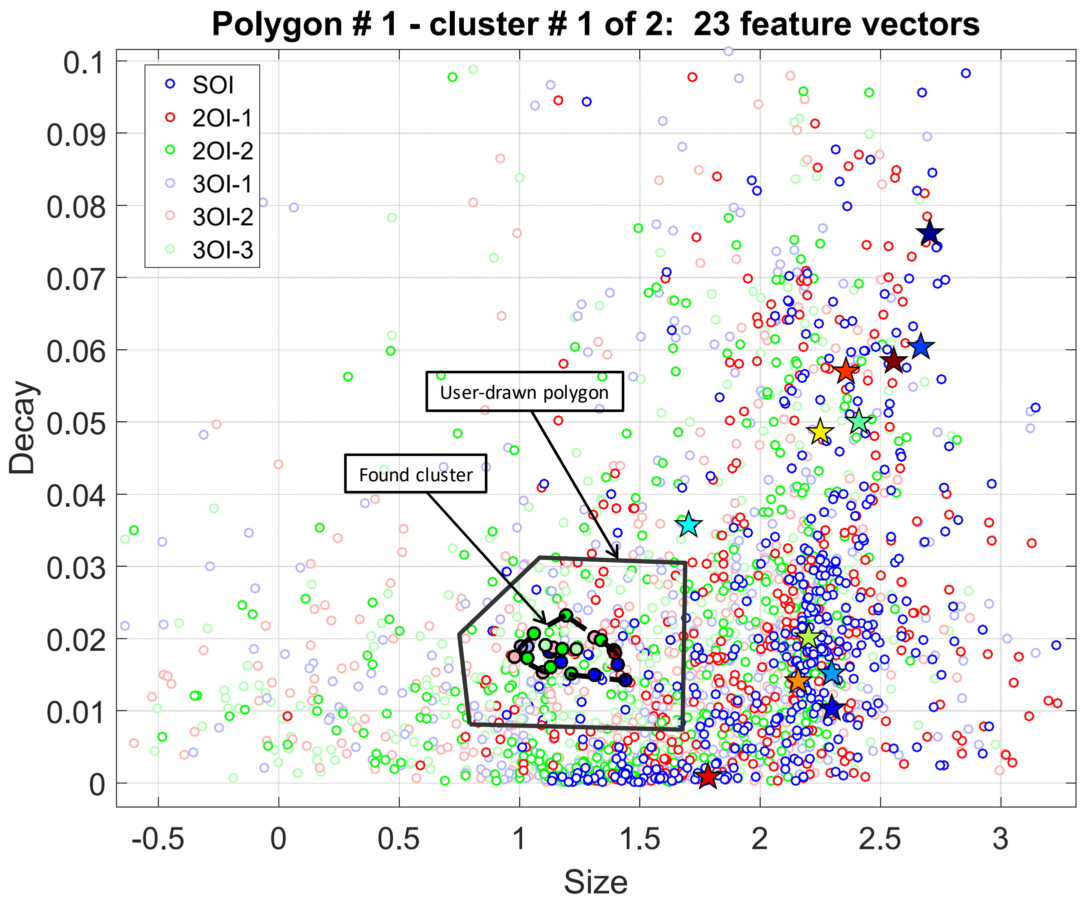

Figure 5. Example of use of the training data selection tool (*TrainZilla*). A polygon (solid black line) is drawn in feature space. Clusters of items with self-similar polarizabilities are automatically found based on the specified cluster search parameters. In this case a cluster comprising 23 features from 11 unique targets is visible (solid feature symbols encompassed by broken line). Polarizabilities for some of the models in this cluster are shown in Figure 6.

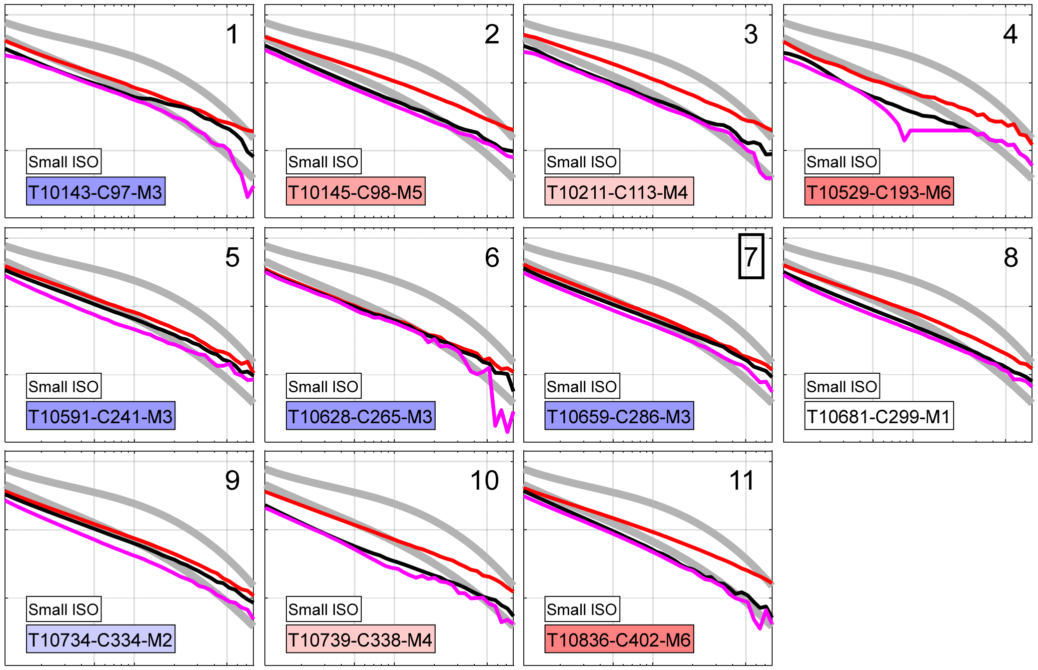

Figure 6. Polarizabilities for some of the models in the cluster shown in Figure 5. Colored lines are predicted polarizabilities. Grey lines are best fitting reference polarizabilities. Training data were requested for the target 100659 (index number 7), which was identified as 3.5" rocket frag (non-TOI).

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.

We submitted two training requests prior to submitting our first dig list for a total of 31 items. Of these, 14 were TOI: four 2.36" rockets, eight 2.36" rocket motors, one 3.5" rocket motor, and one rifle grenade. Based on the results from training we added seven items to our reference library.

3.2.2 Classification method

Our dig lists were developed using our visual classification software *DigZilla* (Figure 7), 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.

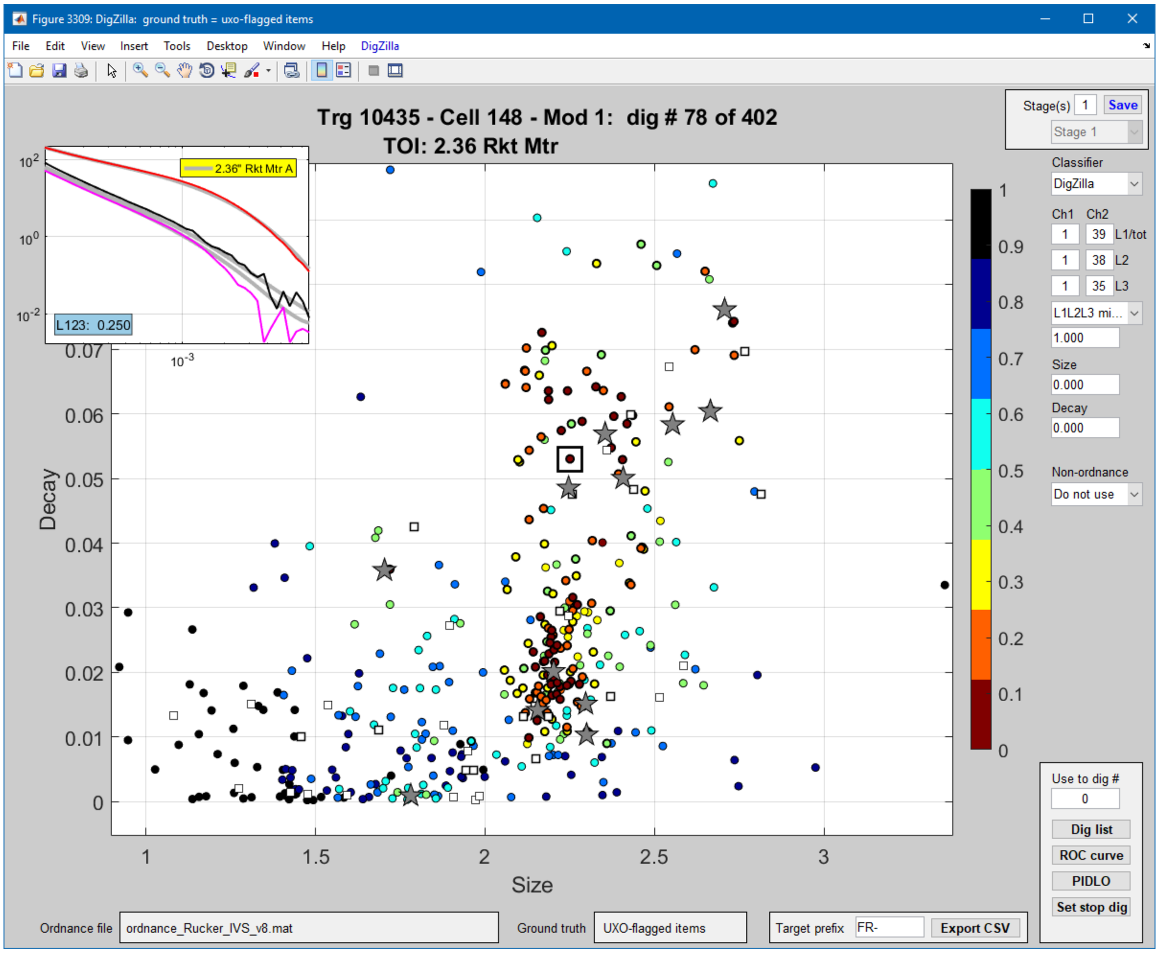

Figure 7. UXOLab *DigZilla* graphical user interface. Features in the decay versus size feature plot are color coded according to dig list order (red earliest; black latest).

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 39 (5.77 ms), 38 (5.19 ms) and 35 (3.78 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 12 items (Figure 8). The stop dig point for this list was dig number 208.

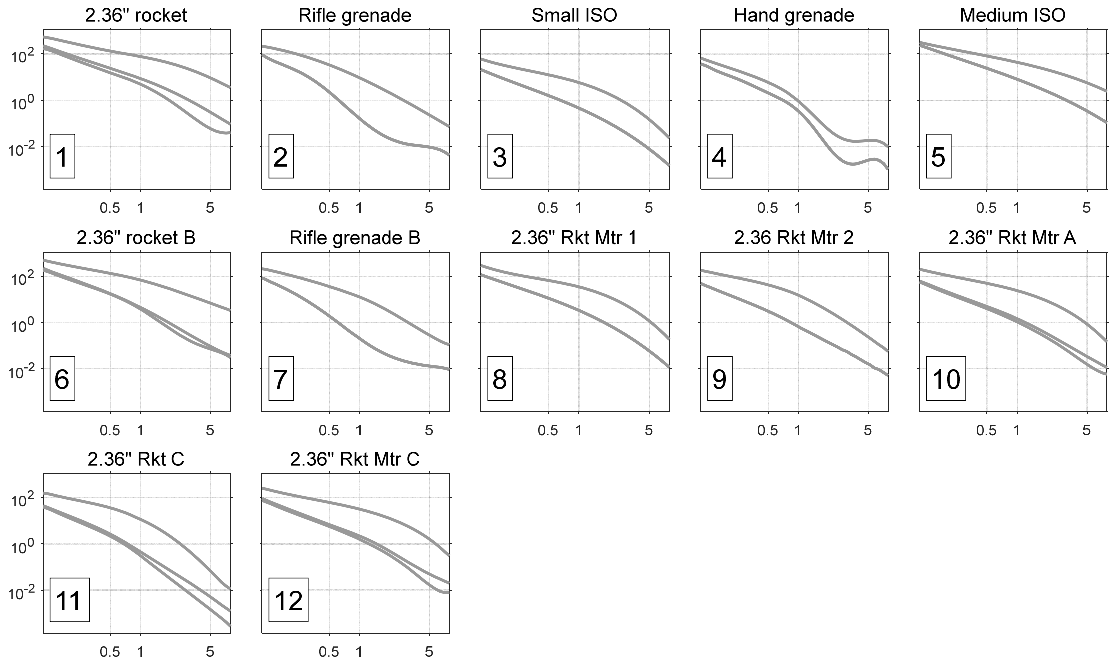

Figure 8. Items in the ordnance reference library used for the stage 1 dig list. The first five items were derived from IVS measurements; the remaining seven were based on training data.

Our stage 1 dig list missed five QC seeds, requiring a failure memo, which is included in its entirety below.

Failure Analysis Memo

Site: Rucker Proof of Principle Area

Analyst: Black Tusk Geophysics

Data: MM Cued

Date: June 14, 2013

Our stage 1 dig list missed five QC seeds (Table 1).

Table 1. List of missed QC seeds.

Anomaly	Depth (inches)	Identification	Dig Type
FR-10160	8	Seed #088 Rifle Grenade	TOI
FR-10384	6	Seed #002 Rifle Grenade	TOI
FR-10548	4	Seed #017 Mk 2 Hand Grenade	TOI
FR-10732	5	Seed #024	TOI
FR-10771	10	Seed #020 or 030 Mk 2 Hand Grenade	TOI

Seed 24 was not identified in the supplied ground truth, but based on the similarities of our polarizabilities for this anomaly with those of FR-10160 and FR-10384, we assume this is a rifle grenade.

a. Analysis of the factors that resulted in the misclassification of each missed seed

Missed Rifle Grenades

Our classification method is based primarily on matching polarizabilities with items in an ordnance reference library. Polarizabilities for the three missed rifle grenade TOI are quite consistent, but bear no resemblance to the polarizabilities for the IVS rifle grenade (Figure 9). Our semi-automated automated cluster analysis did not find this class of TOI because the minimum cluster size we search for is typically four. Of the remaining anomalies, the ones that most closely resemble the missed rifle grenades are different enough that our clustering algorithm did not find four or more self-similar models. Also, we have not previously come across a TOI with similar polarizabilities, so we were not specifically looking for such an item. We did however request training data for one of the anomalies that most closely matches the missed seed (FR-10225; Figure 10); however, this item turned out to be frag.

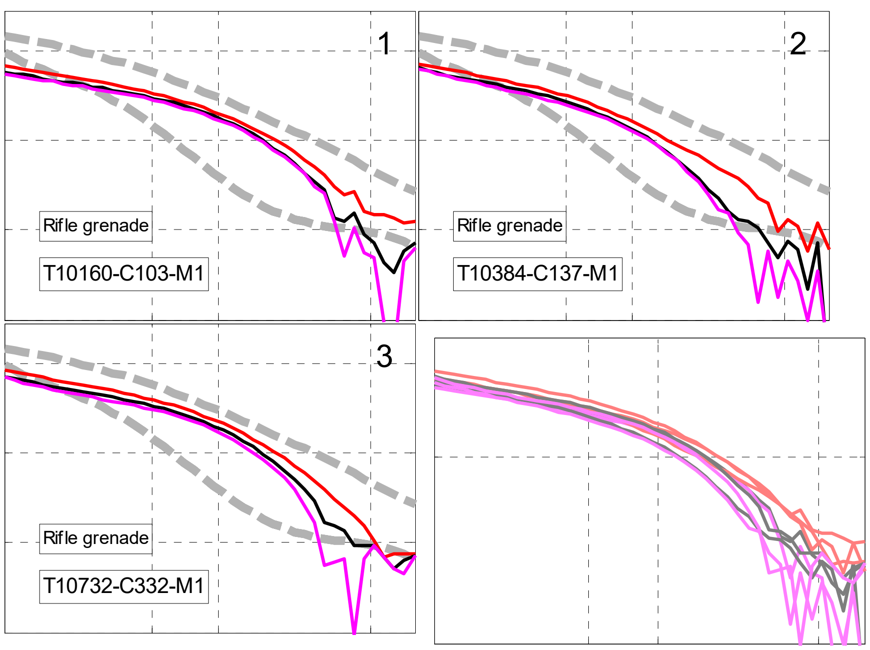

Figure 9. Polarizabilities for three missed rifle grenades (red, black and magenta lines) relative to polarizabilities for the IVS rifle grenade item (broken grey lines). Polarizabilities for all three models are overlain in lower right panel.

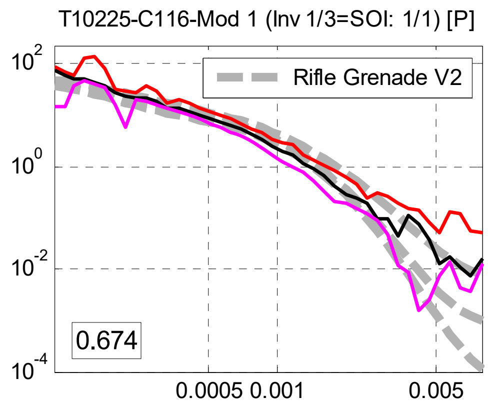

Figure 10. Polarizabilities for FR-10225. We requested training data for this item, which has polarizabilities similar to the missed TOI, but this one turned out to be frag. Broken grey lines are reference polarizabilities based on the three missed rifle grenade TOI.

Missed Hand Grenades

Polarizabilities for the two missed hand grenade TOI are relatively consistent, but bear no resemblance to the polarizabilities for the IVS hand grenade (Figure 11). Our reasons for missing these items are similar to those stated above for the missed rifle grenades. This is a very small class of TOI: there does not appear to be any other items in the dataset with polarizabilities that closely resemble those of the missed seeds.

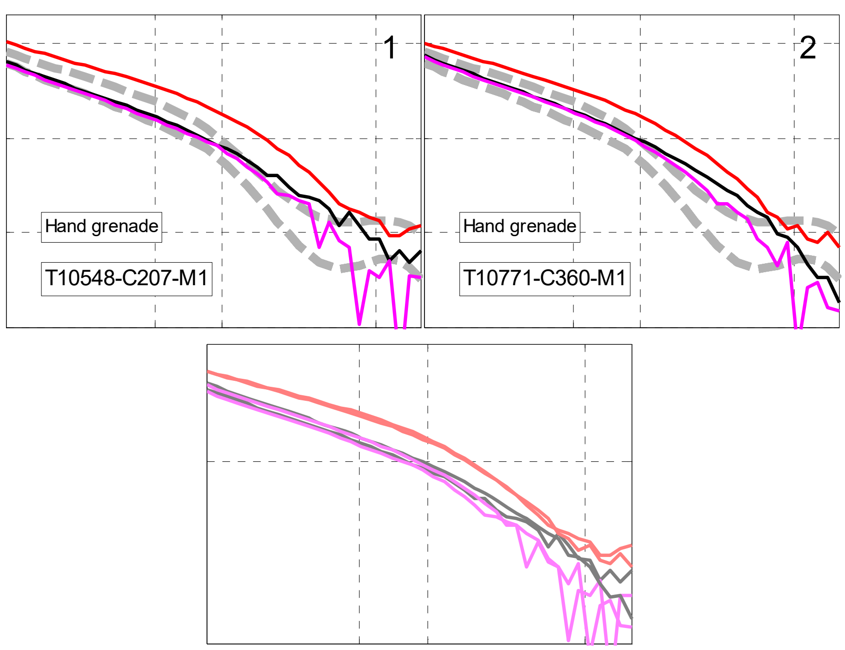

Figure 11. Top: polarizabilities for two missed hand grenades relative to polarizabilities for the IVS hand grenade item (broken grey lines). Bottom: polarizabilities for both models are overlain.

b. Description of how the analysis procedures have been modified based on the additional information provided

We have created two sets of reference polarizabilities based on the missed rifle grenades and hand grenades. Adding these to our ordnance reference library will ensure 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 two missed classes of TOI to our ordnance reference library ensures that if these items were to be classified (and not treating them as training items) they would all occur before our stop dig point (in fact, at digs 49, 149, 87, 47 and 59, respectively for the six items listed in Table 1). Our augmented reference library also ensures that other items with sufficiently similar polarizabilities will be found.

- End of failure memo -

For the stage 2 dig list we added three items (two rifle grenades, hand grenade) to our reference ordnance file based on the missed QC seeds. For the stage 2 dig list, the stop dig point was set to dig number 215 (i.e., digging 53.5% of the 402 targets in the dataset). The stage 2 partial ROC curve is shown in Figure 12.

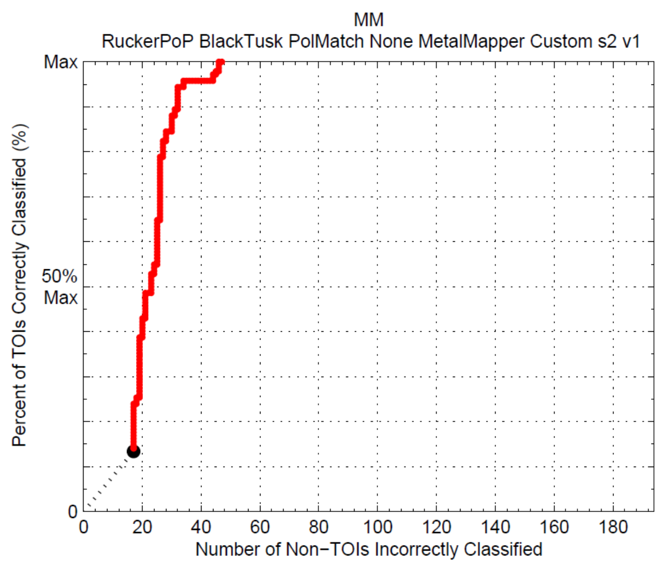

Figure 12. Partial ROC curve for the stage 2 dig list.

Based on the stage 2 results, we added two more items to the reference library (both 2.36” rocket motors). For the stage 3 dig list we extended the stop dig point to dig number 256 (i.e., digging 63.7% of the 402 targets in the dataset). The stage 3 partial ROC curve is shown in Figure 12. Of the 40 additional digs beyond the stage 2 stop dig list, 17 were found to be TOI: two 2.36” rockets, thirteen 2.36” rocket motors, one rifle grenade, and one 2.36” rocket warhead. The latter was a new class of TOI for this site; however, we found no other items similar to the warhead within the dataset.

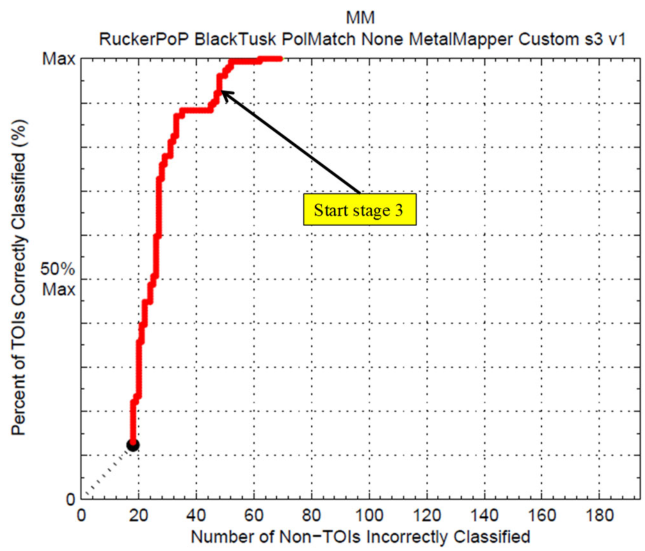

Figure 13. Partial ROC curve for the stage 3 dig list. Of the 40 digs beyond the stage 2 stop dig point, 17 (42.5%) were TOI.

For stage 4 we decided to dig nine additional items using a reference library with ISOs and hand grenades removed. Of the 9 digs beyond the stage 3 stop dig point, 4 (44.4%) were TOI; all were 2.36” rocket motors.

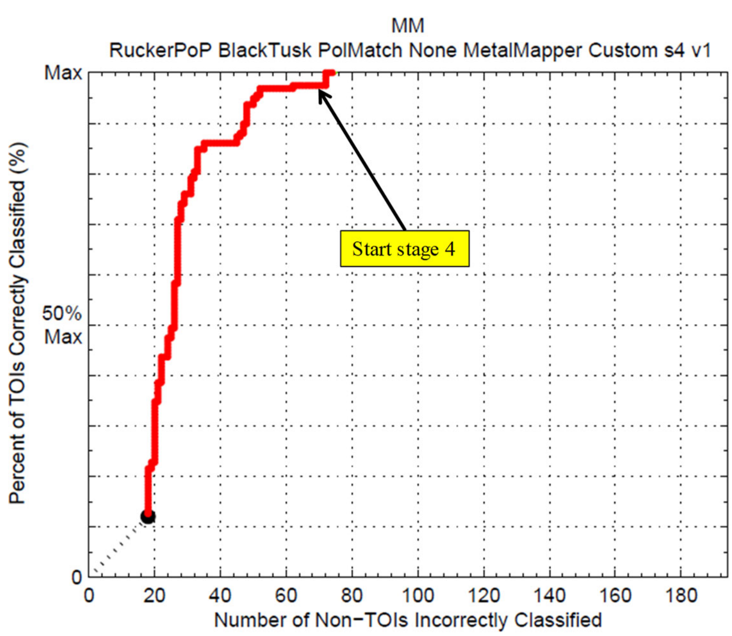

Figure 14. Partial ROC curve for the stage 4 dig list. Of the 9 digs beyond the stage 2 stop dig point, 4 (44.4%) were TOI.

Visual inspection of the polarizabilities in dig list order suggested that none of the targets after the stage 4 stop dig point were likely to be TOI. We submitted a stage 5 dig list with no additional digs, but targets after the stop dig point were classified using the full Fort Rucker ordnance file (comprising 17 members of n different classes: 2.36" rocket motors (7); 2.36" rockets (2); hand grenades (2); rifle grenades (4), and small and medium ISOs. After receiving the partial ROC for stage 5 we finalized the dig list and received final scoring (Figure 15) and full ground truth.

The final dig list missed 13 TOI. We dug 265 of 402 targets (65.9%) and found 188 TOI out of 201 total TOI (93.5%).

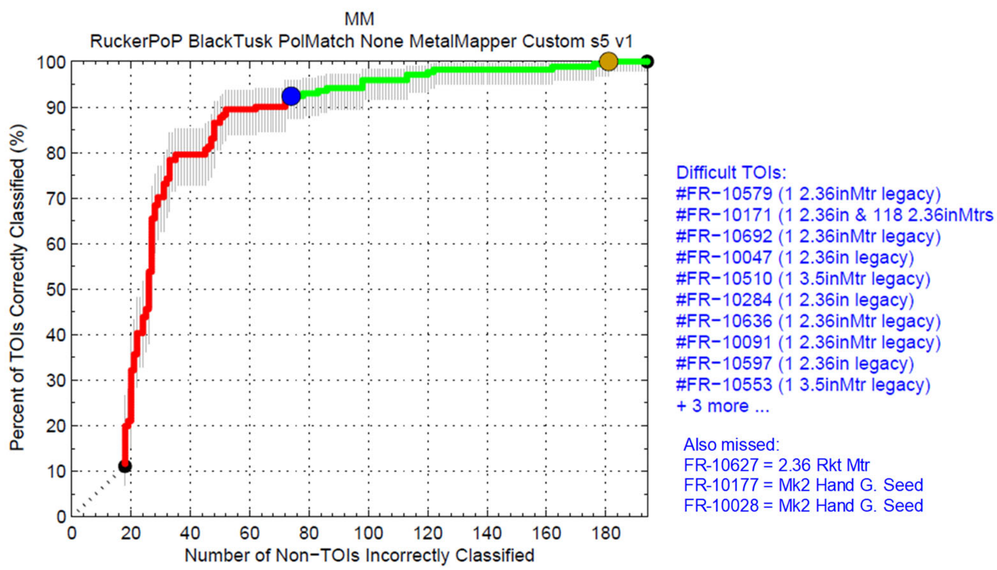

Figure 15. ROC curve for the final (stage 5) dig list with list of thirteen missed TOI.

3.2.3 MetalMapper cued retrospective analysis

The thirteen missed TOI are listed in Table 2. The missed TOI fall into four classes: 2.36" rocket (2); 2.36" rocket motor (5); 2.36" rocket warhead (2); 3.5" rocket motor (2); and hand grenade (2).

Table 2. List of missed TOI. The stop dig point was dig number 265.

Anomaly	Depth (cm)	Identification	Stage 5 dig #
FR-10028	8	Seed #010 Mk 2 Hand Grenade Practice	270
FR-10177	20	Seed #007 Mk 2 Hand Grenade Practice	277
FR-10627	8	2.36 Rkt Mtr	281
FR-10553	15	3.5Rkt Mtr	294
FR-10597	20	2.36 rkt & 2pcs frag	295
FR-10091	10	2.36 Rkt Mtr	296
FR-10636	5	2.36 rkt mtr	313

FR-10284	20	2.36 Rkt Warhead & 10 pcs frag	314
FR-10510	36	3.5 Rkt Mtr & 6 pcs frag	322
FR-10047	5	2.36 Rkt Whd & 5 pcs frag	325
FR-10692	8	2.36 Rkt Mtr & 2pcs frag	367
FR-10171	61	2.36 Rkt (1 = UXO 3lbs), 2.36 Rkt Mtrs (118 of which 9 are MDEH = 236lbs), 6lbs Mdas & 34 lbs Target Debris	383
FR-10579	5	2.36 rkt mtr	389

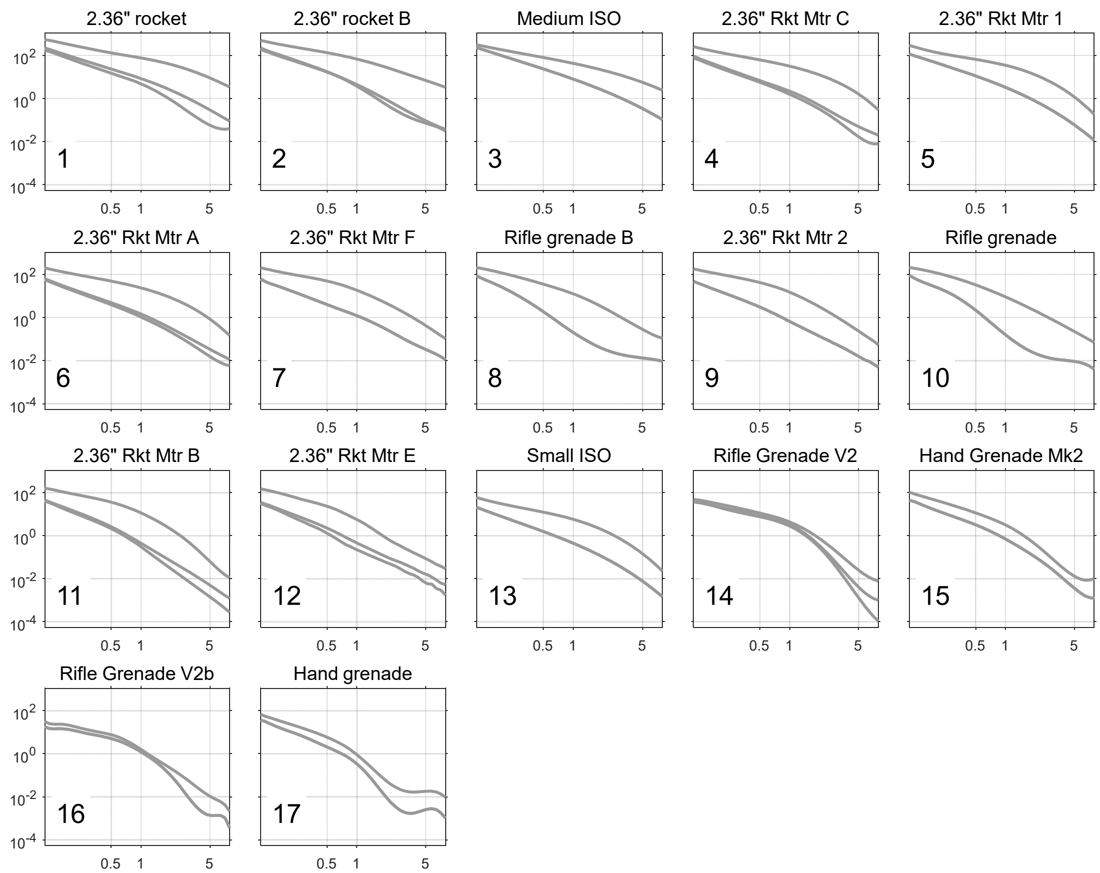

Figure 16. Library of seventeen reference ordnance polarizabilities used for classification, sorted approximately from largest to smallest. Some are based on IVS measurements; others are based on ground truth received during the analysis.

Our classification method is based on matching polarizabilities with items in an ordnance reference library. Figure 16 shows the polarizabilities of all seventeen items in our reference library used for classification. Some of these are based on IVS measurements. Others are based on ground truth obtained from training requests and partial ground truth obtained from pre-stage 5 dig list submissions. In all cases the similarity between the polarizabilities of the missed TOI and those in the reference library was insufficient to result in a dig. In several cases, the polarizabilities of the missed TOI bear little resemblance to the expected polarizabilities for that class of item.

In this retrospective analysis, we will look at each class of missed TOI separately. Regrettably, without ground truth photos and detailed ground truth information (including, e.g., the size/depth of objects found at each anomaly) it is difficult to ascertain with certainty the potential cause(s) of each missed TOI.

Analysis of the factors that resulted in the misclassification of each missed TOI

(1) FR-10028 - Dig 270 - Mk 2 Hand Grenade at 8 cm depth (seed #10)

(2) FR-10177 - Dig 277 - Mk 2 Hand Grenade at 20 cm depth (seed #7)

Figure 17 shows the predicted polarizabilities for FR-10028 and FR-10177 compared to the polarizabilities for our Mk 2 hand grenade reference item (which were based on models obtained for FR-10548 and FR-10771). The polarizabilities for FR-10028 and FR-10177 are consistent, but note that the decay at late times is substantially different from the reference polarizabilities, resulting in moderately large calculated misfit values. Furthermore in Figure 18 we show polarizabilities for other similar models in the dataset. All of these correspond to rocket frag or target debris. Without ground truth photos, it is not known if the grenades used as seeds #7 and #10 were significantly different from the ones used at FR-10548 and FR-10771, thus it is difficult to speculate why the polarizabilities at late time are so different. There is no indication of frag found with either seed, so presumably the discrepancy is not caused by having multiple objects within view of the sensor. In the end, because both FR-10028 and FR-10177 look very much like rocket frag and target debris, they were not dug, although they did appear only slightly after the stop dig point of our dig list.

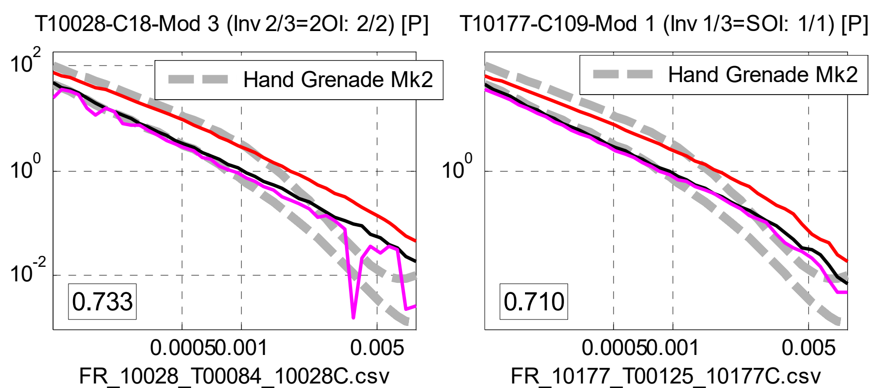

Figure 17. Predicted polarizabilities (red, black and magenta lines) for FR-10028 and FR-10177 (both Mk 2 practice hand grenade) and polarizabilities of Mk2 hand grenade from our reference library (broken grey lines), which were based on polarizabilities from FR-10548 and 10771. Misfit between predicted and reference polarizabilities calculated using L1, L2 and L3 is shown in the bottom left.

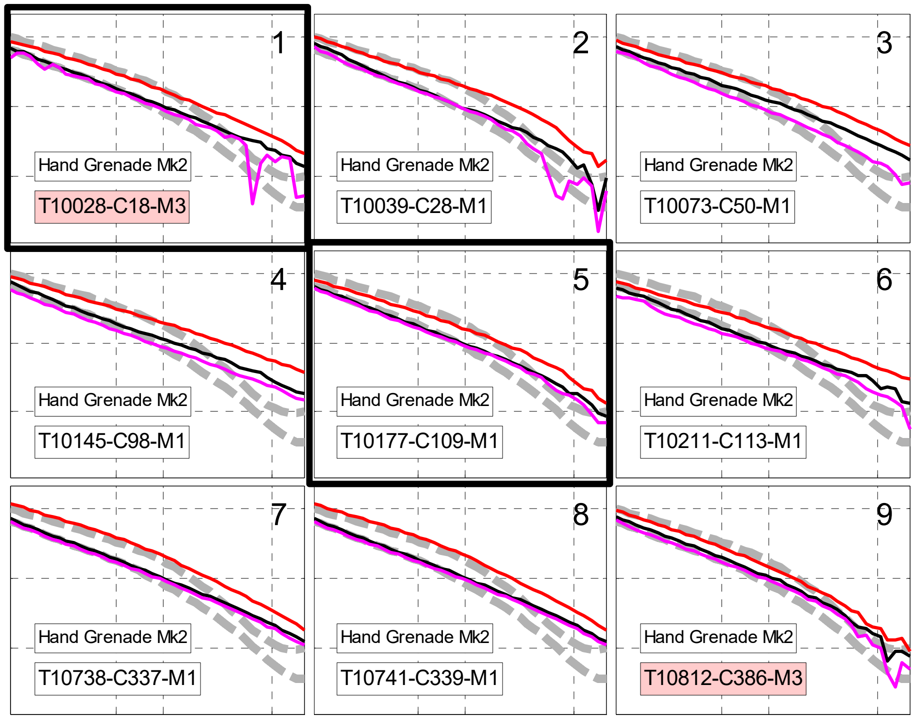

Figure 18. Polarizabilities for FR-10028 and FR-10177 (thick black boxes) and other similar models from other anomalies, all compared to the polarizabilities for our reference Mk 2 hand grenade. All of the other models correspond to rocket frag or target debris – none are TOI. Anomaly numbers appear in the label at lower left preceded by "T".

(3) FR-10627 - Dig 281 - 2.36" rocket motor at 8 cm depth

(4) FR-10091 - Dig 296 - 2.36" rocket motor at 10 cm depth

(5) FR-10636 - Dig 313 - 2.36" rocket motor at 5 cm depth

(6) FR-10692 - Dig 367 - 2.36" rocket motor at 8 cm depth & 2 pieces of frag

(7) FR-10579 - Dig 389 - 2.36" rocket motor at 5 cm depth

Figure 19 shows the predicted polarizabilities for the five missed 2.36" rocket motors compared to the polarizabilities of the best fitting 2.36" rocket motor variant in our reference library (of which there were seven variants; see Figure 16). FR-10627 is somewhat similar to our 2.36" rocket motor "E" variant but decays much more quickly at late times than the reference model. The resultant misfit is large enough that this item was not dug, though it did occur only 15 digs after our stop dig point. The other four are not close to matching any of our reference items. Again, without detailed ground truth information or ground truth photos, it is not possible to speculate on the reason(s) that these rocket motors are so dissimilar to the majority of rocket motors found at the site.

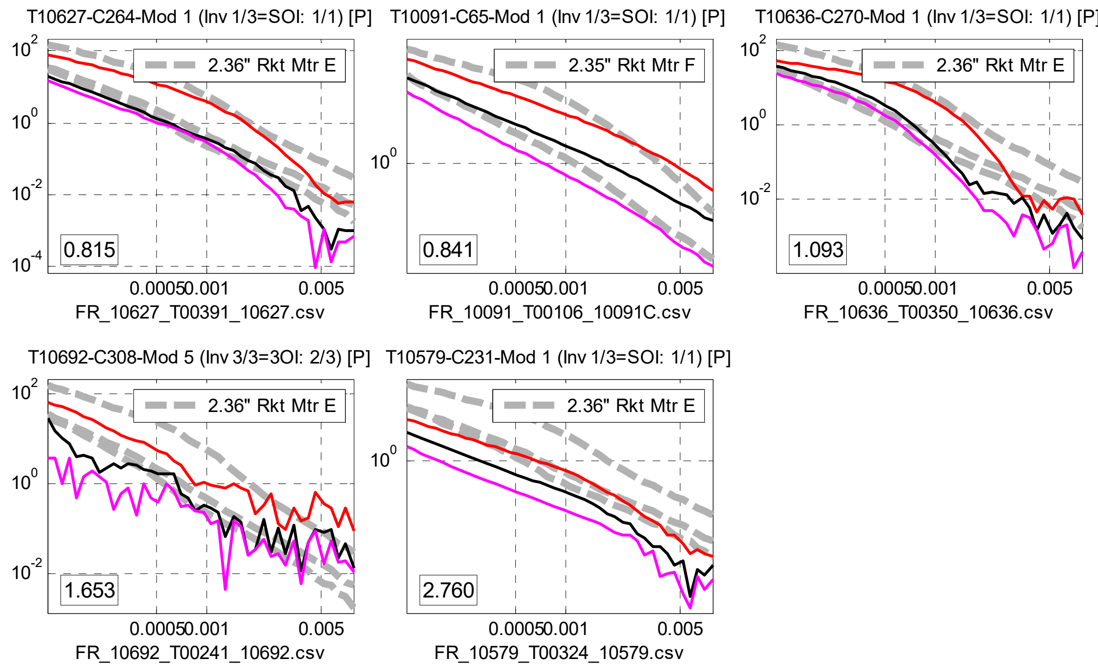

Figure 19. Predicted polarizabilities (red, black and magenta lines) for five missed 2.36" rocket motors and polarizabilities of the best fitting 2.36" rocket motor variant from our reference library (broken grey lines). Anomaly numbers appear in the title of each plot preceded by "T".

(8) FR-10553 - Dig 294 - 3.5" rocket motor at 15 cm depth

(9) FR-10510 - Dig 322 - 3.5" rocket motor at 36 cm depth & 6 pieces of frag

Figure 20 shows the predicted polarizabilities for the two missed 3.5" rocket motors compared to the polarizabilities of the best fitting 2.36" rocket motor variant in our reference library. Note that we are comparing the 3.5" motors to the 2.36" motors because, based on existing ground truth, all 3.5 rocket motors were excellent fits to the existing 2.36" rocket motor items in our reference library (in particular, the "1" and "F" variants; Figure 21). Presumably the motors for the two different types of ordnance are similar in size/shape. Both of the missed TOI are poor fits to the best-fitting 2.36" rocker motor reference item. The shape of polarizabilities for FR-10510 are vaguely similar to our "A" reference item, but the amplitudes are much lower and the tertiary polarizability is of poor quality (possibly because of the depth and/or large number of frag at this location), leading to a large misfit value.

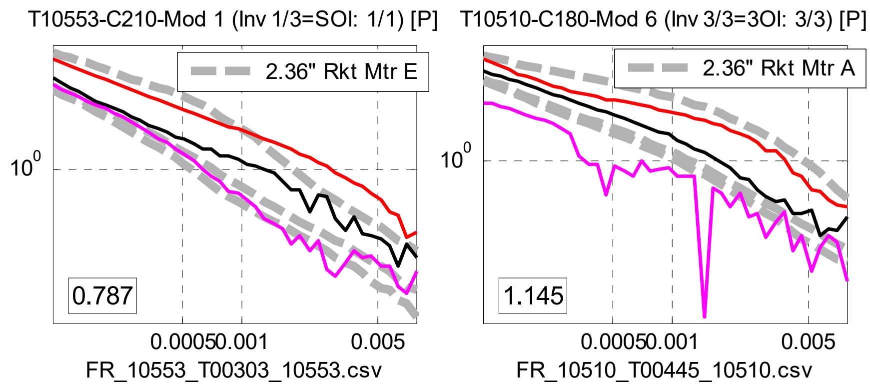

Figure 20. Predicted polarizabilities (red, black and magenta lines) for two missed 3.5" rocket motors (FR-10553 and FR-10510) and polarizabilities of the best fitting 2.36" rocket motor variant from our reference library (broken grey lines).

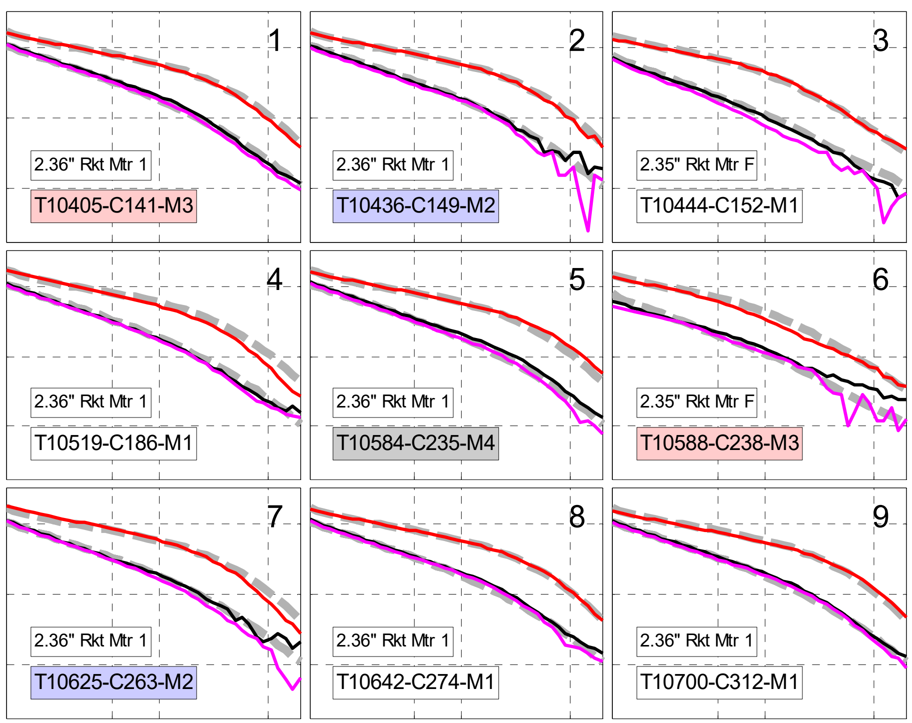

Figure 21. Predicted polarizabilities (red, black and magenta lines) for nine 3.5" rocket motors obtained from ground truth requests prior to the stage 5 dig list and polarizabilities of the best fitting 2.36" rocket motor variant from our reference library (broken grey lines).

(10) FR-10597 - Dig 295 - 2.36" rocket at 20 cm depth & 2 pieces of frag

Figure 22 shows the predicted polarizabilities for FR-10597 compared to the polarizabilities of the best fitting 2.36" rocket variant in our reference library. The two variants in or reference library (Figure 16 – library items 1 and 2) are quite similar to each other and bear no resemblance to the predicted polarizabilities for FR-10597; the latter has a primary polarizability of significantly lower amplitude. FR-10597 is moderately deep (20 cm) and is accompanied by 2 pieces of frag of unknown size and depth. These two factors may be responsible for the difference between predicted and reference polarizabilities; otherwise we suspect a possible error in the ground truth. Because of the large misfit, this item was not dug.

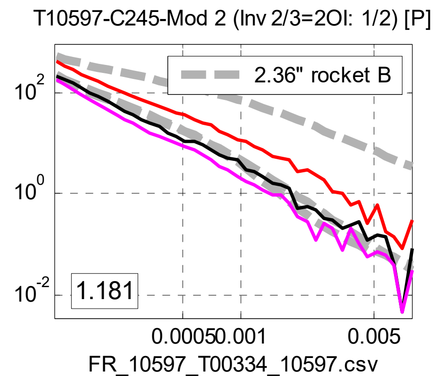

Figure 22. Predicted polarizabilities (red, black and magenta lines) for FR-10597 (2.36" rocket) and polarizabilities of the best fitting 2.36" rocket variant from our reference library (broken grey lines).

(11) FR-10284 - Dig 314 - 2.36" rocket warhead at 20 cm depth & 10 pieces of frag

(12) FR-10047 - Dig 325 - 2.36" rocket warhead at 5 cm depth & 5 pieces of frag

Figure 23 shows the predicted polarizabilities for the two missed 2.36" rocket warheads compared to the polarizabilities of the Mk 2 hand grenade from our reference library. We are comparing to the hand grenade because pre-stage 5 ground truth obtained for FR-10538 (2.36" rocket warhead) showed that polarizabilities for this item were very similar to those of the hand grenade, hence we did not add a specific set of reference polarizabilities for the warhead. The predicted polarizabilities for FR-10284 and FR-10047 were sufficiently different from the hand grenade that the large misfits resulted in them not being dug. It is likely that the large number of frag at each location may be responsible for poor polarizability match.

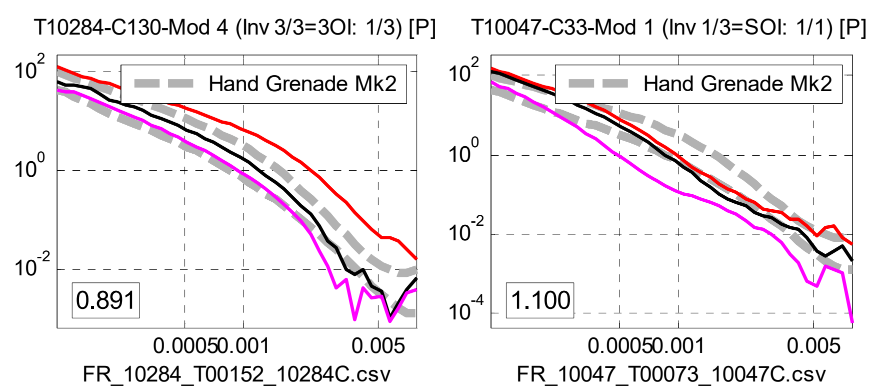

Figure 23. Predicted polarizabilities (red, black and magenta lines) for two missed 2.36" rocket warheads (FR-10284 and FR-10047) and polarizabilities of the Mk 2 hand grenade from our reference library (broken grey lines).

(13) FR-10171 - Dig 383 - Burial pit comprising 2.36" rocket at 61 cm depth & 118 rocket motors & target debris

Figure 24 shows the predicted polarizabilities for FR-10171 compared to the polarizabilities of the best-fitting item from our reference library. This is truly a one-off item, which stands out only because of its size (in terms of polarizability amplitude) – it is significantly larger than the largest item in our reference library (2.36" rocket). The predicted polarizabilities are not typical of UXO and the fits with our reference items are very poor, hence this anomaly ended up very late on our dig list. In retrospect, given the size of the predicted polarizabilities, training data should have been requested for this item.

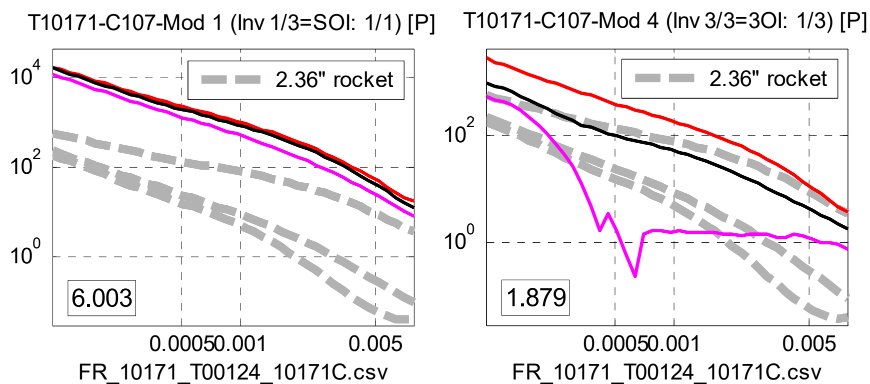

Figure 24. Predicted polarizabilities (red, black and magenta lines) for FR-10171, a burial pit comprising 2.36" rocket, 118 2.36" rocket motors and a large amount of target debris, and polarizabilities of the closest matching item from our reference library (2.36" rocket; broken grey lines). Polarizabilities for two different models are shown (left: single object inversion; right: three object inversion).

3.2.3.1 Summary of site difficulty

In retrospect it is clear that, with an objective of clearing 100% of the TOI at site, Fort Rucker is not an appropriate site for library based classification. Fifty percent of the targets (201 of 402) at the site are TOI. 167 of the 201 TOI are rocket motors and about 40% of these are multi object scenarios with multiple pieces of frag present. Because detailed ground truth information and photos are not available, the typical size and depth of the frag is unknown. Regardless, the large amount of frag is bound to result in recovered polarizabilities that in some cases will not be a good match to typical rocket motor polarizabilities.

Our "dataset degree of difficulty" is an objective measure of the likely difficulty of classification based on data and model metrics and the reference library used for classification. Our final measure of difficulty for Fort Rucker indicates it is essentially the most challenging ESTCP live site of those that were performed between 2011 and 2013 and processed by BTG. Measures of data and model quality for Fort Rucker are, in fact, relatively good compared to other sites. The main source of difficulty is the overlap in size-decay space of the majority of non-TOI features with some of the TOI features. I.e., much of the scrap at Fort Rucker has polarizabilities that look like TOI (particularly, rocket motors).