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Man Portable Vector EMI Sensor for Full UXO Characterization

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ACRONYMS AND ABBREVIATIONS

ATC	Aberdeen Test Center
BOR	body-of-revolution
BUD	Berkeley UXO Discriminator
CRREL	Cold Regions Research and Engineering Laboratory
CWS	Chemical Warfare School
DAQ	data acquisition system
DGM	digital geophysical mapping
DoD	U.S. Department of Defense
EMI	electromagnetic induction
ERDC	Engineering Research and Development Center
ESTCP	Environmental Security Technology Certification Program
FAR	false alarm rate
FY03	Fiscal Year 2003
GPS	Global Positioning System
ISO	industry standard object
IVS	Instrument Verification Strip
m	meter
mm	millimeter
MPV	man portable vector
m/s	meters per second
ms	millisecond
MR	Munitions Response
Pc	probability of correct UXO classification
Pd	probability of detection
PI	principal investigator
QC	quality control
RDP	remote desktop protocol
ROC	receiver operating characteristic
RTK	real-time kinematic
SERDP	Strategic Environmental Research and Development Program
SKY	Sky Research, Inc.

ACRONYMS AND ABBREVIATIONS (continued)

SNR	signal-to-noise ratio
SOP	standard operating procedure
SVM	Support Vector Machine
TEMTADS	Time Domain Electromagnetic Towed Array Detection System
TOI	target of interest
VRM	viscous remanent magnetization
UXO	unexploded ordnance
YPG	Yuma Proving Ground

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The man portable vector (MPV) demonstrations at Yuma Proving Ground (YPG) and former Camp Beale, CA, were entirely funded by the Environmental Security Technology Certification Program (ESTCP) Munitions Response (MR) project MR-201005. This second generation MPV is a U.S. government-funded prototype sensor that was initially developed and tested with support by the Strategic Environmental Research and Development Program (SERDP) under the 2009 extension of Project MR-1443 with Drs. Kevin O'Neill and Benjamin Barrowes (Cold Regions Research and Engineering Laboratory [CRREL]-Engineering Research and Development Center [ERDC]), David George (G&G Sciences) and Dr. Nicolas Lhomme (Sky Research, Inc. [SKY]). This ESTCP project funded completion of the sensor-head fabrication and purchase of new data acquisition system.

The two field deployments mostly involved Jon Jacobson and the principal investigator (PI) (both from SKY). David George fabricated the sensor and supported the field surveys by preparing and maintaining the technology and helping in survey setups and data collection. Ben Barrowes participated in setting up and initiating the surveys and analyzing the cued interrogation data for classification. The PI was the main performer for most technical, reporting and management tasks with assistance from colleagues at SKY. Joy Rogalla and Erik Russell assisted with project management and coordination. Drs. Laurens Beran, Leonard Pasion, and Stephen Billings advised on technical aspects and Dr. Gregory Schultz reviewed this report.

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1.0 EXECUTIVE SUMMARY

1.1 OBJECTIVES OF THE DEMONSTRATION

There are many U.S. Department of Defense (DoD) sites where unexploded ordnance (UXO) cleanup is difficult because current technology is inadequate in forested areas and in challenging terrain. The man portable vector (MPV) is a handheld technology that is designed to extend the classification performance of the latest vehicle-based geophysical platforms to sites where vegetation or terrain limit access to these platforms. The objective of this study was to demonstrate through data collection and analysis that a handheld sensor such as the MPV could be utilized for detection and classification of shallow UXO at live sites. The MPV was first validated at the Yuma Proving Ground (YPG) Standardized Test Site and subsequently participated in the Environmental Security Technology Certification Program (ESTCP) demonstration of man-portable systems at the former Camp Beale, which contained areas with forest and rolling terrain. The performance objectives were met by achieving high rates of detection, classification, and clutter rejection.

1.2 TECHNOLOGY DESCRIPTION

The MPV sensor head is a handheld, wide-band, time-domain, electromagnetic induction (EMI) sensor that comprises of a 50-cm diameter transmitter loop and an array of five three-dimensional receivers. This second-generation prototype was specially designed for this study to improve maneuverability and ruggedness over the initial sensor that was developed by Cold Regions Research and Engineering Laboratory (CRREL) in Strategic Environmental Research and Development Program (SERDP) Munitions Response (MR) Project MR-1443 (O'Neill and Barrowes). The MPV is field programmable through a user interface that also provides immediate feedback on field data for quality control (QC) and target localization. Generally operated by a two-person team, the MPV can be operated in dynamic survey for digital geophysical mapping (DGM) and target detection, and for cued interrogation of detected anomalies. In cued mode, high quality data are collected by taking multiple static soundings for joint interpretation through geophysical inversion. Reliable inversion requires accurate positioning. The MPV utilizes a dedicated, local, portable positioning receiver station that monitors the primary transmitter field from the MPV—like a beacon—and returns relative location estimates with cm-level accuracy out to a range of 4 m. This approach overcomes line-of-sight constraints of standard survey methods such as Global Positioning System (GPS) and roving laser rangefinders and, unlike a fixed template, facilitates adaptive choice of sounding locations according to target response and environmental conditions.

The MPV was deployed at two sites by Sky Research, Inc. (SKY) with technical assistance from G&G and CRREL. The data were subsequently analyzed and processed by SKY. The YPG demonstration, which occurred in October 2010, was aimed at verifying detection and classification on a blind grid after training on calibration lanes. The survey protocol involved operating in a detection search mode until a target was encountered. The detection survey was then interrupted and a cued survey, designed to collect sufficient high quality data for classification, was executed. The technology was further tested in the Desert Extreme area for its ease of use and ruggedness. The Camp Beale demonstration was conducted in June 2011 and tested classification at a live site through cued interrogation of 912 anomalies previously

identified in a DGM survey using an EM-61-MKII sensor. The Camp Beale targets were split between a forested area, where vehicular access was precluded, and an open field, where performance with vehicular platforms could be compared.

1.3 DEMONSTRATION RESULTS

High detection performance was demonstrated at the YPG site with 100% and 90% detection rates for UXO within 0.3 m and 1 m depth, respectively. Successful classification performance was also demonstrated with 95 and 100% of detected UXO (within 0.3 and 1.0 m depths respectively) correctly identified. Beacon position estimates were confirmed to be sufficiently accurate to meet classification requirements. Sensor hardware proved to be maneuverable and generally resilient. Efficient survey protocols were established and an average daily productivity rate of 100-anomaly characterizations was achieved. The system was deemed fit for live-site testing.

At the Camp Beale demonstration site, cued interrogation data were collected within the planned schedule with a daily productivity rate of 90 anomalies. To address potential issues with highly magnetic soils at the site and to mitigate anomaly location uncertainties additional soundings were collected, thus lowering the production rate below that achieved at YPG. Data were pre-processed and made available to external data analysts for advanced processing and classification. Interpretations conducted by SKY and several other research groups resulted in the identification of 100% of the targets of interest while avoiding excavation of over 80% of the clutter. All demonstration objectives were successfully met.

1.4 IMPLEMENTATION ISSUES

The YPG and Beale studies constitute the first step at establishing the performance, limitations, optimum usage, and costs of the MPV technology. The initial demonstrations were successful and showed a strong potential for detection and classification at shallow depth (up to 1 m) with a handheld technology. Of particular note is the significant reduction in the number of nonhazardous clutter items that need to be excavated: over 80% of these items could be left in the ground. Additional surveys are scheduled through 2012-2013 as part of the ESTCP Live-Site Demonstration program (Projects MR-201158 and MR-201228).

Today there is no commercially available system with similar capabilities, though there is some overlap with cart-based and man-portable prototypes that are currently being tested with the ESTCP (such as the Time Domain Electromagnetic Towed Array Detection System [TEMTADS] 2x2 and the handheld Berkeley UXO Discriminator [BUD]). The MPV sensor itself is a unique prototype. It was fabricated by G&G with U.S. government funding using “standard” components similar to those found on the Geometrics MetalMapper in addition to a number of custom features. Maintenance and integration of surveying sensors such as GPS and heading sensors currently relies on the involvement of G&G.

Technology transition efforts are ongoing. The MPV will now be field-tested without the presence of the technology developer. A wider range of surveying sensors (such as tilt meters) will be made compatible with the MPV so that legacy sensors can be replaced. All MPV data that have and will be collected in the ESTCP demonstration will continue to be made available

for testing of inversion and classification algorithms and for training of analysts. Commercial partners are scheduled to participate and be trained by SKY at data collection and interpretation in upcoming field demonstrations. Demonstration reports will document survey protocols and results and will promote adoption of the MPV technology by industry.

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2.0 INTRODUCTION

This project demonstrates the capability to perform classification of buried UXO with a handheld sensor, the MPV EMI sensor. The MPV technology was designed to extend the advanced classification capabilities of new-generation geophysical platforms to sites with challenging surveying conditions and thus provide a solution for UXO cleanup at most land locations. This project comprises development of the technology, live-site testing, and data analysis for classification.

2.1 BACKGROUND

Decades of training have left millions of acres of UXO-contaminated land in the United States. The Defense Science Board observed in 2003 that existing methods for UXO detection generally caused expensive digging of abundant scrap and suggested that use of classification technology could significantly reduce remediation cost. ESTCP received funding in 2006 to stimulate the “development of advanced, sophisticated discrimination technologies for UXO cleanup” and initiated a discrimination pilot study to test emerging technology. The first three discrimination studies showed that a significant fraction of nonhazardous scrap could be safely left in the ground when combining new-generation sensors and advanced classification methods. The new technology relied on the deployment of large, vehicular and cart-based geophysical platforms that required favorable survey conditions, minimal vegetation, and modest topographical variations. Many DoD sites are less amenable to vehicular deployment. Terrain and vegetation conditions (e.g., dense forests and steep terrain) can also preclude use of traditional location systems like GPS and laser ranging by disrupting their line-of-sight requirements.

The MPV was designed to extend UXO classification to challenging survey environments. The MPV EMI sensor incorporates new-generation multi-axis receivers, electronics, and programmability into a handheld form factor for improved portability and reduced logistical requirements. The MPV can be utilized for detection and classification. Detection can be achieved through dynamic data collection and DGM. Classification relies on the collection and processing of high quality data, which are generally obtained through cued interrogation, where a series of static soundings are collected near a detected anomaly. Classification requires accurate positioning. In environments where line-of-sight requirements cannot be met and preclude use of GPS or laser ranging methods, the MPV is accurately located with a MPV-dedicated local positioning system that was designed and tested for this project. The system is based on monitoring the MPV EMI field—like a beacon—from a portable base station with receivers. This project tested the second-generation MPV. The first MPV prototype was developed under the SERDP Project MR-1443 originally led by Dr. Kevin O’Neill and Dr. Benjamin Barrowes. The MPV showed a strong potential for UXO classification in preliminary field tests and was redesigned for improved ruggedness and maneuverability as part of the original SERDP project and this project.

The demonstration design consisted of testing the MPV at a controlled site in the first year and at a live site in the second year. The first demonstration was set at the UXO Standardized Test Site at YPG, AZ, in October 2010. The MPV was tested for the capabilities to endure an extended field survey and achieve satisfactory detection and classification performance in a systematic, controlled experiment. The second study tested classification at a live site in June 2011 as part of

the ESTCP demonstration at former Camp Beale, CA, where the performance of emerging portable technologies was tested in areas with terrain features and variable forest density.

2.2 OBJECTIVES OF THE DEMONSTRATION

The goal of this demonstration was to implement the MPV technology, to test the capability to carry out effective surveys at live-munitions sites and to assess data quality for the detection and classification of buried munitions. The technology was tested by field deployment and data analysis for two sites with specific purposes.

2.2.1 First Demonstration at Standardized Test Site

The first demonstration took place at YPG and comprised of two main objectives: (1) to achieve high performance at detection and classification and (2) to test field survey procedures at an environmentally easy site. Detection and classification were practiced on the Calibration Lanes, where survey parameters and protocols were verified and a classifier was trained, and applied to the Blind Grid where 400 potential anomalies had to be classified.

The main objectives were largely met and the demonstration was a success. Detection objective of 80% was exceeded with 100% target detection within 0.3 m and 90% within 1 m depth range and no false alarms. Classification goals of 80% were met with over 90% correct classification of UXO within 1 m depth. The false alarm rate for classification was higher (60-75%) than the stated objective (50%) because the UXO-to-clutter ratio was orders of magnitude greater than that of a live site. Beacon positioning was tested relative to real-time kinematic (RTK) GPS and yielded similar cm-level accuracy, which met accepted requirements for classification. Field-readiness was also tested. The technology was generally straightforward to operate. The hardware was resilient to the 2 week field deployment, with only some minor damage to a few connectors. In terms of productivity, a daily average of 100 anomalies was achieved on the Blind Grid. Data were processed and interpreted within the expected 4 weeks of survey completion.

2.2.2 Live-Site Demonstration

The second demonstration was set at former Camp Beale, a live site that was chosen for the specific purpose of testing classification with man-portable systems in areas with sloped, forested terrain where vehicular platforms could not survey (Figure 1). Cued interrogation data were collected over 912 anomalies while using the beacon system for positioning. The data were preprocessed and made available to other research groups for analysis and classification.



Figure 1. Survey with MPV and beacon positioning boom at former Camp Beale.

The demonstration was successful. High quality EMI data were collected with accurate positioning and allowed all analysts to identify all buried UXO and leave over 80% of the clutter in the ground. The data collection was completed well within the planned schedule. The MPV and beacon endured the field survey without any major breakdowns—some cable connectors attached to the control unit got strained and were replaced. The initial productivity objective was 100 targets per day. Though 100 targets were collected on one day, the daily average was 90 targets. The objective can be considered to be met given that the survey protocol had to be amended to increase the number of soundings per anomaly to accommodate offsets between flagged and detected target locations and sample the significant and variable background response from magnetic soil.

2.3 REGULATORY DRIVERS

The Defense Science Board Task Force on UXO noted in its Fiscal Year 2003 (FY03) report that 75% of the total cost of a current clearance is spent on digging scrap. A reduction in the number of scrap items dug per UXO item from 100 to 10 could reduce total clearance costs by as much as two-thirds. Thus, classification efforts focus on technologies that can reliably differentiate UXO from items that can be safely left undisturbed.

Classification only becomes a realistic option when the cost of identifying items that may be left in the ground is less than the cost of directly digging them. Because classification generally requires a detection survey as a precursor step, the investment in additional data collection and analysis must result in sufficient clutter rejection to recuperate the investment. Even with perfect detection performance and high signal-to-noise ratio (SNR) values, successfully sorting the

detections into UXO and nonhazardous items is a difficult problem but, because of its potential payoff, one that is the focus of significant current research. This demonstration represents an effort to transition a promising classification technology into widespread use at UXO-contaminated sites across the country.

3.0 TECHNOLOGY

The MPV technology is based on EMI sensing using one transmitter coil and multiple vector receivers in a handheld form factor. The sensor presented in this study is the second-generation prototype MPV.

3.1 MPV TECHNOLOGY DESCRIPTION

3.1.1 Electromagnetic Sensor

The MPV is a handheld sensor with wide-band, time-domain, EMI technology. The sensor head is composed of a single transmitter coil and an array of five receiver units that measure all three components of the electromagnetic field (Figure 2). This second-generation MPV was specifically designed to (1) be man portable and therefore easy to deploy, maneuver, and adapt to a survey environment, and (2) acquire data that is suitable for discriminating UXO from non-UXO targets. The MPV head is a 50 cm diameter transparent disk. The transmitter coil is wound around the disk and intermittently illuminates the subsurface. Five multi-component receiver units (cubes) measure the three orthogonal components of the transient secondary electromagnetic field decay with three air-induction 8 cm square coils. One receiver cube is co-axial with the transmitters while four receivers are placed off axis around the transmitter loops in a cross pattern. Having multiple receivers generally improves the recovery of target parameters for classification (Gasperikova et al., 2007).

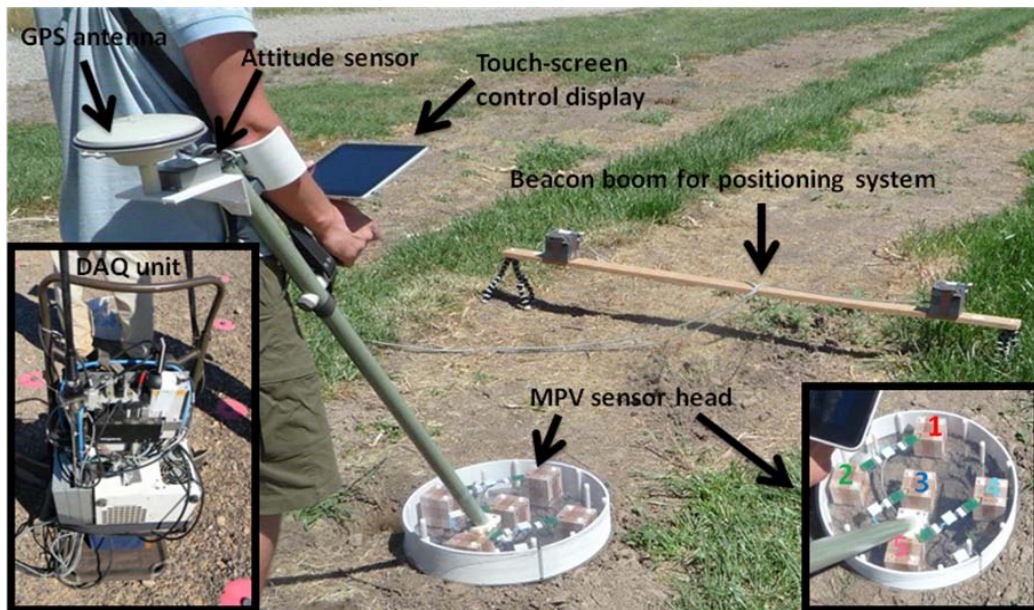


Figure 2. The second generation MPV with beacon positioning.

Positioning can be achieved with GPS (for open field survey) or beacon receivers (for survey in a forest or in steep terrain). Left inset shows data acquisition system (DAQ) and power unit mounted on a backpack frame. Right panel shows view of sensor head from above with cube numbers.

The MPV is a programmable instrument. The duration of the excitation and time decay recording can be adjusted to any given time to accommodate survey needs. The MPV is generally with two

main modes: detection and classification. Detection survey consists of dynamic data collection for DGM using fast EMI transmit-receive cycles so that the sensor can continuously move (e.g., 1 millisecond [ms] time decay, similar to Geonics EM-61). Discrimination maximizes data quality for classification. The sensor is static to stack the recorded signal and reduce noise. Longer EMI cycles are applied to capture variations in time decay rates (e.g., 25 ms, similar to Geonics EM-63). This late-time information has been shown to improve distinction between intact ordnance and thinner walled shrapnel and cultural debris (Billings et al., 2007).

The MPV is a handheld sensor. The sensor head weighs 12 pounds and the backpack-mounted DAQ and batteries weigh 35-40 pounds. Existing sensors with multiple time channel measurement capabilities (e.g., BUD, Geonics EM63, TEMTADS) are required to be mounted on a cart platform due to the size and weight of the multiple coils of wire required for the transmitters and receivers.

The MPV user interface has real-time data monitoring capabilities. The recorded data can be displayed to verify data quality and detect potential disturbances such as presence of magnetic soil or a damaged receiver. The past and present sensor location is displayed on a map along with preset survey points to verify spatial coverage and global location. A target detection and location tool indicates the origin of measured EMI fields with arrows (the so-called “dancing arrows” in top left corner of Figure 3). These features assist the field operator in efficient data collection, so that detection and discrimination data can be collected as part of the same survey, thus limiting the need to revisit an anomaly for further characterization.



Figure 3. The MPV detection display window in dynamic data collection mode.

The top left panel indicates with arrows the direction of the nearest compact metallic object relative to the MPV receiver cubes and directs the operator to the target (here the MPV sits atop the target). The top middle panel shows a field map with the MPV location (red dot) and azimuth (black line), potential target locations (blue dots), and cued interrogation soundings (green crosses). The middle left panel provides feedback on positioning sensors. The bottom panel has the data acquisition options for simple one-button-touch operation.

3.1.2 Geolocation

The sensor requires positioning for detection and classification, though with different spatial accuracy requirements for each. Therefore a field survey with the MPV can utilize two complementary positioning systems. Detection mapping has decimeter accuracy requirements and can be performed with a GPS or a spool-mounted cotton thread and optical encoder. Classification is based on geophysical inversion of multiple soundings and generally requires cm-level sensor positioning when surveying a target (Bell, 2005). Being designed to extend UXO classification to difficult survey environments, the MPV technology was augmented with a local positioning system that remains accurate in steep terrain and under thick tree canopy, where GPS cannot guarantee high accuracy. We implemented the MPV-beacon positioning system for cued target interrogation (San Filippo et al., 2007; Lhomme et al., 2011). The operating principle consists of locating the origin of the MPV transmitter, acting as a beacon, with a pair of EMI receivers rigidly attached to a portable beam that serves as a base station (Figure 2). The azimuth of the MPV and boom are recorded with a 3-component attitude sensor. Field trials showed 1-2 cm and 1-2° accuracy for position and orientation—similar to GPS—out to distances of 3-4 m.

3.2 MPV TECHNOLOGY DEVELOPMENT

The project was initiated in 2005 under SERDP MR-1443 and led by Drs. Kevin O'Neill and Benjamin Barrowes of the CRREL Engineering Research and Development Center (ERDC) in Hanover, NH. The first MPV prototype was built in 2005-2006 by David George of G&G Sciences, Grand Junction, CO. It was tested in 2007 at ERDC in a laboratory setting. Data analysis showed that stable target parameters could be retrieved and used for UXO classification.

The SERDP project was first extended in 2008 to continue testing. The first field tests took place at the SKY test plot in Ashland, OR, in the summer. A series of UXO was surveyed in static and dynamic mode using a template with marked locations and the ArcSecond laser ranging system. Data analysis confirmed stable target parameter recovery for classification. The effect of magnetic soil on EMI sensors was investigated. Adverse soil effects could be defeated owing to the MPV's array structure. The ArcSecond laser positioning technology that had supported early MPV tests proved to be impractical and not reliable enough for field application due to the requirement to keep line-of-sight with all three rovers, and long setup and calibration time. This experience stimulated development of an alternative positioning method based on the beacon principle.

The SERDP project was extended by SKY in 2009 to test the beacon concept and prepare modification of the original MPV prototype for extensive field deployments. The sensor head was redesigned with lighter materials and a smaller head diameter to reduce weight and improve maneuverability while maintaining its expected performance (Appendix D of Lhomme, 2011). The receiver cubes were brought inside the transmitter coil to reduce fragility, and transparent material was employed to allow the operator to see the ground through the unit. Actual fabrication of the new head and replacement of the DAQ was funded through the SERDP project and this ESTCP project. The sensor head was lightened from 23 to 12 pounds.

3.3 ADVANTAGES AND LIMITATIONS OF THE MPV TECHNOLOGY

The MPV is the only available non-cart-based system that can acquire multistatic, multicomponent data on a wide and programmable range of time channels. The MPV offers several key benefits:

- **Handheld form factor:** The MPV can be deployed at sites where terrain and vegetation preclude use of heavier, cart-based systems. Portability can improve productivity in rough terrain. The system is easy to pack and can ship with standard regular courier services;
- **Five receivers simultaneously record three orthogonal components of electromagnetic field with near-perfect relative positioning among receivers.** Multicomponent, multi-axis design reduces number of soundings for target characterization and relaxes positional accuracy (Grzegorzczuk et al., 2009). Test with low-noise test-stand MPV (first generation) data showed that UXO could be identified with as few as 5 soundings (Barrowes et al., 2007). This was confirmed at YPG and Camp Beale.
- **Magnetic soil can be detected and mitigated:** The geometric arrangement of receivers and the wide-band time range offer potential for identifying and neutralizing the effect of magnetic soil through techniques developed in SERDP MR-1414 and MR-1573.
- **Fully programmable through field display:** Graphical field-user interface controls acquisition parameters such as transmitter waveform characteristics, duration of excitation, number of measurement cycles, stacking, and recorded time channels.
- **Highly stable EMI components:** Responses are directly predictable using standard EMI theory. Field tests verified that MPV components had imperceptible measurement drift and were largely insensitive to survey conditions.
- **Small target characterization:** Small items have localized, rapidly-varying spatial response. Voltage in an air induction receiver coil is an average of a target scattered field through the face of the loop. Therefore, large receivers tend to “smear out” secondary fields. The MPV’s 8 cm square coils are typically smaller than most multichannel sensors (e.g., Geonics EM-63 has 50 cm loops and TEMTADS has 25 cm) and thus better suited to detecting and sampling signals from small targets.

The MPV has some limitations. Because there is only one transmitter, multiple soundings must be collected to characterize a target. Therefore the MPV requires (1) an accurate positioning system for cued interrogation and (2) manual intervention to move the sensor, which reduces productivity relative to a multitransmitter platform for which a single sounding is often sufficient.

4.0 PERFORMANCE OBJECTIVES

The MPV studies presented herein cover data collection and data analysis for classification. The performance objectives were similar for the YPG Blind Grid and the Camp Beale site. The classification problem was relatively more difficult at the YPG test site than at a live site because of the low clutter rate and the large number of target types. Results are presented in Table 1. Success is indicated in the “Results” column with a bold font to help readability.

Table 1. Performance objectives.

Performance Objective	Metric	Data Required	Success Criteria	Results
Quantitative Performance Objectives				
Detection of all munitions of interest	Percent detected of seeded items	<ul style="list-style-type: none"> Location of seeded items Prioritized dig list 	YPG only: Probability of detection (P_d) \geq 0.90	Pd=1 within 0.3 m depth and Pd=0.90 within 1 m
Correct classification of munitions	Rate of identified munitions	<ul style="list-style-type: none"> Prioritized dig list 	Probability of correct UXO classification (P_c): YPG: P_c \geq 0.90 Beale: P_c \geq 0.95	YPG: P_c>0.90 Beale: P_c=1
Reduction of false alarms	Number of false targets eliminated at a specified confidence level	<ul style="list-style-type: none"> Prioritized dig list with probabilities Validation data for all selected targets 	Reduction of false alarms by more than: <ul style="list-style-type: none"> 50% at YPG 40% at Beale 	YPG: 40% and 25% (0.3 and 1 m) Beale: over 80%
Location accuracy	Average error and standard deviation in northing, easting, and depth for validated anomalies	<ul style="list-style-type: none"> Validated targets surveyed with 1 cm accuracy Estimated location from data analysis 	YPG: ΔN , ΔE and ΔZ <0.25 m Beale: ΔN , ΔE <0.05 m and ΔZ <0.10 m	YPG: ΔN, ΔE and ΔZ <0.05 m Beale: ΔN, ΔE <0.10 m and ΔZ <0.05 m
Production rate	Acreage of data collection per day Time required to analyze each target	<ul style="list-style-type: none"> Log of field work and data analysis time accurate to 15 minutes 	Survey: 100 anomalies per day Preprocessing time: 3 minutes per target	YPG: 100 targets/day Beale: 90 targets/day Beale: Data preparation of 5 minutes/target
Qualitative Performance Objectives				
Field usability		<ul style="list-style-type: none"> Feedback from field technician Training time Rate of anomalies requiring resurvey 		<ul style="list-style-type: none"> Easy operation Difficult trouble-shooting/maintenance Quick training Resurvey: 0 at YPG, 1% at Beale

4.1 OBJECTIVE: DETECTION OF ALL MUNITIONS OF INTEREST

Detection was only tested at YPG. The objective for a handheld sensor was to detect shallow targets. The objective was met with 100% detection of munitions within 0.3 m depth and 90% within 1 m depth. Note that some targets were also detected beyond 1 m depth. There was no false detection from any nonmetallic object.

4.2 OBJECTIVE: CORRECT CLASSIFICATION OF MUNITIONS

All shallow munitions should be recommended for excavation. This objective relied both on data collection and analysis. It required that sufficient, high-quality data would be collected, and that the ensuing data analysis, inversion, and classification process identified munitions. The

objective was met at both sites: 95% of the seeded munitions were identified within 0.3 m depth and 90% between 0.3-1 m at YPG (100% of detected targets); Camp Beale had 100% success.

4.3 OBJECTIVE: REDUCTION OF FALSE ALARMS

The ultimate goal of classification is to identify all potential munitions and leave a maximum of clutter. Our initial goal was a clutter rejection rate of 40-50%. At YPG that objective was not realistic as the clutter-to-munitions ratio was orders of magnitude larger than at a live site. The reported clutter rejection rates were 40% at 0.3 m depth and 25% beyond, which is acceptable—difficulty of classification is compounded by the large number and variety of munitions (14 potential types instead of three to five, typically). The results at Camp Beale are promising with over 80% clutter rejection at stop-dig point.

4.4 OBJECTIVE: LOCATION AND DEPTH ACCURACY

Classification relies on reliable target-parameter extraction, including target location and depth. Accurate prediction of target location and depth is also important for safe and efficient remediation. The objective was met at both sites as target location and depth were predicted within 0.1 m, which is less than half the width of a typical shovel blade for all munitions.

4.5 OBJECTIVE: PRODUCTION RATE

Cued interrogation survey and data analysis should be quicker than excavating every potential target. Here the productivity objective focused on the specific tasks of data collection and data preprocessing (before geophysical inversion). The latter task included digitizing field notes, consolidating all soundings for each anomaly, inferring sensor position with GPS or beacon, merging with electromagnetic data and correcting for background and transmitter current intensity.

The objective was to characterize 100 anomalies per day with a mean preprocessing time of 3 minutes per target. The averages were 100 anomalies per day at YPG and 90 at Camp Beale, where the number of soundings per anomaly was increased from seven to 12 to ensure sufficient spatial coverage and frequently sample the geologic background. Preprocessing time was generally slower because the process was still experimental. At Beale the treatment of soil response added post-survey QC tasks to validate background soundings against a soil model; beacon verification procedures also had to be revised to accommodate complex terrain.

4.6 OBJECTIVE: FIELD USABILITY

Field usability consisted of qualitative assessment of the technology by field users. This objective is important for industry adoption. It was found that it was generally easy to set up and operate the technology; ergonomics and maneuverability were adequate though the DAQ/power backpack felt too heavy; hardware seemed resilient to field use though some connectors were weak; troubleshooting and field maintenance were difficult and vastly relied on the sensor manufacturer. Details are presented in Section 8.5.

5.0 SITE DESCRIPTION

This section provides a brief summary of the conditions in which the demonstrations took place at YPG and former Camp Beale. Further information can be found on the U.S. Army Environmental Command website (<http://aec.army.mil/usaec/technology/uxo01.html>) for YPG and the Site Inspection Report for Beale.

5.1 SITE LOCATION AND HISTORY

The first site was chosen as a standardized validation site for DoD and the second by ESTCP in the context of the Live-Site Demonstration program as the next in a progression of increasingly more complex sites for demonstration of the classification process. The YPG Standardized Test Site is located near Yuma, AZ. The site was chosen over Aberdeen Proving Ground mostly for weather considerations to maximize the chance of favorable conditions in October. Three areas were surveyed at YPG: the calibration lanes are set for training and contain a wide selection of targets whose type and location are known to the demonstrators. The blind grid is used for testing. The desert extreme area is covered with desert-type vegetation and used to test the performance of different sensor platforms in a more severe desert environment. The calibration lanes and blind test grids measure 30 m by 40 m and 40 m by 40 m, respectively. The desert extreme area is located southeast of the open field site and has dimensions of 50 m by 100 m.

The Camp Beale site is located near Marysville, CA, and was selected for demonstration because it was composed of hilly open field and forests and it was thought to contain a wide mixture of munitions. These features increased site complexity and were likely to be encountered on production sites. The tree cover posed a navigation challenge by increasing the difficulty of obtaining accurate GPS readings. The broader former Camp Beale area currently consists of multiple land use property areas. It includes cattle grazing and ranching, some rural residential use, and the central Spenceville Wildlife and Recreation Area. In terms of military use, Camp Beale was selected in 1943 as the site for the West Coast Chemical Warfare School (CWS), and then became in 1945 a point for classification, rehabilitation, and repacking of the CWS materiel. In 1947, the War Assets Administration assumed custody with certain regions being reserved for use by the National Guard. In 1948 the Air Force acquired the land (designated it as Beale Air Force Base) to train bombardier-navigators in radar techniques. By 1956, the Navy began using two of the target areas until 1957, when there was no more need for the bombing areas and ranges. At that time, a large portion of the site (approximately 65,000 acres) was declared excess. The demonstration area spread over 10 acres divided into sub-areas for the MetalMapper, the portable systems, and a combined area where both collected data. An EM-61 cart surveyed all three sub-areas at 100% coverage. The 50-acre demonstration site is shown in Figure 4 with the extent of the three sub-areas shown. Shape files delineating the final sub-area boundaries are available from the ESTCP Office.

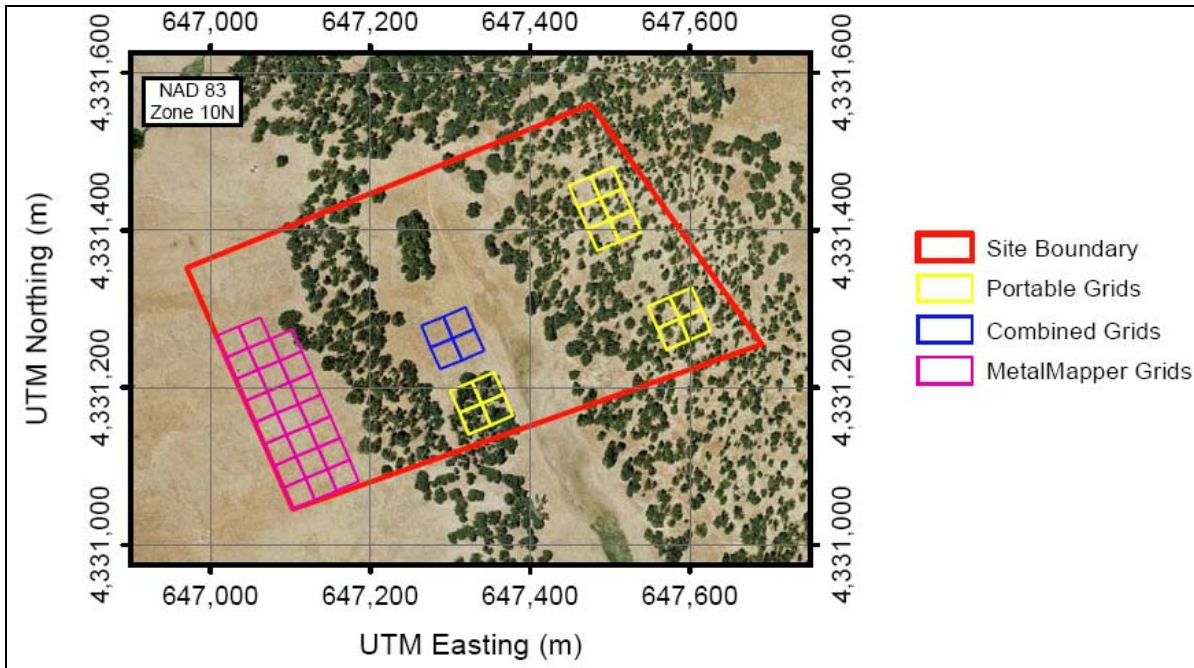


Figure 4. Camp Beale site overview with delineation of survey grids for each sensor type.

5.2 SITE GEOLOGY

The YPG site is located in the desert and consists of sand and pebbles with minimal effect on an EMI sensor. Minimal information was available for Camp Beale, though red soils were noticed during the site visit. Red soils are often magnetite rich and can therefore affect EMI sensors.

5.3 MUNITIONS CONTAMINATION

The YPG site contains a wide selection of standard projectiles, mortars, rockets and submunitions: 155 mm, two types of 105 mm, 81 mm, 2.75-inch, 60 mm, 57 mm, 37 mm, 40 mm, 20 mm, M75, BDU28, M42, and BLU26. The calibration portion of the test site consists of 19 lanes, most of which containing six identical munitions buried in various orientations and at three different depths. There are also steel spheres buried at a depth of 0.5 to 2 m, circular steel plates buried at 0.3 m and 0.9 m, copper wire hoops of various diameter and gauge at 0.3 m depth. The first and last opportunity of each Calibration Lane contains a 3.6 kg steel ball buried at 15 cm to provide a uniform signature that can be identified when looking at raw data. Any of these items could be encountered on the Blind Grid.

At Camp Beale, the particular demonstration area showed evidence of 81 mm mortars and 105 mm projectiles that were found during the Site Inspection intrusive investigation in 2005. It was also suspected that 60 mm mortars may be present, as well as 37 mm projectiles that had been found scattered throughout the former Camp Beale. Due to the complex historical usage of this site over many years and the overlapping network of historical ranges throughout, it was also likely that other munitions types beyond those listed above may be encountered. The principal list of targets of interest (TOI) comprised of 105 mm, 81 mm, 60 mm, 37 mm, and industry standard object (ISO) (1.25-inch steel cylinders).

6.0 TEST DESIGN

The goal of the study was to demonstrate and characterize detection and discrimination with the MPV. Sensor discrimination performance was characterized as a function of the size and depth of the buried targets and the presence and effect of aggravating factors (nearby object, magnetic soil, and complex terrain). This section describes data collection and analysis.

6.1 CONCEPTUAL EXPERIMENTAL DESIGN

At YPG, the Calibration Lanes were used to define survey protocols for detection and cued interrogation. The survey method consisted of a one-pass survey in which a detection search is performed until an anomaly is detected and approximately localized, at which point the search is momentarily interrupted for cued interrogation, where a series of five to 10 static soundings are acquired on top of and around an anomaly. Key parameters such as time ranges, detection threshold, and number of soundings for cued survey were tested. Given that the target type, location, and depth were known, sensor performance could be immediately evaluated. The data were analyzed, inversion parameters were tested, classification strategies were assessed, and classifiers were trained. The calibrated procedures were subsequently applied to the Blind Grid, where detection and classification were to be evaluated and scored.

The Camp Beale study focused on classification through cued interrogation. Training was initially performed at a test pit, where data were collected over site-representative targets—37, 60, and 81 mm mortars, 105 mm projectiles, and a 4-inch-long steel cylinder also known as ISO—and scrap buried in at least three different orientations. Calibration was also performed on a daily basis by surveying over an Instrument Verification Strip (IVS), where one instance of the 5 target types was buried. The IVS was emplaced to verify data quality, stability of the target responses and accuracy of beacon positioning.

6.2 SITE PREPARATION

The U.S. Army Aberdeen Test Center (ATC) manages YPG. The test site layout was prepared to test multiple sensor platforms over several years. The calibration and blind areas had all vegetation removed. For Camp Beale the site preparation was organized by the ESTCP Office. Transect surveys were organized to assess target density, demonstration grids were chosen in collaboration with demonstrators, and targets were seeded to increase the number of buried UXO.

6.3 SYSTEM SPECIFICATION

At both sites the MPV was programmed with two different acquisition modes for detection and cued interrogation. Both modes were based on a 50% duty cycle for the transmitter so that the time for excitation and target response recording were equal. At YPG the highest quality data were collected during cued interrogation for classification with 8 ms excitation and time decay, similar to typical MetalMapper parameters—the MetalMapper uses similar technology. Detection was set to a relatively long 2.6 ms excitation to test the possibility to invert the detection data and perform some level of classification. Forty-five logarithmically spaced time gates were recorded for each of the 15 MPV receiver data channels, the transmitter, and the six

beacon receivers. After the YPG demonstration we postulated that late-time information could improve separation between targets of similar size. Therefore we used a longer 25 ms excitation-decay at Beale with 133 time gates.

Local positioning was based on the GPS for detection survey and on the beacon system for cued interrogation (with GPS QC in open field). An Applied Physics 543 orientation sensor was mounted at the far end of the MPV handle to measure azimuth. The three-axis sensor data were also used for verifying the pitch and roll inferred from the beacon measurements. The beacon boom was laid on the ground within 2 m of the interrogated anomaly. Boom orientation was recorded by placing the MPV head at the boom center and lining up the MPV's main direction (Y-axis) with the boom's direction. To facilitate quality checks, the boom was generally oriented in the north-south direction, and when the terrain was sloped, the boom was placed uphill from the flag. After data processing, beacon-derived positions were located relative to the local flag and the geographic North, and subsequently globally-referenced using the supplied GPS coordinates of each flag. A Novatel RTK GPS was also mounted on the MPV handle. It was used to locate preprogrammed flag locations and verify beacon accuracy whenever enough satellites were visible, in particular at the IVS and in the open-field "combined area," where we started the demonstration. The GPS operated at 20 Hertz; its base station was located at a marked monument, whose position was convenient to service the entire site.

6.4 DATA COLLECTION

6.4.1 Scale

At YPG, the Calibrations Lanes had approximately 100 anomalies distributed over 0.3 acres with 2 m spacing. The Blind Grid had 400 1 m H 1 m cells with a potential target over 0.5 acres. Both areas were surveyed in detection and cued interrogation mode.

Beale had 912 targets distributed in four different areas over 4 acres. The combined area had 259 targets distributed over 1 acre in sloped, open field to allow joint testing of MetalMapper surveys. The nearby area had 250 targets over 1 acre of terrain with dense forest and steeper slope. These areas had multiple cases of close targets. The remaining targets were buried in sparsely treed, rolling terrain.

6.4.2 Survey Pattern and Sample Density

At YPG, detection had the field operator walk along preprogrammed straight lines while sweeping the sensor head following an "S" pattern along track with amplitude and period of 0.5-0.6 m for full coverage of 1 m wide lanes. Given 10 Hertz update rates and 0.08 m receiver coils, sweeping speed was kept below 0.5 meters per second (m/s), which corresponds to along-line speed of 0.2-0.3 m/s.

Cued interrogation soundings were collected around the expected target location. At YPG, that location was determined by the detection survey and generally coincided with the center of a cell, whereas at Beale the location was marked by a flag and paint on the ground. Simulations have suggested that a five-point pattern made of the corners and center of a 0.8 to 1 m square centered on an anomaly is sufficient to characterize a buried target (approximately 0.2 m cube

spacing). This approach was successfully applied at YPG. At Beale we found at an early stage that there could be significant offsets between marked locations and peak anomaly. Given that there could also be multiple targets, we adopted a conservative approach by collecting a 3H3 point grid pattern centered on the flag with 0.5-0.6 m station spacing (Figure 5). An additional sounding was collected by placing the MPV sensor head above the anomaly peak at 45°E pitch to stimulate a different excitation direction with high signal while remaining as close as possible to the target. Only one tilt test was performed because it was difficult to keep the sensor steady on its side.

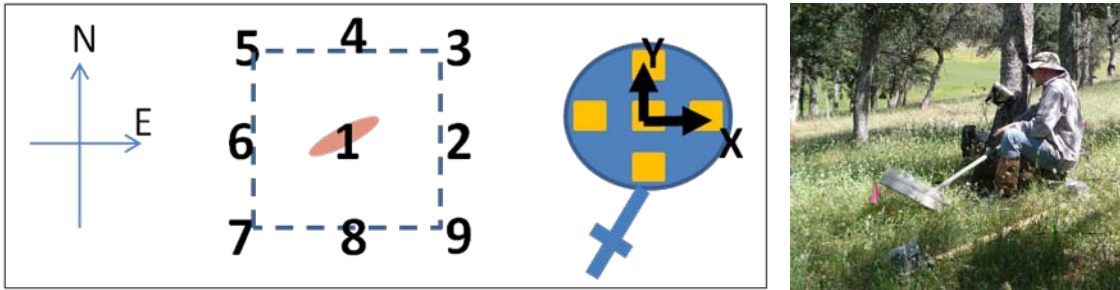


Figure 5. Survey pattern and tilt test for cued interrogation with MPV.

Left: Nine-point survey pattern is centered on target.

Right: Sensor head is tilted with 45°E pitch.

6.4.3 Quality Checks

System checks were performed by surveying the IVS on a daily basis at Camp Beale, while each survey lane started and finished with the same kind of calibration target at YPG. In-air measurements were acquired several times a day to monitor sensor drift relative to battery power. Geologic background had a weak response at YPG, thus requiring occasional sampling only. At Camp Beale the surface material had the distinct red tint of magnetite-rich soil. Significant soil response through viscous remanent magnetization (VRM) was detected due to its typical log-liner time decay effect on vertical and radial receivers. One background sounding was acquired near each interrogated anomaly.

Field soundings were reviewed on the sensor control screen immediately after acquisition. Recorded decay curves were displayed to locate the anomaly, assess spatial coverage, and verify data quality (Figure 6). Sufficient coverage was controlled by verifying that the receivers furthest from the specified target location had weak signal. Otherwise, additional soundings were collected. Detected abnormal soundings were re-acquired and documented in field notes. If a receiver failed, then the survey was interrupted to verify that the failure was persistent and consider solutions. David George, who built the sensor, participated in the surveys and brought tools and spares for repair.

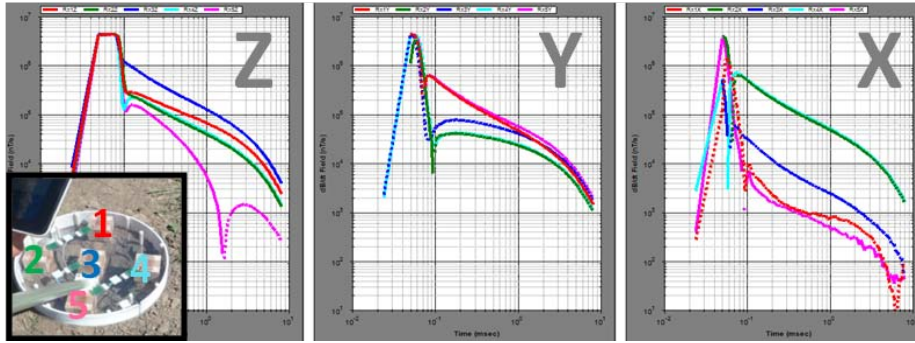


Figure 6. Typical target response above a buried metallic target.

The Z-component data show that the target is closest to center cube (#3) and equally distant from lateral cubes 2 and 4, while signal in 5 seems to be due to background. The Y data confirm that target is buried between front and back cubes (1, 5) and X data confirm that target is located between side cubes 2 and 4.

Data quality was also reviewed after data collection (during the demonstration). Any issue was investigated and potentially problematic anomalies were resurveyed. For instance, we found at Beale that 10 of 912 anomalies had insufficient spatial coverage. This could be due to large target offset, a shrunk survey imprint (operator distraction), or absence of a target at a flag.

Beacon-positioning followed a specific survey protocol. Beacon signals were monitored on the sensor display similar to Figure 6 to detect perturbations or weak signal. Data were preprocessed and visualized onsite, when possible, to infer beacon locations, compare with GPS, and verify accuracy.

6.4.4 Data Handling

Data were stored as .tem files on the DAQ and converted to .csv files before every battery change. A copy of all .tem and .csv files was kept on the DAQ and on portable hard-disk drives. Field notes recorded the association of target identities and file numbers, in addition to any relevant comment for nonstandard events. Notes were digitized every day by taking pictures of the notes and filling out a spreadsheet to be used for preprocessing.

6.4.5 Data Summary

Raw data sets were archived by both SKY and G&G Sciences. Target data comprise of a configuration file and an electromagnetic data file. Files were later merged and preprocessed.

6.5 VALIDATION

Targets were seeded at YPG. Validation at Beale was organized by the ESTCP Office.

7.0 DATA ANALYSIS AND PRODUCTS

7.1 PREPROCESSING

7.1.1 Field Data

The MPV DAQ computer records data streams from the sensor head, beacon receivers, attitude sensor, and GPS with the GPS time stamp. The DAQ saves the data into a .tem binary file. Each sounding data is converted to a .csv file without any data alteration. Several preprocessing stages are performed before delivery to the analysts.

7.1.2 Positioning Data

The beacon receiver data, the MPV transmitter current, and the digital compass reading are combined to infer the MPV head location. The method is similar to a dipole inversion (Lhomme et al., 2011) and generally yields better than 2 cm accuracy. When the GPS has maximum accuracy, its reading and the attitude sensor data can be utilized to predict the sensor head location for comparison with the beacon prediction. In case of aberration with a beacon location, GPS readings and field notes can provide information to diagnose the issue. Otherwise the sounding may be discarded. In practice there was no detected issue with the beacon at Beale.

7.1.3 Preprocessed Data

The preprocessed data were consolidated in individual files, each containing all the data associated with one target: EMI data, beacon-inferred sensor-head location, GPS-derived head location, and nearby background sounding. The EMI data were normalized by the transmitter current to remove EMI data dependency on battery power, which can vary by up to 20%. In-air background was subtracted from the EMI data to remove the transmitter ringing that can still be detected at early time (0.1-0.3 ms). The data were reduced to 25 (YPG) or 32 (Beale) time gates by logarithmic integration (through the same process that had reduced the 4 microsecond signal to the recorded 45 to 133 time gates).

At Beale, a nearby background soil signal, clean of any metallic clutter, was associated to each target for the analyst to devise his own soil correction. One complicating factor was the occurrence of close targets. There were many targets with less than 1 m spacing, sometimes within 30 cm. Under such circumstances the soundings collected between the two neighboring targets could combine responses from both targets. The preprocessed data included the data tiles for both targets to be jointly analyzed.

7.2 TARGET SELECTION FOR DETECTION

At YPG target detection was performed in real time based on the MPV detection window (dancing arrows, signal amplitude and time decay) and verified after completion of data collection by generating a digital map of the recorded dynamic detection data. The calibration lanes were surveyed with detection thresholds based on shakedown tests. The thresholds set the sensitivity of the arrows display to obtain high sensitivity to low amplitude signal using linear scaling, and a logarithmic scaling for larger amplitude to avoid saturating the window with large

responses. The detection rule for the remainder of the survey (blind grid and open field) was defined after evaluation of the calibration lanes, where targets were located and identified. There was a detection survey in this study at Beale.

7.3 PARAMETER ESTIMATION

The preprocessed data were imported in the UXO Lab software that was jointly developed by SKY and the University of British Columbia and used in numerous ESTCP and SERDP projects. Each anomaly was treated separately and generally included five-10 soundings. Data were inverted using a three-dipole instantaneous polarization model. In the EMI method, a time varying field illuminates a buried, conductive target. This illumination, or primary field, induces currents in a target that subsequently decay, generating a decaying secondary field that is measured at by the receivers on the instrument. In the UXO community, it is commonly assumed that the secondary field can be accurately approximated as a point dipole (e.g., Bell et al., 2001; Pasion and Oldenburg, 2001; Gasperikova et al., 2009). The process of estimating the target parameters of the dipole forward model from the data is called data inversion. The objective of data inversion is to determine the parameters that most accurately predict the observed data.

The target parameters include the position, orientation, and polarizability tensor elements. The magnitude and decay of the polarizabilities is a function of the size and electromagnetic properties of the target. Like principal axes of an ellipsoid, the magnitude of the principal polarizabilities (L1, L2, and L3) is indicative of the target shape. If ordering tensor elements such that $L1 > L2 > L3$, then a steel body-of-revolution (BOR) would have $L2 = L3$ for a rod-like object and $L1 = L2$ for a plate-like object.

Inversion setup parameters such as noise estimation were decided upon examination of the training data and background measurements. The main factors affecting data quality are instrument noise, environmental noise, and positional error. The first two mostly depend on the sensor characteristics and on electromagnetic interference with the background host (e.g., magnetic soil at Beale). Baseline background was subtracted from sensor data before inversion; its variability was utilized to estimate expected data misfit errors. Positional accuracy is considered as data quality factor; positional error is equivalent to measurement error in target response. Therefore data errors were parameterized as a floor value plus a percentage of the data amplitude.

Solutions with one or multiple targets were always tested. At highly contaminated sites, anomalies often overlap due to the close proximity of multiple targets. The inversion strategy for overlapping targets was to decompose the inverse problem into several steps. Each step resolved a subset of model parameters. The first step was to solve for nonlinear location parameters and subsequently solve for linear polarization parameters. With an optimal estimate of locations and dipolar polarizations, the orientations and polarizability decays of each object could be extracted from estimated magnetic polarizability tensors. This approach was successfully tested in numerous ESTCP studies. Decisions regarding the number of targets at a given location were automatically decided through statistical classification by prioritizing munitions-like models. Inversion results were reviewed by an experienced geophysicist to identify any potential issues with the inversion setup or the sensor data.

7.4 TRAINING DATA

The classification approach was based on the capability to recognize that a given target had similar features as a known object. The method therefore required a library of known target features to train a classifier. The classification features were the polarizability decays, which are known to depend on target size, shape, and material properties.

At YPG the target library was built on calibration lanes data, which contained 14 different types of munitions as well as clutter. These were buried at various depths and orientations and provided an opportunity to estimate the variance of these features. The YPG library was also utilized at Beale, though its decay range of 8 ms was shorter than the 25 ms decays retrieved at Beale. Training pit and IVS data completed the library. Site-specific training data were also requested for distinctive targets. These were useful to characterize unknown UXO-like objects, understand complex target signatures and diminish the risk of misclassifying unexpected targets. A clustering algorithm was applied to identify re-occurring targets that could require particular attention. The method was based on comparing all recovered polarizabilities with one another and grouping self-similar objects.

7.5 CLASSIFICATION

The classification approach was chosen to address the particular classification question at each site. The following guiding principles were adopted:

- Selection of models in classification: We assumed that classification could be performed in an automatic and repeatable manner. Therefore user input was limited to verifying that acceptable fit to MPV data was achieved. Every model meeting that criterion was considered for classification without further user-dependent pre-screening.
- Selection of features: By analysis of the training data, those features that contribute to separation of the different classes (comprising UXO types and clutter) were selected.
- Choice of classification algorithm: Through analysis of the training data, the best performing classifier was selected. We focused on Support Vector Machine (SVM), which historically had yielded the best results.
- Classification: Anomalies were placed in a prioritized dig-list by using the classifier to compute probabilities of class membership for unlabeled feature vectors.
- Number of UXO-classes: One or more UXO classes could be defined when seeking UXO of widely different sizes. When multiple UXO classes need to be used (assume there are M of them) then one can either train an $(M+1)$ -class classifier, or train M two-class classifiers and combine the results.

Historically, classification was generally based on a combination of a size and a time decay feature for the early ESTCP classification studies. The ESTCP Camp Butner study (MR-201004) showed that new-generation sensors such as the Geometrics MetalMapper could support richer

feature vectors for classification owing to their extended time range and improved recovery of all three polarizability-component decays. Classification was improved by using the polarizability-decay description of target properties. These features could either be compared to library items—through a misfit metric—or be used with a statistic classifier such as SVM, which can accommodate nonlinearity and large feature vectors and can include multiple targets within a given class.

The SVM framework was preferred for both studies. At YPG the main reason was the large variety of munitions types: comparing library misfits and defining thresholds for 14 munitions types seemed more hazardous than grouping similar size targets in four to six classes. At Beale the presence of magnetic soil could produce secondary models accounting for the soil. These models could have similar amplitude and decay as an 81 mm or 105 mm projectile and thus could bias a library misfit, whereas SVM could be systematically trained to dismiss soil models without any manual intervention (a trained geophysicist could eliminate these models during inversion QC). The SVM classifier was trained on each class to separate that class against the other classes and clutter. The SVM classifiers were then applied to all field targets. For each class the SVM statistic indicated the likelihood that a target belonged to that class. Targets could be given priority for digging by sorting the SVM statistic by decreasing order.

The ranked classification anomaly list was formatted as shown in Figure 7. The first items on each anomaly list were the requested training targets. Next were to be those targets for which reliable parameters cannot be extracted and therefore had to be dug. In practice data quality was such that we considered that every anomaly could be analyzed. The list continued with the “high confidence munitions” targets. Items were ranked according to decreasing confidence that the item was hazardous. Any items that were analyzed without reaching an unambiguous classification decision were placed next on the anomaly list. Finally, all items that were confidently classified as nonhazardous were ranked by their confidence.

Rank	Anomaly ID	Decision Statistic	Category	Dig on First Pass	Comment
-9999	2498	-9999	0	1	Can't extract reliable features
1	247	.97	1	1	
2	1114	.96	1	1	High confidence munition
3	69	...	1	1	
...	...	...	2	1	
...	...	...	2	0	Can't make a decision
...	...	...	2	0	
...	...	...	3	0	
...	...	...	3	0	
...	...	...	3	0	
...	...	...	3	0	
...	...	...	3	0	High confidence non-munition
...	...	.03	3	0	
...	...	.03	3	0	
...	...	.02	3	0	
N	...	.01	3	0	

Threshold

Figure 7. Format of prioritized anomaly list to be submitted to the ESTCP Office.

7.6 DATA PRODUCTS

The primary data products were the prioritized dig lists as described above for each site.

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8.0 PERFORMANCE ASSESSMENT

8.1 DETECTION OF MUNITIONS OF INTEREST

The MPV detection survey method tested at YPG was simply based on detecting metallic objects. Having smaller receiver coils and keeping closer to the ground than an EM61 cart survey, the MPV can potentially detect and locate much metallic clutter such as nails and bolts. Therefore the MPV detected equally well munitions and clutter at YPG with over 90% detection of munitions and over 90% false positives, though there was false alarm from background. The relatively high sensitivity to small, shallow clutter could be compensated through data-based logic, such as detection on few receivers and fast time decay. More detection data will be collected in upcoming demonstrations to support clutter-rejection analyses.

8.2 CORRECT CLASSIFICATION AND REDUCTION OF FALSE ALARMS

8.2.1 Stability of the Recovered Target Parameters

Classification relied on comparison with reference target signatures—namely their polarizability decay curves. The inferred polarizabilities for each munitions types are shown in Figure 8 for YPG Calibration Lanes (Blind Grid identity are not available to preserve the test site) and in Figure 9 for field targets at Beale. For both studies the tight distributions of polarizability decay curves indicate that data quality was sufficiently high to recover at least two of three polarizabilities. Predicted models were stable and could support relatively aggressive classification using 2-3 polarizability decays.

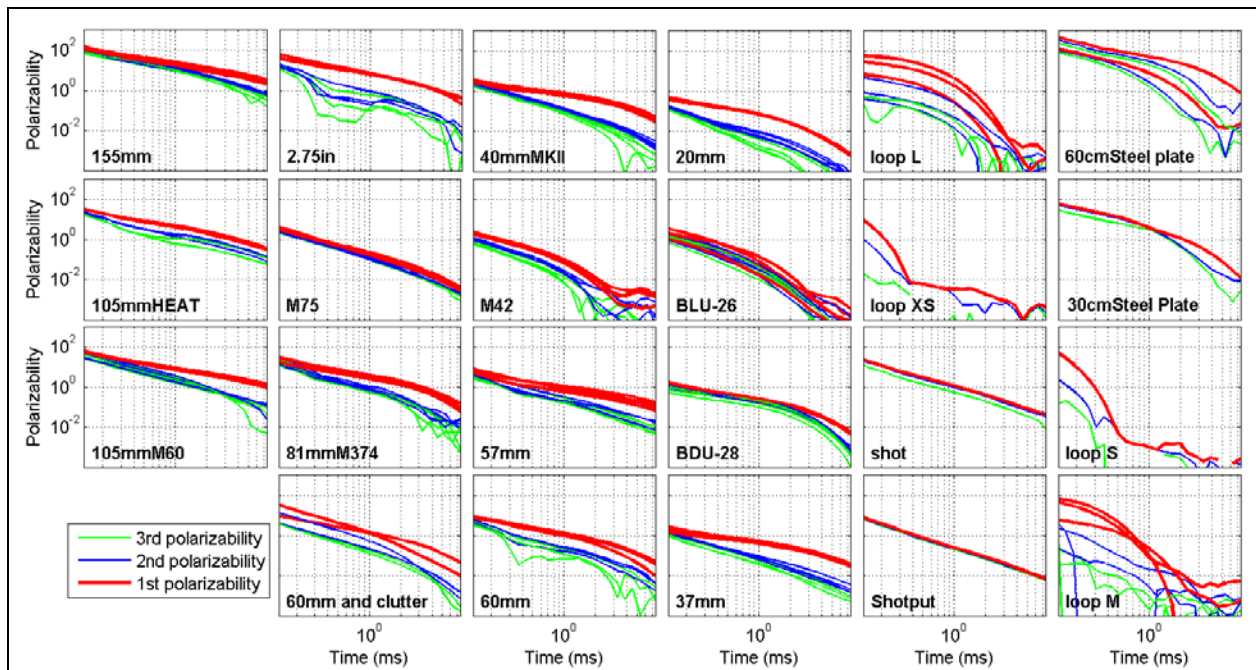


Figure 8. Recovered polarizabilities of training targets at YPG calibration lanes (8 ms decay). Main polarizability (L1) is showed in red; secondary polarizabilities (L2, L3) are showed in blue and green. Results are shown for single-target inversions, hence the parameter variance for “60 mm and clutter.”

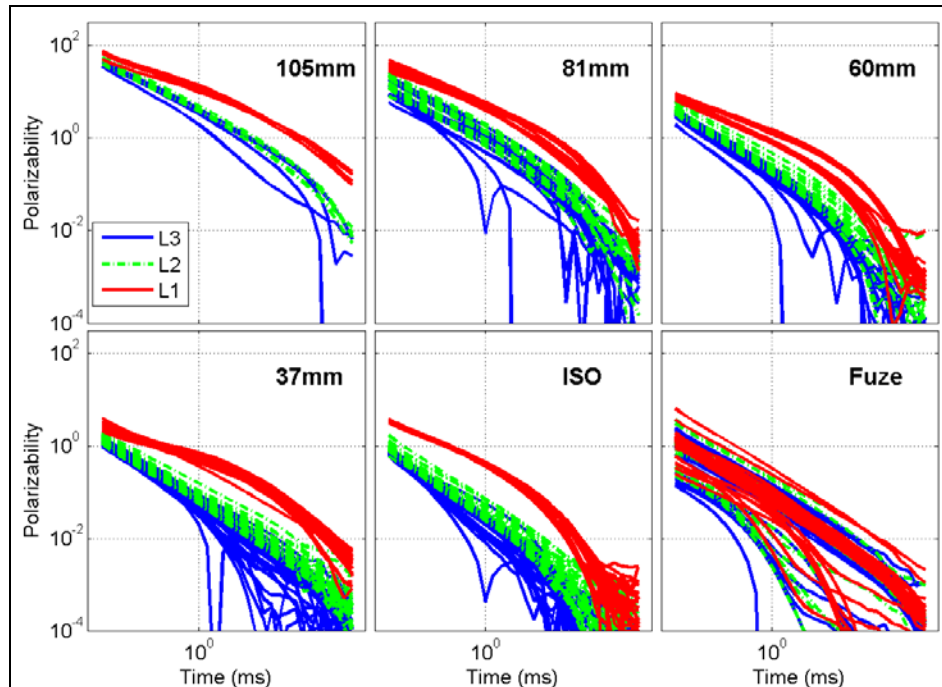


Figure 9. Recovered polarizabilities for Camp Beale field targets (25 ms decay).
 Note several fuze types. Large fuzes were recognized, though no fuze was deemed of interest.

8.2.2 Prioritized Dig List

At YPG, the rate of correctly classifying munitions reached 95% for shallow depth and 90% for medium depth (Table 5 of ATC report). Detection and classification rates were similar; therefore most detected munitions were properly identified. Caliber identification was 88% for small munitions and 57% for medium and large ones (Table 7 of ATC report). The lower rates are explained by the SVM method, in which munitions were grouped in size classes instead of seeking to recognize each individual target type.

For Beale classification performance is illustrated in Figure 10 in the form of receiver operating characteristic (ROC) curves. Note that the presence of fuzes disrupted the classification process, as large fuzes were originally considered as TOI but scored otherwise. All 89 TOI were recovered after approximately 95 pieces of clutter had to be excavated, leaving over 700 items in the ground—88% clutter rejection rate. Efficiency could have been even higher in the absence of fuzes. Having retrained and applied the classifier in a fully automated manner without fuzes, we found that only 48 pieces of clutter would need to be excavated to retrieve all TOI (Figure 10B). The presence of fuzes also promoted a conservative stop-digging point because fuzes tend to have low SNR and less reliable polarizabilities.

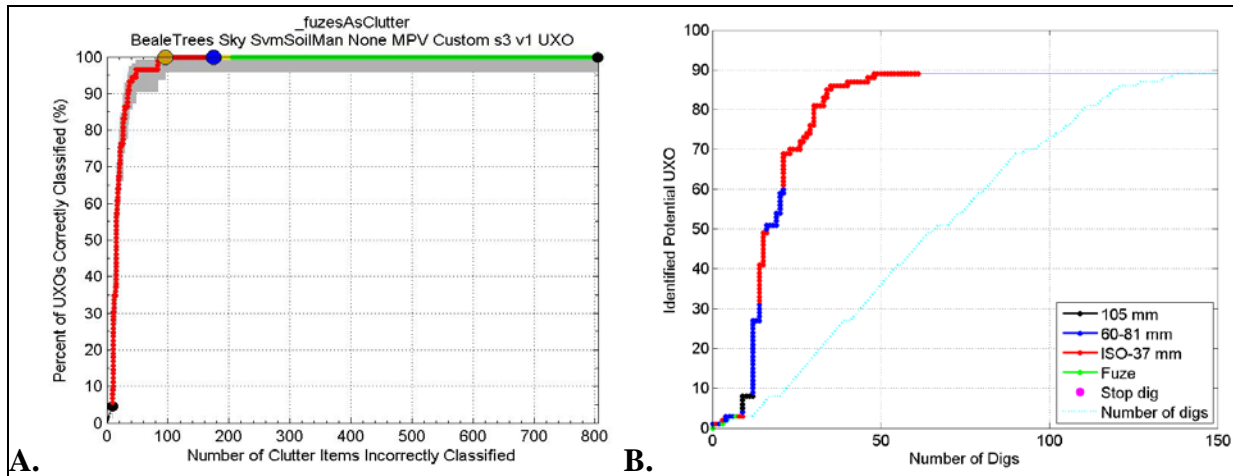


Figure 10. Best ROC curves for SKY analysis of Camp Beale MPV data.

A: Submitted ROC trained to search for large fuzes. “Can’t decide” category (yellow) corresponds to targets that were predicted to be more than 0.5 m away from their associated flag.

B: ROC curve without fuzes.

8.2.3 Data Quality

Success at correctly identifying TOI and keeping low false alarm rate (FAR) suggests that relatively high quality data were obtained with the MPV. The expectation for a handheld sensor is the detection and classification of shallow targets—larger systems can investigate deeper targets through use of larger transmitters and higher power. The YPG demonstration showed that 100% of munitions were detected and 95% were correctly classified within 0.3 m depth. These probabilities remained high at 90% for each stage within 1 m depth. As expected, and by design, performance is much poorer at greater depth. All munitions were buried within 0.45 m at Camp Beale and 100% correct classification was achieved.

8.3 LOCATION AND DEPTH ACCURACY

This section addresses accuracy of the beacon positioning technology for locating the MPV and accuracy of the predicted target location. The former was critical to the Beale demonstration as GPS could not be used as an alternative. Beacon accuracy was tested by comparing predicted positions with GPS and beacon during cued interrogation both at YPG, where open field conditions prevailed, and at Beale, where the IVS and combined area had open sky view. Given the accuracy of the RTK GPS and attitude sensor and their location relative to the MPV sensor head, the head location can be predicted with approximately 2 cm accuracy. Results presented in Figure 11 and in Lhomme et al. (2011) show that similar accuracy was achieved with the beacon, which directly predicts the MPV transmitter location and orientation—azimuth is irresolvable and obtained with the compass heading. In the YPG technical report, we showed that the addition of 2 cm positional and 2° attitude errors had minimal effect on the recovered polarizabilities.

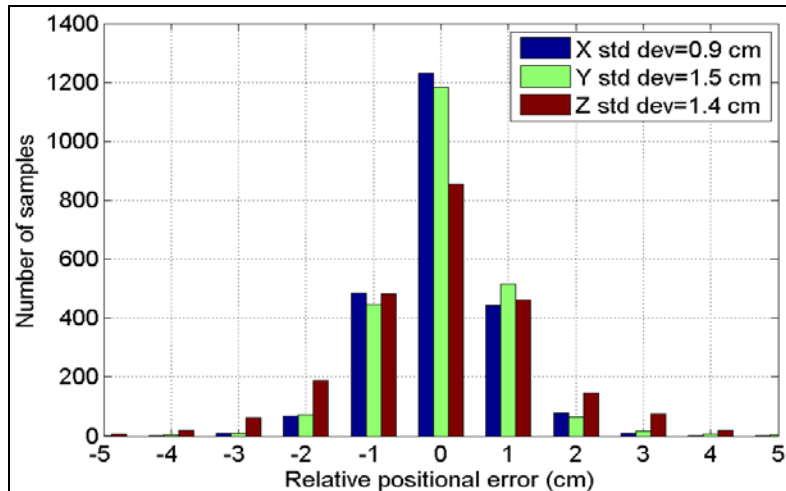


Figure 11. Relative accuracy of beacon positioning system compared with GPS.

The beacon method predicts MPV transmitter location. The GPS and attitude sensor are mounted at the far end of the MPV handling boom and can also be used to predict the MPV transmitter/receiver head location with 2 cm accuracy in open field (1.5 m lever arm).

Relative positional error was compared in open field.

Ability to locate an anomaly source is critical for reliably retrieving target parameters and performing classification. The YPG Calibration Lanes provide ideal conditions for verifying location and depth accuracy since targets were seeded at the center of each cell. Location and depth errors were normally distributed with less than 0.01 m mean and 0.07 m standard deviation. Targets were well-located due the information from horizontal receiver components that sense the crossover in scattered field direction above the anomaly source. At Beale, geographic location was generally correct within 0.2 m, which was satisfactory given survey uncertainty under tree canopy. Depth was matched within 0.05 m for most TOI, with expected larger spread for 81 mm and 105 mm, as their slow decay rates resembled that of magnetic soil.

8.4 PRODUCTIVITY

Ultimately, the time and cost associated with cued interrogation and classification of all detected anomalies and excavation of selected anomalies should be smaller than that of a UXO-technician excavating every anomaly with a shovel. Survey time is determined by the number of cued interrogation soundings and any additional time-consuming field procedure. Classification time depends on the amount of non-automated user input that is required for data analysis.

8.4.1 Data Collection

The original MPV procedure for cued interrogation was based on adaptive sampling of a field anomaly with the assumption that five-six soundings would be sufficient if the anomaly was well located. That approach was successfully applied at YPG, where single targets were seeded at known locations. The survey was not truly adaptive though, since no formal metric was derived after each sounding acquisition. Instead, the operator was instructed to follow a virtual square pattern and add soundings if the signal was found to extend beyond that pattern. Subsequent data analysis showed that as few as three high-fidelity soundings could be sufficient for classification of many targets. Live-site conditions have positional offsets between flags and sensed anomalies

and potential occurrence of multiple targets. At Beale, the standard operating procedure (SOP) was modified to a conservative 9-point grid, which decreased productivity while alleviating reliance on operator. In retrospect we re-inverted the data after selecting only the 5-point square pattern and found that similar classification performance could be obtained. These results suggest that fewer soundings could be collected in future deployments while keeping similar classification performance. The average survey rate at Beale was approximately 4 minutes per target and 90 targets per day. That included moving the equipment, positioning the beacon boom and acquiring one sounding on top of it to register azimuth (30 seconds), collecting 10 soundings with 6.3-second stacks, waiting 2-10 seconds for the sensor display to register each sounding, and collecting and verifying a background sounding (15-20 seconds). Productivity could be improved. Reduction from 10 to 5 soundings per target would save approximately 1 minute, thus increasing productivity by 30%. Depending on environmental conditions, in particular the magnetic soil setting, fewer background soundings could be collected.

Productivity could improve through hardware upgrades. A proper touch-screen monitor wired to the DAQ would reduce lags, instead of the current setup, which relies on the monitor of a Panasonic Toughbook computer or an Apple iPad linked to the DAQ through marginally stable wi-fi network with limited bandwidth remote desktop protocol (RDP). An audible notification after stacks are completed would further speed acquisition by telling the operator to move on. Beacon azimuth registration is time consuming because the MPV head has to be lined up with the beacon boom with great care. At least 20 seconds could be saved and positional accuracy could be improved by installing a dedicated compass on the beacon boom. A standard digital compass with 1E accuracy would be more reliable than a careful operator. This would require minor modifications to the data format to accommodate this new data stream.

8.4.2 Data Management and Analysis Time

Procedures were developed and tested as part of these demonstrations to meet the challenges of handling a new sensor and managing large amounts of live-site data. Therefore productivity was lower than expectations for a more mature system.

Data management took significant time (5 minutes per target). With over 900 targets with 10 soundings per target and two files per sounding, Beale generated approximately 20,000 files for which names, and sequence numbers had to be matched with targets through spreadsheets. This process could be easier with a strict data collection such that file number sequence would be invariable and not rely on manual spreadsheet entries. Though automated, computation of beacon-inferred locations required the analyst to visually compare with GPS predictions until sufficient confidence in the process was gained. The process is now stable and should require less manual QC in the future. Background effects had to be investigated at Beale to characterize their amplitude, variability, and spatial distribution.

At the data interpretation level, methods had to be devised and tested for defeating potential soil disturbance through background compensation and inversion of soil sensitive receiver data. Close targets had to be identified and jointly processed to account for potential interaction and overlapping signals. The task was occasionally complicated by ambiguity on the expected target to be characterized. These cases required manual intervention to mask and interpret the data and apply close scrutiny to inversion results. Specific classification algorithms were implemented

with multistage cascading SVM to seek 14 target types at YPG. The framework was easily transferable to the Beale study, though special methods for automatically identifying and weaning off soil models had to be developed and incorporated. We expect that data processing will be faster for the upcoming demonstrations through use of the numerous algorithms and QC protocols that were implemented as part of this project.

8.5 FIELD USABILITY

Field usability is critical for future technology adoption. It was tested by having the principal investigator (PI) and a field geophysicist trained to set up surveys, program data acquisition parameters, and collect data in detection and cued interrogation mode.

Programming data collection parameters through G&G EM3DAcquire user interface was relatively straightforward. Parameters from previous surveys could easily be adapted and modified to serve a new survey. Survey lines and cued locations had to be prepared before the survey (e.g., in Oasis Montaj or Matlab) and saved in a specifically formatted text file. Programming of the GPS base station was a complex and time consuming task and required use of external communication software such as HyperTerminal. As a result, there was no integrated method for troubleshooting peripheral sensors such as GPS and the attitude sensor. This caused delays in setting up reference coordinates at the beginning of the survey, and further delays when these peripherals were suspected to cause system instability and stop the survey. The problem was particularly acute at YPG, when the MPV's computer had trouble keeping stable communication between its peripherals. This was mostly due to low signals and bandwidth via the wireless network—required for the control display—and volatility of the Windows 7 operating system. At YPG the MPV computer had to be restarted numerous times without any troubleshooting protocol. The problem was mostly resolved for the Beale survey.

Data collection in detection and cued interrogation mode were quickly assimilated and generally resulted in high performance. In detection mode, most metallic targets were found and there was no false detection. Survey conditions were relatively easy on the YPG Blind Grid. However, detection was significantly more difficult in the Desert Extreme area, where the operator was tasked to monitor detection arrows and spatial coverage while keeping the sensor head close to the ground and watching for vegetation and surface relief. This process would benefit from automated alarms for target detection and spatial coverage gaps. High quality data were generally collected in cued interrogation. There was no need to resurvey any anomaly at YPG, where targets were always located at the center of a cell. At Beale the crew was sent to resurvey 1% of the anomalies (10 out of 912 targets). Targets required resurvey because their peak anomaly was significantly offset from the flag location, resulting in insufficient spatial coverage. The current display requires constant focus for the operator to locate detected anomalies; this taxing effort could be relieved with a data gridding display capability.

In terms of hardware, the sensor head was maneuverable with one or two arms and was sufficiently robust not to incur any damage. The backpack with DAQ and batteries felt heavy (approximately 40 pounds), especially at Beale where missing power cables forced use of a metal enclosure with four batteries—instead of no case and two batteries—thus increasing weight by approximately 10 pounds. Receiver cable connectors with the DAQ were fragile: two beacon cables were pulled and damaged at YPG; two MPV receiver cable connectors were

damaged at Beale, causing significant challenge for diagnostic and survey delays of 1.5 days. Although spares will be available for the upcoming deployments, standard troubleshooting procedures have yet to be defined.

Overall the technology is generally reliable and has a strong potential for successful field surveys and classification in future ESTCP Live-Site Demonstrations.

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9.0 COST ASSESSMENT

The figures presented hereafter reflect the costs incurred to date for system maintenance, software modifications and upgrades, shakedown testing, and deployment and analysis of data collected during the Camp Beale demonstration. The costs pertain to a prototype technology and are expectedly higher than commercial operation, as there remained development tasks, sensor data characterization studies, and instrument issues that had to be addressed. Some of the cost will likely decrease as the technology matures, survey procedures get formalized and data QC tools and data processing methods become stable.

9.1 COST MODEL

Time and resources were tracked to assess the cost of deploying the technology for future live sites. The site had particular environmental conditions (active magnetic soil) that required in-depth background noise analysis and testing of alternative parameter extraction and classification strategies for defeating potential noise disturbance. Identification of closely spaced targets was also a new challenge for MPV surveying and required special care at the parameter extraction stage. A cost model is proposed in Table 2 based on field survey with three people, a \$104 hourly rate for all personnel, and interrogation of 912 anomalies over a 15-day period. Costs of planning field deployment, retrospective analysis, and reporting are not included.

Table 2. Cost model for MPV demonstration at former Camp Beale.

Cost Element	Data Tracked During Demonstration	Estimated Hours	Estimated Cost
Instrument cost	Component costs and integration costs <ul style="list-style-type: none"> • Engineering estimates based on current development • Lifetime estimate • Consumables and repairs 	N/A N/A 5 days	N/A \$10,000
Survey cost		400 hours	\$45,000
Mobilization and demobilization	Cost to mobilize to and demobilize from site <ul style="list-style-type: none"> • Travel to town base (time+ticket) • Daily travel to site (time+car rental) 	10 h/ppl/trip 2 hours	\$10,000 \$6500
Pre-survey activities	Before mobilization: Cost of one-time event <ul style="list-style-type: none"> • Sensor verification at G&G workshop 	20 hours	\$2000
	On site: Cost of one-time preparation and testing <ul style="list-style-type: none"> • Programming of GPS • Preparation of target location list • Collection of training data (test pit) 	2 hours 4 hours 3x4 hours	\$200 \$500 \$1500
	Preparation of QC tools: Total cost <ul style="list-style-type: none"> • Hours per anomaly • Personnel required 	40 hours 1 geophysicist	\$4000
Instrument setup costs	Unit: Set up, calibrate at IVS and review data <ul style="list-style-type: none"> • Hours required • Personnel required • Frequency required 	0.3 hours/ppl 2 ppl Daily	\$1500

Table 2. Cost model for MPV demonstration at former Camp Beale (continued).

Cost Element	Data Tracked During Demonstration	Estimated Hours	Estimated Cost
Data collection costs	Unit: Cost of collecting data per anomaly <ul style="list-style-type: none"> Hours per anomaly Personnel required 	4 min 2 field ppl	\$13,000
Preprocessing costs	Unit: Cost per anomaly <ul style="list-style-type: none"> Hours per anomaly Personnel required 	4 min 1 geophysicist	\$6500
Discrimination data processing		255 hours	\$30,000
Data extraction	Unit: Cost per anomaly <ul style="list-style-type: none"> Time required Personnel required 	3 min 1 geophysicist	\$5000
Parameter extraction, including inversion and review	Analysis of local background noise: Total cost <ul style="list-style-type: none"> Time required Personnel required 	60 hours 1 geophysicist	\$6500
	Unit: Cost per anomaly <ul style="list-style-type: none"> Time required Personnel required 	3 min 1 geophysicist	\$5000
Classifier training	Define strategy for defeating soil: Total cost <ul style="list-style-type: none"> Time required Personnel required 	40 hours 1 geophysicist	\$4000
	Unit: Cost per anomaly <ul style="list-style-type: none"> Time required Personnel required 	1 min 1 geophysicist	\$2000
Classification and production of prioritized dig lists	Unit: Cost per anomaly (multiple list stages) <ul style="list-style-type: none"> Time required Personnel required 	3 min 1 geophysicist	\$5000

9.2 COST DRIVERS

The MPV was developed to provide a moderate cost, reliable portable sensor with advanced discrimination capabilities that can operate at sites with challenging surveying conditions. As a portable system, deployment logistics and costs for transport and operation are quite low relative to towed arrays or other vehicular-based systems. The primary costs are incurred for labor and travel for the operators, and the primary cost driver becomes the duration of deployment, directly related to the acreage to be surveyed as well as the difficulty of the terrain (steep, rocky, very uneven, and wooded terrain will take somewhat longer to survey just because it is more difficult to hike across these areas).

9.3 COST BENEFITS

The primary driver for developing the MPV is to make discrimination feasible at a wide range of sites where field conditions prohibit the use of cart-based systems, and for small-scale deployment where a small area needs to be surveyed or where anomalies need to be resurveyed at a lower cost than a cart-based system.

10.0 IMPLEMENTATION ISSUES

Use of the MPV technology is not expected to be affected by any particular regulation. The MPV has low impact on its environment owing to its handheld deployment mode. Though GPS positioning uses regulated radio frequency, there is no reliance on GPS as cued interrogation is supported with the beacon and detection surveys can afford lower spatial accuracy requirements, for instance, with cotton thread and spool.

The original implementation objectives were to prove that high quality data could be collected and support reliable classification, to verify that such performance could be achieved within a handheld form factor that could sustain field use, and to assess viable deployment modes. Detection and classification were clearly demonstrated. Maneuverability and ruggedness were considered to be adequate by our team, though commercial users have not yet been confronted with the technology. The MPV still has fragile hardware parts that can readily be protected. Different survey modes were tested and productivity is expected to improve as the volume of data to collect can be reduced without compromising performance.

The MPV tested in this study is a second-generation prototype built by G&G Sciences. It is not commercially available and only one government-owned unit currently exists, and its maintenance has to be sourced to G&G. Basic components are commercially available—receiver cubes and National Instrument DAQ computer and receiver modules—while receiver filters, transmitter coils and switches, and DAQ software (EM3DAcquire) are G&G custom builds that cannot be replicated or maintained by other vendors. The MPV requires an attitude and heading sensor; there is no standard communication protocol and few models are currently supported, which can incur significant costs if alternative attitude sensors are to be integrated such that they are compatible with EM3DAcquire. Any GPS can be used as long as it is set to send a standardized data sequence (e.g., NEMA formats).

The MPV is relatively straightforward to operate in the field. Field crews were quickly trained to collect data and define basic principles for locating the signal origin and detecting malfunctioning receivers. Note that crews had significant experience with geophysical data analysis, which was useful for immediate review and interpretation of the recorded data. Setting up and troubleshooting communication with peripherals, GPS, and attitude sensor requires experience of less user-friendly tools. Experience with setting up GPS is useful. Troubleshooting DAQ software crashes is currently difficult.

Instructions on survey protocols, such as acquisition parameters and cued survey patterns, are contained in the YPG and Camp Beale reports. General guidance on EM3DAcquire can be found on the Geometrics website for the MetalMapper sensor, which uses similar underlying technology. At this point, we would recommend that an experienced geophysicist be associated with any data collection to guide field operators and frequently verify data quality.

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APPENDIX A

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