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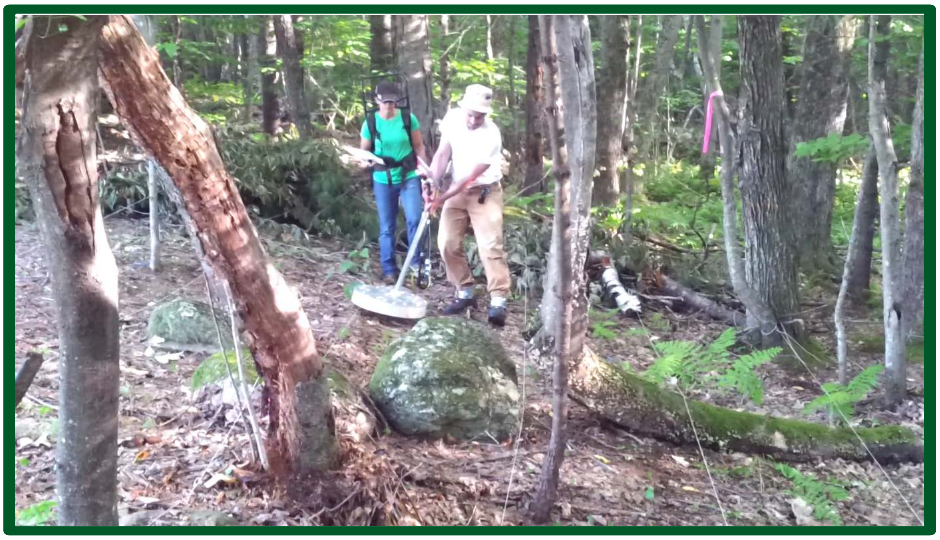

UXO Characterization in Challenging Survey Environments Using the MPV

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14. ABSTRACT
Many Department of Defense sites are contaminated by munitions and explosives of concern that are difficult to clean up because commercially available technologies are inadequate in forested areas and in rugged terrain. The Man Portable Vector (MPV) is a handheld technology designed for detection and classification of munitions in challenging survey environments. Following Environmental Security Technology Certification Program (ESTCP) projects MR-201005 and MR-201158, this MPV project extended the characterization of suitable conditions and expectable performance with live-site demonstrations at New Boston Air Force Station (NB), Former Waikoloa Maneuver Area (WK), Tobyhanna Artillery Range (TOAR), and Puako village in Waikoloa (PK). The project also paved the way for transition of the technology to the munitions response industry.

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ACRONYMS AND ABBREVIATIONS

3D	Three-dimensional
AHRS	Attitude and Heading Reference System
BTG	Black Tusk Geophysics, Inc.
cm	Centimeter
COTS	Commercial-Off-The-Shelf
CRREL	Cold Regions Research and Engineering Laboratory (ERDC)
DAQ	Data Acquisition System
DGM	Digital Geophysical Mapping
EM	Electromagnetic
EMI	Electromagnetic Induction
ERDC	Engineering Research and Development Center
ESTCP	Environmental Security Technology Certification Program
FUDS	Formerly Used Defense Site
GPS	Global Positioning System
IDA	Institute for Defense Analyses
IVS	Instrument Verification Strip
ISO	Industry Standard Objects
m	Meter
mm	Millimeter
MPV	Man Portable Vector
ms	millisecond
MR	Munitions Response
MRS	Munitions Response Site
mV/A	millivolt per ampere
NB	New Boston Air Force Station
PI	Principal Investigator
PK	Puako Village
POC	Points of Contact

ROC	Receiver-Operating Characteristic
RTK	Real-time Kinematic
RTS	Robotic Total Station
s	Second
SERDP	*Strategic Environmental Research and Development Program*
SNR	*Signal to Noise Ratio*
TEMTADS	Time Domain Electromagnetic Towed Array Detection System
TH	Tobyhanna
TOAR	Tobyhanna Artillery Range
TOI	Target of Interest
UXO	Unexploded Ordnance
WMA	Waikoloa Maneuver Area
WK	Former Waikoloa Maneuver Area

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This project was funded by the Environmental Security Technology Certification Program, project MR-201228. The MPV technology is based on the pioneering work of 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, and David George of G&G Sciences, through funding provided by the *Strategic Environmental Research and Development Program (SERDP)* project MM-1443. The technology was subsequently developed and demonstrated by the current Black Tusk Geophysics, Inc. (BTG) team through the Environmental Security Technology Certification Program (ESTCP) projects MR-201005 and MR-201158 (Principal Investigator Nicolas Lhomme) and this project.

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EXECUTIVE SUMMARY

OBJECTIVES OF THE DEMONSTRATION

Many Department of Defense sites are contaminated by munitions and explosives of concern that are difficult to clean up because commercially available technologies are inadequate in forested areas and in rugged terrain. The Man Portable Vector (MPV) is a handheld technology designed for detection and classification of munitions in challenging survey environments. Following Environmental Security Technology Certification Program (ESTCP) projects MR-201005 and MR-201158, this MPV project extended the characterization of suitable conditions and expectable performance with live-site demonstrations at New Boston Air Force Station (NB), Former Waikoloa Maneuver Area (WK), Tobyhanna Artillery Range (TOAR), and Puako village in Waikoloa (PK). The project also paved the way for transition of the technology to the munitions response industry.

TECHNOLOGY DESCRIPTION

The MPV sensor is a handheld metal detector based on electromagnetic (EM) induction. The MPV sensor head comprises a 50-centimeter (cm) diameter vertical axis transmitter loop in which five receivers are placed in a cross pattern. The transmitter generates an energizing pulse that induces time-varying “eddy” currents within buried metallic targets. The MPV is equipped with vector receivers to accurately measure the three orthogonal components of the secondary field from these eddy currents, using a wide time range to best capture target-specific decay rates.

The standard MPV configuration is used to collect full-coverage, dynamic data along survey lines for digital geophysical mapping of the metallic contamination of an area. Detected anomalies can be subsequently selected for further investigation and classification by processing the dynamic data or acquiring additional data with the MPV. The properties of the buried objects can be reliably inferred by geophysical inversion if the object is energized by a complete set of transverse directions and if high-quality, accurately positioned data are available. The detection data alone may be sufficient for classification at sites with favorable environmental conditions. Otherwise, anomalies are revisited with the MPV for cued interrogation, where higher quality data are collected in stationary mode. With the standard MPV, the vertical-axis transmitter can generate transverse excitation by placing the sensor at multiple locations around an anomaly. This effect can also be achieved by using three orthogonal transmitters from a single location above the target, using a detachable set of two orthogonal, horizontal-axis transmitter coils placed on top of the MPV head. The latter method was validated at WK for its performance and became the new standard for static acquisition as it saved time and simplified data collection: one or two soundings are generally sufficient instead of five to six. Infield, near-real-time inversion of the data predicts target parameters, confirms data usability, indicates target location, and reduces the complexity of infield data interpretation.

The MPV head is tethered to a data acquisition system (DAQ) that regulates transmitter current and samples receiver signals. It draws power from high-capacity lithium-ion batteries that are mounted on a backpack with the DAQ. A computer tablet provides an interface for controlling the DAQ and the navigation system. The MPV position is either obtained using Real-Time Kinematic (RTK) Global Positioning System (GPS) or, at sites with obstructed view of the sky, a Robotic Total Station (RTS) optical ranger. The GPS rover or RTS prism is attached to the top of the MPV handling boom. An Attitude and Heading Reference System (AHRS) sensor provides the boom orientation to derive the MPV head geo-location.

The MPV technology was initially designed and laboratory tested by the Engineering Research and Development Center (ERDC) at the Cold Regions Research and Engineering Laboratory (CRREL) in *Strategic Environmental Research and Development Program (*SERDP) project MM-1443 (Kevin O'Neill and Benjamin Barrowes) with a prototype fabricated by G&G Sciences. Its field worthiness was demonstrated by BTG personnel in the ESTCP projects MR-201005 and 201158, after fabrication by G&G of a second-generation prototype with improved maneuverability and ruggedness. The technology was successfully demonstrated at Yuma Proving Ground and at three live sites (Camp Beale, Spencer Range, Camp George West) from 2010–2012. The same MPV unit was used for this project at NB and WK. In 2015, G&G fabricated a first production unit that was demonstrated at TOAR and PK.

METHOD AND CONDITIONS

The MPV was tested at live sites for full-coverage detection mapping and for cued interrogation. ESTCP contractors prepared the sites by removing surface debris and some vegetation and seeding unexploded ordnance (UXO) surrogates to measure performance.

Each site posed different challenges and required specific survey methods. Two sites were staged in forests where thick overhead canopy blocked GPS. At NB, dense forest, deadfall, and boulders meant that only handheld sensors could be used. A hybrid fiducial method was tested for mapping, assuming a constant walking speed along line and inferring across-track position from the AHRS-recorded yaw. For cued interrogation, targets were first reacquired in dynamic search mode by activating the transmitter to find the optimum EM response, and then multiple static soundings were collected. Positioning was based on the EM beacon, a custom technology to locate the MPV transmitter relative to a portable base station equipped with EM receivers. Positioning in the forested TOAR site relied on RTS, which required line of sight between RTS and MPV. Line segments hidden behind trees required special interpolation to predict the sensor motion state and fill in position gaps.

The two Hawaii studies were staged at sites with mostly open sky conditions with good GPS signal. The first study, at WK, was in an open field where numerous patches of rocky outcrops required use of a portable sensor like the MPV for full coverage. Data processing was complicated by intense geological background noise from magnetic soils that could hide the response of buried items and cause false alarms. The noise required special processing that exploited the MPV sensor geometry in which some receivers are naturally immune to these soil effects. In contrast, the PK study was staged in a residential area where utilities could obscure potential targets of interest, while trees and walls would locally degrade GPS positions. Six properties were investigated. At one property, the tree canopy completely blocked GPS. The detection map was constructed using fiducial positioning methods, and target reacquisition was performed in dynamic search mode followed by cued interrogation.

DEMONSTRATION RESULTS

The main performance metrics were the probabilities of detection and correct classification and the rate of coverage. The objectives were met at all sites. At NB, all seeds were found in the open field and the forest area and 95% of the targets of interest (TOI) were correctly classified while rejecting 40% of the clutter. At WK, the full site was covered, including rocky outcrops; however, one target was not detectable. All UXO were correctly classified, while clutter rejection was 81% for the standard cued method and 67% for the first-time use of the three-dimensional (3D) transmitter coils method. At TOAR, all ground was surveyed, all seeds were detected and all UXO were correctly classified while rejecting 83% of the clutter. At PK full coverage was achieved, all seeds were detected, and all TOI were correctly classified with 80% clutter rejection.

A secondary performance metric is production rate. In general, dynamic surveys took more time than expected because the challenges and delays associated with surveying in dense forest, operating RTS, or working in a residential area make the survey considerably slower than open field GPS operation. On average, detection surveys covered 0.2–0.5 acres per day, whereas cued data was more predictable at 100–170 targets per day.

IMPLEMENTATION ISSUES

During this project, there was significant progress towards making the MPV a production sensor. The manufacturer overhauled and standardized the sensor hardware, producing a sensor head that is now relatively sturdy and maneuverable for an advanced classification system. The DAQ is smaller, lighter, and requires fewer batteries. The cued interrogation process is made simpler and more robust through use of 3D transmitters and immediate data inversion, which predicts the target parameters and ensures that high quality data are acquired at the correct location. Field practices have been tested and refined under a wide range of conditions. Technology transfer to industry has also started, with involvement and training of commercial field crews at each site (CH2MHill, Environet, and Parsons).

The technology, including hardware and software support, is commercially available from the manufacturer, who is actively working on a long-term solution for manufacturing and support. Durability is adequate for an advanced EMI system—no failure or instrument-caused field delay to report as of 2017. Portability and maneuverability allow access to most man-trafficable areas and offer higher coverage rates than larger sensors. However, this also makes the MPV technology more complex to operate. The operator must take care to keep the sensor head in line with the survey path to avoid creating gaps and must monitor sensor height above ground to guarantee detection at depth. A high-accuracy AHRS sensor is indispensable because the MPV head is not always aligned with the direction of travel (the head can be rotated and tilted). These aspects also affect data processing: variation in ground clearance can introduce varying background noise in geologically active environments and positioning issues, gaps, or deviations from straight lines cannot unequivocally be traced to issues with the operator path or the positioning system. Field procedures, data quality checks, and processing algorithms have been developed over the course of this project to mitigate these effects.

Finally, these demonstrations have shown that the MPV can be used at live-munitions sites and fulfill the objectives of full-coverage mapping, detection, and reliable classification of UXO—even in challenging environments with terrain, vegetation, geologic background, and urban structures.

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1.0 INTRODUCTION

This project demonstrates the capability to perform detection classification of buried unexploded ordnance (UXO) at live-munitions sites with a handheld sensor, the Man Portable Vector (MPV). The MPV technology is 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 costs. The Environmental Security Technology Certification Program (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 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 sensors ranged from vehicular-mounted to cart-based and handheld to cover the wide range of environmental conditions that can be found at Department of Defense sites, from open ranges to steep hills and dense forests.

The MPV is a handheld technology designed for classification in challenging survey environments where terrain and vegetation conditions can limit use of larger sensor platforms. 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 both for detection survey, where full-coverage data are dynamically acquired to map the munitions contamination, and for classification of detected anomalies, where the physical attributes of the detected buried metallic objects are inferred and compared to the attributes of typical UXO. The latter process generally relies on extracting three-dimensional (3D) polarizability features that relate to the intrinsic size, shape, and material of the object, and requires that the buried item be energized in transverse directions. This extraction can be based on dynamic data from the detection stage, or, more commonly, on cued-interrogation data, whereby the MPV revisits detected anomaly of interest to collect high-quality, static soundings.

Before this project, the MPV technology was demonstrated in two ESTCP projects, MR-201005 and 201158, where four site studies were visited between 2010 and 2012: Yuma Proving Ground in Arizona, former Camp Beale in California, Spencer Artillery Range in Mississippi, and former Camp George West in Colorado. These studies included detection mapping, classification with dynamic and cued data in flat and rugged open field, and classification with cued data in a wooded environment.

1.2 OBJECTIVES OF THE DEMONSTRATION

The technical objective of the demonstration was to extend the characterization of the type of sites where detection and classification could be achieved with a handheld sensor such as the MPV and to estimate the performance that could be expected.

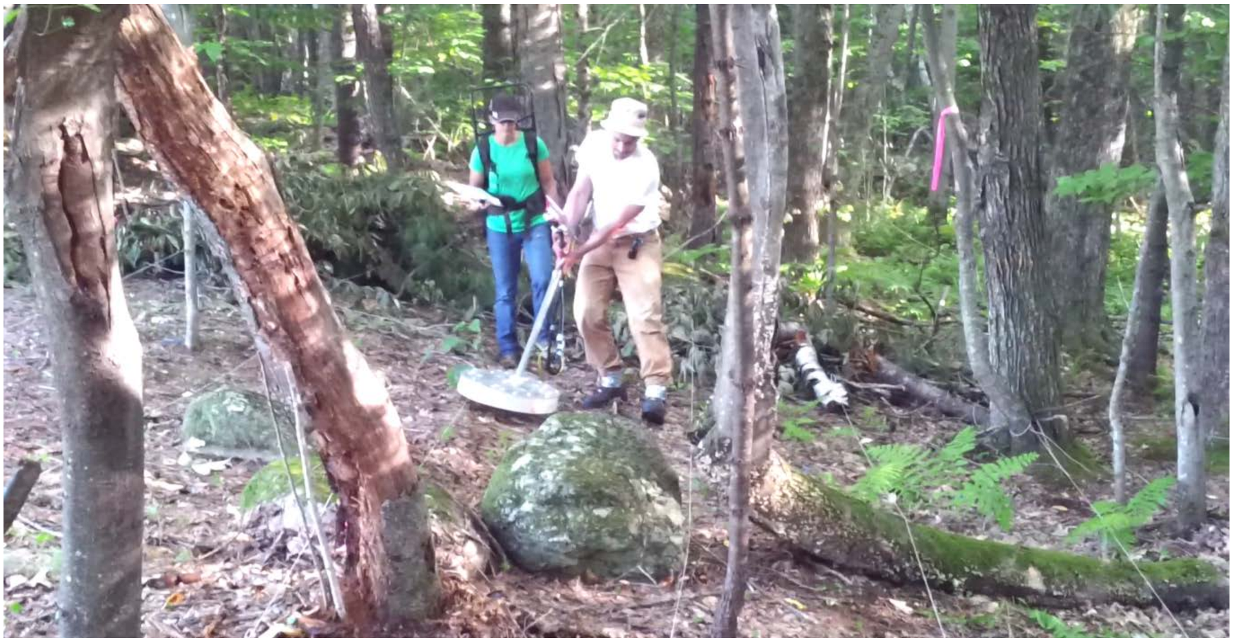

Figure 1. Detection Survey with the MPV Among Dense Trees and Boulders at New Boston.

This project included four demonstrations that each posed different challenges and required different deployment methods. Two sites involved survey in dense forest with thick overhead canopy, where alternative approaches to sensor positioning had to be employed.

- At New Boston Air Force Station (NB), dynamic detection was collected by walking lines between fixed ropes and sweeping the sensor across track (Figure 1). Positioning was derived from a hybrid fiducial method, where the across-track location was inferred from the Attitude and Heading Reference System (AHRS) yaw and the location along line from an assumption of constant speed. For cued interrogation, targets were reacquired according to their predicted location, then searched locally by observing real-time EM responses. Multiple soundings were then collected with an EM beacon for positioning.

- At Tobyhanna Artillery Range (TOAR), positioning was based on a Robotic Total Station (RTS) optical ranger, which updates positions only three times per second and may fail when trees obstruct the laser beam. This required the use of dead-reckoning interpolation over a significant portion of the survey area to predict the sensor motion state and location.

The two Hawaii studies utilized GPS for positioning. The 2014 study at the Former Waikoloa Maneuver Area (WK) was challenging due to the presence of highly magnetic soils that caused a strong geological background noise that could hide the response of buried items and cause false alarms. The noise required special data processing that benefited from the geometry of the transmitters' and receivers' relative locations, and the natural immunity of some receivers to these soil effects. The site also had large rocky outcrops that were inaccessible to wheel-based platforms and required use of a man-portable system. The 2015 study at Puako village in Waikoloa (PK) was staged in an urban setting, around private homes where utilities could potentially obscure potential targets of interest, and trees and walls would locally degrade GPS positions.

This project also paved the way for transition of the technology to the munitions response industry:

- A production unit was fabricated with improved robustness and ergonomics. Components of the sensor head were built in a more durable casing; receiver cubes were standardized; and the handling boom was improved with a sturdier bracket to attach to the head, adjustable handles and carrying straps, and a telescopic boom to accommodate operators of different height and to pack in a smaller box.

- The data acquisition system was completely overhauled with a National Instrument CompactRio system that is significantly lighter and requires only one battery to operate.

The cued interrogation process was simplified and accelerated by the addition of detachable transmitters and improved real-time processing.

- The additional transmitters helped reduce cued interrogation to one or two soundings instead of five to six and eliminated the need for a local positioning system such as the EM beacon.

- Data were inverted in near-real time to predict target parameters, which provided more explicit guidance on target location and data usability than the previous process where the operator had to guess based on the receivers' responses around a target.

- Data processing was standardized to match that of other advanced EMI sensors.

For technology transfer, every deployment involved participation and training of commercial field crews in operating the MPV: CH2MHill at NB and TOAR, Environet and USACE in WK, and Parsons in PK.

1.3 REGULATORY DRIVERS

The Defense Science Board Task Force on UXO noted in its 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 non-hazardous items is a difficult problem; its potential payoff, however, makes it 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.

2.0 TECHNOLOGY

The MPV technology is based on EMI sensing and the use of multiple vector receivers in a handheld form factor. The sensors demonstrated in this ESTCP project were the second- and third-generation MPV prototypes. The following description refers to the third-generation model, which is the first production model and the current standard for the MPV technology.

2.1 MPV TECHNOLOGY DESCRIPTION

2.1.1 EM Sensor

The MPV is a handheld sensor with wide-band, time-domain, EMI technology. This third-generation sensor is specifically designed to (1) acquire data that is tailored for classification of UXO, (2) be man portable and therefore easy to deploy, maneuver, and adapt to a survey environment, and (3) be sufficiently rugged for intensive field use. The main EMI-sensing components are a transmitter coil and an array of five vector receiver units (cubes) that measure the EM field (Figure 2). The EMI components are contained in the sensor head, a plastic disk enclosure with 50-centimeter (cm) diameter and 8.5-cm height. The circular transmitter coil is wound around the disk while the receiver cubes are distributed in a cross pattern inside the disk. While the main sensor head only has a vertical-axis transmitter loop, it can be augmented with a pair of orthogonal horizontal-axis transmitter loops. These are packaged as detachable rectangular-shaped units that can be placed on top of the main sensor head (Figure 3). Their main purpose is for cued interrogation mode, where they help provide transverse excitation of a buried object of interest[1]. This configuration is called the MPV3D. Operationally, the transmitter intermittently illuminates the subsurface. When the transmitter is turned off, the receiver cubes measure the three orthogonal components of the transient secondary EM field decay response of buried metallic objects with three air-induction 8-cm square coils (use of multiple receivers generally improves the recovery of target parameters for classification). The MPV is powered by a new, G&G Sciences custom-made compact transmitter, receivers, and filter board and a compact National Instrument (NI) data acquisition system (DAQ) that digitizes the measured signal. The new DAQ weight is one third of the original one, consumes approximately 70% less battery energy, and operates with a single battery.

The MPV is a handheld sensor weighing approximately 11.6 kg, including 5.3 kg for the sensor head, 0.6 kg for the control display (Panasonic ToughPad) and 5.7 kg for the handles and cables (excluding GPS rover or laser prism). The new DAQ weighs 6.5 kg with one battery and is generally mounted on a light, plastic framed backpack that the main operator can carry (Figure 2, top right). The backpack features adjustable straps with carabiners that clip to the MPV handle to help support its weight in dynamic mode. The horizontal transmitter set, that is only required for cued interrogation, adds 5 kg to the sensing unit. It can remain affixed to the sensor head when moving between cued locations.

[1] In past demonstrations, the sensor head had to be moved to a series of 4–5 secondary locations around an anomaly to generate that transverse excitation, with the inconvenience of increasing the separation between the receivers and the buried object, the requirement of high-accuracy positioning, and the complexity of defining the appropriate secondary locations and interpreting the responses.

Figure 2. Picture of the MPV Technology in Detection Mode over Rocky Outcrops (WK, 2014).

The MPV, shown in operation on the left, is comprised of an EMI sensor head, a handling boom sensor, and a GPS mount. The MPV is tethered to a DAQ and batteries that are here carried by a second operator (detail in top right panel). A touch-screen display can be attached to the handle or be carried by the second operator, and be used to control survey parameters and acquisition events (bottom right).

The duration of the excitation and time decay recording can be adjusted to accommodate the specific needs of target detection and classification. The highest quality data is acquired when the sensor is static, which allows for multiple cycles of target excitation and response to be averaged or stacked to reduce the effect of noise sources. Use of long transmit-receive cycles (e.g., 8 ms or 25 ms time decay) can be applied to capture the time decay rate of the target response, which relates to the target type and can help distinguish between intact ordnance and thinner walled shrapnel and cultural debris (Billings et al., 2007). A data block consists of a number of repeats of the EMI receive-transmit cycle over a given time. For the detection survey, dynamic data are collected in full-coverage mode for digital geophysical mapping (DGM). Short data blocks, typically 0.1 s, are applied so that the sensor can continuously move without smearing the data. There is a tradeoff between the duration of a transmit-receive cycle and the amount of stacking than can be done within a data block. Depending on site conditions, we use 2.7, 8.3, or 25 ms time decay, which allows nine, three, or just one full cycle, respectively. The 2.7 ms default setting allows more stacking to reduce noise and false alarms while still retaining some capability for screening fast decaying objects. In cued mode, 25 ms decay length is preferred to capture the full decay spectrum of most target types.

The MPV user interface's real-time data monitoring capabilities display the recorded data to verify quality and detect potential disturbances such as the presence of magnetic soil or a damaged receiver. The past and present sensor location can be displayed on a map along with pre-set survey points to verify spatial coverage and global location. A target detection and location tool indicates the origin of measured EMI fields either with arrows (the so-called "dancing arrows") or with the real-time dipole inversion (lower right panel in Figure 2). Cued data are inverted in near-real time and the target location, depth, and polarizability decays can be displayed. These features assist the field operator in efficient data collection and provide some immediate quality control. This capability could also enable alternative deployment modes, where detection and classification data could be collected as part of the same survey, thus limiting the need to revisit an anomaly for further characterization.

Figure 3. MPV in Cued Interrogation Mode with Detachable Coils for 3D Excitation of Buried Targets.

Positioning at TOAR was achieved with an RTS system. The prism was placed on top of an extended mast that stood higher than the operator's head. The RTS (in this figure, to the right behind the operators) remained in sight to locate the prism during acquisition.

2.1.2 Geo-location

The sensor requires geo-located EMI data for detection and classification, though with different spatial-accuracy requirements. In general, a positioning technology would provide the location of one component of the MPV, and the rest of the elements, namely the transmitter and receivers, would be derived relative to that point by translation and rotation using the yaw, pitch, and roll measured by an Attitude and Heading Reference System (AHRS) sensor. The MPV used the XSens MTi for these demonstrations. Different geo-location technologies and methodologies were tested during the project.

In the field with open sky, a Real-Time Kinematic (RTK) GPS provided the location of the rover that was attached at the far end of the MPV handling boom, behind and above the operator. This method was used for mapping and cued interrogation in open field at NB and at the two Hawaii studies.

There were two studies in dense forest. At NB, dynamic detection was collected by walking lines between fixed ropes and sweeping the sensor across track. Positioning was derived from a hybrid fiducial method, where the across-track location was inferred from the AHRS yaw and the location along line assumed survey at constant speed. For cued interrogation, targets were reacquired according to their predicted location (usually within one foot of the detection peak location), then searched locally by observing real-time EM responses. Then multiple soundings were collected while relying on the EM beacon for positioning (San Filippo et al., 2007; Lhomme et al., 2011). This method 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. The horizontal and vertical location of the center of the MPV head and its roll and pitch can be predicted from the beacon measurements. Field trials showed 1–2 cm and 1–2 degrees accuracy for position and roll-pitch within a range of 3–4 meters. At TOAR, positioning was based on a RTS optical ranger, which updates positions only three times per second and may fail when trees obstruct the laser beam. This method required special interpolation over a significant portion of the survey area to predict the sensor motion state and location.

2.2 TECHNOLOGY DEVELOPMENT

The MPV project was initiated in 2005 under the *Strategic Environmental Research and Development Program* (SERDP) Project MM-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 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 beacon concept was tested in 2009 as an alternative to the ArcSecond positioning, an optical ranger system that was deemed impractical. The second MPV prototype was designed 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 Munitions Response (MR) 201005 to continue developing the MPV and conduct field demonstrations at live sites. The second-generation prototype was fabricated and demonstrated at Yuma Proving Ground UXO Test Site in October 2010 and at former Camp Beale in June 2011, where the technology performed similarly to existing advanced EMI sensors designed for UXO classification (Lhomme 2011b, 2012). The MPV was subsequently demonstrated in the ESTCP project MR-201158 at Spencer Artillery Range in June 2012, and at former Camp George West in October 2012 (Lhomme et al. 2013a, 2013b), with similar performance.

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.
- Real-time feedback: Cued data can be automatically inverted and provide within seconds the target location and polarizability decay curves. All sensor data, EM, and positioning sensors can be displayed in real time for cued and dynamic mode for quality control and interpretation. EM decays can be viewed as decay curves. Positioning data can be viewed on a map of present and past locations and anomaly locations.
- Multi-static data for reliable classification in dynamic and static operation modes: Buried items can be energized in transverse directions to energize them in different directions by varying the sensor location (dynamic mode) or using three orthogonal transmitters (cued mode); the EMI vector field can accurately be measured in multiple location with five vector receivers.
- 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.

Portability has one main limitation: the MPV has lower production rate for mapping than larger cart-based sensors. A large sensor platform would be more appropriate in wide-open field if the environmental impact of a heavy vehicle was not a concern.

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3.0 PERFORMANCE OBJECTIVES

The objectives listed in Table 1 include data collection in dynamic detection and cued interrogation, data analysis for detection and classification, and productivity.

Table 1. Performance Summary for NB, WK, TOAR, and PK.

Performance Objective	Metric	Data Required	Success Criteria	Results
Data Collection Objectives				
Spatial coverage in detection survey	Rate of coverage for subject area (excluding obstacles)	• Mapped survey data	NB: > 98% WK: > 98% TOAR: 100% PK: 100%	NB: Pass WK: Pass TOAR: Pass PK: Pass
Repeatability of Instrument Verification Strip (IVS) survey	Variation factor on amplitude of EM anomaly (detection) & Size factor or match metric (cued)	• Twice-daily IVS survey data	NB: < 2 & 1.5 WK: < 2 & 1.5 TOAR: < 2 & 1.5 PK: < 2 & match >0.9	NB: Pass WK: Pass TOAR: Pass PK: Fail 2% cases
Detection of all targets of interest (TOI)	Percent detected of seeded anomalies	• Location of seeded items • Anomaly list	100%	NB: Pass WK: One miss TOAR: One miss PK: One miss
Production rate	Daily acreage (detection) & Number of cued anomalies	• Field log	NB: 0.7 & 100 WK: 0.7 & 100 TOAR: 0.4 & 150 PK: 0.7 & 210	NB: Fail (0.5 & 72) WK: Pass (0.7 & 150) TOAR: Fail (0.2 & 150) PK: Fail (0.37 &173)
Analysis and Classification Objectives				
Maximize correct classification	Rate of TOI retained	• Ranked dig list • Scoring reports by IDA	NB: > 95% WK: >95% TOAR: 100% PK: 100%	NB: Pass (96%) WK: Pass (100%) TOAR: Pass (100%) PK: Pass (100%)
Maximize correct classification of non-TOI	Rate of non-TOI rejected	• Ranked dig list • Scoring reports by IDA	NB: > 40% WK: > 40% TOAR: > 50% PK: > 70%	NB: Pass (41%) WK: Pass (83%) TOAR: Pass (83%) PK: Pass (80%)
Minimize number of unclassifiable anomalies	Rate of anomalies with reliable classification parameters	• Ranked dig list	NB: > 90% WK: > 90% TOAR: > 90% PK: > 95%	NB: Pass (95%) WK: Pass (99%) TOAR: Pass (99%) PK: Pass (99%)
Correct location and depth of TOI	Accuracy of estimated target parameters for seed items	• Results of intrusive investigation • Predicted location	$\sigma Z < 0.10$ m σN & $\sigma E < 0.15$ m	NB: Pass WK: Pass TOAR: Pass PK: Pass

3.1 OBJECTIVE: SPATIAL COVERAGE FOR DETECTION

Dynamic detection survey should cover as much of the area of interest as possible so that all detectable targets are illuminated. The effective footprint of the MPV is approximately 10 cm wider than the sensor head.

3.1.1 Metric

The footprint of the MPV survey compared with surface area of interest.

3.1.2 Data Requirements

The geographic coordinates of the survey perimeter and the survey track are used to determine if there are any gaps in coverage.

3.1.3 Success Criteria and Result

Required rates of coverage were site dependent and ranged from 98% at NB and WK to 100% at TOAR and PK. This metric was met or exceeded at all sites.

3.2 OBJECTIVE: REPEATABILITY OF INSTRUMENT VERIFICATION TESTS

Reliability of survey data depends on the stability of survey equipment. To meet this objective, twice-daily verifications were performed on a test strip where metallic targets would be buried. The IVS was surveyed in detection mode during the detection survey. The IVS targets were 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 milliseconds (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. For PK, the cued data metric was the polarizability match to the reference library item.

3.2.2 Data Requirements

This metric required twice daily surveys of the IVS as well as the positions and depths of the items emplaced in the IVS.

3.2.3 Success Criteria and Result

The objective was that target response amplitude and size remained within a factor 2 and 1.5, respectively, of their mean value. These objectives were generally met.

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. At WK, a 60-millimeter (mm) mortar at 0.4 m depth was missed as the dynamic data showed no sign of metal at that location; no cued data was collected. One seed was missed at TOAR due to positioning issues and an aggressive picking strategy. At PK, a small Industry Standard Object (ISO) at 0.28 m was not detected; the item was buried too deep relative to the high-noise environment at the site.

3.4 OBJECTIVE: PRODUCTION RATE

The production rate of dynamic and cued-interrogation surveys has a significant impact on the cost of the technology.

3.4.1 Metric

This objective is measured by the mean daily acreage for dynamic survey and number of unique targets for cued interrogations.

3.4.2 Data requirements

Acreage and number of interrogations, which were recorded every day.

3.4.3 Success criteria and result

Expected production rates should factor in the complexity of the site environment and positioning method. Expectations were often too optimistic. In open field conditions, a coverage of 0.5 acre per day was achieved at NB and exceeded (0.75 acre per day) at WK. In a forest using fiducial positioning, a rate of 0.5 acre per day was achieved at NB. In a forest using RTS positioning, productivity drastically fell below expectations at 0.2 acre per day at TOAR. Around houses at PK, the rate was 0.37 per day, though it is noted that the objective was designed for large portions of unobstructed terrain.

The rate of anomalies characterized in cued mode follows that pattern. At NB the rate was lower due to the need to search targets in dynamic mode before acquiring cues. At WK the rate was exceeded: 150 instead of 100. At TOAR we achieved 90 on average instead of 150 due to frequent moves of the RTS base and other delays. At PK the rate of 173 was high, yet below the 210 expectation, which we note did not account for delays due to covering multiple houses in a same day.

3.5 OBJECTIVE: MAXIMIZE CORRECT CLASSIFICATION OF TOI

This objective, one of the two primary measures of the effectiveness of the classification approach, concerns the classification problem of 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 list for the targets on the sensor anomaly list. Groundtruth was maintained by the Institute for Defense Analysis (IDA), where results were scored.

3.5.3 Success Criteria and Result

Success was defined as 95% for the first two projects, then 100%. These criteria was met at all sites (see scores in section 6.5.2).

3.6 OBJECTIVE: MAXIMIZE CORRECT CLASSIFICATION OF NON-TOI

The second main measure of effectiveness for classification, this objective concerns the classification problem of 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

Success was defined as the rejection of at least 40% of the clutter for the first two sites, then 50%, and 70%. These criteria were met with 41% at NB and over 80% at the other sites.

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 to classify at least 95% of the cued anomalies was met.

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 objective to predict the depth within 0.10 m and the geographic location within 0.15 m for all TOI was met.

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4.0 SITE DESCRIPTION

4.1 NEW BOSTON

The demonstration site was located at the Shooting Field at NBAFS, New Hampshire. Detailed description of the site is included in the *ESTCP Munitions Response Live Site Demonstrations, New Boston Air Force Station, NH, Demonstration Plan* (ESTCP, 2013). The primary areas of interest for the dynamic and cued MPV study were located in grid J22 and covered one acre equally split between an open field for the east half, and a dense forest for west part.

Figure 4. Open Field and Dense Forest at NB.

4.2 WAIKOLOA

The site is on the northwest side of the Big Island of Hawaii between Waikoloa Village and Waimea. The study area was Task Order Area 20. A detailed description of the site can be found in Parsons demonstration report (Van et al., 2015) for the MetalMapper study that took place in the fall of 2013.

Figure 5. Detection and Cued Interrogation Surveys at WK.

4.3 TOBYHANNA

The demonstration site was located within Munitions Response Site (MRS) R04A (West) at the Tobyhanna Artillery Range (TOAR) Formerly Use Defense Site (FUDS). The site encompasses approximately 250 acres characterized by densely wooded, uneven terrain. The MRS is located within Pennsylvania State Game Lands. Parts of the MRS are located within a designated natural area open only to passive recreation and hunting.

Figure 6. Tree Obstacles and Deadfall at TOAR.

4.4 PUAKO

The Former Waikoloa Maneuver Area (WK) is located on the northwest side of the Big Island of Hawaii. The demonstration was conducted in the northeast area of Sector 17C within WK, an area of ongoing remedial investigation (RI) that covers approximately 1,020 acres located in the coastal portion of Waikoloa Maneuver Area (WMA) west of Queen Ka'ahumanu Highway. Six residential properties on the south side of the highway were selected.

Figure 7. Survey in a Residential Area at PK.

4.5 MUNITIONS CONTAMINATION

The following munitions were expected at the different sites:

- NB: 20-mm projectile, 2.25-inch and 5-inch rockets, practice bombs (3 lb, 4.5 lb, 100 lb, 500 lb, and 1,000 lb), general purpose 100-lb HE bomb, HE depth bomb (325 lb and 350 lb), M69 incendiary bomb, photoflash bomb M46 and practice landmine.
- WK and PK: 60-mm and 80-mm high explosive mortars, 75-mm, 105-mm, and 155-mm projectiles, 2.36-inch rocket propelled anti-tank rounds, US MK II hand grenades, rockets, M1 anti-tank land mines, Japanese ordnance.
- TOAR: 75-mm and 155-mm HE projectiles.

In addition to their legacy contamination, all sites were seeded with small and medium ISO, which are surrogates for munitions similar to 37-mm and 75-mm projectiles.

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5.0 TEST DESIGN

The goal of the study was 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 to test performance under different site conditions. At each site the two data collection stages were preceded by 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.

5.2 SYSTEM SPECIFICATION

The dynamic survey mode was set to a 2.8 ms excitation and 2.8 ms recording of EMI transients, and a short, 0.1-s data block to reduce smearing of the signal by sensor motion. The data were recorded with logarithmically spaced time gates (10% gate width) starting at 0.1 ms. For cued interrogation, the time window was set to 25 ms. When only using the Z-component transmitter, station time was set to 6.3 s (the 63 cycles are averaged). When using the 3D coils, station time was set to 20.1 s, stacking 67 cycles for each transmitter.

5.3 CALIBRATION ACTIVITIES

Calibration activities were designed to verify correct sensor operation and calibrate the recorded sensor response over known targets. When examples of site-specific targets were available, data were collected over a clutter-free test pit to retrieve the specific polarizability signature of these items and add it to the classification library.

Repeatability of the sensor data and field procedures 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 monitor detection and classification performance at the beginning and end of each day.

Background 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.

5.4 DATA COLLECTION PROCEDURES

Different procedures were applied over the multiple demonstrations as a result of testing alternative methods and using the new MPV in 2015.

5.4.1 Detection Survey

The sites were covered by acquiring dynamic data along lines. At NB the sensor head was carried in front of the operator and swept side to side on 1-m wide lines, whereas for the other sites, the lines were 0.5-m wide and the sensor head was following straight lines. For the WK study, the sensor was carried sideways, with the MPV head pointing at 90 degrees relative to the direction of travel. For the remaining two studies, the sensor head was carried in front of the operator and pointing in the direction of travel, owing to use of the new MPV with improved ergonomics for carrying. In all cases, the maximum recommended sensor motion speed was one meter per second, which ensured a maximum station spacing of 0.1 m.

5.4.2 Cued Interrogation

Detected anomalies were characterized by collecting high quality, static data at the anomaly location. Navigation to anomaly locations was achieved by first loading their location into the MPV DAQ, then following the map display that integrated the GPS or RTS and the AHRS data to predict, in real time, the sensor head location relative to the anomalies.

At NB and WK, before use of the 3D coils, the process for cued interrogation was to collect a first sounding at the picked location, followed by four soundings in a square pattern and a separation of 0.6–0.7 m. The operator would assess whether the source of the anomaly had been satisfactorily sampled by observing the data polarizability decay curves for all receivers. Additional points were collected at the operator's discretion if the spatial coverage of the anomaly was deemed insufficient.

With use of 3D coils, cued data were collected at the anomaly location. The source location was predicted by immediately inverting the data. If the location was further than 0.15 m, an additional sounding would be collected at the predicted source location and the data be inverted again to confirm the source. At most one additional sounding would be subsequently taken if the source location was still offset, so as not to chase elusive sources.

5.4.3 Quality Checks

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

At each cued interrogation, all data decay curves were displayed immediately after acquisition to verify the data quality (Figure 8). Any abnormal sounding was indicated in notes and a new sounding was acquired at the same location. In case of faulty receiver data, the survey would be halted until the source of the problem would be identified and then rectified. No abnormal data issues were encountered. Data quality was also verified post-survey, while still onsite, to identify possible issues and anomalies that needed to be re-surveyed for quality issues or incomplete coverage.

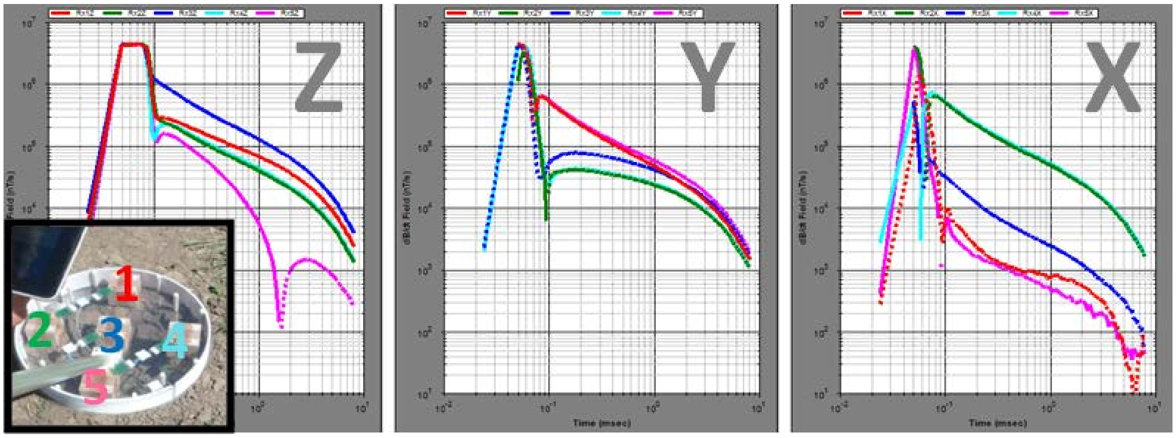

Figure 8. Typical Target Response when the MPV Head is Placed Directly Above a Buried Target.

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, 4).

5.4.4 Data Handling

Data were stored as .tem files on the DAQ and converted to .csv files for processing. The .tem and .csv files were stored on the DAQ and copied on a portable hard-disk drive and on the computers that were used for reviewing the data.

Operators took notes of target names and file numbers in addition to any remarks made by the main operator in a field logbook. Notes were digitized every day by taking pictures of the notes and filling out a spreadsheet that was used for importing data and controlling quality.

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6.0 DATA ANALYSIS

6.1 PREPROCESSING

The MPV computer records data streams from the EMI DAQ, the attitude sensor, and the GPS. The data are saved into a .tem binary file that is converted to a .csv file. The .csv files are imported into the UXOLab software for processing. The EMI data are normalized by dividing 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 background response produced by the sensor electronics and site conditions is attenuated by filtering for the dynamic data using a de-median filter, and by removing background measurements for the cued data using cued data collected at two-hour frequency over locations where no metal was detected.

6.2 TARGET SELECTION FOR DETECTION

Dynamic survey data were assimilated and processed to produce a full-coverage digital map of the area and identify anomalies that required further investigation. A single 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. That threshold was confirmed after verifying that its amplitude significantly exceeded the variability of the background noise. Quantitatively, the common practice is to require that the signal be larger than five times the standard deviations of the background noise (after the signal has been de-median filtered). If the noise was too high relative to the simulation threshold, the noise-based threshold was used and the detection depth objective was revised to reflect the limitation of a noisy site. There were slight variations in the approach for determining the threshold at each site.

At NB, the background noise statistics were analyzed for the field data acquired in the open field and in the forest, where similar characteristics were observed. The standard deviation was estimated for the 1.4-ms time channel, which put the detection threshold at 1 mV/A (millivolt per ampere). Dynamic data were acquired by sweeping the MPV sensor head over a test pit where 20-mm projectiles and 20-mm surrogates were buried at 20–25 cm depth in various orientations. We found that the maximum signal over the buried target exceeded that threshold. The detection threshold was confirmed by Monte Carlo simulations. For the other sites, the site noise characteristics were calculated and compared with the output of the Detection Modeller program developed under SERDP MR-2226. For WK the noise conditions favored a late detection channel at 1.66 ms for the Z-component data. The detection objective was reduced to finding a small ISO at 15-cm depth due to the high noise. Additional targets were selected based on receivers that are least coupled with the strong magnetic background noise. At TOAR the threshold was based on the 0.95-ms time channel. The site noise characteristics were compatible with the predicted threshold for a small ISO at 30-cm depth. The 0.26-ms time channel was used at PK and the threshold was set to detect a small ISO at 25-cm depth.

For all sites, the detection algorithm was based on picking along profiles. Each receiver cube was processed as an independent survey line. An anomaly was selected wherever at least two consecutive data points exceeded the detection threshold. The line profile algorithm was preferred to the gridded image detection method because the latter is more sensitive to positional error and data gaps, which can create grid artifacts.

6.3 PARAMETER ESTIMATION

Classification was based on inversion of cued data. As with previous ESTCP projects, data were processed within UXOLab, a MatLab-based software developed and tested in numerous SERDP and ESTCP projects. Data were inverted using a three-dipole instantaneous polarizability model (Pasion and Oldenburg, 2001), solving for the potential presence of one, two, or three underlying sources for every cued location. Decisions regarding the number of targets at a given location were made by prioritizing the most munitions-like models, using the target polarizability decay parameters as the main features for classification.

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 obtain information about particular targets. Training data was requested to characterize clusters of unknown items with similar features or items with unusual inferred size.

6.5 CLASSIFICATION

6.5.1 Method

The classification method followed standard practices that have been validated in past ESTCP demonstration studies. Classification was based on the three polarizability decay parameters. The polarizabilities were matched to the library of polarizabilities that had been validated through the previous training stage. Classification produced a ranked anomaly list similar to Figure 9, starting with targets for which reliable parameters cannot be extracted and therefore must be dug, following with “high confidence” munitions. Items are ranked according to decreasing confidence that the item is hazardous.

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		

First Pass Threshold (between 1642 and 713)

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 (between 713 and 406)

Figure 9. Prioritized Anomaly List Format for an ESTCP Demonstration.

6.5.2 Results

Classification performance is presented in terms of Receiver Operator Characteristic (ROC) curves that illustrate the efficiency of the methods at finding all TOI before clutter.

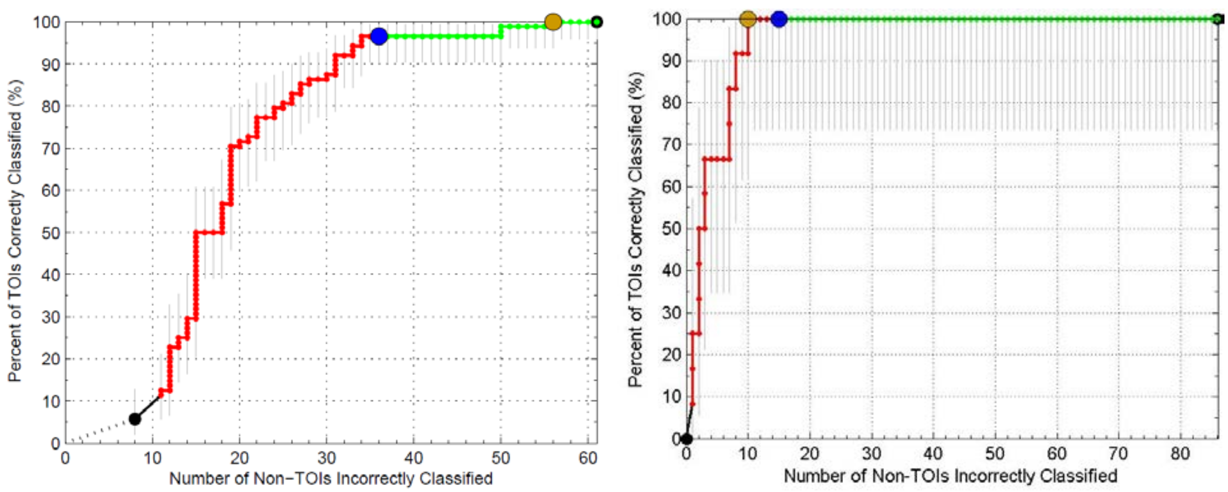

Figure 10. ROC Curve for NB (left) and WK (right).

At NB the 95% correct classification goal was achieved despite three 20-mm projectiles being missed.

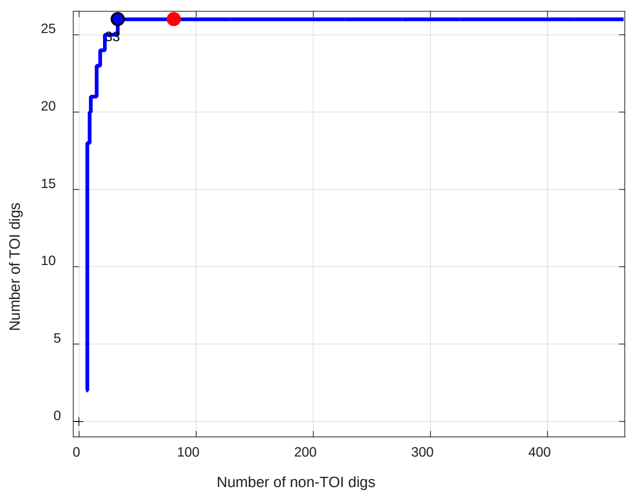

Figure 11. ROC Curve for the TOAR Classification Study.

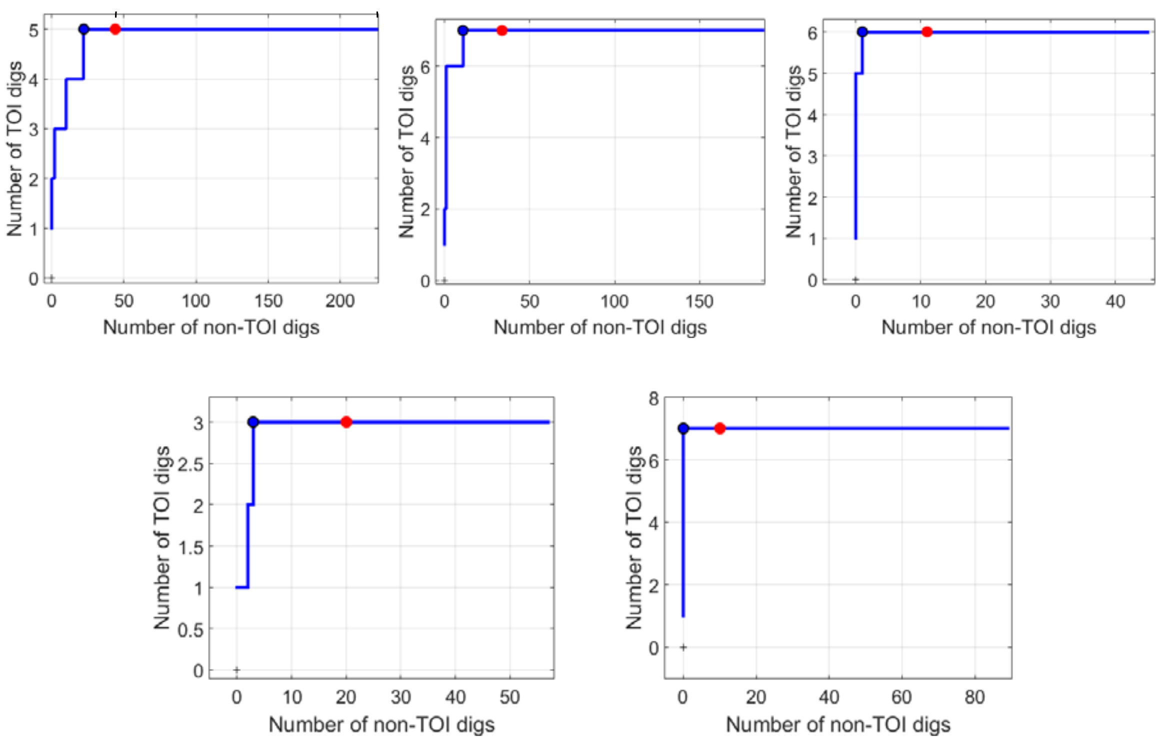

Figure 12. ROC Curves for the Classification Study at PK Based on MPV Data.

The analyst-defined stop-dig point is indicated with a red dot. Last TOI is indicated with blue dot. Ground truth was available for a small number of digs after the stop-dig point. From left to right: Top row: 1745, 1765, and 1853 Puako Drive. Bottom: 1877 and 1951 Puako Drive.

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. The main interpreted products were the classification dig lists for each data set at each site.

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7.0 COST ASSESSMENT

Time and resources were tracked for each task and projects to assess the cost of deploying the technology at future live sites.

7.1 COST MODEL

A cost model for a typical ESTCP demonstration is proposed in Table 2. As this project covered sites with different survey conditions and production rates, we make the following assumptions:

- **Dynamic collection: 4 days.** This would cover two acres in open field with GPS, or close to one acre in residential areas or in a forest.
- **Cued interrogation: 4 days**. This would characterize up to 800 anomalies in open field, and close to 500 anomalies in more adverse conditions.
- Burdened hourly rate of $100 for any of the personnel involved.
- Field studies are conducted with three people.
- Personnel mobilization costs are here excluded.
- Reporting and retrospective analysis costs are excluded.

Table 2. Cost Model for an MPV Demonstration.

Cost Element	Data to be Tracked	Quantity	Total Cost
$20,000			
Sensor maintenance	Unit: $ Cost • MPV maintenance and testing	30 h	$5,000
Pre-survey activities	Personnel: Geophysicist • Demonstration plan and coordination • Preparation of survey data • Packing and shipping	60 h 20 h 16 h	$6,000 $2,000 $4,000
Instrument setup	Personnel: Geophysicist + two crew • First day: assemble, set up, test pit and IVS • Analysis and QC	24 h 6 h	$2,400 $600
$21,000			
Rentals, materials and miscellaneous	Survey equipment rental (GPS) Material supplies Miscellaneous tasks and interruptions Car rental (SUV) Hotel and per diem	2 weeks 3 h 24 h 2 weeks 36 days	$3,000 $1,000 $2,400 $2,000 $7,600
Instrument verification	Personnel: Geophysicist + two field crew • Field: Daily set up and IVS • Analyze IVS data (Geophysicist)	48 h 12 h	$5,000
$13,000			
Data collection	Field personnel (three) Time to collect data	96 h	$9,600
Data extraction and QC	Personnel: Geophysicist • Data extraction and QC (per acre)	16 h	$1,600
Anomaly selection	Personnel: Geophysicist • Threshold analysis and memo • Anomaly selection and QC	6 h 12 h	$1,800

Table 2. Cost Model for an MPV Demonstration. (Continued)

Cost Element	Data to be Tracked	Quantity	Total Cost
$10,800			
Data collection	Field personnel (three) Time to collect data	96 h	$9,600
Pre-processing and QC	Personnel required: Geophysicist Extraction and QC	12 h	$1,200
$8,800			
Parameter extraction	Personnel: Geophysicist Time for reviewing backgrounds, setting up inversion, and QC	32 h	$3,200
Classification (training and dig list)	Personnel: Geophysicist Time for selecting classifier, dealing with training, and preparing dig list	40 h	$4,000
Validation	Personnel: Geophysicist Time for comparing dig list and ground truth	16 h	$1,600
COST SUMMARY			
Dynamic data collection and QC per acre			**$11,000 – 22,000**
Detection analysis per acre			**$1,500 – 2,000**
Cued data acquisition and QC per anomaly			**$40**
Cued data classification per anomaly			**$18**

7.2 COST DRIVERS

The MPV was developed to provide a portable sensor with advanced classification 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 incurred are for operator labor and travel and depend on the duration of deployment, which is directly related to the site acreage and the terrain difficulty.

7.3 COST BENEFIT

The primary driver for developing the MPV is to make digital geophysical mapping and classification 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 would allow.

8.0 IMPLEMENTATION ISSUES

During the execution of this project significant progress was made toward turning the MPV into a production sensor. The manufacturer overhauled and standardized the sensor hardware so that the sensor head is now relatively sturdy and maneuverable for an advanced-classification system. The DAQ is smaller, lighter, and requires fewer batteries. The cued interrogation process is simpler and more robust through use of 3D transmitters and immediate data inversion that predict target parameters and help acquire high-quality data at the correct location. Field practices have been tested and refined on a wide range of conditions. Technology transfer to industry has also started, with involvement and training of commercial field crews at each site (CH2MHill, Environet and Parsons).

There are no particular implementation issues with the MPV. The technology is commercially available from the manufacturer, who provides full integration of the MPV with an AHRS sensor, field computer, tablet and carrying backpack, which are all commercial off the Shelf (COTS) components. The MPV itself combines COTS elements such as the National Instrument DAQ chassis and modules, while receivers, transmitter coils, handling boom, and signal conditioning module are G&G builds for which spares are available. The manufacturer provides support for the MPV hardware and for its data acquisition software, EM3D, and is actively working on a long term solution for manufacturing and support. The MPV has become relatively straightforward to operate in the field. Field crews were quickly trained to collect dynamic and static data of sufficient quality. Some MPV-specific information is available within EM3D help menus. Guidance on survey protocols is included in demonstration reports.

The handheld design brings advantages and challenges. Durability is adequate for an advanced EMI system—no failure or instrument-caused field delay to report as of 2017. Portability and maneuverability allow access to most man-trafficable areas and offer higher coverage rate than larger sensors. However, the small sensor footprint reduces the productivity in detection mode relative to a classic MetalMapper; the small footprint may also reduce the tolerance on positional error for cued interrogation and require more recollects, although maneuverability helps compensate with a fast target acquisition. Portability can make the MPV technology relatively more complex to operate. In particular, the operator must take great care in monitoring the sensor height above ground to guarantee detection at depth, and the sensor position across the line to avoid creating gaps. As opposed to a cart sensor, the MPV head is not necessarily aligned with the direction of travel, requiring a high-accuracy AHRS sensor to resolve azimuthal rotation and tilt. Contrary to GPS and RTS that output data through standard format, there is no standard for AHRS communication; therefore, use of a different AHRS model would require custom alterations to EM3D. Portability also complicates data processing: variation in ground clearance can introduce variability in background noise in a geologically active environment, and positioning issues, gaps, or deviations from straight lines cannot unequivocally be traced to issues with the operator path or the positioning system. Field procedures, data quality checks, and processing algorithms have been developed over the course of this project to mitigate these effects.

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

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All technical demonstration reports for this ESCTP MR-201228 project are available at https://www.serdp-estcp.org/Program-Areas/Munitions-Response/Land/Live-Site-Demonstrations/MR-201228/MR-201228

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