

DEMONSTRATION REPORT

TEMTADS 2X2 Survey
Andersen Air Force Base, Guam

ESTCP Project MR-201226

NOVEMBER 2017

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Executive Summary

This report describes advanced classification processing of TEMTADS2x2 time-domain electromagnetic data collected at Anderson Air Force Base, Guam. Black Tusk Geophysics processed approximately 1200 cued interrogations to recover estimates of intrinsic dipole polarizabilities for detected sources. Quality Control (QC) of the inversion results flagged high-likelihood TOI anomalies and failed bad models and inversions. In addition, estimated polarizabilities were used to identify potential novel targets of interest (TOI) at the site via cluster analysis and comparison with a comprehensive polarizability library. One TOI was found in the training request.

A dataset degree of difficulty (DDD) analysis indicated that the classification problem at this site was of moderate difficulty. Our classification approach used matching with a site-specific library to generate a prioritized diglist. The first stage classification diglist identified all 17 TOI seeded at the site: four 37 mm projectiles and 13 small industry standard objects (ISOs). Additional stages of the diglist were used to verify that no novel TOI were present. The final stop dig point identified all 17 TOI with 176 total digs. 88 non-TOI were excavated after the last TOI.

Retrospective analysis of the small ISO polarizabilities was consistent with the *a priori* DDD analysis: the spread of estimated polarizabilities indicates comparable data quality to previous ESTCP demonstrations with moderate classification difficulty (e.g. Spencer Range).

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Acronyms

| | |
|---------|---|
| AFB | Air Force Base |
| BTG | Black Tusk Geophysics |
| cm | Centimeter |
| CSV | Comma Separated Variable |
| DGM | Digital Geophysical Mapping |
| EM | Electromagnetic |
| ESTCP | Environmental Security Technology Certification Program |
| GPS | Global Positioning System |
| IVS | Instrument Verification Strip |
| m | Meter |
| mm | Millimeter |
| ms | Millisecond |
| MEC | Munitions and Explosives of Concern |
| MTADS | Multi-Sensor Towed Array Detection System |
| NRP | North Ramp Parking |
| QC | Quality Control |
| ROC | Receiver Operating Characteristic |
| s | Second |
| SOI | Single Object Inversion |
| 2OI | Two Object Inversion |
| 3OI | Three Object Inversion |
| TDEM | Time Domain Electromagnetic |
| TEMTADS | Time-Domain Electromagnetic MTADS |
| TOI | Target of Interest |
| UXO | Unexploded Ordnance |

1 Introduction

Andersen Air Force Base (AFB) is a United States Air Force base located on Guam. In 2014, an ESTCP munitions response study was carried out in the North Ramp Parking (NRP) area of Andersen AFB. The NRP area was undergoing a munitions and explosives of concern (MEC) removal action, and suspected MEC items at the site included:

- MK II Hand Grenades
- 20-mm, 105-mm, 155-mm, 5-inch, and 6-inch projectiles
- 60-mm and 81-mm mortars
- 100-lb bombs.

Advanced geophysical classification was incorporated into the digital geophysical mapping (DGM) phase of the removal action. The TEMTADS2x2, an advanced EMI system, was used to collect four acres of dynamic detection data at the site. Approximately 1200 anomalies were subsequently cued with the TEMTADS2x2.

This report summarizes the processing carried out by Black Tusk Geophysics on TEMTADS2x2 cued data collected as part of this demonstration.

2 Technology description

2.1 Detection

Advanced time-domain electromagnetic (TDEM) sensors have dramatically improved classification of buried MEC. In contrast to commercial standard mono-static sensors, the multi-static, multi-component geometries of next generation TDEM sensors provide diverse excitations of a detected target. Inversion of observed data using the parametric TDEM dipole model typically produces well-constrained estimates that can subsequently be input into a classification algorithm.

The TEMTADS2x2 (Figure 1) used for this demonstration is an advanced TDEM 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.

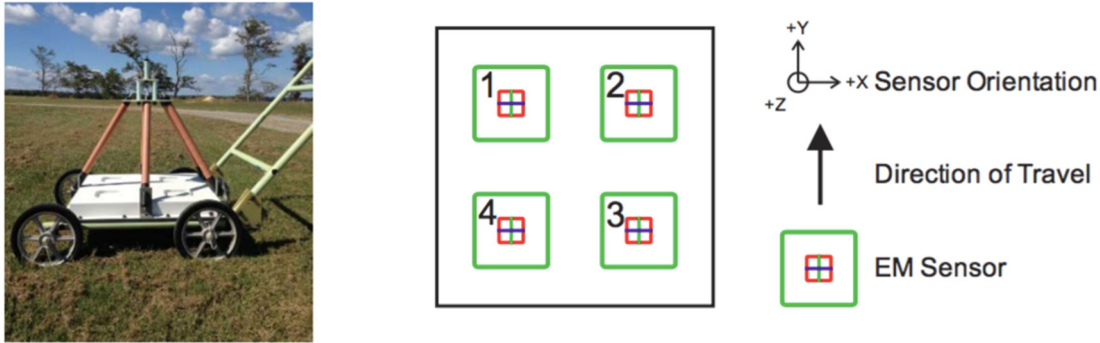


Figure 1. Left: Cued TEMTADS2x2 array with GPS mount. Right: Sensor geometry showing four transmitters (solid green lines) and concentric 3-axis receivers (red, green, blue lines). Image credits: TEMTADS2x2 user manual.

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 TEMTADS2x2 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 TEMTADS2x2 Processing

3.1 Feature extraction

TEMTADS2x2 cued data for all anomalies were received as a set of 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 22 cm. Noise standard deviation estimates were based on more than 80 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 eight 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 complete overview of the observed and predicted data, predicted model parameters, and measures of data/model quality. Display of the gridded dynamic TEMTADS2x2 data at each anomaly provides a useful visual indicator of the anomaly size and strength.

Predicted polarizabilities were compared to reference polarizabilities for various ordnance items initially derived from instrument verification strip (IVS) and test pit measurements. The Guam IVS comprised only four items: small, medium and large ISOs, and a shotput. Test pit measurements were made over 20mm, 37mm (three types) and a small ISO. As the analysis proceeded, the library of reference items was augmented with additional items based on a comparison with TOI from previous live sites, and from 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 < 50 mm; 2 for $50 < \text{diameter} \leq 100$ mm; and 3 for diameter > 100 mm) 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) flag 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 (i.e., significantly outside the footprint of the sensor). Bad models and inversions were identified in a semi-automated manner. For example, models were sorted by different measures of polarizability/data quality and a visual QC process focused 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 2)

In such 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 the Guam dataset, seven anomalies (GU-11, 279, 1894, 2791, 12195, 13375 and 134111) were classified as “cannot extract reliable parameters”. An example is shown in Figure 3. 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. For anomalies with recollects, the classification procedure will consider all passed models from all versions of the anomaly and use the one that is “best” based on the classification metric.

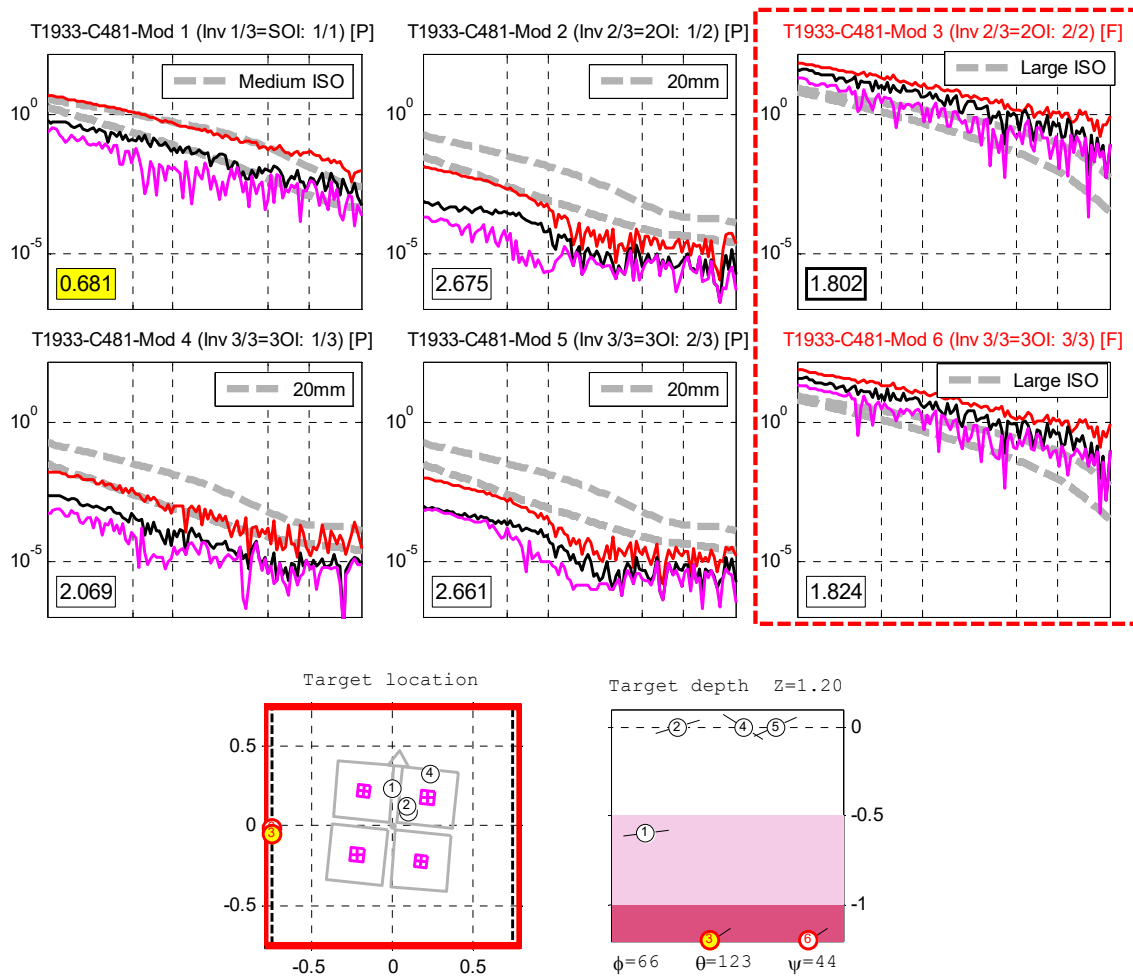


Figure 2. Example of an unrealistic models (GU-1933; cultural debris). Top row shows models from SOI and 2OI; middle row shows models from 3OI. For both models 3 and 6 (inside box with broken red lines) the predicted depths are 1.2m and the predicted horizontal location is on an inversion boundary (0.75m from the center of the instrument). The polarizabilities for both of these models are high in amplitude have a jittery appearance; these are classic signs that these models are an artifact of the multi-object inversion process. Accordingly, these models were failed during QC. Lower left plot shows predicted model locations (number circles) relative to the instrument receivers (grey lines) and transmitters (magenta lines). Models 3 and 6 are on the left edge. Broken black line denotes the horizontal inversion bounds. Plot at lower right shows predicted model depths (numbered circles).

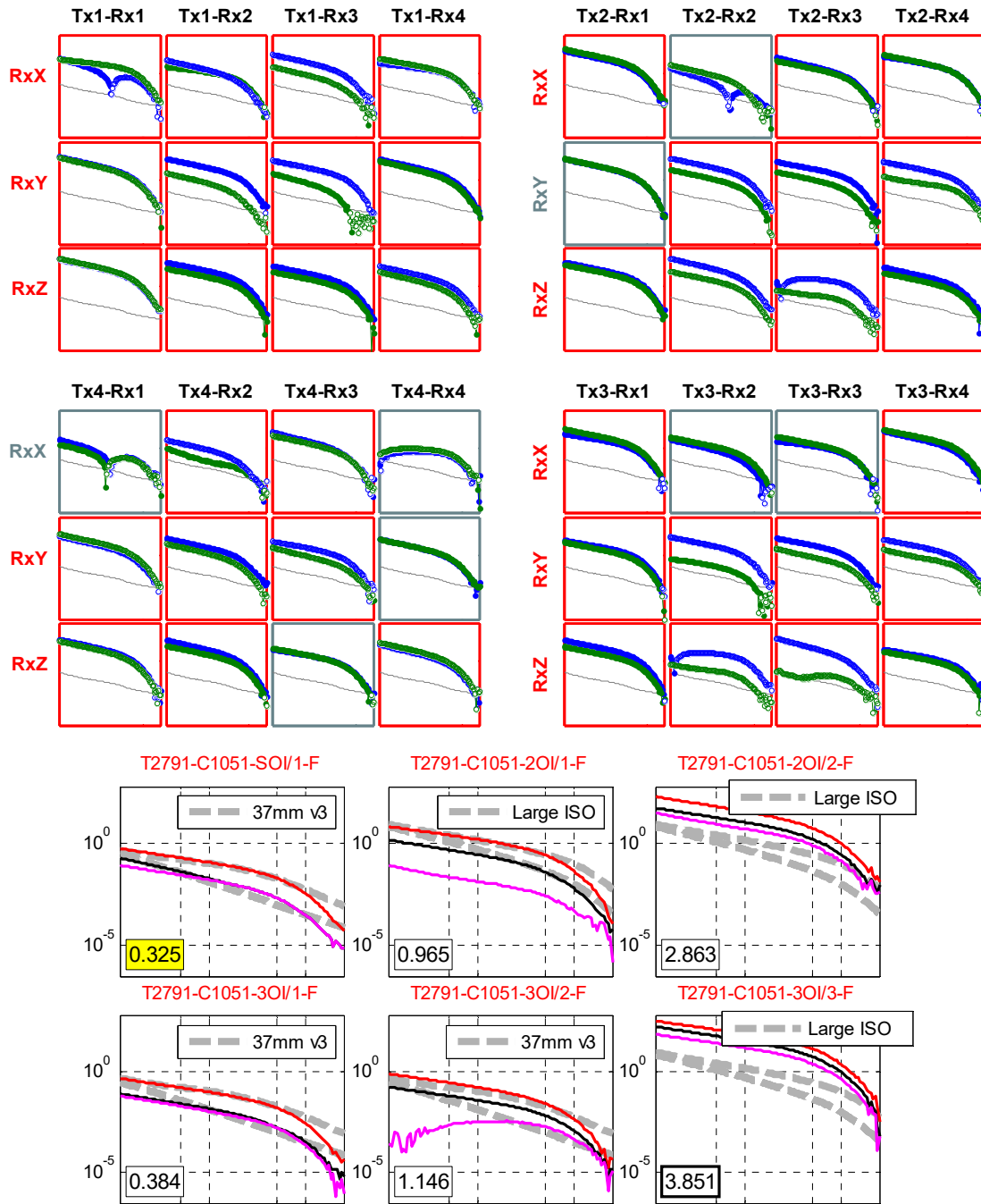


Figure 3. Example of an anomaly with no passed models (“cannot extract reliable parameters”): GU-2791; scrap metal at a depth of 16 cm. Top: data fits (blue = observed; green=predicted). Bottom: polarizabilities. The data fits for all inversions were very poor.

The Guam TEMTADS2x2 Cued dataset comprised 1194 unique anomalies. Data were not available for GU-1772, so this anomaly was treated as “cannot extract reliable parameters”. Of the 7836 total models (including models from recollects), 6848 were passed and used in the classification process; 988 were failed. Initially, 33 anomalies were classified as “high likelihood UXO” during QC; 17 of these (52%) correspond to actual TOI. The total number of unique TOI in the TEMTADS2x2 Cued dataset is 17, i.e., all TOI were identified during QC.

3.2 Classification

3.2.1 Training data selection

Figure 4 shows the distribution of models in decay versus size feature space. The overlap between the majority of features and reference items suggests that this may be a challenging site for classification because a relatively large proportion of the non-TOI will have size/decay characteristics similar to the TOI. Our *ad hoc* dataset degree of difficulty measure, which is based on various polarizability and dataset metrics, for this site suggests it will be significantly more difficult than MMR and Beale, but easier than Rucker and New Boston. This inference is based on the assumption that our ordnance library is appropriate for the site (i.e., all of the items present in our library will be found in the ground).

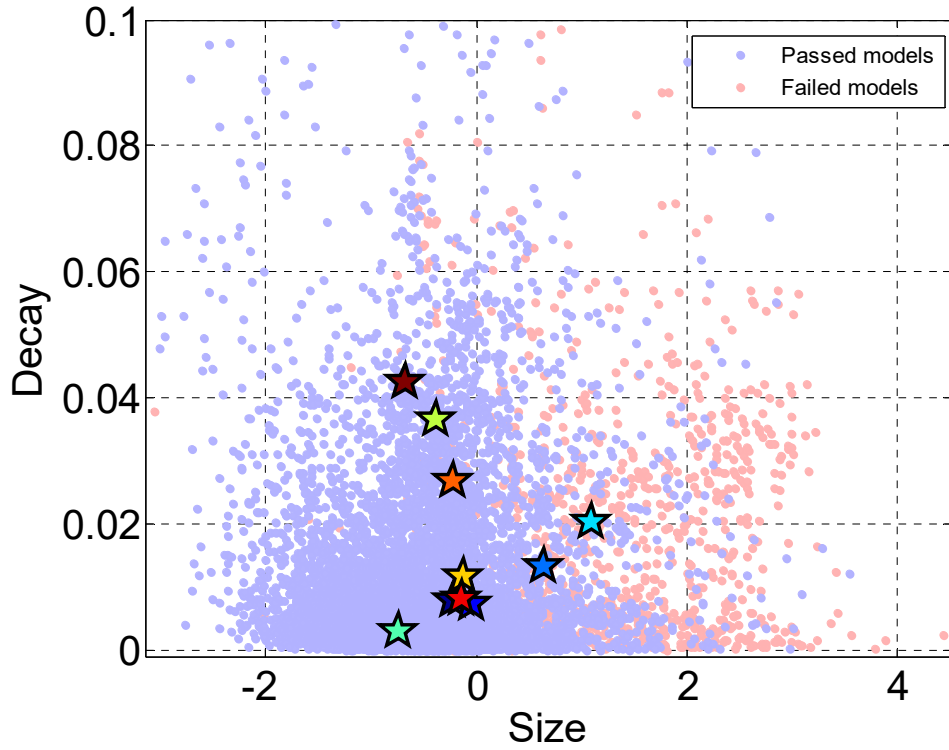


Figure 4. Distribution of models in Decay versus Size feature space. In this plot we define Size as the base 10 logarithm of the total polarizability measured at the first time channel ($t_1=0.117$ ms). We define the Decay as $\text{size}(t_{75})/\text{size}(t_1)$ where $t_{75}=5.232$ ms. A few outliers are not shown. Stars represent selected ordnance library reference items ranging in size from small ISOs and 20mm to large ISO (approximately equivalent to 105mm).

Our classification 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, were 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 \mathbf{M} with elements

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

where L_{total}^j 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.

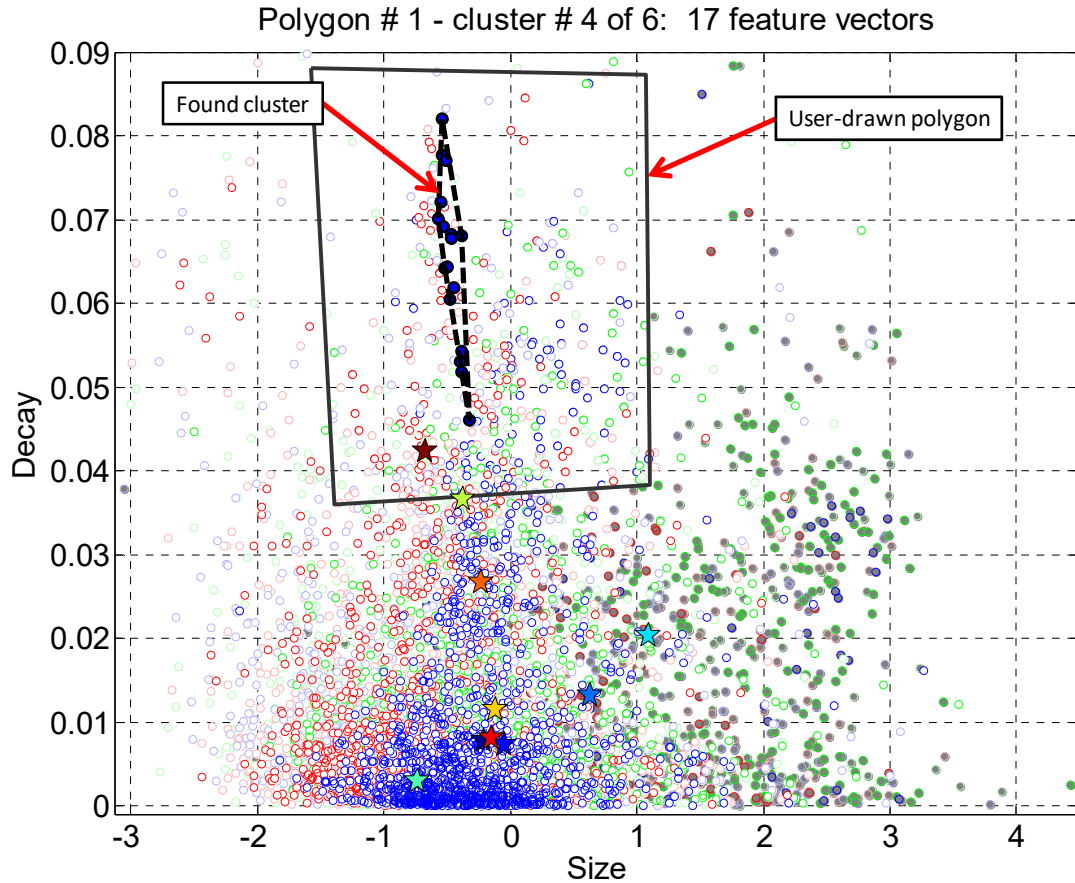


Figure 5. Example of use of the training data selection tool (*TrainZilla*). A polygon (solid black line) is drawn in feature space. Clusters of items with self-similar polarizabilities are automatically found based on the specified cluster search parameters. In this case a cluster comprising 17 features is visible (solid feature symbols encompassed by broken line). Polarizabilities for the models in this cluster are shown in Figure 6.

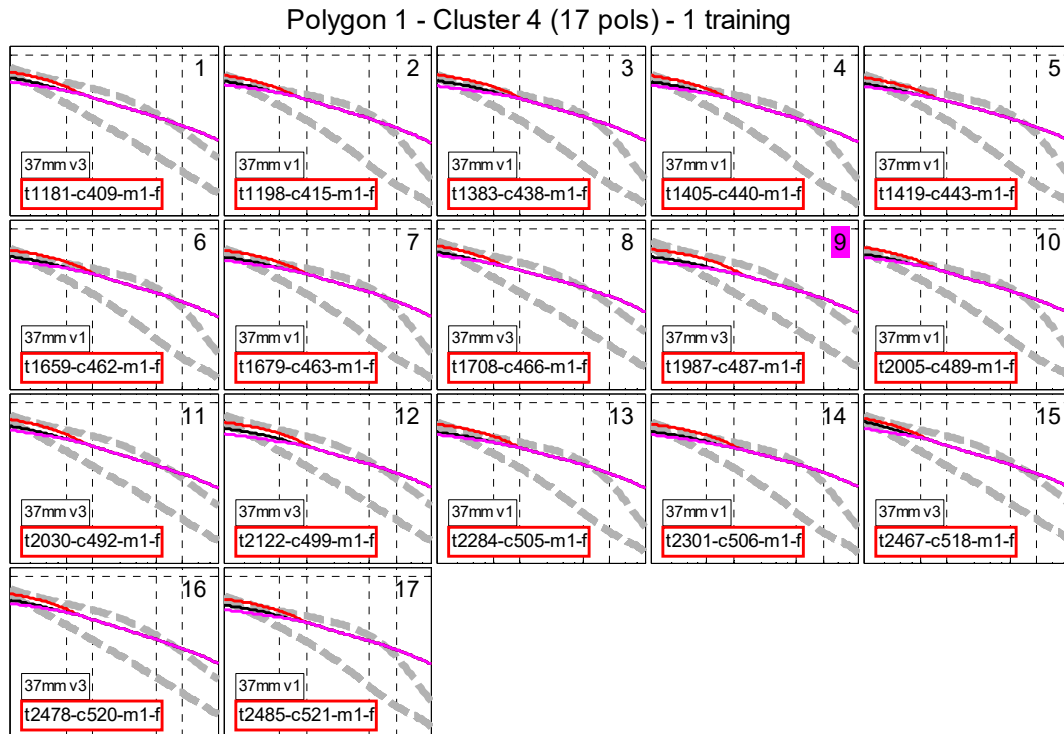


Figure 6. Polarizabilities for the models in the cluster shown in Figure 5. Colored lines (which are mostly on top of each other) are predicted polarizabilities. Broken grey lines are best fitting reference polarizabilities. Target labels are number following “t” in the bottom label of each plot. Training data were requested for the 9th item (magenta-highlighted index number). This turned out to be a non-TOI, though no description of the item was given in the provided ground truth.

Our training data requests typically focus on: (1) items whose polarizabilities exhibit UXO-like properties distinct from those of items in our reference library; (2) items with polarizabilities similar to items in our reference library, but with degraded quality; (3) items from a cluster that do not necessarily have UXO-like properties but are from an unknown source; and (4) one-off items.

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 7), which, for TEMTADS2x2 cued data, comprises polarizabilities for approximately 130 items (ranging in size from 20mm to 155mm) from past ESTCP live site demonstrations. Approximately 100 of these items were derived from the UX-Analyze

polarizability library. With the *Ordnance Museum*, we can easily search for models in our dataset with similar polarizabilities to any of the museum items. For Guam 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 8. We requested training data for these items; all were non-TOI.

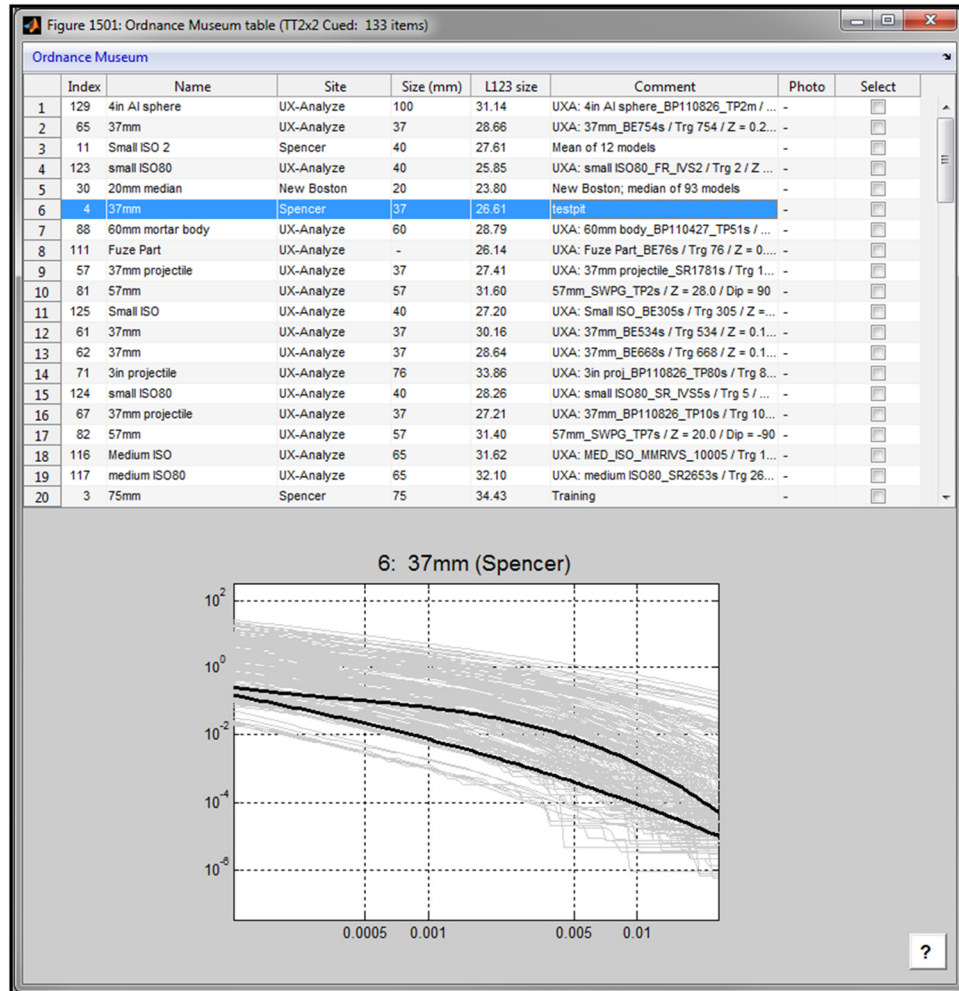


Figure 7. *UXOLab Ordnance Museum* interface. This is a library of reference polarizabilities compiled from several ESTCP live site demonstrations, and other projects. The ordnance museum for TEMTADS2x2 Cued data currently comprises approximately 130 items ranging in size from 20mm to 155mm projectiles.

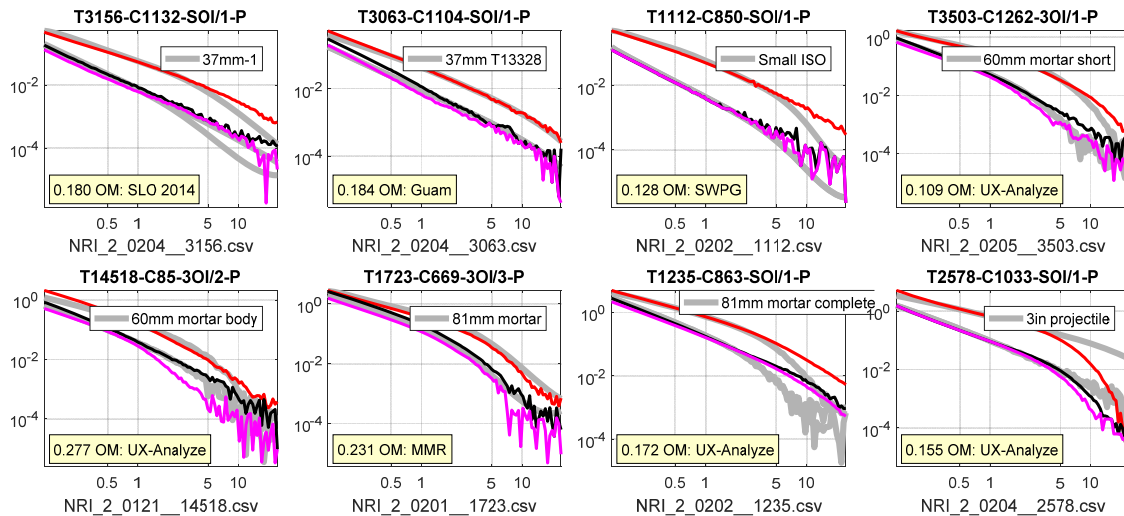


Figure 8. Polarizabilities of eight models with close matches to items in the *Ordnance Museum*. Anomaly labels are the number following the “T” in each plot title. Label at top right of each plot is best fitting ordnance museum item name. Box at bottom left in each plot shows the polarizability misfit and source of the model. We requested training data for these items; all were non-TOI.

We submitted three training requests prior to submitting our first dig list for a total of 40 training items. Only one of these was a TOI: GU-13341 (small ISO). Although our training data did not reveal any 20mm, medium ISO or large ISO items, to be conservative, we left these items in our classification ordnance library.

3.2.2 Classification method

Our dig lists were developed using our visual classification software *DigZilla* (Figure 9), 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.

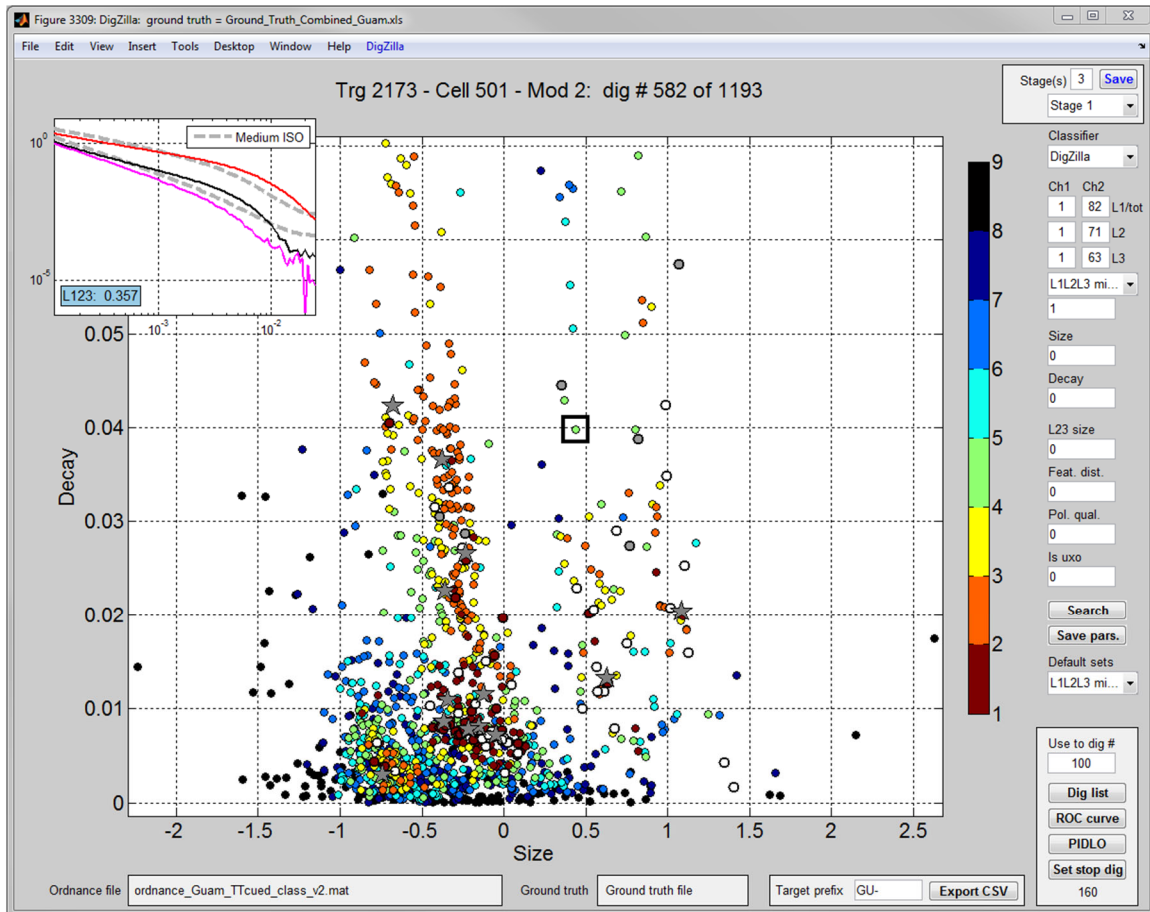


Figure 9. Screen shot of the *UXOLab DigZilla* graphical user interface. Features in the decay versus size feature plot are color coded according to dig list order. Stars are reference items.

Our initial (stage 1) dig list used a classification approach based on polarizability misfit (to the best fitting library reference item for each model) using all three polarizabilities. Misfits were calculated between the first time channel (0.12 ms) and channels 82 (7.49 ms), 71 (4.26 ms) and 63 (2.83 ms), respectively for L1, L2 and L3. The end time channels for the misfits were determined automatically based on a measure of polarizability reliability. The ordnance library used for our first dig list comprised 11 items (Figure 10). The stop dig point for this list was dig number 160.

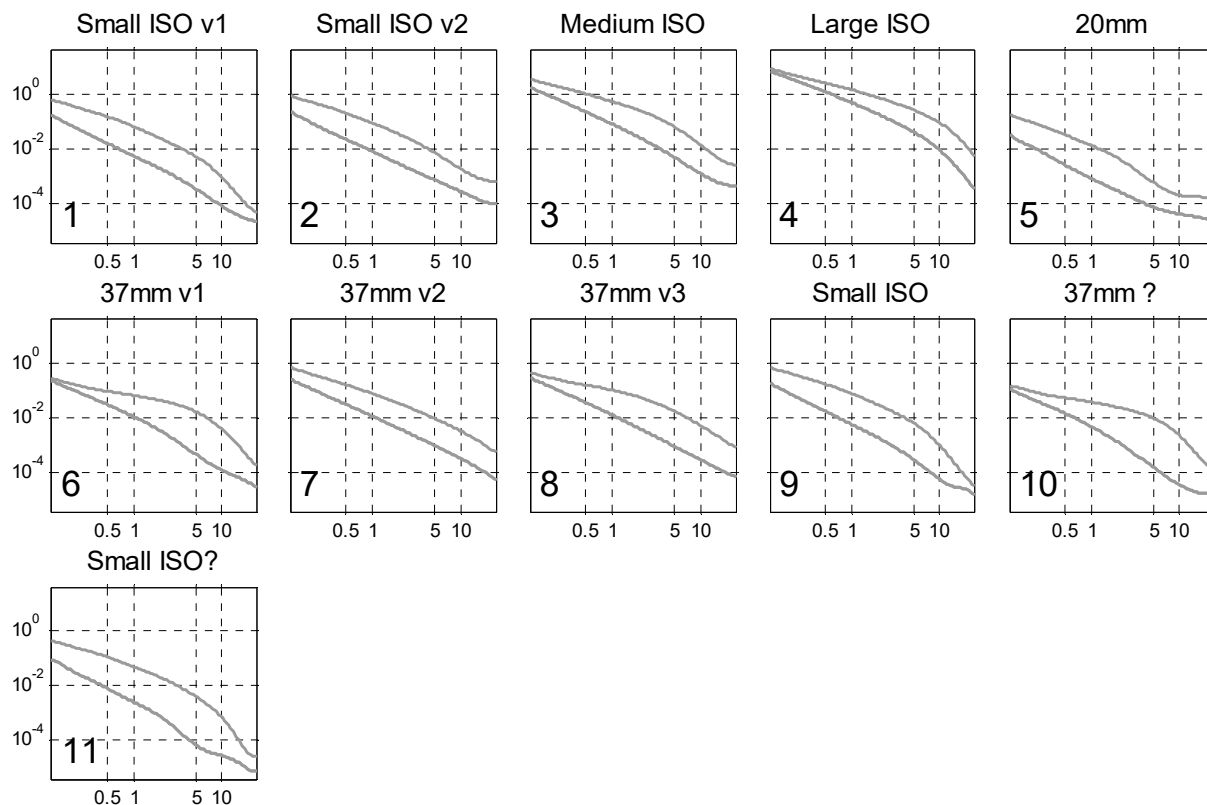


Figure 10. Items in the ordnance reference library used for the stage 1 dig list.

Our stage 1 dig list found all of the QC seeds; the partial ROC curve is shown in Figure 11. The stage 1 list found 16 TOI. Although not all of the TOI are explicitly identified in the available ground truth file they appear to be small ISOs and 37mm projectiles (Figure 12).

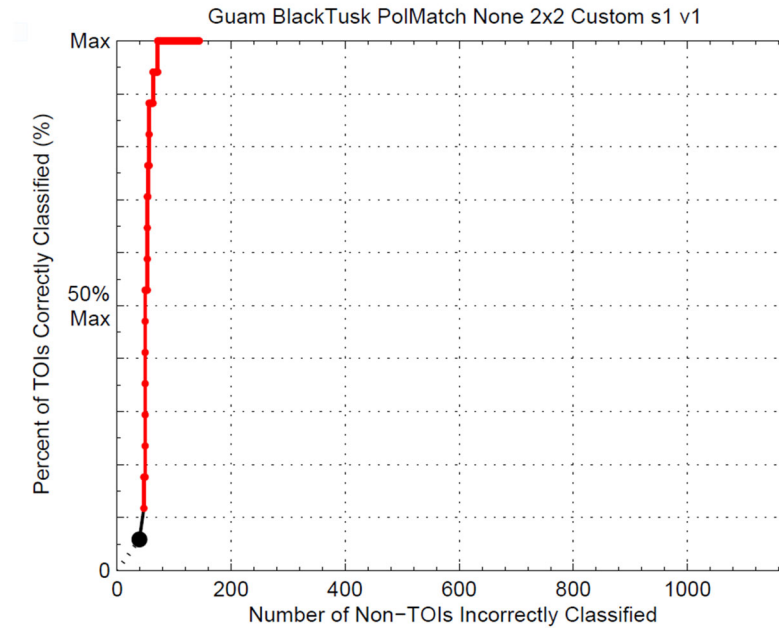


Figure 11. Partial ROC curve for the stage 1 dig list.

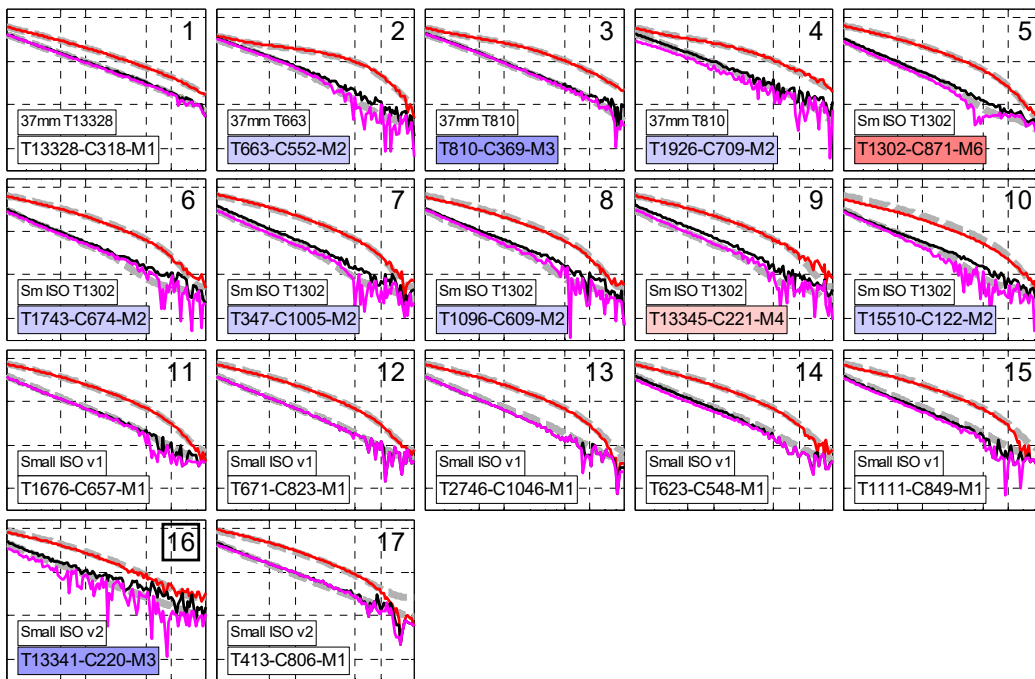


Figure 12. Polarizabilities for TOI identified in ground truth. Item 16 was found in training. The rest were found in the ground truth for the stage 1 dig list. All items are 37mm projectiles or small ISOs.

Based on the stage 1 ground truth we added a few variants of the small ISO and 37mm to the ordnance library. Using the same classification approach used for stage 1 with the augmented ordnance library, we decided to dig a further 12 targets (stopping at dig number 172). The stage 2 dig list found no additional TOI. After additional visual inspection of the polarizabilities plotted in dig list order, we decided to dig an additional 3 targets with TOI-like polarizabilities. These three items were moved up manually on the dig list. The stage 3 stop dig point was then dig number 175. All three of these items turned out to be non-TOI.

By fitting the stage 3 ROC curve to a binormal model it is possible to estimate the posterior probability that each target is a UXO (Beran and Zelt, 2014). Doing so (Figure 13) shows that at the 98.5% confidence level, all TOI have been dug. Additional visual inspection of the polarizabilities after the stage 3 stop dig point supports the assertion that, with very high confidence, all TOI have been dug. The stage 3 dig list was our final dig list.

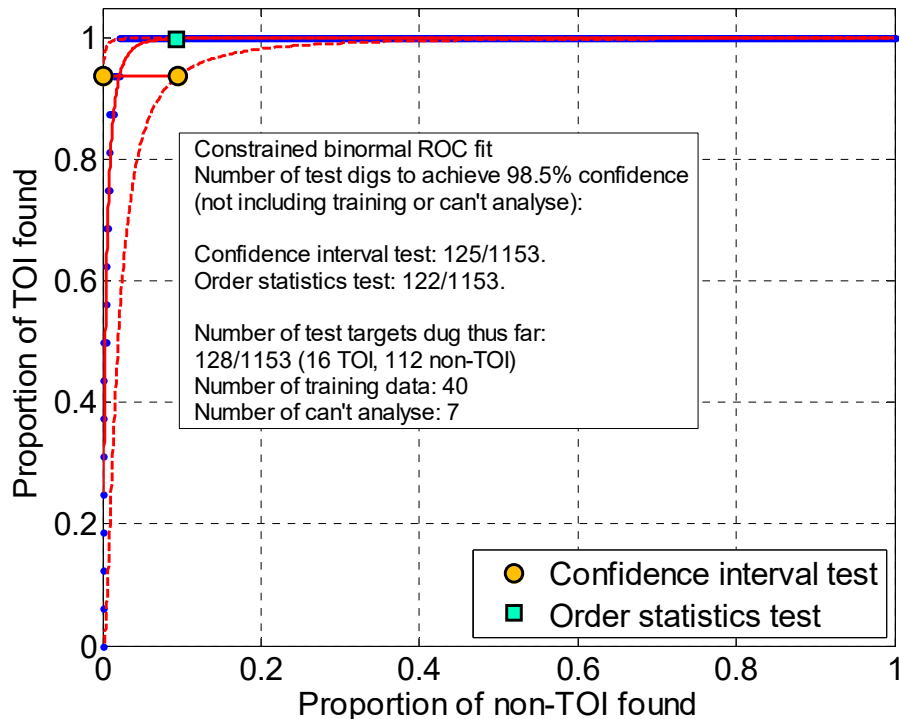


Figure 13. Results of statistical tests, which show that at the 98.5% confidence interval we have found all TOI.

The final dig list found all TOI before the stop dig point (Figure 14). We dug 176 items to find 17 TOI, which gives a FAR of 10.35 non-TOI digs per TOI dig.

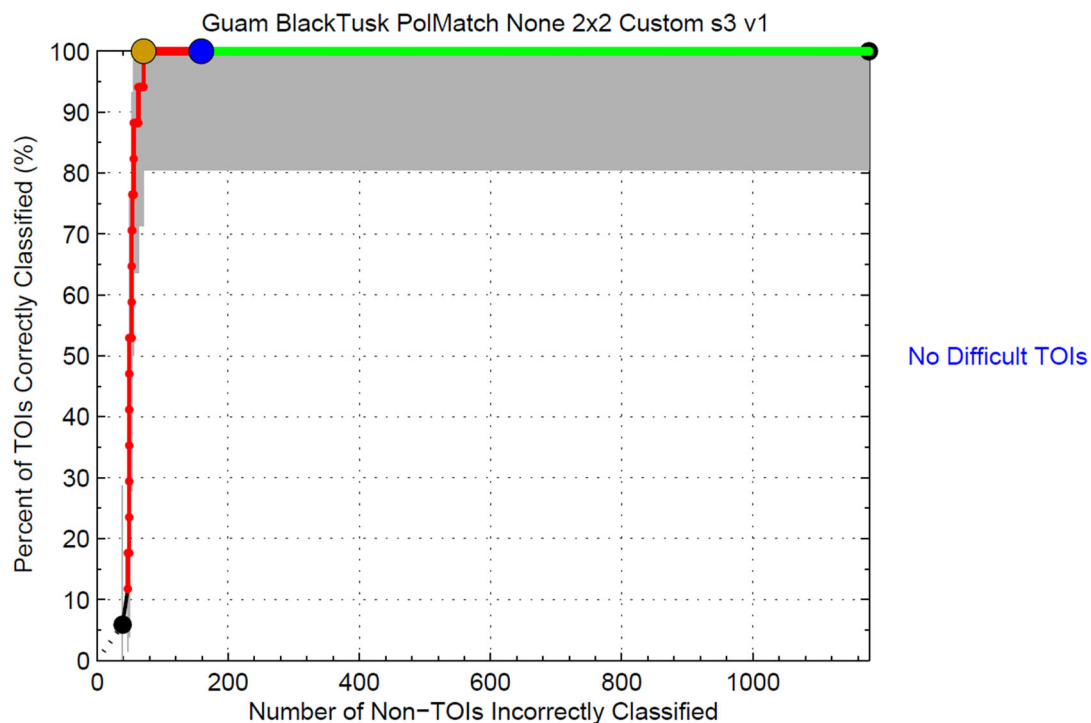


Figure 14. Final ROC curve. All TOI were found before the stop dig point (dig number 176). We dug 88 non-TOI after the last TOI (GU-15510, dig number 88) was found.

3.2.3 TEMTADS2x2 cued retrospective analysis

3.2.3.1 *Small ISO consistency as measure of site difficulty*

Small ISOs have been used as seed items at a number of Live Site demonstrations starting in 2011. The consistency of the recovered polarizabilities at each site can be viewed as a measure of the difficulty of each site for classification. Figure 15 shows the recovered polarizabilities for all small ISO anomalies at Guam.

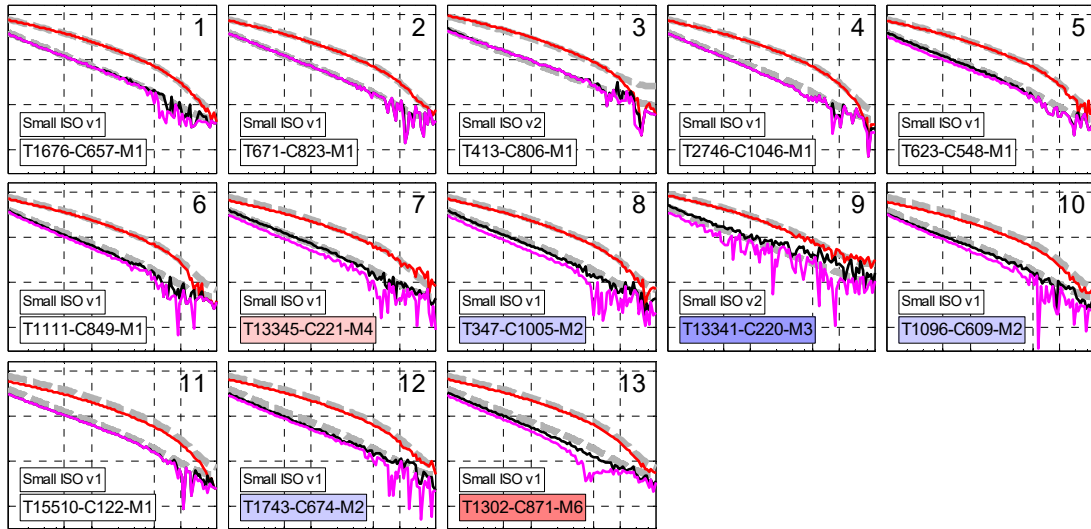


Figure 15. Polarizabilities for the 13 small ISOs at Guam. Colored lines are predicted polarizabilities. Broken grey lines are small ISO reference polarizabilities taken from IVS measurements. Anomaly ID is the number after the “T” in each label. Polarizabilities are sorted by misfit (from best to worst) with respect to the small ISO reference models.

Figure 16 shows a compilation of the polarizabilities for small ISOs at recent Live Site demonstrations. The mean misfit values, calculated with respect to the median of the set of polarizabilities, is a good measure of site difficulty.

Of the previous sites shown, Waikoloa and Beale are the most challenging. The Beale Parsons and Beale CH2M Hill data sets comprise the same set of anomalies and the data were collected using the same MetalMapper instrument. For reasons that are not totally clear, but most likely related to differences in field practices, the Beale Parsons data resulted in more consistent ISO polarizabilities than the Beale CH2M Hill data. The excellent consistency of the Pole Mountain ISO polarizabilities reflects that site’s reputation as an easy site for classification. The Spencer URS ISO polarizabilities are slightly less consistent than the those from Pole Mountain, suggesting it is a slightly more challenging site. The consistency of the polarizabilities for the Spencer dataset collected by NAEVA is marginally better than that of the URS dataset. The consistency of the Camp Ellis ISO polarizabilities actually exceeds that seen at Pole Mountain; however, note that the small ISOs used at Pole Mountain and Beale were slightly different (thinner walls) than the ISOs used at the other sites. Regardless, the consistency of the Ellis ISO polarizabilities is a good reflection of the relative ease of classification at this site. The Waikoloa small ISO dataset is small (only 10 samples) and all ISOs were located in a single area (TO17)

with a strong soil response. The large misfit value (0.155) is indicative of a very challenging site, and it is likely that the overall poor consistency of the small ISOs at Waikoloa results from the strong soil response. All of these previous sites were MetalMapper surveys. Castner Range is a TEMTADS2x2 dataset. The relatively large misfit is somewhat skewed by two very difficult small ISOs (CR-754 and CR-780), both of which were outside the footprint of the sensor and both of which had a fuze on the surface beneath the center of the sensor. Ignoring these two results in a misfit of 0.072 for Castner Range. The Guam small ISO sample size is fairly small (13), but the consistency is good (similar to Spencer), with a misfit value of 0.054. The consistency is an accurate indicator of the relative ease of classification at this site.

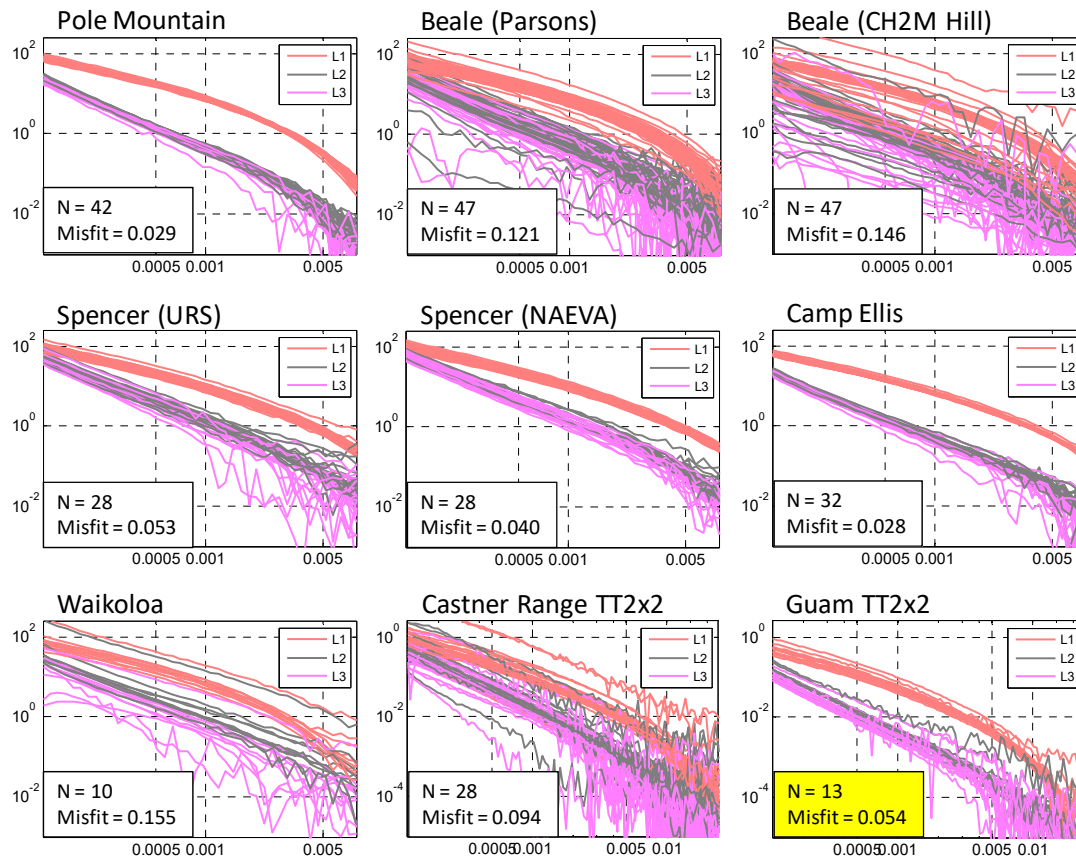


Figure 16. Compilations of polarizabilities for small ISOs from recent Live Site demonstrations. The two Beale and Spencer datasets each comprise the same set of anomalies but the data were collected by two different companies. The small ISOs used for Pole Mountain and Beale had slightly thinner walls relative to the ones used at later live site demonstrations. Misfit values are the mean misfits with respect to the median calculated over all time channels using all three polarizabilities (L1, L2 and L3). All but the Castner Range and Guam results are based on MetalMapper data.

4 Conclusions

Processing of TEMTADS2x2 data collected at Guam presented no significant challenges for advanced classification. All seeded TOI were readily identified with a minimal number of non-TOI digs using our standard data processing procedures.

5 References

Beran, L and Zelt, B. “Risk Assessment for Unexploded Ordnance Remediation.” *Stochastic Environmental Research and Risk Assessment*, vol. 29 no.1 (March 2015): p1051-1061.