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Cost and Performance Report

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EMI Array for Cued UXO Discrimination

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ACRONYMS AND ABBREVIATIONS

AOL	advanced ordnance locator
APG	Aberdeen Proving Ground
ATC	Aberdeen Test Center
CNG	California National Guard
E	efficiency
EMI	electromagnetic induction
ESTCP	Environmental Security Technology Certification Program
FQ	fix quality
FUDS	Formerly-Used Defense Site
FY	fiscal year
GPS	Global Positioning System
GSA	General Services Administration
Hz	Hertz
IDA	Institute for Defense Analyses
MTADS	Multisensor Towed Array Detection System
NRL	Naval Research Laboratory
Pd	probability of detection
PDOP	Position Dilution of Precision (Global Positioning System)
PI	principal investigator
QC	quality control
Rfp	false positive rejection rate
RMS	root mean square
ROC	receiver operating characteristic
RTK	real-time kinematic
Rx	receiver
s	second(s)
SAIC	Science Applications International Corporation
SERDP	Strategic Environmental Research and Development Program
SI	site investigation
SLO	San Luis Obispo
SNR	signal-to-noise ratio

ACRONYMS AND ABBREVIATIONS (continued)

TEM	time-domain electromagnetic
TEMTADS	time-domain electromagnetic MTADS
TOI	target of interest
Tx	Transmitter
USCOE	U.S. Corps of Engineers
UXO	unexploded ordnance

ACKNOWLEDGEMENTS

This project was a collaborative effort between the Naval Research Laboratory (NRL), Science Applications International Corporation (SAIC), and G&G Sciences. Dave George of G&G Sciences was responsible for the development of the electromagnetic induction (EMI) sensor technology on which the Time-domain Electromagnetic Multisensor Towed Array Detection System (TEMTADS) array was built. Tom Bell of SAIC and Dan Steinhurst and Glenn Harbaugh of Nova Research, Inc. collaborated on the design of the integrated TEMTADS array and the deployment of the system. Jim Kingdon, Bruce Barrow, and Dean Keiswetter of SAIC were also involved in the modeling and analysis of the resultant data.

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1.0 EXECUTIVE SUMMARY

1.1 BACKGROUND

The Chemistry Division of the Naval Research Laboratory (NRL) has participated in several programs funded by the Strategic Environmental Research and Development Program (SERDP) and the Environmental Security Technology Certification Program (ESTCP) whose goal has been to enhance the classification ability of the Multisensor Towed Array Detection System (MTADS). The process has been based on making use of both the location information inherent in an item's magnetometry response and the shape and size information inherent in the response to electromagnetic induction (EMI) sensors. To date, most of these systems have used time-domain EMI (TEM) sensors with the notable exception of the Geophex GEM-3 frequency-domain sensor. In past efforts, classification performance has been limited by both the information available from the EMI sensors and by signal-to-noise limitations. Three of the largest noise terms are inherent sensor noise, motion-induced noise, and sensor location uncertainty.

The three most successful demonstrations to date of EMI-based discrimination all involved cued detection with gridded collection of EMI data. The success of the gridded data collections was due to the combination of minimal location uncertainty, no motion-induced noise, and sufficient signal-to-noise ratio (SNR). The downside of the implementations previously demonstrated is that they were relatively slow and inefficient, especially on a large site. The time-domain electromagnetic MTADS (TEMTADS) array was designed to combine the data quality advantages of a gridded survey with the coverage efficiencies of a vehicular system. The design goal of this system was to collect data equal, if not better, in quality to the best gridded surveys (the relative position and orientation of the sensors being known better for gridded data) while prosecuting many more targets each field day.

1.2 OBJECTIVES OF THE DEMONSTRATION

The objective of this demonstration was to validate the performance of the TEMTADS platform through two blind tests. The TEMTADS was evaluated in terms of both classification performance (e.g., false alarm rejection) and appropriateness for fielding (i.e. production rate, usability, etc.). The first demonstration was conducted at the Aberdeen Proving Ground (APG) Standardized Unexploded Ordnance (UXO) Test Site. The second demonstration was conducted as part of the ESTCP UXO Classification Study at the former Camp San Luis Obispo (SLO). At each demonstration, the site had been blind seeded with a significant number of intact, inert UXO types to challenge UXO classification systems and methodologies.

1.3 DEMONSTRATION RESULTS

The raw signature data from the TEMTADS array reflect details of the sensor/target geometry as well as inherent EMI response characteristics of the targets themselves. In order to separate out the intrinsic target response properties from sensor/target geometry effects, the measured signature is inverted to estimate principal axis magnetic polarizabilities using a standard induced dipole response model. The performance metrics used to monitor the success of the technology relate to production rate, accuracy of inverted features, analysis time, correct classification, and ease of use.

The system was able to consistently interrogate 125 or more cued targets per day. The analysis, which required roughly 15 minutes per target, resulted in a false alarm reduction by over 50% with 95% correct identification of munitions. The average error in predicted location was less than 10 cm in northing and easting, and the average error in depth estimation was less than 5 cm for non-overlapping targets with reasonable SNR. Qualitatively, the TEMTADS array was found to be easy to use and proved to be a robust and reliable sensor platform.

1.4 IMPLEMENTATION ISSUES

Implementation issues for this system and technology fall into two categories: operational concerns and data quality/analysis issues. In terms of operational concerns, the TEMTADS as implemented is a large, vehicle-towed system that operates best in large, open areas. As seen at the former Camp SLO demonstration, it is possible to operate the system in rocky terrain with grades approaching 20% but at reduced operating capacity and increased system wear. Smaller versions of the system are currently under development under several ESTCP and SERDP projects to address these concerns. The goal is to design and field units more amenable to operation in more confined terrain and topology and smaller tow vehicles, man-portable and handheld operation. Another serious limitation is anomaly density. For all sensors, there is a limiting anomaly density above which the response of individual targets cannot be separated. We have chosen relatively small sensors for this array, which should help with this problem, but we cannot eliminate it. Anomaly densities of 300 anomalies/acre or higher would limit the applicability of this system as more than 20% of the anomalies would have another anomaly within a meter. In terms of data quality, one pays a small penalty in signal amplitude to use the smaller TEMTADS sensor coil as compared to other systems such as a high-power EM61 MkII. The dramatically improved electrical performance of these new sensors helps counterbalance this issue, particularly in the ability to perform better averaging (or stacking). However, one needs to have in place robust data quality control (QC) techniques to know when to employ these capabilities in an efficient manner.

2.0 INTRODUCTION

2.1 BACKGROUND

UXO detection and remediation is a high priority triservice requirement. As the Defense Science Board recently wrote, "Today's UXO cleanup problem is massive in scale with some 10 million acres of land involved. Estimated cleanup costs are uncertain but are clearly tens of billions of dollars. This cost is driven by the digging of holes in which no UXOs are present. The instruments used to detect UXOs (generally located underground) produce many false alarms—i.e., detections from scrap metal or other foreign or natural objects—for every detection of a real unexploded munition found." [1]

There is general agreement that the best solution to the false alarm problem involves the use of EMI sensors which, in principle, allow the extraction of target shape parameters in addition to a size and depth estimate. We and others have fielded systems with either time-domain or frequency-domain EMI sensors with the goal of extracting reliable target shape parameters and thus improving the classification capability of our surveys. In practice, the classification ability of these sensors has been limited by signal-to-noise limitations. Three of the largest noise terms are inherent sensor noise, motion-induced noise, and sensor location uncertainty.

The three most successful demonstrations of EMI-based classification all involved cued detection with gridded collection of EMI data [2,3,4]. The success of the gridded data collections was due to the combination of minimal location uncertainty, no motion-induced noise, and sufficient SNR. The downside of the implementations previously demonstrated is that they were relatively slow and inefficient, especially on a large site. We have constructed an EMI sensor array that combines the classification ability of a gridded survey with the coverage efficiency of a vehicular array. By coming to a stop over each target to be investigated, we are able to obtain all the benefits of a gridded survey (negligible relative sensor location uncertainty, no motion-induced noise, and high SNR), while moving rapidly to the next target with no setup required gives us the coverage efficiency required for practical success.

2.2 OBJECTIVE OF THE DEMONSTRATION

The objective of this demonstration was to validate the technology through a series of blind test demonstrations. We conducted a shake-down demonstration of the technology at our Blossom Point, MD, field site, but a blind test is the only true measure of system performance. The first demonstration was conducted at the APG Standardized UXO Test Site. The second demonstration was conducted as part of the ESTCP UXO Classification Study at the former Camp SLO. At each demonstration, the site had been blind-seeded with a significant number of intact, inert UXO types to challenge UXO classification systems and methodologies. Demonstration scoring was conducted by third parties to maintain the integrity of the ground truth and to provide an unbiased evaluation.

2.3 REGULATORY DRIVERS

Stakeholder acceptance of the use of classification techniques on real sites will require demonstration that these techniques can be deployed efficiently and with high probability of discrimination. The first step in this process was to demonstrate acceptable performance on synthetic test sites such as that at Aberdeen. As a second step, demonstration on a carefully prepared and blind-seeded live site presented a more real-world scenario while providing sufficiently complete validation data to accurately determine system performance. After these hurdles have been passed, successful demonstration at live sites will further facilitate regulatory acceptance of the UXO classification technology and methodology.

3.0 TECHNOLOGY

3.1 TECHNOLOGY DESCRIPTION

3.1.1 EMI Sensors

The EMI sensor used in the TEMTADS array is based on the Navy-funded advanced ordnance locator (AOL), developed by G&G Sciences. The AOL consists of three transmit coils arranged in a 1 m cube; we have adopted the transmit (Tx) and receive (Rx) subsystems of this sensor directly, converted to a 5×5 array of 35 cm sensors, and made minor modifications to the control and data acquisition computer to make it compatible with our deployment scheme.

A photograph of an individual sensor element under construction is shown in the left panel of Figure 1. The transmit coil is wound around the outer portion of the form and is 35 cm on a side. The 25 cm receive coil is wound around the inner part of the form, which is re-inserted into the outer portion. An assembled sensor with the top and bottom caps used to locate the sensor in the array is shown in the right panel of Figure 1.

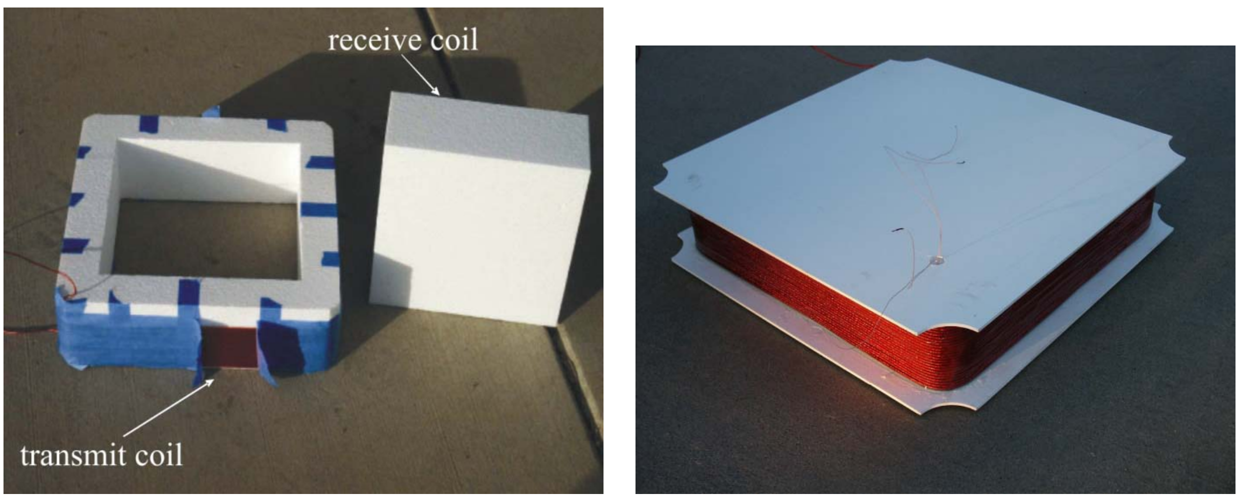

Figure 1. Construction details of an individual EMI sensor (left panel) and the assembled sensor with end caps attached (right panel).

Decay data are collected with a 500 kHz sample rate until 25 ms after turn off of the excitation pulse. This results in a raw decay of 12,500 points, too many to be practical. These raw decay measurements are grouped into 115 logarithmically spaced "gates," whose center times are between 42 µs to 25 ms with 5% widths and are saved to disk. Examples of the measured transmit pulse, raw decay, and gated decay are shown in Figure 2.

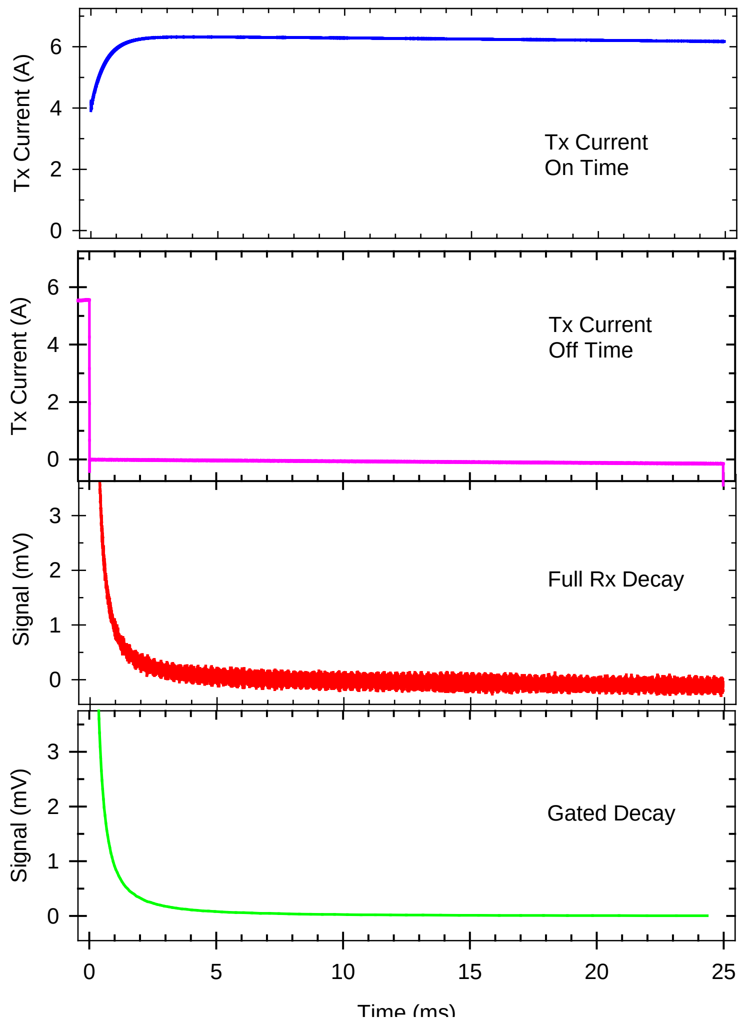

Figure 2. Measured transmit current (on time upper panel, off time second panel), full measured signal decay (third panel), and gated decay (fourth panel), as discussed in the text.

3.1.2 Sensor Array

The 25 individual sensors are arranged in a 5×5 array, as shown in Figure 3. The center-to-center distance is 40 cm yielding a 2 m×2 m array. Also shown in Figure 3 is the position of the three Global Positioning System (GPS) antennae that are used to determine the location and orientation of the array for each cued measurement. A picture of the array mounted on the MTADS EMI sensor platform is shown in Figure 4.

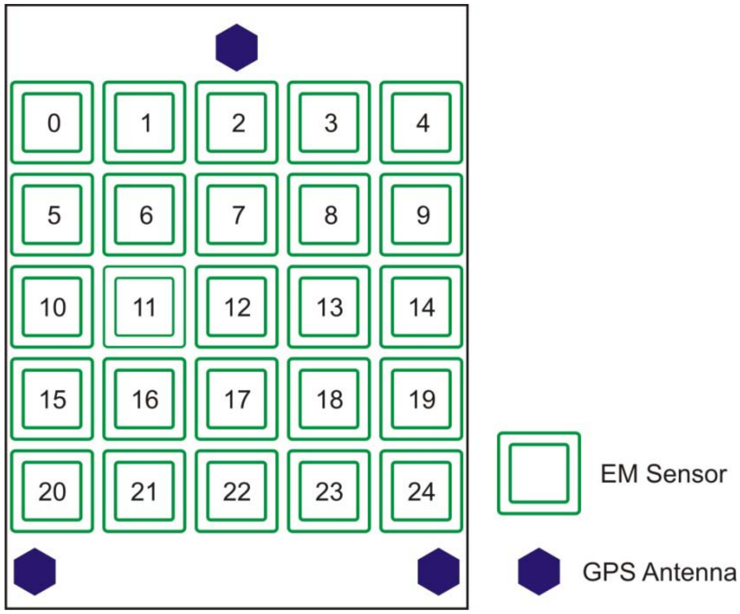

Figure 3. Sketch of the EMI sensor array showing the position of the 25 sensors and the three GPS antennae.

Figure 4. Sensor array mounted on the MTADS EMI sensor platform.

3.2 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

The TEMTADS array was designed to combine the data quality advantages of a gridded survey with the coverage efficiencies of a vehicular system. The design goal of this system was to collect data equal, if not better, in quality to the best gridded surveys (the relative position and orientation of the sensors being known better for gridded data) while prosecuting many more targets each field day.

There are obvious limitations to the use of this technology. The array is a 2 m square so fields where the vegetation or topography interferes with passage of a trailer that size will not be amenable to the use of the present array. The other serious limitation will be anomaly density.

For all sensors, there is a limiting anomaly density above which the response of individual targets cannot be separated. We have chosen relatively small sensors for this array, which should help with this problem but we cannot eliminate it. Based on experiments at our test pit at Blossom Point, the results of this demonstration, and work done on the former Camp Sibert data sets, anomaly densities of 300 anomalies/acre or higher would limit the applicability of this system as more than 20% of the anomalies would have another anomaly within a meter. For low SNR targets, our standard data acquisition parameters may not be sufficient. The system software has built in the capability to vary the data acquisition parameters on-the-fly based on flags in the target file and can be reconfigured manually as required. One area in need of development is a robust, consolidated data collection/data QC methodology for determining when there is a low SNR anomaly and when there is no anomaly present. This issue is an area of ongoing research.

4.0 PERFORMANCE OBJECTIVES

The TEMTADS array was deployed to demonstrations at both the APG Standardized UXO Test Site and the ESTCP UXO Classification Study site at the former Camp SLO. Due to the nature of the demonstrations at each site and the employed scoring methods, separate Performance Objectives were used for each demonstration, as documented in the individual demonstration reports [5,6] and the project final report [7]. The Performance Objectives for the two demonstrations have been grouped into a unified collection given in Table 1 due to significant overlap. Please refer to the references for the specific objectives for each demonstration. Since the TEMTADS array is a discrimination technology, the performance objectives focus on the second step of the UXO survey problem; we assume that the anomalies from all targets of interest have been detected and included on the target list that we worked from.

Table 1. Performance objectives for the demonstrations.

Performance Objective	Metric	Data Required	Success Criteria	Results
Quantitative Performance Objectives				
Site coverage	Fraction of assigned anomalies interrogated	Survey results	100% as allowed for by topography/vegetation	Yes
Calibration strip results	System response consistently matches physics-based model	System response curves Daily calibration strip data	≤ 15% rms variation in amplitude Down-track location ± 25cm All response values fall within bounding curves	No
Reduction of false alarms	Number of false alarms eliminated at demonstrator operating point	Prioritized dig list Scoring report from APG	Reduction of false alarms by > 50% with 95% correct identification of munitions	Yes
Location accuracy	Average error and standard deviation in both axes for interrogated items	Estimated location from analysis Scoring reports	ΔN and ΔE < 10 cm σN and σE < 15 cm	No
Depth accuracy	Standard deviation in depth for interrogated items	Estimated location from analyses Ground truth from validation effort	ΔDepth < 5 cm σDepth < 10 cm	No
Production rate	Number of targets interrogated each day	Log of field work	75 targets per day	Yes
Data throughput	Throughput of data QC process	Log of analysis work	All data QCed on site and at pace with survey	Yes
Analysis time	Average time required for inversion and classification	Log of analysis work	15 min per target	Yes
Qualitative Performance Objective				
Ease of use		Feedback from operator on ease of use	No significant operational issues identified by operator	Yes

4.1 OBJECTIVE: SITE COVERAGE

Each demonstration commenced with a list of previously identified anomalies, whose locations were determined using some other data. The expectation of the demonstration was to gather cued data with the TEMTADS system over each assigned anomaly.

4.1.1 Metric

Site coverage is defined as the fraction of the assigned anomalies surveyed by the TEMTADS. Exceptions were made for topology/vegetation interferences. This is particularly true for demonstrations where the footprints of the detection and classification systems are significantly different (e.g. EM61 MkII cart and TEMTADS).

4.1.2 Data Requirements

The collected data were compared to the original anomaly list. Any interference was noted in the field log book as it occurred.

4.1.3 Success Criteria

The objective is considered met if 100% of the assigned anomalies are surveyed with the exception of anomalies located in areas that cannot be surveyed due to topology/vegetation interferences.

4.1.4 Results

This objective was successfully met. All assigned anomalies at APG were successfully investigated. At the former Camp SLO, all but five of the assigned anomalies were measured. Failure to measure these five anomalies was due to the presence of rocks, which prevented the operator from positioning the TEMTADS over the target.

4.2 OBJECTIVE: CALIBRATION STRIP RESULTS

This objective supports that each sensor system is in good working order and collecting physically valid data each day and applies only to the former Camp SLO demonstration. The calibration strip was surveyed twice daily. The peak positive response of each emplaced item from each run was compared to the physics-based response curves generated prior to data collection on site using each item of interest.

4.2.1 Metric

The reproducibility of the measured response of each sensor system to the items of interest and the comparison of the response to the response predicted by the physics-based model defines this metric.

4.2.2 Data Requirements

Response curves for each sensor/item of interest pair were used to document what the physics-based response of the system to the item should be. The tabulated peak response values from each survey of the calibration strip were used to demonstrate the reproducibility and validity of the sensor readings.

4.2.3 Success Criteria

The objective will be considered met if all measured responses fall within the range of physically possible values based on the appropriate response curve. Additionally, the root mean square (RMS) variation in responses should be less than 15% of the measured response and the down-track location of the anomaly should be within 25 cm of the corresponding seeded item's true location.

4.2.4 Results

This objective was not successfully met in full. The measured peak signals for all of the emplaced items generally fit well within the physics-based response bounding curves, with the 4.2-inch mortar and the shotput results giving the poorest match, with a tendency to underestimate the peak value. Careful examination of the data shows that this variation is the result of the shot-to-shot precision with which the array was positioned in exactly the same spot each time. Because the response curves are generated assuming the target is directly below the sensor, any offset in the sensor position will result in the derived peak signal being smaller than that predicted by the curve, as is observed. Due to the large footprint of the TEMTADS array and number of sensor elements contained in the array, the array is considered to have been properly positioned from a field work prospective for a measurement if the array center is within 20 cm of the target location. This does not impact the values of the inverted parameters and offers the vehicle operator some flexibility in the field. It does, however, affect the measured peak signal amplitudes. For future demonstrations, the metric of fitted polarizability amplitude is recommended as a replacement metric as these values are invariant to array position.

4.3 OBJECTIVE: REDUCTION OF FALSE ALARMS

This is the primary measure of the effectiveness of this technology. By collecting high-quality, precisely located data, we expect to be able to discriminate munitions from scrap and frag with high efficiency. This metric was not part of the performance criteria for the former Camp SLO demonstration, so it was evaluated only for the APG demonstration.

4.3.1 Metric

At a seeded test site such as the APG standardized test site, the metric for false alarm elimination is straightforward. We prepared a ranked dig list for the targets we interrogated with a dig/no-dig threshold indicated, and Aberdeen Test Center (ATC) personnel used their automated scoring algorithms to assess our results.

4.3.2 Data Requirements

The identification of most of the items in the test field is known to the test site operators. Our ranked dig list was the input for this objective, and ATC's standard scoring is the output.

4.3.3 Success Criteria

The objective will be considered to be met if more than 50% of the non-munitions items were labeled as no-dig while retaining 95% of the munitions items on the dig list.

4.3.4 Results

This objective was successfully met. The TEMTADS surveyed anomalies detected by the MTADS magnetometer system in the blind grid and indirect fire areas. Efficiency (E) and false positive rejection rate (Rfp) are used to score discrimination performance ability at two specific operating points on a receiver operating characteristic (ROC) curve: one at the point where no decrease in probability of detection (Pd) is incurred and the other at the operator-selected threshold. Efficiency is defined as the fraction of detected ordnance correctly classified as ordnance and the false positive rejection rate is defined as the fraction of detected clutter correctly classified as clutter. The results for the blind grid and indirect fire test areas were E = 0.99 and Rfp = 0.99, and E = 0.98 and Rfp = 0.92 at the operating point, respectively. With no loss of Pd, the results were E = 1.00 and Rfp = 0.95, and E = 1.00 and Rfp = 0.58, for the blind grid and the indirect fire areas, respectively. These data are summarized from Tables 7a and 7c of Reference 8.

4.4 OBJECTIVE: LOCATION ACCURACY

An important measure of how efficiently any required remediation will proceed is the accuracy of predicted location of the targets marked to be dug. Large location errors lead to confusion among the UXO technicians assigned to the remediation costing time and often lead to removal of a small, shallow object when a larger, deeper object was the intended target.

4.4.1 Metric

The average error and deviation in both horizontal axes was computed for the items which are selected for excavation during the validation phase of the demonstration. We provided an estimated position for all targets we interrogated to the appropriate personnel at each site, and they used their scoring algorithms to assess our results. At APG, all the items were emplaced and the locations are known. Therefore the items were not excavated. Aggregate results for the APG demonstration were provided by ATC.

4.4.2 Data Requirements

The location of most of the items in the test field is known to the appropriate personnel at each site. Our dig list was the input for this objective, and a standard scoring report is the output.

4.4.3 Success Criteria

The objective was considered to be met if the average position error (low bias) and the standard deviation (accurate location) in both dimensions was less than 10 and 15 cm, respectively for APG, and less than 5 and 10 cm, respectively for the former Camp SLO.

4.4.4 Results

This objective was not successfully met in full. For APG, the location accuracy of fit parameters generated from the TEMTADS array data, taken from Tables 9a and 9c of Reference 8, are within 5 cm horizontally (1 σ) and 6 cm vertically (1 σ) for the indirect fire area. Horizontal errors are not calculated for the blind grid. The vertical accuracy was 4 cm (1 σ) for the blind grid. For the former Camp SLO, the average northing position error for all measured data was 1.5 cm, while the average easting position error was 3 cm. The standard deviations, however, were larger than desired, with both values about 25 cm. Excluding those anomalies for which multiple targets were found produces negligible improvement. We suspect the higher values are due to the large number of small, low SNR clutter items, which result in greater uncertainty in both the measured and fitted values. Indeed, if we restrict ourselves to those anomalies which we classified as likely UXO, the northing and easting standard deviations drop to 7 cm and 5 cm, respectively.

4.5 OBJECTIVE: DEPTH ACCURACY

An important measure of how efficiently any required remediation will proceed is the accuracy of predicted depth of the targets marked to be dug. Large depth errors lead to confusion among the UXO technicians assigned to the remediation costing time and often leading to removal of a small, shallow object when a larger, deeper object was the intended target.

4.5.1 Metric

The standard deviation of the predicted depths with respect to the ground truth was computed for the items that were selected for excavation during the validation phase of the former Camp SLO study. At APG, all the items were emplaced and the locations are known. Therefore the items were not excavated. Aggregate results for the APG demonstration were provided by ATC.

4.5.2 Data Requirements

The anomaly fit parameters and the ground truth for the excavated items were required to determine the performance of the fitting routines in terms of the predicted depth accuracy.

4.5.3 Success Criteria

This objective was considered as met if the average error in depth was less than 5 cm and the standard deviation less than 10 cm.

4.5.4 Results

This objective was not met successfully in full. For APG, the accuracy of the depth fit parameter generated from the TEMTADS array data, taken from Tables 9a and 9c of Reference 8, was within 6 cm vertically (1 σ) for the indirect fire area. The vertical accuracy was 4 cm (1 σ) for the blind grid. For the SLO demonstration, the average depth error for all measured data was 2.5 cm. The standard deviation was a bit larger than desired, with a value of 14 cm. Excluding those anomalies for which multiple targets were found and restricting the analysis to those anomalies classified as “likely UXO” to exclude low SNR clutter items, the standard deviation reduces to 7 cm.

4.6 OBJECTIVE: PRODUCTION RATE

Even if the performance of the technology for the metrics listed above is satisfactory, there is an economic metric to consider. There is a known cost of remediating a suspected munitions item.

If the cost to interrogate a target is greater than this cost, the technology will be useful only at sites with special conditions or target values. Note, however, that in its ultimate implementation this technology will result in reacquisition, cued interrogation, and target flagging in one visit to the site.

4.6.1 Metric

The number of targets interrogated per day was the metric for this objective. Combined with the daily operating cost of the technology, this gives the per-item cost.

4.6.2 Data Requirements

The metric was determined from the combination of available field logs and the survey results. The field logs record the amount of time per day spent acquiring the data, and the survey results determine the number of anomalies investigated in that time period.

4.6.3 Success Criteria

For the APG demonstration, the objective was considered to be met if at least 75 targets were interrogated each survey day. For the former Camp SLO demonstration, the production rate target was 125 anomalies/day.

4.6.4 Results

This objective was successfully met. At APG, 214 anomalies were investigated on the blind grid over the course of 1.43 work days, or on average 149 anomalies/work day, and 694 anomalies were investigated in the indirect fire area over the course of 32 hours and 30 minutes, or on average 170 anomalies/work day. At the former Camp SLO, a total of 1547 anomalies (including redos) were measured over a 10-day period for an average of 155 anomalies/day.

4.7 OBJECTIVE: DATA THROUGHPUT

The collection of a complete, high-quality data set with the sensor platform is critical to the downstream success of any UXO classification effort. This objective considers one of the key data quality issues, the ability of the data analysis workflow to support the data collection effort in a timely fashion. To maximize the efficient collection of high quality data, a series of MTADS standard data quality checks are conducted during and immediately after data collection on site. Data that pass the QC screen are then processed into archival data stores. Individual anomaly analyses are then conducted on those archival data stores. The data QC/preprocessing portion of the workflow needs to keep pace with the data collection effort for best performance.

4.7.1 Metric

The throughput of the data quality control workflow was at least as fast as the data collection process, providing real time feedback to the data collection team of any issues.

4.7.2 Data Requirements

The data analysts log books provided the necessary data for determining the success of this metric.

4.7.3 Success Criteria

This objective will be considered met if all collected data can be processed through the data quality control portion of the workflow in a timely fashion.

4.7.4 Results

This objective was successfully met. Data were normally downloaded several times during each workday, and quality control on these datasets was usually completed on the same day. QC checks successfully caught missed anomalies, a small number of corrupt data files, and targets that needed remeasuring.

For low SNR targets, our standard data acquisition parameters may not be sufficient. The system software has built in the capability to vary the data acquisition parameters on-the-fly based on flags in the target file and can be reconfigured manually as required. To date these capabilities have not been demonstrated and could potentially have an impact on data throughput. A robust, consolidated data collection/data QC methodology for determining when there is a low SNR anomaly present and when there is no anomaly present is necessary to accurately and efficiently utilize these capabilities. This issue is an area of ongoing research.

4.8 OBJECTIVE: ANALYSIS TIME

The ultimate implementation of this technology will involve on-the-fly analysis and classification. The time for this will be limited to the driving time to the next anomaly on the list. We will track the near-real-time analysis time in this demonstration.

4.8.1 Metric

The time required for inversion and classification per anomaly was the metric for this objective

4.8.2 Data Requirements

Analysis time was determined from a review of the data analysis logs.

4.8.3 Success Criteria

The objective was considered to be met if the average inversion and classification time was less than 15 min.

4.8.4 Results

This objective was successfully met. The average inversion time per target was approximately 2.5 min on our field laptop computer. The total average analysis time amounted to 12.5 min per anomaly. For these extensive tests of the system in field mode, we took the opportunity to consider various discrimination and classification methods, some of which proved unfruitful. As a result of lessons learned from this undertaking, we expect the average analysis time for future field runs to be less.

4.9 OBJECTIVE: EASE OF USE

This qualitative objective is intended as a measure of the long-term usability of the technology. If the operator does not report that the technology is easy to use, shortcuts that can compromise the efficiency of the technology will begin to creep into daily operations.

4.9.1 Data Requirements

This objective was evaluated based on operator feedback.

4.9.2 Results

This objective was successfully met. Based on vehicle operator feedback, there were no significant limitations to the efficient use of the system in the field. Several suggestions were made for additional improvements to the navigation and data collection software. They have been subsequently incorporated.

5.0 SITE DESCRIPTION

Two demonstrations were conducted for this project. The first was conducted at the Standardized UXO Test Site located at the APG, MD, May through June 2008. The second was conducted at the former Camp SLO, CA, ESTCP UXO Classification Study Demonstration Site in June 2009.

5.1 APG STANDARDIZED UXO TEST SITE

5.1.1 SITE LOCATION AND HISTORY

The Standardized UXO Test Site is adjacent to the Trench Warfare facility at the APG. The specific area was used for a variety of ordnance tests over the years. Initial magnetometer and EMI surveys conducted by the MTADS team performed after a “mag and flag” survey of the same area identified over a thousand remaining anomalies. These data were used for a final cleanup of the site prior to the emplacement of the original test items. Prior to the two subsequent reconfiguration events, unexplained anomalies identified by demonstrators using the site were also investigated and removed.

This was the site of our first field demonstration of this combination of EMI sensors and survey mode. The APG site is located close to our base of operations in southern Maryland and therefore minimizes the logistics costs of the deployment. Use of this site allowed us to receive validation results from near-real-world conditions without incurring the logistics and intrusive investigation expenses that would be required for a demonstration at a live site.

5.1.2 SITE TOPOGRAPHY AND GEOLOGY

According to the soils survey conducted for the entire area of APG in 1998, the test site consists primarily of Elkton Series type soil [9]. The Elkton Series consist of very deep, slowly permeable, poorly drained soils. These soils formed in silty aeolin sediments and the underlying loamy alluvial and marine sediments. They are on upland and lowland flats and in depressions of the Mid-Atlantic Coastal Plain. Slopes range from 0 to 2%.

Overall, the demonstration site is relatively flat and level. There are some low-lying areas in the northwest portion of the site that tend to have standing water during the wet periods of the year. The current sensor system is not sufficiently weatherproofed to operate through standing water. However, during the most recent reconfiguration, the areas most prone to being underwater were excluded from the survey scenarios. Anomalies that were located underwater or near water at the time of survey were deferred until the end of the survey and were interrogated by carefully, if less efficiently, maneuvering the array into position.

5.1.3 MUNITIONS CONTAMINATION

The area currently occupied by the site has seen an extensive history of munitions use. As an example, in 2003 we conducted a magnetometer survey of a previously unremediated area directly adjacent to the site [10]. In a survey area of approximately 1 hectare, we identified 2479 anomalies, of which 1921 were amenable to a model fit using our standard analysis. Historical records provided by ATC and previous remediation results indicated that the likely munitions of interest for this site were:

- Grenades, MkI, MkII, and French VB Rifle without chute
- Grenades, French VB Rifle with chute
- 60 mm mortars (including 2-inch Smoke)
- 3-inch Stokes (Smoke and HE)
- 105 mm projectiles
- 155 mm projectiles

5.1.4 SITE CONFIGURATION

Figure 5 is a map of the Standardized UXO Test Site at APG. The calibration and blind grids are shown along with the various open field areas.

5.2 FORMER CAMP SAN LUIS OBISPO

5.2.1 SITE LOCATION AND HISTORY

The site description material reproduced here taken from the recent site investigation (SI) report [11]. More details can be obtained in the report. The former Camp SLO is approximately 2101 acres situated along Highway 1, approximately 5 miles northwest of San Luis Obispo, CA. Most of the area consists of mountains and canyons. The site for this demonstration is a mortar target on a hilltop in MRS 05 (within former Rifle Range #12).

Camp SLO was established in 1928 by the State of California as a National Guard Camp. Identified at that time as Camp Merriam, it originally consisted of 5800 acres. Additional lands were added in the early 1940s until the acreage totaled 14,959. From 1943 to 1946, Camp SLO was used by the U.S. Army for infantry division training including artillery, small arms, mortar, rocket, and grenade ranges. Following the end of World War II, a small portion of the former camp land was returned to its former private owners. The U.S. Army was making arrangements to relinquish the rest of Camp SLO to the State of California and other government agencies when the conflict in Korea started in 1950. The camp was reactivated at that time.

The U.S. Army used the former camp during the Korean War from 1951 through 1953 where the Southwest Signal Center was established for the purpose of signal corps training. Following the Korean War, the camp was maintained in inactive status until it was relinquished by the Army in the 1960s and 1970s. Approximately 4685 acres were relinquished to the General Services Administration (GSA) in 1965. GSA then transferred the property to other agencies and individuals beginning in the late 1960s through the 1980s; most was transferred for educational purposes (California Polytechnic State University and Cuesta College). A large portion of Camp SLO (the original 5880 acres) has been retained by the California National Guard (CNG) and is not part of the Formerly-Used Defense Site (FUDS) program.

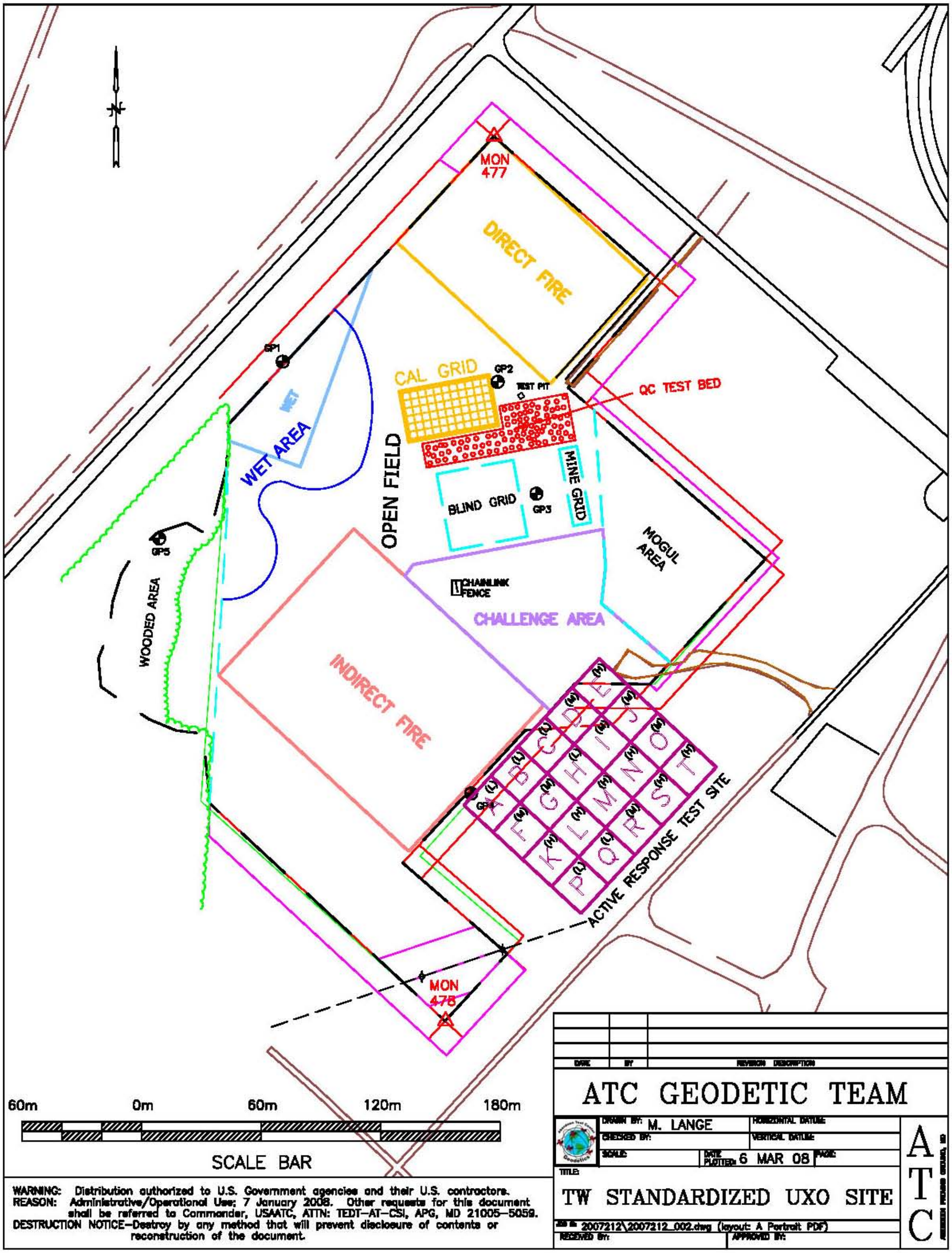

Figure 5. Map of the reconfigured APG Standardized UXO Test Site.

This site was chosen as the second in a progression of increasingly more complex sites for demonstration of the classification process as part of the ESTCP UXO Classification Study. The first site in the series, former Camp Sibert, had only one target-of-interest and item "size" was an effective discriminant. At this site, there are at least four targets-of-interest: 60-mm, 81-mm, and 4.2-inch mortars and 2.36-inch rockets. This introduces another layer of complexity into the process.

5.2.2 SITE TOPOGRAPHY AND GEOLOGY

The former Camp SLO site consists mainly of mountains and canyons classified as grassland, wooded grassland, woodland, or brush. A major portion of the site is identified as grassland and is used primarily for grazing. Los Padres National Forest (woodland) is located to the north-northeastern portion of the site. During the hot and dry summer and fall months, the intermittent areas of brush occurring throughout the site become a critical fire hazard.

The underlying bedrock within the former Camp SLO site area is intensely folded, fractured, and faulted. The site is underlain by a mixture of metamorphic, igneous, and sedimentary rocks less than 200 million years old. Scattered throughout the site are areas of fluvial sediments overlaying metamorphosed material known as Franciscan mélange. These areas are intruded by plugs of volcanic material that comprise a chain of former volcanoes extending from the southwest portion of the site to the coast. Due to its proximity to the tectonic interaction of the North American and Pacific crustal plates, the area is seismically active. Additional details are available in Reference 11.

5.2.3 MUNITIONS CONTAMINATION

A large variety of munitions are reported to have been used at the former Camp SLO. Munitions debris from the following sources was observed throughout MRS 05 during the 2007 SI:

- 4.2-inch white phosphorus mortar
- 4.2-inch mortar base plate
- 3.5-inch rocket
- 37-mm projectile
- 75-mm projectile
- flares found of newer metal, suspected from CNG activities
- 105-mm projectile
- 60-mm mortar
- 81-mm mortar
- Practice bomb
- 30 caliber casings and fuzes

At the particular site of this demonstration, 60-mm, 81-mm, and 4.2-inch mortars and mortar fragments have been observed. During the initial EM61 MkII cart survey, two 2.36-inch rockets were found on the surface. The excavation of two 50-ft × 50-ft grids in October 2008, as part of the preparatory activities, has confirmed these observations and provided information on the depths of munitions at this target site.

5.2.4 SITE CONFIGURATION

The 11.8-acre demonstration site is shown in Figure 6 as a series of 30-m × 30-m cells with a topographical map as the background. The cells are color-coded based on the data collection systems that were deployed on them, tan color for all systems and blue for vehicular systems only. The site spans a significant fraction of the hillside that is the historical mortar target. The test pit was located near the logistics base, and the calibration strip was located outside the inner fence line, convenient to the site access road.

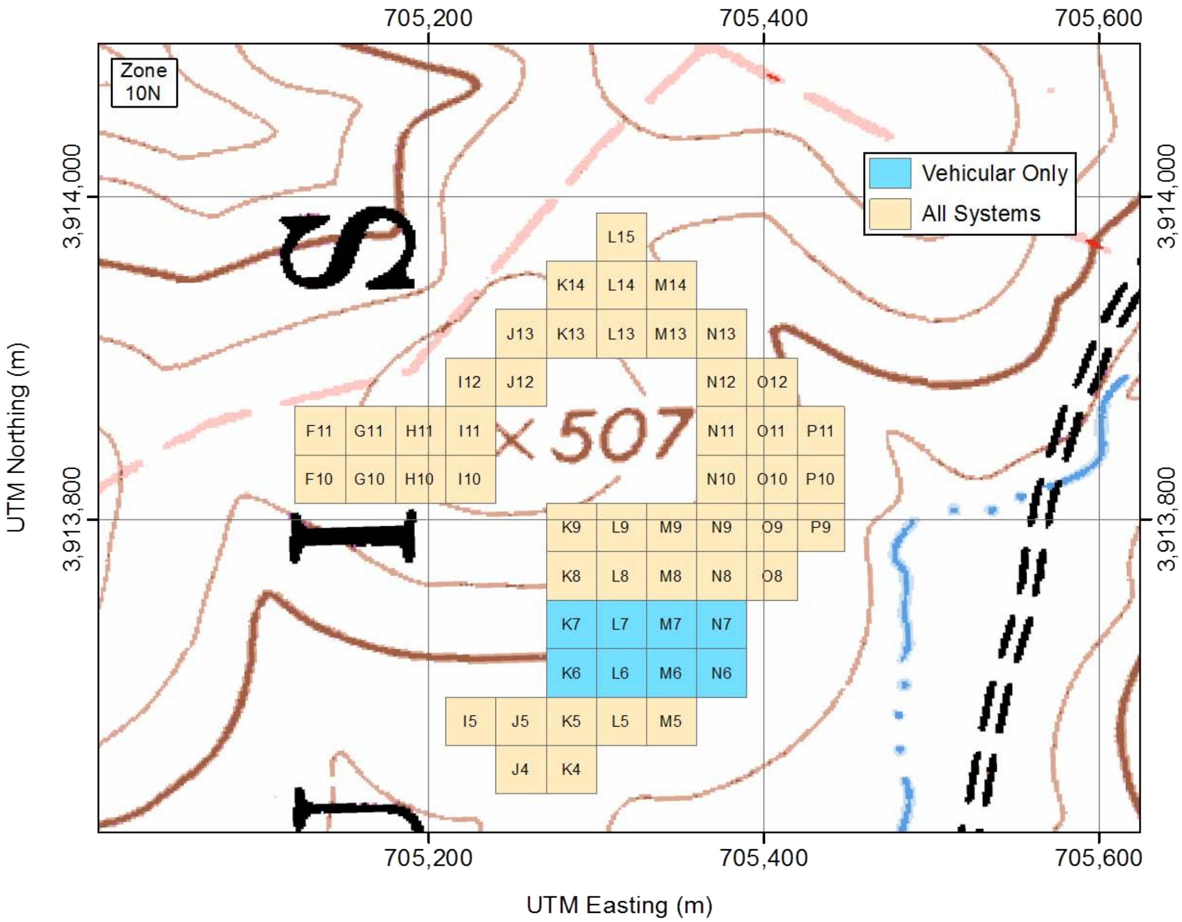

Figure 6. ESTCP UXO Classification Study demonstration site at the former Camp San Luis Obispo.

The site is shown as a series of 30-m × 30-m cells. See the text for further discussion.

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6.0 TEST DESIGN

6.1 CONCEPTUAL EXPERIMENTAL DESIGN

Each demonstration was designed to be executed in two stages. The first stage consisted of a standard MTADS dynamic survey of the site. For the APG demonstration, the MTADS magnetometer array was the survey instrument. The details of the magnetometer survey can be found in Reference 5. For the former Camp SLO demonstration, the MTADS EM61 MkII array was the survey instrument. The details of the MkII survey can be found in Reference 12. The choice of the appropriate technology for the first stage of the survey is governed by the combination of site history (expected target of interests [TOI] and clutter) and opportunity costs. The APG Standardized Test Site had recently completed a reconfiguration in April 2008, and NRL was requested to conduct a magnetometer survey of the entire APG Standardized UXO Test Site. Past experience at APG and with the seeded TOIs indicated that the magnetometer survey would provide acceptable detection for the later TEMTADS survey. For the former Camp SLO demonstration, both the MTADS magnetometer and EM61 MkII array were deployed to the site and available. Based on characterization measurements of both the site geology and the TOIs with both arrays, the EM61 MkII array data had a significantly higher SNR for detection of the known TOIs, so it was selected.

Anomaly locations were identified from the survey data in a combination automated/manual method. A data segment around each anomaly center was extracted and analyzed using the UX-Analyze subsystem of the Oasis montaj software package to fit the data to a dipole model and extract the associated fit parameters (position, depth, equivalent size). These fit results constituted the source anomaly list for the second stage of each demonstration.

This method relies on the establishment of an anomaly detection threshold. At the former Camp Sibert demonstration site, a single munitions type was present [13]. Pit measurements at various depths and orientations of an example article were made and bounding response curves generated for the 4.2-inch mortar, the munitions of interest. The anomaly detection threshold was then set based on the least favorably predicted response at the U.S. Corps of Engineers (USCOE) standard 11 times depth. These demonstration sites each contained different mixes of emplaced munitions and suspected existing munitions contamination. Individual anomaly detection thresholds were established for each site/area based on sets of pit measurements made for each of the emplaced items. For each site/area, the smallest appropriate least favorable response was used to determine the threshold. The details of the anomaly selection process, including the response curves, can be found in the demonstration data reports [5, 12].

The second stage of each demonstration was the survey of each site/area using the TEMTADS array developed as part of ESTCP Project MR-0601. The array was positioned roughly over the center of each anomaly on the source anomaly list and a data set collected. Each data set was then inverted using the data analysis methodology discussed in Section 7.3, estimated target parameters determined, and ultimately a classification made for each anomaly. The resulting prioritized dig lists were then submitted to either the ATC or Institute for Defense Analyses (IDA) for scoring and performance assessment.

The schedule of field testing activities is provided in Figure 7 as a Gantt chart.

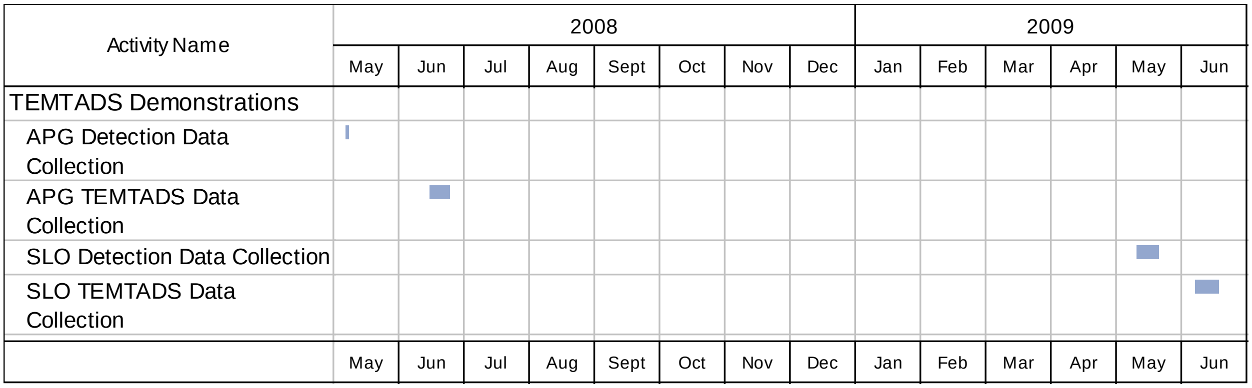

Figure 7. Schedule of field testing activities.

6.2 SITE PREPARATION

Each demonstration site had been previously configured with clearly marked calibration and open field scenarios. At least one GPS control point was provided at each site. Basic facilities such as portable toilets and field buildings were provided at APG and acquired for SLO. Secure storage for larger vehicles and sensor arrays was limited at both sites. A 40-ft shipping container was mobilized to each site for the duration of each demonstration to provide convenient, secure storage for the MTADS tow vehicle and the sensor trailer. The container was removed at the end of each demonstration.

6.3 SYSTEMS SPECIFICATION

This demonstration was conducted using the NRL MTADS tow vehicle and subsystems. The tow vehicle and each subsystem are described further in the following sections.

6.3.1 MTADS Tow Vehicle

The MTADS has been developed by the NRL Chemistry Division with support from ESTCP. The MTADS hardware consists of a low-magnetic-signature vehicle that is used to tow the different sensor arrays over large areas (10-25 acres/day) to detect buried UXO. The MTADS tow vehicle and TEMTADS array are shown in Figure 8.

Figure 8. MTADS tow vehicle and TEMTADS array.

6.3.2 RTK GPS System

Positioning is provided using cm-level real-time kinematic (RTK) GPS receivers. To achieve cm-level precision, a fixed reference base station is placed on an established first-order survey control point near the survey area. The base station transmits corrections to the GPS rover at 1 Hertz (Hz) via a radio link.

The TEMTADS array is located in three-dimensional space using a three-receiver RTK GPS system shown schematically in Figure 3 [14]. The three-receiver configuration extends the concept of RTK operations from that of a fixed base station and a moving rover to moving base stations and moving rovers. The lead GPS antenna (and receiver, Main) receives corrections from the fixed base station at 1 Hz. The corrected position of the Main GPS antenna is reported at 10-20 Hz. The Main receiver also operates as a moving base, transmitting corrections (by serial cable) to the next GPS receiver (AVR1), which uses the corrections to operate in RTK mode.

A vector (AVR1, heading [yaw], angle [pitch], and range) between the two antennae is reported at 10 Hz. AVR1 also provides moving base corrections to the third GPS antenna (AVR2), and a second vector (AVR2) is reported at 10 Hz. All GPS measurements are recorded at full RTK precision, ~2-5 cm. The GPS position is averaged for 2 seconds (s) as part of the data acquisition cycle. The averaged position and orientation information are then recorded to the position data file.

6.3.3 Time-Domain Electromagnetic Sensor

The TEMTADS array is a 5×5 square array of individual sensors. Each sensor has dimensions of 40 cm×40 cm, for an array of 2 m × 2 m overall dimensions. The rationale of this array design is discussed in Reference 15. The result is a cross-track and down-track separation of 40 cm. Sensor numbering is indicated in Figure 3. The transmitter electronics and the data acquisition computer are mounted in the tow vehicle. Custom software written by NRL provides both navigation to the individual anomalies and data acquisition functionality. After the array is positioned roughly centered over each anomaly, the data acquisition cycle is initiated. Each transmitter is fired in a sequence winding outward from the center position (12) in a clockwise direction. The received signal is recorded for all 25 Rx coils for each transmit cycle. The transmit pulse waveform duration is 2.7 s. While it is possible to record the entire decay transient at 500 MHz, we have found that binning the data into 115 time gates simplifies the analysis and provides additional signal averaging without significant loss of temporal resolution in the transient decays [16]. The data are recorded in a binary format as a single file with 25 data points (one data point per Tx cycle).

6.4 DATA COLLECTION

6.4.1 Scale of Demonstration

The APG demonstration was conducted at the APG Standardized UXO Test Site. A magnetometer survey was conducted on the calibration and blind grids, as well as the indirect fire area (approximately 4.3 acres) on May 7, 2008. The TEMTADS array surveyed the calibration and blind grids. The array was also deployed to approximately 700 anomalies in the indirect fire area that were detected from the magnetometer data set. The TEMTADS array portion of the demonstration occurred June 16–23, 2008.

A cued discrimination survey of the former Camp SLO demonstration site was conducted within the 11.8-acre final demonstration site of approximately 1500 previously identified anomalies from the anomaly list generated from the MTADS EM61 MkII data set. This survey was conducted using the NRL TEMTADS. The MTADS EM61 MkII data collection occurred May 11 – 18, 2009. The TEMTADS demonstration occurred June 8–18, 2009.

6.4.2 Sample Density

Magnetometer data were collected with nominal down-track spacing of 6 cm and cross-track spacing of 25 cm. EM61 MkII EMI data were collected with a nominal down-track spacing of 15 cm and a cross-track spacing of 50 cm. Two orthogonal surveys were conducted to increase target illumination and data density. The EMI data spacing for the TEMTADS is fixed at 40 cm in both directions by the array design.

6.4.3 Quality Checks

Since the TEMTADS operates in a cued mode, the data QC procedures and checks differ from that of survey mode instruments. The status of the RTK GPS system can be visually verified by the operator prior to starting the data collection cycle, assuring that the position and orientation information are valid (fix quality [FQ] 3, Position Dilution of Precision [PDOP] < 4) during the collection period.

Two data quality checks were performed on the TEMTADS data. After background subtraction, contour plots of the signal were generated for the 25 transmit/receive pairs at a decay time of 0.042 ms. An example of a good data set from a single anomaly with a large SNR is shown in Figure 9 for the APG Calibration Area item I6. The plots were visually inspected to verify that there was a well-defined anomaly without extraneous signals or dropouts. QC on the transmit/receive cross terms was based on the dipole inversion results. Our experience has shown that data glitches show up as reduced dipole fit coherence.

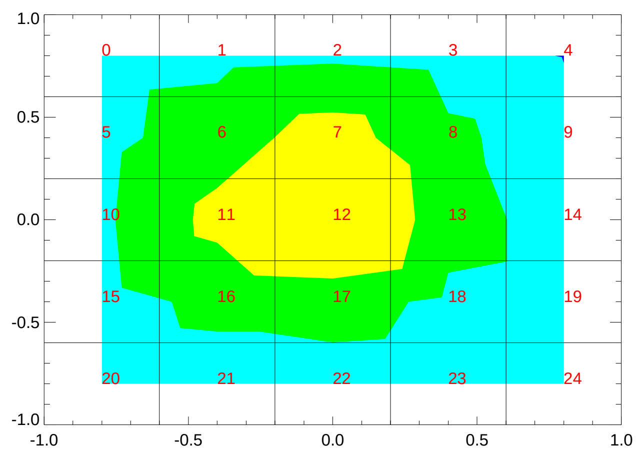

Figure 9. Monostatic QC contour plot for Calibration Area item I6.

The issue of when multiple objects are found to be under the array simultaneously, generating overlapping signatures, can also be addressed at this point in the data QC process. An example case is shown in Figure 10. There are two apparent issues in the data set. First, there appears to be a small, shallow bit of scrap on top of the target. Second, there was a bit of scrap present in the background file used. This latter issue is seen in the data from element 0. The fit coherence using all elements is 0.652. If elements 0, 5, 10, 11, 15, 16, 17, 20, 21, 22 are excluded, the fit coherence for the remaining elements is 0.985 and the betas match our library 105 mm HEAT betas very well.

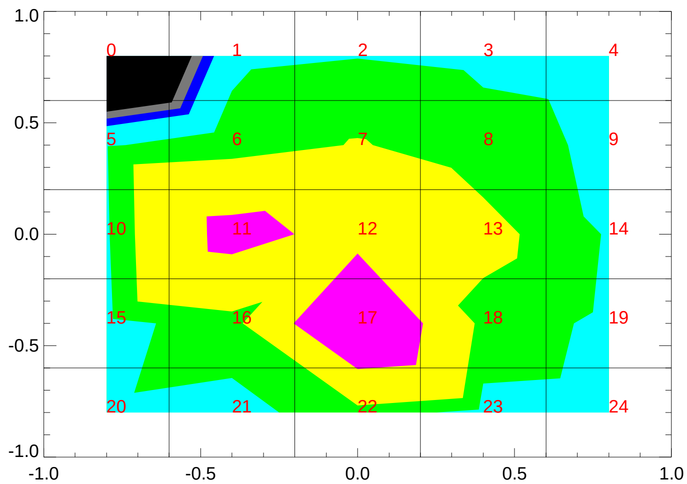

Figure 10. Monostatic QC contour plot for example anomaly.

Any data set that was deemed unsatisfactory by the data analyst was flagged and not processed further. The anomaly corresponding to the flagged data was logged for future re-acquisition. Data which meet these standards are of the quality typical of the MTADS system.

6.4.4 Data Summary

The primary performance metrics for this demonstration are the classification performance results for the TEMTADS array at the two demonstration sites. The first demonstration was conducted at the APG Standardized UXO Test Site. The performance results are provided by the site managers after the classification rankings are submitted [8]. The ground truth of this site is held by the principal investigators (PI), and results are only reported in aggregate. For the former Camp SLO demonstration, there is no single set of performance results as the UXO Classification Study involves multiple analysis of each collected data set. See the UXO Classification Study for former Camp SLO Final Report [17] for results by combination.

6.5 VALIDATION

6.5.1 Aberdeen Proving Grounds

With the exception of the Calibration Grid, the ground truth for the standardized sites is held back from individual technology demonstrators to preserve the utility of the blind grid and open field areas. Results from the blind grid and the indirect fire area were submitted to ATC for performance evaluation. Scoring results have been received and are available [8].

6.5.2 Former Camp San Luis Obispo

At the conclusion of data collection activities, all anomalies on the master anomaly list assembled by the Program Office were excavated. Each item encountered was identified, photographed, its depth measured, its location determined using cm-level GPS, and the item removed if possible. All nonhazardous items were saved for later in-air measurements as appropriate. This ground truth information, once released, was used to validate the objectives listed in Section 4.0.

7.0 DATA ANALYSIS AND PRODUCTS

The TEMTADS is a cued UXO classification system. There were two parts to the data collection in each demonstration: an initial survey, which served primarily to locate targets, and TEMTADS measurements made over each target detected in the survey. The TEMTADS data were used for target classification.

7.1 PREPROCESSING

The collected survey data were preprocessed on site for quality assurance purposes using standard TEMTADS procedures and checks as discussed in Section 6.4.3 and References 5 and 6.

The TEMTADS has 25 transmitters/receiver pairs. For each transmit pulse, the response measured at all of the receivers was recorded simultaneously. For each target, a 25×25×N data array is generated, where N is the number of recorded time gates. The current system configuration bins the data in 121 logarithmically spaced gates. During the preprocessing step, the recorded signals are normalized by the transmitter currents to account for any transmitter variations. To account for time delay due to effects of the receive coil and electronics, we subtract 0.028 ms from the nominal gate times [18]. The delay was previously determined empirically by comparing measured responses for test spheres with theory. The measured responses include distortions due to transmitter ringing and related artifacts out to about 40 μs. Consequently we included only the responses from decay times beyond 40 μs in our analyses. This leaves 115 gates spaced logarithmically between 0.042 ms and 25 ms.

The background response was subtracted from each target measurement using data collected in a nearby target-free region, or background. Background locations were selected from quiet areas observed in the survey data. All the background measurements were intercompared to evaluate background variability and to identify outlier measurements potentially corresponded to measurements over nonferrous targets. We have not observed significant background variability in our measurements at our Blossom Point test site and were able to use blank ground measurements from 100 m away for background subtraction on targets in the test field.

Geo-referencing of the array data is based on the GPS data, which gives the location of the center of the array and the orientation of the array. Sensor locations within the array are fixed by the array geometry. Dipole inversion of the array data (Section 7.3) determines target location in local array-based coordinates. The local position was then transformed to absolute coordinates using the array location and orientation determined from the corresponding GPS data.

7.2 TARGET SELECTION FOR DETECTION

Targets were selected from the survey data using the threshold exceedance methods described in References 5 and 12 using a physics-based threshold in Oasis montaj. The data chips associated with the detected anomalies were then processed in an automatic processing mode of UX-Analyze. The results of the automatic processing were then reviewed in UX-Analyze's interactive mode to allow operator experience to be included in the target selection. In the case of the APG demonstration, a small number of additional anomalies were identified by the operator and added to the anomaly list. For the former Camp SLO demonstration, the operator coalesced double-peaked features into a single anomaly where appropriate.

7.3 PARAMETER ESTIMATION

The raw signature data from the TEMTADS reflect details of the sensor/target geometry as well as inherent EMI response characteristics of the targets themselves. In order to separate out the intrinsic target response properties from sensor/target geometry effects, we invert the signature data to estimate principal axis magnetic polarizabilities for the targets. The TEM data are inverted using the standard induced dipole response model wherein the effect of eddy currents set up in the target by the primary field is represented by a set of three orthogonal magnetic dipoles at the target location [19].

Given a set of measurements of the target response with varying geometries or "look angles" at the target, the data can be inverted to determine the (X, Y, Z) location of the target, the orientation of its principal axes (ϕ, θ, ψ), and the principal axis polarizabilities (β_1, β_2, β_3). The basic idea is to search out the set of nine parameters (X, Y, Z, ϕ, θ, ψ, β_1, β_2, β_3) that minimizes the difference between the measured responses and those calculated using the dipole response model.

For the TEMTADS data, inversion is accomplished by a two-stage method. In the first stage, the target's (X, Y, Z) dipole location is solved for non-linearly. At each iteration within this inversion, the nine element polarizability tensor (**B**) is solved linearly. The non-linear inversion is done simultaneously over all time gates, such that the dipole (X, Y, Z) location applies to all decay times. At each time gate, the eigenvalues and angles are extracted from the polarizability tensor. In the second stage, six parameters are used: the three spatial parameters (X, Y ,Z) and three angles representing the yaw, pitch, and roll of the target (Euler angles ϕ, θ, ψ). In this second stage both the target location and its orientation are required to remain constant over all time gates. The value of the best fit X, Y, and Z from the first stage, and the median value of the first-stage angles are used as an initial guess for this stage. Additional loops over depth and angles are included to better ensure finding the global minimum.

Not every target from the detection surveys had a strong enough TEM response to support extraction of target polarizabilities. All the data were run through the inversion routines, and the results were manually screened to identify those targets that could not be reliably classified. Several criteria were used in this process: signal strength relative to background, dipole fit error (difference between data and model fit to data), the visual appearance of the polarizability curves.

For moderate-to-good SNR, our derived polarizabilities can be directly compared with those of our target library. In these cases, a metric was computed based on how well the amplitude and the ratio of the target polarizabilities match those of library objects. For anomalies in the APG demonstration with lower SNR or for cases where a visual inspection suggested a match, but the match quality was below our cutoff, target classifications were done using library matching procedures similar to those used by Sky Research, Lawrence Berkeley Lab, and ourselves in the ESTCP Discrimination Study Pilot Program at the former Camp Sibert [20]. The fit quality of an unconstrained dipole inversion of the TEMTADS data was compared to the fit quality of a dipole fit constrained by a set of principal axis polarizabilities drawn from a signature library.

The scoring rules for the SLO demonstration were different than those used for APG submissions, including the introduction of the "can't decide" category; therefore, a similar but modified process was used. The primary library match algorithm compares the polarizabilities of an unknown target with each library entry based on three criteria: the amplitude of β_1, and the two shape parameters, β_2/β_1 and β_3/β_1. For each anomaly, this match was performed on both the polarizabilities from the single dipole fit and those of each target obtained by a multi-dipole fit. The metric was set to whichever set of β's produces the best match.

7.4 CLASSIFIER AND TRAINING

Prior to the demonstrations we collected training data in air for all of the 14 standard APG ordnance targets and the four known munitions types for the former Camp SLO site. These data were used to generate the fit library entries. Many of the targets are composites of two or more distinct parts, like a steel body combined with an aluminum tail assembly. Depending on the distance between the sensors and the target, such items can exhibit a range of slightly different EMI signatures corresponding to excitation from different directions. We included measurements with the target oriented nose up, towards the sensor array, nose down, away from the array, flat and obliquely in the fit library. We have assembled a fairly extensive polarizability database for clutter items recovered from several different sites. This library was used as training data for establishing UXO/clutter discrimination boundaries on the direct match metric and on the coherence ratio.

7.5 DATA PRODUCTS

The primary data products generated are the ranked dig lists submitted for scoring. Additionally, the archival data sets, stored individually by site and by area are provided for future data analysis/classification efforts.

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8.0 PERFORMANCE ASSESSMENT

The TEMTADS array was constructed in 2007, field tested at the APG Standardized UXO Test Site in June 2008 [5, 8], and participated in the ESTCP UXO Classification Study at the former Camp SLO site in June 2009 [6]. Due to the nature of the demonstrations at each site and the employed scoring methods, separate performance objectives were used for each demonstration. In this section, as in Section 4.0, the performance results are discussed as a whole.

The performance objectives for these demonstrations were summarized in Table 1. The analyses which were used to evaluate these criteria are discussed in the following sections. The ATC scoring report for the demonstration, Reference 8, provides the source material for evaluating several of the performance objectives.

8.1 OBJECTIVE: CALIBRATION STRIP RESULTS

This objective is supported by each sensor system operating in good working order and collecting physically valid data each day. A calibration strip, consisting of two samples of each of the four targets of interest plus two shotputs (Table 2), was emplaced on site as a means of verifying proper system operation on a daily basis. The strip was surveyed twice daily, once at the beginning of the day, and once at the end.

Table 2. Details of former Camp SLO Calibration Strip.

Item ID	Description	Easting (m)	Northing (m)	Depth (m)	Inclination	Azimuth (°cw from N)
T-001	shotput	705,417.00	3,913,682.00	0.25	N/A	N/A
T-002	81 mm	705,420.92	3,913,687.63	0.30	Vertical down	0
T-003	81 mm	705,424.10	3,913,692.95	0.30	Horizontal	120
T-004	60 mm	705,427.53	3,913,698.54	0.30	Vertical down	0
T-005	60 mm	705,430.85	3,913,704.10	0.30	Horizontal	120
T-006	4.2-inch mortar	705,434.54	3,913,709.44	0.30	Vertical down	0
T-007	4.2-inch mortar	705,437.99	3,913,715.04	0.30	Horizontal	120
T-008	2.36-inch rocket	705,441.46	3,913,720.24	0.30	Vertical down	0
T-009	2.36-inch rocket	705,445.00	3,913,725.91	0.30	Horizontal	120
T-010	shotput	705,448.50	3,913,731.50	0.35	N/A	N/A

Prior to our demonstration at the former Camp SLO, we obtained measurements of each of the four munitions types with the TEMTADS array. Using the derived polarizabilities from these measurements and the forward model of our TEMTADS code, response curves were generated for each munition. These curves plot the minimum expected peak signal (the peak signal when the target is oriented horizontally) and the maximum expected peak (the peak signal when the target is oriented horizontally) from each target as a function of distance below sensor or depth below ground. The peak signal is that obtained from the monostatic term of the center element of the array at the first time gate. The measured peak signals for the 60-mm mortars are given in Figure 11 as an example.

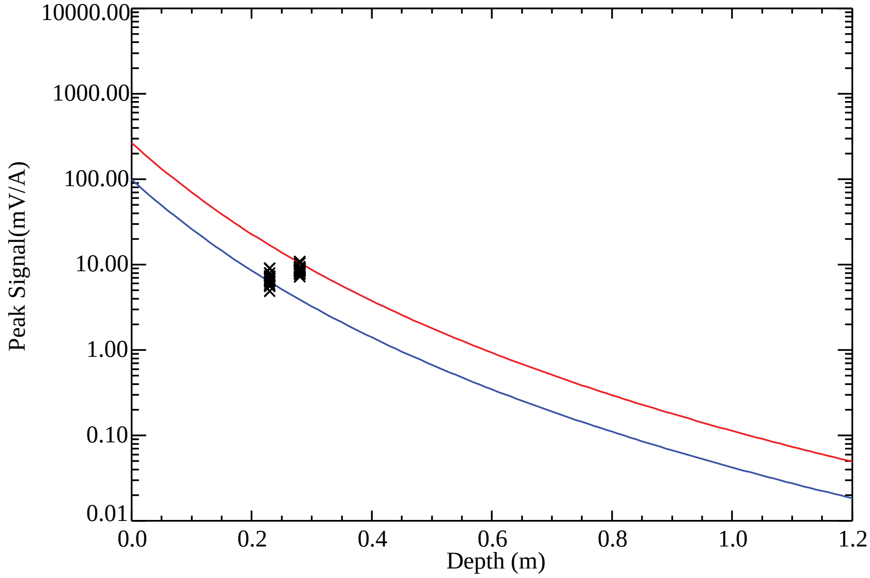

Figure 11. Peak signals compared with response curve for a 60-mm mortar.

This objective was not successfully met in full. The maximum (red) and minimum (blue) response curves are plotted. For self-consistency, we have plotted the measurements at the mean inverted depth rather than the reported depths. The measured values generally fit well within the bounding curves, with the 4.2-inch mortar and shotput results the poorest, with a tendency to underestimate the peak value.

Careful examination of the data shows that this variation is the result of the shot-to-shot precision with which the array can be positioned in exactly the same spot each time. Because the response curves are generated assuming the target is directly below the sensor, any offset in the sensor position will result in the derived peak signal being smaller than that predicted by the curve, as is observed. For future demonstrations, the metric of polarizability amplitude is recommended as these values are invariant to array position.

Table 3 shows the mean and standard deviation in the peak measured signal for all the emplaced Calibration Strip items. Of the 10 items, three give RMS variations above our stated goal of 15%, with only T-008 being significantly above. This target consistently inverted to a depth of 18.5 cm, and thus showed the largest spatial variation in signal. This, coupled with the array not always being properly centered on the target, explains the larger variation for this object.

Table 3. Peak signals for former Camp SLO calibration strip emplaced items.

Item ID	Description	Depth (m)	Mean Signal (mV/Amp)	Std Dev. (mV/Amp,1σ)	Variation (%)
T-001	shotput	0.25	27.44	4.18	15.23
T-002	81 mm	0.30	15.46	1.39	8.99
T-003	81 mm	0.30	10.96	0.91	8.30
T-004	60 mm	0.30	8.74	0.89	10.18
T-005	60 mm	0.30	6.73	1.13	16.79
T-006	4.2-inch mortar	0.30	52.38	5.82	11.11
T-007	4.2-inch mortar	0.30	41.75	5.25	12.57
T-008	2.36-inch rocket	0.30	32.70	7.91	24.19
T-009	2.36-inch rocket	0.30	4.04	0.32	7.92
T-010	shotput	0.35	11.82	1.52	12.86

The variability and accuracy of the positional fit parameters for the Calibration Strip emplaced items were determined by comparing the inverted northing and easting values with reported values. These numbers are shown in Table 4. We give the mean vector offset dR between the inverted and reported position as well as the easting (dx) and northing (dy) components. The dx and dy values are computed using the inverted positions minus the reported ones.

Table 4. Position accuracy and variability for former Camp SLO calibration strip emplaced items.

Item ID	Description	Depth (m)	Mean dR (m)	Std Dev dR (m, 1σ)	Mean dx (m)	Std Dev dx (m)	Mean dy (m)	Std Dev dy (m)
T-001	shotput	0.25	0.209	0.007	0.167	0.013	0.124	0.011
T-002	81 mm	0.30	0.413	0.008	-0.372	0.008	-0.178	0.010
T-003	81 mm	0.30	0.058	0.014	0.028	0.010	-0.049	0.020
T-004	60 mm	0.30	0.026	0.013	0.013	0.010	0.015	0.019
T-005	60 mm	0.30	0.038	0.012	-0.003	0.011	0.035	0.017
T-006	4.2-inch mortar	0.30	0.098	0.008	0.082	0.009	0.054	0.009
T-007	4.2-inch mortar	0.30	0.063	0.008	0.061	0.009	0.013	0.010
T-008	2.36-inch rocket	0.30	0.035	0.010	-0.027	0.011	0.018	0.011
T-009	2.36-inch rocket	0.30	0.112	0.016	0.051	0.010	-0.099	0.018
T-010	shotput	0.35	0.166	0.006	0.133	0.008	-0.098	0.014

Two points are clear from the values in Table 4. First, the inversion process is very robust, with no standard deviations larger than 2 cm. Second, there are a few large discrepancies between our inverted positions and the reported ones. All offsets are below our target value of 25 cm, with the exception of T-002. It is possible that some items have drifted or settled since their original emplacement.

8.2 OBJECTIVE: REDUCTION OF FALSE ALARMS

This is the primary measure of the effectiveness of this technology. By collecting high-quality, precisely-located data, we expect to be able to discriminate munitions from scrap and frag with high efficiency. At a seeded test site such as the APG standardized test site, the metric for false alarm elimination is straightforward. We prepared a ranked dig list for the targets we interrogated with a dig/no-dig threshold indicated, and ATC personnel use their automated scoring algorithms to assess our results.

This objective was successfully met. The TEMTADS surveyed anomalies detected by the MTADS magnetometer system in the blind grid and indirect fire areas. For the blind grid test area, the discrimination stage results are summarized in Table 5 and Table 6 (subsets of Table 6a of Reference 8), broken out by munitions type and emplacement depth. For the Indirect Fire Test Area, the discrimination stage results are summarized in Table 7 and Table 8 (subsets of Table 6c of Reference 8), broken out by munitions type and emplacement depth. The discrimination stage probability of detection (P_d^{disc}) is defined as the number of correctly identified munitions divided by the number of emplaced munitions, and the corresponding probability of false positive (P_{fp}^{disc}) is the number of clutter items incorrectly identified as munitions divided by the number of emplaced clutter items.

Table 5. TEMTADS blind grid test area P_d^{disc} results.

P_d^{disc}	All Types	105 mm	81/60 mm	37/25 mm
Munitions scores	0.97	0.93	0.97	1.00
0 to 4D [a]	1.00	1.00	1.00	1.00
4D to 8D	1.00	1.00	1.00	1.00
8D to 12D	0.67	0.67	0.00	1.00

[a] Burial depths are reported in units of the munitions' outer diameter, or D

Table 6. TEMTADS blind grid test area P_{fp}^{disc} results.

P_{fp}^{disc}	All Masses	0 to 0.25 kg	>0.25 to 1 kg	>1 to 10 kg
All depths	0.01	0.02	0.00	0.00
0 to 0.15m	0.01	0.02	0.00	0.00
0.15 to 0.3m	0.00	0.00	0.00	0.00
0.3 to 0.6m	N/A	N/A	N/A	N/A

Table 7. TEMTADS indirect fire test area P_d^{disc} results.

P_d^{disc}	All Types	105 mm	81/60 mm	37/25 mm
Munitions scores	0.92	0.93	0.93	0.91
By Density				
High	0.88	0.92	0.91	0.80
Medium	0.94	0.97	0.89	0.97
Low	0.94	0.90	0.97	0.94
By Depth				
0 to 4D	0.96	0.94	0.97	0.97
4D to 8D	0.92	0.94	0.92	0.86
8D to 12D	0.72	0.75	0.78	0.67

Table 8. TEMTADS indirect fire test area P_{fp}^{disc} results.

P_{fp}^{disc}	All Masses	0 to 0.25 kg	>0.25 to 1 kg	>1 to 10 kg
All depths	0.04	0.03	0.02	0.11
0 to 0.15m	0.04	0.04	0.02	0.13
0.15 to 0.3m	0.04	0.00	0.06	0.06
0.3 to 0.6m	0.08	0.00	0.00	0.20

Discrimination efficiency (E) and false positive rejection rate (Rfp) measure the effectiveness of the discrimination stage processing. The goal of discrimination is to retain the greatest number of munitions detections from the anomaly list, while rejecting the maximum number of anomalies arising from non-munitions items. Efficiency measures the fraction of detected munitions retained after discrimination, while the rejection rate measures the fraction of false alarms rejected. The measures are defined relative to the number of munitions items or the number of clutter items that were actually detected by the sensor. The results for the blind grid and indirect fire test areas are summarized in Table 9 and Table 10, from Tables 7a and 7c of Reference 8. Performance levels are shown at two specific operating points on the ROC curve: one at the point where no decrease in Pd is incurred and the other at the operator-selected operating point or threshold. In the blind grid, 98% of the emplaced munitions items were detected. Of these, 99% (97% of the emplaced munitions) were correctly classified at our selected operating point, with a corresponding false positive rejection rate of 99%. Moving out the ROC to the point where 100% of the detected munitions items are correctly classified reduces the false positive rejection rate to 95%. In the indirect fire area, 94% of the emplaced munitions were detected, and 92% of the emplaced munitions were correctly classified, resulting in a discrimination efficiency of 98%. The corresponding false positive rejection rate was 92%.

Table 9. TEMTADS blind grid test area efficiency and rejection rates.

	Efficiency (E)	False Positive Rejection Rate
At operating point	0.99	0.99
With no loss of P_d	1.00	0.95

Table 10. TEMTADS indirect fire test area efficiency and rejection rates.

	Efficiency (E)	False Positive Rejection Rate
At operating point	0.98	0.92
With no loss of P_d	1.00	0.58

8.3 OBJECTIVE: LOCATION AND DEPTH ACCURACY

An important measure of how efficiently any required remediation will proceed is the accuracy of predicted location of the targets marked to be dug. Large location errors lead to confusion among the UXO techs assigned to the remediation, costing time and often leading to removal of a small, shallow object when a larger, deeper object was the intended target. The average error and deviation in both horizontal axes was computed for the items that are selected for excavation during the validation phase of the demonstration. We provided an estimated position for all targets we interrogated to the appropriate personnel at each site, and they used their scoring algorithms to assess our results.

This objective was not successfully met in full. For the APG demonstration, the location accuracy of fit parameters generated from the TEMTADS array data are given in Table 11 and Table 12, taken from Tables 9a and 9c of Reference 8. Horizontal errors are not calculated for the blind grid.

Table 11. TEMTADS blind grid test area location error and standard deviation.

	Mean (m)	Standard Deviation (m)
Northing	N/A	N/A
Easting	N/A	N/A
Depth	0.02	0.04

Table 12. TEMTADS indirect fire test area location error and standard deviation.

	Mean (m)	Standard Deviation (m)
Northing	0.01	0.05
Easting	0.01	0.05
Depth	0.00	0.06

For the former Camp SLO demonstration, the average northing position error for all measured data was 1.5 cm, while the average easting position error was 3 cm. The standard deviations, however, were larger than desired, with both values about 25 cm. Excluding those anomalies for which multiple targets were found produces negligible improvement. We suspect the higher values are due to the large number of small, low SNR clutter items, which result in greater uncertainty in both the measured and fitted values. Indeed, if we restrict ourselves to those anomalies that we classified as "likely UXO," the northing and easting standard deviations drop to 7 cm and 5 cm, respectively. The average depth error for all measured data was 2.5 cm. The standard deviation was a bit larger than desired, with a value of 14 cm. Excluding those anomalies for which multiple targets were found and restricting the analysis to those anomalies classified as "likely UXO" to exclude low SNR clutter items, the standard deviation reduces to 7 cm.

9.0 COST ASSESSMENT

The costs for a 3000 anomaly cued survey using the TEMTADS are detailed in Table 13. The costs associated with the former Camp SLO demonstration were used as the basis for this assessment. The costs reported here do not include any costs associated with the reconnaissance data that was used to identify and create the cued list of anomalies. Implicit in our assessment is that that the 3000 anomalies are bounded within an area of roughly 25 acres, or 120 anomalies/acre. Survey time would increase incrementally as the anomaly density decreased as transit time between anomalies increased. All costs are estimated in fiscal year (FY) 2009 dollars.

Table 13. Summary of costs for a 25-acre, 3000 anomaly TEMTADS survey.

Cost Category	Sub-Category	Cost
Mobilization costs	Preliminary site visit	$6500
	Test plan preparation	$10,250
	Equipment prep and packing	$9750
	53-ft trailer transportation	$5800
	Analysts set-up	$10,000
	Outbound travel for 3 personnel	$2250
	Subtotal	**$44,550**
Logistics (if required)	Establish GPS control points	$2000
	Delivery/removal of logistics items	$2000
	Rental of logistics items/fuel	$6000
	Materials	$6500
	Subtotal	**$16,500**
Operating costs (4-week Survey)	Supervisor	$19,000
	On-site analyst	$31,800
	Vehicle operator	$12,750
	Field technician (2 each)	$17,250
	Per diem (3 personnel × 4 weeks × $1250)	$15,000
	Rental vehicles	$8650
	System maintenance	$13,000
	Sensor repair	$21,600
	Subtotal	**$139,050**
Analysis & reporting	Data reduction to anomaly list	$28,000
	Demonstration data report	$16,750
	Subtotal	**$44,750**
Demobilization costs	Equipment unpacking	$3500
	53-ft trailer transportation	$5800
	Inbound travel for 3 personnel	$2250
	Subtotal	**$11,550**
Total Cost		$256,400

9.1 COST MODEL

A cost model was constructed from the costs associated with the TEMTADS survey of the former Camp SLO demonstration site. Cost categories were mobilization, logistics (if required), field work, demobilization, data analysis, and reporting. Based on the demonstrated production rate for the former Camp SLO demonstration, 4 weeks of field work would be required. Based on the production rate for the APG demonstration, the SLO production rate is a conservative lower bound. This model does not include the cost of anomaly classification and producing a prioritized dig list.

9.2 COST DRIVERS

Two factors were expected to be strong drivers of cost for this technology as demonstrated. The first is the number of anomalies that can be surveyed per day. Higher productivity in data collection equates to more anomalies investigated for a given period of time in the field. The time required for analyzing individual anomalies can be significantly higher than for other more traditional methods and could become a cost driver due to the time involvement. The thoughtful use of available automation techniques for individual anomaly analysis with operator QC support can moderate this effect.

9.3 COST BENEFIT

The main benefit to using a UXO classification process is cost-related. The ability to reduce the number of nonhazardous items that have to be dug or dug as hazardous directly reduces the cost of a remediation effort. The additional information for anomaly classification provided by the TEMTADS array provides additional information for the purposes of anomaly classification. If there is buy-in from the stakeholders to use these techniques, this information can be used to reduce costs.

As an example of the potential cost benefit of using this technology on an actual cleanup, an example scenario is presented. The two demonstrations discussed in this report were both of short duration with a small number of anomalies to capitalize mobilization costs across. Therefore, considering only the field work and data analysis costs given in Table 13, a reasonable estimate of the cost/anomaly for deploying the TEMTADS array long term is $61/anomaly. The staffing level assumed in Table 13 is appropriate for a new research and development project demonstration and could be reduced to support sustained production operations.

Similarly, the cost of fielding an appropriately certified UXO dig team without mobilization costs can range between $37,000 and $50,000 per week (FY 2010 dollars). Assuming that the team can clear between 310 and 420 anomalies a day, the cost to dig an anomaly is $90 – $160/anomaly. Assuming that 1% of the items dug are in fact UXO, the remediation of those UXO must be accounted for and a remediation cost of $1000/UXO, the average cost per dig would range from $100 – $170/anomaly.

Finally, for the example, assume a hypothetical actual cleanup site with 10,000 anomalies to be cleared. Using the above analysis, the cost of the cleanup with all anomalies dug would range from $1,000,000 to $1,700,000 total. If one assumes that the TEMTADS classifies the anomalies sufficiently well to reduce the number of actual digs required to 10% of the original number, the combined cost of the TEMTADS survey and the resultant digging drops to $713,000 – $783,000 total, for a potential savings of 29 – 54% overall.

10.0 IMPLEMENTATION ISSUES

Implementation issues for this system/technology fall into two categories: operational concerns and data quality/analysis issues. In terms of operational concerns, the TEMTADS as implemented is a large, vehicle-towed system that operates best in large, open areas. As seen at the former Camp SLO demonstration, it is possible to operate the system in rocky terrain with grades approaching 20%, but at reduced operating capacity and increased system wear. Smaller versions of the system are currently under development under several ESTCP and SERDP projects to address these concerns. The goal is to design and field units more amenable to operation in more confined terrain and topology and smaller tow vehicles/man-portable and handheld operation. Another serious limitation will be anomaly density. For all sensors, there is a limiting anomaly density above which the response of individual targets cannot be separated. We have chosen relatively small sensors for this array, which should help with this problem, but we cannot eliminate it. Based on experiments at our test pit at Blossom Point, the results of this demonstration, and work done on the former Camp Sibert data sets, anomaly densities of 300 anomalies/acre or higher would limit the applicability of this system as more than 20% of the anomalies would have another anomaly within a meter.

In terms of data quality, one pays a small penalty in signal amplitude to use the smaller TEMTADS sensor coil as compared to other systems such as a high-power EM61 MkII. The dramatically improved electrical performance of these new sensors helps counterbalance this issue, particularly in the ability to perform better averaging (or stacking). However, one needs in place robust data QC techniques to know when to employ these capabilities in an efficient manner.

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APPENDIX A

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