FINAL REPORT

Detection and Discrimination in One-Pass Using the OPTEMA Towed-Array

ESTCP Project MR-201225

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14. ABSTRACT

The primary objective of this demonstration was to assess the feasibility of acquiring classification quality data during dynamic Electromagnetic Induction (EMI) surveys of Munitions Response Sites (MRS). The process of obtaining both detection and classification data during a single dynamic survey is known as the one-pass or dynamic classification method of data collection. By demonstrating the dynamic classification methodology using the One Pass Time-domain EMI Array (OPTEMA) to survey areas of the Former Southwestern Proving Ground (SWPG), we acquired a data set that allowed us to quantify the detection and classification performance enabled by this methodology with performance metrics (e.g., probability of detection, probability of false alarm, etc.) corresponding to a standard set of targets of interest. The intent of this demonstration was to determine if the dynamic classification approach can enable detection and classification performance comparable to that of the existing set of cued classification sensors.

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ACRONYMS AND ABBREVIATIONS

AOL	Advanced Ordnance Locator
APG	Aberdeen Proving Ground
DAQ	Data Acquisition system
DGM	Digital Geophysical Mapping
DGPS	Differential GPS
EMI	Electromagnetic Induction
FPR	False Positive Rejection
IVS	Instrument Verification Strip
MEC	Munitions and Explosives of Concern
MLE	Mean Location Error
MR	Munitions Response
MRS	Munitions Response Site
NI	National Instruments
OPTEMA	One Pass Time domain EMI Array
P_{cc}	Probability of correct classification
P_d	Probability of TOI detection
QC	Quality Control
RF	Recovery Field
ROC	Receiver Operating Characteristic
ROI	Region of Interest
RTK	Real Time Kinematic
SDV	Standard Deviation
SNR	Signal to Noise Ratio
SWPG	Southwestern Proving Ground
TEMTADS	Time domain EMI Towed Array Detection System
TOI	Target of Interest
UTM	Universal Transverse Mercator
UXO	Unexploded Ordnance
WRT	White River Technologies

YPG	Yuma Proving Ground

EXECUTIVE SUMMARY

This project was undertaken by White River Technologies, Inc. (WRT) to assess the feasibility of acquiring classification quality data during dynamic Electromagnetic Induction (EMI) surveys of Munitions Response Sites (MRS). We performed a dynamic classification survey using the One Pass Time domain EM Array (OPTEMA) at the former Southwestern Proving Ground near Hope, AR. Over the course of 6 days in September, 2015 our team surveyed 4 acres of Recovery Field 15. Survey activities included mobilization of equipment to the site, initial calibration and instrument verification activities, dynamic data collection over the 4 acre area, daily instrument verification and data quality checks, and demobilization.

During the 4 acre survey, we achieved a production rate of approximately 0.5 acre/hr. Instrument verification was performed three times daily in the Instrument Verification Strip (IVS) to confirm sensor functionality. Quality checks included evaluation of system positioning accuracy and data sample density, as well as evaluation of classification feature quality (obtained from IVS data analysis). These quality checks ensured that our team departed the site with classification-level data that met the following objectives:

1. 100% coverage of the 4 acre site with 1.2m transect spacing (33% sensor footprint overlap) and average along track sample spacing <8 cm;
2. Dynamic sensor noise levels low enough to enable classification of munitions as small as 20mm projectiles;
3. Positioning accuracy sufficient to determine target source locations to within 15 cm of actual ground truth locations.

Post-survey data analysis activities included dipole model-based inversion of the dynamic data to acquire classification features associated with anomalies. Analyzing these features, we classified 2022 anomalies that were intrusively investigated by dig teams for ground truth verification. Of the 2022 anomalies, 29 were Targets of Interest (TOI) and the remaining items were non-hazardous debris. Independent scoring of our classification analysis revealed that we correctly classified 100% of the TOI with a clutter rejection rate of 94% and we achieved a clutter rejection rate of 82% at our stop dig point. These results indicate that dynamic classification methods provide an efficient data collection alternative to cued surveys and can produce classification results comparable in quality to those obtained with cued methods.

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1.0 INTRODUCTION

This project was undertaken by White River Technologies, Inc. (WRT) to assess the feasibility of acquiring classification quality data during dynamic Electromagnetic Induction (EMI) surveys of Munitions Response Sites (MRS). During the first stage of this project, we demonstrated a dynamic classification system known as the One-Pass Time-Domain EMI Array (OPTEMA) at the Aberdeen Proving Ground (APG) standardized UXO Technology Demonstration Site. Results from this demonstration indicated that it is possible to achieve high quality classification data from a dynamic survey system [1]. To further elucidate the capabilities and limitations of dynamic classification methods/systems applied to relevant "live site" environments, we performed an additional survey using the OPTEMA system at the Former Southwestern Proving Ground near Hope, Arkansas.

The process of obtaining both detection and classification data during a single dynamic survey is known as the one-pass method of data collection. Currently, standard practice for classification surveys incorporates a two-step data collection process where a preliminary detection-level survey is performed as part of the Digital Geophysical Mapping (DGM) operations. The DGM data serve as a basis for identifying anomalies (i.e., target picking) that are subsequently interrogated during a secondary survey by static (or cued) EMI measurements.

Commercial sensors such as the Geometrics MetalMapper are optimized for cued surveys and, accordingly, have demonstrated significant success when applied in this two-step process. While this cued mode is extremely effective for distinguishing Munitions and Explosives of Concern (MEC) items from non-hazardous objects, it has two significant drawbacks. First, incorporating a secondary cued EMI survey creates additional costs. While the cued survey is more efficient than excavation of all anomalies, it is typically more time consuming than the preliminary detection/DGM survey and thus adds significantly to the survey costs allocated for the project. Second, because the DGM and cued portions of the survey are performed sequentially, there can be a disconnect between the target picking process and the cued survey process. Inaccuracies in the target picking, particularly in high anomaly density areas, can lead to sub-optimal placement of the sensor during the cued survey. Without accurate localization of the anomaly source, cued sensor classification performance can be compromised.

The one-pass method offers improvements over the cued method in regards to these limitations. Detection and classification achieved from a single EMI survey is efficient and could significantly reduce the costs associated with the burden of an additional cued survey. Furthermore, using high resolution classification sensors for detection and identification of anomalies could ultimately provide better initial characterization of the target space than that typically afforded by other DGM sensors. This improved characterization could lead to better classification results in high density areas.

In conducting this project, our primary objective is to determine whether it is possible, using a one-pass survey mode, to achieve classification results comparable to those achieved during cued surveys. Because of the anticipated lower operating costs associated with one-pass surveys, comparable classification quality would indicate that one-pass survey modes may offer a better solution than cued surveys for many projects.

1.1 BACKGROUND

The practical basis for munitions classification is founded on the development of advanced EMI sensors that provide high spatial and temporal resolution data. The data produced by these sensors enable the application of advanced physical models to extract useful classification parameters that correspond to physical properties of the object. The initial intent of these classification technologies was to provide a means for inserting additional steps into the existing data collection and processing workflows for Munitions Response (MR) projects without altering the established protocols. Accordingly, the cued survey process was developed as an add-on to the existing geophysical survey workflow for such projects. By relying on the standard DGM survey data for target picking, advanced sensors could be incorporated in cued mode into the existing process with minimal impact to the overall flow. This process has demonstrated significant success for discriminating Targets of Interest (TOI) from clutter at demonstration and production sites [2].

With the gradual trend towards acceptance of classification technologies in the production environment, the possibility now exists for shifting the focus of classification technology development from improved performance to improved efficiency and feasibility. One-pass detection and classification may provide the greatest return on investment for future classification technology development. One-pass surveys could effectively reduce excavation costs without significantly increasing geophysical survey costs.

Given the recent successes of cued EMI sensors and the potential benefits of dynamic classification, several demonstrations have been performed to evaluate the effectiveness of applying cued EMI sensors, such as the TEMTADS 2x2 variant and MetalMapper advanced sensors, in a dynamic mode. These demonstrations have typically combined a dynamic/cued approach where the dynamic surveys are used primarily to reduce the number of cued reacquisitions rather than to provide the level of classification necessary to eliminate the cued survey entirely. While this reduction in cued reacquisitions represents some cost improvements, additional cost benefits would be realized with complete elimination of any follow-on cued activities (i.e., one-pass).

We developed the OPTEMA for the specific purpose of acquiring classification-level data in a one-pass dynamic survey mode. Consequently, the OPTEMA comprises certain features that are designed to produce high quality classification data during dynamic surveys. Details of these design elements are presented in Section 2.

1.2 OBJECTIVE OF THE DEMONSTRATION

The primary objective of this demonstration is to quantify the detection and classification performance of the OPTEMA sensor operating in one-pass dynamic mode. By demonstrating the system at the former Southwestern Proving Ground (SWPG), we acquired a dynamic data set that enabled us to quantify the detection and classification performance of the OPTEMA with performance metrics (e.g., probability of detection, probability of false alarm, etc.) corresponding to munitions types found in a relevant environment. Specifically, we performed a dynamic survey of approximately four acres within the former proving grounds that contained seeded items, native clutter, and potentially native MEC as well. The intent of this demonstration was to determine if the OPTEMA could provide, in one-pass dynamic mode, detection and classification performance that would provide significant cost savings relative to both cued classification surveys and combined dynamic/cued classification surveys. If so, this one-pass technology would represent a potentially significant improvement in operational efficiency for classification surveys.

1.3 REGULATORY DRIVERS

Demonstration of this technology elucidates the potential cost savings to munitions remediation projects as a result of decreased time and labor devoted to classification surveys. DoD directives for munitions response projects now include scope for classification technologies at a number of sites. We expect that over the next 5-10 years, the list of sites amenable to classification practices will increase significantly. Consequently, any technologies that streamline operations associated with munitions classification could have a large impact on the DoD's ability to effectively implement these technologies. By replacing, to the extent possible, the detection/cued survey sequence with a one-pass detection and classification survey, it may be possible to extend the feasibility of applying classification to a broader range of sites.

One potential regulatory barrier to leveraging this technology in production surveying is the current limitation of the Geophysical Classification for Munitions Response Quality Assurance Project Plan (GCMR-QAPP) template documentation, which currently does not provide for dynamic classification or related advanced one-pass technological solutions. However, this document does provide guidance that may be useful for organizations that desire to realize the benefits of dynamic classification methods. Because dynamic classification as we are demonstrating with OPTEMA essentially combines the DGM and cued interrogation steps into a single procedure, we anticipate that the quality assurance procedures will readily transfer in a general context.

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2.0 TECHNOLOGY

The OPTEMA comprises an array of multi-directional transmitters and receivers that are optimally configured to provide good EMI characterization across the entire sensor swath. This capability is the basis for effective dynamic classification since sensor position during dynamic surveys is based on survey transects rather than on a priori target location. Consequently, it is likely that a large number of targets will be located at some lateral offset relative to the array center during a dynamic survey. Details of the OPTEMA design and operation are presented in the following subsections.

2.1 TECHNOLOGY DESCRIPTION

The OPTEMA sensor is built around the G&G Sciences National Instruments (NI)-based data acquisition framework. These data acquisition components are similar to those incorporated in the first generation commercial MetalMapper systems. Data acquisition hardware is housed in a National Instruments PXI-1042 chassis and includes an NI PXI-8108 embedded controller (Windows OS) and six 8-channel 16-bit NI PXI-6143 A/D cards. Intermediate hardware is housed in an external module and includes the transmitter controller and power distribution board, and three 16-channel receiver boards. These components along with a 2000 Watt inverter are contained in a ruggedized vehicle-mounted chassis (Figure 1) and compose the OPTEMA sensor electronics.

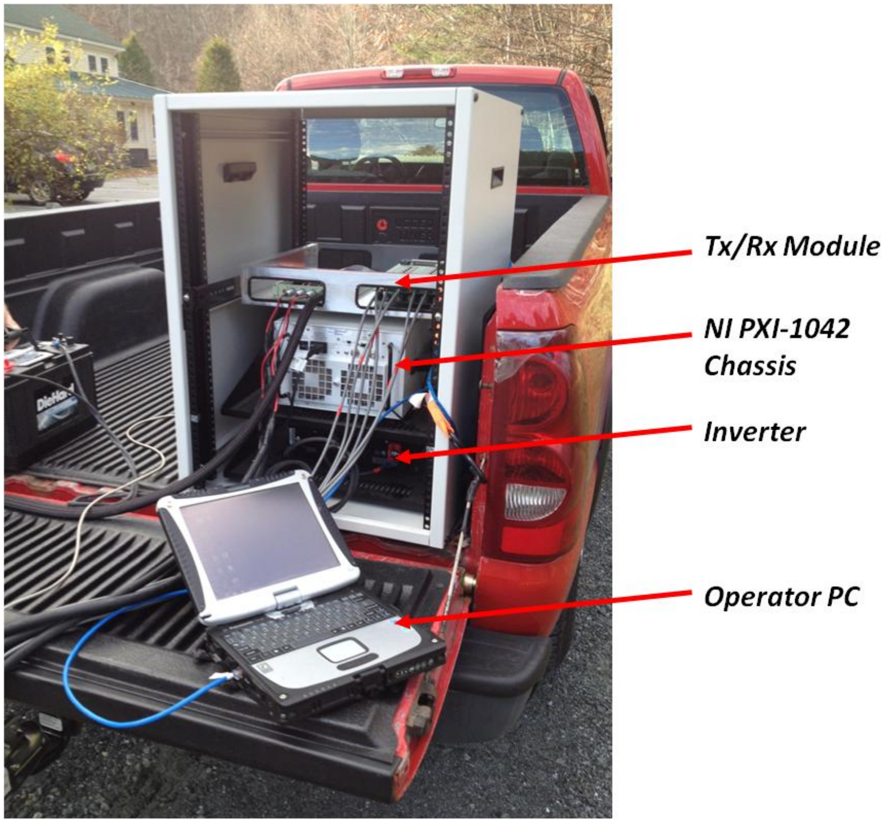

Figure 1. The OPTEMA Sensor Electronics Include Transmitter/Receiver Boards, Analog-to-digital Data Acquisition Hardware, Embedded Controller, Inverter, and Operator PC.

One of the key differences between the OPTEMA and MetalMapper data acquisition components is the effective doubling in number of receiver channels (OPTEMA provides 42 receiver channels compared to the MetalMapper's 21 channels). The increase in receiver channels led to the addition of three PXI-6143 cards in the hardware design. Additionally, a modified version of the MetalMapper data acquisition software (EM3DAcquire) is needed to manage the additional data channels.

The OPTEMA sensor head comprises five transmitters and fourteen 3-axis receivers across a 1.8 meter sensor swath (Figure 2). This design ensures that three orthogonal magnetic fields are produced at any across track location. The distribution of the 14 receivers also ensures that fields scattered by any target located across the sensor swath will be characterized sufficiently to constrain inversion of the data.

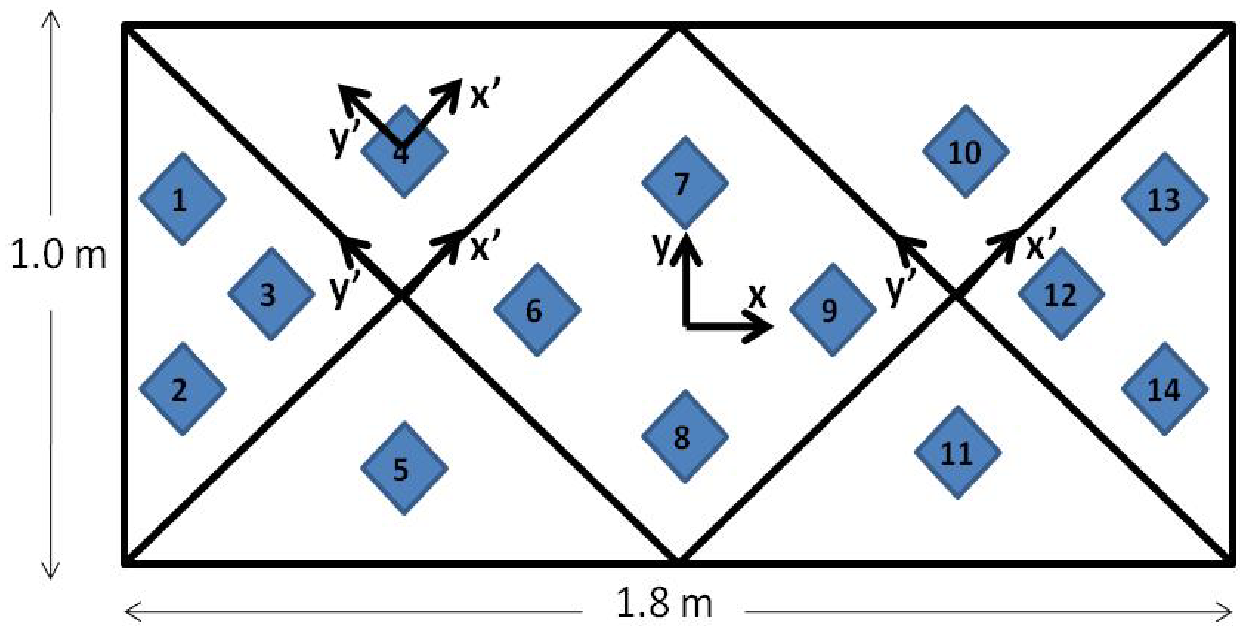

Figure 2. OPTEMA Sensor Head Configuration.

Horizontal axis (x'- and y'-) transmitters are electrically connected in pairs (x'- with x'- and y'- with y'-) to provide two orthogonal excitation axes. The larger base vertical axis (z-) transmitter provides the third excitation axis. Blue squares represent the location of the 3-axis receivers.

The transmitter coils include four horizontal axis transmitters (x'- and y'- axes) and one large vertical axis transmitter (z- axis). The horizontal axis transmitters are wired in series pairs (i.e., x'- with x'- and y'- with y'-) to provide two effective orthogonal excitation axes. The horizontal axis transmitters and receiver cubes share the same reference coordinate frame (primed) that is rotated 45 degrees from the principal coordinate system (i.e., referenced to the direction of travel).

Sensor head position and orientation data are provided by a Trimble RTK DGPS R8 receiver and a Microstrain 3DM-GX3-25 inertial sensor, respectively. Position and orientation sensors are mounted on the sensor tow sled, which provides undercarriage protection and mobility for the sensor head. Pictures of the complete sensor head and tow sled assembly are shown in Figure 3.

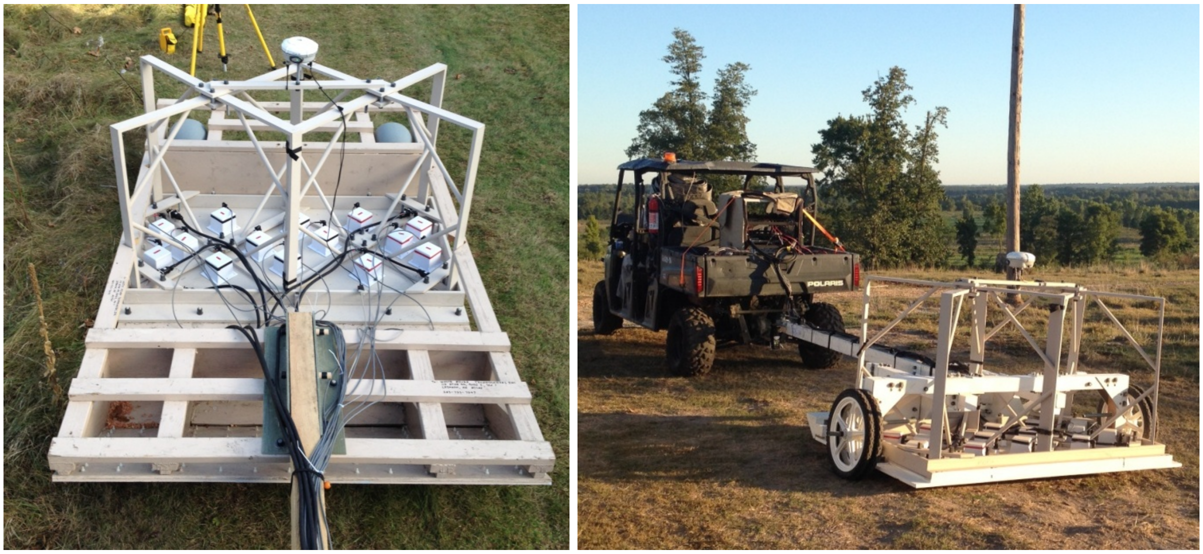

Figure 3. OPTEMA Sensor Head Assembly on Tow Sled (Left) and Complete System in Operation (Right).

Two versions of the sensor sled have been tested. The sled shown on the right (and used at SWPG) was developed for easier transport and mobilization of the system.

Each OPTEMA transmitter produces an exponential current ramp that is rapidly terminated to generate a strong electromotive force in nearby targets. The receivers measure the decay of secondary magnetic field contributions over time gates spanning a period from 24 microseconds to up to approximately 8 milliseconds. The combination of three effective transmitters (including horizontal axis transmitters in pairs) and fourteen 3-axis receivers provides 126 data channels. The magnetic field decays measured by the receivers usually include contributions from system components (e.g., supporting hardware, survey vehicle, etc.). To maximize sensitivity to anomalies, a background response is typically acquired to establish these intrinsic sources, and later subtracted from subsequent data sets to isolate the anomaly response. In addition to a background subtraction, a transmitter current normalization is applied to all data files to account for any small discrepancies in current between the three transmitters.

The OPTEMA uses a 50% duty cycle 60 Hz sub-harmonic as the base waveform. Data blocks (of duration BlockT) are built from a specified number of repeats (nRepeats) of this base waveform. The base waveform comprises a single period of a 50% duty cycle square wave voltage. During the voltage-on periods, the current in the energized transmitter coil ramps exponentially according to the coil time constant parameters. During the voltage-off periods, the receivers measure the ambient magnetic field decays. These decays are averaged with the appropriate sign changes for the positive and negative half cycles of the base period. Further signal averaging is applied for each repeat of the base waveform within the data block. In addition to the base repeats, the operator can select a number of blocks to “stack” (nStk) or average, in order to improve signal-to-noise ratio. Thus, the OPTEMA provides noise reduction through the inherent base repeat averaging and the explicit stack averaging.

Understanding the effect of these data acquisition parameters on detection and classification performance is key to optimizing these parameters for specific survey requirements.

The OPTEMA can be operated in either static or dynamic mode. As with cued EMI sensors, the static mode is ideal for maximizing signal-to-noise ratio (SNR). Because there are no restrictions on sample rate when the sensor is operated in static mode, data stacking can be maximized to reduce noise. Increasing the number of samples stacked significantly decreases the sample rate. Thus, for dynamic mode where higher sample rates are required to maximize data density, stacking must be reduced as much as possible while allowing the sensor to maintain adequate SNR for detection and classification. Table 1 provides an example of typical data acquisition parameters applied during static operation of the OPTEMA.

Table 1. OPTEMA Static Data Acquisition Parameters.

Mode	Hold-Off Time (μs)	BlockT (s)	nRpts	Window Width (%)	nStks	RxMode	TxMode
Static	50	0.033	1	10	20	Decay Decimated	ZYX

Notes:
μs = microsecond
nRpts = number of repeats
nStks = number of stacks
% = percent
s = second

For the OPTEMA system, the static mode is used primarily for collection of reference library data. Library data sets can be acquired with targets placed directly beneath the sensor (e.g., test pit data collection) or with targets placed above the sensor (e.g., test jig data collection). For library static mode, stacks are increased to 20 samples to maximize SNR. Targets are placed in several orientations and at several depths/heights to ensure recovery of consistent polarizability features for all potential target encounters. Once a sufficient sample of orientations/depths is achieved, polarizability features recovered from inversion of each static file are averaged to produce a library set of polarizabilities for the target. Figure 4 shows an example of OPTEMA library features corresponding to an 81mm mortar.

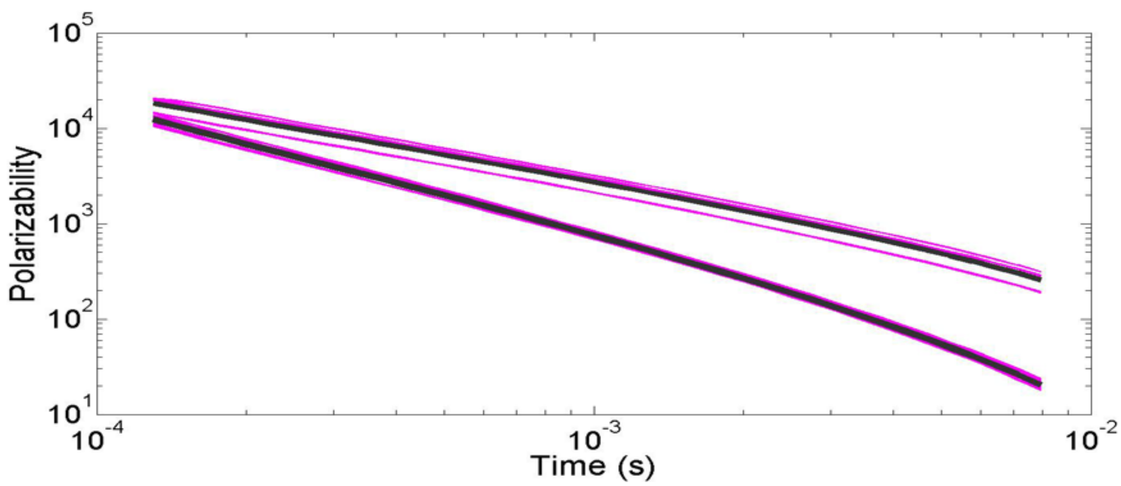

Figure 4. OPTEMA Library Data for an 81mm Mortar.

Magenta lines correspond to principal polarizabilities recovered from static data files associated with 6 different target orientations/standoffs. Dark grey lines correspond to the averaged library polarizabilities.

Polarizabilities recovered from inversion of OPTEMA data are comparable to features recovered from other cued EMI sensors such as the MetalMapper. Figure 5 shows an example of library data collected by the OPTEMA and MetalMapper systems.

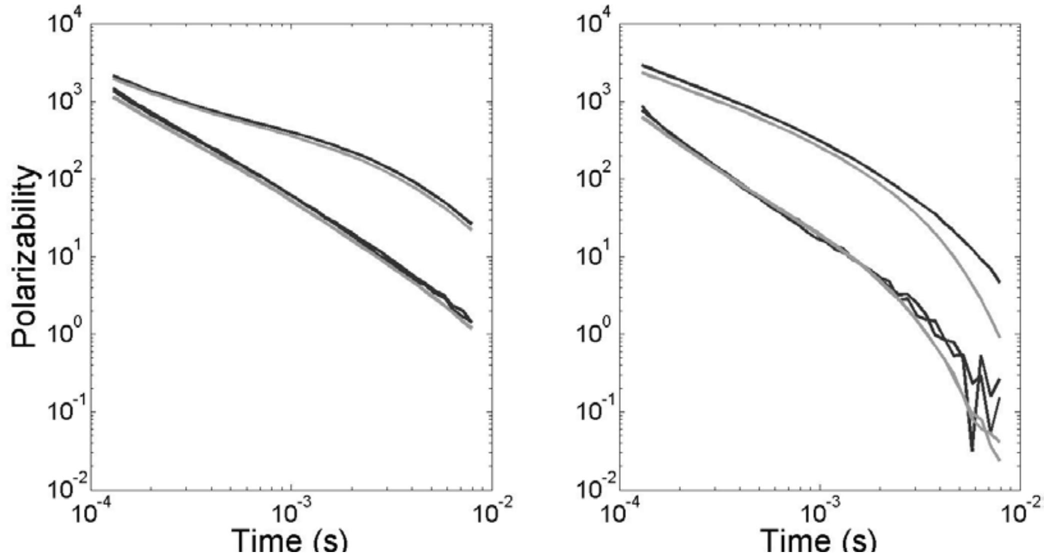

Figure 5. Library Polarizabilities Recovered from OPTEMA Data (Dark Grey Lines) and MetalMapper Data (Light Grey Lines).

Polarizabilities correspond to a 37mm projectile (left) and a small ISO (right). The slight difference in late time decays between the OPTEMA and MetalMapper polarizabilities corresponding to the ISO is likely due to variations in material permeability (different test objects were used).

With the exception of the static mode used for library data collection and sensor calibration, the primary data collection mode for the OPTEMA is dynamic. In dynamic mode the OPTEMA provides both detection and classification information. Several data acquisition parameter options are possible for dynamic survey mode. The target survey speed is approximately 0.5 m/s. Because the nominal data block size (a single Transmit-Z, Transmit-Y, or Transmit-X sequence) is 33 ms, this advance rate results in 1 OPTEMA data sample (the combined Transmit-Z, Transmit-Y, Transmit-X sequence) every 5 cm (assuming only 1 sample per stack). If multiple stacks are used, the sampling resolution decreases (for example, 3 stacks produces 1 sample every 15 cm). Within each data block, multiple waveform cycles may be averaged depending on the decay window selected. For an 8.3 ms decay period, only a single bipolar waveform is acquired for each transmitter cycle within the data block. If the decay time is changed to 2.8 ms, three waveform periods are acquired for each transmitter block, thus producing an inherent stacking of 3 samples (i.e., nRpt=3).

The primary tradeoff to consider when selecting dynamic data acquisition parameters is between data SNR and data density (i.e., spatial resolution). Increasing the number of stacks will provide higher data SNR, but will compromise spatial sampling resolution both of which are factors that influence the quality of classification parameters. Another consideration is the tradeoff associated with decay period. Inherent stacking (nRpts), and therefore data SNR, can be increased by shortening the decay period from 8.3 ms (1 effective stack) to 2.8 ms (3 effective stacks); however, the shorter decay period limits the ability to extract late time parameters from the data, features that can be useful for classifying larger or thick-walled objects.

During our system validation tests at APG, we tested two acquisition parameter settings in the blind grid area to elucidate some of the tradeoffs between increased time decay measurement and decreased SNR. Table 2 lists the parameter settings tested at APG. After analyzing 400 grid encounters applying each of these parameter settings in the APG grid, we did not find any instances where the marginal increase in SNR (2.8 ms setting) outweighed the benefits of the longer decay measurement (8.3 ms setting). Consequently, we applied the 8.3 ms decay for the SWPG demonstration.

Table 2. OPTEMA default dynamic data acquisition parameter settings.

Setting	Decay (ms)	nStk	nRpt	Total Stacks	Sample Resolution (cm)
1	8.3	1	1	1	5
2	2.8	1	3	3	5

Once dynamic acquisition parameters are set, the OPTEMA is ready for operation. Line files generated for the survey area are loaded into a WRT navigation program. These files contain the coordinates of pre-determined transects within the survey area. The navigation software provides the vehicle operator with line following based on RTK GPS data from the survey vehicle rover. Using the line following display, the OPTEMA is aligned with the starting coordinates of the selected transect. Once the sensor is sufficiently aligned (i.e., vehicle and sled heading is approximately in-line with transect), the EM3DAcquire "start acquisition" button is selected and the program will start recording dynamic data. Figure 6 shows an image of the OPTEMA collecting data along a transect in our test field.

Figure 6. OPTEMA System in Dynamic Survey Mode.

After completing a transect (or transects) the OPTEMA data can be gridded to form a detection map. Several options exist for detection. Early, middle, or late time gates within the Z-, Y-, or X-component data can be used to generate a detection map. Subsequently, Regions of Interest (ROIs) are selected from the map based on a detection threshold value (described in Section 6.2). Figure 7 shows a detection map generated from data collected over one of our test lanes.

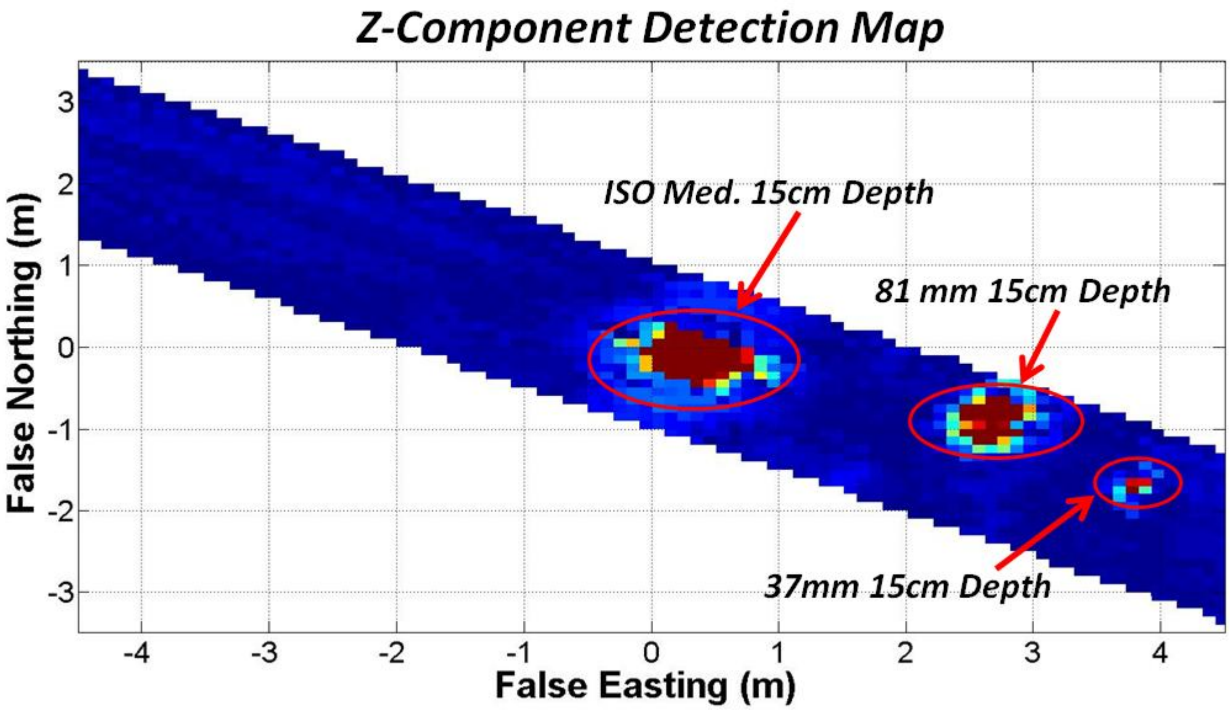

Figure 7. OPTEMA Z- component (Transmit Z-, Receive Z-) Detection Map Generated from Test Lane Data.

This lane contains three targets (ISO medium, 81 mm mortar, and 37mm projectile) all buried at 15 cm depth. ROIs corresponding to each target are circled in red.

Once threshold analysis is complete; classification is performed on each ROI extracted from the data grid. Each ROI comprises a number of EMI soundings. Depending on the target size, target depth, and data sample resolution a typical ROI will comprise 25-50 useful soundings. Thus, a very large volume of data exists for classification.

There are several options for selecting data to classify. Inversion may be performed on each individual sounding in the ROI or on a subset of soundings within the ROI and the resulting classification features can be averaged to provide one set of polarizabilities for the ROI. Alternatively, data from multiple soundings within the ROI can be aggregated and an inversion can be performed on the resulting aggregate data block. This latter approach can have the benefit of providing a data set that provides optimal constraint on the inversion; however, its effectiveness depends heavily on the accuracy of the position and orientation data. The relative (i.e., point-to-point) position and orientation of the sensor head for each sounding must be incorporated in the forward model to produce effective results. Any errors in the relative position for each sounding can lead to a poor model fit when the inversion is applied.

Based on our APG validation testing, we have found two approaches that produce high quality classification results. Both methods require selecting a subset of soundings to use for inversion. Soundings are automatically selected using data-based metrics, such as the number of receiver channels in each sounding that exceed an SNR threshold or the across-track position of the anomaly peak within the ROI (across-track position of the anomaly determines which soundings provide the best orthogonal magnetic field excitation). Typically, 3-10 soundings within each ROI will meet these criteria. Once the subset of soundings is selected, our first method is to invert the data in each sounding separately to produce several sets of polarizabilities that may be analyzed in "clusters" that correspond to the anomaly source. The second method involves inverting the aggregated data to produce one initial set of polarizabilities. Figure 8, Figure 9, and Figure 10 show the results of applying the first method (inversion on an individual basis and subsequent averaging of the polarizabilities) to the three ROIs shown in Figure 7. The second method (aggregated data) is less practical for high anomaly density areas where increasing the sensor footprint through aggregation increases the number of anomalies in the field of view.

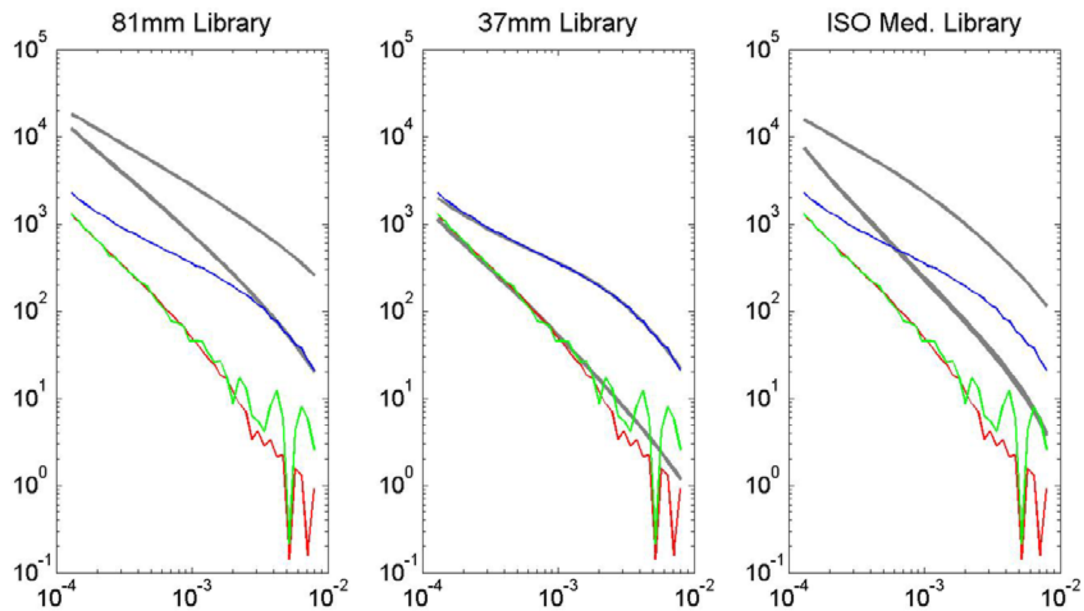

Figure 8. Polarizabilities Recovered from Inversion of the First ROI.

Blue, red, and green lines represent the primary, secondary, and tertiary (respectively) polarizabilities recovered from the ROI dynamic data. Grey lines represent library polarizabilities generated from static calibration data. The results indicate a good match to the 37mm library.

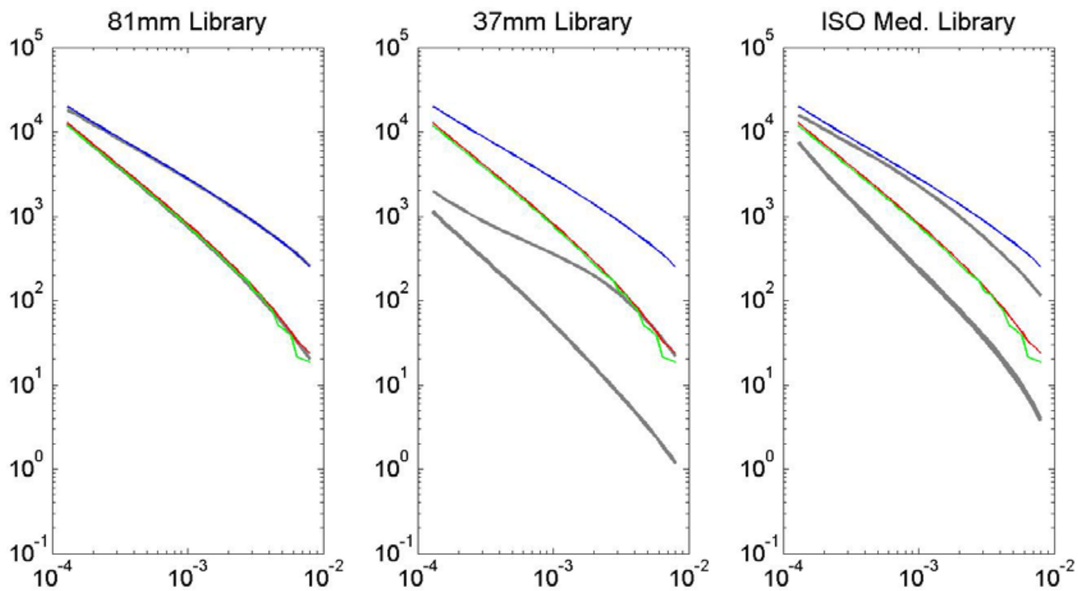

Figure 9. Polarizabilities Recovered from Inversion of the Second ROI.

Blue, red, and green lines represent the primary, secondary, and tertiary (respectively) polarizabilities recovered from the ROI dynamic data. Grey lines represent library polarizabilities generated from static calibration data. The results indicate a good match to the 81mm library.

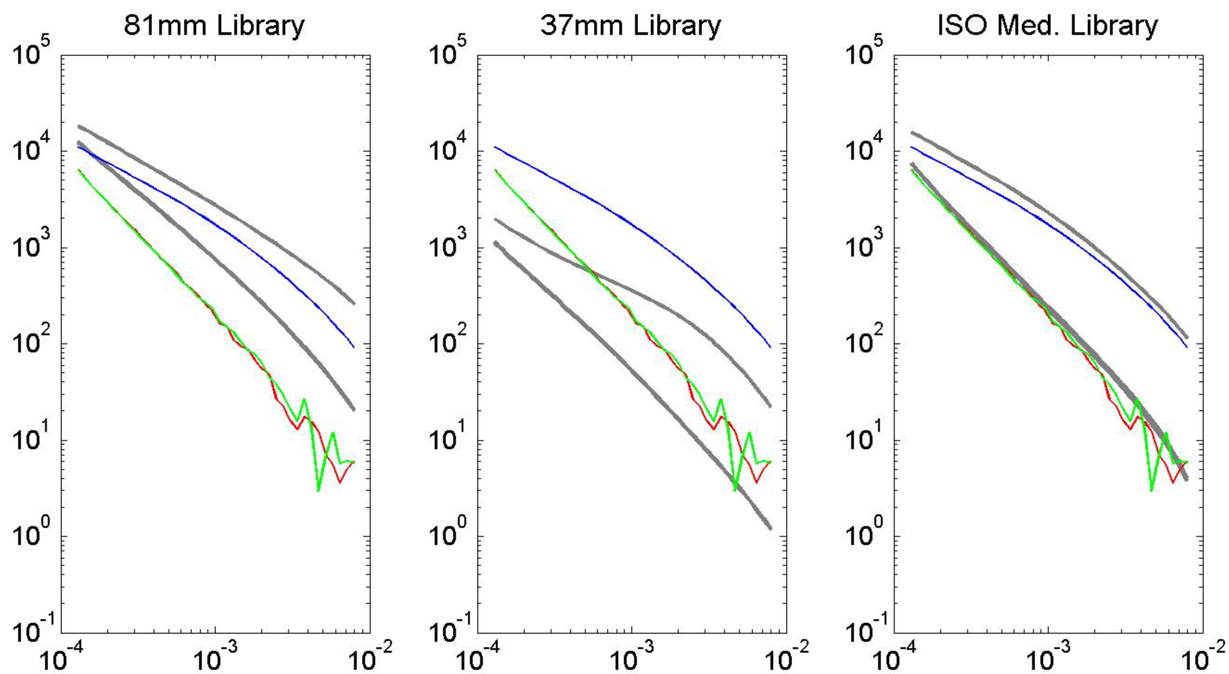

Figure 10. Polarizabilities Recovered from Inversion of the Third ROI.

Blue, red, and green lines represent the primary, secondary, and tertiary (respectively) polarizabilities recovered from the ROI dynamic data. Grey lines represent library polarizabilities generated from static calibration data. The results indicate a good match to the ISO medium library.

For the SWPG demonstration data analysis, we applied the data inversion methods validated during the APG tests. These methods primarily employ inversion of individual soundings (rather than data aggregated from several soundings). Inversion of each sounding on a unique basis provides a greater number of "looks" at each target encounter and minimizes the effects of point-to-point positional error and multiple targets in the field of view.

2.2 TECHNOLOGY DEVELOPMENT

Development of the OPTEMA technology has progressed through two stages. Under project MM-0908, the initial design concept for a one-pass detection and classification system was evaluated to identify optimal hardware components. Initially, this system concept was based on modifications to the Time domain ElectroMagnetic Towed Array Detection System (TEMTADS) hardware, which comprised mono-loop (i.e., single-axis) transmitter and receiver coils. During this preliminary phase of development, early proof-of-concept tests in conjunction with modeling results indicated that it would be beneficial to use three-axis components instead of the TEMTADS coils. Consequently, a first prototype OPTEMA was developed using a modified version of the Advanced Ordnance Locator (AOL) system architecture.

A key feature of this first generation system was the incorporation of the Novatel SPAN, which integrates RTK GPS with a high performance Inertial Navigation System (INS) to produce extremely high precision/accuracy position and orientation data. The initial development stage (project MM-0908) culminated with a demonstration of the first generation OPTEMA prototype at the Yuma Proving Ground (YPG) Standardized UXO Demonstration Site [3].

Under the current demonstration project (MR-201225), we have performed several additional modifications to the earlier prototype. These advances are related primarily to improvements in design feasibility and functionality for production operations. Specifically, we redesigned the sensor head to cover a wider swath. This feature required the addition of 5 receiver cubes (from 9 to 14) and 2 transmitter coils (from 3 to 5) as well as the complete reconfiguration of the sensor head layout. The sensor head design now provides thorough multi-axis illumination and enables high spatial resolution sampling across the entire 1.8m sensor swath. The increase in receivers and transmitters also required several modifications to the data acquisition system, which included the addition of several A/D boards as well as a new version of the data acquisition software.

Another key difference in this next generation system is the absence of the Novatel SPAN. While the SPAN provided very high quality position/orientation data, it proved to be cost prohibitive from a feasibility standpoint. Accordingly, this current stage of development has focused on reducing the classification performance dependency on extremely high accuracy position/orientation data such that standard RTK differential GPS combined with a low cost inertial sensor will suffice for position/orientation requirements. We have tested and implemented the aforementioned data processing methods to create an approach that is not reliant on the highest quality position/orientation data.

A timeline summarizing OPTEMA system development is provided:

- Initial Design Concept 2009 (MM-0908): modeling, simulation, and benchtop data collection to identify optimal hardware components; modified design concept from TEMTADS variant to AOL variant;
- Positioning Requirements Assessment 2009 (MM-0908): proof-of-concept data collection to assess the necessity for high quality position/orientation data; resulted in the incorporation of the Novatel SPAN into the first generation prototype design;
- First Generation System Demonstration 2010/2011 (MM-0908): initial development stage culminated with a demonstration of the AOL-based system at YPG; system included the high performance SPAN during this demonstration;
- Next Generation Design Evaluation 2012 (MR-1225): design and fabrication of custom sensor head components; integration of components in new configuration; integration, testing, and development of new data acquisition hardware and software;
- Data Processing Refinement 2013/2014 (MR-1225): evaluated testbed data to refine classification processing methods that would reduce reliance on position and orientation data; developed software processing modules that incorporated these methods for processing production level data;
- Next Generation System Demonstration 2014 (MR-1225): performed dynamic classification surveys at APG demonstration site to gauge system performance enhancements; system included hardware components described in the previous subsection;
- Live Site Demonstration 2015 (MR-1225): validated dynamic classification performance in live site environment at the Former Southwestern Proving Ground.

2.3 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

The primary advantage of the OPTEMA technology over existing cued EMI sensors is the ability to acquire effective classification data in one-pass dynamic mode. This capability means that the OPTEMA could deliver detection and classification in what would effectively be a DGM survey mode, thus obviating the need for a secondary cued survey. By eliminating the cued survey from the classification work flow, the one-pass method would also eliminate the ambiguity associated with reconciling cued EMI data with dynamic (or DGM) data. Ultimately this approach could lead to higher confidence in classification decisions at reduced project costs.

The main limitation of the current technology is the reduced data SNR compared to that of the advanced sensors (e.g., MetalMapper) operated in cued mode. This lower SNR is due to the data acquisition parameter constraints imposed by the dynamic survey mode (i.e., reduced stacking). These constraints are fundamental to dynamic surveys and will need to be overcome through optimal selection of data processing and inversion methodologies as described in this report.

We believe the challenges associated with reduced data SNR during dynamic surveys can be overcome with effective processing strategies. Results from the initial validation tests at APG did not reveal any significant limitations in detection or classification performance when compared to performance of other advanced cued sensors tested in the same areas [1][4][5].

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3.0 PERFORMANCE OBJECTIVES

Performance objectives for the SWPG demonstration are summarized in Table 3.

Table 3. Performance Objectives.

Performance Objective	Metric	Data Required	Success Criteria
Quantitative Performance Objectives			
Detection of all TOIs	Probability of detection (P_d) of all seeded and native TOIs	• Dynamic OPTEMA data • Ranked anomaly list • Independent scoring report	P_d =1.0 for all TOIs encountered
Maximize False Positive Rejection (FPR) Rate at maximum P_d value	Number of non-TOIs correctly classified as non-TOIs out of total number of non-TOIs	• Dynamic OPTEMA data • Ranked anomaly list • Independent scoring report	FPR>=0.70 for all TOIs detected (i.e., at least 70% digs saved with maximum detection of TOIs)
Effective stop dig decision	Number of TOIs selected as a "dig" out of the total number of TOIs on the list	• Ranked anomaly list • Independent scoring report	Selection of 100% of TOIs on the list as digs with FPR>=0.70
Maximize correct classification of TOIs	Number of TOIs classified as correct type out of total number of TOIs encountered	• Dynamic OPTEMA data • Ranked anomaly list • Independent scoring report	P_{cc}>=0.90 (i.e., 90% or greater correct classification)
Accurate estimation of target locations	Northing, Easting, and depth mean location error (MLE)	• Dynamic OPTEMA data • Estimated target locations • Independent scoring report	N, E, depth MLE <=.10m
Precise estimation of target locations	Northing, Easting, and depth error standard deviation (SDV)	• Dynamic OPTEMA data • Estimated target locations • Independent scoring report	N, E, SDV <=.10m Depth SDV <=.20m
Quantitative Survey Objectives			
Production rate	Effective area surveyed per hour of operation	• Field logs, OPTEMA data file time stamps	>=0.5acre/hr
Area coverage	Effective area covered by the array	• GPS and IMU data from OPTEMA data files	=100% coverage at 1.2m line spacing
Along track sample separation	Distance between consecutive EMI samples	• GPS and IMU data from OPTEMA data files	Mean sample distance throughout each survey line <=.08m Max. sample distance <=.15m SDV of sample distance <=.02m
IVS survey position accuracy	Northing, Easting, and depth location error	• Dynamic OPTEMA data files collected daily over IVS • Estimated target locations	N, E, depth maximum location error <=.15m
IVS survey polarizability accuracy	IVS target polarizability match to library	• Dynamic OPTEMA data files collected daily over IVS • Recovered target polarizabilities	>=95% match to library
Qualitative Performance Objectives			
Ease of use		• Operator feedback regarding ease of operation (e.g., navigation, speed control, etc.)	

3.1 OBJECTIVE: DETECTION OF ALL TARGETS OF INTEREST

Our objective is to detect all seeded and native TOIs encountered for data collected during the dynamic survey. This test establishes the OPTEMA's ability to function as a detection sensor.

Data Requirements

Detections will be identified from the OPTEMA data acquired during the dynamic survey. We will apply a threshold based on the most difficult target scenarios that are specific to the SWPG demonstration site (see Section 6.2 Detection Processing for details on detection threshold selection). After applying dipole model fitting to each ROI, we will generate a list of target locations that correspond to anomaly sources. Independent scoring analysis of our target list will determine detection performance.

Metric

This objective applies a Probability of Detection (Pd) metric to assess performance. Pd values for each area will be generated by taking the ratio of the total number of TOIs detected to the total number of TOIs encountered by the OPTEMA (as determined by ground truth).

Success Criteria

A Pd =1.0 (100% of TOIs detected) will be considered successful.

3.2 OBJECTIVE: MAXIMIZE FALSE POSITIVE REJECTION RATE (FPR)

Our objective is to maximize rejection of false positives (i.e., unnecessary digs) while maintaining correct identification of all TOIs detected (i.e., with Pd value maximized). This metric will be used to assess discrimination performance. Accordingly, we will determine the false positive rejection rate at the maximum Pd level achieved. In other words, if there is a missed TOI detection (i.e., Pd < 100%), we would still determine a FPR rate based on the total number of TOIs detected (i.e., the total number of TOIs presented in the list). If a TOI is present on the list, but is rated with a "no-dig" decision, the FPR rate would be assessed only for non-TOI ranked lower than this item. This approach ensures that potential discrimination performance can be assessed independently of detection performance or analyst confidence.

Data Requirements

We will apply classification to all targets identified from the ROI detections generated from the dynamic survey data. Each ROI will contain a subset of soundings from the dynamic data that corresponded to the anomaly source(s). Based on the results of inverting these data, we will generate a ranked list of likely TOIs. We will place highest confidence TOIs at the top of the list and highest confidence non-TOIs (i.e., clutter) at the bottom of the list. Our objective will be to rank the list such that the last TOI identified on the list would be ranked above at least 70% of the non-TOIs. This list will be submitted for independent ground truth scoring.

Metric

This objective applies a False Positive Rejection (FPR) rate. FPR values will be generated by taking the ratio of the number of non-TOIs ranked below the last TOI on the list (regardless of dig decision for that last TOI) out of the total number of non-TOIs on the list.

Success Criteria

An FPR value >=0.70 (70% clutter rejection) will be considered successful. It should be noted that this value would include any non-TOI that are placed in a "can't analyze" category (which would mean these items would be ranked above the last TOI). This objective FPR value is based on cost estimates described in [6][7] and may be adjusted depending on the site characteristics (i.e., anomaly density) and relative performances of other classification sensors used at the site.

3.3 OBJECTIVE: EFFECTIVE STOP DIG DECISION

The stop dig point provides a good assessment of practical implications for achieving effective classification. The stop dig point indicates the analyst's overall confidence in the system.

Data Requirements

After ranking the anomalies on the list, we will select a stop dig point. Since all anomalies will be assigned a dig or no-dig decision, the last anomaly to be assigned a dig decision will represent the stop dig point.

Metric

The dig decision metric will divide the number of TOIs assigned as a "dig" out of the total number of TOIs on the list.

Success Criteria

Our objective will be to select 100% of the TOIs on the list as a "dig" while maintaining an FPR >=0.70.

3.4 OBJECTIVE: MAXIMIZE CORRECT CLASSIFICATION OF TOIS

Our objective is to correctly classify TOIs by type.

Data Requirements

We will apply classification to all targets identified from the ROI detections generated from the dynamic survey data. Each ROI will contain a subset of soundings from the dynamic data that corresponded to the anomaly source(s). Based on the results of inverting these data, we will generate polarizability curves corresponding to each anomaly source. We will compare these polarizabilities to those of known TOIs at the site to classify each ranked TOI by type. These classifications will be recorded on the ranked anomaly list submitted for independent ground truth scoring.

Metric

This objective applies a Probability of Correct Classification (Pcc) metric. Pcc values will be generated by taking the ratio of the number of TOIs correctly classified by type out of the total number of TOIs encountered.

Success Criteria

A Pcc>=0.90 (90% correct classification) will be considered successful.

3.5 OBJECTIVE: ACCURATE AND PRECISE TARGET LOCATION ESTIMATION

Our objective is to provide accurate and precise estimates of TOI x, y, and z locations (i.e., Easting, Northing, and depth positions).

Data Requirements

We will apply classification to all targets identified from the ROI detections generated from the dynamic survey data. Each ROI will contain a subset of soundings from the dynamic data that corresponded to the anomaly source(s). Based on the results of inverting these data, we will extract position and orientation estimates for each anomaly source, including those corresponding to TOIs. These position estimates will be compared to the ground truth locations of all TOIs.

Metric

Mean Location Error (MLE) and location error Standard Deviation (SDV) will be used as metrics to gauge TOI localization accuracy and precision. The MLE value will be calculated by taking the mean error value of the Northing, Easting, and depth location estimates for all TOIs. The SDV value will be calculated by taking the standard deviation for each of these errors.

Success Criteria

An MLE<=.10m for the Northing/Easting and depth estimates, and an SDV<=.10m and <=.20m for the Northing/Easting and depth errors, respectively, will be considered successful. These values are well within the detection radius used for scoring as well as the search radius used for target reacquisition. The depth error SDV bounds are increased over those of the horizontal location error due to the potential for ground surface standoff variability across the array. Although the target location estimates are equally accurate in all 3 dimensions, because the array is fairly wide (almost 2m) it is likely that ground standoff (i.e., vertical) variation across the array would be greater than any horizontal location errors from the GPS.

3.6 OBJECTIVE: PRODUCTION RATE

Production rate is a useful indicator of the overall efficiency of the one-pass method. It provides a quantifiable metric to be used for comparison to combined production rates associated with DGM/dynamic surveys and cued surveys.

Data Requirements

To determine production rate, we will use the detection maps to identify the total survey area covered by the OPTEMA system. We will then consult field logs and file time stamps to determine an effective survey time. Production time will include time required to collect data along each transect, time required to maneuver the vehicle around obstacles and turn the vehicle around at the end of each line, and time required for regular equipment checks (e.g., battery voltage check, operation parameter adjustments, etc.). To the extent possible, we will not include time spent on inadvertent system down-time associated with delays not related to standard production operations (e.g., sensor malfunctions, survey vehicle stalling, etc.).

Metric

Production rate will be calculated based on the average area surveyed per hour.

Success Criteria

A production rate of 0.5acre/hr or greater will be considered successful. This value forms the basis for our survey cost assumptions (see section 3.2 above).

3.7 OBJECTIVE: AREA COVERAGE

Our objective is to maximize sensor coverage of the survey area. While we have seen that it is possible to detect and classify objects outside of the sensor footprint, full coverage of the survey area will ensure optimal performance.

Data Requirements

To determine the area covered by the array, we will use the GPS and inertial sensor data recorded in the dynamic OPTEMA data files to calculate the sensor position and orientation on the ground during each sample and, therefore, the surface area covered by the array for each survey line. We can then determine if any gaps occurred between adjacent survey lines. We plan to implement 1.2m line spacings. With the 1.8m physical width of the array, this spacing should provide about 60cm overlap between adjacent lines, allowing for +/- 30cm line following error for each survey line.

Metric

Area coverage will be determined by dividing the surface area covered by the array within the survey area by the total survey area.

Success Criteria

Area coverage of 100% will indicate success.

3.8 OBJECTIVE: ALONG TRACK SAMPLE SEPARATION

Our objective is to sample the survey area with enough spatial resolution to detect and classify all TOIs. Because dynamic classification performance is influenced by the density of data acquired, maximizing the number of "looks" at each target by decreasing the along track sample spacing will ensure optimal classification performance is achieved.

Data Requirements

To determine the along track sample spacing, we will use the GPS and inertial sensor data recorded in the dynamic OPTEMA data files to calculate the linear distance between each sounding location.

Metric

For each line we will calculate the distance moved between each consecutive EMI sample.

Success Criteria

Our target sample spacing is 5 cm. Therefore, for each survey line we will require a mean sample distance <=8 cm, a maximum sample distance (over the entire line) <=15 cm, and a sample distance standard deviation <=2 cm.

3.9 OBJECTIVE: IVS SURVEY POSITION ACCURACY

To verify instrument functionality we will conduct regular surveys of the IVS. One metric that indicates basic system functionality is recovery of accurate estimated target locations (based on inversion of dynamic IVS survey data). Recovery of accurate target location estimates ensures that both the EMI and positioning sensors are functioning properly.

Data Requirements

IVS target location estimates require dynamic OPTEMA data files acquired over the IVS targets. These files can be processed in the field to provide estimates of anomaly locations within the IVS.

Metric

The estimated target locations will be compared to the ground truth coordinates for each IVS item location to indicate the accuracy of these location estimates.

Success Criteria

Location estimates that are within 15 cm of the ground truth coordinates will indicate that system components are functioning properly.

3.10 OBJECTIVE: IVS SURVEY POLARIZABILITY ACCURACY

Another metric that indicates basic system functionality is recovery of accurate polarizabilities (based on inversion of dynamic IVS survey data) for targets located in the IVS. Recovery of accurate classification features, such as polarizabilities, is a good indication that the system is functioning properly.

Data Requirements

Recovery of IVS target polarizabilities will require dynamic OPTEMA data files acquired over the IVS targets. These files can be processed in the field to provide classification features, such as polarizabilities, for each anomaly encountered in the IVS.

Metric

Polarizabilities recovered from each IVS target encounter will be compared to standard libraries for each of these IVS items. A mean squared difference is applied to produce a metric that indicates the fit quality between the recovered polarizabilities and the library polarizabilities.

Success Criteria

A fit quality of >=95% between the recovered and library polarizabilities for each IVS target will indicate success.

4.0 SITE DESCRIPTION

The live site demonstration was conducted at the former Southwestern Proving Ground located near Hope, AR. The SWPG was built in 1941 to prepare for the U.S. engagement in World War II. Between 1942 and 1945, the proving ground served for testing small arms ammunition, 20 to 155 mm projectiles, mortars, rockets, grenades, and up to 500-lb bombs [8]. Following the end of World War II, the proving ground was closed and surface clearance activities were performed to remove ordnance prior to transferring the lands back to private, municipal, and state owners. Since the initial clearance, however, MEC have continually surfaced and over 8,000 ordnance items have been removed from private property located on the former proving ground. More detailed information regarding the SWPG site history can be found on the USACE web site:

http://www.swl.usace.army.mil/Missions/MilitaryMissions/FormerlyUsedDefenseSites.aspx

4.1 SITE SELECTION

Our survey area was a 4 acre portion of Recovery Field 15 (RF-15), which is located in a part of the former SWPG that has been repurposed for agricultural use (see Figure 11). The site is suitable for towed array surveys as there is minimal vegetation (hayfield), moderate terrain (mostly flat to rolling), and minimal surface disturbance (periodic agricultural activity).

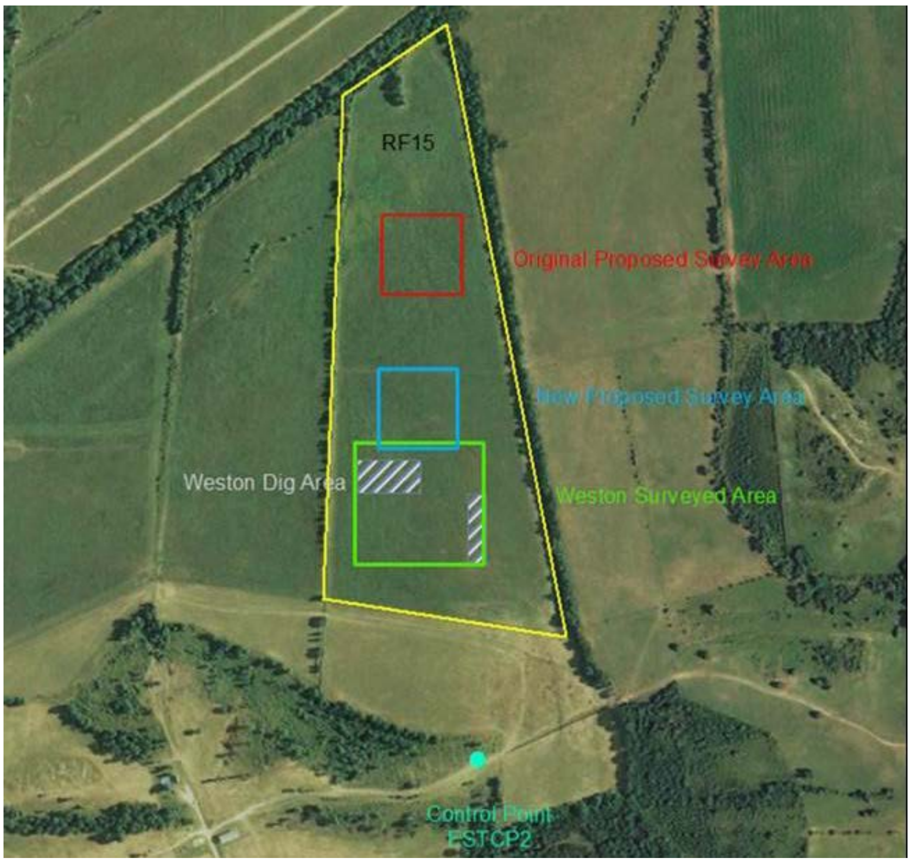


Figure 11. The Survey Area (Blue Square) is a 4 Acre Portion of Recovery Field 15 Located within the Boundaries of the Former SWPG.

This site was selected for its surface conditions (Figure 12), which are amenable to larger towed systems, and its anomaly density (previous activities at this site have indicated that it provides a fairly high anomaly density of ~2000+/acre). The most notable feature of the site topography was the pockmarked surface resulting from the daily grazing activities of a nearby herd of cattle. These ground conditions did not impact the vehicle advance rate, but did jostle the sled noticeably throughout the survey.

Figure 12. OPTEMA Dynamic Survey in RF-15 of the Former SWPG.

4.2 TARGETS OF INTEREST

Suspected targets of interest at the site include: 20mm, 37mm, 40mm, 57mm, 75mm, 76mm, 90mm, 105mm, 120mm, and 155mm projectiles, as well as 81mm mortars. The most difficult target scenarios are expected to be 20mm projectiles buried at 6 inch depths and 37mm projectiles buried at 12 inch depths. Libraries for all of the aforementioned targets were included in our analysis.

5.0 TEST DESIGN

The field component of the demonstration was designed to provide the data required for evaluating the performance objectives described in section 3. Details of the field test are described in the following subsections.

5.1 CONCEPTUAL EXPERIMENTAL DESIGN

The OPTEMA field study was coordinated with other advanced sensor survey activities within the same 4 acre portion of RF-15 during September 2015. A field team from Tetra Tech was performing dynamic MetalMapper and cued TEMTADS data collection as part of an on-going live site demonstration project (MR-201423). The Tetra Tech project provided the logistical support for the multi-system demonstration in RF-15. This support included target seeding, IVS setup, and intrusive investigation. The OPTEMA survey was scheduled over a 6 day period that coincided with the Tetra Tech team's ongoing cued TEMTADS survey.

The OPTEMA demonstration comprised site mobilization, sensor calibration/verification, a one-pass dynamic OPTEMA survey conducted over the 4 acres in RF-15, in-field data quality control, transect recollects (as indicated by the in-field QC), and demobilization. Initial calibration activities were used to verify instrument functionality following site mobilization, develop site specific noise thresholds, and to generate any site specific TOI libraries. These initial test activities included: static data collection over calibration items to generate polarizability libraries for items likely to be encountered in the survey area, and dynamic surveys over the IVS to test positional accuracy and instrument functionality as well as to determine noise characteristics. Once initial system verification was complete, our team conducted a dynamic survey of the 4 acre area. Table 4 presents a schedule of the completed field activities.

Table 4. Schedule of SWPG Field Activities.

5.2 SITE PREPARATION

Site preparation was provided by the Tetra Tech team under project MR-201423. Preparation included TOI seeding, IVS installation, and control point surveys. The IVS layout used for the SWPG RF-15 demonstration is presented in Table 5.

Table 5. SWPG RF-15 IVS

Item ID	Description	Northing (m)	Easting (m)	Depth (m)	Inclination	Azimuth
T-001	Shot put	3744124.466	438750.535	0.15	N/A	N/A
T-002	57 mm projectile	3744129.371	438749.624	0.3	Horizontal	Across Track
T-003	37 mm projectile	3744134.255	438748.74	0.15	Horizontal	Across Track
T-004	Blank space	3744139.208	438747.903	N/A	N/A	N/A
T-005	90 mm projectile	3744144.35	438747.003	0.45	Horizontal	Across Track

5.3 SYSTEM SPECIFICATION

The OPTEMA comprises five transmitter coils and fourteen 3-axis receiver cubes. The five transmitters include one large base Z-directed (vertical axis) transmitter that surrounds two pairs of X'- and Y'- directed (horizontal axis) transmitters. The Z-transmitter dimensions are 1.8m x 1.0m and the X'- and Y'- (primed coordinates denote 45 degree rotation to primary reference frame) transmitters are 1.22m x 1.0m. Figure 13 shows a diagram of the transmitter layout and dimensions.

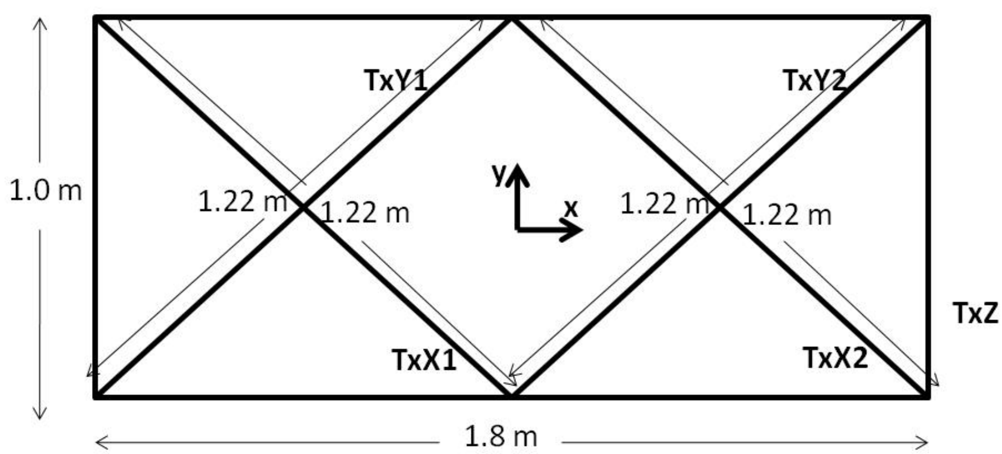
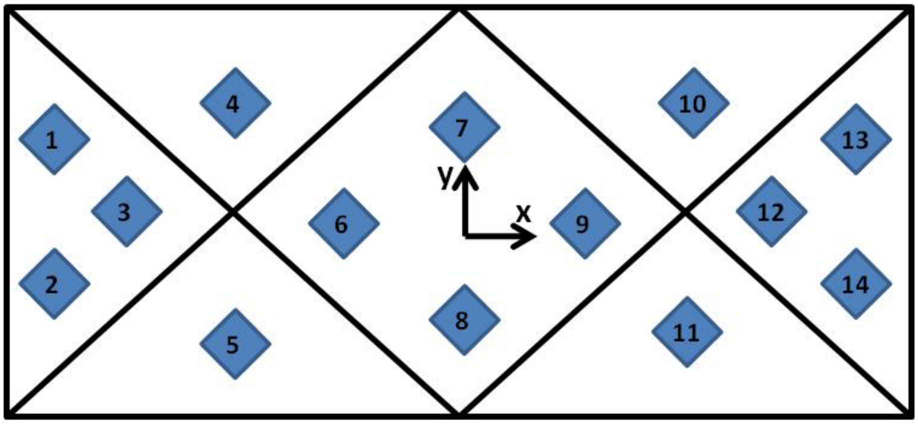


Figure 13. OPTEMA Transmitter Layout and Dimensions.

The receivers are the standard G&G Sciences 10cm cubes developed for advanced EMI sensors (Figure 14). These cubes are rotated 45 degrees to the main reference frame, in-line with the horizontal axis transmitters. Figure 14 shows the layout of the receiver cubes within the OPTEMA sensor head.



Rx positions: [x y z] (unprimed):

```
rx1=[-.765 .107 0.01];
rx2=[-.765 -.162 0.01];
rx3=[-.629 -.032 0.01];
rx4=[-.412 .242 0.01];
rx5=[-.413 -.257 0.01];
rx6=[-.188 -.046 0.01];
rx7=[.042 .182 0.01];
rx8=[-.026 -.205 0.01];
rx9=[.200 .017 0.01];
rx10=[.419 .237 0.01];
rx11=[.422 -.241 0.01];
rx12=[.626 .044 0.01];
rx13=[.761 .173 0.01];
rx14=[.770 -.107 0.01];
```

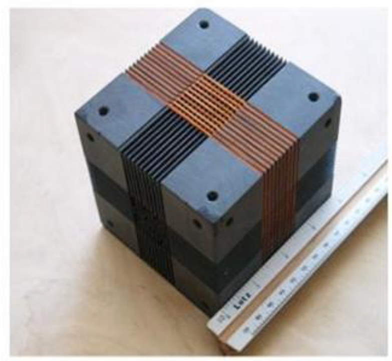


Figure 14. OPTEMA Sensor Head Receiver Cube Layout.

Receiver cubes are 10cm.

The OPTEMA sensor head is mounted in a non-metallic tow sled. The sled features a wooden tow boom, a protective skid plate, and solid rubber tires. In flat terrain, the sled rolls on the wheels; however, the skid plate provides additional support in more challenging terrain conditions. During the SWPG demonstration, the pockmarked ground surface meant that some portion of the skid plate on the bottom of the sled was typically in contact with ground. The vehicle tow bar puts the leading edge of the OPTEMA sensor head approximately three meters behind the hitch point on the vehicle. Figure 15 shows a picture of the sensor tow sled operating in RF-15.

Figure 15. OPTEMA Tow Sled at SWPG.

The OPTEMA incorporates a Trimble Real Time Kinematic Differential GPS for sensor head position data. A Trimble R10 receiver is mounted directly above the center of the sensor head. Inertial measurements are provided by a Microstrain 3DM-GX3-25 orientation sensor. The Euler angle outputs provide pitch, roll, and yaw measurements for the OPTEMA sensor head. The IMU is co-located with the GPS receiver.

OPTEMA sensor electronics include the transmitter and receiver modules, data acquisition computer, and power inverter. Electronics are mounted in a 2’x 2’x 3’ (LxWxH) enclosure that can be fastened to the bed of any tow vehicle. A pair of deep cycle marine batteries provide +/-12V for the transmitter and receiver modules. A single deep cycle battery provides 12V for the inverter, which supplies power for the data acquisition computer. An operator PC can be connected to the data acquisition computer via remote desktop through an Ethernet cable.

The transmitter controller provides switching at 60 Hz subharmonics at 50% duty cycle. This design produces a bipolar square waveform with a user selected period. The waveform period determines the decay window measured by the receivers. For the SWPG demonstration, an 8.3ms decay window was used for dynamic survey mode (see Table 2 for reference). The number of waveform repeats in each data block (a single Transmit-Z, Transmit-Y, or Transmit-X sequence) is a function of the waveform period selected. Figure 16 shows an example of a sequence of 3 data blocks corresponding to an 8.3ms decay period.

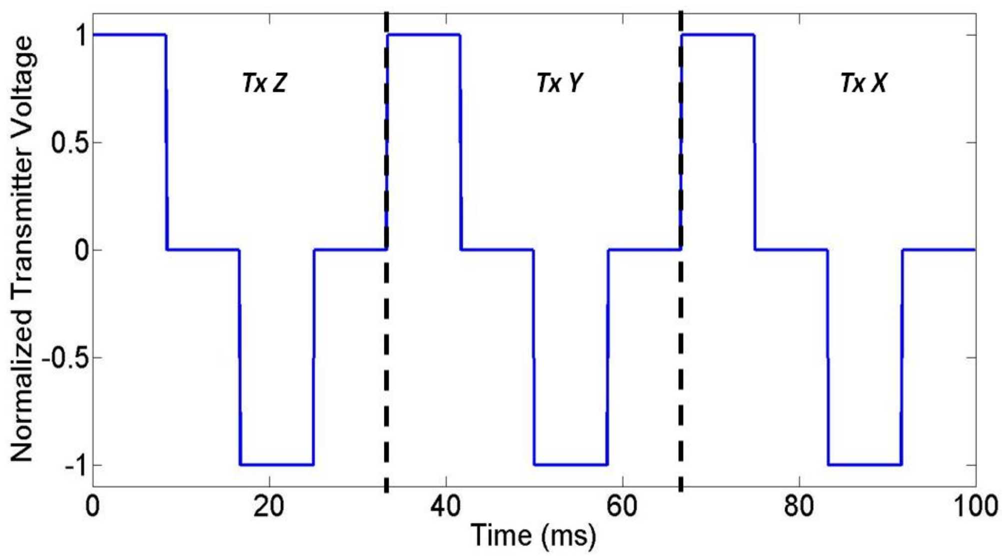


Figure 16. Waveform Corresponding to 3 OPTEMA Data Blocks.

Each block comprises one sequence of Transmit-Z, Transmit-Y, or Transmit-X. The number of base waveform repeats for each transmitter cycle depends on the decay period selected. This example shows an 8.3ms decay period. This period produces only 1 repeat for each transmitter cycle. If stacking is increased, this complete sequence (three blocks) is repeated and the result is averaged.

5.4 CALIBRATION ACTIVITIES

Calibration activities at the SWPG demonstration site consisted of both initial and daily calibration routines. We performed initial system verification and baseline measurements over the IVS. Initial calibration activities included basic instrument verification measurements such as noise and static (spike) tests. These instrument verification measurements were conducted with the OPTEMA system located in a clean (anomaly free) area within the IVS (T-004 in Table 5).

For the initial noise test, we acquired dynamic OPTEMA data over the blank portion (~2-3m) of the IVS. These data provided approximately 40 – 80 samples from which we acquired baseline dynamic noise characteristics for the site. To calculate the OPTEMA noise floor, the standard deviation of these N data points from each time-channel for each of the 126 transmitter-receiver combinations was calculated. We then compared the baseline standard deviation spread to the typical operating thresholds we have applied at other sites (e.g., APG, WRT facility, etc.). These thresholds set the typical upper and lower bound limits that are used to quantify the normal noise characteristics expected during dynamic operations. During our initial calibration tests, we found that the OPTEMA dynamic noise characteristics acquired in the SWPG IVS were within the bounds used for previous sites. Therefore, no adjustments were made to these dynamic noise operating thresholds.

Regular monitoring of dynamic noise levels during IVS surveys helps to identify any significant deviations in sensor noise on a day-to-day basis. Significant deviations in data channel noise may be indicative of a hardware fault. An example of instrument noise standard deviation for SWPG IVS data is shown in Figure 17, which also shows the upper and lower bounds applied throughout the SWPG survey. This standard deviation analysis was performed on an initial basis for verification of the threshold settings, and subsequently on a twice daily basis for quality monitoring purposes.

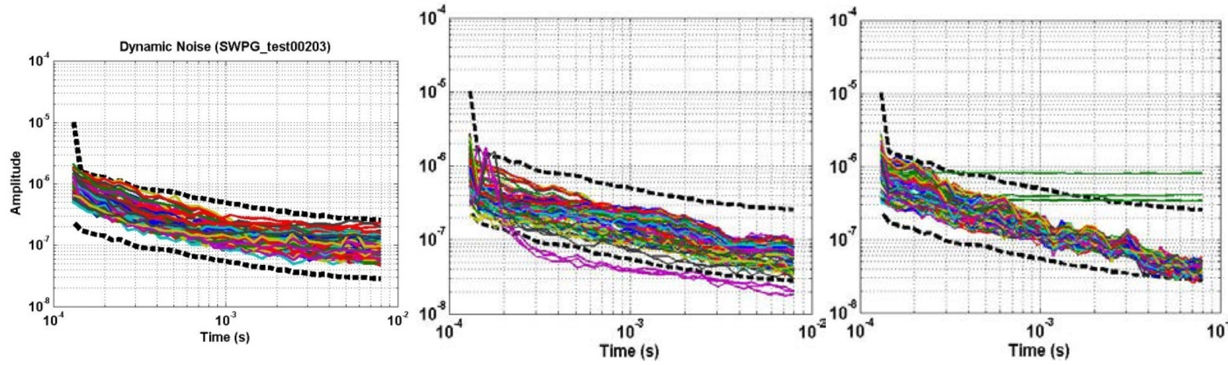


Figure 17. Example of Instrument Noise Standard Deviation for all 126 OPTEMA Data Channels.

The dashed black lines represent the normal operating bounds used for the SWPG data. The left plot shows normal noise characteristics acquired in the IVS. The center plot shows non-conformities caused by a bad cable. The right plot shows non-conformities caused by a spurious receiver channel.

Static, or spike, tests were used to verify consistency in data channel output on a daily basis. Static tests were performed with the OPTEMA stationed in the blank IVS spot. Setting the OPTEMA data acquisition parameters to static mode (Table 1) a calibration ball was placed in a test jig centered over each receiver cube (Figure 18). This test provides another measurement of instrument consistency. The calibration ball response in each principal data channel (i.e., Transmit-Z/Receive-Z, Transmit-Y/Receive-Y, Transmit-X/Receive-X) should be repeatable within 10% deviation on each test (some deviation may be caused by small jig placement inconsistencies). Any significant deviations in the calibration ball response may be indicative of hardware faults. An example of the principal data channel calibration ball response is shown in Figure 19. This test was performed on an initial basis for baseline reference, and subsequently on a twice daily basis for quality monitoring.

Figure 18. Calibration Ball Spike Test.

A calibration ball is placed over each receiver cube in a repeatable location to identify any inconsistencies in data channel output.

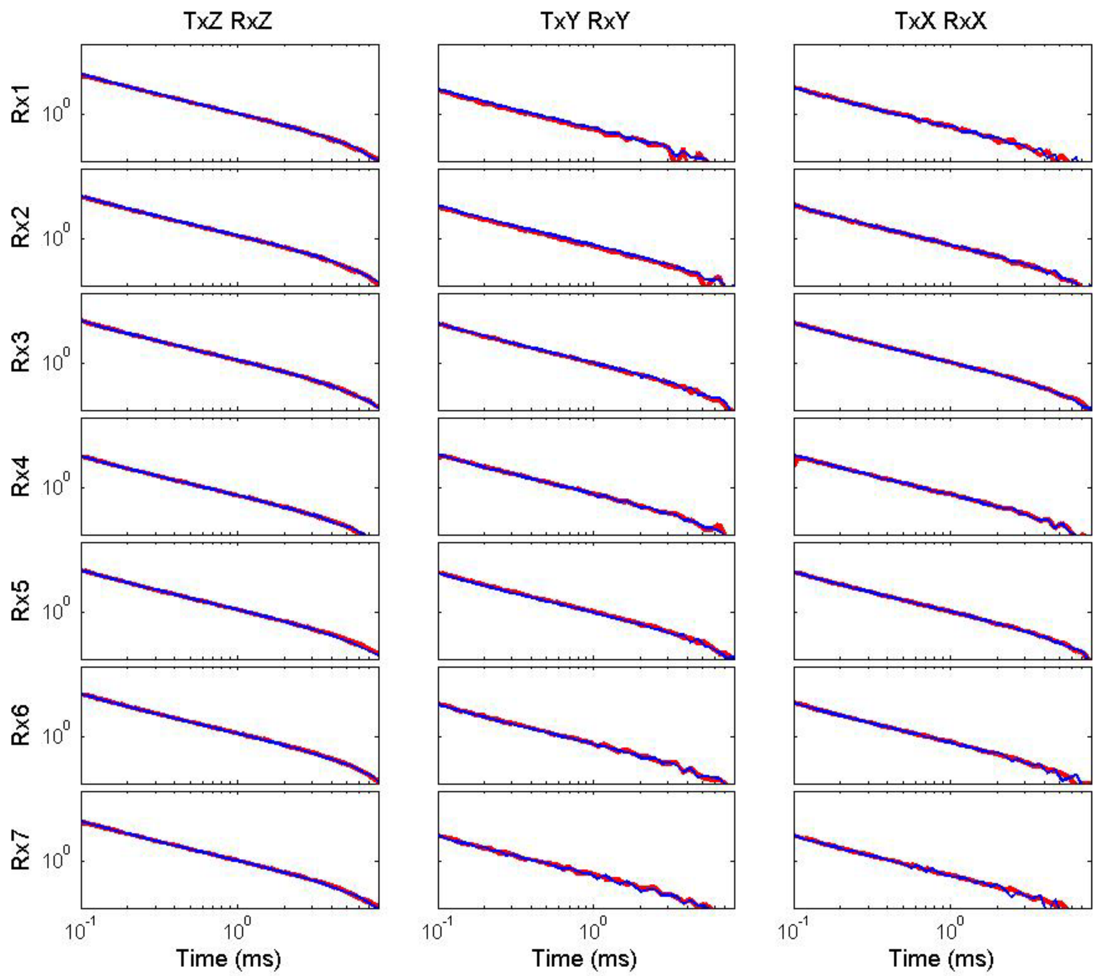
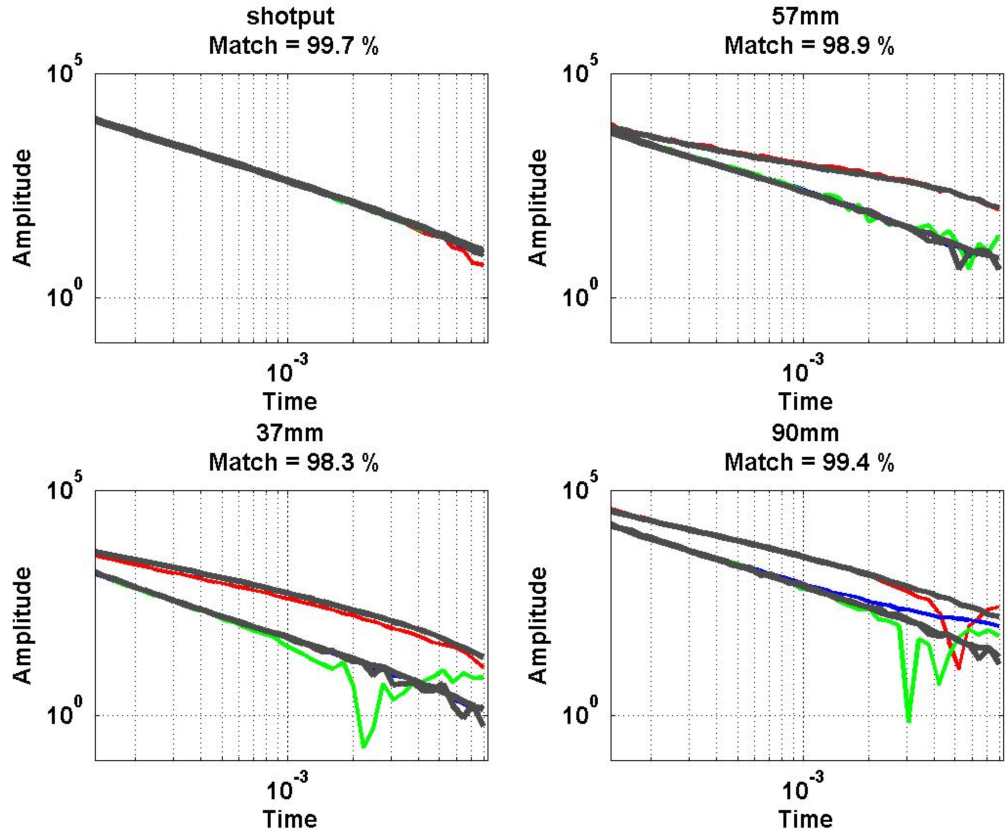


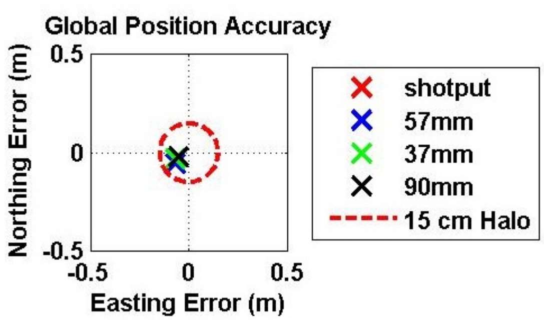
Figure 19. Calibration Ball Response in Principal Tx-Rx Pairings for Seven Receiver Cubes.

The red line indicates the reference measurement; the blue line indicates the measured response.

Initial calibration activities also included static measurements over IVS items. These static data were used to generate polarizability libraries for TOIs in the survey area and to provide reference libraries for subsequent dynamic IVS measurements. For each TOI type in the IVS, we acquired 3-4 static measurements with each X’-/Y’- pair of transmitters approximately centered over the target. By centering each transmitter pair over the target, we could measure the response across the complete sensor swath; ensuring consistent results were achieved using any subset of data channels within the array.

Reference IVS polarizabilities were also used on a daily basis for instrument verification. During the daily IVS tests, we acquired dynamic data over IVS targets to ensure that the polarizabilities recovered from dynamic data were consistent on a day-to-day basis. Polarizabilities recovered from IVS data should match the reference libraries with 95% fit for dynamic IVS survey data. Additionally, estimated target location coordinates recovered from inversion of the IVS data should be within 15cm of the ground truth coordinates. Thus, this test serves as a measurement of instrument consistency as well as model consistency. Figure 20 shows an example of dynamic IVS data results from a daily SWPG IVS survey.





Inverted Depth Accuracy

IVS Target	Burial Depth (m)	Inverted Depth (m)	Error (m)
T001	0.15	0.10	-0.05
T002	0.30	0.31	0.01
T003	0.15	0.10	-0.05
T005	0.45	0.43	-0.02

Figure 20. Examples of Library Matching and Estimated Location Accuracy for Dynamic IVS Data Polarizabilities.

Because the dynamic polarizabilities are noisier than those from static measurements, the fit metric is adjusted to be less sensitive to model noise beyond the 2ms decay period. As an example this figure shows polarizabilities obtained from dynamic survey data over the four targets in the SWPG IVS. These measurements were performed at least twice daily to ensure consistent data quality.

Instrument verification surveys were conducted at least twice daily (morning, afternoon, and typically mid-day) to ensure consistency throughout each day of operation. For each IVS survey, we performed two dynamic passes over the IVS. The first pass was performed with the left side horizontal transmitter pair centered over the targets and the second pass was performed with the right side horizontal transmitter pair centered over the targets. These two offsets ensured that all receiver channels were adequately assessed. For each pass, we determined the polarizability match and estimated location for each target, and assessed the dynamic noise standard deviation.

5.5 DATA COLLECTION PROCEDURES

OPTEMA data collection procedures included those for both static and dynamic modes. The static data collection mode was used initially for library data collection and daily for instrument verification (calibration ball spikes). Dynamic mode was used daily for instrument verification as well as for the primary data collection effort in the survey area. Table 1 and Table 2 (section 2.1) show the default static and dynamic (8.3 ms decay) mode acquisition parameter settings, respectively.

Static measurements were only performed in the IVS for initial calibration and daily instrument verification. These measurements required an initial background measurement acquired in the IVS blank. We applied this measurement for background subtraction from subsequent static measurements made during calibration. We collected static measurements for library data and daily spike tests. Static measurements over library targets were made with both pairs of horizontal axis transmitters centered over the target to verify measurement consistency across the entire swath of the array.

We performed dynamic measurements as part of the IVS tests as well as for the survey. Initial and daily dynamic measurements were performed over the IVS using two full passes over the IVS targets to verify functionality and positioning accuracy in dynamic mode. We performed these procedures at least twice daily to ensure that recovery of IVS target locations and polarizabilities were consistent throughout the duration of the survey. We applied the same data acquisition parameters for both the IVS tests and the 4 acre survey.

Background measurements are not required for dynamic data collection. Because dynamic surveys cover both anomalies and background regions, background measurements can be pulled directly from the dynamic data to be used for subtraction from the ROIs.

Navigation for both static and dynamic measurements was provided by WRT navigation software. Line segment files (for dynamic measurements) and cued files (for static measurements) were generated prior to conducting the survey. We used the surveyed coordinates of the IVS items to generate cues for each target in the IVS. Applying the grid coordinates for the 4 acre survey area, we generated transect lines for the one pass survey. Format for each cue is a standard longitude, latitude coordinate in decimal degrees. Format for line segments is the longitude, latitude of each line endpoints in decimal degrees. For the SWPG survey, we used a 1.2m spacing for transect lines in the survey. This spacing provided sufficient array overlap to minimize the potential for line gaps.

Two survey control points (ESTCP1 and ESTCP2) were established prior to the demonstration activities. We initially planned to use ESTCP2, which was closest to the survey area (see Figure 11); however, due to the ongoing TEMTADS survey activities, this control point was already allocated to the TEMTADS team. Instead, we used a third (unnamed) control point established by the TEMTADS team before our arrival on site. This control point was a short distance (10-20m) from ESTCP2 so provided the same line-of-sight to the survey area. We used the surveyed IVS locations to verify the base station was configured with the proper reference coordinates. By placing the GPS rover over the IVS target locations, we verified that these measurements matched the ground truth IVS coordinates (Table 5).

Throughout the survey, we ensured that all EMI survey activities maintained the highest RTK GPS quality of “RTK Fixed”. We performed in-field quality checks of each survey line for along-track sample spacing and GPS quality to identify any potential drop in positional accuracy. Lines containing any data acquired without RTK Fixed quality would be recollected.

Regular quality checks also included identification of any discrepancies in receiver channel output that might indicate sensor faults. Such faults could be identified through the analysis of the daily calibration ball tests and the dynamic noise tests conducted in the IVS. Additionally, we performed in-field quality checks of data from each line collected in the survey area. For each survey line, we assessed the along track sample spacing, the across track line spacing, and the dynamic noise levels acquired over background locations. This in-field analysis was conducted using the survey quality metrics described in Section 3. This procedure ensured that any survey lines containing faulty data, sample errors, low GPS quality, or line gaps would be recollected before demobilizing.

Dynamic data files can be quite large. The OPTEMA generates data samples at a rate of 10 Hz in dynamic mode, which can produce as much as 250MB for 10 minutes of operation. We acquired over 20GB of data to complete the 4 acre area. To facilitate daily data transfer and storage, we used an external drive to periodically offload data files from the DAQ. At the end of each day, these files were brought back to the hotel, where we transferred them to a Google Drive folder. This practice ensured that all data were secured before demobilizing.

5.6 VALIDATION

Upon completion of the SWPG data collection, we generated detection and dig lists using standard UXO live site demonstration scoring formats. Because of the high anomaly density, intrusive investigation of the entire 4 acre area could not be performed under the demonstration scope. A subset of 3 focus areas was identified for intrusive investigation. These areas contained a total of 2022 anomalies that were intrusively investigated. Due to the sequence of the multi-system demonstration, target picks were based primarily on the TEMTADS picks (from a dynamic MetalMapper survey performed earlier in the summer); however, we did provide a list of OPTEMA picks for the largest of the three focus areas (Figure 21) that was incorporated in the intrusive investigation.

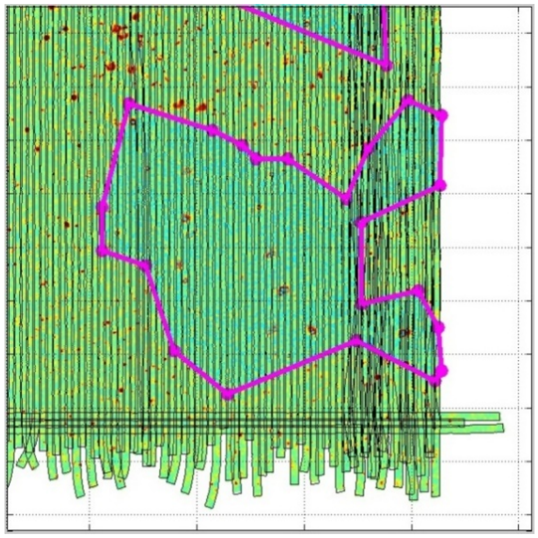


Figure 21. The Largest of the Three Sub-areas was the Southeast Corner Focus Area (Highlighted Here on the OPTEMA Detection Map).

OPTEMA target picks in this sub-area were submitted for intrusive investigation.

We generated ranked anomaly lists for the three focus areas. Final ranked anomaly lists included confidence rankings of anomalies in the focus areas with highest confidence TOI rankings at the top of the list and highest confidence non-TOI rankings at the bottom of the list. These results were submitted to the Program Office for subsequent independent scoring by the Institute for Defense Analyses (IDA).

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6.0 DATA ANALYSIS AND PRODUCTS

OPTEMA data analysis includes preprocessing, detection processing, and classification processing and analysis stages.

6.1 PREPROCESSING

Initial preprocessing steps are similar for both static and dynamic data. A transmitter current normalization is performed on all OPTEMA data files by dividing all data channel values by the peak current value corresponding to the appropriate transmitter (e.g., Transmit-Y/Receive-Z data channels are divided by the peak Y-transmitter current). This process ensures that only the size and number of windings (both of which are constant) for each transmitter affect the response measured. Thus, no discrepancies in transmitter current (which may vary) will influence the data. Current normalization is performed once for a static data file and is repeated for each sounding in a dynamic file.

After each data file is current-normalized, a background subtraction step is performed using different methods for static and dynamic files. For static data files, background subtraction is performed by subtracting the value of each data channel in a background data file from the corresponding data channel value in a data file. Background data are collected with the OPTEMA sensor stationed over a clean (anomaly free) area of the site (e.g., IVS blank). Background subtraction for dynamic files is performed by detrending the data acquired along each survey line. A window length containing N-samples is selected and the median value of the N samples contained in this window is removed from the datum centered in the window. The window is then moved by one sample and this process is repeated along the entire line for each receiver channel.

For dynamic files only, a final preprocessing step is performed to smooth the data. This step includes low-pass filtering of each data channel throughout a transect line to reduce point-to-point jitter. This smoothing step greatly improves SNR of the data for classification (Figure 22).

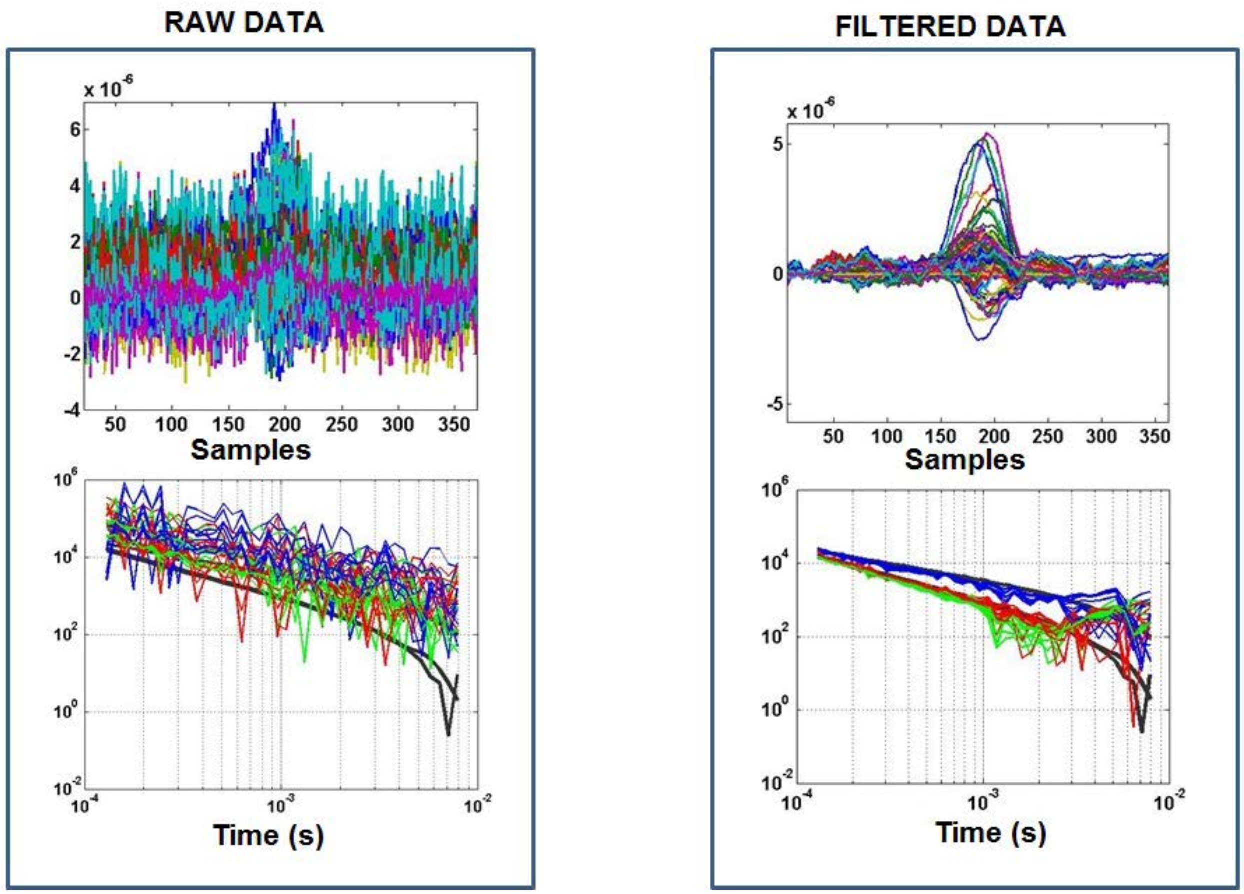

Figure 22. Raw (Left) and Filtered (Right) Dynamic Data Corresponding to an 81mm Projectile at 1 Meter Depth.

The top plots show the transect profile over the 81mm for all receiver channels. The bottom plots show the polarizabilities (green, red, and blue) resulting from inversion of the data compared to the 81mm library (grey). It is evident that the filtered data produce higher quality polarizabilities for classification.

6.2 DETECTION PROCESSING

Detection maps are created by processing dynamic data files. Detection processing requires data gridding for each transmit/receive pairing. GPS latitude/longitude values are converted to UTM coordinates (Easting / Northing). Each sounding in a dynamic file is associated with a GPS Easting and Northing coordinate and a measurement of sensor head pitch, roll, and yaw angles. Receiver cube positions for each sounding are calculated by applying an Euler transformation to the vector from the center of the GPS antenna to the center of each receiver cube. This transformation creates an Easting/Northing position for each receiver cube for each sounding.

For each principal transmit/receive pairing (i.e., Transmit-Z/Receive-Z, Transmit-Y/Receive-Y, Transmit-X/Receive-X), a data value is generated for each receiver cube by summing the values of the time gates spanning 130 μs to 566 μs in the corresponding data channel. These data values are then mapped to a 2-D space using the receiver cube locations. Finally, 2-D interpolation is applied to generate the final uniformly-spaced X-, Y-, and Z- data maps. Figure 23 shows the Z-data map for the 4-acre survey area in RF15.

WRT Data Collection Display Tool

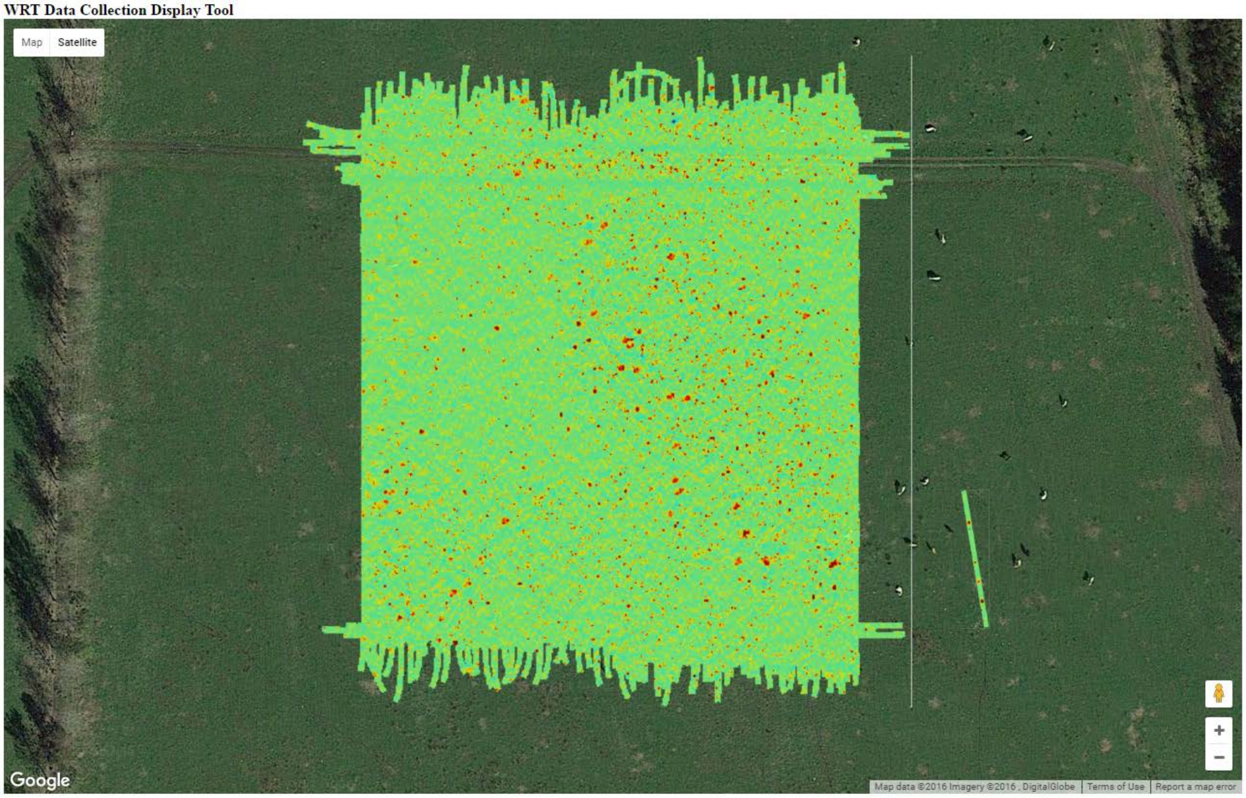

Figure 23. OPTEMA Z-component Data Map for the 4-acre Area in RF15.

A peak detection algorithm is applied to the Z-component map using a threshold based on the data noise floor standard deviation or site-specific TOI detection thresholds. A detection radius is applied to identify the ROI surrounding each peak. The radius size is based on the local gradient associated with the peak and the number of peaks associated with an anomaly (1 peak for Z-component data). If ROIs associated with multiple peaks overlap, a combined ROI is generated that encompasses the multiple detections. Finally, across track and along track indices are generated for each alarm in an ROI. These indices correspond to the receiver cube and sounding number associated with each alarm and provide the initial starting parameters for the inversion. Each ROI is saved as a data volume (number of soundings X number of time gates X number of data channels) in .mat format. Alarm indices and UTM coordinates are saved as part of the data structure as well.

For the SWPG demonstration, we selected a detection threshold based on the suspected TOI's for the site. Prior to the survey, we generated depth response curves for the most difficult orientations for each TOI and verified these response curves with test stand data. Figure 24 shows response curves plotted for different TOI's. These curves show the detection channel outputs (sum time gates 130 µs to 566 µs) at each depth for each TOI. The detection threshold applied to the SWPG data is shown as the red dashed line in Figure 24.

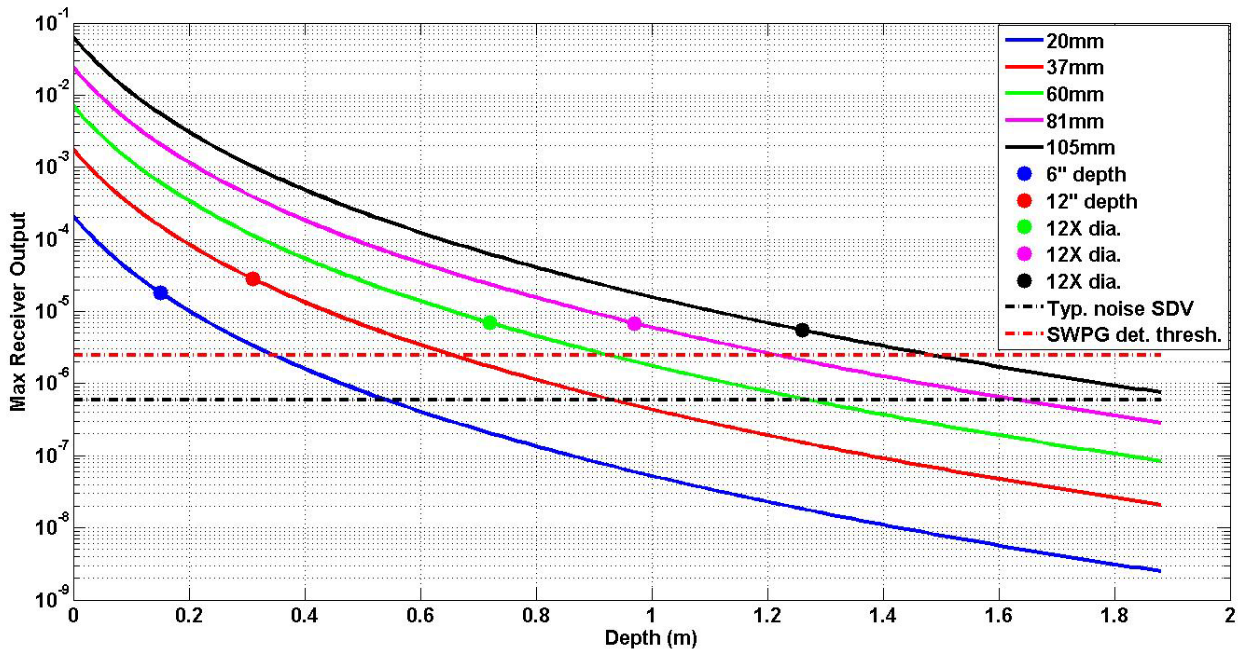

Figure 24. OPTEMA Response Curves for Different TOI's.

The dots indicate the expected depth of clearance for each TOI. The red dashed line is the detection threshold for SWPG to ensure all TOI's are detected to the required clearance depths. For reference, the black dashed line shows the typical dynamic noise floor for all data channels (taken from dynamic data collected in an anomaly free area).

6.3 CLASSIFICATION PROCESSING

Following detection processing, all ROIs are further processed for classification analysis. The first step in classification processing is to improve the relative point-to-point positional accuracy within each ROI. Because the inversion algorithm relies on relative, not absolute, positioning between consecutive soundings removing small absolute positioning errors associated with GPS accuracy can enhance the classification performance by improving the accuracy of the calculated relative distance traveled between each sample. An initial filtering step is performed by comparing the calculated point-to-point GPS heading to the value calculated by averaging consecutive IMU heading measurements. The calculated GPS point-to-point distance traveled is projected onto the IMU heading vector to establish the relative position traveled between consecutive soundings. These relative positions are then assigned to each sounding within the detection ROI.

Position vectors corresponding to the center of the OPTEMA array at each sounding location within the ROI are generated using the relative point-to-point positions. These relative position vectors are referenced to the position of the OPTEMA during the peak response measurement (i.e., peak detection position of the OPTEMA center is [0 0 0] in [x y z]).

Based on the across track and along track indices for each ROI alarm, a subset of soundings is selected from the ROI dynamic data for inversion. For the SWPG data processing, we selected all soundings acquired when the sensor head center was within 1 meter of the ROI alarm peak. For each of these soundings, an inversion was applied to fit a dipole-based forward model to the data using a least squares method. The forward model accounts for the sensor array geometry, the position of the array relative to the target, and the target physical features, which are modeled as a set of orthogonal magnetic dipoles (i.e., polarizability tensor). Once model parameters are chosen to minimize the error between the data and the model output, the resulting target polarizabilities are selected for feature classification.

Starting parameters for the inversion, such as target position, are chosen based on the detection parameters (i.e., across track and along track indices for each alarm). Additionally, these detection parameters may be used to identify potential multi-object scenarios. For an example, if an ROI includes two unique alarms a two-source forward model is applied to the data inversion.

Finally a clustering step is performed such that each ROI detection is associated with a unique set of polarizabilities generated from the data inversion. Clusters are generated by grouping polarizabilities that have similar size and decay characteristics and that are associated with estimated locations within a confined area (e.g., within a 15 cm radius). This process removes any outlier polarizabilities that do not present features resembling those of a nearby group. Each remaining group of polarizabilities is assigned to an ROI detection and these groups are used to classify and rank the anomalies.

6.4 CLASSIFICATION ANALYSIS

After classification processing is complete, principal polarizabilities for each ROI detection are analyzed for classification of features. Automated TOI rankings are assigned based either on polarizability fits to TOI libraries or on specific classification features derived from the polarizabilities. For the SWPG demonstration, we used the ratio of the late time to early time separation between the primary and tertiary polarizabilities as the ranking feature (larger values at the top of the list; smaller values at the bottom of the list). This feature was used in lieu of a library match given the possibility for new TOI that were not in the libraries. For each ROI detection, the feature is derived from the average of the associated polarizability cluster.

Once the initial automated ranking stage is complete, an analyst reviews the polarizability clusters against the nearest library match as well as the estimated location clusters plotted on the 2D detection map (Figure 25).

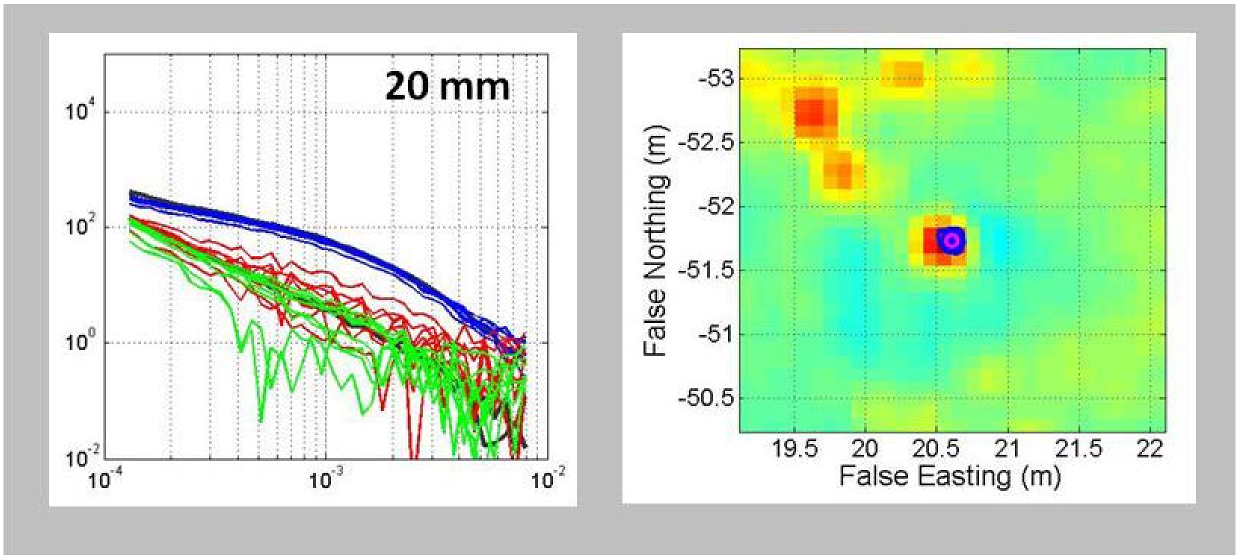

Figure 25. Analyst's Review.

Polarizability clusters (left: blue, red, and green curves) are compared to the closest library match (left: 20mm shown, grey curves). The detection map (right) presents the associated clusters of estimated locations (right: blue dots) and average estimated location (right: magenta circle) for the anomaly.

Based on the analyst's review, adjustments to the initial ranking order can be made to create a final ranked anomaly list. Highest confidence TOI rankings are assigned to anomalies that provide good fits (e.g., >90% match) to library TOI for all three polarizabilities. Lower confidence TOI rankings are assigned to anomalies that provide good fits (e.g., >90% match) to library TOI for the primary polarizability only.

Non-TOI rankings are assigned to anomalies based on symmetry features (e.g., ratio of secondary to tertiary polarizabilities), decay features (e.g., ratio of late time to early time for primary polarizability), and size features (e.g., primary polarizability sum of all time gates). Lowest confidence non-TOI rankings are assigned to anomalies showing good symmetry, large size, and long decay features. Highest confidence non-TOI rankings are assigned to anomalies showing poor symmetry, small size, and short decay features.

For the final classification list, categories are assigned to all anomalies using the standard ESTCP ranked anomaly format: -1 – training set; 0 – can't extract; 1 – likely TOI; 2 – can't decide; 3 – likely non-TOI. Additionally, a dig decision is provided for each anomaly: 1 – dig; 0 – don't dig. This dig decision defines the stop dig point. Type (i.e., size) is also provided for any item listed as a TOI (category 1).

Finalizing the target ranking and stop dig point is an iterative process where training data are requested if the analyst suspects the presence of potentially new TOI types specific to the site. Once the analyst is confident all TOIs have been identified as such on the list, the dig sheet is submitted for independent scoring. For this demonstration, we submitted two requests for training data before submitting the final ranked anomaly list.

7.0 PERFORMANCE ASSESSMENT

The IDA-generated Receiver Operating Characteristic (ROC) curve for scoring of the 2022 target picks within the three RF-15 focus areas is presented in Figure 26. This curve shows the OPTEMA classification performance.

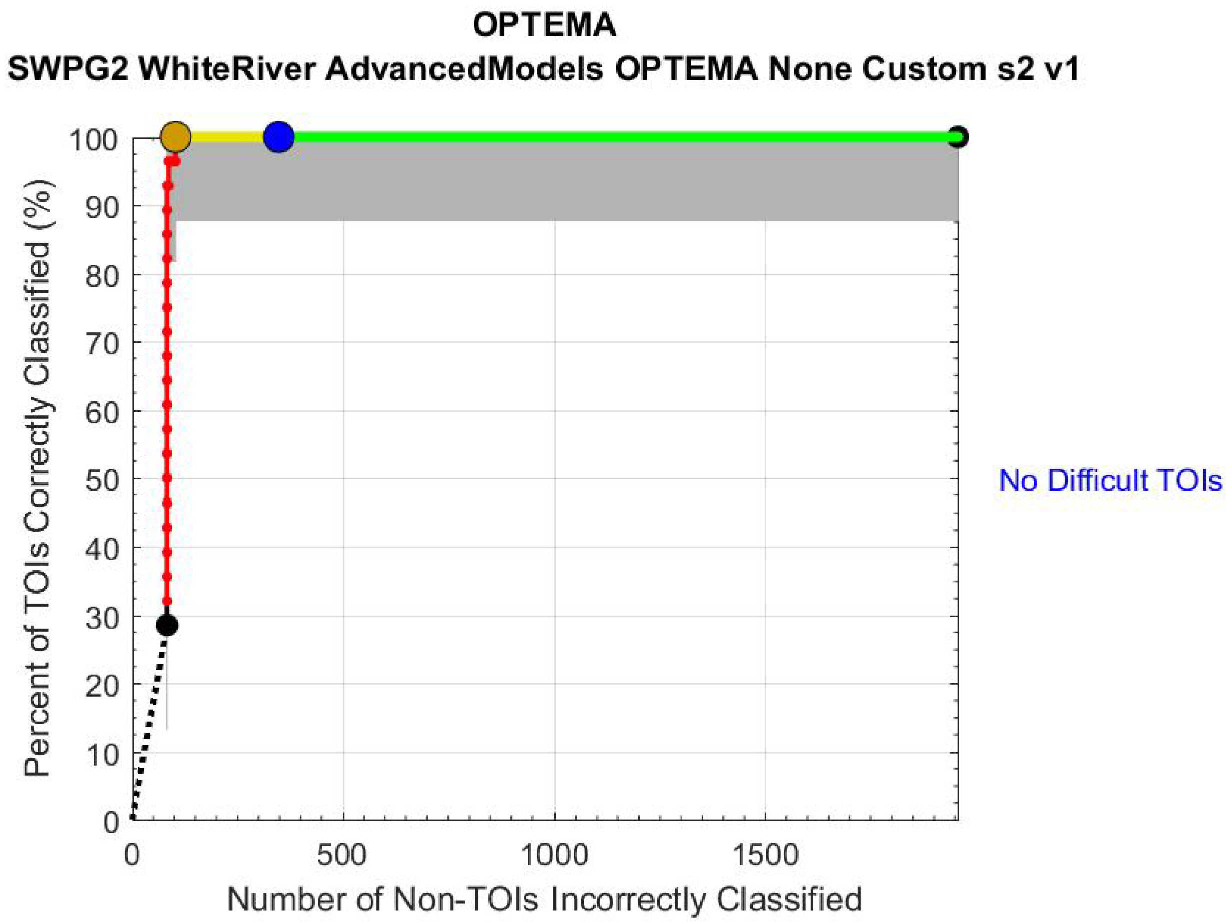

Figure 26. OPTEMA ROC Curve for the 2022 Target Picks Identified in the Three Focus Areas of RF-15.

The orange dot represents the 100% TOI classified correctly operating point. The blue dot represents the stop dig point. The red line corresponds to items classified as UXO. The yellow line corresponds to items classified as low-confidence non-UXO (digs). The green line corresponds to items classified as high-confidence non-UXO (no-digs). The black dashed line corresponds to training dig requests.

Overall, these results indicate that we were able to achieve correct classification of 100% of the TOI with 82% clutter rejection at the stop dig point. At the 100% efficiency operating threshold (i.e., the point where maximum clutter rejection can be achieved with no missed TOI) we achieved 95% clutter rejection. Details of the specific performance objectives are presented in the following subsections.

7.1 OBJECTIVE: DETECTION OF ALL TARGETS OF INTEREST

Of the 2022 targets identified within the three focus areas, 29 were TOI (all seeded). Table 6 presents a breakdown of TOI by type.

Table 6. SWPG2 TOI

TOI TYPE	NUMBER PRESENT
20mm	7
Small ISO	2
37mm	5
40mm	6
57mm	6
75mm	2
90mm	1

Of these 29 TOI, 13 were located within the southeast focus area. OPTEMA detections were submitted for this southeast focus area only due to time constraints on the dig team activities at the site. For each of the 13 TOI in this focus area, we calculated the lateral offset to the closest OPTEMA detection. All 13 TOI had an OPTEMA detection that was within 15 cm of the ground truth location (mean offset error = 5.0cm, maximum offset error = 11.0cm, standard deviation of error = 3.4cm). Therefore, the OPTEMA detected 100% of the TOI for which we were able to assess detection performance.

7.2 OBJECTIVE: MAXIMIZE FALSE POSITIVE REJECTION RATE

Our objective was to reject at least 70% of the clutter encountered at the site. At the 100% TOI correctly classified operating point, we achieved 95% clutter rejection (104 clutter items dug out of 1993 total clutter). At the 100% classified UXO operating point (i.e., all items classified as UXO on our list), we achieved 94% clutter rejection (122 clutter items dug out of 1993 total clutter). At our stop dig point, we achieved 82% clutter rejection (353 clutter items dug out of 1993 total). The OPTEMA performance results are summarized in Table 7.

Table 7. OPTEMA Performance Summary

OPERATING POINT	CLUTTER REJECTION ACHIEVED
100% TOI Dug	95%
All Items Classified UXO Dug	94%
Stop Dig	82%

7.3 OBJECTIVE: EFFECTIVE STOP DIG DECISION

One of the challenges of this site was the large amount of munitions debris (fragments) that were of similar size to the 20mm projectile TOI. Determining a stop dig point that would reject the majority of these clutter items without producing a false negative required several training digs to confirm the selection of appropriate ranking criteria.

Our initial ranking compared the mean separation between the primary and tertiary polarizabilities at early time (subsequently referred to as the K1 parameter) to the mean separation between the primary and tertiary polarizabilities at late time (subsequently referred to as the K2 parameter) for each polarizability cluster associated with a detected anomaly. After this initial ranking, an analyst reviewed the polarizabity cluster associated with each ranked anomaly against TOI libraries. Items near the top of the list (within the first 400) that presented polarizabilities similar to those of known TOI (particularly the 20mm projectile) were flagged by the analyst for training dig requests to confirm whether the item was a TOI or non-TOI (Figure 27). Additionally, items associated with a high K2/K1 value that did not match known TOI libraries were also flagged for training dig requests (Figure 28).

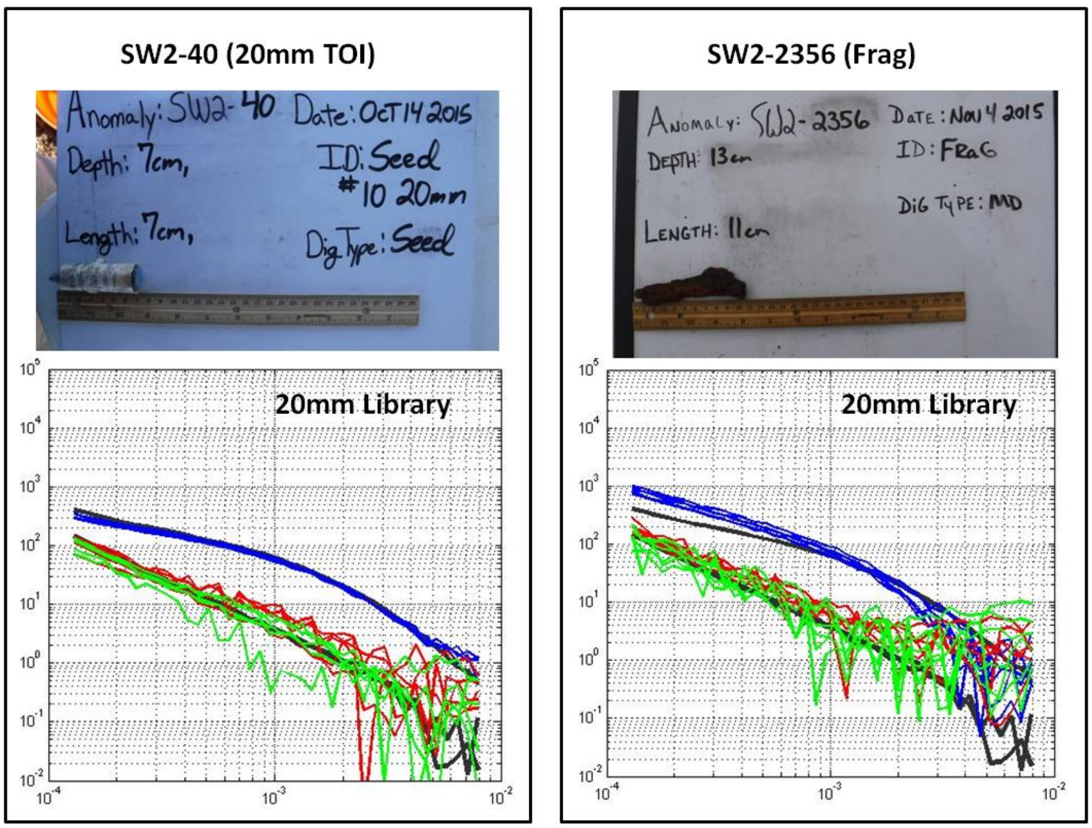

Figure 27. Items Selected for Training included those that Presented Polarizabilities Similar to those of Known TOI.

Examples include SW2-40 (a 20mm TOI) and SW2-2356 (a 20mm-sized clutter item). SW2-40 was selected to confirm the expected TOI result. SW2-2356 was selected to confirm that the slight deviation from the 20mm library in early time could be used reliably to distinguish 20mm-sized debris from 20mm TOI. The polarizability clusters associated with each item (blue, red, and green curves) are compared to the 20mm TOI library (grey curves).

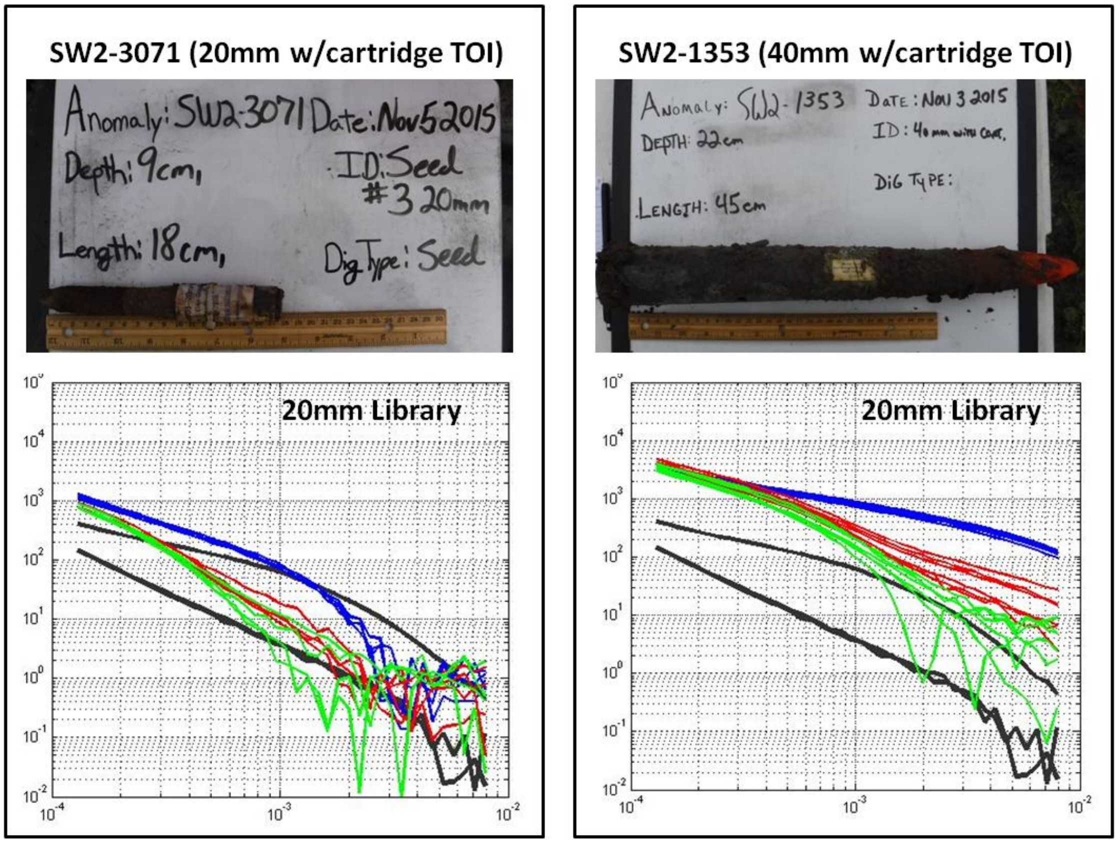

Figure 28. Additional Training Items included those that had High K2/K1 Ratios, but did not Match Known TOI Libraries.

Examples include items SW2-3071 and SW2-1353 (polarizabilities shown compared to the 20mm TOI libraries). Both of these items were projectiles with cartridges still intact. Once these items were identified, their polarizability profiles were added to the TOI libraries.

We requested a total of 91 training digs (8 TOI, 83 clutter) from the ranked list. For the remaining ranked anomalies, we set the stop dig point at 230 anomalies after the last anomaly classified as a UXO (based on the analyst's assessment of library match). Ground truth delivery revealed that this stop dig decision was effective as it did not lead to any false negatives. Additionally it accomplished the objective of at least 70% clutter rejection (82% clutter rejection achieved). Given the large amount of 20mm-sized debris, we believe this stop dig threshold was appropriately conservative to reduce the possibility of a missed 20mm TOI.

Retrospective analysis of the K2/K1 ranking shows that this ranking method performed similarly to the analyst-reviewed final ranking submitted to IDA (if considering the number of false positives at 100% TOI classification). Figure 29 shows the ROC curves for the two ranked lists (initial and analyst-reviewed). For this site, the analyst's review did not result in the placement of any TOI higher on the list; however, the review was critical for building confidence in the stop dig threshold. Much of the uncertainty in the classification of the 20mm-sized debris was removed by placing a number of these items on the training dig list. This review ultimately allowed the analyst to set a stop dig point that would not produce any false alarms while maintaining significant clutter rejection.

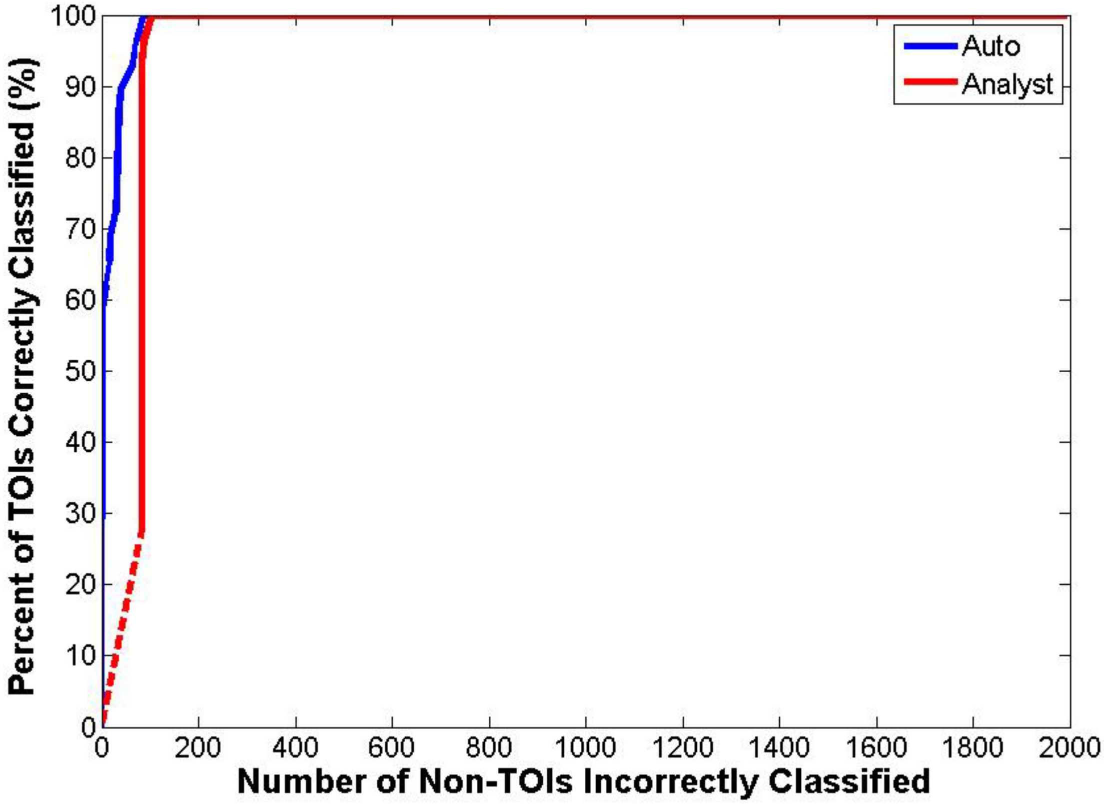

Figure 29. Comparison of Automatic Ranking Performance to Analyst-reviewed Ranking Performance.

The blue curve shows the ROC curve for the ranked list based solely on the K2/K1 ratio. The red curve shows the ROC curve corresponding to the ranked list reviewed by the analyst. Many of the low confidence TOI rankings (upper left portion of blue curve) were assigned training digs (lower left portion of the red curve) by the analyst to improve confidence in the stop dig decision.

To provide additional insight into the stop dig decision process, we can also observe the distribution of the anomalies in the K2/K1 parameter space. Maximum efficiency could be achieved by setting the stop dig point at the K2/K1 value just below that of the last TOI. Figure 30 shows what this threshold would look like (black dashed line). While such a threshold would not be implemented in practice as it would be too aggressive to always ensure zero false negatives, this feature space analysis demonstrates the effectiveness of the K2/K1 threshold for discriminating TOI from non-TOI at this site. Lowering the K2/K1 threshold is equivalent to lowering the slope of the black dashed line in Figure 30.

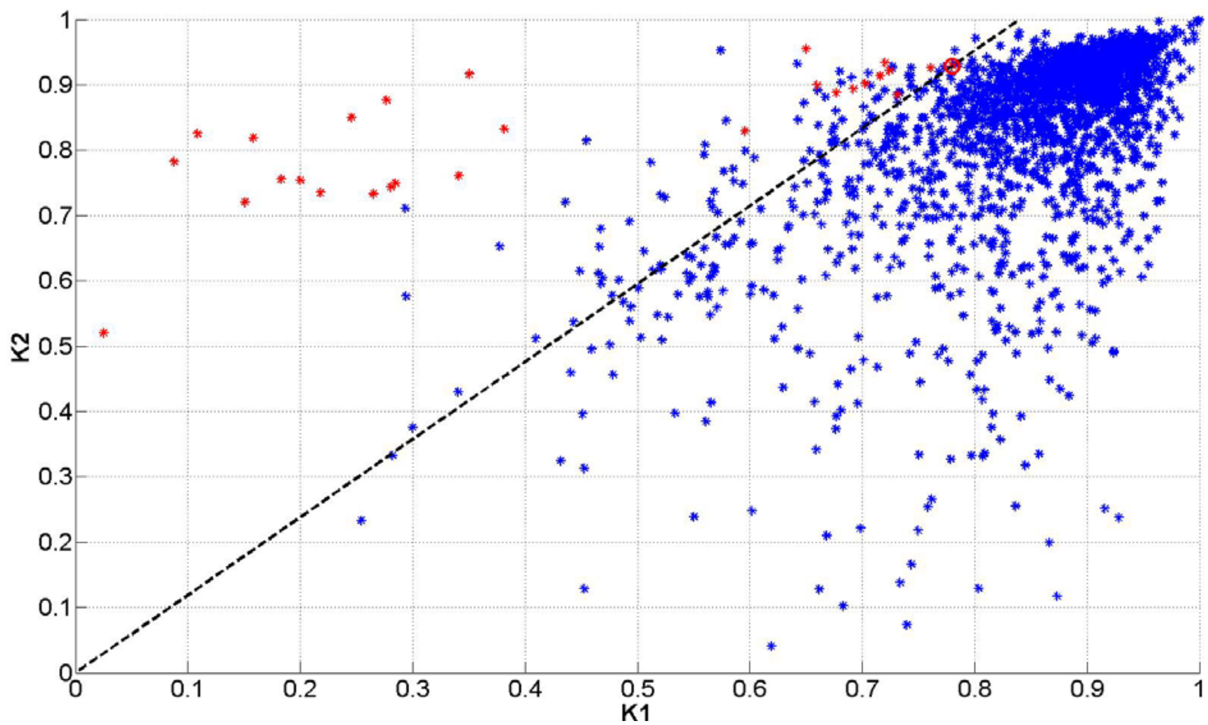

Figure 30. K2/K1 Parameter Space Showing the Distribution of Anomalies.

The blue stars represent non-TOI and the red stars represent TOI. The black dashed line represents the K2/K1 value for the last TOI (circled red near the upper right portion of the dashed line).

7.4 OBJECTIVE: MAXIMIZE CORRECT CLASSIFICATION OF TOI

All 29 TOI were correctly classified as such on the final ranked anomaly list. Additionally, size estimates for whether each TOI diameter was: diam. < 50mm, 50mm < diam. < 100mm were provided correctly for all TOI. Size estimates were based on the library match observed during the analyst's review.

7.5 OBJECTIVE: ACCURATE AND PRECISE TARGET LOCATION ESTIMATION

Our estimated target locations (Northing, Easting, and depth) were calculated from the average values recovered from the polarizability cluster analysis for each anomaly (i.e., model output). Using this mean value proved to be an effective method to localize each source location.

Mean error values and standard deviation are reported in Table 8 for each TOI localization parameter (i.e., Northing/Easting, depth). Errors were calculated by comparing the estimated TOI locations derived from the polarizability clusters to the values recorded in the ground truth sheet, which were based on intrusive investigation results. For each of these parameters, we were within the objective values of 10cm for the mean and 10cm (Northing/Easting) and 20cm (Depth) for the standard deviation.

Table 8. Mean Location Error and Standard Deviation for TOI Location Estimates.

	RF-15 FOCUS AREA TOI		
	Mean Error (cm)	**Standard Deviation (cm)**	**Maximum Error (cm)**
Northing/Easting	5.5	2.4	11.8
Depth	3.3	4.6	14.0

7.6 OBJECTIVE: PRODUCTION RATE

We completed our initial survey of the 4 acre area over the course of two days. The first day included transport of the equipment to the field area, initial calibration, and initial IVS testing. Therefore, we did not start surveying lines until the middle of the first day.

We collected data along north/south transects that were approximately 130 meters in length. Transects were spaced 1.2 meters apart, resulting in a total of 110 lines to complete the 4 acre survey area. We surveyed using a race track pattern (skipping adjacent lines for each return path) in order to increase the turning radius at the end of each transect. This procedure helped to minimize time spent turning the vehicle between lines.

Typical survey activities included a morning IVS test, a mid-day IVS test followed by a break to recharge batteries, and an end-of-day IVS test. Time stamps from the data files indicate that we spent 3 hours on the first day (following the initial calibration activities) collecting survey data and 8 hours on the second day to complete the data collection of the four acre area. Thus, total time collecting data was approximately 11 hours; however, during this period we encountered some minor data collection issues that required some inadvertent down time. These issues included a cow knocking over the GPS base station, a broken axle on the tow sled, and implementing a different GPS rover on the survey vehicle (described in more detail in Section 9.0: Implementation Issues). When factoring in these incidents, our actual survey time for the 4 acres was very close to 8 hours, which produces the objective 0.5 acre/hr production rate.

Following this initial survey, we recollected data over portions of the survey area before demobilization. Some of these recollects were a result of the aforementioned data collection issues. Additional data recollects were performed due to the presence of a large east/west swale at the north end of the area. We recollected several lines in east/west transects along the swale to ensure that the sensor maintained closer ground standoff in these areas. Data recollects were not factored in to our production rate calculation.

7.7 OBJECTIVE: AREA COVERAGE

Before demobilization, we performed a quality check of the data coverage for the survey area. All data files were processed in Matlab to determine the total sensor footprint (in UTM coordinates) along each transect. After processing all files, we confirmed that there were no gaps between adjacent lines at any location within the 4 acre area. This process ensured, prior to departing, that we had achieved 100% coverage of the area.

7.8 OBJECTIVE: ALONG TRACK SAMPLE SEPARATION

To ensure sufficient sample density, we implemented an in-field QC software tool that enabled quality checks of data from each survey line. For each data line collected, we reviewed the average along track sample spacing (objective: ≤ 8cm), the maximum sample spacing (objective: ≤ 15cm), and the standard deviation of the sample spacing (objective: ≤ 2cm). Figure 31 shows the QC output for one of the survey lines. This process ensured that all data met the along track sample objectives.

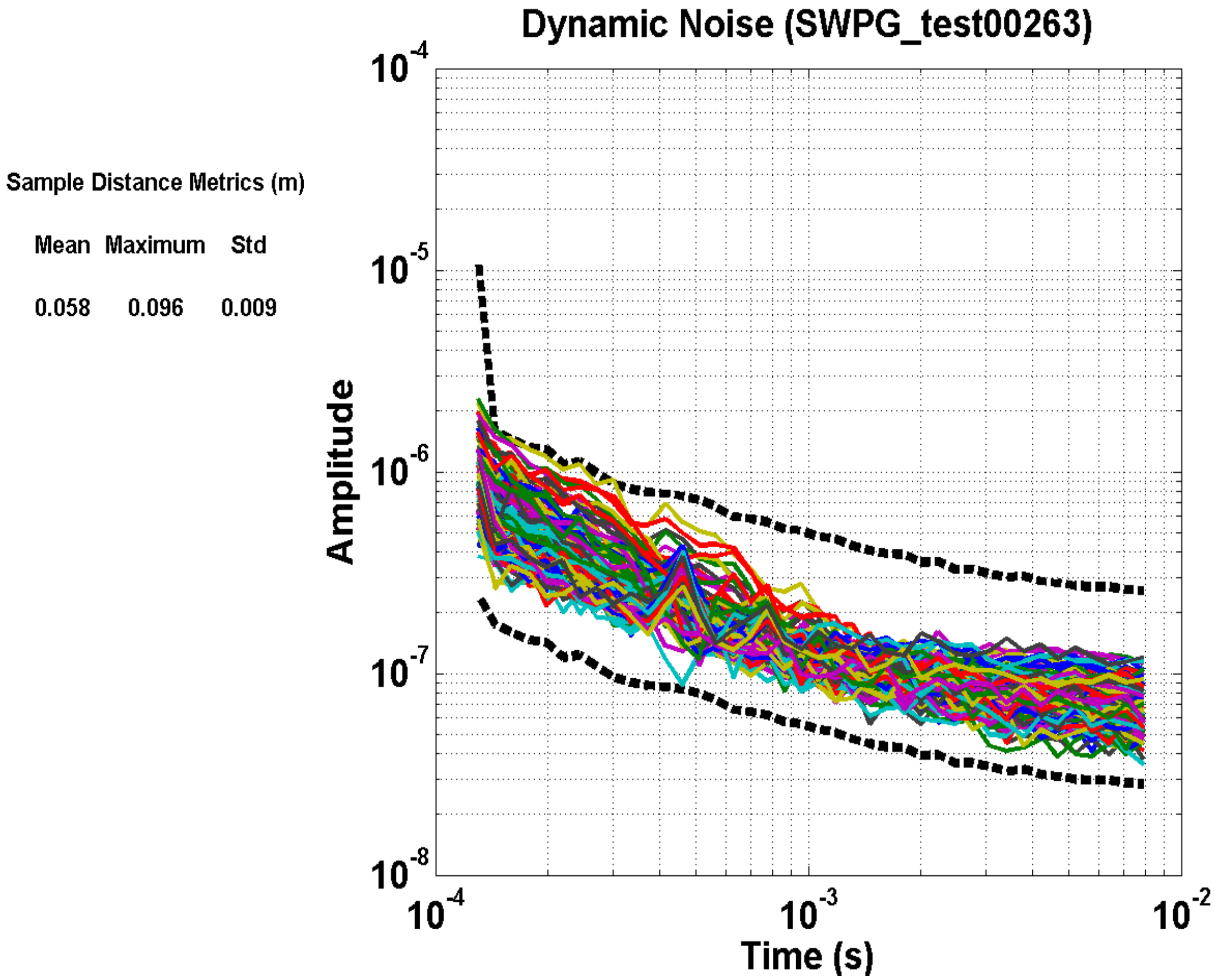

Figure 31. QC Output for Data File SWPG_test00263.

The display shows the along track sample metrics (mean, maximum, and standard deviation) for the data file as well as the dynamic noise profile (plot shown at right).

7.9 OBJECTIVE: IVS SURVEY POSITION ACCURACY

We performed IVS tests three times each day: prior to the day's survey activities, mid-day during a battery change, and at the end of the day. For each IVS target, our in-field QC software processed the relevant data to produce polarizabilities and an estimated target location.

This processing step was performed immediately after collecting IVS data, allowing the operators to view results in real-time to assess instrument functionality. The relevant information provided to the operator is shown in Figure 20. In-field quality checks included observing the offset between the estimated location for each IVS target and the corresponding ground truth location. An offset ≤15cm was required for passing the IVS quality check. Throughout the survey, all IVS tests performed passed this position accuracy test.

7.10 OBJECTIVE: IVS SURVEY POLARIZABILITY ACCURACY

In addition to target location estimates, the in-field IVS check also provided a library match metric for each set of IVS target polarizabilities (Figure 20). A match of 95% or better was required for passing this quality check. All IVS tests performed passed this polarizability match test for all IVS targets.

7.11 QUALITATIVE PERFORMANCE OBJECTIVES

From a user's perspective, dynamic classification survey procedures using a tow sensor such as the OPTEMA are very similar to those of standard DGM surveys. Consequently, many of the sensor positioning requirements that create challenges during cued surveys are not an issue. The main operational requirements for the OPTEMA include basic line following in the survey area such that complete coverage is achieved and periodic (i.e., beginning and end of the day) calibration routines to ensure instrument functionality. Some of the more onerous tasks associated with cued surveys, such as frequent background data collection and extensive maneuvering to center the sensor over a set of 2-D coordinates are not required. From this perspective, the OPTEMA provides a straightforward solution for classification-level surveys and offers some distinct advantages over the cued approach.

During the SWPG demonstration, the in-field quality checks were straightforward to implement and enabled the identification of any data quality problems (see Section 9.0: Implementation Issues) and subsequent corrective actions (i.e., recollects) before demobilization. The quality checks included the IVS test, which evaluated location accuracy and polarizibility accuracy, and the data QC test, which evaluated dynamic noise profile and along track sample spacing for each survey line. The efficiency of the dynamic survey operations coupled with the effective in-field quality checks enabled the field team to mobilize, perform the survey, and demobilize within a period of 6 days.

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8.0 COST ASSESSMENT

The primary cost benefit of the OPTEMA is the removal of the cued survey from the classification workflow. The costs of the one-pass classification method would be comparable to those of the remaining portions of the existing workflow. The OPTEMA survey itself is similar to the standard DGM survey conducted as part of production operations. The 0.5 acre/hr production may be slightly lower than the rate achieved using conventional DGM arrays. Requirements for field personnel are also similar to those for standard DGM surveys (i.e., two technicians for vehicle-towed surveys).

Regarding the costs associated with the post-survey data analysis, we believe that costs associated with analysis of OPTEMA data would be comparable to the combined costs of the target picking and classification analysis stages currently required for cued classification. The one-pass and cued methods both require target detection and target classification stages as part of the analysis. Time and personnel requirements for both methods are similar (i.e., review of each target by a trained analyst). Processing of OPTEMA data is more computationally intensive due to the increased volume of data; however, any associated costs due to the higher data density would be negligible since any increased burden is placed on processing hardware, not on personnel.

8.1 COST MODEL

Table 9 provides a summary of the cost elements associated with an OPTEMA survey.

Table 9. Cost requirements for OPTEMA survey.

Cost Element	Data Tracked During Demonstration	Cost
Mobilization and demobilization	• Shipment to and from site • Labor required to pack and prep equipment (2 field technicians) • Air travel for 3 field personnel	$28,811
Site preparation	• Labor for equipment assembly on-site, initial calibration and IVS test (2 field technicians, 1 project geophysicist) • Per diem rates (3 personnel, 1 day) • Equipment rental (survey vehicle and GPS, 1 day)	$5,929
Survey costs	• Labor for 0.5 acre/hr production rate (2 field technicians) • Labor for on-site QC (project geophysicist) • Labor for back-office QC support as needed • Per diem rates (3 personnel) • Equipment rental (survey vehicle and GPS)	$1,941 per acre (3 acre/day production)
Detection data analysis costs	• Labor for target picking analysis of OPTEMA data (1 data analyst and 1 QC geophysicist) • Labor for project management	$409 per acre
Classification data analysis costs	• Labor for classification analysis of OPTEMA data (1 data analyst, analysis of 400 anomalies/day) • Labor for final dig list review (project geophysicist, review and QC geophysicist final review) • Labor for project management	$4.81 per anomaly

8.1.1 Mobilization and Demobilization

Mobilization costs include shipping costs to transport equipment to and from the site, labor required to disassemble, prepare, and pack equipment, and travel costs for the field team. The OPTEMA system is shipped in two large crates (4' x 4' x 8') for the sensor head and tow sled parts, and two smaller crates (3' x 3' x 4') for the electronics, spares, and survey tools. All crates can be maneuvered and loaded on to a lift-gate equipped box truck using a pallet jack so delivery to remote sites is possible (i.e., those with no formal receiving facilities as was the case for the SWPG demonstration). Preparation requires approximately 1 week for two field technicians. Additional costs include materials for sled reinforcement and spares (e.g., fiberglass parts).

8.1.2 Site Preparation

Site preparation includes the assembly of the system upon arrival, initial function and system verification tests, and related on-site quality control analysis. Associated labor includes 1 full day for 2 field technicians and an on-site geophysicist. Additional costs include per diem for 3 personnel and equipment rental (GPS and survey vehicle).

8.1.3 Survey Costs

Survey costs include per diem and labor for 2 field technicians and 1 on-site geophysicist, as well as labor for back-office quality support by a data analyst. A production rate of 0.5 acre/hr (3 acre/day) is assumed. Additionally for each day of data collection, 2 hours of back-office support are required. Additional costs include equipment rental (GPS and survey vehicle).

8.1.4 Detection Data Analysis Costs

Detection analysis is performed off-site so is not associated with any travel or per diem costs. Most of the detection processing is automated, but some analyst oversight is required including the selection of appropriate detection thresholds, and quality review of the detection map (i.e., visual confirmation that the thresholds are implemented properly to identify anomalies on the map). Associated labor costs for this effort include 1 day for a data analyst and 4 hours for a QC geophysicist for 4 acres of data collected. Additional costs include labor for project management.

8.1.5 Classification Data Analysis Costs

Classification analysis is also performed off-site. These costs include labor for a data analyst, project geophysicist, QC geophysicist, and project/technical manager. Initial classification analysis includes visual review by the analyst of classification features associated with each polarizability cluster (i.e., each anomaly). The analyst reviews the polarizabilities against the TOI libraries, identifies any potential new TOI, and modifies the ranking order appropriately. Our experience with this demonstration indicated that it is possible for an analyst to review approximately 400 anomalies per day during this stage. Final classification includes a review by the project geophysicist of the analyst's final ranked anomaly list followed by subsequent review by the QC geophysicist for QC seed identification. Labor for this final analysis cost includes 1 day for the project geophysicist and 4 hours for the QC geophysicist.

8.1.6 Overall Cost Analysis

Here we provide an example to demonstrate the potential cost savings that could be achieved by implementing an OPTEMA survey. Consider a 100 acre site with an anomaly density of 250 anomalies/acre. We can apply a few basic cost assumptions using data from the 2014 ESTCP Spencer Range summary report [6]. We assume combined field survey and analysis rates of $1000/acre for an EM-61 DGM survey and $30/anomaly for a MetalMapper cued survey. At the aforementioned 250 anomalies/acre density, this creates a total survey/analysis rate of $8500/acre or $850,000 total for the site.

To determine an estimated cost for using the OPTEMA at this site, we can apply the aforementioned cost elements. These include a total survey and target identification analysis cost of:

($1941/acre + $409/acre) x 100 acres = $235,000

Classification analysis costs are based on cost per anomaly and would be:

$4.81/anomaly x 250 anomalies/acre x 100 acres = $120,250

This brings the total cost to:

$235,000 + $120,250 = $355,250

For the aforementioned site, we therefore have a total cost of $355,250 or an approximate 58% reduction in total survey/analysis costs when compared to the cued classification approach. The cost savings becomes even more significant when anomaly densities are higher; for example if the anomaly density for the same site were 600 anomalies/acre. For the DGM/cued approach survey costs would be:

($1000/acre x 100acres) + ($30/anomaly x 600 anomalies/acre x 100 acres) = $1,900,000

OPTEMA costs for the same site would be:

($2350/acre x 100acres) + ($4.81/anomaly x 600 anomalies/acre x 100 acres) = $523,600

In this case, the OPTEMA would provide an approximate 72% cost savings, which emphasizes the increased cost benefit at higher density sites.

8.2 COST DRIVERS

While the one-pass detection/classification method could provide significant cost savings at any site, the greatest returns for OPTEMA deployments would be realized in large open field areas and high density sites. Highest production rates would be achieved in areas amenable to vehicle-towed surveys, particularly those sites that allow for long, straight survey transects. Additionally, sites that contain higher anomaly densities would also realize significant cost savings. Because cued survey costs scale considerably with anomaly density (i.e., production rates for cued systems are generally given in anomalies/hr rather than acres/hr), high density areas significantly drive up cued survey costs, but have no significant effect on OPTEMA production.

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9.0 IMPLEMENTATION ISSUES

Over the course of the survey, we encountered a few data collection issues that required corrective actions. The first incident occurred as we started collecting data over the first few survey lines. We initially used the GPS rover on the tow sled to provide the position data for the navigation software; however, after the first few lines we quickly realized that the offset between the sled and the vehicle made it difficult to precisely follow the survey lines using the navigation software. This issue was quickly resolved by incorporating a second GPS rover into the survey operations. The additional rover was placed on the hood of the survey vehicle and the data stream was tied into the navigation software. This change enabled line following with much greater precision. The initial lines that were surveyed using the sled rover were subsequently recollected.

Another incident occurred towards the end of the second day of surveying. As we turned the vehicle after completing a line, one of the fiber reinforced polyester (FRP) axles on the sled broke. This issue was caused because the wheel collar had loosened, allowing the wheels to slide down the axle and place significantly more torque on it when turning. We replaced the axle in the field without any challenges and we subsequently monitored it to ensure the collar did not slip again. We have since redesigned the axle, adding an outer Garolite sleeve for additional reinforcement, and incorporating a threaded lock nut to ensure the wheels will not slide.

During the second day of surveying we also encountered a GPS problem that was unique to the site. One of the cows grazing in the area knocked over our GPS base station. Fortunately this incident occurred while we were collecting data and the driver was watching the navigation display. An immediate shift in the vehicle position on the display let the driver know there was a problem with the GPS base. After halting the survey and going to investigate we discovered the reason for the shift (Figure 32). This problem was caught quickly enough that it required recollecting only a few lines; however, it is an issue worth noting because if it were not identified by the driver, we would not have discovered it until the end-of-day IVS test. If not identified until the IVS, this problem would have resulted in many more recollects. Because the navigation display is the only real-time indicator of base station position, it should be monitored during survey operations to identify such issues.

Figure 32. Cow-base Station Encounter.

A final issue worth noting was identified during the in-field data quality checks. In performing these checks, we noticed that some of the data files produced above normal dynamic noise profiles in some of the late time channels (Figure 33). Because these high noise occurrences were inconsistent, we at first attributed them to the effects of the pockmarked ground surface. On further inspection, however, we were able to trace the problem to loose receiver cubes. Several of the glued inserts to which the cubes were fastened had loosened up during the survey. This condition allowed some of the cubes to vibrate slightly (a few millimeters of movement) when the sled encountered particularly bumpy areas. The movement was enough to create elevated noise levels in some of the late time channels. We refastened these affected cubes and noise levels returned to the expected values. While the overall classification quality of the data was not impacted significantly, we recollected several of the lines associated with the noisier data files (we have since modified the fasteners for these cubes to ensure they do not loosen again).

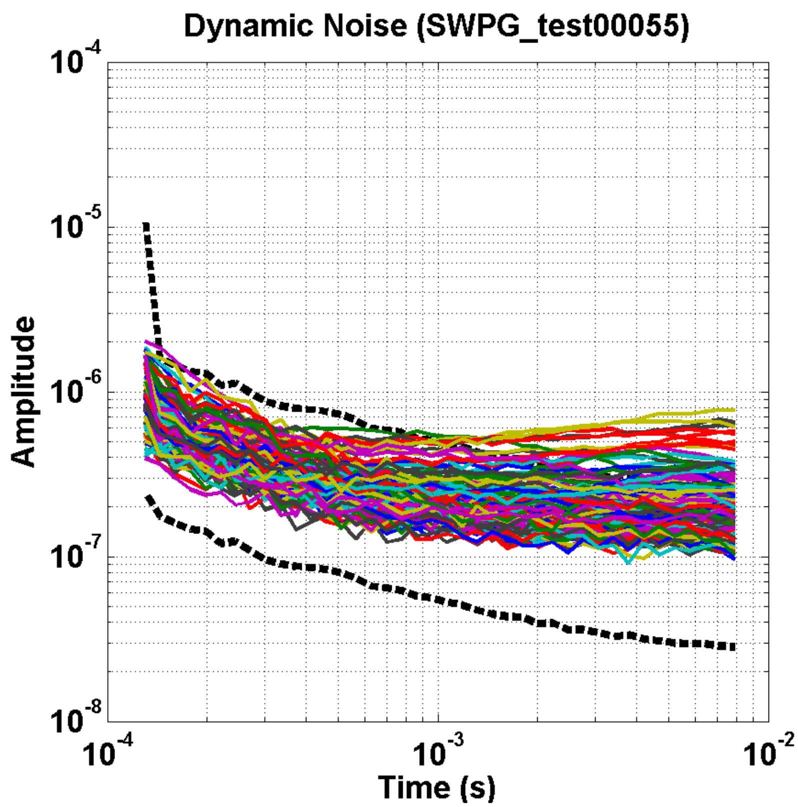

Figure 33. Dynamic Noise Profile Indicating above Normal Noise Levels in Some of the Late Time Channels.

These elevated levels were the result of motion-induced noise caused by loose receiver cubes.

Ultimately, all of the in-field quality checks proved successful. We were able to identify all data quality issues and recollect the required data before demobilizing. These data quality issues highlight the importance of implementing effective data quality checks as part of standard operating procedures. Because dynamic surveys create large volumes of data in a relatively short time period when compared to data production from cued surveys, it is critical that appropriate quality checks are in place to ensure that the field team departs with classification-quality data.

10.0 REFERENCES

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