ESTCP

FINAL REPORT

Analysis of Multi-axis, Multi-coil EMI Sensor Data for UXO Classification

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ACRONYMS AND ABBREVIATIONS

BRAC	Base Realignment and Closure
ESTCP	Environmental Security Technology Certification Program
FUDS	Formerly Used Defense Site
GPS	Global Positioning System
IDA	Institute for Defense Analyses
IMU	Inertial Measurement Unit
ISO	Industry Standard Object
IVS	Instrument Verification Strip
MMRP	Military Munitions Response Program
QC	Quality Control
RMS	Root Mean Square
SERDP	Strategic Environmental Research and Development Program
TOI	Target of Interest
UXO	Unexploded Ordnance

ABSTRACT

The focus of this project was to design and demonstrate an application for processing and analyzing electromagnetic induction (EMI) for the purpose of successfully classifying military munitions that are buried in the ground and not visually identifiable. Our primary objective was to create a software environment and capabilities for analyzing data acquired by advanced EMI sensors that is transparent, modular, and commercially available, and demonstrate the software's capabilities.

UX-Analyze provides the means and methods to analyze EMI sensor data for the purposes of classifying UXO. It is transparent, modular, and commercially available and can be used for dynamic and static survey data. At a high level, data from classification-grade EMI sensors are first characterized by means of a solver, then classified based on quantitative model parameters associated with the characterization.

UX-Analyze is embedded into Oasis montaj and activated using their commercial licensing scheme. Data handling, processing, analysis, and documentation tools are included. Specific capabilities include (1) support for, and inversion of, multi-coil, multi-axis EMI data, (2) a modularized workflow, (3) single and multi-source solvers, (4) quality control checks and standard products, and (5) online help & documentation. Customized GUIs streamline the inversion and classification phases. Once processed, the analyst utilizes an information rich, analysis environment to review the decision rationale.

Our primary technical performance metric of correctly classifying all TOI was achieved. The clutter rejection rate at the analysts' threshold was 86%, which easily surpassed the desired rejection rate of 50%. Less than 1% of the anomalies were classified as Cannot Analyze, which also passed the desired benchmark. The XY offsets for TOI had a standard deviation of 0.17m. The XY offsets for all sources, regardless of TOI or not, was 0.36m. The performance metric objective of 0.15m for the horizontal standard deviation or less was not achieved

We did not run into any major implementation issues. Although major changes have been made to modularize the code and simplify the process, the workflow presents many options during analysis and is still perhaps a bit too verbose. Most of these relate to making the machine work harder so that the analyst can focus on assessment of the decisions and data quality. As design-lead of the UX-Analyze software suite, we want to strike a balance between providing options versus unnecessary complications.

EXECUTIVE SUMMARY

INTRODUCTION

The focus of this project was to design and demonstrate an application for processing and analyzing electromagnetic induction (EMI) for the purpose of successfully classifying military munitions that are buried in the ground and not visually identifiable.

OBJECTIVE

Create a software environment and capabilities for analyzing data acquired by advanced EMI sensors that is transparent, modular, and commercially available, and demonstrate the software's capabilities.

TECHNICAL DESCRIPTION

UX-Analyze provides the means and methods to analyze EMI sensor data for the purposes of classifying UXO. It is transparent, modular, and commercially available and can be used for dynamic and static survey data. At a high level, data from classification-grade EMI sensors are first characterized by means of a solver, then classified based on quantitative model parameters associated with the characterization (Figure 1).

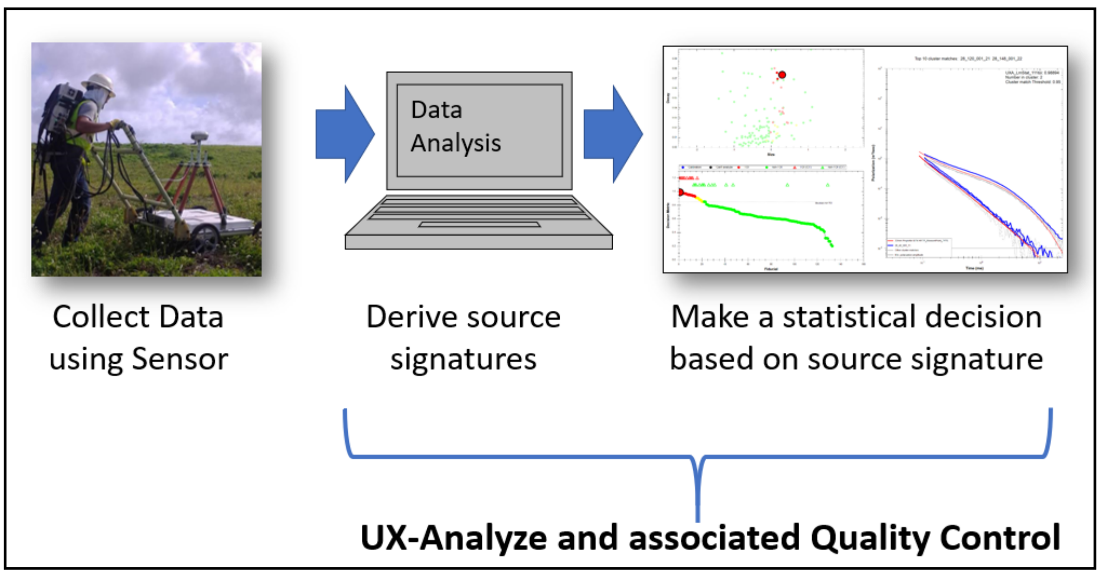

Figure 1. Advanced Geophysical Classification (AGC) Data Collection and Analysis Flow.

The technology developed under this program is a combination of (i) Oasis montaj - a software application that focusses on georeferenced data and serves the MMRP community, (ii) analysis algorithms for the quantitative characterization of EMI data, and (iii) advanced geophysical instruments capable of high quality, broadband EMI data (Figure 2).

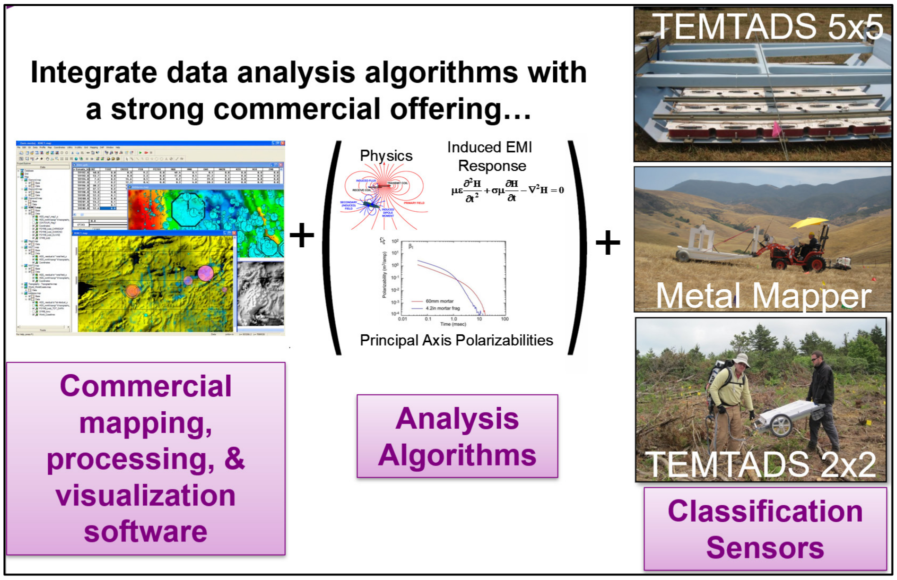

Figure 2. Conceptual Model of UX-Analyze – the Sum of a Commercial Mapping and Data Handling Software Package, Physics-based Analysis Algorithms and Statistical Classifiers, and Prototype Advanced EMI Sensors.

UX-Analyze is embedded into Oasis montaj and activated using their commercial licensing scheme. Data handling, processing, analysis, and documentation tools are included. Specific capabilities include (1) support for, and inversion of, multi-coil, multi-axis EMI data, (2) a modularized workflow, (3) single and multi-source solvers, (4) quality control checks and standard products, and (5) online help & documentation.

Customized GUIs streamline the inversion and classification phases. Once processed, the analyst utilizes an information rich, analysis environment to review the decision rationale (Figure 3).

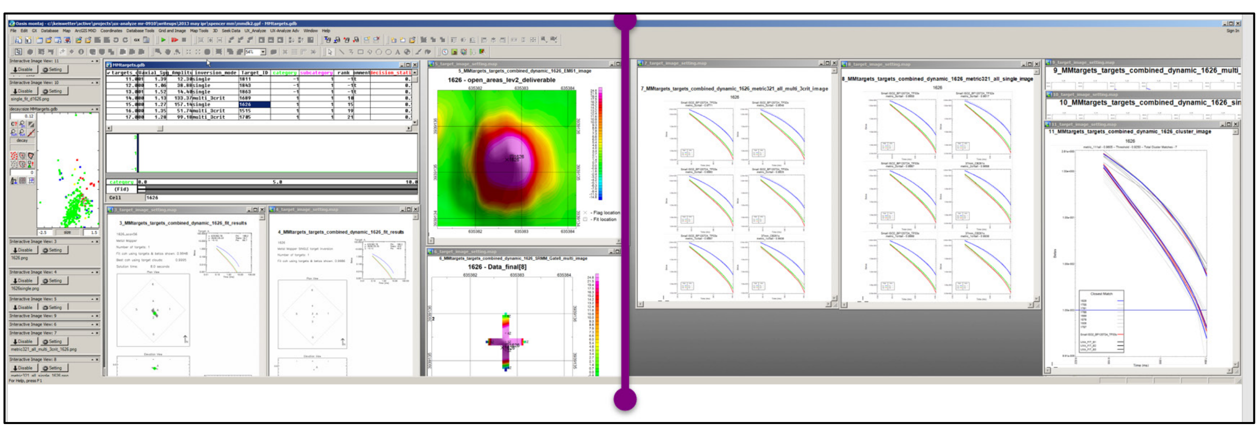

Figure 3. Interactive Review with Multiple Linked Views, Including Scatter Plots, Databases, Images, and Polarizations.

A mouse click in the scatterplot or database changes all images automatically.

PERFORMANCE ASSESSMENT

Objective: Maximize Correct Classification of TOI: All TOI were correctly classified at the operator's stop dig point. Performance metric passed.

Objective: Maximize Correct Classification of Non-TOI: Our classification dig list incorrectly classified 300 of the 2,117 non-TOI. In other words, 14% of the clutter items were incorrectly classified. Performance metric of less than 50% passed.

Objective: Correct Specification of No-dig Threshold: All TOI at the site were correctly identified as TOI, and the number of false positives was reduced by more than 50 percent of the total number of false positives. Performance metric passed.

Objective: Minimize Number of Anomalies that Cannot be Analyzed: Our classification dig list included five out of 2,368 sources as Cannot be Analyzed. This equates to less than 1%. Performance metric of less than 2% achieved.

Objective: Correct Estimation of Source Parameters: The XY offsets for TOI had a standard deviation of 0.17m. The XY offsets for all sources, regardless of TOI or not, was 0.36m. The performance metric objective of 0.15m for the horizontal standard deviation or less was not achieved.

COST ASSESSMENT

We tracked analysts' labor while processing, analyzing, and reviewing the classification decision. Assuming an hourly rate of $120/hour, the cost per decision for this demonstration was approximately $23.

The mix of TOI and clutter at this site allowed the classification method to work well. The costs reported above reflect the fact that we repeated the analysis a few times with different inversion parameters. As such, they are higher than they could have been. That said, the reported costs are probably low if future sites have conditions in which the polarizabilities from the TOI and non-TOI are more similar.

The benefit of the classification method is two-fold. The primary benefit relates to the fact that the decision is documented and transparent. All sensor data are preserved, and the basis of the classification decision is clear. This is true for all non-TOI as well as TOI. The information regarding the non-TOI is very valuable when trying to establish residual risk. A secondary benefit relates to cost. To be effective and widely utilized, the cost of the classification method should be close, or preferably less, than the costs of excavating all encountered sources. Classification methods should be employed even if the classification method is more expensive than the non-classification method, however, because the quality control and archived data products regarding residual sources is so much better than conventional methods.

IMPLEMENTATION ISSUES

We did not run into any major implementation issues. Although major changes have been made to modularize the code and simplify the process, the workflow presents many options during analysis and is still perhaps a bit too verbose. Most of these relate to making the machine work harder so that the analyst can focus on assessment of the decisions and data quality. As design-lead of the UX-Analyze software suite, we want to strike a balance between providing options versus unnecessary complications.

1.0 INTRODUCTION

The focus of this project was to design and demonstrate an application for processing and analyzing electromagnetic induction for the purpose of successfully classifying military munitions that are buried in the ground and not visually identifiable.

1.1 BACKGROUND

In 2003, the Defense Science Board [1] observed: "The … problem is that instruments that can detect the buried UXOs also detect numerous scrap metal objects and other artifacts, which leads to an enormous amount of expensive digging. Typically, 100 holes may be dug before a real UXO is unearthed! The Task Force assessment is that much of this wasteful digging can be eliminated using more advanced technology instruments that exploit modern digital processing and advanced multi-mode sensors to achieve an improved level of discrimination of scrap from UXOs."

Since that report, SERDP and ESTCP have invested heavily in developing survey data analysis and processing techniques for use with commercial sensors that can improve UXO detection and discrimination between UXO and clutter. These techniques include characterization procedures for estimating target features from survey data (size, shape, depth of burial, orientation, etc.) and feature-based classification procedures to aid decision-making. These research-grade algorithms had not been readily available to the user community at the time of this project, however, and had limited exposure to data acquired under 'production-imposed' constraints.

A technology transfer objective of this project is to make available and document the capabilities of feature-based discrimination techniques. Major tasks include (i) transitioning physics-based characterization and classification algorithms for advanced electromagnetic induction data to a commercial product, and (ii) conducting demonstrations at live sites with the aim of discriminating targets of interest from targets that are not of interest to mitigate risk during the recovery process.

Our technical approach promotes the selection of potential UXO targets using quantitative evaluation criteria and transparent decision-making processes. As such, we developed UX-Analyze, an analysis framework within Oasis montaj™ that integrates quantitative analysis algorithms and custom-designed visualization schemes. The analysis algorithms provide quantitative evaluation criteria (e.g., target characterization and classification). Transparency is achieved by leveraging the professional, flexible, and visual computing environment inherent in Oasis montaj™. Oasis montaj™ is a geophysical data processing and visualization package developed and marketed by Geosoft Incorporated. It has a large capacity database, a professional graphic interface, and an established client base. Oasis montaj™ was selected to leverage its significant capabilities, marketing channels, and customer support services.

The demonstrations discussed later were part conducted in support of ESTCP's UXO Classification Program. The objectives of the program were to (i) test and validate UXO detection and discrimination capabilities of available and emerging technologies on real sites under operational conditions, and (ii) investigate how UXO discrimination technologies can be implemented in cleanup operations.

The UXO Classification Program was designed to test and evaluate the capabilities of various UXO discrimination processes which each consist of a selected sensor hardware, a survey mode, and a software-based processing step. These advanced methods were compared to existing practices and used to validate the pilot technologies for the (i) detection of UXO; (ii) identification of features that can help distinguish scrap and other clutter from UXO; (iii) reduction of false alarms while maintaining detection probabilities that are acceptable to all; and finally, to (iv) quantify the cost and time impact of advanced methods on the overall cleanup process as compared to existing practices.

1.2 OBJECTIVE

Create a software environment for analyzing data acquired by advanced electromagnetic induction (EMI) sensors that is transparent, modular, and commercially available, and demonstrate the software's capabilities.

1.3 REGULATORY DRIVERS

In addition to the report by the Defense Science Board [1] mentioned above, Senate Report 106-50 [pages 291–293, accompanying the *National Defense Authorization Act for Fiscal Year 2000* (Public Law 106-65)], included a provision entitled "Research and development to support unexploded ordnance clearance, active range unexploded ordnance clearance, and explosive ordnance disposal." This provision requires the Secretary of Defense to submit to the Congressional defense committees a report that gives a complete estimate of the current and projected costs, to include funding shortfalls, for UXO response at active facilities, installations subject to base realignment and closure (BRAC), and formerly used defense sites (FUDS).

The following statements are taken verbatim out of the DoDs 2001 Report to Congress [2]:

"Decades of military training, exercises, and testing of weapons systems has required that we begin to focus our response on the challenges of UXO. Land acreage potentially containing UXO has grown to include active military sites and land transferring or transferred for private use, such as Base Realignment and Closure (BRAC) sites and Formerly Used Defense Sites (FUDS). DoD responsibilities include protecting personnel and the public from explosive safety hazards; UXO site cleanup project management; ensuring compliance with federal, state, and local laws and environmental regulations; assumption of liability; and appropriate interactions with the public.

…Through limited experience gained in executing these activities, it has become increasingly clear that the full size and extent of the impact of sites containing UXO is yet to be realized. … DoD has completed an initial baseline estimate for UXO remediation cost. This report provides a UXO response estimate in a range between $106.9 billion and $391 billion in current year [2001] dollars. …Technology discovery, development, and commercialization offers some hope that the cost range can be decreased. …

*… **Objective**: **Develop standards and protocols** for navigation, geo-location, data acquisition and **processing**, and performance of UXO technologies.*

Standard, high quality archived data are needed for optimal data processing of geophysical data, re-acquisition for response activities, quality assurance, quality control, and review by all stakeholders. In addition, standards and protocols are required for evaluating UXO technology performance to aid in selecting the most effective technologies for individual sites.

… ***Standard software and visualization tools are needed to provide regulatory and public visibility to and understanding of the analysis and decision process made in response activities****."*

2.0 TECHNOLOGY

2.1 DESCRIPTION

UX-Analyze provides the means and methods to analyze EMI sensor data for the purposes of classifying UXO. It is transparent, modular, and commercially available and can be used for dynamic and static survey data. At a high level, data from classification-grade electromagnetic inductions (EMI) sensors are first characterized by means of a solver, then classified based on quantitative model parameters associated with the characterization (Figure 1).

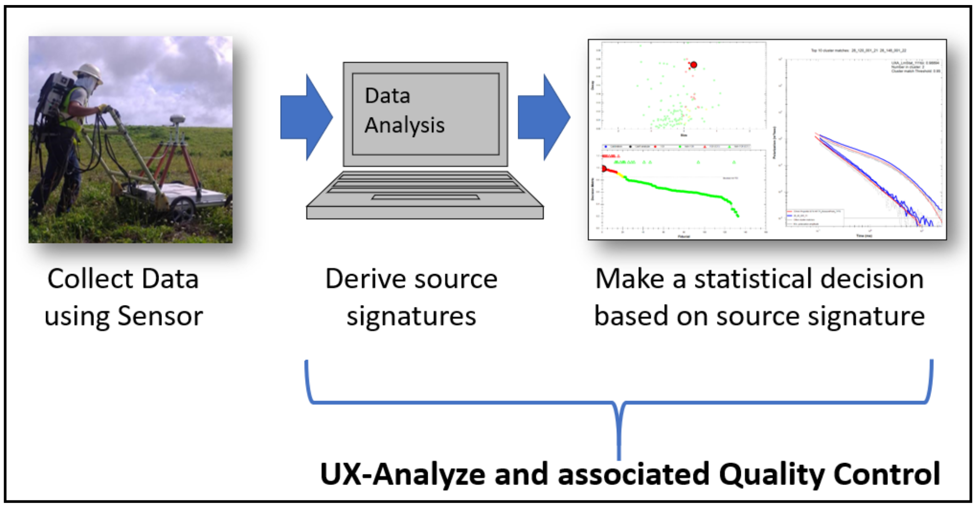

Figure 1. Advanced Geophysical Classification (AGC) Data Collection and Analysis Flow.

This effort significantly expanded the technology foundation developed under MR-200210 (Figure 2).

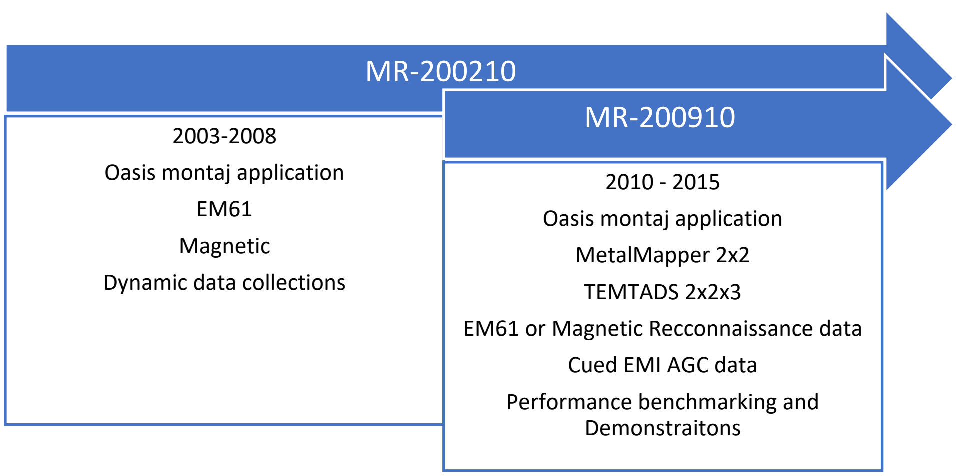

Figure 2. Timeline with Development Details for MR-200210, which this Effort leverages, and for MR-200910.

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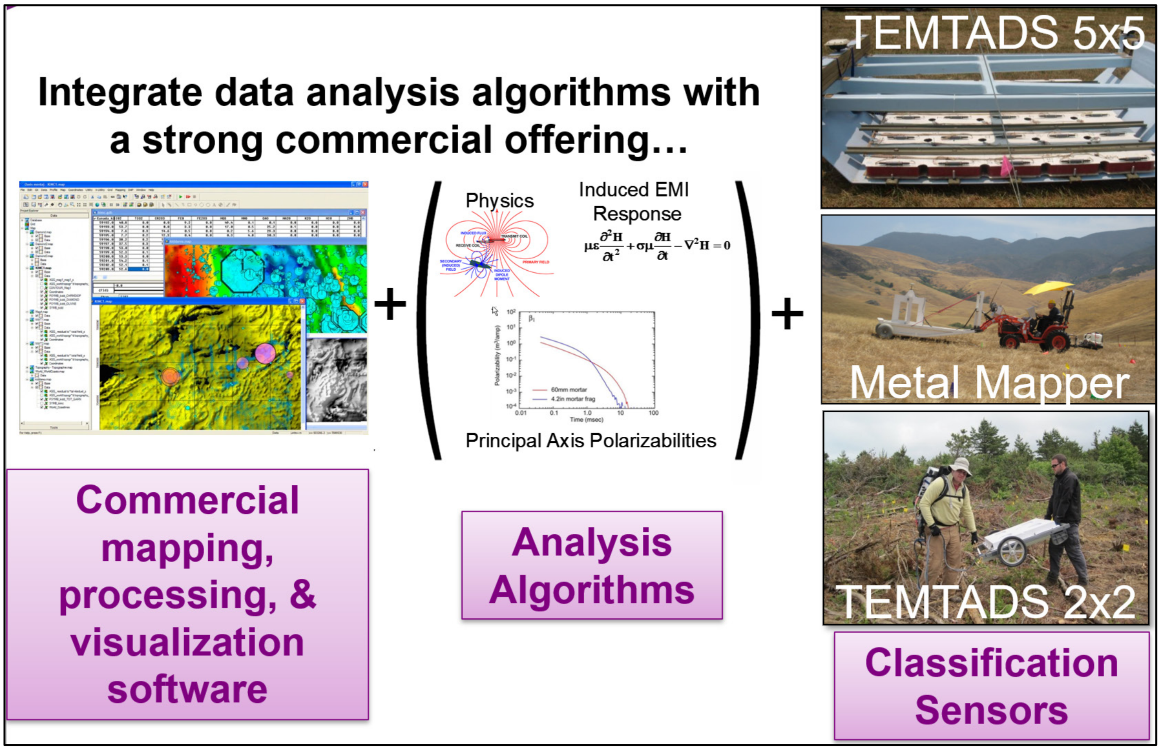

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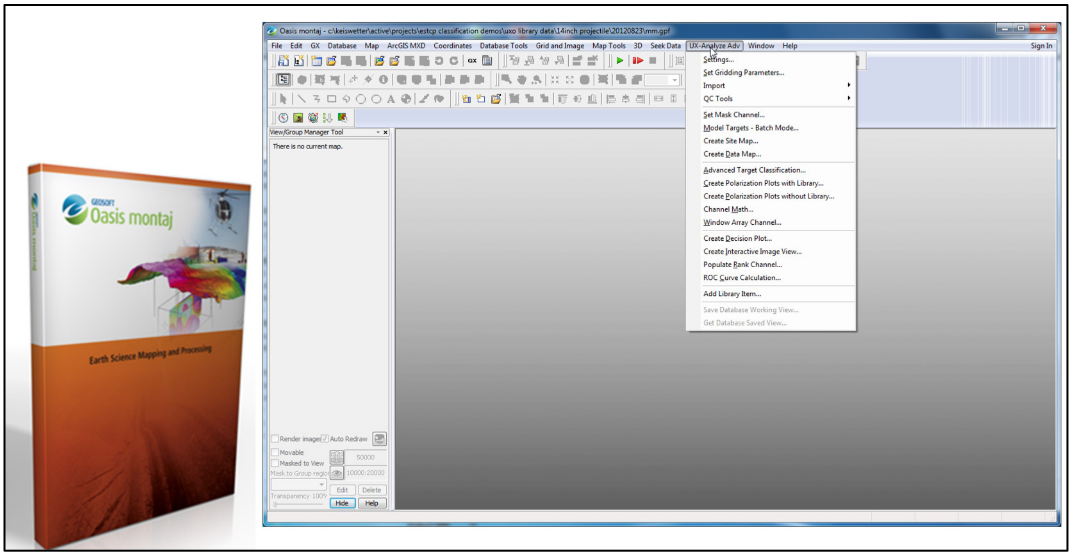


Figure 4. UX-Analyze is Embedded Into Oasis Montaj and Ships with the Product.

It is activated by an online licensing subscription.

Customized GUIs streamline the inversion and classification phases (Figure 5). Once processed, the analyst utilizes an information rich, analysis environment to review data and the decision process (Figure 6 and Figure 7).

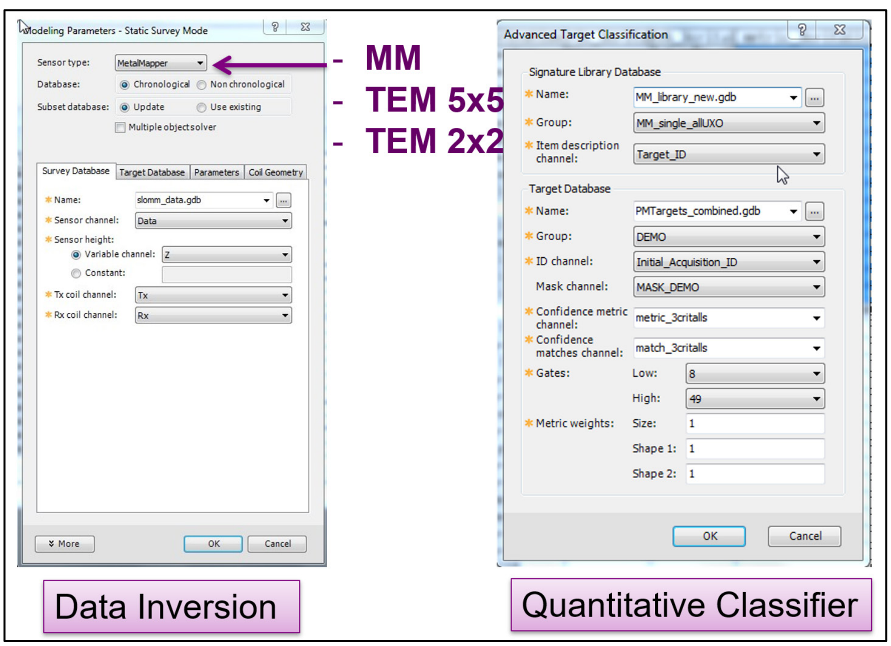
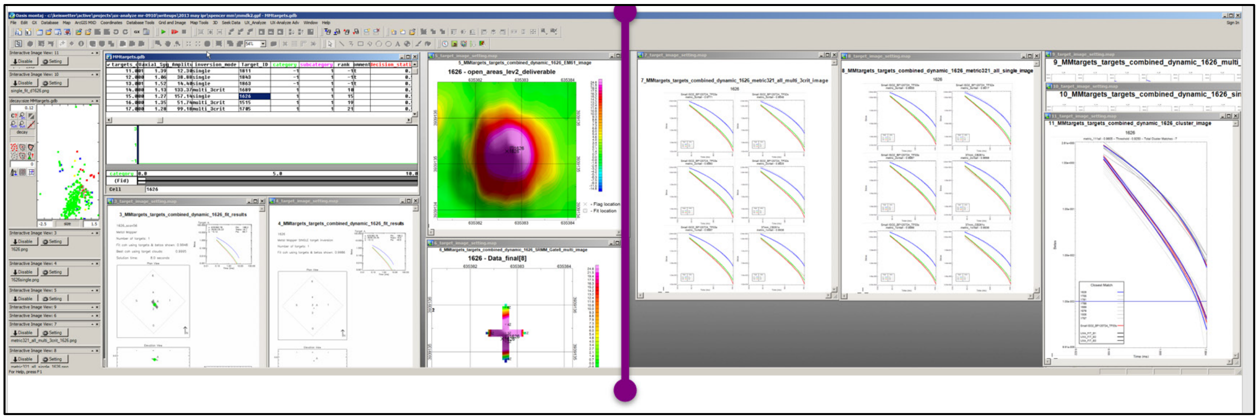


Figure 5. New Tools to Define and Initiate Data Inversions (Left) and Libray Matching Classifier (Right).



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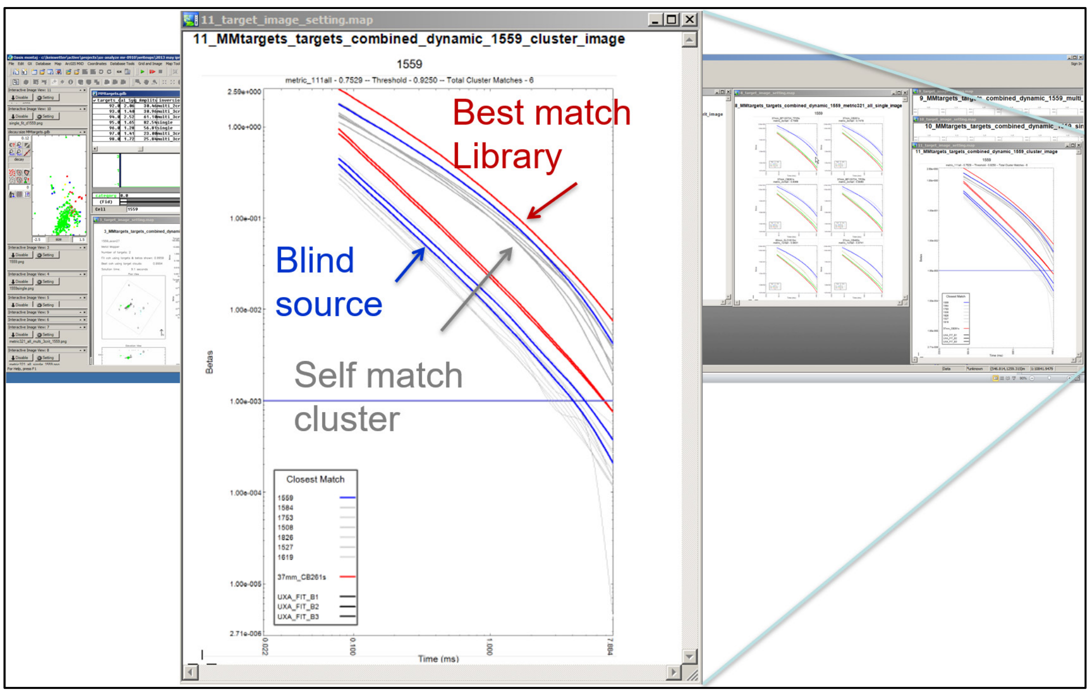


Figure 7. Blow Up of the Polarization Plot Showing the Blind Source Polorizations, the Best Match from the TOI Library, and Self Matches from Its Cluster.

2.2 DEVELOPMENT

At the end of MR-200210 in 2007, a predecessor project to this effort, UX-Analyze was capable of georeferencing, processing, visualizing, and inverting EM61 and magnetic data. Demonstrations conducted in support of MR-200210 demonstrated that the EM61 and magnetic data provide limited classification performance.

Under this project, MR-200910, UX-Analyze was significantly enhanced. The primary enhancement was to modify the inversion routines and data handling tools to process and analyze broadband AGC sensors. In realizing these changes, we modified the database structures and visualizations, and created several new processing bundles to reduce human errors. As we did so, we enhanced and refined user interfaces. Figure 8 through Figure 22 present examples of many of the upgrades and revised user experiences. Detailed captions are included to provide context.

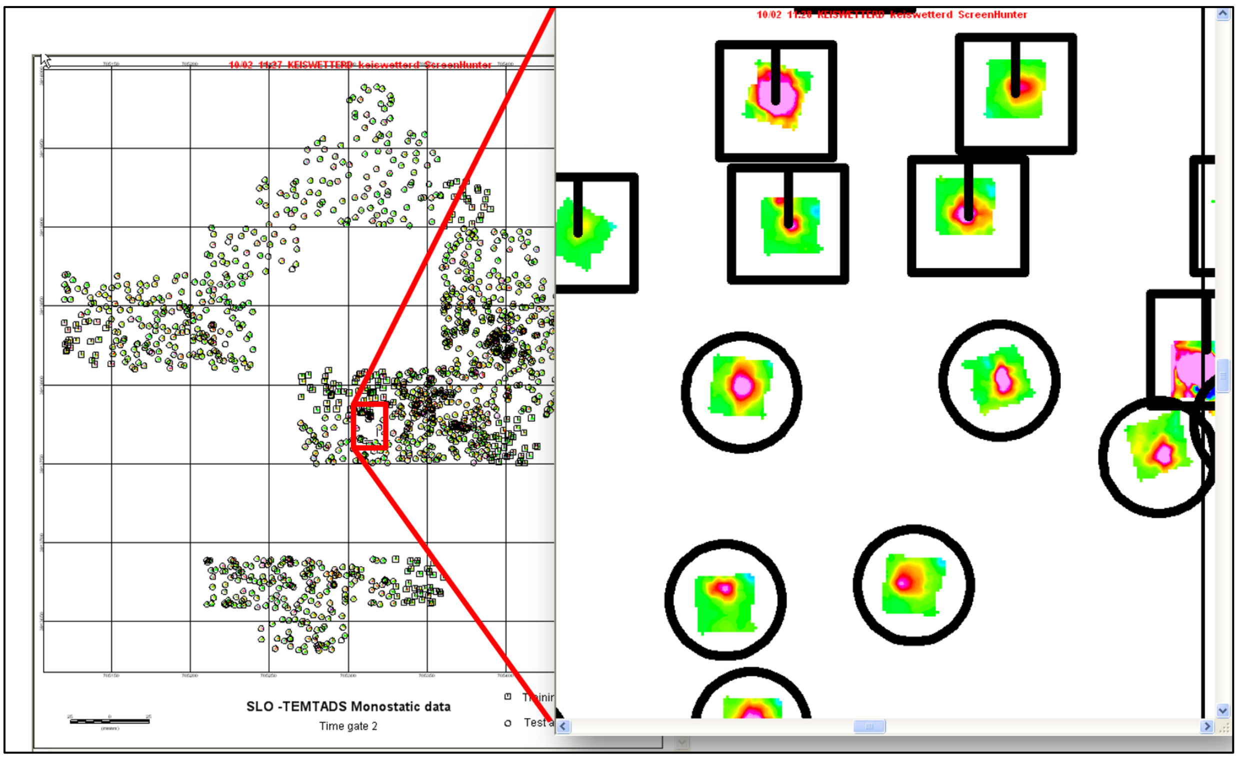


Figure 8. Screen Snapshots Showing the Nature of Cued Collection.

The location of the cued collection was based on the analysis of EM61 or magnetic reconnaissance data. Each cued data collection is inverted and classified.

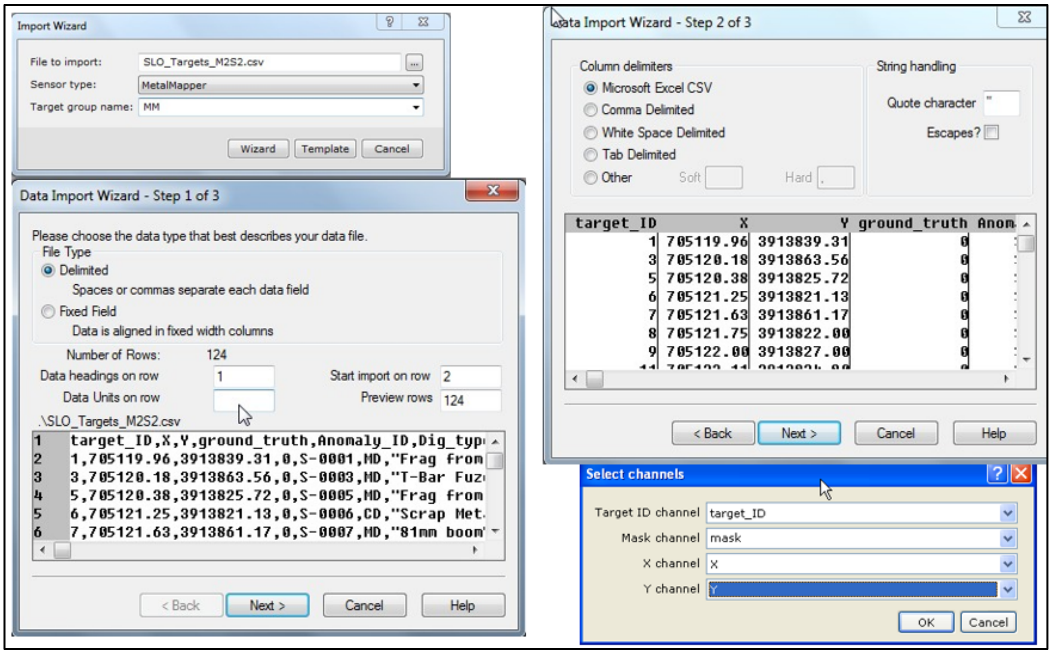


Figure 9. GUI's for Importing Raw Data Files, Each in Their Own Native Format Because There Wasn't a Standard Format at the Time.

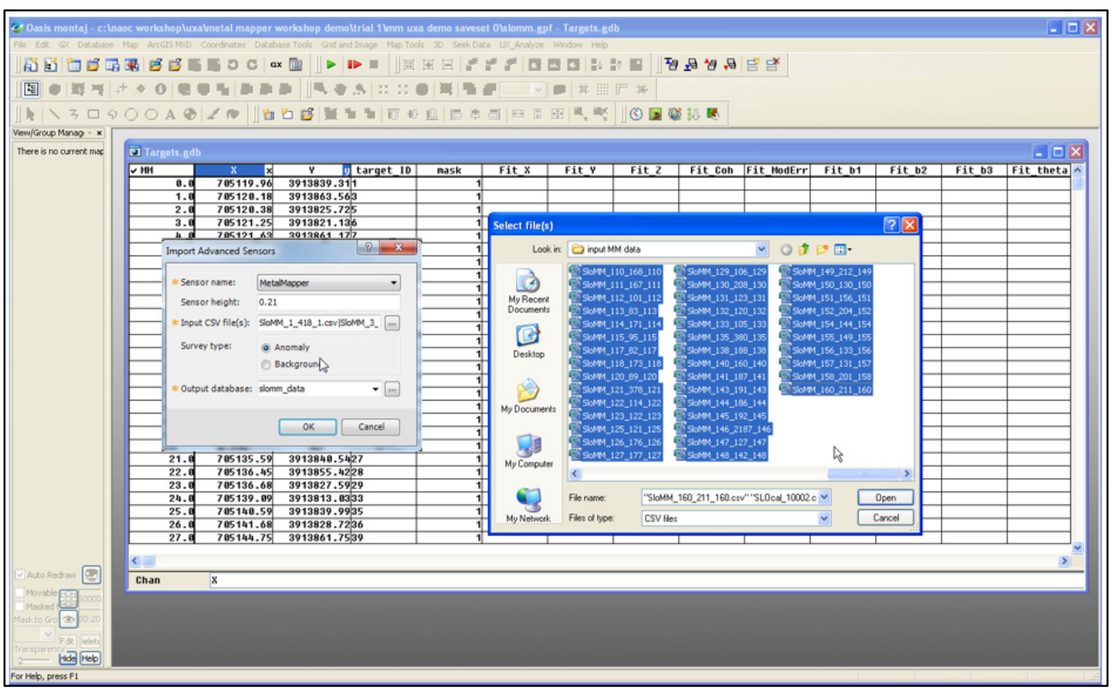


Figure 10. Screen Snapshot Showing Oasis Montaj Databases, and the Importing of Additional Data.

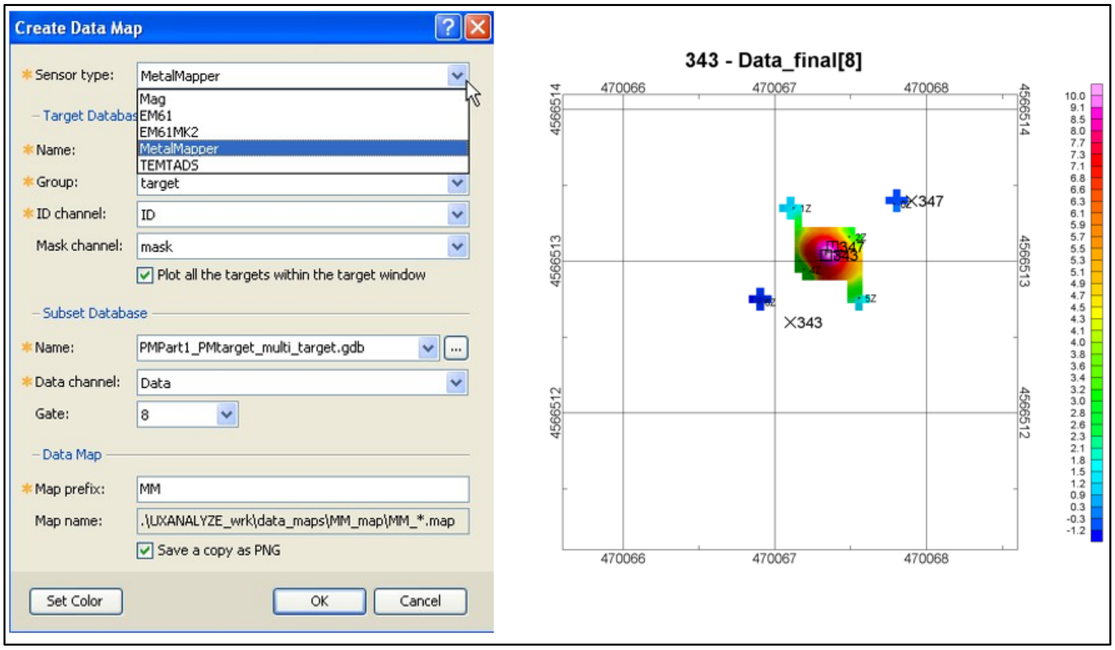


Figure 11. GUI to Create a Data Map (of Dynamic or Cued Data).

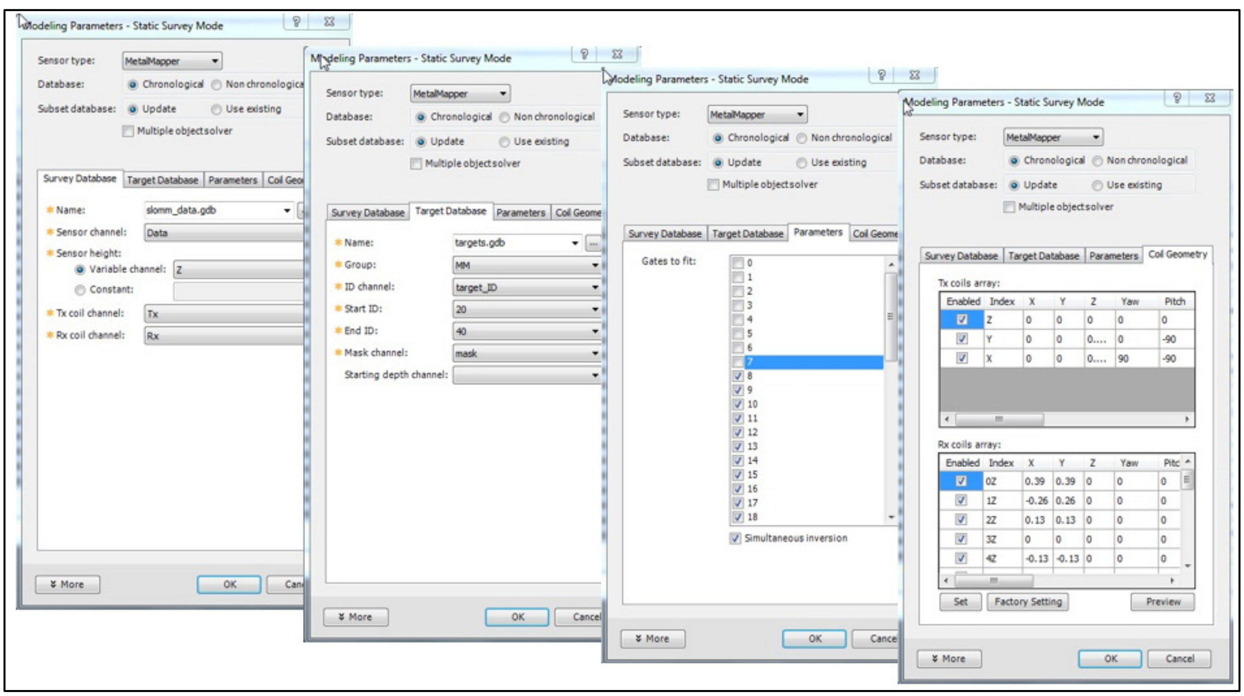


Figure 12. User GUI's Presenting the Options for Inverting and Calling Library Matching Routines.

The workflow and verbose nature of the GUI's was developed during this program.

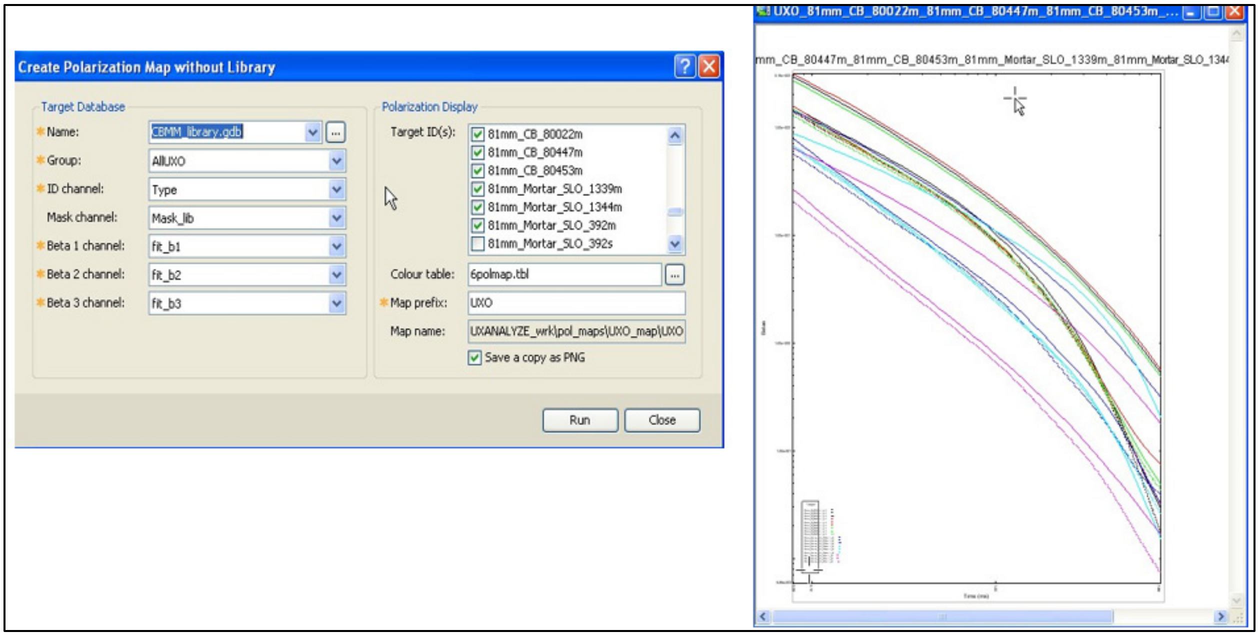


Figure 13. New Tool to View Polarizations and Their Best Match from the TOI Library as Well as to Other Blind Sources.

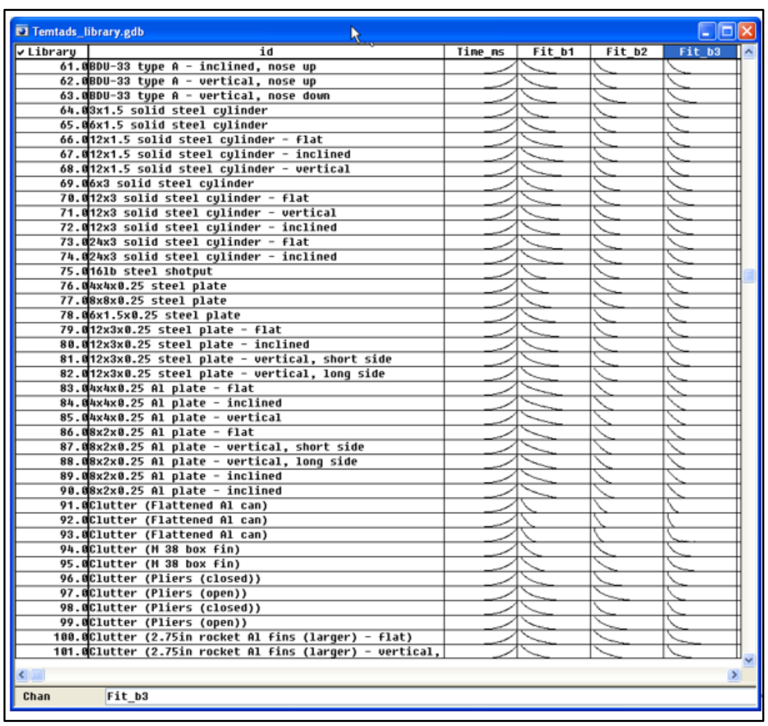


Figure 14. A Signature Library, Which Contains Polarizabilities for High SNR Targets Collected over Many Years, Was Updated.

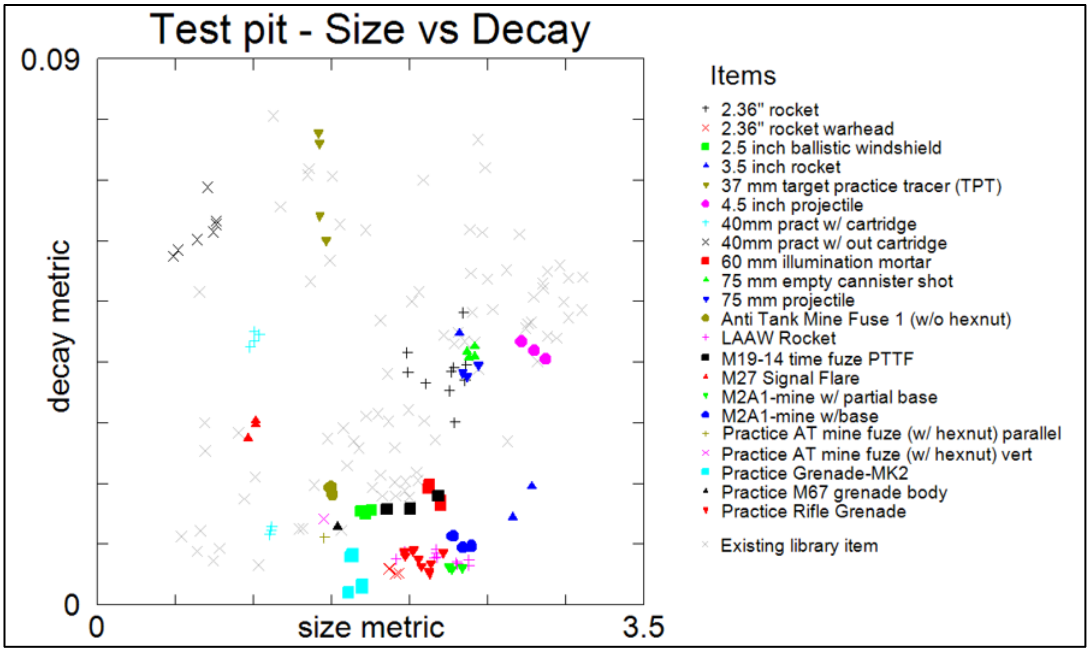


Figure 15. We Added Library Overlays to the Size-decay Display for User-selected TOI During this Program.

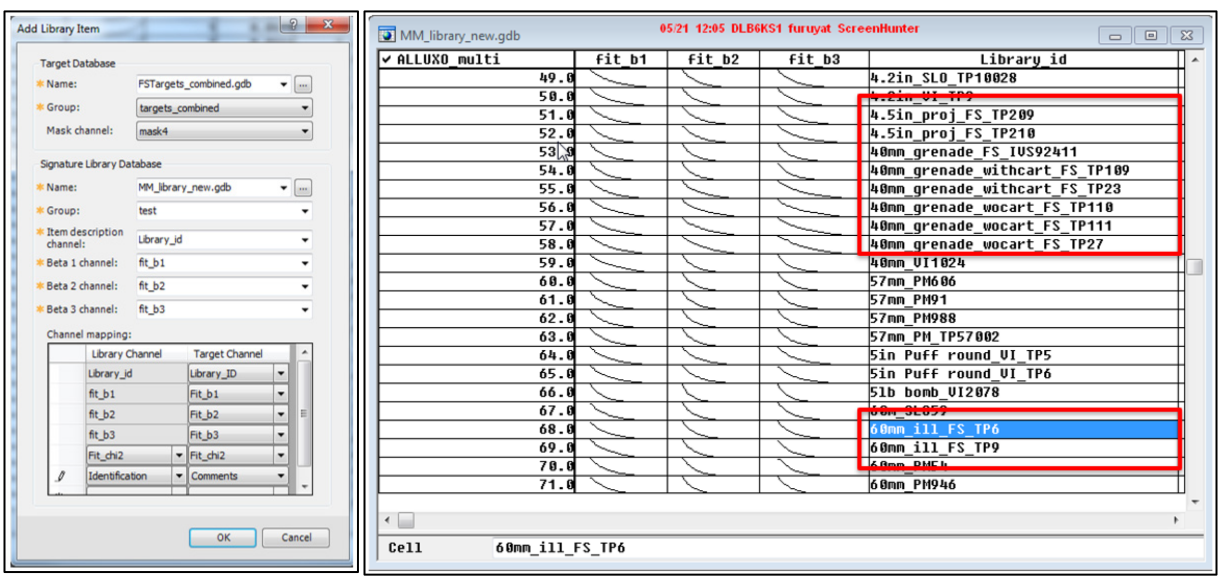


Figure 16. We Developed a Tool to Selectively Add Inverted Polarizations to the Site-Specific Library During this Effort.

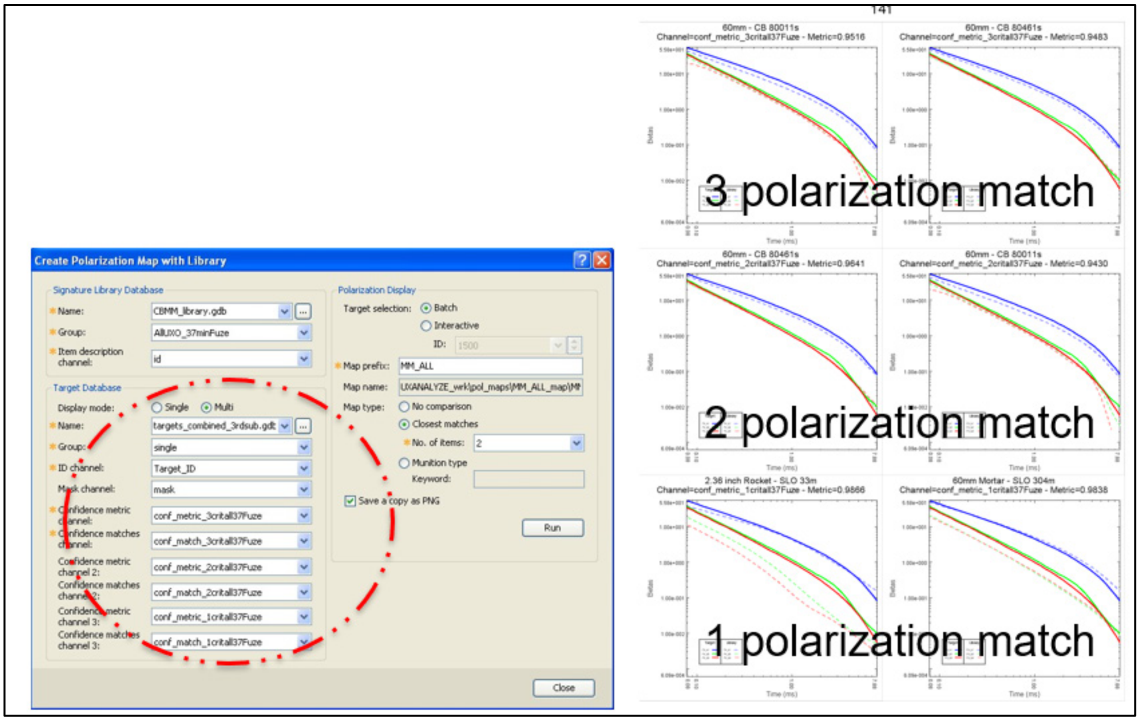


Figure 17. New Tool to Compare Source to Library Based on Up to 3 Metrics and output Image Showing Best Metrics and Matches.

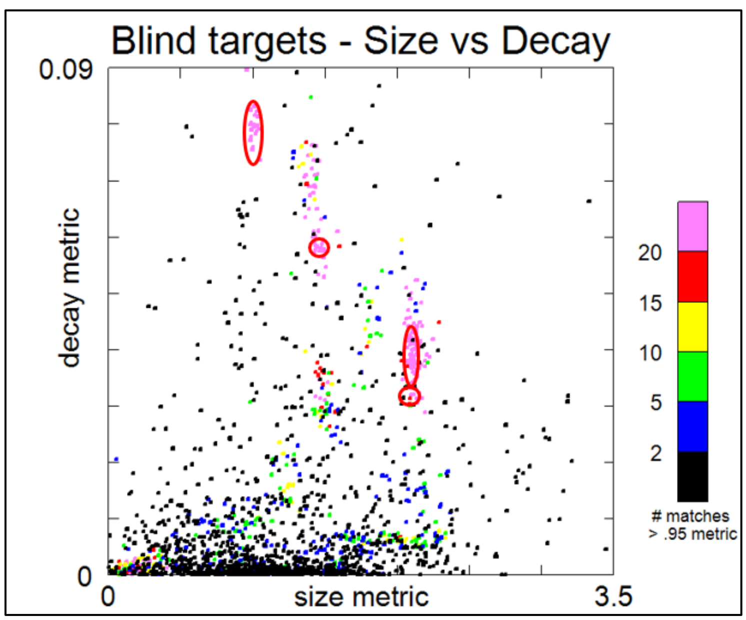


Figure 18. New Tool for Performing Cluster (Self-match) Analyses.

Round-robin library match of blind sources to detect source clusters not labeled by a library item. Plot highlights targets with high number of matches to other blind targets. Once identified, the unlabeled cluster can be investigated by requesting that some, or all, of the clustered sources be excavated.

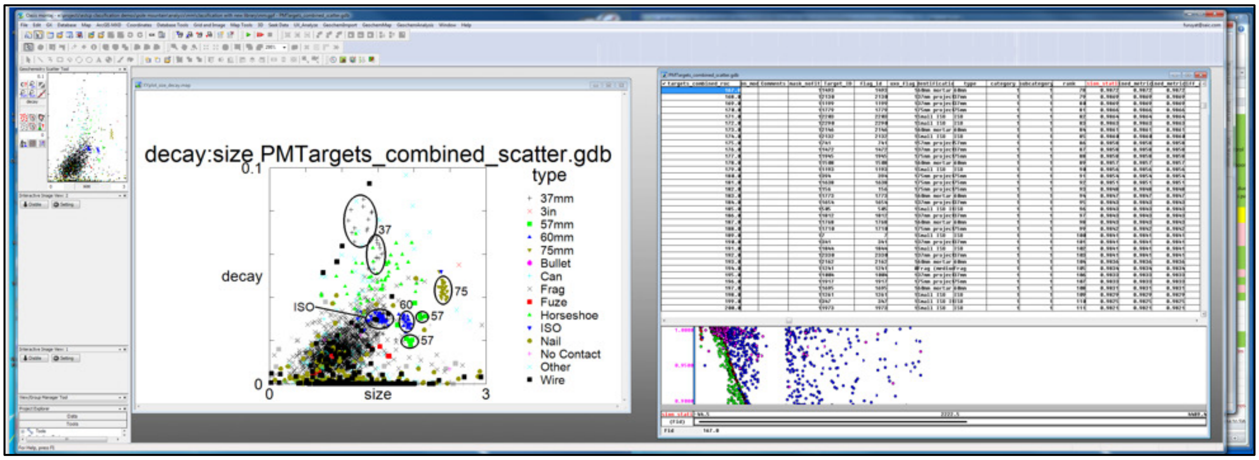


Figure 19. Added Tool to Create XY Scatterplot with Linking to Database and to Image (Such as Polarization Plots).

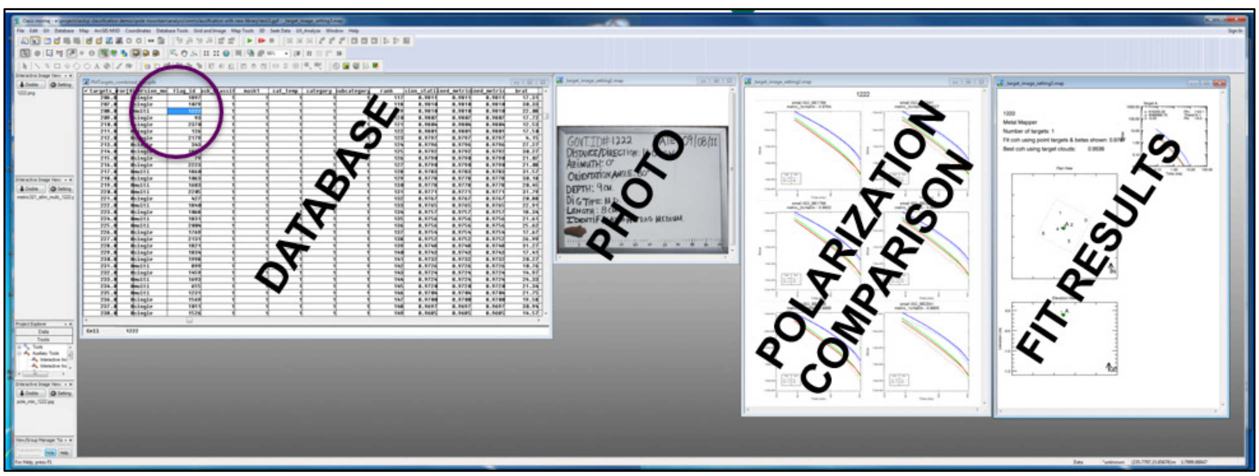


Figure 20. New Tool to Link Database Target IDs with Images.

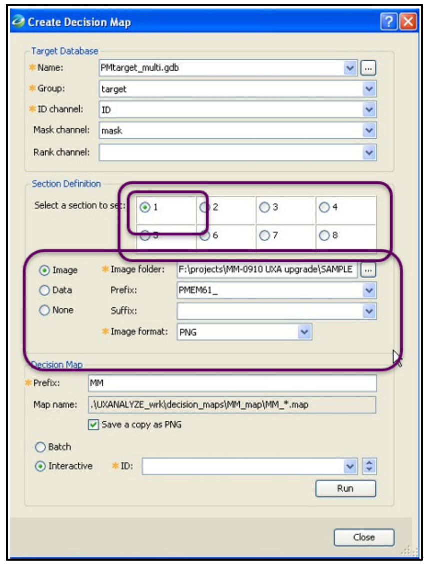


Figure 21. New Tool for Creating Efficient Decision Maps.

Eight separate windows, each of which can show an image, create a custom decision.

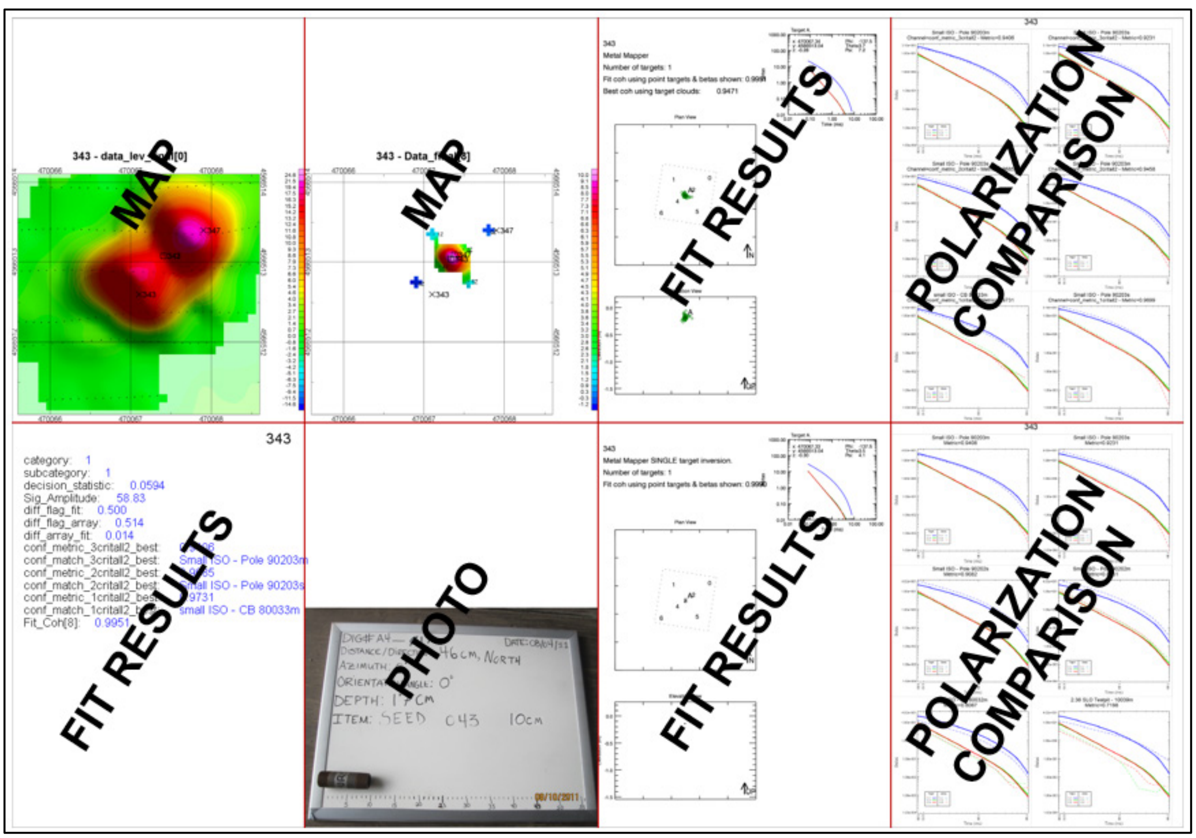


Figure 22. Example Product Showing the Final Decision Plot for a Single Source.

A decision plot is generated for each analyzed source, whether TOI or non-TOI, to aid in the documentation of the decision.

2.3 ADVANTAGES AND DISADVANTAGES OF THE TECHNOLOGY

As used here, the term ‘technology’ refers to classification methods – the sensor, analysis software, and classifier.

The advantage of the classification technology is twofold. First, it provides much higher quality decisions. It not only identifies those items that need to be excavated but it also documents the location and rational for leaving all ancillary metallic objects in the ground. Secondly, it has the potential to save money. At the very least, it redirects funds from activities that are not documented to processes and products that are well documented.

The disadvantage of the technology is that it requires expensive sensors, advanced analysis software, and trained field personnel and analysts.

3.0 PERFORMANCE OBJECTIVE

Table 1. Performance Objectives

Performance Objective	Metric	Data Required	Success Criteria
Maximize correct classification of targets of interest(TOIs)	Number of TOIs correctly classified	Prioritized dig list Results of intrusive investigation	Approach correctly classifies all TOIs
Maximize correct classification of non-TOI	Number of false alarms eliminated	Prioritized dig list Results of intrusive investigation	Reduction of false alarms by > 50% while retaining alltargets of interest
Specification of no-dig threshold	Probability of correct classification and number of false alarms at demonstrator operating point	Demonstrator- specified threshold Results of intrusive investigation	Threshold specified to achieve the above criteria
Minimize number of anomalies that cannotbe analyzed	Number of anomalies that must be classifiedas "Unable to Analyze"	Demonstrator parameters	Reliable target parameters can be estimated for > 98% of anomalies on each sensor's detection list.
Correct estimation of target parameters	Accuracy of estimated target parameters	Demonstrator parameters Results of intrusive investigation	X, Y < 15 cm Z < 10 cm

3.1 OBJECTIVE: MAXIMIZE CORRECT CLASSIFICATION OF TOI

An objective of this demonstration was to correctly classify all seeded items and any MEC items as TOI.

Metric – The metric for this objective was the number of items on the MetalMapper anomaly list correctlyclassified as TOI.

Data Requirements – Prioritized dig lists and results of the intrusive survey.

Success Criteria – The objective is considered met if all items of interest are correctly labeled as TOI on the prioritized anomaly list.

3.2 OBJECTIVE: MAXIMIZE CORRECT CLASSIFICATION OF NON-TOI

In addition to correctly classifying TOI, we want to correctly classify non-TOI so they can be eliminated from consideration during the intrusive investigation.

Metric – The metric for this objective was the number of targets on the ranked anomaly list created using the MetalMapper data that were correctly classified as non-TOI.

Data Requirements – Prioritized dig lists and results of the intrusive survey.

Success Criteria – The objective is considered met if more than 50% of the non-TOI items can be correctly labeled as non-TOI.

3.3 OBJECTIVE: SPECIFICATION OF NO-DIG THRESHOLD

The goal is to correctly position the stop dig threshold such that all TOI are correctly classified while minimizing the number of false positives.

Metric – The probability of correct classification and the number of false alarms at the dig/no dig threshold in the prioritized dig list are the metrics for this objective.

Data Requirements – Prioritized dig lists and results of the intrusive survey.

Success Criteria – The objective is considered met if more than 50% of the non-TOI items can be correctly labeled as non-TOI while retaining all TOI at the specified threshold.

3.4 OBJECTIVE: MINIMIZE NUMBER OF ANOMALIES THAT CANNOT BE ANALYZED

Anomalies for which reliable parameters cannot be estimated using the collected MetalMapper data cannot be classified. These anomalies must be placed in the dig category, which reduces the effectiveness of the classification process.

Metric – The number of anomalies for which reliable parameters cannot be estimated is the metric for this objective.

Data Requirements – Those targets for which parameters could not be reliably estimated were identified as such on theprioritized dig list submitted following analysis of the MetalMapper data.

Success Criteria – The objective is considered met if reliable parameters can be estimated for > 98% of the targets on the prioritized dig list.

3.5 OBJECTIVE: CORRECT ESTIMATION OF SOURCE PARAMETERS

This objective involves the accuracy of the target parameters that are estimated in the first phase of the analysis. Successful classification is only possible if the input features are internally consistent.

Metric – Accuracy of estimation of target parameters is the metric for this objective.

Data Requirements – The inverted source locations and the locations of recovered items, as recorded by the intrusive teams.

Success Criteria – The objective is met if the estimated X, Y locations are within 15 centimeters (cm [1σ]) of the actual locations and if the estimated depths are within 10 cm (1σ).

4.0 SITE DESCRIPTION

Pole Mountain is in southeastern Wyoming, approximately seven miles east of Laramie and 40 miles west of Cheyenne, Wyoming in the Pole Mountain Unit of the Medicine Bow National Forest. The demonstration site totals 50 acres.

ESTCP selected this MRS because of its wide mixture of munitions and variable terrain. The smallest known munitions type on the site is the 37mm projectile; the largest known are 3-in. projectiles and mortars.

4.1 HISTORY

Pole Mountain, which has been known by a variety of names over the years, was extensively used as a target and maneuver area before 1959 by the Army, the Reserve Officers' Training Corps, the Citizens' Military Training Corps, various National Guard units, and the Department of the Air Force. Disposition of portions of Pole Mountain by the Department of Defense or its predecessor agencies included actions between 1945 and 1960. In July 1961, a Public Land Order terminated all military interests in the Pole Mountain District.

4.2 MUNITIONS CONTAMINANTS

Several munitions have been reported as used at Pole Mountain. Physical evidence for the following items was discovered during the Remedial Investigation:

- Projectiles containing high explosive (HE) filler (37-mm to 155-mm, and 2.95-inch),
- Shrapnel projectiles (75-mm and 3-inch),
- 37-mm projectiles (inert and unfuzed),
- 3-inch Stokes mortars (practice, fuzed),
- 60-mm mortars containing HE filler, and
- Small arms ammunition (.30-caliber and .50-caliber)

5.0 TEST DESIGN

5.1 CONCEPTUAL EXPERIMENTAL DESIGN

The objective of this program was to demonstrate a method for the use of classification in the munitions response process. The three key components of this method are 1) collection of high-quality geophysical data and principled selection of anomalous regions in those data, 2) analysis of the selected anomalies using physics-based models to extract target parameters such as size, shape, and materials properties, and 3) the use of those parameters to construct a ranked anomaly list. Each of these components was handled separately in this program, with different contractors responsible for different tasks. Validation digging was also coordinated by the ESTCP Program office. The prioritized anomaly lists were scored by the IDA, with emphasis on the number of items correctly labeled nonhazardous while correctly labeling all TOIs.

5.2 PRE-DEMONSTRATION ACTIVITIES

SAIC was not involved in site preparation for this project. Reported activities from ancillary program participants list the following activities:

- Collection of historical records about the site through coordination with the Omaha District, US Army Corps of Engineers
- EM61 transects to define initial demonstration area
- Establishment of two first order navigation points to be used for all emplacement, data collection, and validation activities.
- Surface clearance of the site
- Development of a seed plan
- Establishment of an instrument verification strip near the demonstration area.

5.3 CALIBRATION ACTIVITIES

SAIC was not involved in site preparation for this project. Reported activities from ancillary program participants list the following calibration activities:

- Twice-daily measurements of the IVS.
- Background measurements in a metal free area conducted at least twice per-day.
- Measurements of several test-objects in a shallow-test pit were completed at the startof the survey period. Each projectile was measured in multiple orientations and at two depths (10 and 20 cm to top of item). Items measured included:
  - 37 mm, 57mm, and 75mm projectile
  - Stokes mortar (also at 30 and 45 cm depths)
  - Calibration ball (single measurements at 10 and 20 cm)

5.4 TARGET SELECTION

SAIC was not involved in site preparation for this project. The area was mapped by URS corporation using an EM61 sensor ([3] MR-201161). The EM61 survey data were processed to identify anomalies and to develop a list of locations for cued investigations.

5.5 COLLECTION OF CLASSIFICATION DATA

SAIC was not involved in site preparation for this project. Sky Research acquired the MetalMapper data ([4] MR-201161) (Figure 23).

Figure 23. Photograph of the MetalMapper System that Was Used to Collect the AGC Data.

5.6 VALIDATION

All anomalies on the master list were excavated by a team led by the URS Corporation. At the conclusion of data collection activities, all anomalies on the master dig list were excavated. Each item encountered was identified, photographed, its depth measured, its location determined using cm-level GPS (global positioning system), and the item removed if possible. These ground truth data were used for evaluation of the dig lists submitted by various analysts.

6.0 DATA ANALYSIS AND PRODUCTS

6.1 PREPROCESSING

The first preprocessing step involves importing the raw sensor data into Oasis montaj using tools embedded into UX-Analyze. Spatial registration algorithms within UX-Analyze which were designed to calculate the true XY location of the sensor head, were then used to establish georeferenced locations in UTM coordinates.

After spatially registering, analyze tools with UX-Analyze were utilized to assign data types, and remove background responses. The background removal process involves identifying appropriate background measurements that can be used to remove signal response from the ground and from the sensor platform itself. The difference between data collected over the source under investigation and the background signature represents signal from the source itself and is submitted to the inversion routine for model parameterization.

Quality control tools within UX-Analyze were used to confirm that the data were complete and of sufficient quality, from a sensor data viewpoint, to analyze. We looked at battery voltage, signal strength, GPS quality metrics, and location of the measurement compared to the planned location.

6.2 TARGET SELECTION

The locations for the cued collections were determined by the ESTCP Program Office based on amplitude thresholds.

6.3 PARAMETER ESTIMATES

Data inversion algorithms based on the dipole model are embedded into UX-Analyze.

The inversion routines accept as input the spatially registered and INS orientated EMI data and return size and burial depth estimates, fitted X and Y locations, polarizabilities, and model coherence for 1, 2, and 3-source scenarios.

6.4 CLASSIFIER AND TRAINING

The classification decision was derived using the methods that are embedded into the UX-Analyze software. The UX-Analyze decision statistic calculated using following equation:

Range of time channels

Polarizability

$$\phi = \sum_{i=1}^{3} W_i \exp\left(-\frac{1}{2} \left(\frac{\left(\sum_{j=1}^{N} \left| L_i^{est}(t_j) - L_i^{ref}(t_j) \right| \right)}{scaleFactor} \right)^2 \right) \qquad \begin{array}{l} L_1 : \beta_1 \\ L_2 : \beta_1 / \beta_2 \\ L_3 : \beta_1 / \beta_3 \end{array}$$

Weighting on each polarizability

Time gate

Equation 1

The decision statistic is used to determine the final classification category:

Category 0: Cannot analyze (dig)

subcategory 1 - cannot extract reliable polarizations
subcategory 2 - too far from
subcategory 3 - poor fit coherence
subcategory 4 - unreasonable depths and negative betas
subcategory 5 - no betas - inversion did not finish

Category 1: TOI (dig)

subcategory 1 - good, combined Library Match statistic fit to TOI library
subcategory 2 - QC TOI - good visual match but statistic less than TOI threshold (optional)

Category 2: Cannot decide (dig)

subcategory 1 - combined Library Match statistic using TOI Library and a lower threshold
subcategory 2 - QC possible TOI - reasonable visual match to TOI but statistic less than TOI threshold (optional)

Category 3 is clutter (do not dig)

subcategory 1 - combined Library Match statistic less than TOI threshold

6.5 DATA PRODUCTS

The data products include standardized quality control plots documenting that the collected data meet measurement quality objectives and decision plots. The Decision Plots include polarizability information, quality control information, spatial coordinates, depth estimates, library match, and decision metrics.

A second data product is the prioritized dig list that contains a list of all inverted sources, an identification number, and the final classification decision.

7.0 PERFORMANCE ASSESSMENT

7.1 OBJECTIVE: MAXIMIZE CORRECT CLASSIFICATION OF TOI

Our submitted classification dig list was compared to ground truth data (Figure 24). All TOI were correctly classified at the operators stop dig point. Performance metric passed.

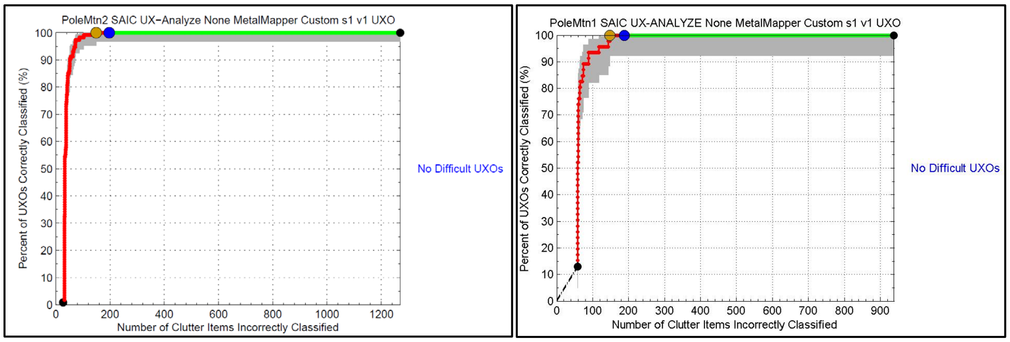


Figure 24. IDA-generated Receiver Operating Characteristic Curves.

The data was analyzed and scored in two submittals because the data was acquired over two years. As shown in the figures, all TOI were correctly identified, and the performance objective of 100% correct TOI classification was met.

7.2 OBJECTIVE: MAXIMIZE CORRECT CLASSIFICATION OF NON-TOI

Our classification dig list incorrectly classified 300 of the 2,117 non-TOI. In other words, 14% of the clutter items were incorrectly classified. Performance metric of less than 50% passed.

7.3 OBJECTIVE: CORRECT SPECIFICATION OF NO-DIG THRESHOLD

All TOI at the site were correctly identified as TOI, and the number of false positives was reduced by more than 50 percent of the total number of false positives. Performance metric passed.

7.4 OBJECTIVE: MINIMIZE NUMBER OF ANOMALIES THAT CANNOT BE ANALYZED

Our classification dig list included five out of 2,368 sources as Cannot be Analyzed. This equates to less than 1%. Performance metric of less than 2% achieved.

7.5 OBJECTIVE: CORRECT ESTIMATION OF SOURCE PARAMETERS

The XY offsets for TOI had a standard deviation of 0.17m. The XY offsets for all sources, regardless of TOI or not, was 0.36m. The performance metric objective of 0.15m for the horizontal standard deviation or less was not achieved.

Due to a database error, we were unable to assess the estimated-vs-actual depth error as part of this study.

8.0 COST ASSESSMENT

8.1 COST MODEL

Cost Element	Data tracked during Demonstration	Costs
Processing	Per source labor costs required to perform inversion of each target using UX-Analyze and to create polarization curve figures	$5.50
Analysis	Per source labor costs required to examine polarization cures for each source, identify unexplained clusters, request analyst training data, and finalize classification decision	$13.50
Dig list Review and Compilation	Per source labor costs required to review final classification dig list and submit for scoring	$3.75

8.2 COST DRIVERS

The mix of TOI and clutter at this site allowed the classification method to work well. The costs reported above reflect the fact that we repeated the analysis a few times with different inversion parameters. As such, they are higher than they could have been. That said, the reported costs are probably low if future sites have conditions in which the polarizabilities from the TOI and non-TOI are more similar.

8.3 COST BENEFIT

The benefit of the classification method is two-fold. The primary benefit relates to the fact that the decision is documented and transparent. All sensor data are preserved, and the basis of the classification decision is clear. This is true for all non-TOI as well as TOI. The information regarding the non-TOI is very valuable when trying to establish residual risk. A secondary benefit relates to cost. To be effective and widely utilized, the cost of the classification method should be close, or preferably less, than the costs of excavating all encountered sources. Classification methods should be employed even if the classification method is more expensive than the non-classification method, however, because the quality control and archived data products regarding residual sources is so much better than conventional methods.

9.0 IMPLEMENTATION ISSUES

We did not run into any major implementation issues. Although major changes have been made to modularize the code and simplify the process, the workflow presents many options during analysis and is still perhaps a bit too verbose. Most of these relate to making the machine work harder so that the analyst can focus on assessment of the decisions and data quality. As design-lead of the UX-Analyze software suite, we want to strike a balance between providing options versus unnecessary complications.

10.0 ANCILLARY PERFORMANCE RESULTS

Several third-party analysts utilized UX-Analyze during the program period, including, commercial firms and USACE employees. Most of them were trained during one or more of the two-day UX-Analyze workshops.

We present classification performance results from Pole Mountain and Camp Beale for several the third-party analysts that utilized UX-Analyze as their software platform in Figure 25. Although minor difference exists in their work and performances, the overall trend and performance is outstanding.

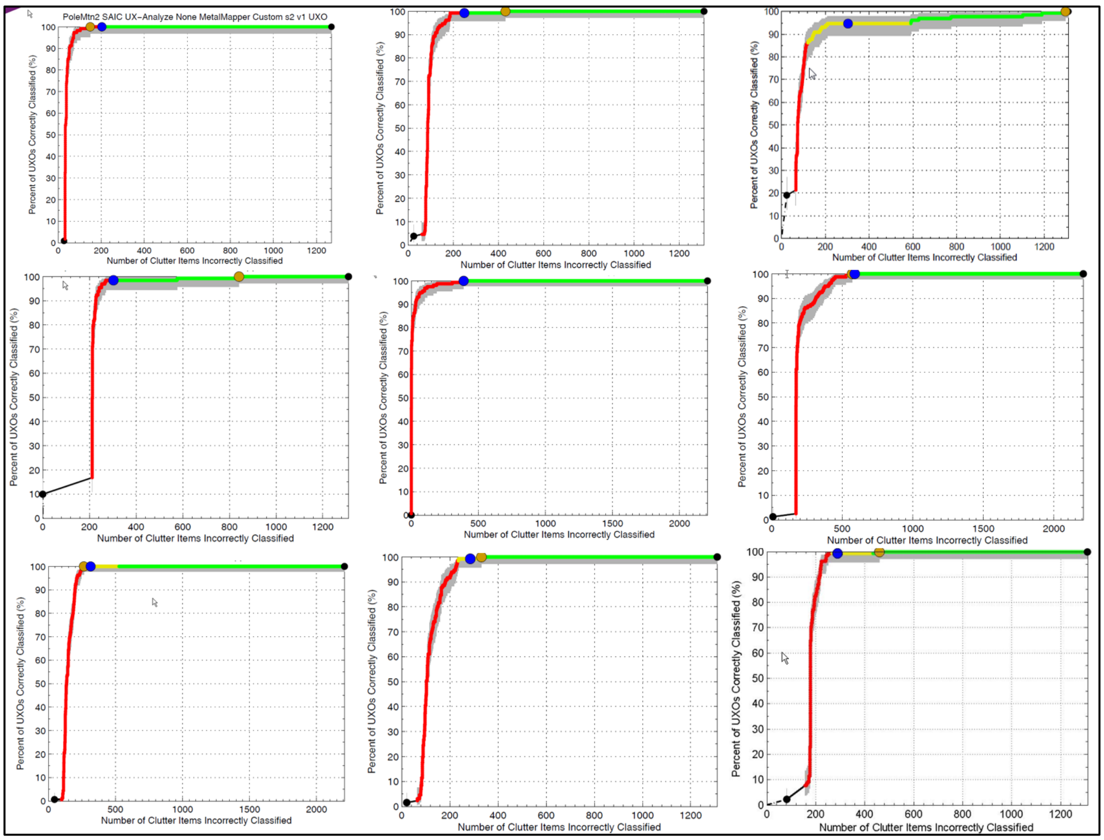


Figure 25. Classification Results for Various Third-party Users for Demonstrations at Pole Mountain or Camp Beale.

That said, many firms tried more than one way of analyzing the data with mixed results. These disparate processing flows allow us to investigate optimal methods and realize lessons learned.

The ROC curve in Figure 26, for example, presents results for a commercial contractor during the Classification Demonstration at Camp Beale. Their initial classification scheme only suffered one false negative, but the clutter rejection rate was not superb. Over 85% of the TOI were easily classified, but the remaining 15% proved more difficult. As a result, only 30% or so of the clutter items were correctly classified.

After working through the details of how their final classification decision was made, we suggested some changes to their classification logic and QC process. The revised result, shown in Figure 27, are much better.

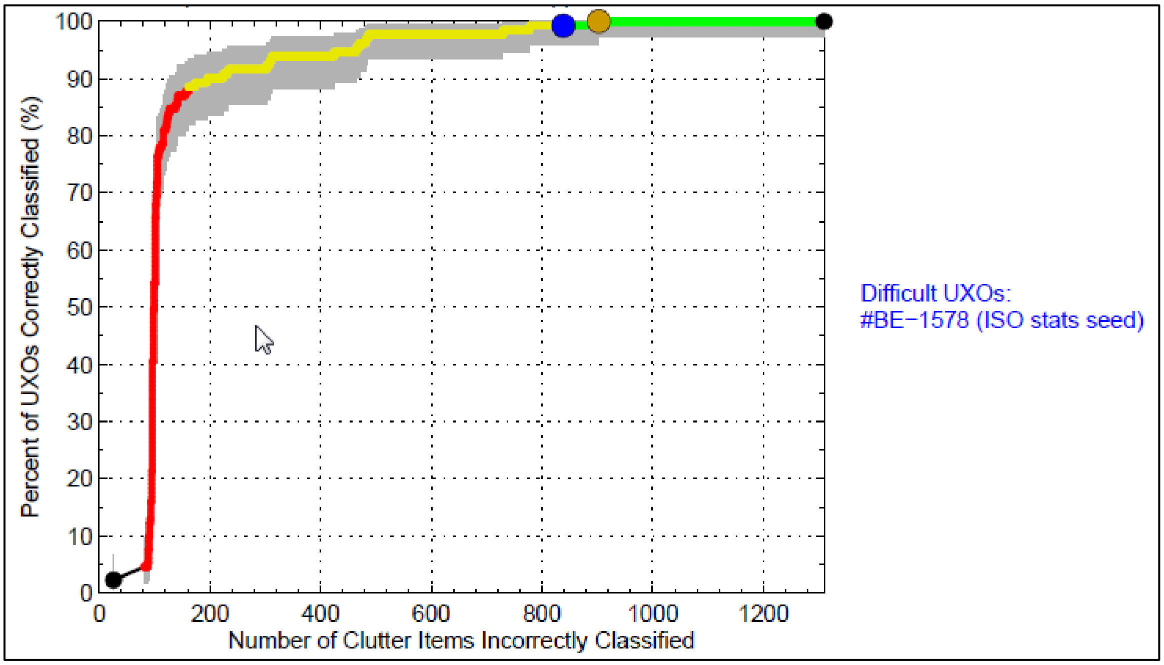


Figure 26. Contractor classification performance for the Camp Beale Demonstration.

This classification scheme resulted in one false negative, but a poor clutter rejection ratio.

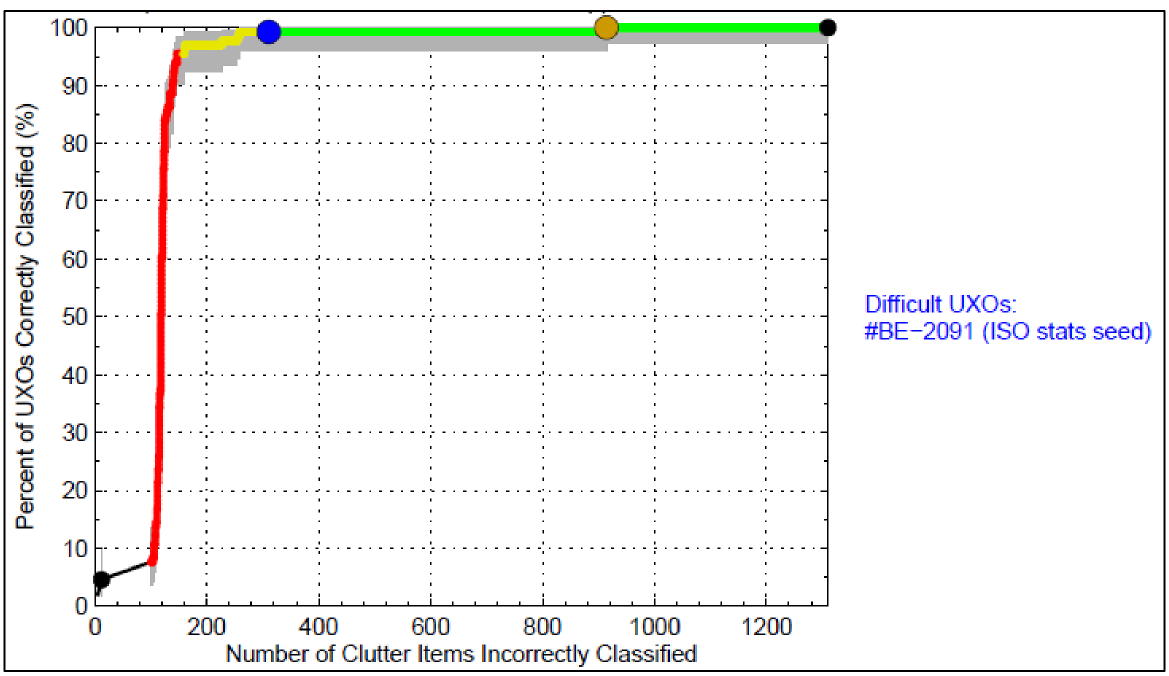


Figure 27. Revised Contractor Performance after Adjusting Classification Logic and QC Processes.

The clutter rejection ratio was greatly improved, but one false negative remains.

After discussing the schemes put in place by contractors and comparing the details with the scheme that we used for Pole Mountain above, we developed a scheme that leveraged the best approaches and largely remove man-in-the-loop decisions. The idea to automate as much of the process as possible (Figure 28), then review, modify, and repeat if necessary.

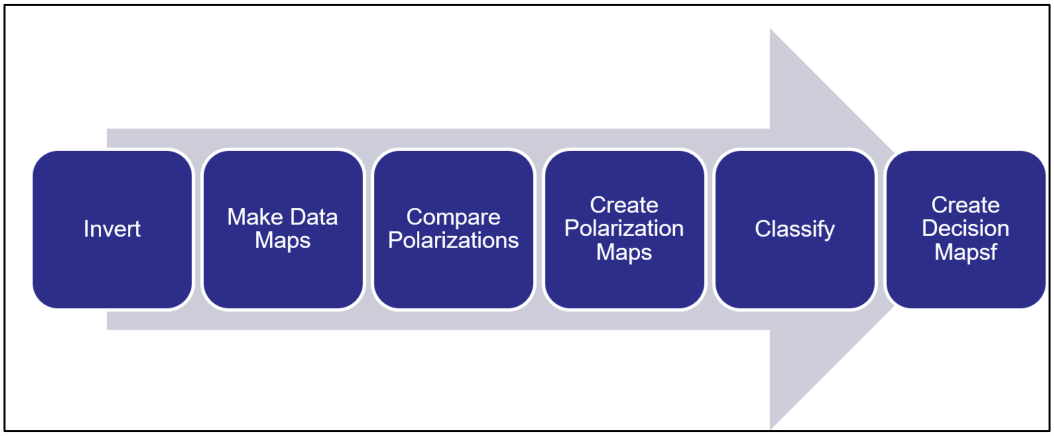


Figure 28. Schematic Showing the Basic processing Steps Included in the Revised, Post-Demonstration Processing Effort.

The revised flow required just under 12 hours to process the 2,370 anomalies at Pole Mountain (Table 1).

Table 2. 'Automated' Processing Time Required for 2,370 Anomalies Acquired During the Pole Mountain Demonstration.

Replacing the single source solver with a multi-source solver increased the total time by approximately three hours.

	Single Source Solver
Import MM data	0.08
Invert*	1.07
Library match	0.23
Data maps	3.67
Prioritization	0.02
Polarization maps	3.73
Decision maps	3.0
Total (hours)	11.8

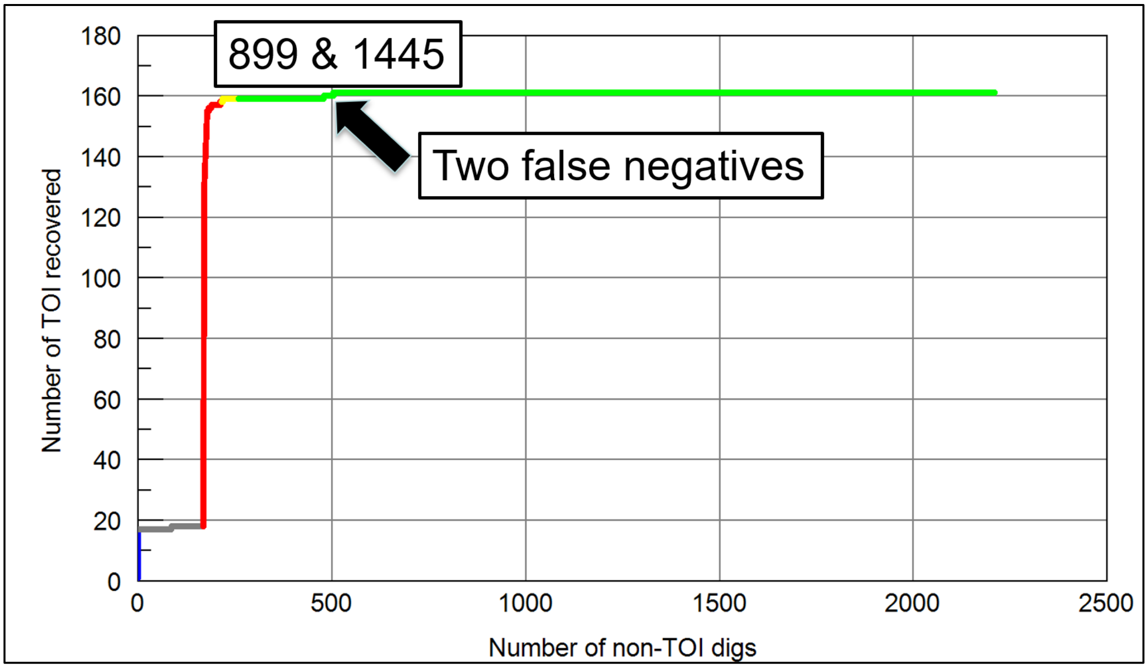


Figure 29. ROC Curve for the Automated Single-solver Processing Run.

Two TOI were incorrectly classified. These results were achieved post demonstration to define a generalized analysis scheme to minimize man-in-the-loop decisions.

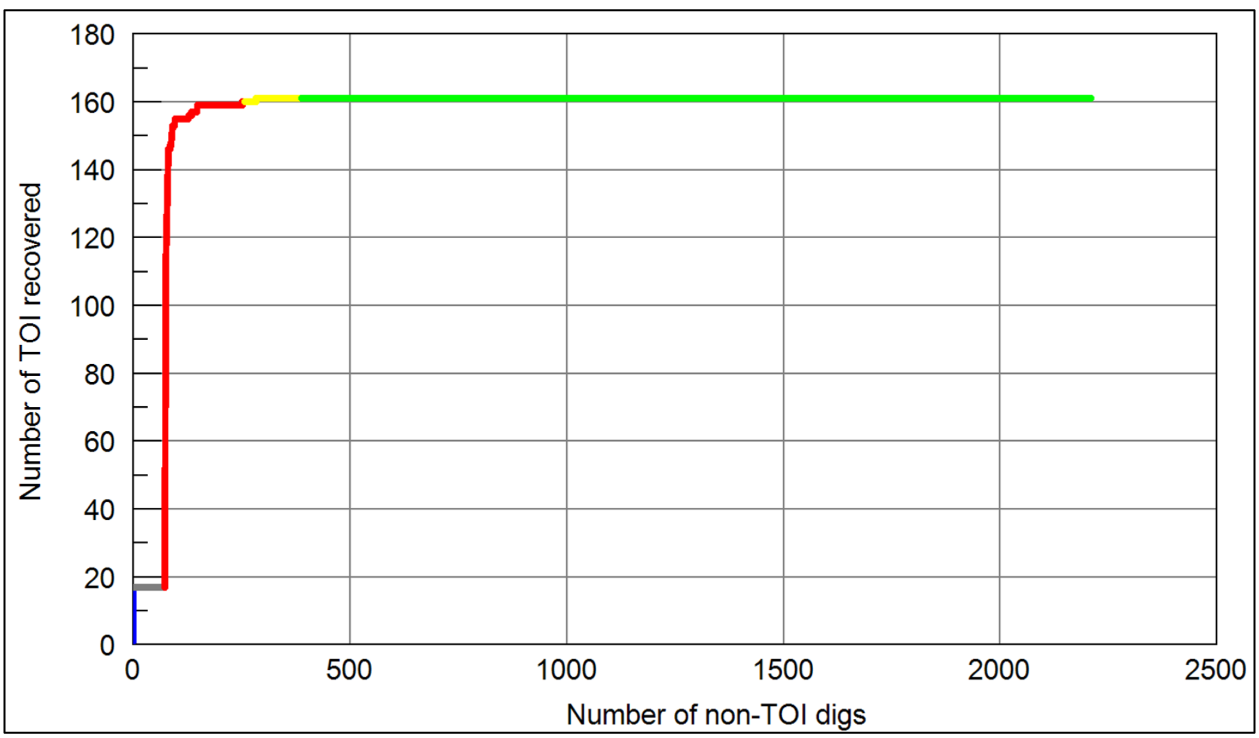


Figure 30. ROC Curve for the Automated Multi-solver Processing Run.

This scheme added computer time to the mix but did not suffer any false negatives.

In addition to the Pole Mountain demonstration discussed in detail above, SAIC utilized the UX-Analyze software at sites that had a range of anomaly densities and a range of UXO types. The process at these additional sites followed that described for Pole Mountain in that extreme care was taken collecting the AGC data, all anomalies were excavated, and results scored by IDA. Results of these efforts are shown in Figure 31, where individual ROC curves are positioned in anomaly density versus UXO diversity feature space.

The fact that a significant amount of non-TOI was correctly classified at each site, indicates that the classification method was successful at each site. The ROC curve for the Massachusetts Military Reservation (MMR), however, looks different than rest. At MMR, the inverted attributes for TOI and non-TOI were similar, which in addition to many multisource scenarios, made it difficult to confidently label clutter. As a result, the ROC curve rises relatively quickly at first, but then levels off.

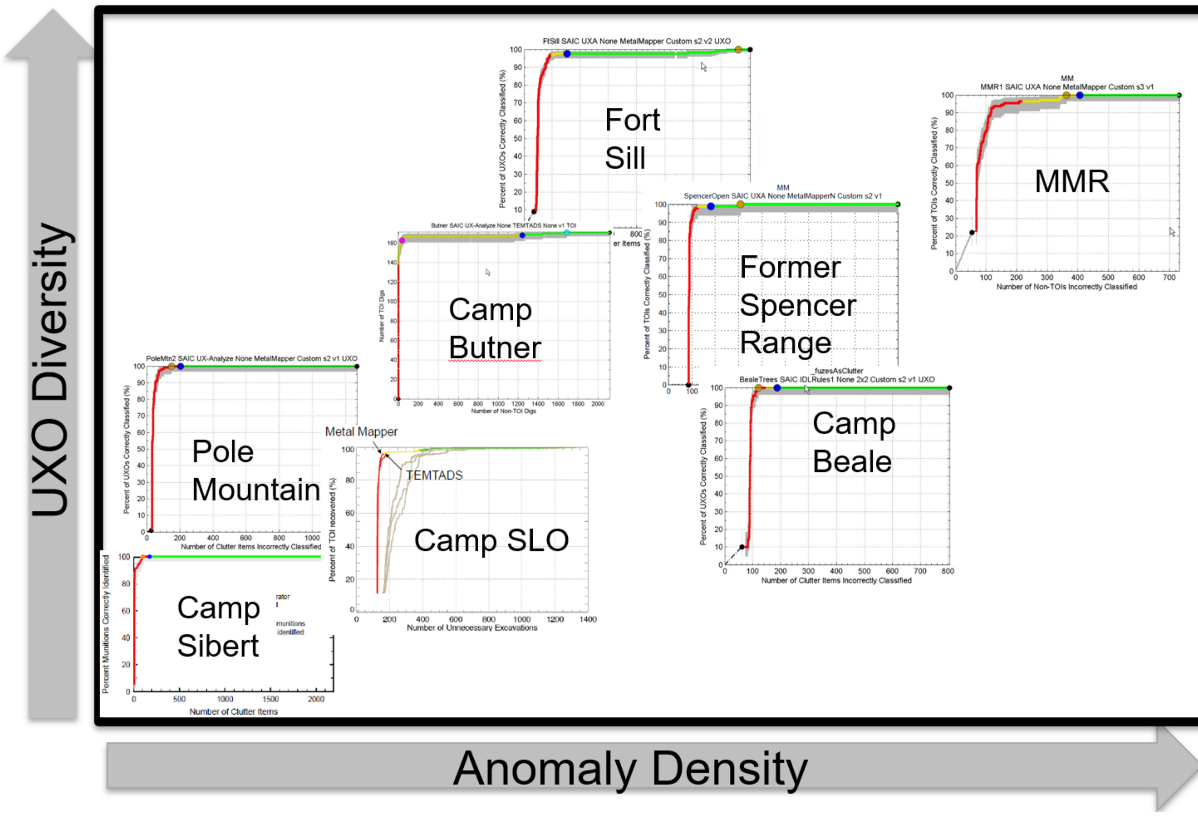


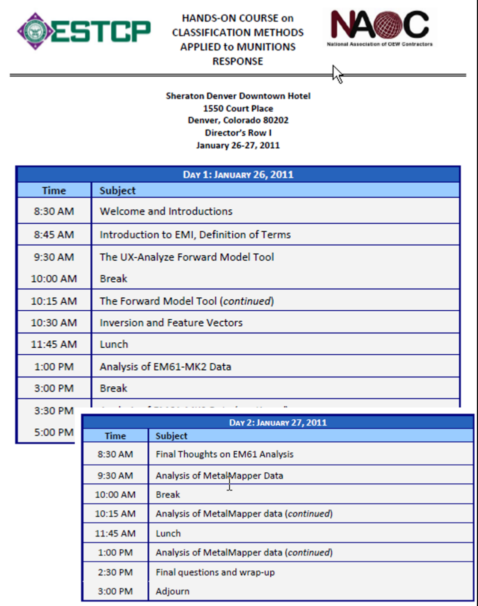
Figure 31. ROC Curves Realized Using UX-Analyze During the Development and Demonstration Phases of the UX-Analyze Software Suite.

11.0 TECHNOLOGY TRANSFER

In support of this ESTCP project, SAIC developed and delivered several training workshops to the user community (Figure 32). All told, over 210 people, representing 30+ firms, participated during the period (Figure 33). We also partnered with Geosoft to promote the approach online (Figure 34).

Training Workshops

- *March 2010: 2½ day, Huntsville, AL (32)*
- *April 2010: ½ day, Denver, CO (2)*
- *December 2010: ½ day, Wash. DC (40)*
- *Jan 2011: 2 day, Wash. DC (21)*
- *Jan 2011: 2 day, Denver, CO (21)*
- *March 2011: 1 day, Huntsville AL (30)*
- *Dec 2011: 1 day, Huntsville (20)*
- *Feb 2012: 2 day, Denver, CO (24)*
- *April 2012: 2 day, Wash. DC (20)*
- June 2012: ½ day, Denver (24)


ESTCP
HANDS-ON COURSE on CLASSIFICATION METHODS APPLIED to MUNITIONS RESPONSE
NAOC

Sheraton Denver Downtown Hotel
1550 Court Place
Denver, Colorado 80202
Director's Row I
January 26-27, 2011

Time	Subject
Day 1: January 26, 2011	
8:30 AM	Welcome and Introductions
8:45 AM	Introduction to EMI, Definition of Terms
9:30 AM	The UX-Analyze Forward Model Tool
10:00 AM	Break
10:15 AM	The Forward Model Tool (*continued*)
10:30 AM	Inversion and Feature Vectors
11:45 AM	Lunch
1:00 PM	Analysis of EM61-MK2 Data
3:00 PM	Break
3:30 PM	[illegible]
5:00 PM	[illegible]

Time	Subject
Day 2: January 27, 2011	
8:30 AM	Final Thoughts on EM61 Analysis
9:30 AM	Analysis of MetalMapper Data
10:00 AM	Break
10:15 AM	Analysis of MetalMapper data (*continued*)
11:45 AM	Lunch
1:00 PM	Analysis of MetalMapper data (*continued*)
2:30 PM	Final questions and wrap-up
3:00 PM	Adjourn

Figure 32. List of UX-Analyze Training Workshops Presented in Support of this Project and Classification Technologies in General.

IDA	ARM	Matrix Design	AMEC
USACE	Fugro	EODT	Weston Solutions
GeoVision	ITSI	CH2M Hill	UXB
3DGeophysics	Zapata Inc.	URS Corp	Malcolm Pirnie
Sky Research	UXA Environ.	Parsons	Nova Research
TetraTech	SAIC	NAEVA	Zonge
PDQ	ECC	Shaw	InDepth
ERT Corp	GEL	HydroGeologic	TLI

Figure 33. Partial List of Commercial Firms Who Participated in the ESTCP-Sponsored Analysis Workshops.

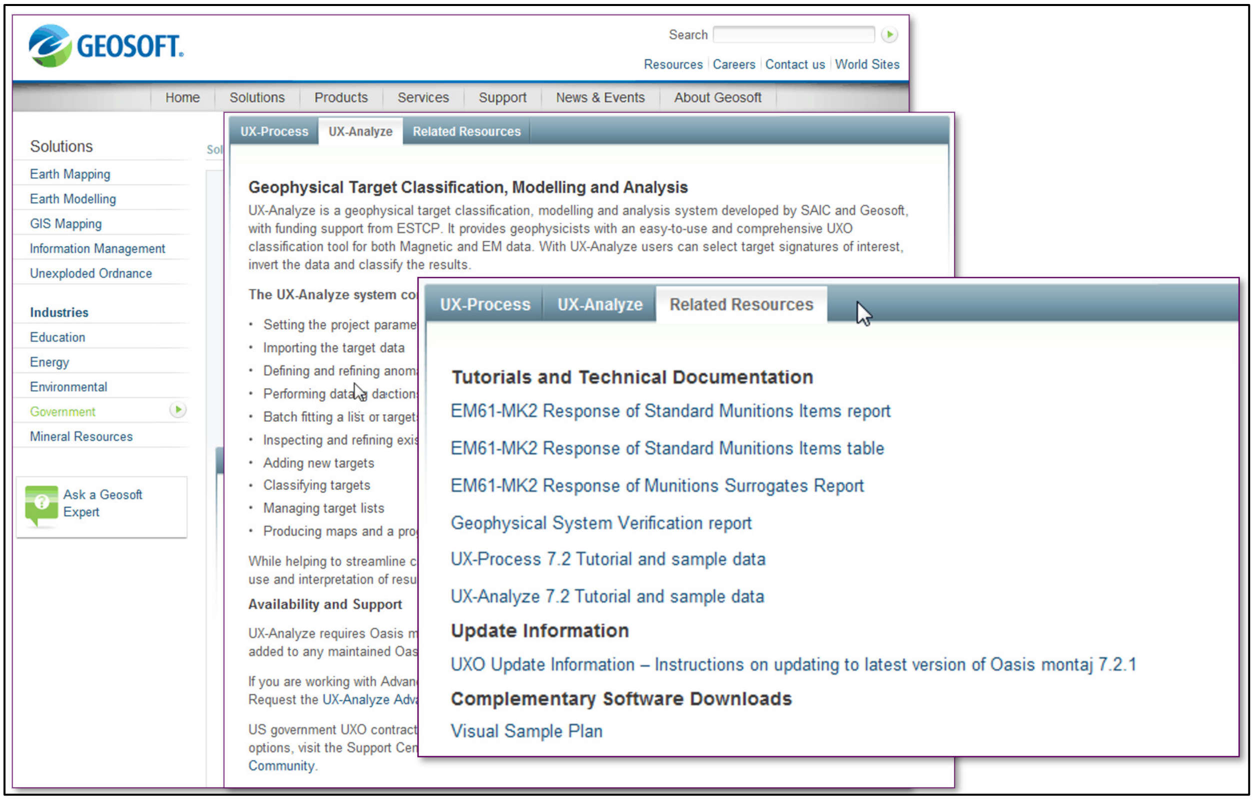


Figure 34. Technology Transfer via Online Materials.

12.0 REFERENCES

[1] "Report of the Defense Science Board Task Force on Unexploded Ordnance," December 2003, Office of the Under Secretary of Defense for Acquisition, Technology, and Logistics, Washington, D.C. 20301-3140, http://www.acq.osd.mil/dsb/reports/uxo.pdf.

[2] Department of Defense, Unexploded Ordnance Response: Technology and Cost, Report to Congress, March 2001

[3] URS, Demonstration of Advanced Geophysics and Classification Technologies on Munitions Response Sites, Pole Mountain Target and Maneuver Area, Wyoming. ESTCP Web site, MR-201161. 2012.

[4] Black Tusk Geophysics, Data collection with vehicular-based systems, ESTCP Web site, MR-201160, 2012.

APPENDIX A POINTS OF CONTACT

POINT OF CONTACT Name	ORGANIZATION Name Address	Phone E-mail	Role in Project
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Darren Mortimer	Geosoft	416 369 0111 Darren.Mortimer@geosoft.com	Software