# ESTCP
# Cost and Performance Report

(MR-201158)

## Man-Portable Vector (MPV) EMI Sensor for UXO Contamination Assessment at Munitions Sites - Spencer Range and Camp George West

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ESTCP

ENVIRONMENTAL SECURITY
TECHNOLOGY CERTIFICATION PROGRAM

U.S. Department of Defense

# COST & PERFORMANCE REPORT
Project: MR-201158

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## ACRONYMS AND ABBREVIATIONS

| | |
|---|---|
| 3D | 3-dimensional |
| AHRS | attitude heading and reference system |
| ARNG | Army National Guard |
| BTG | Black Tusk Geophysics |
| BUD | Berkeley UXO Discriminator |
| CRREL | Cold Regions Research and Engineering Laboratory |
| DAQ | data acquisition system |
| DGM | digital geophysical mapping |
| DoD | U.S. Department of Defense |
| EM | electromagnetic |
| EMI | electromagnetic induction |
| ERDC | Engineering Research and Development Center |
| ESTCP | Environmental Security Technology Certification Program |
| FAR | false alarm rate |
| FY | fiscal year |
| GPS | global positioning system |
| GW | George West |
| IDA | Institute for Defense Analyses |
| ISO2 | small industry standard objects (second generation) |
| ISOmed | medium size industry standard objects |
| IVS | instrument verification strip |
| mm | millimeter |
| MPV | Man Portable Vector |
| ms | millisecond |
| MRS | Munitions Response Site |
| NDNODS | Non-DoD Owned, Non-Operational Defense Site |
| ROC | Receiver-Operator Characteristic |
| RTK | Real-time Kinematic |
| SERDP | Strategic Environmental Research and Development Program |
| SNR | signal to noise ratio |
| SR | Spencer Range |
| SVM | Support Vector Machine |

## ACRONYMS AND ABBREVIATIONS (continued)

| | |
|---|---|
| TEMTADS | Time Domain Electromagnetic Towed Array Detection System |
| TOI | target of interest |
| UXO | unexploded ordnance |
| YPG | Yuma Proving Ground |

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This project was funded by the Environmental Security Technology Certification Program (ESTCP), project MR-201158. Initial development and testing of the Man Portable Vector (MPV) technology was performed by Kevin O'Neill and Benjamin Barrowes from the Engineering Research and Development Center (ERDC) at the Cold Regions Research and Engineering Laboratory (CRREL) in Dartmouth, New Hampshire, in conjunction with David George of G&G Sciences, through funding provided by Strategic Environmental Research and Development Program (SERDP) project MM-1443. The Spencer Range and George West studies were conducted with the second-generation MPV, a lighter and ruggedized sensor, also fabricated by George but this time as part of ESTCP project MR-201005 (Principal Investigator [PI] Nicolas Lhomme).

The field deployments involved Jon Jacobson, Kevin Kingdon, Tom Ladd, James Gayer, and Lhomme (all with Sky Research at the time; Kingdon and Lhomme are now with Black Tusk Geophysics [BTG]). Most of the data analysis was performed by Lhomme, with Jacobson and Kingdon participating in the classification of cued data for George West. Data processing and analysis was accomplished within the UXOLab software package, a suite of MatLab-based programs for digital geophysical mapping, target picking, inversion of single and multiple sources and classification. The software has been jointly developed by BTG (Billings, Pasion, Beran, Zelt, Kingdon, Lutes and Lhomme) and the University of British Columbia (Song, Sinex and Oldenburg) and funded through various SERDP and ESTCP projects. This report was written by Lhomme and reviewed by Billings.

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# EXECUTIVE SUMMARY

## OBJECTIVES OF THE DEMONSTRATION

Many Department of Defense (DoD) sites are contaminated by munitions and explosives of concern that are difficult to clean up because commercially-available technology is inadequate in forested areas and in rugged terrain. This project demonstrates the Man Portable Vector (MPV), a handheld technology designed to extend the classification performance of the latest vehicle- and cart-based geophysical platforms to sites where vegetation or terrain limit access to these platforms. The MPV technology was evaluated through involvement in two ESTCP live-site demonstrations. The demonstration objectives were to show that the technology could be effectively utilized to map metallic object contamination, and reliably characterize the buried items as, either potentially hazardous munitions and explosive of concern, or non-hazardous shrapnel, range scrap or cultural debris. All pertinent demonstration objectives were met.

## TECHNOLOGY DESCRIPTION

The MPV sensor is a handheld, wide-band, time-domain, electromagnetic induction (EMI) sensor. The sensor head comprises a 50-centimeter (cm) diameter transmitter loop and an array of five receivers that measure the three components of the secondary magnetic fields induced by the transmitter. The MPV is field-programmable through a user interface that also provides immediate data feedback for quality control and target localization. The technology was initially tested by Engineering Research and Development Center (ERDC)-Cold Regions Research and Engineering Laboratory (CRREL) in SERDP project MM-1443 (O'Neill and Barrowes). The second-generation MPV demonstrated here was specially designed to improve maneuverability and ruggedness and was tested through ESTCP project MR-201158. Both MPVs were fabricated by G&G Sciences (George). Generally operated by a two-person team, the MPV can be utilized in dynamic survey mode to map and locate potential targets, and in cued interrogation mode to characterize detected items. In cued mode, the sensor is placed at multiple locations to provide different "looks" at the buried target and is kept stationary to maximize data quality. The multiple soundings collected in cued-mode are jointly interpreted through geophysical inversion, which requires accurate positioning for accurate recovery of intrinsic target parameters. The accuracy of standard positioning methods, such as global positioning system (GPS) and roving laser rangers, may be compromised by thick canopy or the presence of obstacles. The MPV overcomes this limitation with a dedicated, local positioning system based on a portable receiver station that monitors the primary transmitter field from the MPV—like a beacon. This feature returns relative location estimates with centimeter-level accuracy out to a range of 4 meters and thus provides accurate positioning in most environmental conditions, including dense forest and under thick forest canopies.

This project included two demonstrations. The first one was conducted at the former Spencer Artillery Range near Spencer, Tennessee in June 2012. The MPV and a number of other advanced sensor technologies were tested on 1.3 acres of a flat open field area, where approximately 300 targets were encountered and classified. Portable systems were also tested in a forest where 700 targets were reacquired for classification. The second demonstration for this project took place with participation of the local stakeholders in October 2012 at the former Camp George West (GW) on the steep sides of Green Mountain in Lakewood, Colorado. MPV

data were collected in both full-coverage dynamic survey mode on approximately 2 acres and in cued-interrogation mode over approximately 500 anomalies selected from the full coverage data.

## DEMONSTRATION RESULTS

The primary performance metrics were the probabilities of detection and correct classification. At Spencer Range (SR), classification of MPV cued-interrogation data resulted in the correct identification of 99% of the buried targets of interest (TOI) with rejection of 85% of the clutter. In most cases, the caliber of the munitions was correctly inferred from the MPV data. One seeded item, which was buried in a "fragmentation pit," was incorrectly labeled as non-hazardous. The dynamic area was surveyed with 95% coverage and detection of all TOI. Classification was applied in two stages. The first stage used dynamic data as a pre-screener and eliminated the need for cued-interrogation on 50% of the anomalies. In the second stage, cued-data were collected and used for classification of the remaining anomalies. Using this hybrid approach, all TOI were found while rejecting 90% of the clutter.

At the GW site, the detection survey achieved 99% coverage and localization of all seeded items. Two independent classification studies were performed: one based on the full-coverage (dynamic) data and the other on the cued-interrogation data. Analysis of the cued data resulted in correct classification and prediction of the target caliber for 100% of the target while rejecting 90% of the clutter. Due to favorable environmental conditions and the absence of any small caliber TOI, analysis of the dynamic data resulted in 98% correct classification and 85% clutter rejection (one target was missed in the dynamic data set due to mislabeling). These results from SR and GW suggest that, under favorable conditions, dynamic data can be sufficient to classify some of the field anomalies without the need for cued interrogations, resulting in further reductions in data collection and analysis costs.

## IMPLEMENTATION ISSUES

The MPV technology has now been successfully demonstrated at four sites in conditions including open field, mountainous terrain and moderately dense forest. The demonstrations proved the concepts of detection and classification with a handheld technology at a prototype stage. The novelty of each study required the presence of an expert geophysicist to overview operations and to provide immediate feedback on the data collection procedures and data quality. Although the prototype may appear to be fragile, surveys were completed without any issues. Troubleshooting would still require intimate knowledge of the sensor. The average daily production rates were 0.6-0.7 acre for detection survey and 125-135 targets in cued interrogation. Detection was most efficient when using a third operator to lay out survey lines.

Efforts toward technology transition have been initiated, with training of three new field operators that successfully collected high quality data. Classification has also been successfully performed by multiple analysts and on different software platforms. Technical documentation on data collection and analysis procedures have been published in demonstration reports (ESTCP MR-201005, 201158). A user manual with standard operating procedures is being written.

New demonstrations are scheduled as part of the ESTCP ongoing live-site demonstration program in project MR-201228. The upcoming sites will test conditions specifically tailored for

the MPV sensor, such as dense forests, and will employ commercial crews to accelerate technology transfer and obtain feedback from seasoned industry professionals.

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# 1.0 INTRODUCTION

This project demonstrates the capability to perform detection classification of buried unexploded ordnance (UXO) at munitions live site with a handheld sensor, the Man Portable Vector (MPV). The MPV technology was designed to extend the classification capabilities of new-generation geophysical platforms to sites with challenging surveying conditions such as forests and mountains, and thus provide a solution for UXO cleanup at most land locations.

## 1.1 BACKGROUND

Decades of training have left millions of acres of UXO-contaminated land in the United States of America. 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. The 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 studies showed that a significant fraction of non-hazardous 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 Department of Defense (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 global positioning system (GPS) and laser ranging by disrupting their line-of-sight requirements.

The MPV was designed for classification in challenging survey environments. The MPV electromagnetic induction (EMI) sensor incorporates new-generation multi-axis receivers, electronics and programmability into a handheld form factor for improved portability. The MPV can be utilized for both detection and characterization (classification) of buried objects. Detection survey consists of full-coverage dynamic data collection to produce a Digital Geophysical Map (DGM) of the munitions contamination. Classification is the characterization of detected objects through extraction of physical attributes from the data. For classification to be reliable the underlying physical attributes extracted from the data must also be reliable. Accurate recovery of these physical attributes requires high quality data that typically need to be obtained through cued interrogation, whereby multiple static soundings are collected near the detected anomaly. Joint interpretation of multiple soundings requires accurate positioning. The MPV is designed for survey at sites where dense canopy or obstacles preclude use of GPS or laser ranging methods. Accurate locations are obtained relative to an MPV-dedicated local positioning system in which a portable base station with multiple receivers monitors the MPV primary field, like a beacon, to locate its origin.

In the ESTCP MR-201158 project, the MPV technology was demonstrated at two different field sites with different survey challenges and different target ordnance. The first demonstration took place at the Spencer Artillery Range near Spencer, Tennessee in June 2012, and the second one on Green Mountain at former Camp George West (GW) next to a residential area in Lakewood near Denver, Colorado, in October 2012. The Spencer Range (SR) study was a large ESTCP demonstration in which the MPV was tested alongside the NRL 2x2 Time Domain

Electromagnetic Towed Array Detection System (TEMTADS), the miniature Berkeley UXO Discriminator (BUD), and two industry-operated MetalMappers. It included a classification study through cued interrogation in a forest (for portable sensors), similar to the former Camp Beale study (Lhomme, 2012), though with higher occurrence of target clusters to increase the classification challenge. The Spencer study also featured a "dynamic area" where the detection performance of multiple sensors was tested in an open field scenario. The survey data were to be quickly assimilated and interpreted to identify potential targets that required characterization. Selected anomalies were interrogated in a cued-mode and then classified. The novelty of the GW study was the rugged terrain setting with a relatively steep slope (Figure 1), and the fact that the entire site characterization effort was based on the MPV. Data were collected with the MPV in different modes for DGM, target picking and classification.

**Figure 1. Detection survey near ravine at George West.**

## 1.2 OBJECTIVES OF THE DEMONSTRATION

The demonstration was designed to establish the detection and classification potential of the MPV relative to non-handheld sensors at SR, and to carry a Pilot Study for a remedial investigation with participation of local stakeholders at Camp GW. This report covers the definition of survey protocols, the data collection and the data analysis efforts. The measured performance is an assessment of the sensor capabilities, the deployment method and the data analysis process.

The data collection objectives include repeatability over the instrument verification strip (IVS), data quality requirements for detection and classification, and field productivity. The IVS data were found to be consistent. The mapping requirement to achieve at least 95% spatial coverage

at Spencer and 98% at GW was met at both sites. The cued interrogation objectives to reacquire anomaly locations for cued interrogation and minimize the number of anomalies that need to be resurveyed or classified as “can't analyze” were also met. The survey rate in detection mode was close to expectation at 0.6-0.7 acre per day. The rate of cued interrogation was 125 anomalies per day at SR and 135 at GW, well above the 100 anomalies per day previously achieved. The higher production rate is the result of an improved system configuration and survey methodology.

The detection objective was to detect all seeded targets. The initial detection lists did not include a small number of seeds that were located close to the survey boundaries or to other selected targets – quality control methods had not been tested, since MPV dynamic data collection and analysis were new processes in this demonstration. However, from a sensor and data collection procedure perspective, all seeds were detected with their signal clearly exceeding the detection threshold. The classification objectives were exceeded with over 98% of targets of interest (TOI) correctly classified and over 85% clutter rejection with static data. In addition, detection (dynamic) mode data were also used for classification and the results exceeded the required performance objectives. The predicted target locations closely matched those of the excavated items.

The detection and classification studies showed that the MPV favorably compared with the other sensors at Spencer. Similar performance was achieved at GW, where the environmental conditions were more difficult with steep terrain, though the UXO problem turned out to be simpler with the absence of any smaller caliber TOI. Results are described in the demonstration reports for each site (Lhomme, 2013a; Lhomme et al., 2013b).

## 1.3 REGULATORY DRIVERS

The Defense Science Board Task Force on UXO noted in its fiscal year (FY) 03 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 non-hazardous 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.

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# 2.0 TECHNOLOGY

The MPV technology is based on electromagnetic induction sensing and use of multiple vector receivers in a handheld form factor. The sensor demonstrated in this ESTCP project is the second-generation prototype MPV.

## 2.1 MPV TECHNOLOGY DESCRIPTION

### 2.1.1 Electromagnetic Sensor

The MPV is a handheld wide-band, time-domain, EMI sensor. The sensor head is composed of a single transmitter coil and an array of five receiver units that measure all three components of the secondary magnetic fields induced by the rapid shut-off of the primary field of the transmitter (Figure 2). This second-generation MPV is specifically designed to (1) be man portable and therefore easy to deploy in sites unsuited to cart based and vehicular towed sensors, 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 illuminates the subsurface with a time-varying magnetic field. Five receiver units (cubes) measure the three orthogonal components of the transient secondary magnetic field through three air-induction 8-cm square coils.

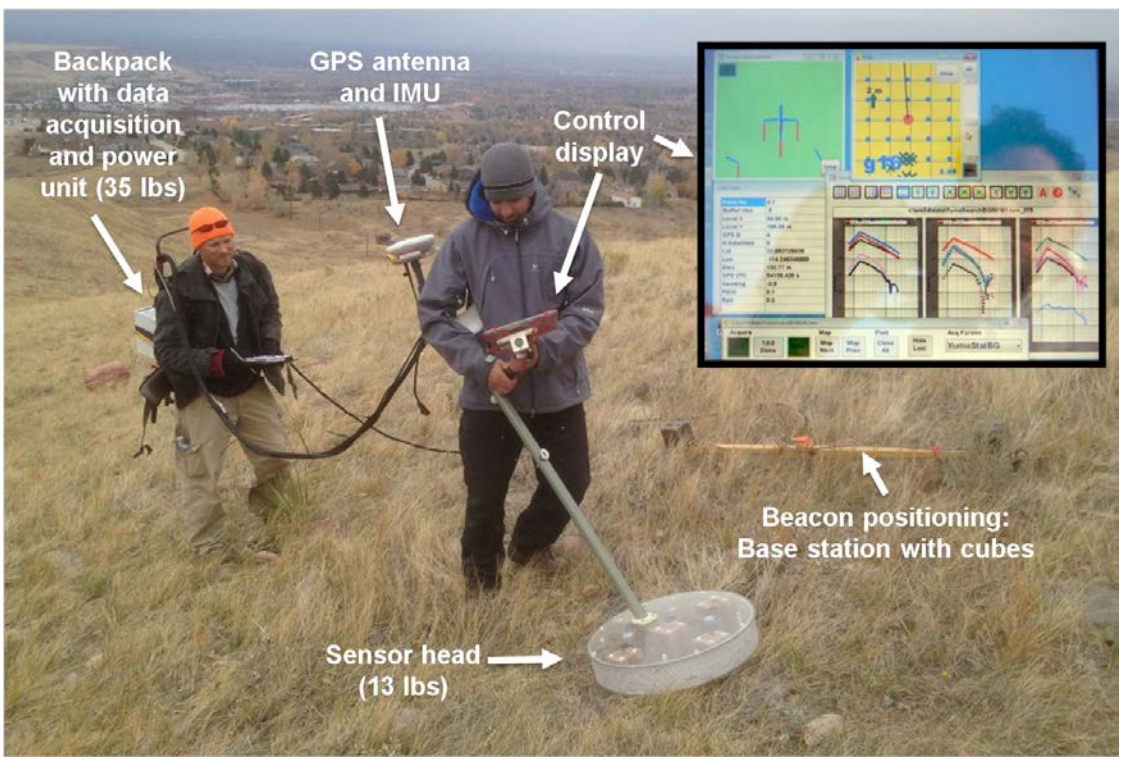


**Figure 2. MPV technology description for George West study in October 2012.**
The sensor head is made of a transparent disk that contains a circular transmitter wound around the side and five 3-dimensional (3D) receiver cubes. A touch-screen display controls survey parameters and acquisition events (right inset). The data acquisition system and batteries are mounted on a backpack frame carried by the second operator. Positioning can be achieved with GPS (only in open field) or a beacon boom (cued interrogation).

The MPV may be configured for specific survey needs. Duration of excitation and time decay recording can be adjusted for the specific data quality requirements of detection and classification. Short EMI transmit-receive cycles are applied for detection mapping so that the sensor can continuously move with minimal smearing of the targets response (e.g., 1 millisecond [ms] time decay, similar to the Geonics EM-61). Data quality may not always be sufficient to retrieve reliable parameters for classification. In such cases a target is reacquired in a "cued interrogation" survey, where data quality is maximized by longer duration and stationary measurements over the detected target. Longer EMI cycles are applied to recover characteristic time decay rates (e.g., 25 ms), as late-time information can 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 13 pounds and the backpack-mounted data acquisition system (DAQ) and batteries weigh approximately 35 pounds. Existing sensors with multiple time-channel measurement capabilities (e.g., BUD, TEMTADS) are required to be mounted on a cart platform or carried in a litter due to the size and weight of the multiple coils of wire required for the transmitters and receivers.

The MPV interface includes real-time data monitoring capabilities. Recorded data can be displayed to verify data quality and potentially detect disturbances from magnetic soil or a damaged receiver. Past and present sensor locations are 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 the top left corner of control display, Figure 2 inset).

### 2.1.2 Geolocation

The sensor requires geo-located EMI data for detection and classification, though with different spatial accuracy requirements. A field survey with the MPV can therefore utilize two complementary positioning systems. Detection mapping has decimeter accuracy requirements; it 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 centimeter-level sensor positioning when surveying a target (Bell, 2005). Being designed to extend UXO classification to difficult survey environments, the MPV technology includes a local positioning system that remains accurate in steep terrain and under thick tree canopy, where GPS positioning is unreliable and potentially inaccurate. The beacon positioning system (San Filippo et al., 2007; Lhomme et al., 2011a) locates the origin of the MPV transmitter with a pair of EMI receivers rigidly attached to a portable beam that serves as a base station (Figure 2). The horizontal and vertical location of the center of the MPV head and its roll and pitch can be predicted from the beacon measurements. The heading is provided by a three-axis attitude sensor (XSens MTi) that also records roll and pitch, which in turn can be compared with the predicted roll and pitch for quality control. Field trials showed 1-2 cm and 1-2 degrees accuracy for position and roll-pitch – similar to GPS and attitude sensors – out to distances of 3-4 m away from the beacon boom.

## 2.2 TECHNOLOGY DEVELOPMENT

The MPV project was initiated in 2005 under the SERDP Project MR-1443. The project was led by Drs. Kevin O'Neill and Benjamin Barrowes with the Cold Regions Research and Engineering Laboratory (CRREL) of the Engineering Research and Development Center (ERDC) in Dartmouth, New Hampshire. The first MPV prototype was fabricated in 2005-2006 by David George of G&G Sciences, Grand Junction, Colorado. It was tested in 2007 at ERDC facilities, where data collected in a laboratory setting suggested a strong potential for UXO classification.

The SERDP project was extended in 2008 and 2009 to continue testing with involvement of Black Tusk Geophysics (BTG) personnel. Field trials were performed to assess static and dynamic acquisition mode over buried targets in a test plot and stable target parameters were recovered. Data collected in the presence of magnetic soil were studied to show that the adverse soil effects could be mitigated owing to the MPV's array structure. The original positioning system – the ArcSecond laser ranger – proved to be impractical for field application and an alternative positioning system was tested in 2009 with the beacon concept. The sensor head was redesigned in preparation for field deployments with lighter materials and a smaller head diameter to reduce weight and improve maneuverability while maintaining expected classification performance.

Funding was obtained in 2010 under ESCTP MR-201005 to continue developing the MPV and conduct field demonstrations. Fabrication of the second-generation prototype was completed. The MPV was successfully demonstrated at Yuma Proving Ground (YPG) UXO test site in October 2010 and at former Camp Beale in June 2011. High detection and classification rates – comparable to existing EMI sensors designed for UXO classification – were achieved (Lhomme 2011b, 2012).

## 2.3 ADVANTAGES AND LIMITATIONS OF THE MPV TECHNOLOGY

The MPV is the only available handheld sensor that can acquire multi-static, multi-component data on a wide and programmable time range. Key benefits include:

- *Hand-held form factor:* Deployable at sites where terrain and vegetation preclude use of heavier, cart-based systems. Portability improves productivity in rough terrain. System is easily packable and transportable;
- *Five receivers with three orthogonal components:* Multi-component, multi-axis design reduces number of soundings for target characterization and relaxes positional accuracy requirements for classification;
- *Magnetic soil effect:* The geometric arrangement of receivers and the wide-band time range offer potential for identifying and neutralizing the effect of magnetic soil (techniques developed in SERDP MM-1414 and MM-1573);
- *Fully programmable in field:* Acquisition parameters such as duration of excitation, number of measurement cycles, stacking and recorded time channels can be modified;

- *Stable EMI components:* MPV components have imperceptible measurement drift and are largely insensitive to changing environmental conditions (temperature, humidity etc); and
- No line-of-sight limitations and accurate positioning in most environments using the beacon.

Portability has two main limitations:

- *Cued interrogation:* With a single transmitter, multiple soundings must be collected to characterize a target. Therefore, the MPV requires (1) an accurate positioning system and (2) manual operation to move the sensor, which reduces productivity relative to a multi-transmitter platform for which a single sounding is often sufficient; and
- *Detection:* Small sensor footprint requires a side-sweep survey or a large number of narrow survey lines.

## 3.0 PERFORMANCE OBJECTIVES

This project includes data collection in dynamic detection and cued interrogation, data analysis and user feedback for evaluation of the MPV technology at SR and GW. The specific objectives for each stage are detailed in Table 1.

**Table 1. Performance objectives.**
Results show SR-GW measures.

| Performance Objective | Metric | Data Required | Success Criteria | Results |
|---|---|---|---|---|
| **Data Collection Objectives** | | | | |
| Spatial coverage in detection survey | Extended footprint coverage | Mapped survey data | Coverage of 95% at SR and 98% at GW | 95% (SR) - 99% (GW) |
| Repeatability of IVS survey | Amplitude of EM anomaly<br>Amplitude of polarizabilities | Twice-daily IVS survey data | Factor 3 on detection amplitude and target polarizability | Detection: Amplitude within factor 1.2<br>Cued: Size within factor 1.1 |
| Detection of all TOI | Percent detected of seeded anomalies | Location of seeded items<br>Anomaly list | 100% of seeded items detected | 100% of seeds were detectable;<br>four seeds were omitted by analyst |
| Production rate | Acreage and number of cued anomalies;<br>Pre-processing time | Log of field work and data pre-processing time | GW: 0.8 acre/day in survey mode<br>100 anomalies/ day in cued mode<br>Pre-processing time <3 min per target | 0.6-0.7 acre per day<br>125-135 anomalies<br>2.5 min processing |
| **Analysis and Classification Objectives** | | | | |
| Maximize correct classification | Number of TOI retained | Ranked dig list<br>Scoring reports by IDA | Approach identifies presence of 95% of TOI | Dynamic: 100-98%<br>Static: 99-100% |
| Maximize correct classification of non TOI | FAR | Ranked dig list<br>Scoring reports by IDA | Reduction of clutter digs by 75% | Reject over 85% of clutter for dynamic and static data |
| Minimize number of unclassifiable anomalies | Number of "Can't Analyze" in classification | Ranked dig list | Reliable parameters for at least 95% of anomalies | Over 99% anomalies were classified |
| Correct location and depth of TOI | Accuracy of estimated target parameters for seed items | Results of intrusive investigation<br>Predicted location | $\sigma Z < 0.10\ m$<br>$\sigma$N and $\sigma$E < 0.15-0.30 m | $\sigma Z < 0.05\ m$<br>$\sigma$N+$\sigma$E < 0.2-0.1 m |

EM = electromagnetic
FAR = false alarm rate
IDA = Institute for Defense Analysis

## 3.1 OBJECTIVE: SPATIAL COVERAGE FOR DETECTION

Dynamic detection survey should cover a maximum of the area of interest so that all detectable targets are illuminated. Targets are detectable if the transmitted field is sufficiently strong to reach the target and if the measured target response is sufficiently strong in return to exceed a given threshold. Simulations suggest that there is negligible loss of detectability when a target is located 10 cm to the side of the MPV (Appendix C).

### 3.1.1 Metric

The survey footprint is compared with dynamic survey surface area. In practice, the geographical coordinates of MPV receivers are binned in 20-cm square cells. The ratio of the number of non-empty cells and the number of cells in survey area provides the rate of coverage.

### 3.1.2 Data Requirements

The geographic coordinates of the survey perimeter and the survey track are utilized.

### 3.1.3 Success Criteria and Result

The project team met the expected 95% at SR and exceeded the 98% requirement at GW with 99%.

## 3.2 OBJECTIVE: REPEATABILITY OF INSTRUMENT VERIFICATION TESTS

Reliability of survey data depends on the stability of survey equipment. This objective concerns twice-daily verification on a test strip where metallic targets will be buried. The IVS is surveyed in detection mode during the detection survey. The IVS targets are surveyed in cued interrogation during the entire demonstration.

### 3.2.1 Metrics

The amplitude of the MPV data over a target and the magnitude of the polarizability components span multiple orders of magnitude. The metric for detection relates to the amplitude of the maximum target response, defined as the norm of the total field on a cube at 0.5 ms. The metric for cued interrogation is the target size, here defined as the norm of the polarizability components also for the 0.5 ms time channel.

### 3.2.2 Data Requirements

The IVS survey data were recorded and analyzed.

### 3.2.3 Success Criteria and Result

The objective was that target response amplitude and size remained within a factor 3 of their mean value. For dynamic data the response was within better than a factor 2 (1.2 in general). The size factor for cued data was within a factor 1.5 (within 1.1 in general).

## 3.3 OBJECTIVE: DETECTION OF ALL TARGETS OF INTEREST

Target detection depends on signal intensity, spatial coverage and the target picking method.

### 3.3.1 Metric

The metric for this objective is the percentage of seed items that are detected using the specified anomaly detection threshold.

### 3.3.2 Data Requirements

The demonstrator submitted a detection list that was compared to seeded items locations.

### 3.3.3 Success Criteria and Result

The objective was to detect 100% of the seeded items. All seeds were detectable in the data, as their signal exceeded the threshold. However, two seeds were not selected at SR because their picked location lay outside of the survey boundary; one seed at SR and one at GW were not explicitly selected and were merged with a nearby target because their anomalies overlapped.

## 3.4 OBJECTIVE: PRODUCTION RATE

This objective concerns data collection and pre-processing time.

### 3.4.1 Metric

This objective is measured by the mean daily acreage for dynamic survey and number of targets for cued interrogations, and the mean pre-processing time per anomaly.

### 3.4.2 Data Requirements

Acreage, number of interrogations and pre-processing time were recorded every day.

### 3.4.3 Success Criteria and Result

The expected daily production rate at GW was 0.8 acre and the project team achieved 0.7 acre. The expected cued interrogation daily rate was 100 anomalies and the project team interrogated on average 125 and 135 anomalies at SR and GW, respectively. The pre-processing time was less than 3 minutes per anomaly as expected.

## 3.5 OBJECTIVE: MAXIMIZE CORRECT CLASSIFICATION OF TOI

This is one of the two primary measures of the effectiveness of the classification approach. This objective concerns the component of the classification problem that involves correct classification of TOI. Detection (dynamic) and cued (static) data were independently analyzed to produce prioritized dig lists.

### 3.5.1 Metric

The metric for this objective is the number of items on the anomaly list for a particular sensor that can be correctly classified as TOI by each classification approach.

### 3.5.2 Data Requirements

Each demonstrator prepared a ranked anomaly list for the targets on the sensor anomaly list. IDA personnel used their scoring algorithms to assess the results.

### 3.5.3 Success Criteria and Result

The objective was met if 95% of the TOI are correctly labeled as TOI on the ranked anomaly list. At SR, the dynamic list identified 100% of the TOI and the static list in the trees 98%, missing one TOI buried in a clutter with four other items. At GW the dynamic dig list achieved 98% correct classification, missing one TOI because of a bookkeeping error in the dig list, and 100% for the diglist with cued data.

## 3.6 OBJECTIVE: MAXIMIZE CORRECT CLASSIFICATION OF NON-TOI

This is the second main measure of effectiveness for classification. This objective concerns the component of the classification problem that involves false alarm reduction.

### 3.6.1 Metric

The metric for this objective is the number of items on the sensor dig list that can be correctly classified as non-TOI by each classification approach.

### 3.6.2 Data Requirements

Each demonstrator prepared a ranked anomaly list for the targets on the sensor anomaly list. IDA personnel used their scoring algorithms to assess the results.

### 3.6.3 Success Criteria and Result

The objective was met if more than 50% at SR and 75% at GW of the non-TOI items were correctly labeled as non-TOI while retaining at least 95% of the TOI on the dig list. The project team rejected 85% of the clutter at SR on each list, while at GW 85% of the clutter was rejected using dynamic data and 92% with static data.

## 3.7 OBJECTIVE: MINIMUM NUMBER OF UNCLASSIFIABLE ANOMALIES

Anomalies for which reliable parameters cannot be estimated cannot be classified by the classifier. These anomalies must be placed in the dig category and be excavated.

### 3.7.1 Metric

The metric is the number of anomalies that cannot be analyzed by our method.

### 3.7.2 Data Requirements

Dig list specified those anomalies for which parameters could not be reliably estimated.

### 3.7.3 Success Criteria and Result

The objective was to be able to classify at least 95% of the cued anomalies. Data quality allowed for 99% (SR) and 100% (GW) of anomalies to be analyzed with cued data.

## 3.8 OBJECTIVE: CORRECT ESTIMATION OF LOCATION AND DEPTH

Correct target classification relies on the capability to extract valid target parameters. Accurate TOI location is also important for safe and efficient site remediation.

### 3.8.1 Metric

The metric is the difference between observed and predicted depth and geographic location.

### 3.8.2 Data Requirements

Target location and depth were recorded and compared to ground-truth validation measurements. This objective requires accurate ground truth.

### 3.8.3 Success Criteria and Result

The depth of TOI should generally be predicted within 0.10 m and geographic location within 0.15 m (GW) of 0.30 (SR). The standard deviations for the differences between measured and predicted depths and locations were 0.05 m and 0.20 m at SR, and 0.04 m and 0.07 m at GW.

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## 4.0 SITE DESCRIPTION

This section includes background information on the SR and GW demonstration sites. The SR site description material reproduced in this section is taken from the ESTCP Demonstration Plan for SR (Draft 3), where additional material can be found. The former Spencer Artillery Range is a 30,618 acre site located near Spencer, Tennessee. The demonstration was conducted in a portion of the Munitions Response Site (MRS) 1. An aerial photo of the demonstration area is shown in Figure 3.

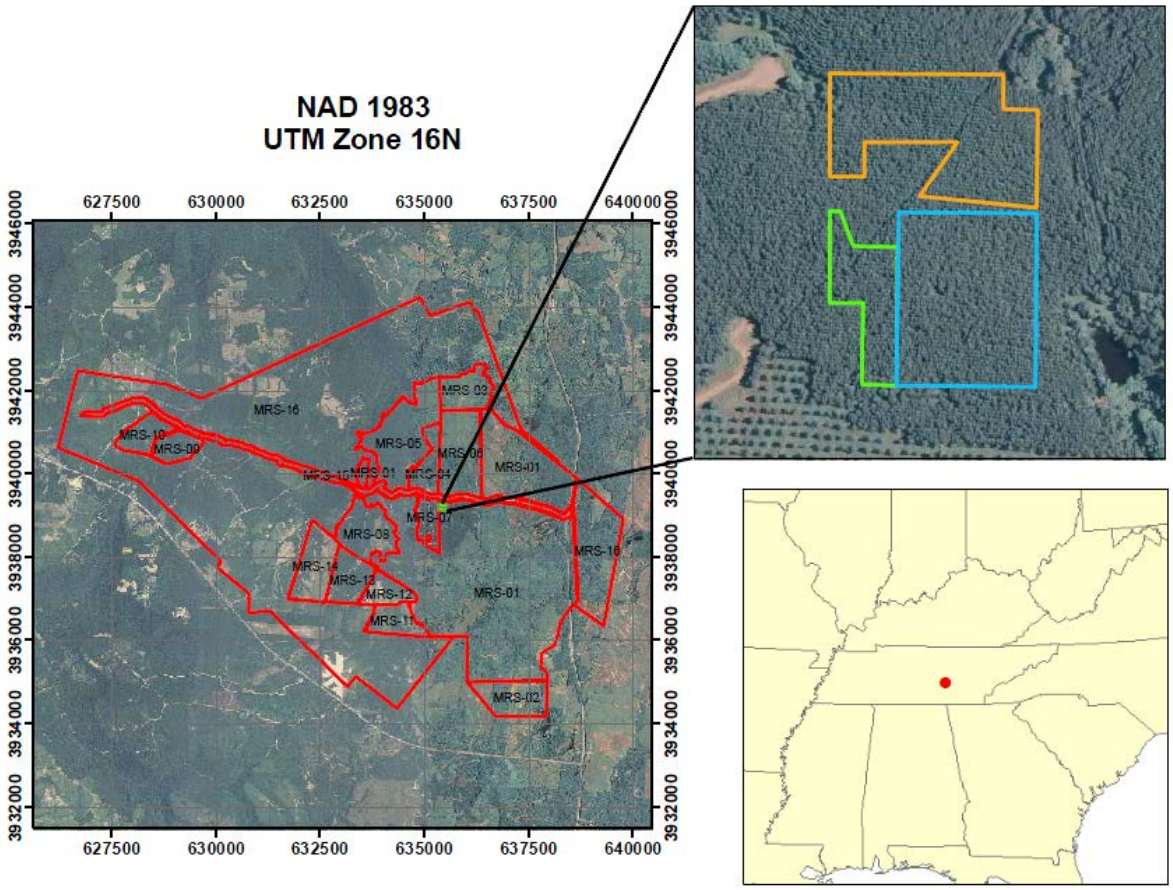


**Figure 3. Aerial photograph of Spencer Artillery Range demonstration site.**
In the upper right panel, the orange contour indicates the forest survey area (portable systems only), the green line limits dynamic area where all sensors were deployed in dynamic and static mode (except BUD) while the blue area was studied by the MetalMappers only. Trees were cleared off the green and blue areas before the demonstration.

The GW site description material reproduced here is taken from a section of the ESTCP Demonstration Plan, which itself borrows from the stakeholder review draft of the Colorado Site Inspection Report, Army National Guard MRSs. Camp GW is located in Jefferson County, Colorado, in Lakewood. The demonstration was conducted in a portion of the Non-DoD Owned, Non-Operational Defense Site (NDNODS) Camp GW Artillery Range located primarily on the northern and eastern faces of Green Mountain. An aerial photo of the demonstration area is shown in Figure 4.

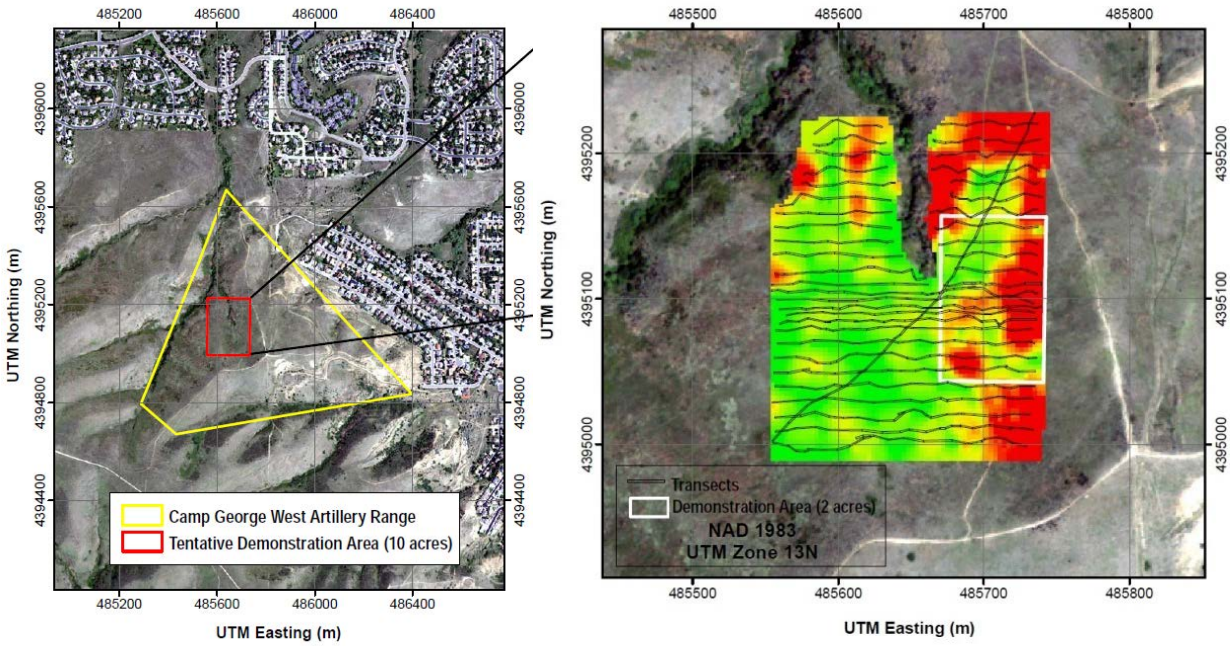


**Figure 4. Aerial photograph of George West demonstration site in Lakewood.**
Left: General setting; the site is located near a residential area on the north side of Green Mountain. Right: False color image of the anomaly density (red color for high density, green for low density) interpolated from EM61 transect surveys over the 10-acre initial area and the 2-acre area chosen for the classification demonstration (white box).

## 4.1 SITE SELECTION

The SR site provided an opportunity to demonstrate the capabilities and limitations of the classification process under a variety of site conditions. It was selected for demonstration because it was more heavily wooded than prior demonstrations and was expected to contain a wide mixture of munitions as small at 37 millimeter (mm) projectiles. These features increased the site's complexity and presented characteristics that are likely to be regularly encountered on production sites. The tree cover posed a navigation challenge by increasing the difficulty of obtaining accurate GPS readings.

The GW site was selected because of its terrain and the opportunity to involve a stakeholder community including state regulators and the Colorado Army National Guard (ARNG) in the classification pilot program.

## 4.2 BRIEF SITE HISTORY

The Spencer Artillery Range was created in 1941. Troop training took place until September 1944, by which time Army ground forces had either departed or were under orders to depart. Subsequent arrangements were made for Dyersburg Army Air Field to use the Spencer Artillery Range as an air-to-ground gunnery range. The land reverted back to the original 25 leaseholders in the summer of 1946. Several surface decontamination sweeps were completed on portions of the former range in the 1950s. Since then, numerous tracts of land have been sold and/or

subdivided, significantly increasing the number of property owners from the original 25 to several hundred landowners today.

The 135-acre Camp GW Artillery Range MRS was used by the Colorado ARNG for artillery training from 1930 to 1945 as an impact area for 75-mm high explosive projectiles. Other portions of the artillery range, including firing points, forward observer position(s), and surface danger zones are not precisely known.

## 4.3 MUNITIONS CONTAMINATION

The suspected munitions at SR include 37mm projectiles, 75mm projectiles, 76mm projectiles, 105mm projectiles, and 155mm projectiles. Small industry standard objects (ISO2) were added to increase the number of native munitions.

The only known munitions type at GW is the 75 mm projectile, though smaller munitions such as 37 mm projectiles could be expected. Medium industry standard objects (ISOmed) were added to increase the number of native munitions.

## 4.4 SITE CONFIGURATION

The SR site includes an open field area, where detection and classification were tested on a subset of 1.3 acres, and a treed area, where 700 anomalies were acquired in cued interrogation mode only (Figure 5).

**Figure 5. Cued interrogation with the MPV at Spencer Range at the edge of the forest.**
The open field area used for the detection tests is located on the right side (west), near the storage containers.

The GW study took place over a 2-acre area chosen from analysis of the initial EM61 transect survey (Figure 4). The survey area lies on the North slope of Green Mountain.

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# 5.0 TEST DESIGN

The goal of the study is to demonstrate and characterize detection and classification as a function of the target type, burial depth and site conditions.

## 5.1 CONCEPTUAL EXPERIMENTAL DESIGN

The technology was evaluated for detection and classification at two sites to test performance under different site conditions. At each site the two data collection stages were preceded with calibration activities, where detection and classification capabilities were tested on known items. For instance, the field procedure for the detection survey and the signal threshold for picking targets were tested on an IVS; test stand data were acquired to verify the detection threshold that had been derived from simulations. Classification was tested on IVS and test pit data, which also provided features to augment the reference library and help characterize some of the variability with these features.

At SR the classification study with cued data provided a reference for comparing the MPV to other sensors that surveyed the same 700 anomalies. The presence of trees interfered with GPS reception and forced use of the beacon positioning system. Multiple occurrences of frag pits and close targets tested the ability to identify a TOI among nearby clutter. The dynamic area offered the first time opportunity to test detection surveys over 1.3 acres and compare the ability to detect and locate 300 targets for most sensors tested by ESTCP (including reference EM-61). The dynamic data was also usable to test the potential to apply classification directly to survey data without need for cued interrogation. Cued data were collected over selected targets for comparison.

The GW study demonstrated feasibility of a full site remediation based on the MPV by testing field procedures, sensor performance and analytic processes. Dynamic data were collected over 2 acres in rugged terrain for full-coverage mapping and localization of the UXO contamination. Data had to be quickly interpreted to select targets for the field crew to interrogate. Cued data were collected for classification of 500 selected anomalies. Detected and cued data could be independently used for classification and comparison.

## 5.2 SITE PREPARATION

The demonstrations were managed by the Program Office, who organized surface clearance and seeding of inert TOI of various size at multiple depths.

## 5.3 SYSTEM SPECIFICATION

For cued interrogation mode the system was set for a 25 ms excitation and 25 ms recording of EMI transients. Station time lasted 6.3 seconds (s) by stacking seven data blocks (effectively 9 x 7 = 63 cycles are averaged). The data were recorded with 133 logarithmically-spaced time gates (5% gate width) from 0.1-25 ms. The dynamic survey mode was set to a 2.7 ms time window and a short, 0.1 s data block to reduce smearing of the signal by sensor motion.

Detection surveys were performed in open sky conditions amenable to use of Real-time Kinematic (RTK) GPS. An industry-standard Trimble R8 GPS was mounted on the operator side of the MPV handling boom. The GPS provided navigation to pre-programmed flag locations. The beacon system provided relative positioning for cued mode with GPS as a backup. Sensor orientation was measured with an XSens MTi three-axis orientation sensor mounted near the GPS. The pitch and roll measurement data were also used for verifying those inferred from the beacon measurements. A secondary XSens orientation sensor was fixed on the beacon boom to record its orientation.

## 5.4 CALIBRATION ACTIVITIES

Calibration activities were designed to verify correct sensor operation and calibrate the recorded sensor response over known targets. A series of test items were studied by collecting data over a test pit (Figure 6). Each sample was successively placed inside a clutter-free training pit and surveyed in cued interrogation mode. Four different orientations and one depth per target were tested. Data were inverted to verify stability of the recovered target parameters.

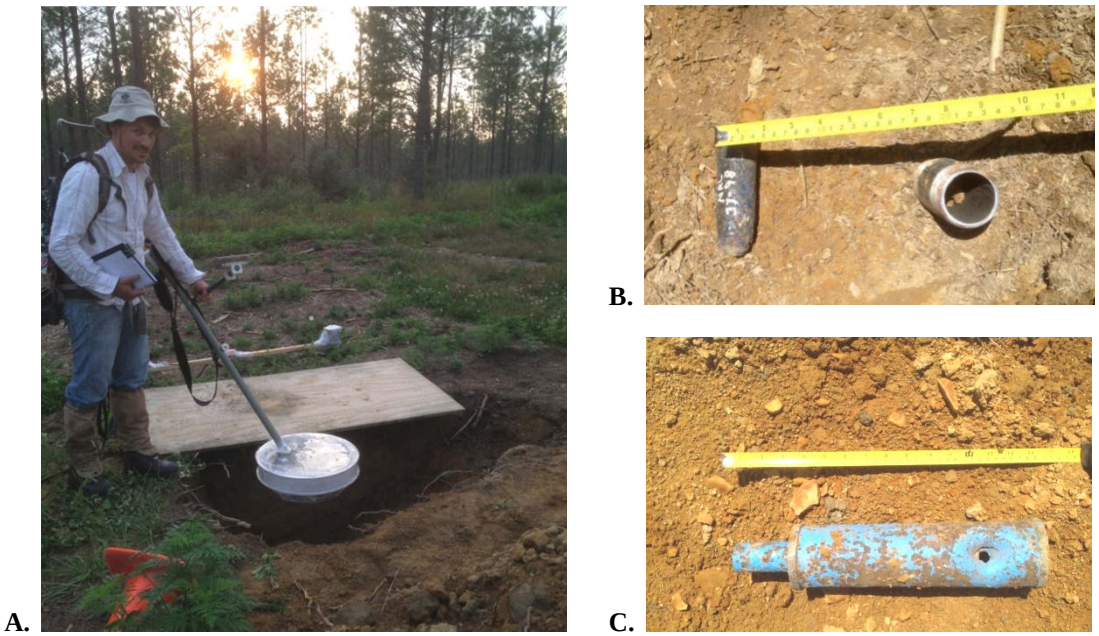


**Figure 6. Test pit measurement over calibration targets at Spencer Range.**
A: Cued interrogation over a large, clutter-free hole covered with a piece of plywood. B. Multi-target test with 37 mm and ISO. C: Test with Stokes mortar.

Sensor drift was verified over an IVS where known targets were buried in a clutter-free environment. The strip was surveyed in dynamic and cued modes to test detection and classification performance. In-air and on-ground measurements were acquired after every twelfth target interrogation and before and after any battery change, so that variations in transmitter power and instrument noise could be verified. Geologic background measurements were acquired by identifying “quiet” areas, which can be recognized by examining the recorded decay curves in static mode. Data were analyzed to quantify the spatial and temporal variability in

background noise and detect variations in soil electromagnetic properties. Beacon positions were compared with the GPS to validate location data.

## 5.5 DATA COLLECTION PROCEDURES

### 5.5.1 Sample Density

The detection survey was carried out by walking along pre-defined survey lines and sweeping the sensor from side to side, while keeping the sensor head approximately parallel to the ground. Given an effective footprint of approximately 0.7 m, the project team adopted 1.2-m line spacing and surveyed by sweeping the sensor with 0.7-m amplitude and 0.7-m period. Station spacing depends on survey speed. Following an empirical rule that the sensor should not move more than the receiver length (8 cm) during acquisition of a data block (0.1 s), sensor-head speed should be between 0.5-1 m/s with station spacing of 0.05-0.1 m along each of the five receiver-cube tracks. The resulting along-line speed is approximately 0.3 m/s.

The process for cued interrogation is to collect data on top of and around the detected target location. The location is programmed into the MPV DAQ and located with the GPS (no ground paint or flags were used at this site). The first sounding was acquired at the picked location, followed by four soundings in a square pattern and a separation of 0.6-0.7 m (Figure 7). The resulting coverage is approximately uniform; with a receiver cube separation of 0.2 m. Additional points were collected at the operator's discretion if the spatial coverage of the anomaly was deemed insufficient.

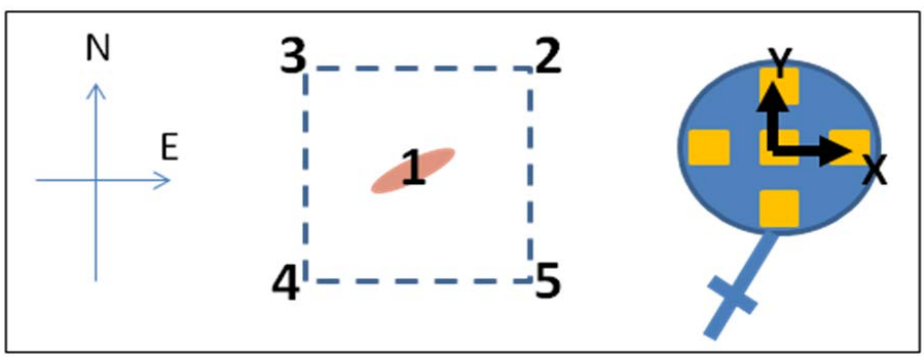


**Figure 7. Cued survey pattern with five points centered on expected target location.**

### 5.5.2 Quality Checks

During a detection survey the sensor track is displayed on the field monitor. The operator regularly checked the monitor for possible gaps. The second operator watched the main operator to verify the survey speed, sweeping amplitude, and to identify obvious gaps in coverage.

For cued interrogation, each sounding is displayed immediately after acquisition. The operator can verify adequate anomaly sampling and data quality by examining data decay curves (Figure 8) and the arrows display. The first sounding requires particular attention to verify that the signal source originates directly below the marked location. Offsets can result from positional errors, differences in sensitivity between the detection sensor and the MPV, error in the picked location, or multiple targets. In such cases, the operator is expected to scrutinize all soundings, locate the

signal source and acquire additional soundings if necessary. Anomaly coverage is verified by ensuring that the farthest receiver is measuring background. If residual signal from the target remains then additional soundings are collected to ensure full coverage of the anomaly. For instance, if the MPV front receivers show above-background signal when the MPV is placed in position 2 (Figure 7), then a sounding is to be collected North of the middle of positions 2-3. If a nearby, interfering target is detected, then supplementary soundings are acquired to improve characterization of the two sources.

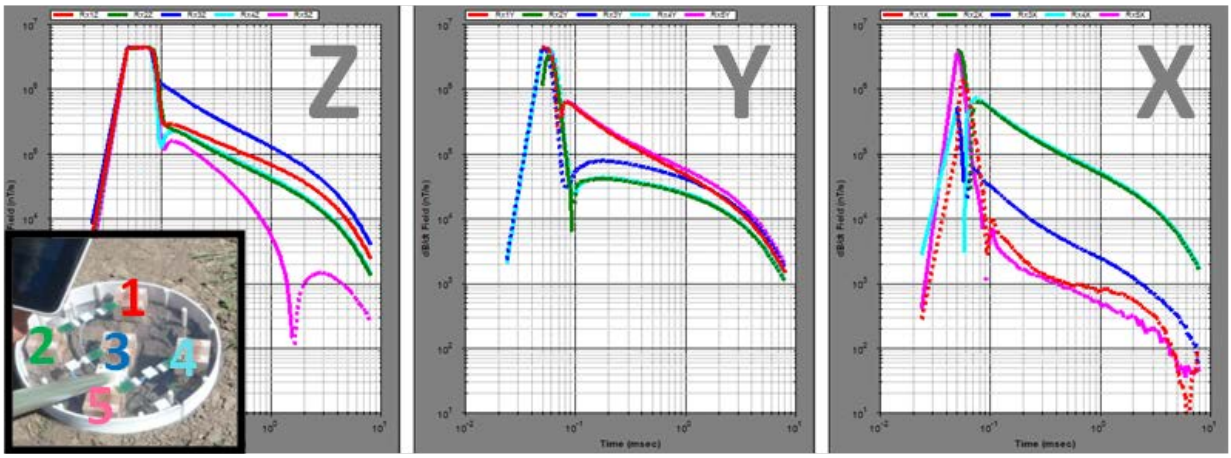


**Figure 8. Typical target response when the MPV head is placed directly above a buried target.**

The Z-component data show that target is closest to center cube (#3) and equally distant from lateral cubes 2 and 4, while signal in cube 5 resembles 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.

Initial data quality checks are performed during the survey to verify that the receivers are properly operating. Any abnormal soundings are tagged and a new sounding is acquired at the same location. In case of faulty receiver data the survey is halted until the source of the problem is identified and then rectified. No abnormal data issues were encountered at either site. Data quality is also verified post-survey, while still on site, to identify possible issues and anomalies that need to be resurveyed. Particular features to monitor are spatial coverage (especially if the flag and anomaly peak are offset), beacon positions, and signal to noise ratio.

The project team ensured that all anomalies are visited by pre-programming their GPS coordinates and displaying their location on the sensor display map. Despite occasional GPS signal drops under canopy, the GPS was generally used to navigate between anomalies. Each visited anomaly is automatically marked on the map.

### 5.5.3 Data Handling

EM data are stored as .tem files on the DAQ, converted to .csv files and copied to a portable hard-disk drive and to the QC computer. The field crew that carries the DAQ takes notes of target names, file numbers in addition to any remarks made by the principal operator. Field notes are digitized every day by taking pictures of the notes and filling out a spreadsheet that is used for pre-processing.

# 6.0 DATA ANALYSIS

## 6.1 PREPROCESSING

The MPV computer DAQ records data streams from the sensor head, beacon receivers, attitude sensor and GPS. The data are saved into a .tem binary file that is converted to a .csv file. Cued interrogation generates multiple files that need to be combined.

The beacon receiver data, transmitter current, and compass reading are combined to infer the MPV head location and orientation. These can be compared with the GPS-AHRS prediction in open field. The project team found close agreement between the two methods.

The MPV EMI data are normalized for analysis. The data are divided by the recorded transmitter current amplitude at turn off to obtain the response to a unit transmitter excitation, hence compensating for fluctuations in transmitter battery power. The sensor electronics and site conditions produce a background response that needs to be subtracted from the cued data. Background measurements were collected to analyze spatial and temporal variability of the background signal levels.

## 6.2 TARGET SELECTION FOR DETECTION

Dynamic survey data were assimilated and interpreted to produce a digital map of the area and identify anomalies that required further investigation. A simple detection threshold was applied to the amplitude of the interpreted signal. Its value was derived from a formal, quantitative assessment based on numerical simulations of the worst case scenario for the expected targets and verification with experimental data from the site. This analytic process is illustrated in Figure 9.

A target is considered to be detectable if the amplitude of its response exceeds the background noise signal. To achieve detection of a given target at a given depth in 99% of cases, the signal amplitude should exceed the typical variability of the background signal by a certain margin. The background noise statistics were analyzed on an initial subset of the field data and compared with the typical response of the target of interest. The detections objectives were to find 37 mm projectiles at 34 cm depth at SR, and 75 mm projectiles at 2 feet (or 61 cm) depth at GW. Monte Carlo simulations were performed to quantify the worst case detection scenarios at that depth by varying the sensor and target offset, target azimuth and inclination, as well as introducing variations in ground clearance and in the sensor attitude. Test stand dynamic data were acquired with a sample projectile to validate the method. The probability of detection was computed as a function of the target response and the threshold was chosen so as to ensure 99% detection of the TOI at the specified maximum depth. Practically the deep detection objective imposed detection threshold amplitudes at 2-3 standard deviations of the background response, which caused numerous false detections. Using gridded data with 5 cm pixel size, some of the false detections were rejected by requiring that more than one pixel exceeded the threshold in the vicinity of the picked anomaly.

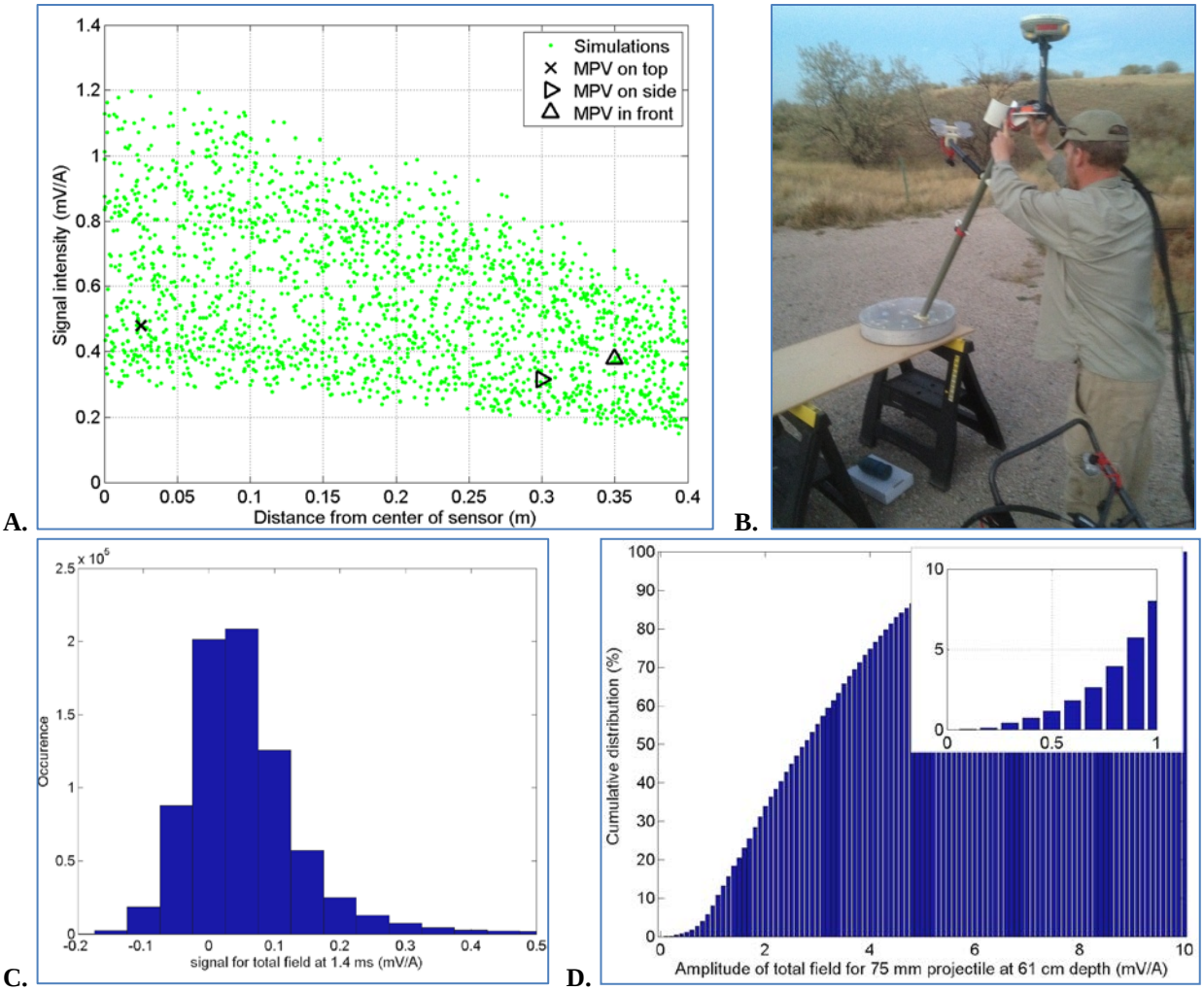


**Figure 9. Target detection analytic process based on simulation and site-specific data at GW.**

A: The response of 75 mm projectile buried at 61 cm depth is simulated for different sensor and target positions and orientations; markers indicate the amplitude of experimental dynamic data collected over a test stand for verification (panel B). C: Background noise is estimated from local field data. D: Probability of detection at 61 cm depth as a function of signal amplitude is derived from simulations.

The probability that the TOI could physically attain the maximum depth was not included in this analysis. The detection threshold would be significantly higher otherwise. Also note that a more elaborate, and recommended, method could combine the anomaly footprint and amplitude. This method would largely reduce the number of false detections caused by noise.

## 6.3 PARAMETER ESTIMATION

Advanced data analysis was achieved within UXOLab, a MatLab-based software jointly developed with the University of British Columbia and tested in numerous ESTCP and SERDP projects. Data were inverted using a three-dipole instantaneous polarization model (Pasion and Oldenburg, 2001). The target polarizability decay parameters are the main features for input into the ensuing classification process. Inversion setup parameters, such as noise estimates, are

generally decided upon by examination of the training pit data. Solutions with one or multiple targets are generated for every selected target. Decisions regarding the number of targets at a given location are made through statistical classification by prioritizing the most munitions-like solutions. Inversion results are reviewed by an experienced geophysicist to identify any potential issues with the inversion setup or with the data, and select data subsets as required for fitting all detected anomalies (masking).

## 6.4 TRAINING

Statistical classifiers are trained on a library of target features that has been accumulated during previous studies. The library was augmented with features associated to local targets. Local information was obtained by extracting target parameters from training pit measurements. Additional information was included by analyzing target features for the field data set, and requesting ground truth (training) data to ESTCP to obtain information about particular targets. Training data was requested to characterize clusters of unknown items with similar features or items with unusual inferred size. Training data could be iteratively requested until sufficient confidence in the classifier was attained.

## 6.5 CLASSIFICATION

As with past ESTCP demonstration studies, the following guiding principles were used:

- *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. Our experience shows that the three sets of instant polarizability decays generally yield successful classification with the MPV (and other sensor data). The data were inverted using single-target and multiple-target inversions and with different noise parameters or mask sizes. Therefore, multiple sets of features can be extracted from the same anomaly and the model that most likely resembles a TOI is automatically selected during classification.
- *Choice of classification algorithm:* Suitable classification methods are determined through analysis of the training data. In past studies a Library Fit method or a Support Vector Machine (SVM) classifier were found to be successful. These methods can be combined or applied multiple times with different parameters.
- *Classification:* Anomaly labels are placed in a prioritized dig-list by using the classifier to compute probabilities of class membership for unlabeled feature vectors. Targets deemed as most likely TOI are prioritized and occur early in the dig sheet.
- *Number of UXO-classes:* Statistical classifiers such as SVM can group multiple UXO types into a single class, while multiple classes can be used to represent a wide size range. The library fit uses a collection of polarizability decay curves. Multiple sets of curves may correspond to the same UXO type if some variability is found, for instance with large objects for which orientation may affect the recovered polarizabilities.

The classification approach was selected after examination of recovered target parameters and analysis of local conditions. Weak magnetic soil disturbance at both sites did not require any particular treatment and allowed use of standard classification protocols based on library misfit.

The dynamic and cued data were independently analyzed and resulted in the submission of two dig lists.

The quality of the detection survey (dynamic) data was deemed sufficiently high to apply classification to 100% of the anomalies at GW. At SR, some spatial gaps and less experience with the process lead to the application of a hybrid classification analysis that used dynamic data where reliable parameters could be extracted, which concerned half of the anomalies, and cued data for the more difficult anomalies.

The TOI library was initially based on items found at previous sites. The library was modified after training: some items were removed as no evidence of their presence was found, while some TOI whose features differed from their typical reference class were added. A multi-stage classifier was applied. The first stage included all polarizabilities (L123) and the next stage only used a combination of two polarizabilities (L12, L13), and the final stage only the primary polarizability (L1). Targets for which training data were available were also included in the classifier to assess the effect of classification parameters on their ranking. The decision to switch from one classifier stage to the next was based on a decision statistic derived from the library misfit metric. For each stage, that metric shows a strong inflection when items strongly differ from library TOI. The stage switch (or stop digging within this classifier stage) was automatically computed and further confirmed by visual inspection of the polarizabilities in ranked order and comparison with ground truth data (obtained from training or earlier dig list stages).

The result of classification is a ranked anomaly list that can be formatted as in Figure 10. The first items on each anomaly list will be those targets for which reliable parameters cannot be extracted and therefore must be dug. Next will be the items that are considered as "high confidence' TOI. Items are ranked according to decreasing confidence that the item is hazardous. Any items that were analyzed without reaching an unambiguous classification decision were placed next on the anomaly list. Finally, all items that are confidently classified as non-hazardous were ranked by their confidence.

**Initial Ranked Anomaly List**

| Anomaly ID | Category | Dig on First Pass | Type | Comment |
|---|---|---|---|---|
| 2498 | -1 | 1 | | Training Data |
| 247 | -1 | 1 | | |
| 1114 | 0 | 1 | | Can't extract reliable parameters |
| 69 | 1 | 1 | 105 | |
| 811 | 1 | 1 | 48 | High likelihood TOI |
| 313 | 1 | 1 | 37 | |
| 883 | 2 | 1 | | |
| 1642 | 2 | 1 | | Unable to classify |
| 713 | 2 | 0 | | |
| 406 | 3 | 0 | | |
| ... | 3 | 0 | | High likelihood not TOI |
| ... | 3 | 0 | | |
| ... | 3 | 0 | | |
| ... | 3 | 0 | | |
| ... | 3 | 0 | | |
| ... | 3 | 0 | | |
| ... | 3 | 0 | | |

First Pass Threshold

**Final Ranked Anomaly List**

| Anomaly ID | Category | Dig | Type |
|---|---|---|---|
| 2498 | -1 | 1 | |
| 247 | -1 | 1 | |
| 1114 | 0 | 1 | |
| 69 | 1 | 1 | 105 |
| 811 | 1 | 1 | 48 |
| 313 | 1 | 1 | 37 |
| 883 | 1 | 1 | |
| 1642 | 1 | 1 | |
| 713 | 1 | 1 | 57 |
| 406 | 3 | 0 | |
| ... | 3 | 0 | |
| ... | 3 | 0 | |
| ... | 3 | 0 | |
| ... | 3 | 0 | |
| ... | 3 | 0 | |
| ... | 3 | 0 | |

Final Threshold

**Figure 10. Format of prioritized anomaly list to be submitted to ESTCP Program Office.**

## 6.6 DATA PRODUCTS

All collected data were made available through the ESTCP Program Office. Reduced dynamic data were also supplied to establish detection maps such as those in Figure 11 and Figure 12. The main interpreted products were the classification dig lists for each data set at each site.

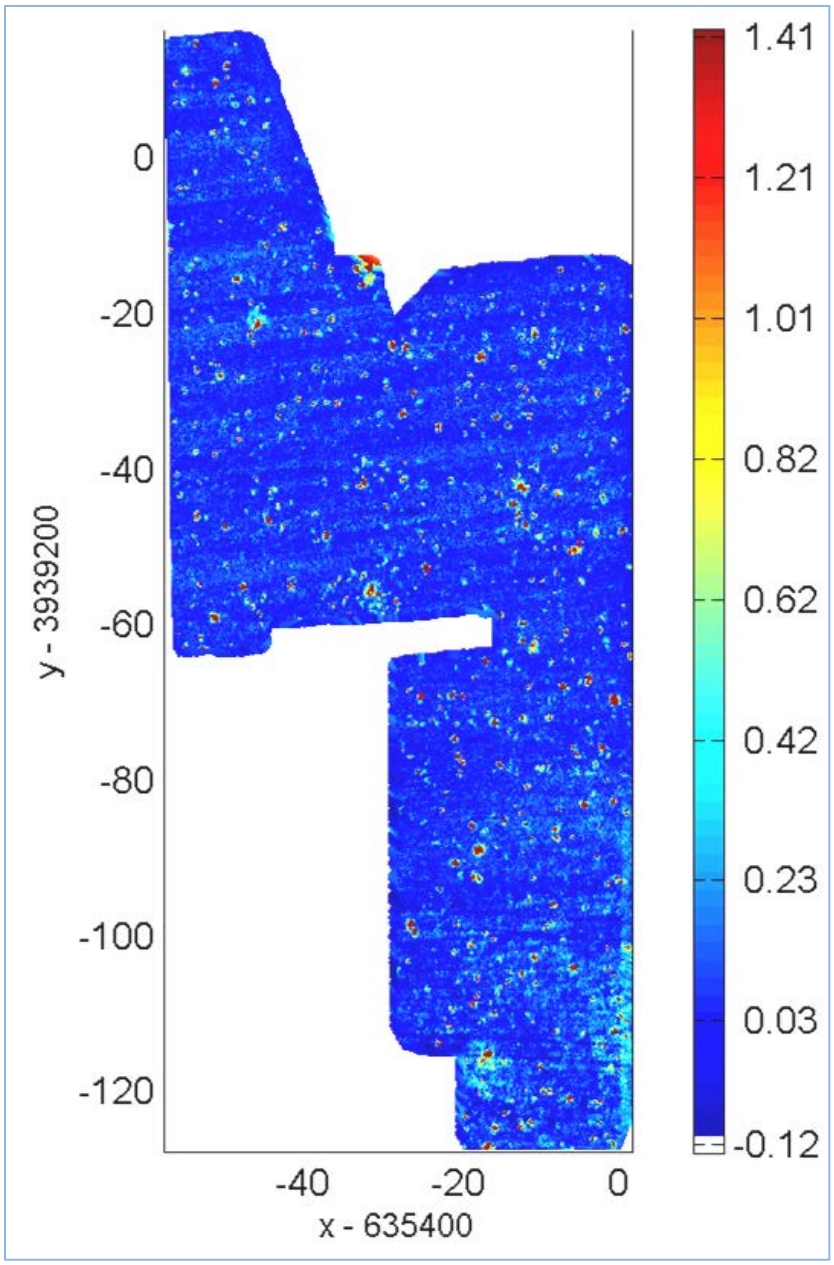


**Figure 11. Detection map for MPV open field survey at Spencer Range (1.3 acre).**

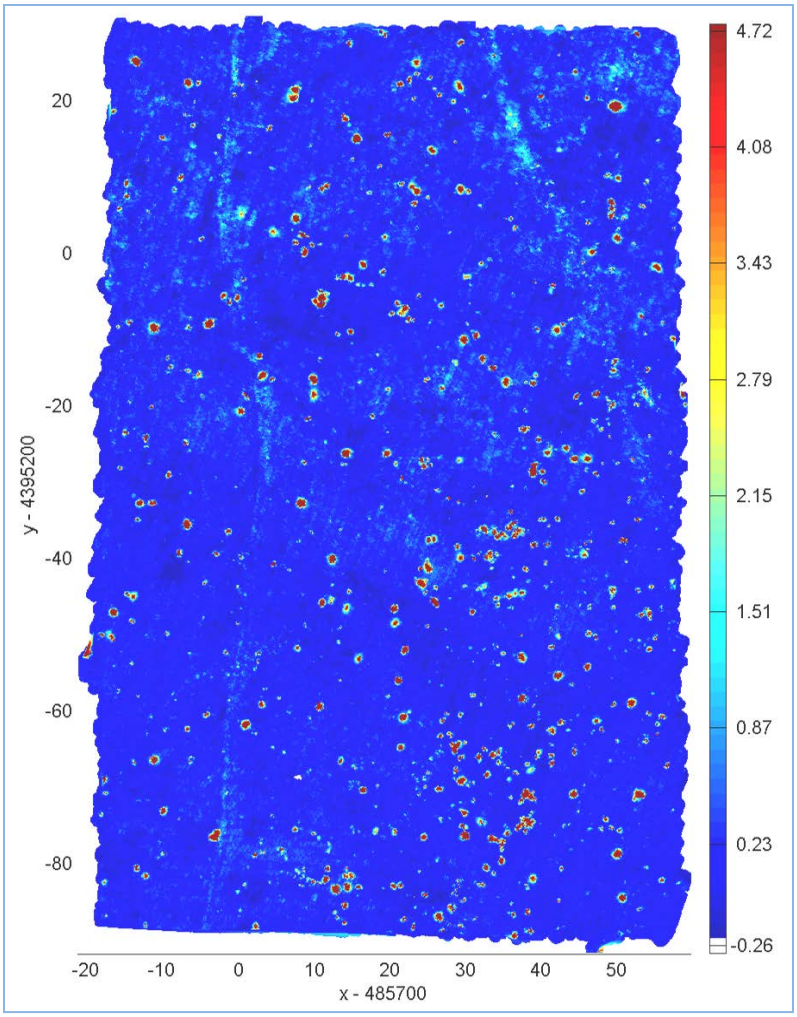


**Figure 12. Detection map for MPV survey at George West (2 acres).**

# 7.0 PERFORMANCE ASSESSMENT

## 7.1 DETECTION OF ALL TARGETS OF INTEREST

The objective was to quickly analyze the detection data while in the field in order to prepare a list of anomalies for the field crew to survey in cued mode. The metric was to detect and locate all seeded targets within 0.5 m.

At SR three seeds were missed in the detection list. The first two were omitted because their picked location lay outside of the survey boundary, although some signal extended past that boundary. The third seed was not selected because it lay within a broad anomaly. The low amplitude threshold merged the seed's anomaly with that of a peak located 1 m away.

At GW the detection objective was attained, although one seeded ISO proved to be more difficult to locate because of the presence of a nearby piece of metal 0.6 m away. The responses overlapped and were difficult to isolate at the low detection threshold, with the clutter piece dominating due to its shallow depth. The project team found that the two separate targets were identifiable by inversion of the dynamic data. Practically, the presence of two separate targets was revealed during cued interrogation, when the field operator detected the presence of a secondary source. The operator correctly extended the survey to cover the footprint of the detected second anomaly, thereby following the standard operating procedure. Inversion of the cued data unequivocally confirmed the presence of a piece of scrap metal (GW-2032) and a medium-size ISO (GW-12032).

## 7.2 CLASSIFICATION WITH DYNAMIC DATA

At SR the dynamic area was processed under the principle that dynamic data could be used as a pre-screener, in which reliable data could be interpreted to directly classify some anomalies without the need for a cued interrogation survey, whereas ambiguous anomalies would be further characterized using cued data. In this study, the project team only processed data for the anomalies that were selected from survey data. The project team retained 288 anomalies, including 272 that were common with the EM-61 and the 2x2 TEMTADS within a margin of positional error. Dynamic data were extracted for the MPV 288 anomalies and inverted to attempt classification. Applying conservative metrics for data fit and spatial coverage, half of the anomalies were deemed to provide unreliable features for classification, while the other half was classified and generated the first stage of classification. The remaining anomalies were classified after inversion of their cued data. Classification was reliable and efficient with no-missed TOI and 90% clutter rejection. Note that 67 anomalies were not included in our dig list because their signal was too low to be considered of interest (these were omitted and indicated as “cannot analyze”). Their associated dynamic data were subsequently inverted and analyzed and the project team confirmed that no TOI had been missed.

The dynamic data from GW were inverted for single and multiple targets and analyzed independently of the cued data. Classification was attempted with the expectation that 75 mm, medium and small ISO and 37 mm projectiles could be encountered. Most targets were clearly identified through classification, leading to an efficient dig list as shown in the Receiver-Operator Characteristic (ROC) graph in Figure 13. Unfortunately, a data management error

introduced confusion between target GW-3274 and its counterpart GW-13274, which had been created as a new label after inversion of cued data. The training data was misinterpreted and target GW-13274 got pushed beyond the stop digging point. Being an obvious target in terms of its classification parameters, its decision statistic put it just after the stop digging point. Besides the missed target, the team found that dynamic data could generally constrain the target location parameters and at least two of the three polarizability components throughout the dynamic time range. The recovered target parameters proved to be reliable for classification at GW, where only large munitions were found.

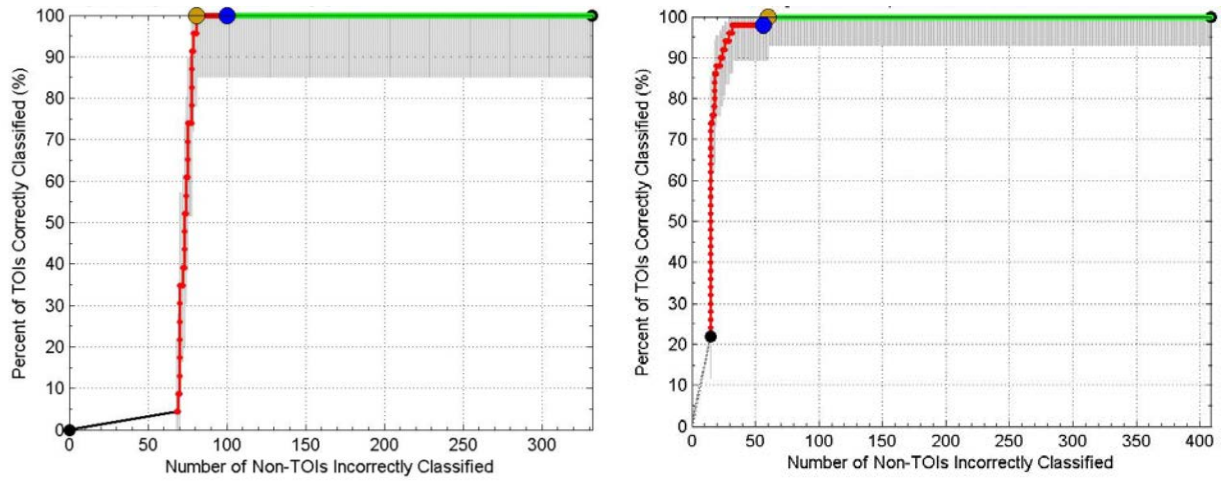


**Figure 13. ROC curve for dynamic data analysis at SR (left) and GW (right).**
Note on the SR list that the first 67 anomalies are non-TOI and were not analyzed because they were already rejected at the detection stage.

## 7.3 CLASSIFICATION WITH STATIC DATA

Classification results for the treed area of Spencer are summarized in the ROC shown in Figure 14. The team predicted 99% of the TOI while excavating only 15% of the clutter, half of which arose from training excavations. Moreover, the caliber of TOI was exactly predicted 92% of the time and differences in caliber were negligible 98% of the time. One TOI was missed. Target SR-2355 is an ISO2 that was buried among four other metallic fragments. In retrospect, scrutiny of the data indicates potential issues with some individual receivers that were not well fit. In general, this could be caused by the presence of more than two sources, or poor positioning, or some noise or malfunction. The recovered polarizabilities showed different decay rates that could have been interpreted as indicative of the presence of additional targets. In retrospect, data were re-inverted with three sources but the recovered polarizabilities for the ISO2 were still too contaminated by a nearby object to allow clear classification.

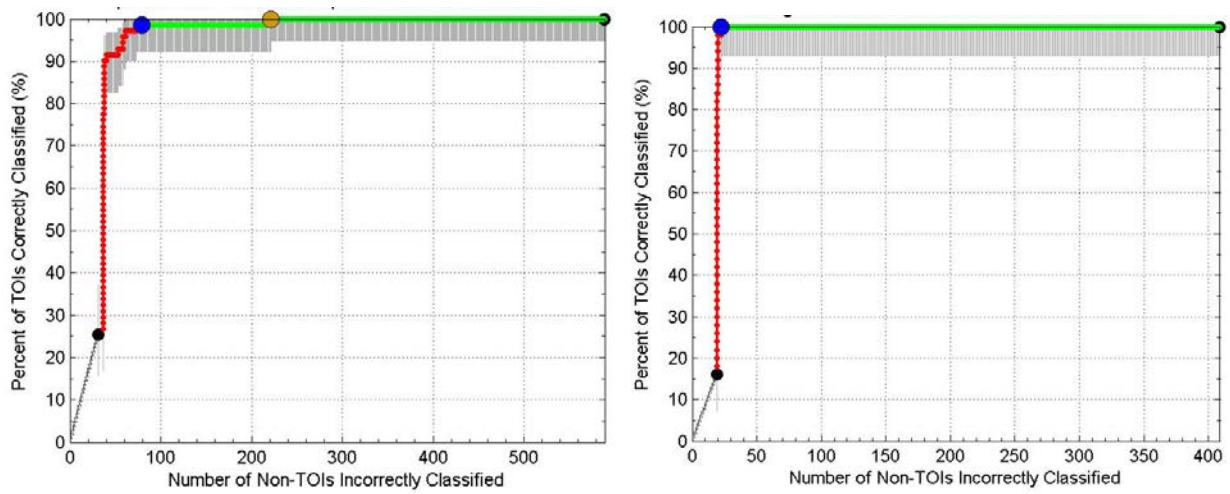


**Figure 14. ROC curve for classification with cued data at SR (left) and GW (right).**

At GW the high data quality and large target size allowed for a clear parameter separation between TOI and scrap. Hence, there was an obvious cut off point in the diglist, after which the remaining objects were clearly metallic scrap. The last item on the diglist was a TOI. Non-TOI items on that list were training items. As a result, 100% correct classification of TOI was achieved with 92% clutter rejection.

## 7.4 TARGET LOCATION BY ANOMALY PICKING AND INVERSION

The following analysis focuses on GW data. Anomaly picking was based on a signal amplitude threshold, as usually practiced. In general, the location of maximum signal amplitude or the center of the anomaly does not necessarily coincide with the actual target location, especially if the target is not vertical – for instance, horizontal anomalies can generate two peaks located near each end of the target. Having inverted all dynamic and static data, the project team can retrospectively compare the predicted target location with the detection pick and ground truth.

The difference between each target location method and the ground truth is shown in Figure 15. Cued inversion provides the best location prediction, as noted above. The anomaly picking method provides the least accurate prediction with a mean error of 0.20 m and standard deviation of 0.16 m. Locations derived from inverted dynamic data are more accurate than anomaly picking with a mean error of 0.14 m and standard deviation of 0.13 m. Practically, the two methods could be combined in a two stage process in which anomalies would first be picked on threshold and subsequently inverted to locate the underlying target. With high quality data some anomalies could readily be classified without the need for re-acquisition and cued interrogation.

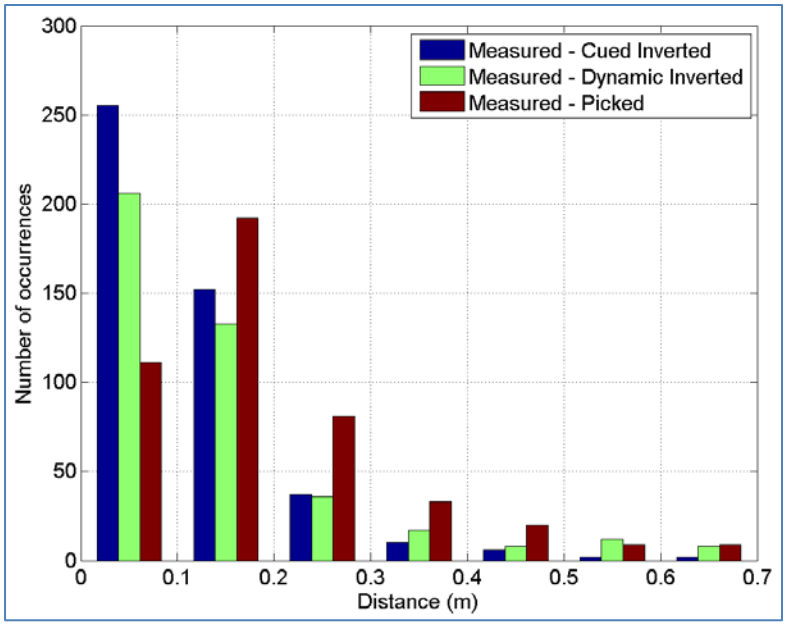


**Figure 15. Target location for detection, cued and dynamic inversion and validation.**

# 8.0 COST ASSESSMENT

Time and resources were tracked for each task to assess the cost of deploying the technology at future live sites. Presented below are the costs for GW, as these reflect the most mature state of the technology, though there remained some development. In particular, processing methods for dynamic data were being tested (optimal channels for picking, reliability of inversion), training of new geophysicists at appraising MPV inversion results and classification parameters occurred, and additional analysis to characterize the new attitude sensors (AHRS) was performed.

## 8.1 COST MODEL

A cost model is proposed in Table 2. It is based on a burdened hourly rate of $100 for any of the personnel involved. The field study was conducted with four people for dynamic survey and three people for cued interrogations. The MPV was generally operated with one field technician and one field geophysicist with MPV experience, as well as one geophysicist who managed the study, provided training, occasionally helped with data collection and handled all data processing tasks. For the dynamic survey a local third field person helped with laying out survey guides.

**Table 2. Cost model for an MPV demonstration.**

| Cost Element | Data to be Tracked | Unit Time | Total Hours | Total Cost |
|---|---|---|---|---|
| **Survey preparation and set up** | | | | **$37,900** |
| Sensor maintenance | Unit: $ Cost<br>• MPV maintenance | | | $5000 |
| Pre-survey activities | Personnel: Geophysicist<br>• Demonstration plan and coordination<br>• Preparation of survey data | | 80 h<br>40 h | $8000<br>$4000 |
| Development time | Personnel required: Geophysicist<br>Time to prepare assimilation of detection data<br>Time to test target picking algorithms<br>Time to review AHRS integration for beacon | | 10 h<br>10 h<br>40 h | $1000<br>$1000<br>$4000 |
| Mobilization and demobilization | Cost to mobilize to site: three people<br>• Flight, hotel, per diem and time<br>• Shipping | 8 h<br>2 h | 48 h<br>4 h | $8700<br>$3000 |
| Instrument setup | Typical field crew: Geophysicist + two technicians<br>• First day: assemble, set up and test pit<br>• Last day: packing | 8 h<br>4 h | 24 h<br>8 h | $2400<br>$800 |
| **Field survey: Daily tasks (8 days)** | | | | **$11,900** |
| Rentals, materials and miscellaneous | Survey equipment rental (GPS)<br>Material supplies<br>Miscellaneous tasks and interruptions<br>Travel to site, car rental, hotel and per diem | <br><br>8 h<br>0.5 h | <br>3 h<br>24 h<br>14 h | $3000<br>$1000<br>$2400<br>$5500 |
| Instrument verification | Typical field crew: Geophysicist + technicians<br>• Typical day (GPS set up and IVS surveys)<br>• Analyze IVS data (Geophysicist) | 1 h<br>0.5 h | 16 h<br>4 h | $1600<br>$400 |

**Table 2. Cost model for an MPV demonstration (continued).**

| Cost Element | Data to be Tracked | Unit Time | Total Hours | Total Cost |
|---|---|---|---|---|
| **Field survey: Detection (2 acres)** | | | | **$12,200** |
| Data collection for detection | Field personnel: Field crew of three<br>Crew: Time to collect & record data per acre<br>Training/QC personnel : Geophysicist | <br>15 h<br>4 h | <br>90 h<br>6 h | <br><br>$9600 |
| Detection: Data extraction, QC and anomaly selection | Personnel: Geophysicist<br>Data extraction and QC (per acre)<br>Built detection map, establish threshold and pick anomalies (per acre) | <br>5 h<br>8 h | <br>10 h<br>16 h | <br>$1000<br>$1600 |
| **Field survey: Cued interrogation (500 anomalies)** | | | | **$13,500** |
| Data collection for cued survey | Training/Overview: Geophysicist<br>Data collection: two field technicians/geophysicists | <br>3.6 min | 10 h<br>60 h | <br>$7000 |
| Pre-processing and QC | Personnel required: Geophysicist<br>Cued data: Cost per flag<br>Cued data: Additional analysis post survey | <br>2.5 min | <br>25 h<br>40 h | <br>$2500<br>$4000 |
| **Classification of dynamic data (500 anomalies)** | | | | **$7600** |
| Data extraction | Personnel: Geophysicist<br>Time to extract and mask dynamic data | <br>2 min | <br>17 h | <br>$1700 |
| Parameter extraction | Personnel: Geophysicist<br>Time for inversion & QC | <br>3 min | <br>25 h | <br>$2500 |
| Classifier training | Personnel: Geophysicist<br>Time to build feature library for dynamic data | <br>2 min | <br>17h | <br>$1700 |
| Classification and dig list production | Personnel: Geophysicist<br>Time to prepare memo, apply classifier and assimilate ground truth | <br>2 min | <br>17 h | <br>$1700 |
| **Classification of cued interrogation data (500 anomalies)** | | | | **$10,000** |
| Data extraction | Personnel: Geophysicist in training + expert<br>Time to extract and analyze cued data | <br>3 min | <br>25 h | <br>$2500 |
| Parameter extraction | Personnel: Geophysicist in training + expert<br>Time for inversion & QC | <br>4 min | <br>34 h | <br>$3400 |
| Classifier training | Personnel: Geophysicist in training<br>Time to identify features and potential TOI | <br>2.5 min | <br>21 h | <br>$2100 |
| Classification and dig list | Personnel: Geophysicist in training + expert<br>Time for memo and groundtruth assimilation | <br>2 min | <br>20 h | <br>$2000 |
| **COST SUMMARY** | | | | |
| **Dynamic data collection per acre** | | | | **$7000** |
| **Detection analysis per acre** | | | | **$1300** |
| **Cued data acquisition and QC per anomaly** | | | | **$25** |
| **Cued data classification per anomaly** | | | | **$20** |

## 8.2 COST DRIVERS

The MPV was developed to provide a 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 relatively lower than those of towed arrays or other vehicular-based systems. The primary costs are incurred for labor and travel for the operators, and depend on the duration of deployment, directly related to the site acreage and the terrain difficulty.

## 8.3 COST BENEFIT

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.

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# 9.0 IMPLEMENTATION ISSUES

The current sensor is a proof-of-concept prototype designed to show that detection and classification could be achieved with a handheld sensor. The demonstrations were successful in meeting these objectives.

The handheld form-factor has some disadvantages including its small footprint and the necessity to carry it all times. The 50-cm diameter head may bring a lower rate of coverage in detection mode (0.6-0.7 acre per day) relative to cart-based detection arrays over flat, even terrain, though this would likely reverse in dense forest or rugged terrain, where the MPV is more suited. For cued interrogation, the production rate is lower because of the necessity to acquire multiple soundings. During the project, production rates were increased from 100 to 125 and then 135 anomalies per day through improved field procedures. The percentage of recollects is particularly low at less than 5%. The MPV is a physically demanding instrument. It is maneuverable and can be handled with one or two arms, although it feels heavy after a day of detection survey when a GPS antenna is attached. The backpack with DAQ computer and batteries is heavy because the National Instrument DAQ is a multi-purpose computer. A lighter, smaller, lower-power field dedicated DAQ would significantly improve the usability of the system. While at first glance the sensor head appears fragile, it endured extensive field use without any incidents. The DAQ is fragile and must be carefully handled and kept dry even though the project team occasionally surveyed under light rain.

This MPV is not yet a commercial instrument. It is a unique prototype fabricated by G&G Sciences. It can be accessed through the ESTCP Office and additional units can be sourced through G&G, who also provide maintenance. The MPV combines commercial-off-the-shelf elements such as receiver cubes and National Instrument DAQ computer and receiver modules, while receiver filters, transmitter coils 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 with EM3DAcquire. Any GPS sending a standardized data sequence is supported (e.g., National Electric Manufactures Association formats).

The MPV is relatively straightforward to operate in the field. Field crews were quickly trained to collect dynamic and static data and to understand the basic principles for locating the signal origin. Setting up and troubleshooting communication with peripherals, GPS and attitude sensor requires experience of less user-friendly tools. Troubleshooting DAQ software crashes may currently be difficult.

Technical reports include instructions on survey protocols, such as acquisition parameters and cued survey patterns. General guidance on EM3DAcquire can be found on the Geometrics website for the MetalMapper sensor, which uses similar underlying technology. An MPV manual is being written. At this point the project team would recommend that an experienced geophysicist be associated with any data collection to guide field operators and frequently verify data quality.

The project team was not aware of any regulation that could negatively affect use of the MPV technology. The handheld factor limits impact on the environment relative to carts and vehicles, which could benefit remediation at sensitive sites.

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# APPENDIX A

# POINTS OF CONTACT

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