FINAL REPORT

MUNITIONS CLASSIFICATION WITH PORTABLE ADVANCED ELECTROMAGNETIC SENSORS

Demonstration at the former Camp Beale, CA, Summer 2011

JULY 2012

Herbert Nelson
Anne Andrews
SERDP and ESTCP

ESTCP

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ACRONYMS

BUD	Berkeley UXO Discriminator
DoD	Department of Defense
EM(I)	Electromagnetic (Induction)
ESTCP	Environmental Security Technology Certification Program
FUDS	Formerly Used Defense Site
GPS	Global Positioning System
IDA	Institute for Defense Analyses
IMU	Inertial Measurement Unit
IVS	Instrument Verification Strip
MM	MetalMapper
MMRP	Military Munitions Response Program
MPV	Man-portable Vector Sensor
MR	Munitions Response
MTADS	Multi-sensor Towed Array Detection System
NRL	Naval Research Laboratory
QC	Quality Control
ROC	Receiver Operating Characteristic
SERDP	Strategic Environmental Research and Development Program
SLO	San Luis Obispo
SNR	Signal to Noise Ratio
TEMTADS	Time Domain Electromagnetic MTADS
TOI	Target of Interest
UXO	Unexploded Ordnance

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EXECUTIVE SUMMARY

Classification using portable advanced electromagnetic sensors, designed to operate in areas where terrain and vegetation preclude the use of vehicle-borne sensors, was demonstrated at the former Camp Beale, CA in 2011. The TEMTADS 2x2, Man-Portable Vector (MPV) and portable Berkeley UXO Discriminator (BUD) were used to successfully classify all of the targets of interest by all analysts. There was some variation among analysts in the percent of clutter rejected. All but two of the 16 performers eliminated about 75% of the clutter. This is comparable to the results achieved using the vehicular-borne MetalMapper on another part of this site.

Even though this was the first live site demonstration for each of the sensors, daily productivity of 90 to 175 anomalies was possible. One of the teams was able to collect cued data, extract parameters, and classify for $26 per anomaly. Using this per anomaly cost for classification and a few reasonable assumptions we calculate that the use of classification would result in a 50% savings for a 100-acre remediation on a site with conditions like Camp Beale.

When a site is remediated, it is typically mapped with a geophysical system, based on either a magnetometer or electromagnetic induction (EMI) sensor, and the locations of all detectable signals are excavated. Many of these detections do not correspond to munitions, but rather to other harmless metallic objects or geology: field experience indicates that often in excess of 99% of objects excavated during the course of a munitions response are found to be nonhazardous items. As a result, most of the costs to remediate a munitions-contaminated site are currently spent on excavating targets that pose no threat. If these items could be determined with high confidence to be nonhazardous, some of this expense could be avoided and the available funding applied to more sites.

Classification is a process used to make a decision about the likely origin of a signal. In the case of munitions response, high-quality geophysical data can be interpreted with physics-based models to estimate parameters that are related to the physical attributes of the object that resulted in the signal, such as its physical size, aspect ratio, wall thickness, and material properties. The values of these parameters may then be used to estimate the likelihood that the signal arose from an item of interest, that is, a munition.

The Environmental Security Technology Certification Program (ESTCP) is charged with demonstrating and validating innovative, cost-effective environmental technologies. ESTCP recently initiated a Classification Pilot Program, consisting of demonstrations at a number of sites, to validate the application of a number of recently developed technologies in a comprehensive approach to munitions response.

The goal of the pilot program is to demonstrate that classification decisions can be made explicitly, based on principled physics-based analysis that is transparent and reproducible. As such, the objectives of the pilot program are to:

- test and validate detection and classification capabilities of currently available and emerging technologies on a real site under operational conditions, and
- investigate how classification technologies can be implemented in cleanup operations in cooperation with regulators and program managers.

1 INTRODUCTION

1.1 BACKGROUND

Classification using portable advanced electromagnetic sensors was demonstrated at the former Camp Beale, CA in 2011. The TEMTADS 2x2, Man-Portable Vector (MPV) and portable Berkeley UXO Discriminator (BUD) all collected data to support successful classification. Camp Beale was also the site of a demonstration of the MetalMapper advanced sensor, described in a separate report. (Ref. 1)

Former Camp Beale, CA – complex historical usage, overlapping network of ranges throughout, moderate geologic interference. The portable demonstration area had moderate slopes and tree cover.

Munitions – 37-mm projectiles, 60-mm mortars, 81-mm mortars, 105-mm projectiles

Results – 2X2 TEMTADS, MPV and portable BUD were used to successfully classify all of the targets of interest by all analysts. There was some variation among analysts in the percent of clutter rejected. All but two of the 16 performers eliminated about 75% of the clutter. This is comparable to the results achieved using the MetalMapper on this site.

Classification is motivated by the need to perform munitions response more cost-effectively so that limited clean up dollars can be used to reduce real risk on munitions-contaminated sites sooner. The estimated liability in the FY10 Defense Environmental Programs Report to Congress for Munitions Response is $15.2B. (Ref. 2) The bulk of this liability is $10.0B for the 1703 sites identified in the Formerly Used Defense Sites (FUDS) program and $4.4B for the 2433 sites identified on Active Installations. The remaining $0.8B is in Base Realignment and Closure (BRAC). The estimated completion dates for many sites, particularly in the FUDS program, are decades out if they are to be cleaned up at planned funding levels using current practice.

When a munitions response site is cleaned up, in most cases, it is mapped with a geophysical sensor and the locations of all detectable signals are excavated. Geophysical sensors detect metal and, therefore, many of the detections do not correspond to munitions, but rather to harmless metallic objects. Field experience indicates that 95-99% or more of objects are found to be nonhazardous. Current technology does not provide a means to discriminate between munitions and other items, termed "clutter." As a result, most of the costs to remediate a munitions-contaminated site using current methods are spent on excavating targets that pose no threat. If buried items could be reliably classified into those that are munitions and those that are not, only the munitions would need to be removed from the site.

The Strategic Environmental Research and Development Program (SERDP) and the Environmental Security Technology Certification Program (ESTCP) have supported the development of purpose-built advanced electromagnetic sensors and associated analysis methods for classification. Following the successful demonstration of classification methods in controlled test environments, ESTCP initiated a Classification Pilot Program to validate the application in real-world conditions. The demonstrations are planned and conducted in cooperation with regulators and program managers in the Services.

The goal of the program is to demonstrate that classification decisions can be made using an explicit approach, based on principled analysis that is transparent and reproducible. Demonstrations will be required at a number of sites to represent the wide variability in munitions types, target densities, terrain, vegetation, geology, land use history, future land use, and other site characteristics that will affect the applicability of classification and to establish cost effectiveness and implementability. The demonstrations also present an opportunity to work out standard operating procedures and establish quality control (QC) measures. Details about past and ongoing demonstrations can be found on the SERDP-ESTCP web site at http://serdp-estcp.org/Featured-Initiatives/Munitions-Response-Initiatives/Classification-Applied-to-Munitions-Response.

The MetalMapper and full-sized TEMTADS and BUD have been successfully demonstrated in prior live-site efforts. These are large, heavy sensors suitable for use in open areas where they can be maneuvered with vehicles. The demonstration at the former Camp Beale is the first test of smaller man-portable advanced EM sensors intended for use where terrain or vegetation demand a more maneuverable option. They are less mature and field procedures were not established prior to this demonstration. Data were analyzed by experienced teams from the developers of the classification methods. These are important considerations in evaluating and applying the results, particularly the production rates. Production rates will likely increase with use and analysis methods will transition to production geophysicists, although they have not yet. For these reasons, we discourage potential customers from using the results from this demonstration to rank performers and make contracting selections. As we conduct more demonstrations of the portable sensors on a variety of sites, the identities of the consistently better performers will emerge.

Table 1-1 shows the participants and their roles in the Camp Beale demonstration of portable sensors.

Table 1-1. Participants in the Portable Sensor Demonstration at the former Camp Beale

Task	Performer(s)	Task	Performer(s)
Site Preparation	Parsons	BUD Data Collection	LBNL
EM61-Mk2 Data Collection and Target Selection	Parsons (with input from ESTCP)	MPV Data Collection	Sky Research
Intrusive Investigation	Parsons	TEMTADS 2X2 Data Collection	NOVA Research/ CH2M HILL
Scoring	Institute for Defense Analyses	Data Analysis	SAIC Sky Research Dartmouth College

1.2 CLASSIFICATION CONCEPT

Classification is a process used to make a decision about the likely origin of a signal. In the case of munitions response, high-quality geophysical data can be interpreted with physics-based models to estimate parameters that are related to the physical attributes of the object that resulted in the signal, such as its physical size and aspect ratio. The values of these parameters may then be used to estimate the likelihood that the signal arose from an item of interest, that is, a munition. Electromagnetic Induction data are typically fit to a three-axis polarizability model that can yield parameters that relate to the physical size of the object, its aspect ratio, the wall thickness, and the material properties. The physics governing the electromagnetic response of a metal object is well understood and predictable. Data collected with these sensors contain the same information content on any site and demonstrations to date have confirmed that classification works predictably.

Munitions are typically long, narrow cylindrical shapes that are made of heavy-walled steel. Common clutter objects can derive from military uses and include exploded parts of targets, such as vehicles, as well as munitions fragments, fins, base plates, nose cones and other munitions parts. Other common clutter objects are man-made nonmilitary items. While the types of objects that can possibly be encountered are nearly limitless, common items include barbed wire, horseshoes, nails, hand tools, and rebar. These objects and geology give rise to signals that will differ from munitions in the parameter values that are estimated from geophysical sensor data.

Once the parameters are estimated, a methodology must be found to sort the signals to identify items of interest, in this case munitions, from the clutter. This is termed classification. In a simple situation, one can imagine sorting items based on a single parameter, such as object size. A rule could be made that all objects with an estimated size larger than some value will be treated as potentially munitions items of interest, such as large bombs, and those smaller could not possibly correspond to intact munitions.

In reality, many classification problems cannot be handled successfully based on a single parameter. Because the parameter-estimation process is imperfect and the physical sizes of the objects of interest may overlap with the sizes of the clutter objects, it is rare to get perfect separation based on one parameter. For complex problems, sophisticated statistical classifiers can combine the information from multiple parameters to make a quantitative estimate of the relative likelihood that a signal corresponds to an item of interest.

1.3 RESULTS FROM THE METALMAPPER DEMONSTRATION AT CAMP BEALE

The MetalMapper was demonstrated at Camp Beale, concurrent with the demonstration of the portable sensors. This sensor is commercially available and its use the most widespread of the advanced sensors. It provides a point of comparison for the performance of the smaller, portable sensors. This demonstration took place in an open and accessible area adjacent to the treed site where the portable sensors were demonstrated. The targets of interest and clutter environment were comparable. Both production contractor geophysicists and the developers of classification methods were successful in using MetalMapper data to achieve substantial classification.

An example of the analysis of the MetalMapper data is shown in Figure 1-1. In this demonstration, there were 1310 total clutter items as determined from the ground truth. This analyst successfully identified all but one of the TOI and eliminated about 75% of the clutter. The cued location from the EM-61 data for the missed seed was not directly over the item and one of the cued surveys moved further away to another item as part of their optimization; thus, the item over which data was collected was not the same as the item dug leading to an incorrect classification. This classification performance was typical for the developers analyzing the MetalMapper data and similar results were achieved by some but not all of the production contractor analysts. (Ref. 1)

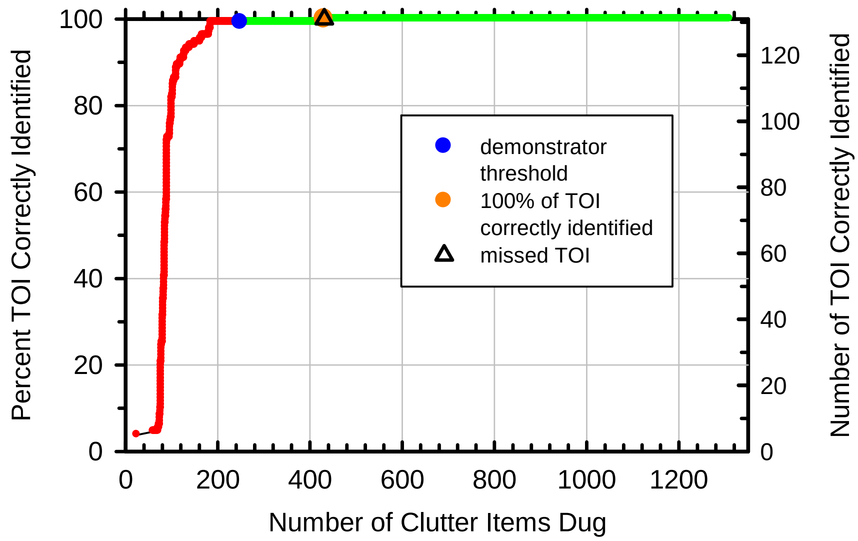

Figure 1-1. Results of SAIC analysis of MetalMapper data acquired by Parsons at the former Camp Beale

1.4 ABOUT THIS REPORT

This report provides an overview of the key results from the demonstration of the portable systems for project managers, regulators, and contractors. All three of these systems are still in development but the results presented here are indicative of their potential. The material covered in this report represents only a small part of a much larger study; more information about the entire demonstration can be found in the individual demonstrator reports (Refs. 3-12) and an independent performance assessment by the Institute for Defense Analyses. (Ref. 13)

The report begins with a description of the site and an overview of the program approach. We then describe the detection and classification performance of the portable sensors. This is followed by a discussion of costs and a summary of the program conclusions.

2 FORMER CAMP BEALE DEMONSTRATION SITE

The former Camp Beale site was selected for demonstration of the portable systems because it is partially wooded and exhibits moderately hilly terrain. It contains a mixture of large and small munitions, which presents a difficult classification problem likely to be encountered on production sites. The tree cover also increases the difficulty of obtaining accurate GPS readings, posing a challenge for navigation and geolocation that will affect reacquisition for the cued systems.

2.1 SITE HISTORY AND CHARACTERISTICS

The site description material reproduced here is taken from the Site Inspection Report. (Ref. 14) More details can be obtained in the report.

The former Camp Beale is an approximately 60,000-acre site located in Yuba and Nevada Counties, CA. Camp Beale was subject to complex historical usage over many years and there is an overlapping network of historical ranges throughout. An aerial photo of Camp Beale showing the location of the demonstration area is shown in Figure 2-1.

The former Camp Beale property area was acquired by the U.S. Government prior to 1940 and consisted of 85,654 acres. During WWII, it was used by armored divisions, served as an induction center and a prisoner of war encampment, and was the site for the West Coast Chemical Warfare School, among other things. Later it was used for a variety of training activities by the National Guard, the Air Force and the Navy. In 1957 approximately 65,000 acres was declared excess.

The demonstration was conducted in an area that is located within the historical bombing Target 4 and the Proposed Toss Bomb target area. An aerial photo of the demonstration area is shown in Figure 2-2. The area includes sections with trees and steeper slopes where the man-portable systems surveyed, in addition to sections that are relatively flat and open, where the MetalMapper demonstrations took place. Both MetalMapper and the portable systems were demonstrated on the area marked Combined. During the demonstration, it was discovered that sensor data showed moderate geologic interference. An example of the measured background variation in the Combined Grids is shown in Figure 2-3. Variations of this magnitude make it important to use backgrounds measured in close proximity when analyzing anomaly data.

The suspected munitions in this demonstration area include, but are not limited to:

- 37-mm projectiles
- 60-mm mortars
- 81-mm mortars
- 105-mm projectiles

At the particular site of this demonstration, evidence of 81-mm mortars and 105-mm projectiles was found during the Site Inspection intrusive investigation in 2005. It is also suspected that 60-mm mortars may be present. In addition, 37-mm projectiles have been found scattered throughout the former Camp Beale and are included as another suspected munition in this area. Due to the complex historical usage of this site over many years and the overlapping network of historical ranges throughout, it is also likely that other munitions types beyond those listed above may be encountered.

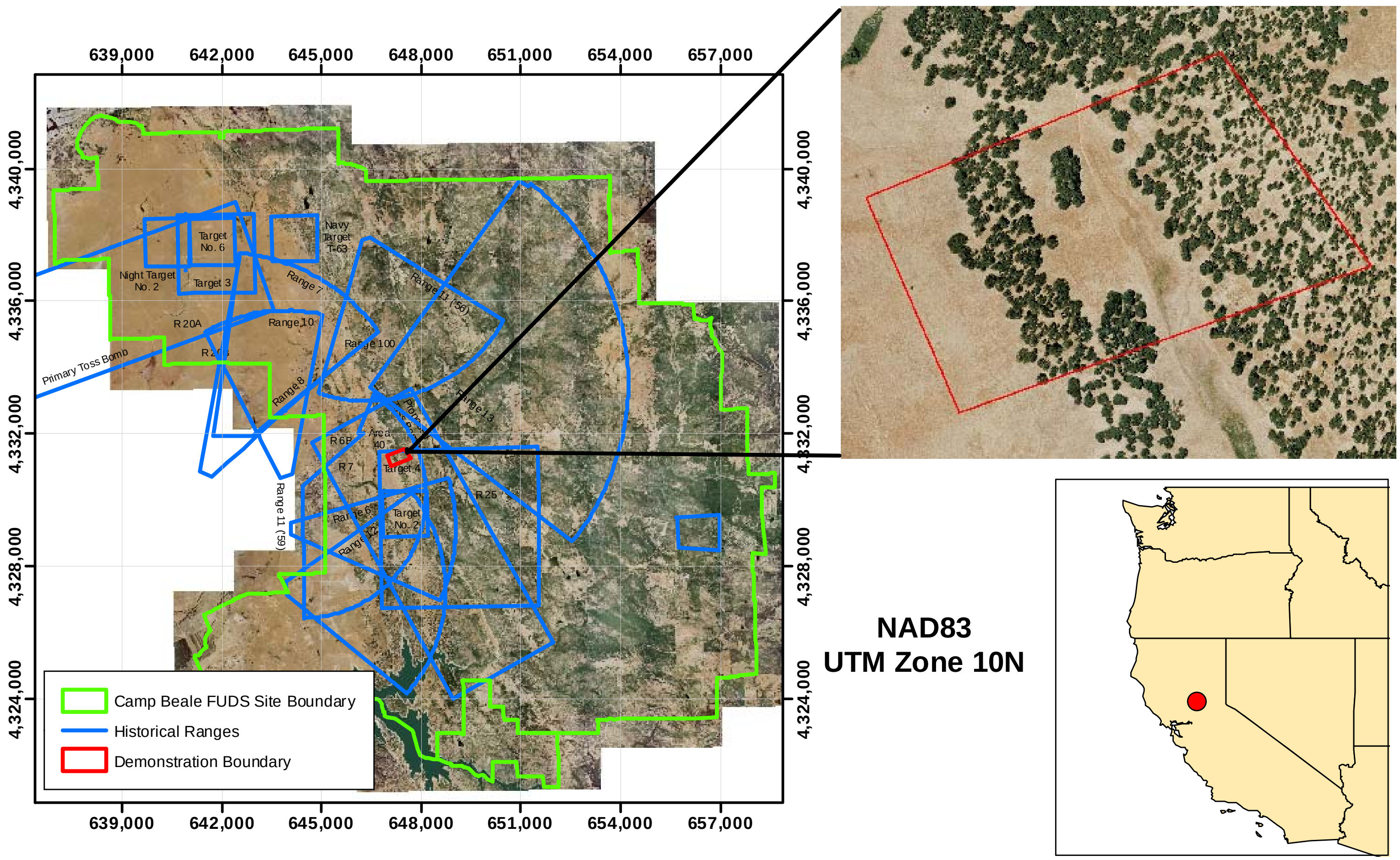

Figure 2-1. Aerial photograph of the former Camp Beale FUDS with historic ranges overlain. The 50-acre site boundary which contains the demonstration areas is shown in the blow-up.

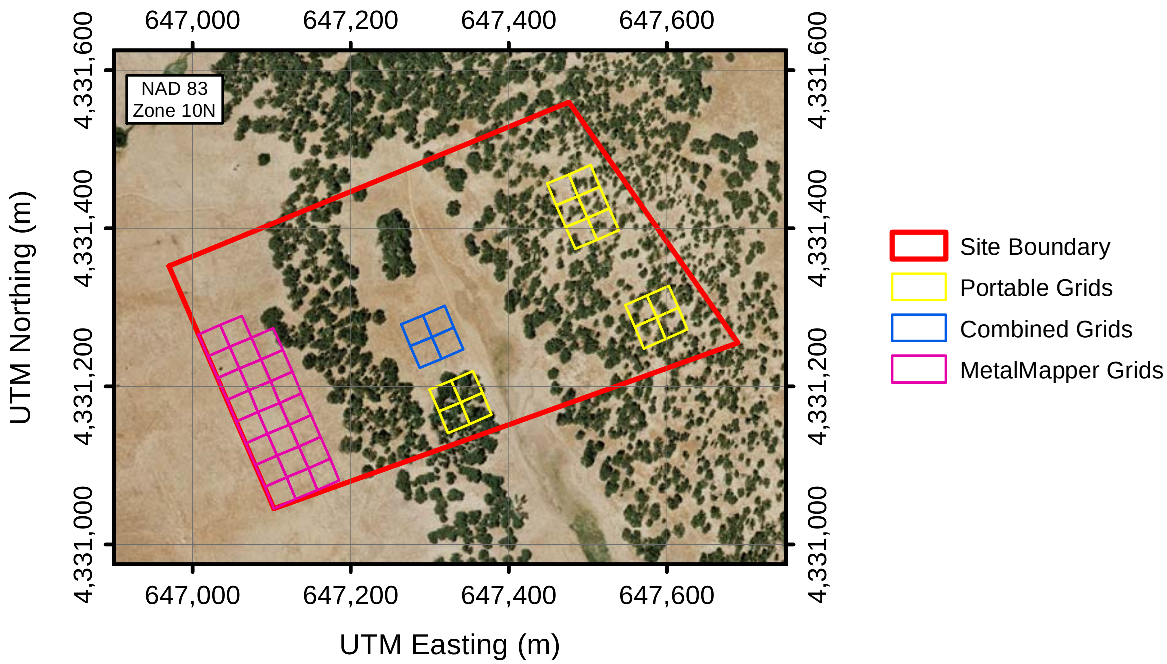

Figure 2-2. The fifty-acre demonstration site with the MetalMapper grids, portable system grids, and combined grids delineated

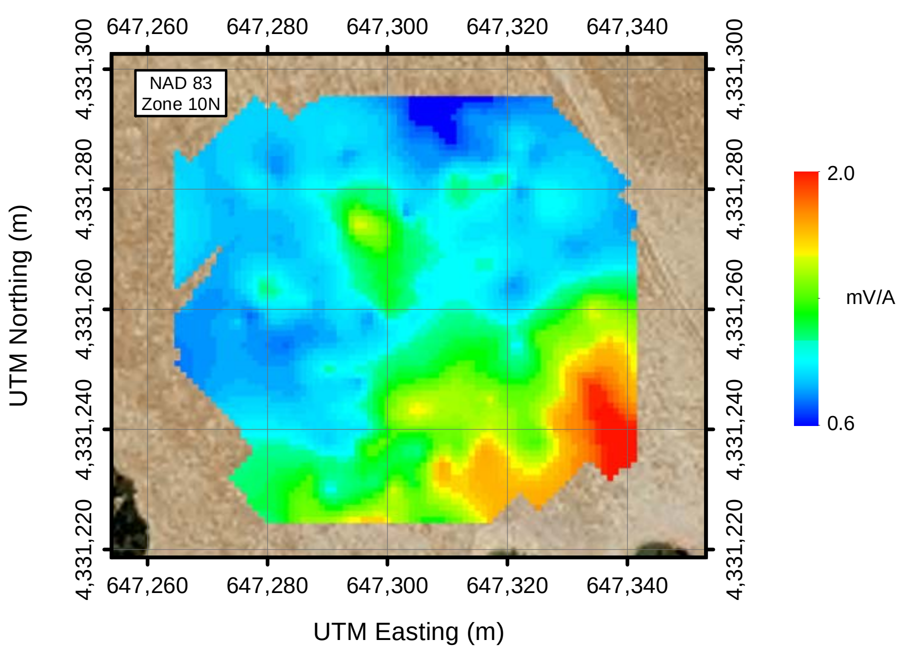

Figure 2-3. Measured geologic background variability in the Combined Grids of the former Camp Beale site

3 PROGRAM DESIGN

3.1 OVERALL APPROACH

An overview of the steps involved in this demonstration is shown in the flow chart in Figure 3-1.

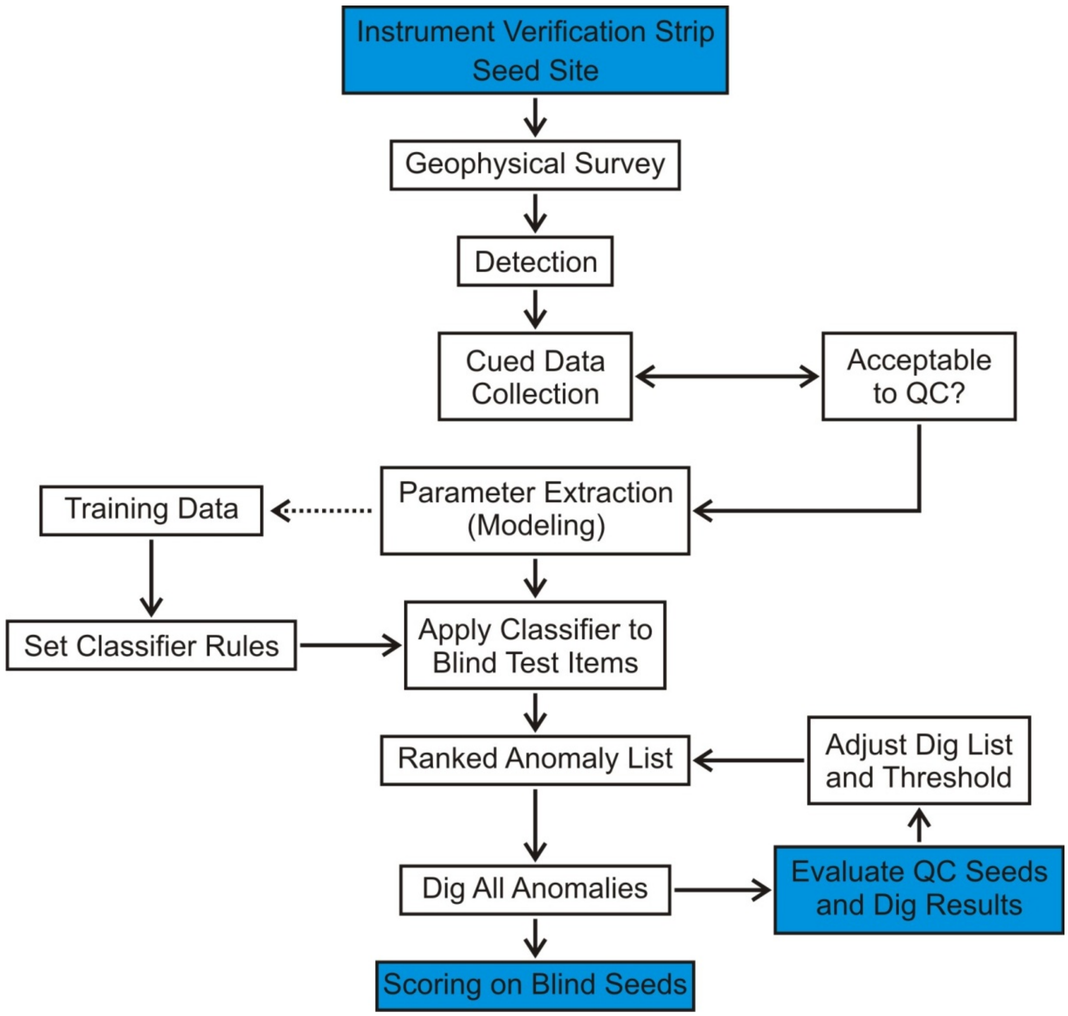

Figure 3-1. Flow chart outlining steps in the demonstration at Camp Beale. Blue boxes are tasks performed by ESTCP. Others are tasks performed by contractors.

The objective of the study was to evaluate classification, as opposed to detection. Multiple classification approaches were applied to data collected using three different portable sensor platforms. For comparisons of different classification approaches to be straightforward, a common set of detections for each data set was required. EM61-MK2 survey data were used to perform detection. The approach to detection is described below in Section 5.1. A common anomaly list was passed to each of the cued data collection teams and all of the analysis demonstrators.

All the targets on the anomaly list were dug and assigned ground-truth labels designating whether or not each was a target of interest (TOI). These labeled data, including the seeded targets, were available to be used as training data or test data. Demonstrators could choose to perform their classification based on no site specific training data or a demonstrator-requested training data set. If requested, all truth information for the training data was provided to the processors and used to train their algorithms. The truth labels for the remaining data were sequestered, and these were used for blind testing. The processors were required to provide their assessment of the TOI/not-TOI labels for each item in the test data part of the detection list. The labels were compared to truth by an independent third party to score performance.

3.2 DEMONSTRATION PREPARATION

Several activities occurred prior to data collection to ensure the resulting data would support a successful demonstration.

3.2.1 Seeding the Site

At a live site, the number of UXO is small, far from enough to determine any demonstrator's classification performance with acceptable statistical confidence bounds. In fact, on the Camp Beale demonstration site, only four munitions were recovered in the intrusive investigation. Therefore, the site was seeded with enough TOI to ensure statistical validity on measures of classification of TOI. The seeds are listed in Table 3-1. For the first time, the seeds included not only inert munitions, but also industry standard objects. (Ref. 15) The ISOs are also considered TOI and expected to be both detected and correctly classified.

Table 3-1. Seeds Emplaced for the Camp Beale demonstration (includes the MetalMapper demonstration area)

Item	Number	Depth range (cm)*
Industry Standard Object Small, Schedule 40	65	10-25
37-mm projectile	59	10-32
60-mm mortar	34	15-40
81-mm mortar	33	15-50
105-mm projectile	9	15-60

*Depths are to the center of the object below ground level.

No attempt was made to separate the seeds from the surrounding clutter. For safety, seeds were emplaced using standard anomaly avoidance procedures. For realism, the emplacement teams were instructed to replace any metal dug up during emplacement back in the hole with the seeded object. All seed depths were specified at 15 cm in the site seeding plan, with direction for crews to bury them deeper where soil conditions allowed. In some cases, the items were buried at shallower depths due to ground conditions.

3.2.2 Instrument Verification Strip and Training

A quiet area near the portable grids was located to establish an instrument verification strip (IVS) to be used for daily verification of proper sensor operation and a training pit to be used to collect sensor data for algorithm training. Details of the contents of the IVS are given in Table 3-2.

Table 3-2. Details of the Instrument Verification Strip

Item ID	Description	Depth (m)	Inclination	Azimuth (° cw from N)
T-001	shotput	0.30	N/A	N/A
T-002	105-HEAT	0.45	Horizontal	Across Track
T-003	37-mm projectile	0.15	Horizontal	Across Track
T-004	60-mm mortar	0.15	Horizontal	Across Track
T-005	small ISO	0.15	Horizontal	Across Track

3.2.3 Surface Clearance

Prior to the digital mapping (DGM) surveys, Parsons UXO personnel conducted instrument-aided surface clearance. The main objective of the surface clearance was to ensure that no hazardous items would be encountered during the nonintrusive phases in the demonstration area and to remove metallic surface debris from the grids. In addition to the surface clearance, Parsons also conducted minor brush clearing, cutting low branches and removed fallen trees from the demonstration area. This operation required one week. The majority of items found on the surface sweeps were barbed wire, along with small munitions fragments. Two notable items identified during the surface clearance were an empty 75-mm projectile and a large pile of barbed wire that was eventually moved out of the survey area. These are shown in Figure 3-2.

Figure 3-2. Examples of the items removed during the pre-survey surface clearance.

3.3 TARGETS OF INTEREST

The main goal of classification in the pilot program is to identify with high confidence items that can be safely left behind. At Camp Beale, the project team determined that targets of interest that must be removed would include:

- seeded munitions and Industry Standard Objects and
- intact munitions recovered at the site, both live and inert.

Eighty eight items were seeded in the areas surveyed with the portable systems and all are TOI. Two 37-mm projectiles were recovered in these areas that were classified by the UXO specialists as munitions debris because they were empty. Both of these projectiles were intact (Figure 3-3) so they were deemed TOI for this study.

Figure 3-3. Two "empty" 37-mm projectiles recovered in this demonstration.

3.4 DATA COLLECTION

The classification pilot study tested combinations of data-collection platforms and analysis approaches. Data-collection plans were generated by all data collectors and shared with the data processors prior to deployment.

An EM61 instrument was used to collect high quality, high density survey data. These data were used both for anomaly detection and to test what can be achieved attempting classification with careful data collection using standard equipment and field techniques. Data were collected with a standard cart platform EM61-MK2 system in the four-channel mode. The sensor height above ground was the standard 40 cm to the bottom of the coil housing. Positioning was accomplished using either RTK GPS, Trimble Robotic Total Station (RTS), or fiducial methods, depending on the availability GPS signal and tree density in the wooded area. (Ref. 6) Data were acquired by running the sensor in closely spaced lines, similar to the pattern of a lawnmower cutting grass. The site was divided into 30-m x 30-m grids, Figure 2-2, and data collected one grid at a time with survey lanes spaced at 0.5-m intervals.

The three prototype portable systems specially designed to maximize classification of munitions collected data over each anomaly detected by the EM61. The geophysical sensors are described briefly below in Section 4. Details may be found in the reports provided by the performers (Refs. 7-9). Each anomaly in the detection survey was reacquired using either GPS or RTS. To account for the relatively poorer geolocation in the survey data taken in the woods, the positions were refined by finding the peak of the EM61 signature. This location was marked with a flag that that was used to position the cued data collection for all three advanced sensors.

3.5 CLASSIFICATION APPROACHES

3.5.1 Geophysical Models

Classification demonstrators could analyze the survey data, the cued data, or a mix of the two; for some anomalies in some analysis schemes decisions could be made from the survey data so there was no need to bear the cost of a cued measurement. The data corresponding to each anomaly were analyzed by the processing teams to extract parameters by fitting the data to a geophysical model. This has the effect of separating the intrinsic target parameters from extrinsic variables such as the distance and orientation between the sensor and the target. All but one of the processing approaches relied on the dipole model.

Some of the intrinsic parameters that were considered included:

- the electromagnetic polarizabilities, which relate to the object's physical size and aspect ratio, and

- the electromagnetic decay constants, which relate to the object's material properties and wall thickness.

3.5.2 Classifiers

Once the parameters are estimated, a mechanism is needed to decide whether the corresponding object is a target of interest or not. Several types of classification processing schemes were evaluated in the classification study. These included both

Statistical classification: Computer algorithms evaluate the contributions of each parameter to defining munitions likeness based on "training" on a subset of the data for which the identities of the objects are known. Then the unknown objects are prioritized based on whether their parameters are statistically similar to known objects in the training data.

Library-matching classification: One or more of the three polarizability decay curves derived for each anomaly are compared to a library of responses of munitions and surrogates. The unknowns are prioritized based on how well they match one of the library responses.

Most classification algorithms require some training to select the parameters or features that are most useful for classification and set thresholds in the decision process. For this demonstration, the analysts had the choice of using training data previously collected at other sites only, supplementing those data with data from the IVS and training pit, or adding training data obtained from excavation of a limited number of anomalies from the site. For those demonstrators that chose to use on-site training data, the anomaly list was divided into training and blind testing sets; for those who did not choose on-site training, the test set consisted of all anomalies. After training, the decision process for each algorithm was finalized and documented, and the demonstrators provided ranked dig lists for the blind test set.

The final step in classification is delineating the targets of interest from those that are not. For example, in the case of a statistical classifier, all the anomalies are ordered by the likelihood that they belong to the class of the targets of interest. These likelihood values do not represent a yes/no answer, but rather a continuum within which a dividing line or threshold must be specified. Depending on the application, this threshold may be set to try to avoid false positives, which may come at the expense of missing some items of interest, or it may be set to try to avoid false negatives, which will come at the expense of a greater number of non-TOI. In this program, where missing an item of interest represented the most serious failure, demonstrators selected thresholds to try to retain all the detected munitions.

3.6 CLASSIFICATION PRODUCT

Demonstrators were asked to produce a ranked anomaly list for each sensor and processing combination. These lists were constructed as shown in Figure 3-4.

Initial Ranked Anomaly List

Rank	Anomaly ID	Decision Statisitic	Dig	Comment
1	2498	-9999	Y	Can't extract reliable parameters
2	247	.97	Y	
3	1114	.96	Y	High likelihood TOI
4	69	···	Y	
5	811	···	Y	
···	313	···	N	Unable to classify
···	883	···	N	
···	···	···	N	
···	···	···	N	
···	···	···	N	High likelihood not TOI
···	···	···	N	
···	···	···	N	
···	···	···	N	
···	···	.02	N	
···	···	.02	N	
N	···	.01	N	

First Pass Threshold

Final Ranked Anomaly List

Rank	Anomaly ID	Decision Statisitic	Dig
1	2498	-9999	Y
2	247	.97	Y
3	1114	.96	Y
4	69	···	Y
5	811	···	Y
···	313	···	Y
···	883	···	N
···	···	···	N
···	···	···	N
···	···	···	N
···	···	···	N
···	···	···	N
···	···	···	N
···	···	.02	N
···	···	.02	N
N	···	.01	N

Final Threshold

Figure 3-4. Format for the initial (left) and final (right) ranked anomaly lists for this demonstration

- GRAY: Targets where the signal-to-noise ratio (SNR), data quality, or other factors prevent any meaningful analysis were deemed "can't extract reliable parameters" and placed at the top of the list.
- RED: The next items were those that the demonstrator was most certain are TOI.
- YELLOW: A band was specified indicating the targets where the data can be fit in a meaningful way, but the derived parameters do not permit a high confidence determination of TOI or not-TOI Some of these anomalies may be marked to be dug in the first round to resolve these ambiguities.
- GREEN: The bottom item in the list was that which the demonstrator was most certain does NOT correspond to a TOI.
- THRESHOLD: A threshold was set at the point beyond which the demonstrator would recommend all anomalies be treated as TOI, either because they are determined to be so with high confidence or because a high-confidence determination that they are not TOI cannot be made. This is indicated by the heavy black dashed line.

Demonstrators were allowed to submit several successive dig lists to refine their analysis but the final list had to include a dig/no-dig judgment for every anomaly.

3.7 SCORING METHODS

The demonstration was scored based on the demonstrator's ability to eliminate nonhazardous items while retaining all detected TOI. A common way to evaluate performance of detection and classification is the receiver operating characteristic (ROC) curve. An example is shown in Figure 3-5. The colored regions on the plot in Figure 3-5 correspond to the colors of the various sections of the ranked dig list in Figure 3-4. The ROC curve is a plot of the percent of the TOI dug, that is it reflects the probability of correctly classifying the detected munitions items, versus the number of non-TOI. A perfect classifier would correctly identify 100% of the munitions and no clutter. We have modified the traditional ROC curve slightly to reflect both the TOI and non-TOI dug for training. This is done to account for the fact that different methods used different amounts of training data.

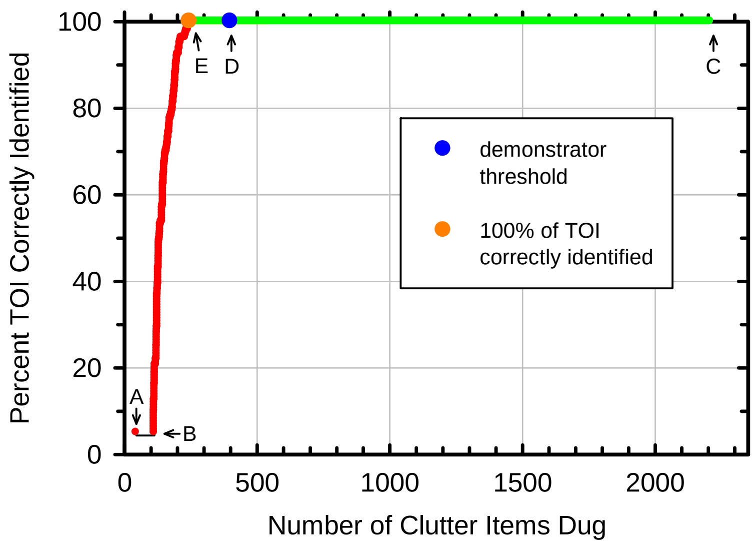

Figure 3-5. Example receiver operating characteristic curve.

The key regions to interpret the ROC curves used in this program are:

- **A**: Targets to the left and below this point were dug for training data. Site specific training data were used in many of the processing approaches and these digs would be required. Different approaches required differing amounts of training data; the ROC curves for those that used no site-specific training data start at the origin.
- **B**: Targets from point A to this point were categorized as can't analyze and would need to be treated as potential TOI because no meaningful classification could be done. In this example, about 30 of the can't analyze targets were false positives, reflected in the position of the point on the horizontal axis. No TOI were included in the can't analyze list.
- **C**: In the absence of any classification, this sensor detected all the TOI and had more than 2100 non-TOI items in the detection list.
- **D**: Based on classification, this is the demonstrator's threshold for the dividing point between TOI and not-TOI. This demonstrator missed one TOI at her threshold.
- **E**: This demonstrator's best threshold chosen retrospectively. If the threshold had been chosen perfectly, only 200 targets could have been left in the ground.

4 ADVANCED SENSOR TECHNOLOGIES

Three portable sensors were used to collect cued data at the locations of anomalies detected by the EM61 cart. These purpose-built EMI systems differ from the EM61 is two important ways. First, they were designed to collect sufficient data to fully characterize the EMI signature of a buried object from a single measurement location or a series of closely-spaced static measurements. Second, they collect a more complete measurement of the time response of the target, both farther out in time and at greater fidelity.

4.1 MAN-PORTABLE VECTOR SENSOR (MPV)

The MPV is a time-domain, EMI sensor composed of a single transmitter coil and an array of five receiver units that measure all three components of the EM field as shown in Figure 4-1. The MPV sensor head for this demonstration comprised a 50-centimenter (cm) diameter circular loop transmitter coiled around a disk that intermittently illuminates the subsurface, and five 8-cm multi-component receiver units (cubes) that measure the three orthogonal components of the transient secondary EM field decay.

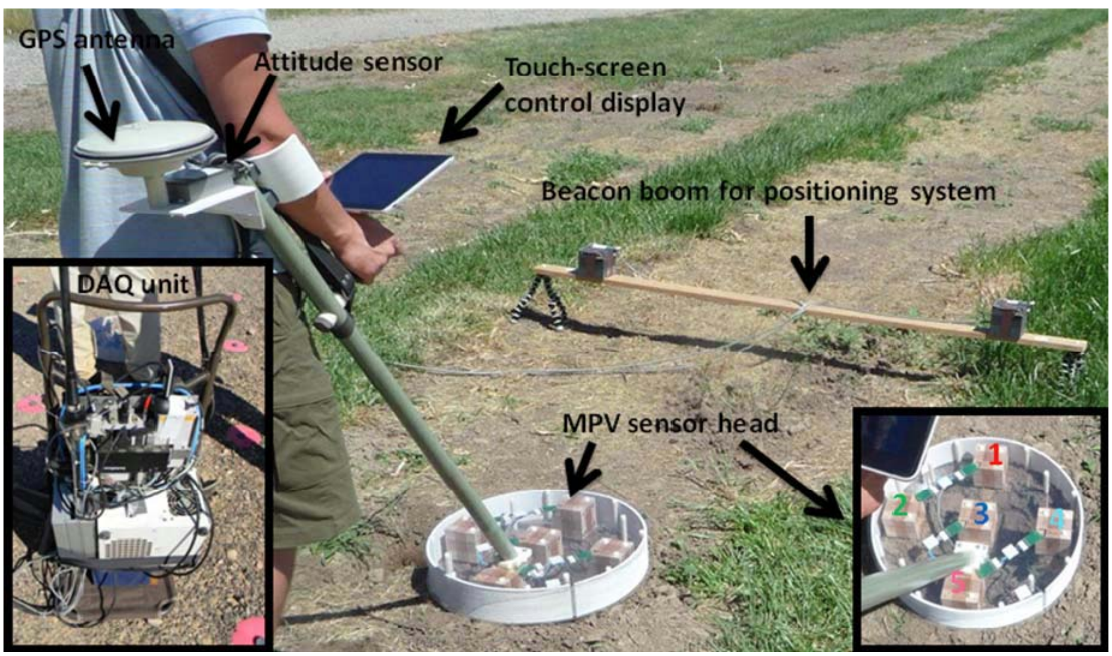

Figure 4-1. Components of the MPV. Left inset shows data acquisition (DAQ) and power unit mounted on a backpack frame. Right panel shows view of sensor head from above with cube numbers.

Cued data were collected in a 9-point grid around the flagged anomaly location using the MPV-beacon positioning system to obtain local sensor positions. (Ref. 7) The positioning system works by locating the origin of the primary field generated by the MPV transmitter coil, acting as a beacon, with a pair of EMI receivers rigidly attached to a portable beam, placed horizontally on the ground and supported by a pair of tripods to act as a base station. The azimuth of the MPV and boom are recorded with 3-component attitude sensor. Decay data were collected to 25 ms after primary field turn-off for this survey. A photo of MPV data collection at Beale is shown in Figure 4-2.

Figure 4-2. MPV data collection in the trees at Camp Beale

4.2 TEMTADS 2X2

The TEMTADS 2x2 array is comprised of four individual EMI transmitters with 3-axis receivers, arranged in a 2 x 2 array as shown in Figure 4-3. The center-to-center distance is 40 cm, yielding an 80 cm x 80 cm array. The data acquisition computer is mounted on a backpack worn by one of the data acquisition operators. The second operator controls the data collection using a personal data assistant (PDA) which wirelessly communicates with the data acquisition computer. The second operator also manages field notes and team orienteering functions.

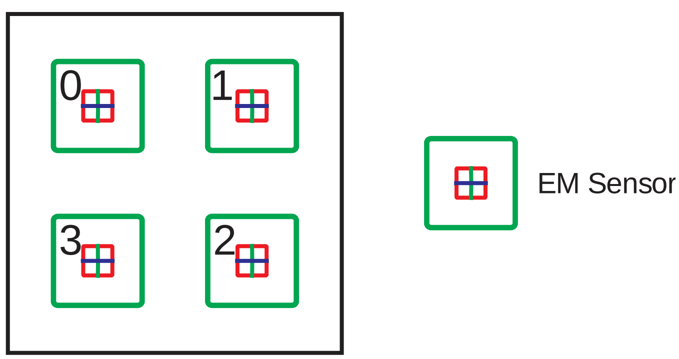

Figure 4-3. Schematic of the TEMTADS 2x2 array

For each series of measurements with the array, the four transmitters are energized sequentially. After each excitation pulse, the response of all twelve receive coils is recorded, resulting in 48 (4 x 4 x 3) transmit/receive pairs. Data were recorded for 25 ms after transmitter turn-off. (Ref. 8) A photograph of the TEMTADS 2x2 array collecting data at Camp Beale is shown in Figure 4-4.

Figure 4-4. Portable TEMTADS 2x2 data acquisition at Beale

4.3 BERKELEY UXO DISCRIMINATOR (BUD)

The prototype hand-held UXO discriminator employs three orthogonal transmitters and ten pairs of differenced receivers in a 35-cm cube, Figure 4-5. Each vertical face of the cube has three induction coils, and two horizontal faces have four induction coils, each sensitive to the magnetic field component normal to the face. Receivers on opposite faces of the cube are paired along the symmetry lines through the center of the system and each pair sees identical fields during the on-time of current pulses in the transmitter coils. The pairs are wired in opposition to produce zero output during the on–time of the pulses in three orthogonal transmitters. This configuration dramatically reduces noise in measurements by canceling background electromagnetic fields (these fields are uniform over the scale of the receiver array and are consequently nulled by the differencing operation), and by canceling noise contributed by the tilt of the receivers in the Earth's magnetic field. Thus, the gradiometer configuration greatly enhances receivers' sensitivity to the target response.

Figure 4-5. Transmit and receive coil configuration for the prototype portable UXO discriminator

At Beale, cued data were collected at each flag, and at 0.15 m before and 0.15 m after it, with the system oriented in a single direction. Soundings were differenced with background reference soundings taken within the previous 30-40 minutes at a nearby site determined by the field operator to be free from metallic objects. When polarizability inversions from all three soundings were suspected to arise from more than one object, an additional two soundings were taken, one on each side of the system, 0.15 m from the flag. (Ref. 9) Decay data were collected at 46 sample times logarithmically spaced from 80 to 1,460 μs. A photograph of the system in use at Camp Beale is shown in Figure 4-6.

Figure 4-6. Portable Berkeley UXO Discriminator at Camp Beale

5 ANOMALY SELECTION AND INVESTIGATION RESULTS

5.1 ANOMALY SELECTION

After the survey sensor completed data acquisition, anomalies were selected from the data using a procedure designed by the program office. Since this sensor detection list was the basis for all subsequent analyses, a rigorous process was used to set this threshold.

5.1.1 Anomaly Selection Threshold

The known targets of interest in this demonstration were 105-mm and 37-mm projectiles and 60-mm and 81-mm mortars. Of these, the 37 mm is the most difficult to detect. Prior to the demonstration, the site team determined that detection of 37-mm projectiles to 1 foot (30 cm) depth was the objective for this demonstration. Accordingly, the anomaly selection threshold was set as the smallest signal expected from a 37-mm projectile at 30 cm depth.

Figure 5-1 illustrates this process. The predicted signal from the EM61-MK2 for 37-mm projectiles (Ref. 16) in their least and most favorable orientations is plotted in the figure along with a vertical line marking the 30 cm depth of interest. The gate 2 anomaly selection threshold for this sensor system was set at 5.2 mV based on this curve. Also plotted on Figure 5-1 is the observed noise in the cued area. As can be seen from the figure, the anomaly selection threshold is well above the measured noise so the anomaly selection process should be relatively unambiguous for this sensor system. This threshold will detect the other TOI to the depths in Table 5-1.

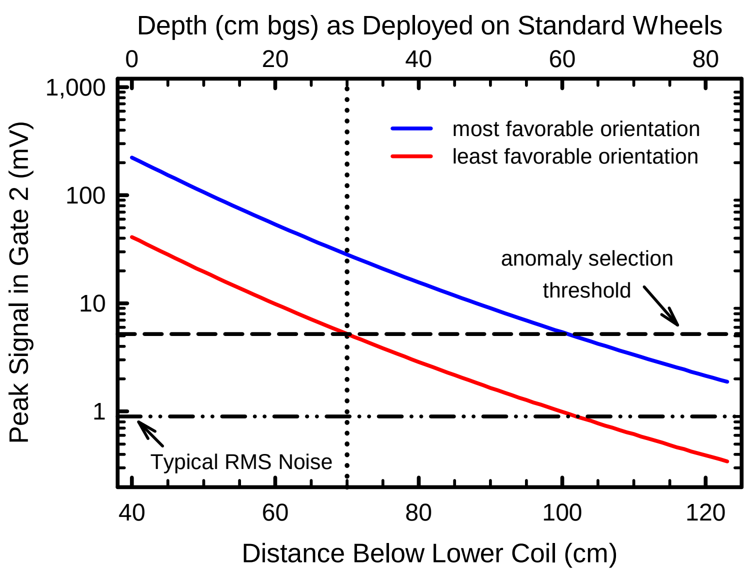

Figure 5-1. Predicted EM61-MK2 anomaly amplitude in gate 2 for a 37-mm projectile in its least and most favorable orientations. Also shown are the RMS noise measured at the site, the 30 cm depth used to set the threshold and the anomaly selection threshold used in this demonstration.

Table 5-1. Depths to which TOI on Camp Beale will be detected at a threshold of 5.2 mV

Munitions	Depth/cm
Small ISO, Schedule 40	24
37-mm projectile	30
60-mm mortar	60
81-mm mortar	65
105-mm projectile	110

Many targets, especially those that with high length to diameter aspect ratios, result in multiple, closely-spaced exceedances. To avoid having redundant locations on the final anomaly list, all exceedances within the distance of 0.6 m were grouped into a single detection. Finally, all pairs of exceedances between 0.6 m and 1.0 m apart were examined by a trained analyst who made a judgment whether they corresponded to a single source or not. This consolidation resulted in 911 identified anomalies in the grids surveyed by the portable instruments with all seeds detected.

5.2 GEOLOCATION ACCURACY

Because of the difficulties with precise navigation and geolocation in the wooded area, the anomaly locations were offset from the true seed locations by larger distances than are typical for surveys in open areas. A histogram of these offsets is shown in the left panel of Figure 5-2. All of the seeds were located within 1 m of the EM61 anomaly, but many are at distances in excess of the 0.4 m specification typically used to acquire cued data with the advanced sensors. For comparison, the results achieved in the open at Camp Butner are shown in the right panel of Figure 5-2. (Ref 17) To ensure that the cued data was taken over the actual targets locations, all anomalies were relocated by first acquiring the location of the anomaly using GPS or RTS. These locations were then refined using an EM61 with the ultimate flag location determined by the peak of the EM61 signal.

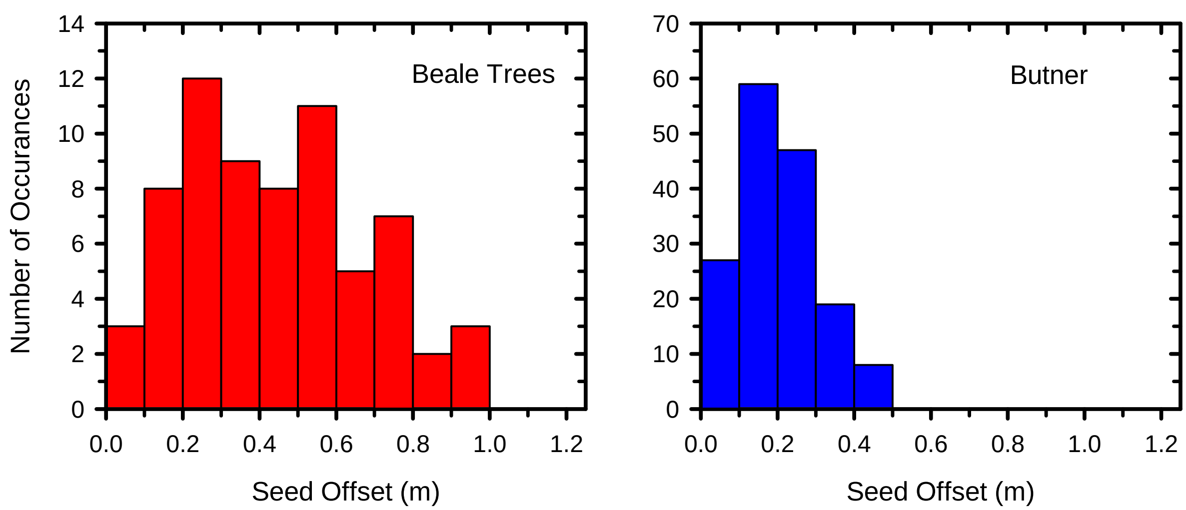

Figure 5-2. Comparison of the distance between seed location and nearest anomaly location in the EM61 survey data from the treed area at Camp Beale (left) and Camp Butner (right)

5.3 INTRUSIVE INVESTIGATION

The distribution of recovered items by class is detailed in Table 5-2. Except for the TOI, all these items are classified as clutter. As at most sites, the vast majority of recovered items were classified as munitions debris. The fuze parts were expended and thus classified by the UXO technicians as munitions debris; they are listed separately for information only. Representative examples of the clutter recovered are pictured in Figure 5-3.

Table 5-2. Distribution of recovered items from this demonstration

Classification	Number of Anomalies
Targets of Interest	93
Munitions Debris	965
Fuze parts	40
Cultural Debris	21
Soil/No Contact	36
Total	1155

Figure 5-3. Examples of items recovered in this demonstration. These items were classified as cultural debris (left), a fuze part (center), and munitions debris (right).

The measured depths of the recovered items (other than seeds) are plotted in Figure 5-4. As expected, most recovered items were quite shallow; 93% of all recoveries corresponded to less than 10 cm to the center of the target and nothing was found deeper than 20 cm. These results confirm our expectation that detection of 37-mm projectiles at 30-cm (1-foot) depth was a reasonable goal for this site. The other TOI would have been detected at depths between 60 cm and 1.1 m, as shown in Table 5-1, although none of these items were recovered in this demonstration.

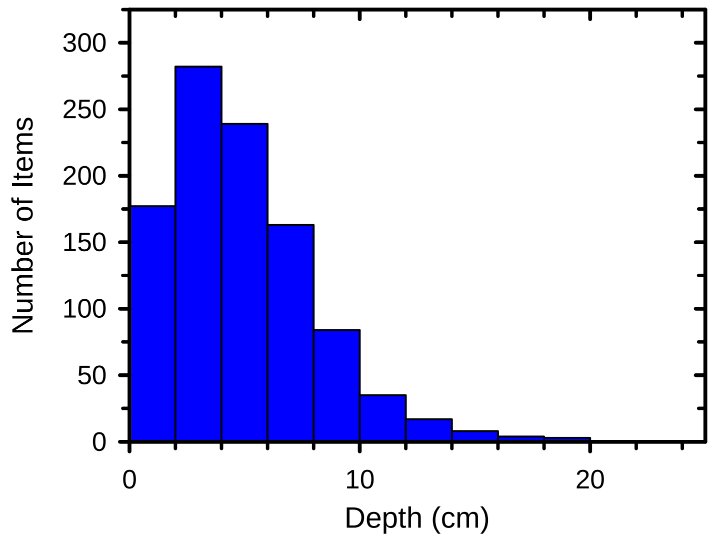

Figure 5-4. Histogram of recovery depths for all items other than seeds

6 PERFORMANCE OF THE PORTABLE SENSORS

This demonstration was the first deployment of the portable sensors to a live munitions site. The primary measure of their performance is the classification results discussed in the next section, but it is instructive to compare the intrinsic target parameters derived from the portable sensor's data to that of the baseline MetalMapper sensor on the common targets measured in the Combined Grids (Figure 2-2) and the Instrument Verification Strip. Figure 6-1 plots the polarizability decay curves for four of the IVS targets from each of the four instruments.

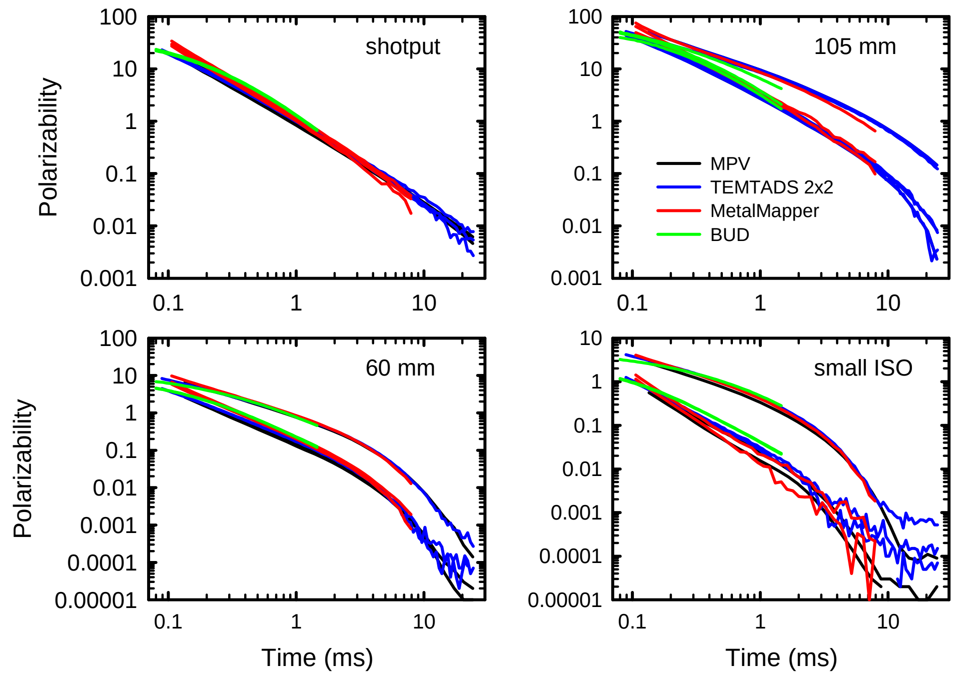

Figure 6-1. Polarizabilities for four items from the IVS derived from measurements of the three portable sensors used in this demonstration compared to those derived using the MetalMapper

Although the sensors collect decay data for different times (1.4 ms for BUD, 8 ms for MetalMapper, and 25 ms for MPV and TEMTADS 2x2), the polarizabilities for the common times are remarkably similar among the four sensors meaning that any classification decision based on polarizabilities will be the same for each of the instruments. The late time (> 5 or 10 ms) data for the smaller objects is noisy but that will have minimal effect on the classification performance.

The three portable sensors and their survey crews have had different levels of field experience. In addition, the MPV and portable BUD sensors acquired cued data at multiple positions per anomaly. These two factors result in the daily productivity listed in Table 6-1.

Table 6-1. Average daily productivity for the portable sensor systems

Sensor	Average Anomalies per Day
MPV	90
TEMTADS 2x2	175
Portable BUD	90

7 CLASSIFICATION RESULTS

A number of the demonstrators investigated multiple methods for training, parameter estimation, and classification during this demonstration. As a result, a total of 19 dig lists were scored in the blind phase of the demonstration, representing the various combinations of sensor data collection systems and processing approaches used. All of the results can be found in the report by IDA (Ref. 13). In the following sections, we present selected results that illustrate important conclusions of the demonstration, focusing on what can be achieved with currently available technologies and the value added of the advanced portable sensors and processing.

The results in this section are presented as ROC curves, which plot the percent of correctly classified munitions versus the number of false positives (i.e., unnecessary digs). Their interpretation is described in Section 3.7. The colored segments of the ROC curve correspond to the categories specified on the dig list and two threshold values are shown on the ROCs. The dark blue dot (•) indicates the demonstrator's threshold beyond which all targets are considered high confidence non-TOI. The orange dot (•) indicates the best that the demonstrator could have done had the threshold been set in the optimal place, the point at which the first TOI would be incorrectly classified as non-TOI, which would produce the first false negative. Missed TOIs on the ROC curve are indicated by open black triangles (△).

7.1 EM61-MK2 CART

The EM61-MK2 is the most common geophysical sensor in use for Munitions Response (MR) projects today. This sensor on a cart platform is our benchmark for what could be accomplished with carefully collected production geophysics data. These data were analyzed by two of the algorithm developers participating in the demonstration. An SAIC analyst used the UX-Analyze module of Oasis montaj to rank the anomalies based on electromagnetic decay with total polarizability used to resolve a few anomalies. The ROC curve resulting from this analysis is shown in Figure 7-1.

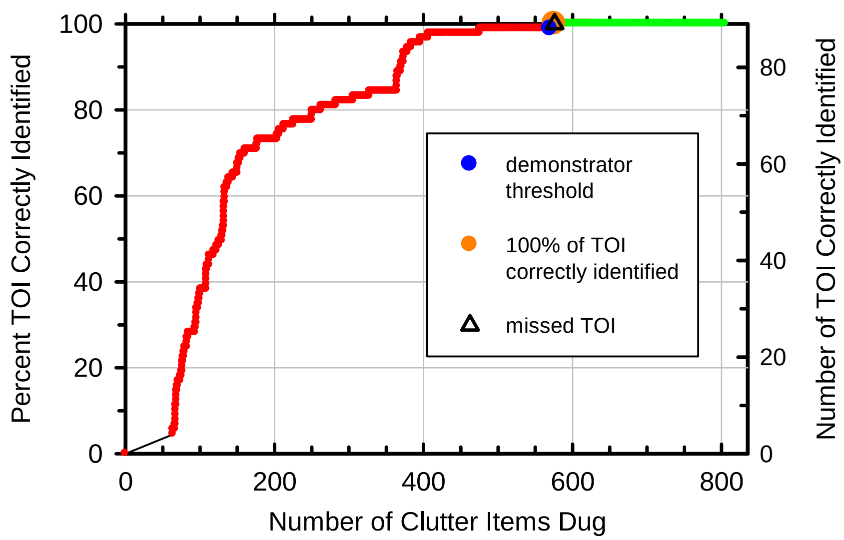

Figure 7-1. SAIC analysis of the EM61-MK2 cart data using UX-Analyze

As at other sites contaminated with 37-mm projectiles mixed with fragments of larger munitions, the EM61 data were not very useful for classification at this site. The best possible performance for this sensor and analysis combination, denoted by the orange dot (●), would only correspond to a little more than 200 avoided clutter digs.

The EM61-MK2 cart data were also analyzed by Sky Research. Sky used a combination of the total polarizability and the polarization decay as inputs to a statistical classifier. These results of this analysis are shown in Figure 7-2. Although in retrospect, the best possible performance from this analysis would have avoided ~450 clutter digs, the analyst was not able to confidently classify any of the anomalies as "high likelihood clutter."

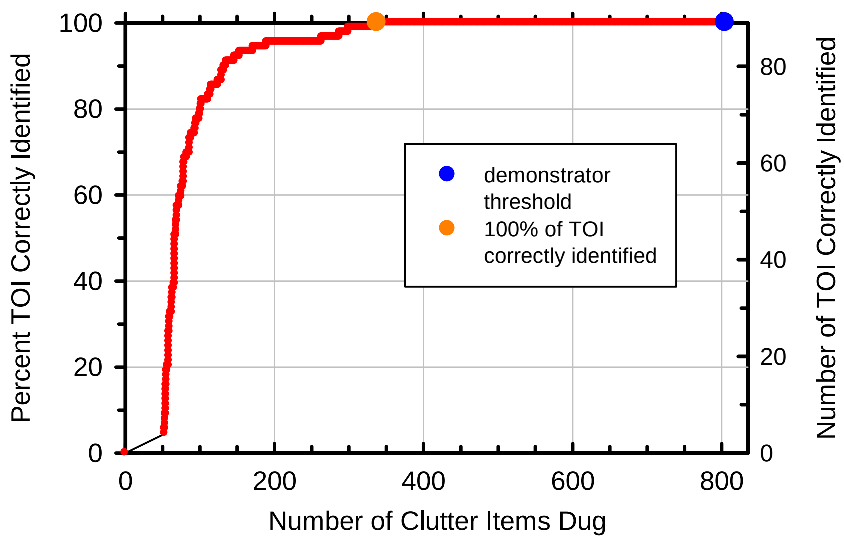

Figure 7-2. ROC curve resulting from Sky's statistical classifier applied to the EM61-MK2 cart data

7.2 MPV

Three analyses of the MPV cued data are shown in Figures 7-3 through 7-5. The team that collected the data used a an analysis that removed the soil background contribution before inverting the geophysical data (Ref. 7) then ranked the anomalies using a statistical classifier with the results shown in Figure 7-3. At their threshold, they were able to correctly classify about 80% of the clutter while identifying 100% of the TOI. Retrospective analysis shows that their threshold was conservative; even better performance was possible.

Two other approaches to the analysis of these data were taken by SAIC and Dartmouth. SAIC used a dipole model (Ref. 11) to extract target features while Dartmouth used a more advanced model (Ref. 12). The results of these two analyses are shown in Figures 7-4 and 7-5. Notice that both of these analysts requested substantially more training data that the Sky analysts; it was these two groups first time working with blind data from the MPV. After accounting for these training data, the classification was relatively efficient; the SAIC ROC curve in particular is nearly vertical in the red portion.

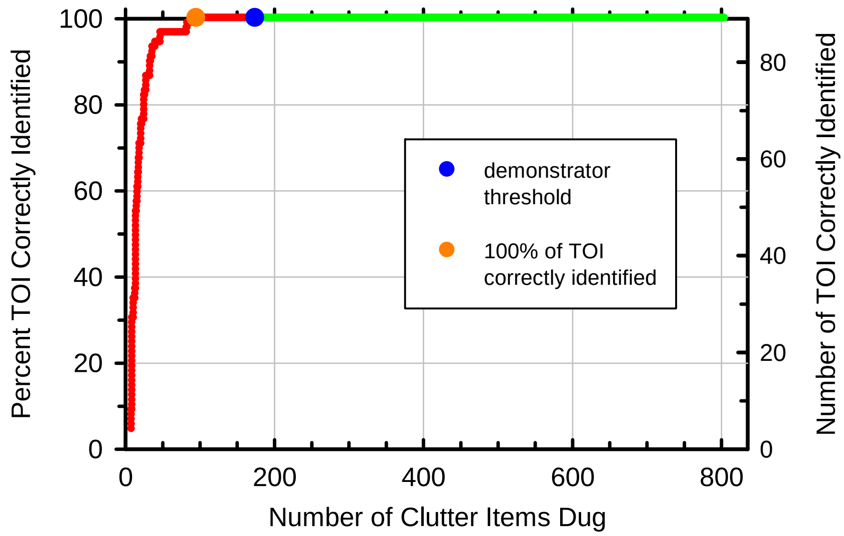

Figure 7-3. ROC curve resulting from the Sky analysis of MPV cued data collected at Camp Beale

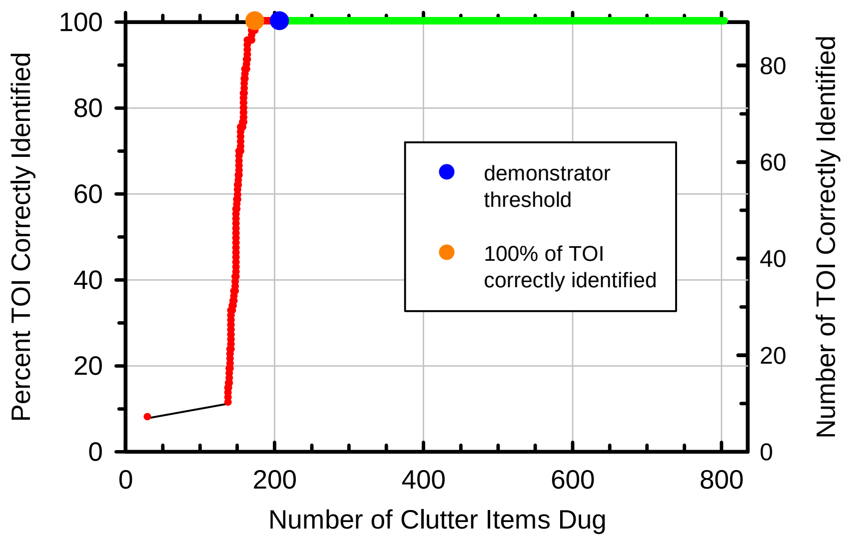

Figure 7-4. ROC curve resulting from the SAIC analysis of MPV cued data collected at Camp Beale

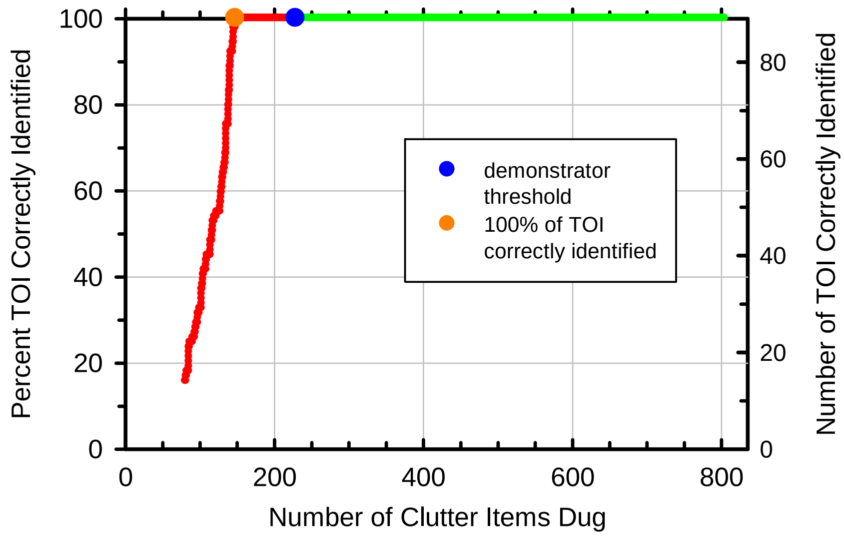

Figure 7-5. ROC curve resulting from the Dartmouth analysis of MPV cued data collected at Camp Beale

7.3 TEMTADS 2X2 ARRAY

Results of analyses of the TEMTADS 2x2 array cued data by Sky and SAIC are shown in Figure 7-6 and Figure 7-7 respectively. The Sky team used features resulting from geophysical inversion of the measured data using a model that handles multiple sources as input to a support vector machine classifier. These analysts were able to correctly label ~650 targets as clutter with no missed munitions.

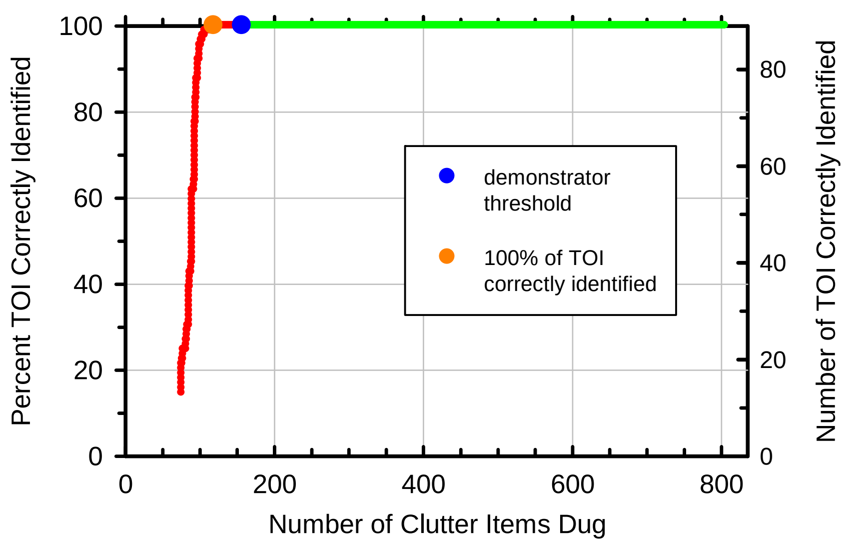

Figure 7-6. Sky analysis of the TEMTADS 2x2 cued data collected at Camp Beale

Similar results were obtained from the SAIC analysis of the TEMTADS data, Figure 7-7. This analysis involved model fits to a multi-source model with a classifier that was rule-based. This analysis resulted in ~25 anomalies classified as "can't extract reliable parameters." As with the MPV data, both of these analysts requested more than 50 on-site training labels.

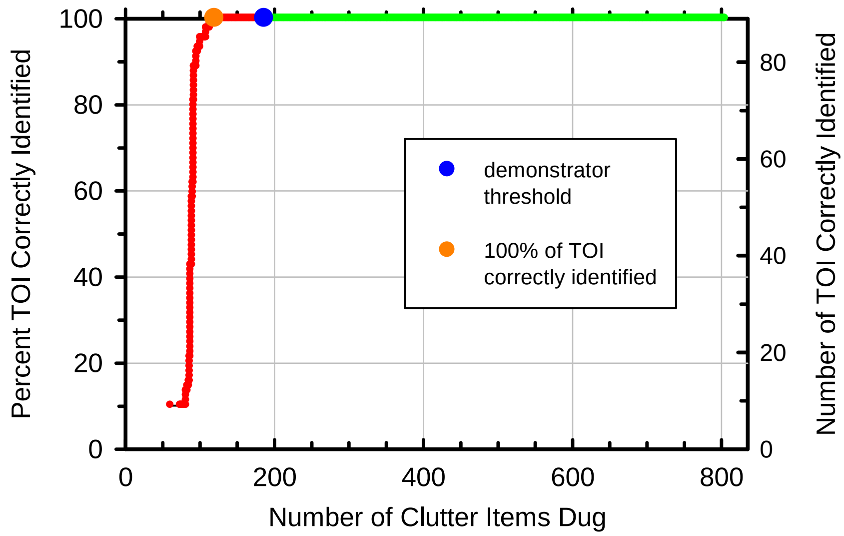

Figure 7-7. SAIC analysis of the TEMTADS 2x2 cued data collected at Camp Beale

7.4 PORTABLE BUD

Two approaches to analyze the portable BUD data were used by Sky analysts and their results are shown in Figure 7-8 and Figure 7-9, respectively. Figure 7-8 shows the results of a library-match classifier and Figure 7-9 plots the results of an analysis using a statistical classifier similar to the TEMTADS 2x2 analysis presented in Figure 7-6.

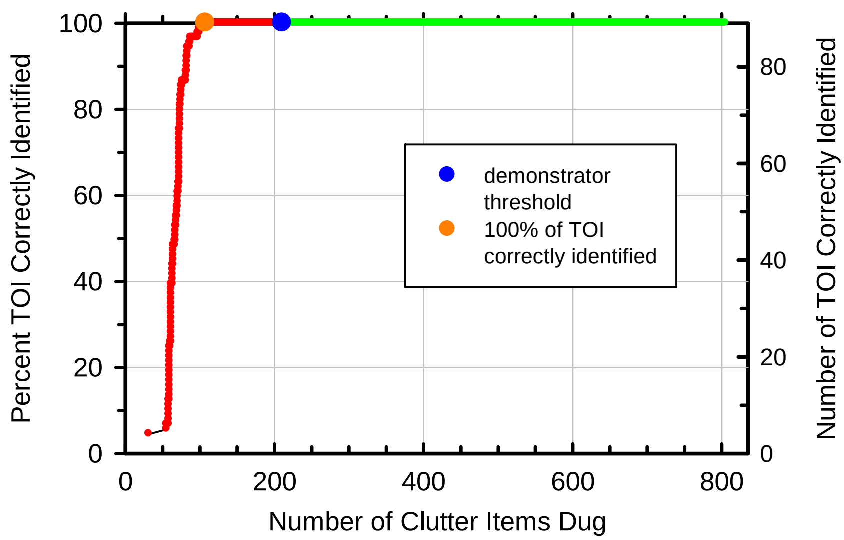

Figure 7-8. Sky library-match analysis of the BUD cued data

The underlying feature extraction was similar for both of these analyses. Both analysts requested about 25 training labels and had a significant number of anomalies they were unable to analyze. Both analysts were also very conservative in their thresholds; retrospective analysis shows the potential for better performance in both cases.

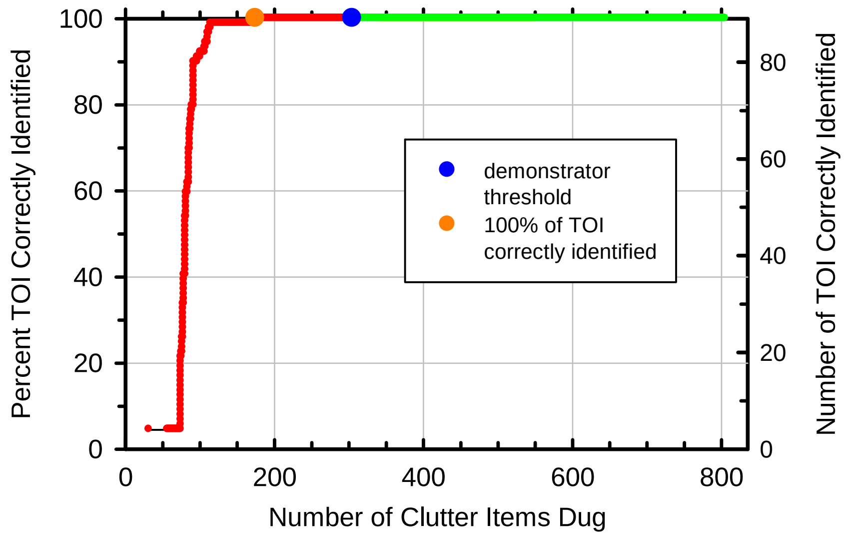

Figure 7-9. Sky analysis of BUD cued data using a statistical classifier

7.5 RESULTS OVERVIEW

An overview of all the results from all analyses of advanced sensor data collected during this demonstration is shown in Figure 7-10. All sixteen analysts were able to correctly identify 100% of the TOI. The blue bars represent the number of clutter items dug at each analyst's operating threshold. The worst performer was able to correctly classify ~40% of the clutter correctly. The best analysts were able to reject > 75% of the clutter using data from any of the three sensors. The orange bars show the number of clutter items that the analyst needed to dig to just get to 100% correct classification of the TOI, regardless of where the analyst put the threshold. This can be thought of as the best the analyst could have done by putting the threshold in exactly the optimum place where the last TOI is found in the ranked list.

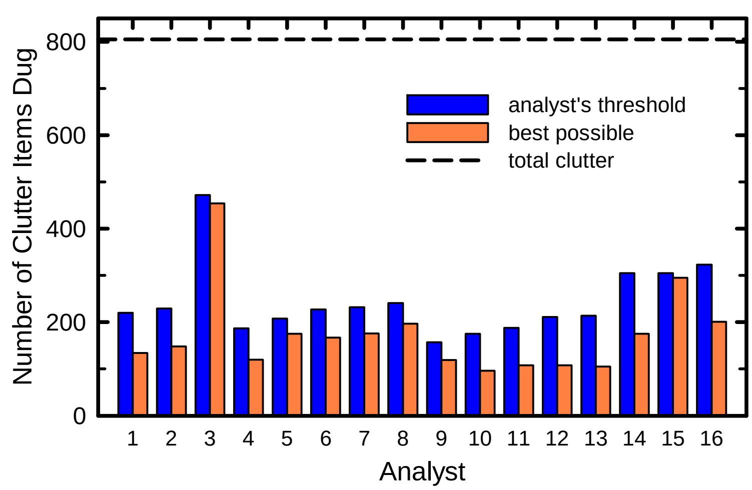

Figure 7-10. Overview of the performance of all analyses of the cued data from the advanced portable sensors at Camp Beale. All analysts correctly identified 100% of the TOI. The blue bars represent the number of clutter items dug at the analysts chosen threshold. The orange bars represent the best performance possible from each sensor/analysis combination.

8 COST SAVINGS

The demonstration took place on a small part of the former Camp Beale site and incurred costs for many items specific to a demonstration that would not be needed in an application of classification to a real site. Nevertheless, we can extract meaningful projected performance for the technology and apply reasonable industry unit costs for various elements to arrive at a total cost comparison for clearing an example 100-acre wooded site with and without the use of classification.

We made the following assumptions:

- The example takes place in an area with similar munitions types and the same density of anomalies as seen in the demonstration. Excluding the seeds, there were 822 anomalies in the 4-acre demonstration area. Extrapolating, we would expect about 20,725 anomalies in a similar 100-acre area, with 20,550 clutter.
- Two TOI were found during the intrusive investigation of the 4-acre area, for a rate of 0.5 TOI per acre. In a 100-acre site we predict about 50 native TOI.
- The baseline is an EM61 survey with 0.5-m line spacing. This would be used to select anomalies for digging without classification and the same anomalies would be interrogated with advanced sensors and classified.
- The site is seeded at a rate so on average one seed will be encountered each day of classification sensor data collection. With an estimate of 20,725 total anomalies and a production rate of 200 anomalies per day, we seed a conservative 125 inert items. These QC seeds would be used whether classification was used on the site or not.
- The classification performance is as achieved by a number of the analysts with ~75% of the clutter correctly identified and remaining undug.

The unit costs assumed are as shown in Table 8-1.

Table 8-1. Unit cost assumptions

Item	Units	Cost
Digs	Per hole	$125
Classification	Per anomaly	$25 and $35
EM61 Survey Data Collection and Analysis	100 acres	$94,000
Seed Emplacement	125 seeds	$22650

With these assumptions the costs were calculated using the elements shown in Table 8-2. A traditional remediation would use 125 QC seeds and be based on an EM61 detection survey. Using the numbers above, this effort would result in the intrusive investigation of the 125 seeds, 50 UXO, and 20,550 clutter items and require nearly $2.9M.

Classification would utilize the same number of QC seeds and, at present, be based on the same EM61 survey. Far fewer items will need intrusive investigation using classification, only 5138 in this example. If classification can be done for $35 per anomaly including both data collection and analysis, a 48% overall savings is possible. If this cost can be lowered to $25 to classify each anomaly, which was the cost for the TEMTADS 2x2 team (Ref. 8), the potential project savings increases to 55%.

Table 8-2. Cost Comparison for 100 acres of a site comparable to Camp Beale

Item	**No Classification**		**Classification**		
	Quantity	**Cost/$**	**Quantity**	**Cost/$ ($35/anomaly)**	**Cost/$ ($25/anomaly)**
Seeds	125 items	65,600	125 items	65,600	65,600
EM61 Survey	100 acres	94,000	100 acres	94,000	94,000
Classification	n/a	0	20,725 anomalies	725,375	518,125
Seeds Dug	125	15,625	125	15,625	15,625
Native UXO Dug	50	6,250	50	6,250	6,250
Clutter Dug	20,550	2,756,250	5138	642,250	642,250
TOTAL		2,894,175		1,506,150	1,298,900
Percent Savings				**48%**	**55%**

In this example, the added cost of classification ranges from $520,000 to $725,000 depending on the cost per anomaly. This is equal to the cost to investigate 4000 to 5000 anomalies. Therefore, in this example, the breakeven point is reached when ~25% of the anomalies are correctly classified as clutter. As shown in Figure 7-10, all analysts in this demonstration exceeded this performance.

9 CONCLUSIONS

The TEMTADS 2X2, MPV, and portable BUD all showed outstanding classification ability. All analysts working with cued data from the three advanced sensors were able to correctly identify 100% of the TOI while typically rejecting 75 to 85% of the clutter. The results among the three sensors were quite similar. Figure 7-10 shows that nearly all of these analysts set their thresholds at a point that rejected all but about 250 clutter, regardless of the source of the data. The ability of analysts to set thresholds correctly has been uneven in past demonstrations: it is now routine for analysts to identify 100% of the TOI at their operating threshold.

Using this performance, we have constructed a cost model for a 100-acre remediation in conditions similar to those of this demonstration. Using reasonable assumptions for the cost of applying these methods, we find that the use of classification would save approximately half of the cost of a traditional remediation.

The man-portable sensor results are comparable to those achieved using the MetalMapper during a concurrent demonstration at the same site. The targets at this site were relatively shallow however, Figure 5-4, so a final judgment on this equivalency will have to await future demonstrations.

These sensors are intended for use on wooded sites. The Camp Beale site was relatively benign in terms of access, but presented geolocation challenges. Primarily, this impacted the detection survey, where less accurate geolocation required a change to procedures for reacquiring targets for cued data collection. The procedures used in this demonstration were effective in collecting cued data over all anomalies, confirmed by the ability to reacquire, collect data and correctly classify all the seeds. Additional demonstrations will present more challenging wooded environments.

It is hard to measure productivity from the first demonstration of these sensors. The field crews were still working out field procedures during this demonstration. Nevertheless, the rate of the most efficient data collectors was similar to what is typically seen with the MetalMapper. All analysts requested more training data for the man-portable sensors than for the MetalMapper. This is expected as there is a much smaller stock of existing library data for these systems and is likely to change as their field use increases.

As with earlier sites with small munitions and relatively high anomaly densities, the standard EM61-MK2 data proved to have limited classification value.

Additional demonstrations of the portable sensors will address new challenges. The smallest munition of interest to date has been a 37-mm projectile. The applicability of these techniques on sites containing smaller munitions and submunitions remains unknown. Upcoming demonstrations will continue to test the performance of these systems on sites with challenging terrain, vegetation and geologic interference.

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