Environmental Security Technology Certification Program

Final Report

for the

Coaxial EMI Sensor for UXO Detection and Discrimination

December, 2006

Approved for public release; distribution is unlimited

ESTCP Seed Project Title (UX-200418)

Contract No. W912HQ-04-C-0018

Geophex, Ltd.
605 Mercury Street
Raleigh, NC 27608

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing this collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden to Department of Defense, Washington Headquarters Services, Directorate for Information Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number. **PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.**

1. REPORT DATE *(DD-MM-YYYY)*
10-06-2006

2. REPORT TYPE
Final

3. DATES COVERED *(From - To)*
Aug. 2004-Aug. 2005

4. TITLE AND SUBTITLE
Coaxial EMI Sensor for UXO Detection and Discrimination

5a. CONTRACT NUMBER
W912HQ-04-C-0018

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
SanFilipo, William, A.

5d. PROJECT NUMBER
ESTCP UX-200418

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Geophex, Ltd.
605 Mercury St.
Raleigh NC 27603-2343

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Environmental Security Technology Certification Program
901 North St, Suite 303
Arlington VA 22203

10. SPONSOR/MONITOR'S ACRONYM(S)
ESTCP

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT
distribution unlimited; approved for public release

13. SUPPLEMENTARY NOTES

14. ABSTRACT
The coaxial coil configuration electromagnetic induction (EMI) sensor is motivated by the potential advantages of the common mode rejection of electromagnetic noise from external sources. The balanced differential receiver (gradient) measurements reject voltages induced by noise fields that are uniform over distances on the scale of the receiver coil separation, including natural sources such as sferics (distant lightning induced), geomagnetic storms (sun spot induced), platform motion in the geomagnetic field, as well as man-made sources such as power line fields. The platform motion induced noise has been shown to be particularly problematic for the vehicular towed concentric-coil system (GEM-3) in the operational frequencies below 100 Hz. One penalty paid with the coaxial geometry is an increased height of the transmitter coil, reducing the excitation field strength over the target. There is a trade-off between increasing the coil separation to increase the difference signal and reducing the separation to reduce the transmitter-target distance, and the design must provide a good compromise for the anticipated target depth envelope. Also, small separations pose an engineering challenge at achieving adequate bucking (receiver coil balance). An existing prototype cart-mounted coaxial sensor was evaluated in order to confirm the noise rejection advantage of the coaxial configuration. Noise associated with platform motion and from external electromagnetic interference is shown to be less, as proposed.

15. SUBJECT TERMS
electromagnetic induction, UXO

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
					William A. SanFilipo
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**	SAR	22	**19b. TELEPHONE NUMBER** *(include area code)*
Unclassified	Unclassified	Unclassified			(919) 239-8515

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39.18

Table of Contents

List of Acronyms

Analog-to-Digital Converter	ADC
Aberdeen Proving Ground	APG
Differential Global Positioning System	DGPS
Digital Signal Processor	DSP
Electromagnetic Induction	EMI
Probability of False Alarm	PFA
Probability of Detection	PD
Probability of Background Alarm	PBA
Receiver Operator Characteristics	ROC
Receiver coil	Rx
Signal-to-noise ratio	SNR
Transmitter coils	Tx
Unexploded Ordnance	UXO

List of Figures

List of Tables

Acknowledgements

Evaluation of the coaxial EMI technology was funded by ESTCP as a seed project (UX-200418).

ABSTRACT

The coaxial coil configuration electromagnetic induction (EMI) sensor is motivated by the potential advantages of the common mode rejection of electromagnetic noise from external sources. The balanced differential receiver (gradient) measurements reject voltages induced by noise fields that are uniform over distances on the scale of the receiver coil separation, including natural sources such as sferics (distant lightning induced), geomagnetic storms (sun spot induced), platform motion in the geomagnetic field, as well as man-made sources such as power line fields. The platform motion induced noise has been shown to be particularly problematic for the vehicular towed concentric-coil system (GEM-3) in the operational frequencies below 100 Hz. One penalty paid with the coaxial geometry is an increased height of the transmitter coil, reducing the excitation field strength over the target. There is a trade-off between increasing the coil separation to increase the difference signal and reducing the separation to reduce the transmitter-target distance, and the design must provide a good compromise for the anticipated target depth envelope. Also, small separations pose an engineering challenge at achieving adequate bucking (receiver coil balance).

A modeling study provided theoretical algorithms for computing apparent conductivity and apparent susceptibility for the coaxial configuration similar to what had been used for GEM-3 target detection, and target signal (metallic sphere model) to background (halfspace) responses compared for the two coil configurations. For either configuration, transforming spectral data into a weighted average apparent conductivity is effective at emphasizing metallic targets over geologic variations.

An existing prototype cart-mounted coaxial sensor was evaluated in order to confirm the noise rejection advantage of the coaxial configuration. This first prototype was a proof-of-concept system was not balanced well over the desired bandwidth (note that coil electronic balance as well as geometric balance is important in order for the bucking to be effective over all frequencies), and some modifications were made, however the system needs additional development to achieve the maturity of the GEM-3 and reach optimal performance.

Noise associated with platform motion and from external electromagnetic interference is shown to be less, as proposed. We note that depending on target depth, the static signal-to-noise ratio (SNR) is sometimes better for the GEM-3 owing to the transmitter coil distance. Final performance comparison in an actual survey remains uncertain; scoring has not yet been published for the coaxial demonstration at the APG ATC, but we present some data in order to show a qualitative comparison.

1. Introduction

1.1 Background

The environmental problem addressed by this project is the need to clear areas of UXO contamination in order to reclaim former DoD practice ranges and weapons test sites for non-military use. This program is directed at the task of detecting and distinguishing from non-ordnance clutter buried UXO in a cost effective method.

The motivation for developing a new coil configuration stemmed from experience related to our cart-mounted concentric coil EMI system – the GEM-3, particularly in adapting it to a vehicle towed array. It was observed that the noise envelope of the low (< 150 Hz) frequency data was several times larger during survey operation over typical field ground conditions than while static – i.e. platform dynamics induced sensor noise degraded the data. Further investigation showed that the cause of the noise was coil angular motion in the geomagnetic field. Another significant contributor to noise (static and dynamic) over a broad frequency range is environmental electromagnetic noise, particularly man-made (power line). Finally, the GEM-3 requires sequential operation when integrated into an array because of primary field cross interference, which limits the sampling rate and number of sensors.

A coil configuration that was more immune to noise induced by platform dynamics in the geomagnetic field and distant electromagnetic field noise sources, and cross-interference from nearby sensors was desired for a towed array EMI system for wide-area survey missions. To achieve these characteristics, a symmetrically balanced coil geometry would allow common mode noise rejection and mutual primary field bucking. The particular geometry that would provide similar sensitivity and spatial resolution to small shallow metallic targets than the GEM-3 is the vertical coaxial arrangement with a central transmitter and symmetric receiver coils in a differential (gradient) mode, whereby any voltage induced in both coils would cancel.

1.2 Objectives of the Demonstration

The main objective of this project is to confirm the benefits of a coaxial coil configuration in an advanced multi-frequency EMI sensor. The focus was on the fundamental capability of a single sensor without significant development costs, while the added benefit in an array deferred to future projects. To that end, we utilized a proof-of-concept prototype cart-mounted sensor that we had already built, shown in Figure 1. Initial testing showed that imperfect bucking precluded use of a preamplifier (and even required an attenuation bridge), so we replaced the receiver coils with smaller radius (from 23 cm to 15 cm) coils wrapped around a single PVC pipe for rigidity, and increased coil separation from 25 cm to 30 cm (Figure 2).

The electronics are the same as our current GEM family, but with the high-power (48 volt) transmitter option similar to that used on the NRL GEMTADS system. The hardware is described in more detail in section 2 below.

Figure 1. Original cart-mounted coaxial EMI system with 23 cm radius coils separated by 25 cm; the transmitter electronics module can be seen adjacent to the central transmitter coil, and the battery pack mounted on the cart handle. The Styrofoam (blue) blocks were inserted to reduce "drumhead" vibrations.

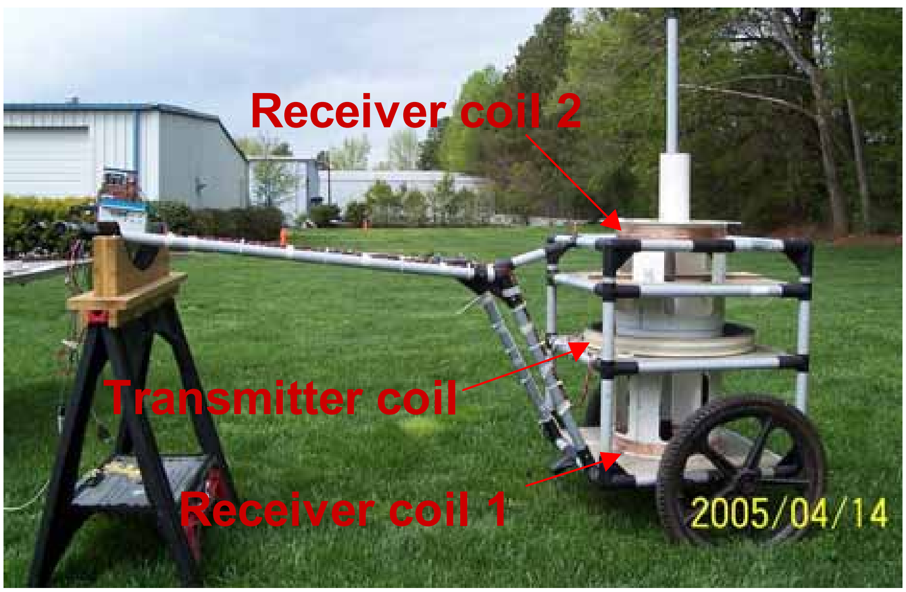

Figure 2. Modified coaxial system with tubular structure (large rectangular holes to reduce weight and wind cross section) incorporating smaller (16 cm radius) receiver coils and coil separation increased to 30 cm.

1.3 Regulatory Drivers/DoD Directives

This program was undertaken in response to the ESTCP Topic 1: Unexploded Ordnance (UXO) Detection, Discrimination, and Remediation.

1.4 Stakeholder/End-User Issues

This demonstration will address decision-making issues concerning end-users associated with the applicability of the coaxial-coil EMI technology for their specific UXO detection and discrimination mission needs. Operational performance under static and dynamic conditions will be assessed, and comparisons with existing concentric-coil systems (GEM-3).

1. Technology Description

1.1 Technology Development and Application

2.1.1 Hardware

The EMI system consists of three basic components: the coaxial-coil sensor, the electronics console, and the user interface (control and display) module. This functional architecture, as well as the essential features of the electronics, is the same as our existing EMI sensors. The key innovation is the coaxial coil configuration, in which the receiver channel (Rx) is the difference voltage between two coils symmetrically arranged around the coaxial transmitter coil (Tx), shown schematically in Figure 3. The sensor axis is oriented vertically during operation, illuminating a target directly below with a vertical primary field, and sensed by the perturbation of the field from the eddy currents and magnetic polarization induced in the target, which breaks the symmetry between the two receiver channel coils. When the target distance is less than the coil separation, the bottom coil measures relatively large (vertical component) field perturbation while the upper coil “sees” relatively no change; for deep targets, the receiver channel acts as a perturbed vertical field gradiometer. More precisely, the gradient integrated from the bottom to top coil is measured.

Any noise source that is uniform over the volume of the sensor is common mode between the two coils, and will be suppressed by virtue of the differential receiver channel mode. This will include electromagnetic fields from distant sources such as sferics (ionosphere-atmosphere wave guide propagation from tropical lightning) and sunspot induced geomagnetic fluctuations, as well as the voltage induced by platform angular motion in the static geomagnetic field.

The architecture of the electronics (Figure 4) is the same as the “next generation” GEM-3 (smaller, faster A/D, iPAQ® user interface and data logger) with high-power (48 volt) transmitter option (as in the GEMTADS system built for the Naval Research Laboratory).

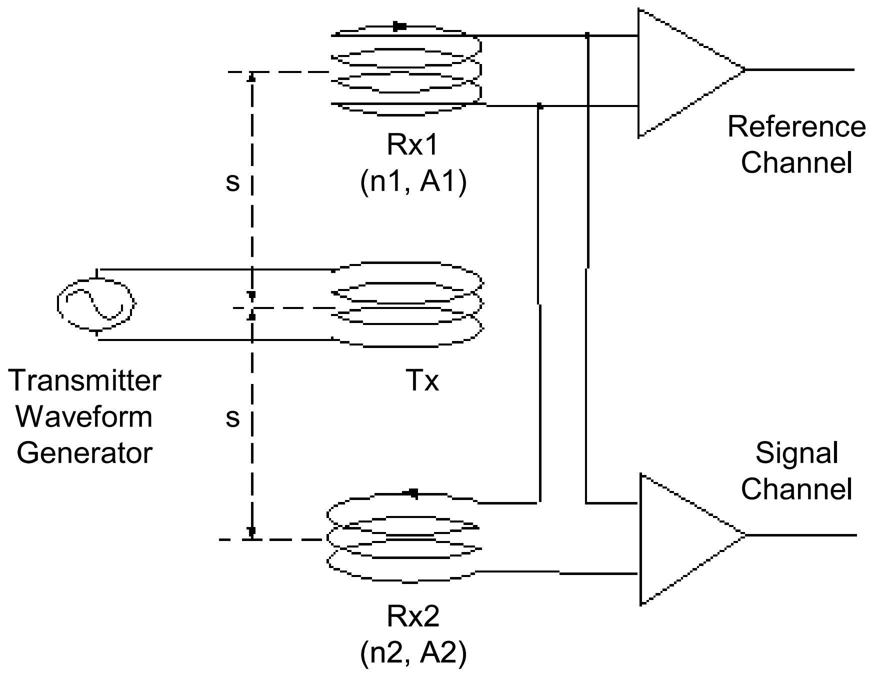

Figure 3. Coaxial coil configuration schematic, showing central transmitter coil (Tx), symmetric receiver coils (Rx1 and Rx2) wired in differential mode to form the signal channel. The upper coil is used as a primary field reference for measurement phase and normalization, providing a dimensionless sensor output in parts-per-million (ppm) independent of the transmitter current.

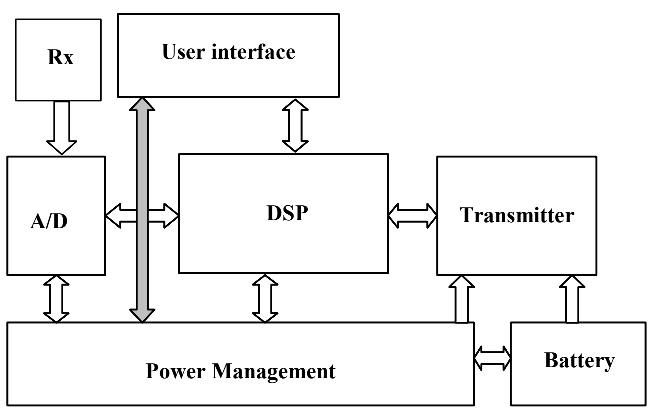

Figure 4. Electronics block diagram, showing functional modules: receiver front-end (Rx), analog-to-digital converter (A/D), digital signal processor (DSP) , and power management – monitors and regulates battery and battery charging and voltages; transmitter current waveform generator (Tx) is a separate module triggered by the DSP.

Details of the electronics design (including the Tx pulse-width modulation scheme for generating the digitally controlled multi-frequency hybrid current waveform, the front-end analog and analog-to-digital converter (A/D) receiver electronics, digital signal processor (DSP) and power management module) have been described in reports for other programs. The electronics have evolved from the original GEM system, with size and cost reductions using newer components as well as elimination of built-in data storage since the commercial hand-held computer can perform that task as well as user interface.

DGPS is tightly integrated by passing the DGPS data stream through the GEM electronics and stamping the EMI and DGPS data with a common DSP time tag based on the GPS PPS Universal Time Clock.

The broad-band multi-frequency capability is accomplished utilizing a continuous transmission hybrid waveform containing a superposition of all of the operational frequencies, typically about ten, logarithmically spaced from 90 Hz to 70 kHz. Odd harmonics of 30 Hz are used exclusively (in the U.S.) to avoid power line 60 Hz harmonics noise.

2.1.2 Software

The algorithm used for discrimination is a simple fit, with arbitrary weights, to a mix of the two library spectral response modes (transverse and longitudinal) (Norton *et al*., 2001, 2nd). Geometry is not modeled, so data sample positions are not needed, nor target position and orientation. The best-fit library target for a set of samples acquired at the peak of the Response Stage is determined, with goodness of fit as a confidence criteria computed from the fitting error as described above to generate the Discrimination Stage. The algorithm incorporated a new module for estimating target depth and dip angle based on library fit weighting factors; depth information must be recorded in the library, and the computed depth depends on the item and therefore can be erroneous if an incorrect match is made.

2.2 Previous Testing of the Technology

Initial testing of the coaxial coil EMI technology was first performed at the Geophex facility in Raleigh, North Carolina. Geophex has a 10 m x 10 m test bed in which 21 metal pipes of various sizes, some ferrous (steel) and some non-ferrous (3 aluminum, 2 copper), have been buried at depths ranging from 10 to 110 cm depth. We have also used this test bed during GEM-3 development to test the performance of each generation of GEM technology.

No other formal demonstration testing of the coaxial coil EMI technology had been done prior to this demonstration.

2.3 Factors affecting Cost and Performance

The coaxial coil EMI technology is in development stage and an operational system not yet built. However, the electronics inherited the design of our GEM systems that have reached a stage of cost effective production and operation. Operational costs will be similar to other cart mounted EMI systems. A towed array version has been demonstrated subsequent to this demonstration, providing a much greater potential cost effectiveness for wide area missions.

2.4 Advantages and Limitations of the Technology

The chief advantage of this technology comes from the coil configuration providing common-mode noise rejection, combined with the multi-frequency capability for potential target discrimination. Also, this coil configuration can be applied to a simultaneously operating array in a straightforward manner.

Limitations relate to the increased transmitter coil height diminishing target response strength. This technology is not yet as mature as existing systems, and has not been fully optimized in terms of design details. Mechanically it is somewhat more difficult to construct than a concentric coil sensor. Also, a hand-held version may not be practical, although it should not be precluded.

3 Demonstration Design

3.1 Performance Objectives

The standard performance metrics for UXO detection/discrimination technology are shown in Table 1. Since the operators will be the demonstrators for this demonstration, Operator acceptance may be interpreted as evaluation by on-site ATC personnel, or their responsible parties in charge of demonstration oversight. Such evaluation can be made by observation of production rates and field problems that arise. The quantitative objectives performance will be determined by ATC resulting from the scoring of the submitted dig sheets.

Type of Performance Objective	Primary Performance Criteria	Expected Performance (metric)	Actual Performance (Objective met?)
qualitative	1.) Ease of use	1.) Operator acceptance	1.) acceptable
	2.) Field worthiness	2.) Operator acceptance	2.) acceptable
quantitative	1.) per cent detected	1.) > 95%	1.) 50%
	2.) false alarms	2.) < .1	2.) .50

Table 1. Performance Objectives

3.2 Selecting Test Sites

APG

The Aberdeen Proving Ground Standardized UXO Technology Demonstration Site is one of two recently completed facilities designed to provide UXO detection and discrimination technologies test scenarios that evaluate the performance and operational usability under the realistic range of conditions that will be met during assessment and clearance operations. These conditions include various vegetative states from barren to moderate brush to densely wooded and various terrain conditions from open and flat to rugged. These conditions provide opportunity for vehicular towed systems, manual pushcart systems, and hand-held systems. The size of the facility is sufficient to provide meaningful performance metrics such as probability of detection, false alarm rates, and production rates.

The choice of the facility at Aberdeen, in Harford County, Maryland was made for proximity to the operator's location of business (Raleigh, North Carolina), and facility availability. An aerial photograph of the site is shown in Figure 5.

Only the calibration and blind grids were utilized for this demonstration, because the technology is not yet operationally mature, and the goal is to confirm specific performance advantages compared to the GEM-3.

3.3 Test Site History/Characteristics

Aberdeen Proving Grounds is an Army facility that has been used for weapons and military vehicle testing since 1917. It encompasses 117 km^2 of land, much of it forested, between Baltimore and Philadelphia. The UXO demonstration site is a seeded site for controlled testing, and includes 1) calibration lanes (ground truth revealed) for system training and target characterization, and a set of blind (ground truth withheld) areas for testing a range of scenarios: 2) blind test grid – a 1600 m^2 rectangular grid including access lanes separating 400 discrete 1 m x 1m square interrogation points; 3) open road terrain – large area that can be surveyed with vehicular towed systems, some varied moderately rough terrain and vegetation; 4) moguls – an area with moguls and craters of about ±1 m vertical relief, requiring manual data acquisition, likely hand-held sensor configuration; 5) wooded – various vegetation including significant areas of dense trees. Information about the UXO test site at APG can be found at http://www.atc.army.mil/fac_guide/facilities/standarduxo.html

Figure 5. Arial photograph of the APG Standardized UXO Technology Demonstration Site

3.4 Present Operations

Present operation of the demonstration sites is restricted to controlled testing and performance evaluation of UXO detection and discrimination technologies. It is a cleaned and seeded area with no ongoing operational remediation.

3.5 Pre-Demonstration Test and Analysis

The GEM-3 system has previously been demonstrated at APG, and a comparison between that and the coaxial configuration is desirable. However, there were differences in the testing that preclude a straight comparison: 1) the blind grid has been reseeded (presumably with similar targets but in different locations, so a performance comparison can still be made); 2) The GEM-3 dynamic testing in the blind grid used an ATV towed sled platform, while the coaxial was surveyed with a manually pushed wheeled cart; 3) data were recorded over only part of the calibration area with the towed GEM-3, and no static data were recorded over the calibration area for the GEM-3.

Critical comparisons for the purpose of this project, shown below, include the noise envelope change between static and dynamic conditions for the two sensors, and sensitivity to an external EM transmitter as a simulated noise source.

3.6 Testing and Evaluation Plan

3.6.1 Demonstration Set-Up and Start-Up

APG

The system was fully assembled and transported in a van; the DGPS mounted and base station set up. Start-Up included recording a library of target responses from UXO samples provided by ATC. Each item requires less than a minute.

3.6.2 Period of Operation

The period of operation at APG was 4/19/05 – 4/26/05, however we were engaged in simultaneous demonstration of another sensor and only a fraction of this time interval (4/19 and 4/20 and morning of 4/26) involved the coaxial coil system.

3.6.3 Area Characterized

Only the calibration and blind grids were characterized; the blind grid was surveyed twice – once statically over each grid point plus a background point, and once dynamically continuously recording in survey mode along each grid lane. The calibration area was only surveyed dynamically.

3.6.4 Residuals Handling

Not applicable.

3.6.5 Operating Parameters for the Technology

Ten frequencies were recorded simultaneously: 90, 210, 390, 750, 1470, 2910, 5850, 11430, 21690, 41010Hz, continuously at 5 Hz sampling; static date were sampled for two seconds at each position.

3.6.6 Experimental Design

The Blind Grid was surveyed twice: Static data were recorded and processed over the grid square centers and an adjacent background point, and dynamic data recorded with the wheeled pushcart configuration, and pushed continuously at a steady walking speed along grid lanes. The calibration grid was also recorded dynamically. Dynamic survey navigation utilized DGPS with a local base station; the rover and antenna mounted directly above the sensor.

We used target detection during post processing based on total apparent conductivity using all frequencies (response stage) to determine if a potential UXO existed in each square, and if so, we executed the matching algorithm to identify the target, with misfit providing the discrimination stage value (mapped into a confidence rank) for clutter/UXO classification. Background was removed using explicit background measurements for the static test, and using a median filtered background removal for the dynamic test. The pre-recorded library provided the training data.

3.6.7 Sampling Plan

Not applicable.

3.6.8 Demobilization

The coaxial EMI technology requires no alteration of the environment and no site restoration was required except for flag removal and lane string removal. All Geophex equipment was removed at the completion of the demonstration.

3.7 Selection of Analytical/Testing Methods

The analytical/testing method consists of enumeration of UXO detected (i.e. probability of detection (PD)) and non-UXO declared as UXO (i.e. probability of false alarm (PFA), and blank grids declared as having a UXO (probability of background alarm (PBA)). Confidence ranking allows generation of Receiver Operator Characteristics (ROC). Correct UXO identification will also be scored.

3.8 Not Applicable

4 Performance Assessment

4.1 Performance Criteria

The formal performance criteria for the scored assessment of the technology under demonstration are described in Table 2.

Performance Criteria	Description	Primary or Secondary
Probability of Detection	# UXO detected / # UXO buried	primary
False Alarm Rate	# anomalies not ordnance/m^2	
Reliability	Down time	
Maintenance	Frequency, required training	
Ease of use	Operator productivity	
Factors affecting performance	Operating conditions affecting performance	
Versatility	Other potential applications	secondary

Table 2. Performance Criteria

4.2 Performance Confirmation Methods

Performance confirmation methods include quantitative calculations of PD, PFA, and PBA. These require ground truth and must be computed by ATC. These may be recomputed as a function of threshold criteria, for generation of ROC curves.

As defined in the ATC scoring record #694 for this demonstration, "The RESPONSE STAGE scoring evaluates the ability of the system to detect emplaced targets without regard to ability to discriminate ordnance from other anomalies. For the blind grid RESPONSE STAGE, the demonstrator provides the scoring committee with a target response from each and every grid square along with a noise level below which the target responses are deemed insufficient to warrant further investigation." Grid squares with a response stage below the stated noise threshold are declared empty (neither UXO nor metallic clutter present).

As defined in the ATC scoring record #694 for this demonstration, "The DISCRIMINATION STAGE evaluates the demonstrator's ability to correctly identify ordnance as such and to reject clutter. For the blind grid DISCRIMINATION STAGE, the demonstrator provides the scoring committee with the output of the algorithms applied in the discrimination-stage processing for each grid square. The values in this list are prioritized based on the demonstrator's determination that a grid square is likely to contain ordnance. Thus, higher output values are indicative of higher confidence that an ordnance item is present at a specified location." Geophex provided a confidence value threshold below which items are deemed likely clutter.

More extensive descriptions of these quantities as well as scoring records for this and other demonstrations are available in .pdf formatted documents from the ATC web site.

Note that a high PFA for the response stage as a fraction (or %) of (metallic) clutter is desirable, because all metal targets (of sizes/depths comparable to UXO) are intended to be detected, and only in the discrimination stage classified as clutter.

The results of the ATC blind grid demonstration are summarized in Table 3 with a column showing the results from a GEM-3 demonstration performed in 2003. Note that the site was reseeded between these tests, and that the GEM-3 was sled mounted and towed with an ATV, while the GEM-5 was built into a wheeled cart and pushed by hand.

APG Blind Grid – static

Performance Criteria	**Expected**	**Confirmation Method**	**Actual (spot)**	**GEM-3 (2003 cart)**
Response Stage 1) probability of detection 2) probability of false alarms 3) background alarms	 1) > 95% 2) > 95% 3) < .01	Government Evaluation	 1) 65% 2) 65% 3) .30	 1) 85% 2) 85% 3) .40
Discrimination Stage 1) probability of detection 2) probability of false alarms 3) background alarms 4) Efficiency 5) Rejection Ratio	 1) > 85% 2) < .2 (< 20% clutter declared UXO) 3) < .01 4) 0.9 5) > 0.5	Government Evaluation	 1) 55% 2) 60% 3) .20 4) .85 5) .08	 1) .70 2) .70 3) .35 4) .82 5) .19

APG Blind Grid – dynamic

Performance Criteria	**Expected**	**Confirmation Method**	**Actual (survey)**	**GEM-3 (2003 towed)**
Response Stage 4) probability of detection 5) probability of false alarms 6) background alarms	 4) > 95% 5) > 95% 6) < .01	Government Evaluation	 4) 70% 5) 75% 6) .30	 4) 30% 5) 40% 6) 0.
Discrimination Stage 6) probability of detection 7) probability of false alarms 8) background alarms 9) Efficiency 10) Rejection Ratio	 6) > 85% 7) < .2 (< 20% clutter declared UXO) 8) < .01 9) 0.9 10) > 0.5	Government Evaluation	 6) 50% 7) 50% 8) .15 9) .72 10) .29	 6) .20 7) .30 8) 0.0 9) .71 10) .22

Table 3. Expected Performance and Confirmation Methods

4.3 Data Analysis, Interpretation and Evaluation

The key point in the results above is the dramatic reduction in detection rate of the GEM-3 as a result of dynamics during survey operation, whereas the GEM-5 did not suffer a drop (in fact, it was slightly higher) from sensor survey-mode dynamics.

4.3.1 Static and Motion Noise

We performed extensive tests using the prototype coaxial coil EMI system and existing GEM-3 sensors. Figure 6 depicts a segment of the EM data at 9 frequencies from 90 Hz to 21,690 Hz obtained from demo surveys at APG for both sensors. The data from x=0 to about x=250 were collected while the sensors stopped at the end of a survey line, i.e., static data, while the rest of the data were collected while the sensors were moving along a survey line, i.e., motion data. No targets exist along this segment, so the signal envelope represents the total. It is obvious that there is a significant difference between static and motion data for the GEM-3 sensor. For the coaxial sensor (designated GEM-5), it is very hard to tell when the sensor starts moving.

To compare the SNR of the two sensors, a closed-loop test coil (Q-coil) can be used, which is placed at the same distance from the sensors, and then their responses serve as the signal. In Figure 7 we show spectral plots for the Q-coil response from 22 cm distance for the GEM-3 and GEM-5 (note, the frequencies for these are over a broader spectrum than used for the SNR). The standard deviations for the static noise and motion noise are used as a measure of noise. Then, the SNR for both sensors is calculated and illustrated in Figure 8.

Since the *ppm*-values cannot be directly compared for the two sensors, we define the motion-noise to static-noise ratio (*MSR*) as

$$MSR = 20 \times \log\left(\frac{N_M}{N_S}\right),$$

where N_M is the standard deviation of the motion-induced noise, and N_S is that of the static noise. As shown in Figure 8a, the *MSR* is much smaller for the GEM-5 (10 dB or less) than for the GEM-3 (20 dB).

For the static test the SNR is higher for the GEM-3 than for the GEM-5 except at 90 Hz. For the motion test, the SNR of the GEM-5 is better than that of the GEM-3, especially at the low frequencies.

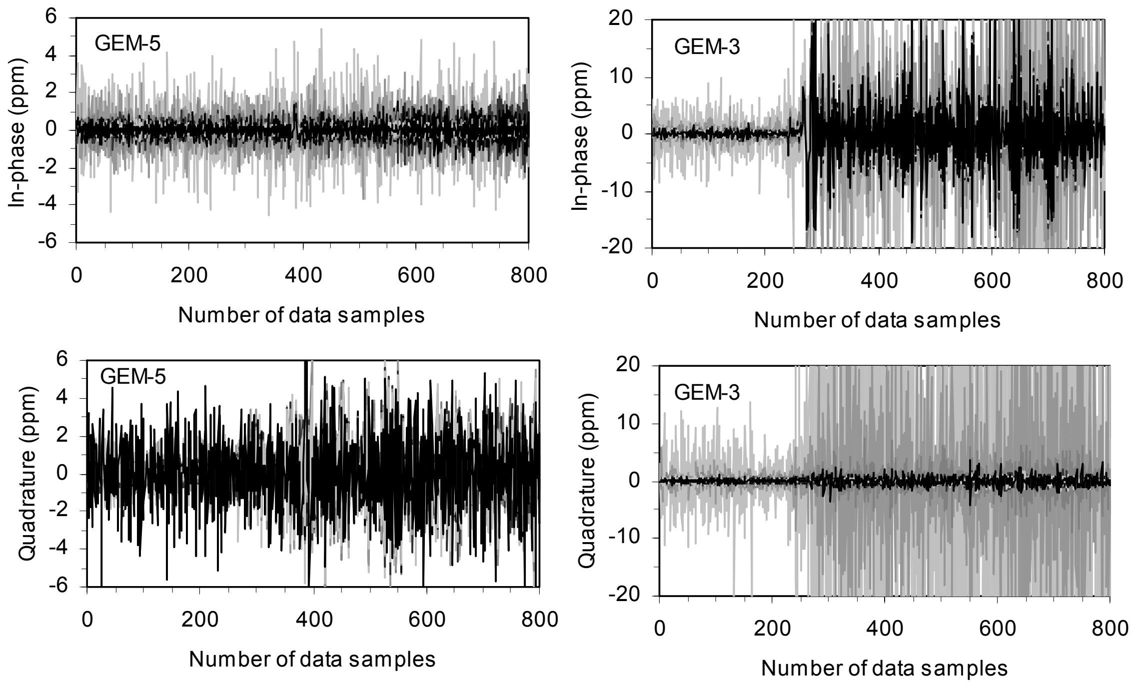

Figure 6. The static (x=0–250) and motion (x>250) noise obtained using both GEM-5 (left) and GEM-3 (right) confirms coaxial-coil immunity.

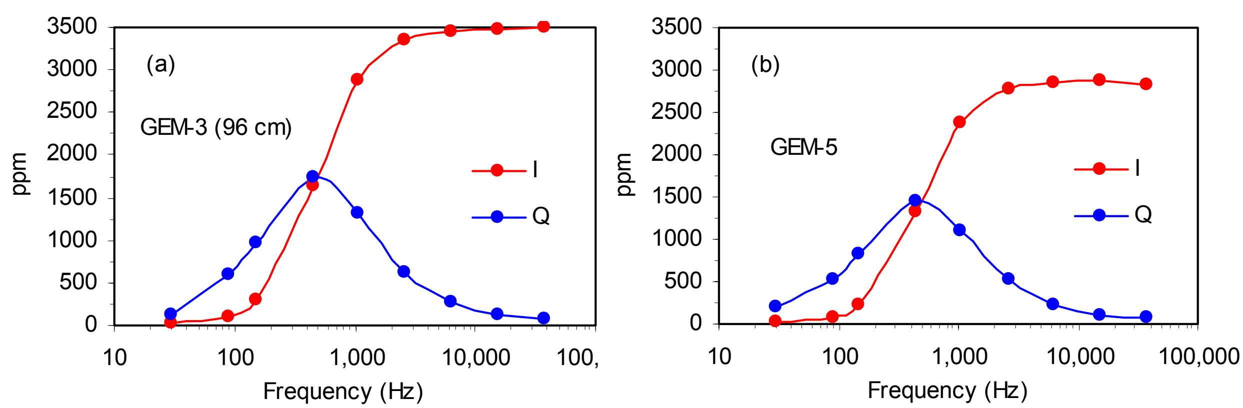

Figure 7. Q-coil spectral responses for the GEM-3 and GEM-5 at 22 cm vertical distance from bottom of sensor, shows consistent character but somewhat different scaling, which changes with distance corresponding to differing falloff functions.

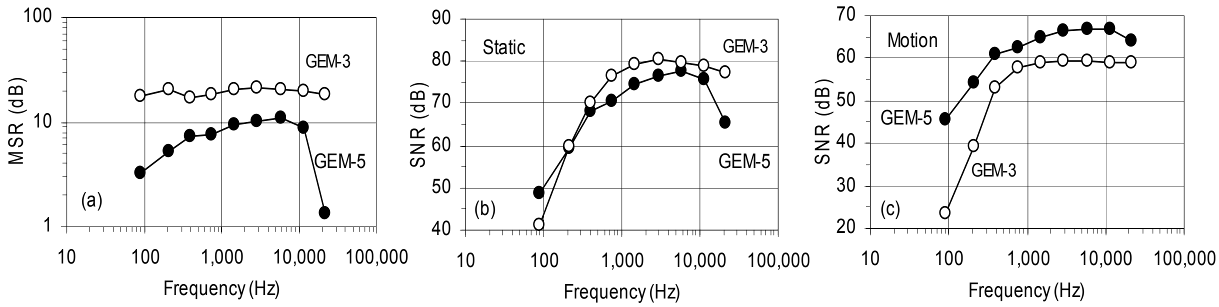

Figure 8. (a) The motion-noise to static-noise ratio, *MSR*, (b) the static and (c) motion SNR as a function of frequency for GEM-5 (solid circles) and GEM-3 (open circles).

4.3.2 Environmental Noise

Compared with the GEM-3, the GEM-5's balanced receiver bucking may largely cancel ambient EM noise such as power lines, radio transmitters, and industrial electrical machinery, as well as natural EM noise such as sferics. We carried out tests against a manmade EM noise at the operating frequencies of the GEM-5 and GEM-3. Figure 9 illustrates the typical data at 7 frequencies from 390 Hz to 21,690 Hz for the two sensors. The noise source is off for the first half of the data sequence (x=0-450); it is on for the rest of the data series (x=450-900). As expected, the noise is almost cancelled out by the gradient measurements, but it significantly distorts the GEM-3 data.

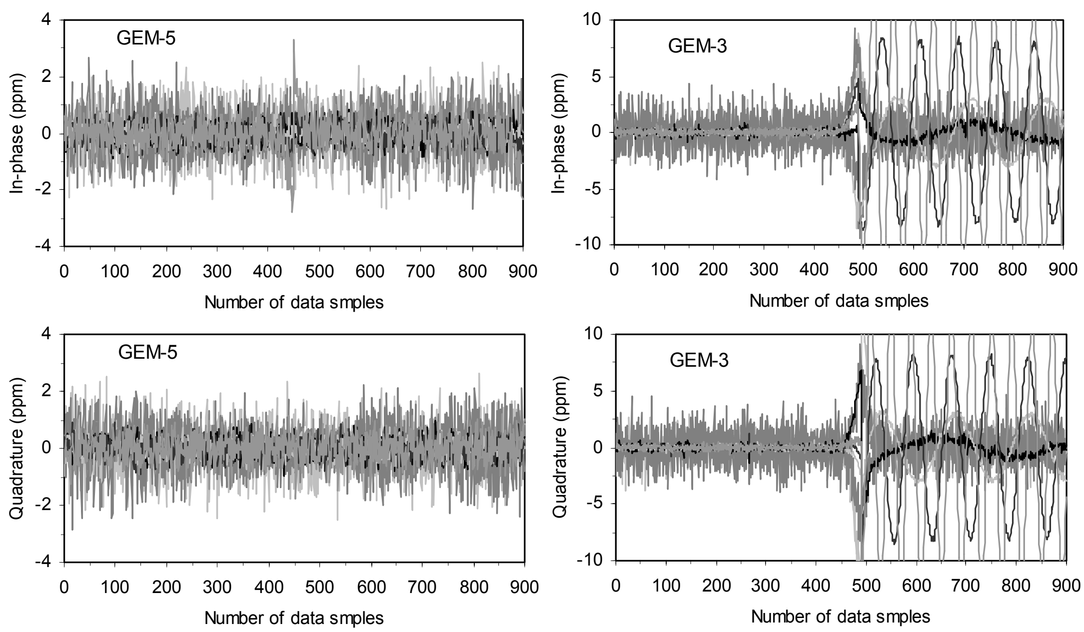

Figure 9. The EM data collected using the GEM-5 (left) and the GEM-3 (right) when the noise source is off (x=0–450) and on (x > 450) shows coaxial-coil insensitivity. There are 7 frequencies ranged from 390 Hz to 21,690 Hz.

4.3.3 UXO Detection

Both GEM-5 and GEM-3 were tested at the Standard UXO Technology Demonstration Site at Aberdeen Proving Grounds (APG), Maryland. The GEM-5 data were obtained in the calibration lanes and the blind test grid in 2005 using a wheeled hand-pushed cart, while the GEM-3 data were obtained in the open area, including the calibration lanes and the blind test grid in 2003 using an ATV towed sled. The targets in the blind grid had been reseeded after 2003, and so the results are not comparable for the two surveys, and the GEM-3 coverage included only half the calibration lanes. In Figure 10 we present the total *Q-Q* conductivity maps for GEM-3 and GEM-5. The data were collected at 10 frequencies from 90 Hz to 41 kHz. The circles indicate the seeded targets. Almost all seeded targets in this portion of the calibration lanes are detected by the GEM-5, while many of them are missed by GEM-3.

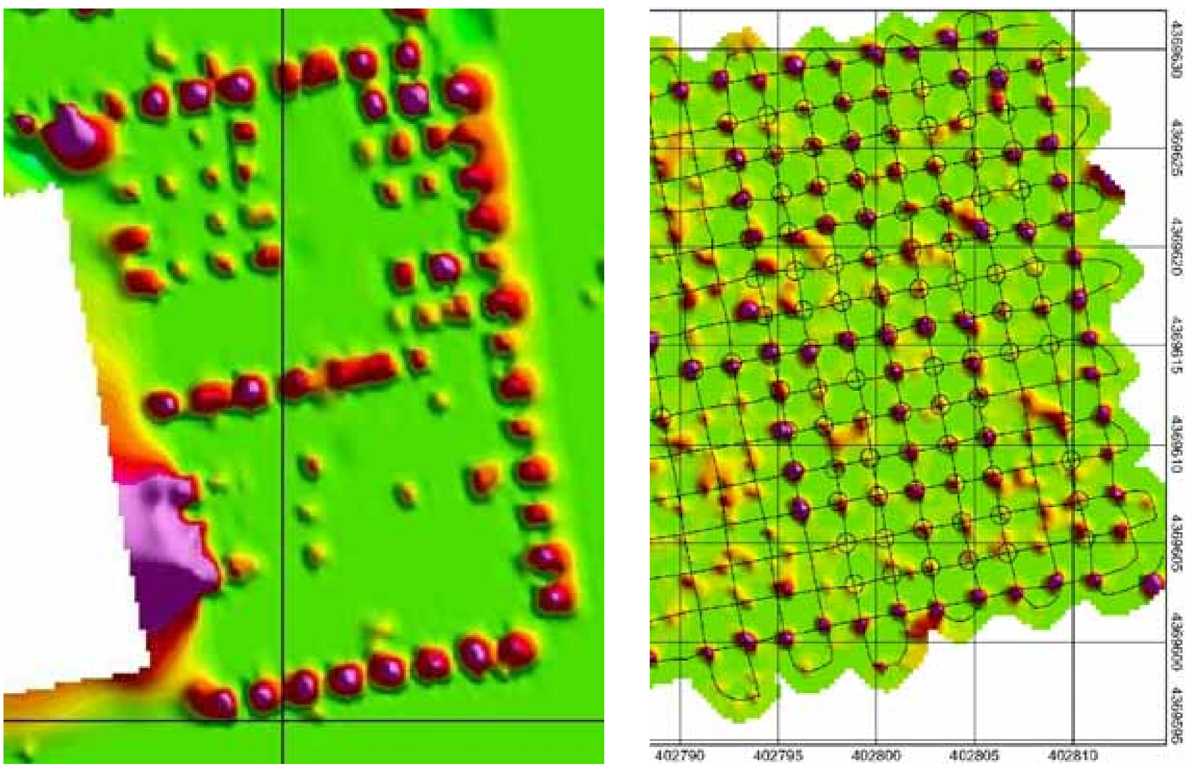

Figure 10. GEM-3 ATV towed apparent conductivity (left) compared to the coaxial coil sensor (right) apparent conductivity over part of the calibration grid at the APG demonstration site shows improved target detection in a dynamic survey.

The advantages of the GEM-5 are more fully realized in a vehicle-towed array; subsequent to this demonstration, a GEM-5 array with seven receiver coil pairs has been demonstrated, and a score report will be published by ATC.

5 Cost Assessment

5.1 Cost Reporting

Only the blind and calibration grids were surveyed, and the blind grid in a (non-production mode) static as well as dynamic mode, for purposes of confirming the improved immunity to motion induced noise. Therefore, cost reporting for this demonstration can only approximate production survey cost. Costs were reported by ATC staff and documented in scoring record 694 and summarized here:

Initial setup time: 11.25 hours, performed by five persons

System calibration time (including in-air tests and calibration lane tests): 1.75 hours, performed by two persons.

Site survey (includes dynamic survey mode only): 4.25 hours, performed by 2 persons.

Demobilization: 0.83 hours, performed by five persons.

Note that another demonstration by Geophex was performed concurrently and occupied some time from the same personnel during initial setup and demobilization.

5.2 Cost Analysis

Only the blind and calibration grids were surveyed, and the blind grid in a (non-production mode) static as well as dynamic mode, for purposes of confirming the improved immunity to motion induced noise. Therefore, cost analysis is subject to bias. As reported by ATC scoring record 694:

Supervisor @ $95/hr, data analyst @ $57/hr, and three support personnel @ 28/hr (setup & demobilization):

Initial setup cost: $2,712.25
Calibration cost: $266.00
Site survey cost: $646.00
Demobilization: $197.13

Total cost for dynamic survey: $3,821.38

6 Implementation Issues

6.1 Environmental Checklist

Not Applicable.

6.2 Other Regulatory Issues

Not Applicable.

6.3 End User Issues

The coaxial technology is particularly advantages in a wide-area survey mission in a vehicle-towed configuration where platform motion is an issue. Exploiting the potential for an array configuration holds the most promise for an operationally advantageous system. Geophex has built and demonstrated a prototype 7-sensor GEM-5 array (designed for robotic land-mine detection) at APG including the blind grid and open area; a complete score report will be published by ATC. Performance, production rates, and costs will be the primary end-user issues; these may vary for different sites and mission objectives.

7 References

S. J. Norton and I. J. Won, 2001, *Identification of buried unexploded ordnance from broadband electromagnetic induction data*, IEEE Trans. Geosci. Remote Sensing, Vol. 39, pp. 2253-2261.

S. J. Norton, I. J. Won and E. R. Cespedes, 2001, *Ordnance/Clutter discrimination based on target eigenvalue analysis*, Subsurface Sensing Tech. Appl., Vol. 2, pp. 285-298.

S. J. Norton, I. J. Won and E. R. Cespedes, 2001, *Spectral identification of buried unexploded ordnance from low-frequency electromagnetic data*, Subsurface Sensing Tech. Appl., Vol. 2, pp. 177-189.

I.J. Won, D.A. Keiswetter, D.R. Hanson, E. Novikova, and T.M. Hall, 1997, *Gem-3: a monostatic broadband electromagnetic induction sensor*, Jour. Environmental and Engineering Geophysics, Vol. 2, Issue 1, pp 53-64.

8 Points of Contact

POINT OF CONTACT Name	ORGANIZATION Name Address	Phone/Fax/Email	Role in Project
I.J. Won	Geophex, Ltd. 605 Mercury St. Raleigh, NC 27603	(919) 839-8515 (919) 839-8528 ijwon@geophex.com	President, Geophex, Ltd.
Bill SanFilipo	Geophex, Ltd. 605 Mercury St. Raleigh, NC 27603	(919) 839-8515 (919) 839-8528 sanfilipo@geophex.com	PI
Dr. Jeffrey Marqusee	ESTCP	(703) 396-2120 (703) 696-2114 marqusj@acq.osd.mil	ESTCP Director
Dr. Anne Andrews	ESTCP	(703) 696-3826 (703) 696-2114 Anne.Andrews@osd.mil	ESTCP UXO Program Manager
Dr. George Robitaille	AEC	(410) 612-6865 (410) 612-6836 gerobita@aec2.apgea.army.mil	DoD Liaison Contact (2005)
Jeffrey Fairbanks	ESTCP	jef@hgl.com	
Larry Overbay	ATC	Larry.overbay@atc.army.mil	APG site director (2005)
Anthony Buscher	Hydrogeologic	(703) 736-4540 abuscher@hgl.com	SERDP/ESTCP Assistant Manager

Table 4. Points of Contact

Bill SanFilipo date
(Principle Investigator)
Geophex, Ltd

Appendix A – ROC curves - dynamic

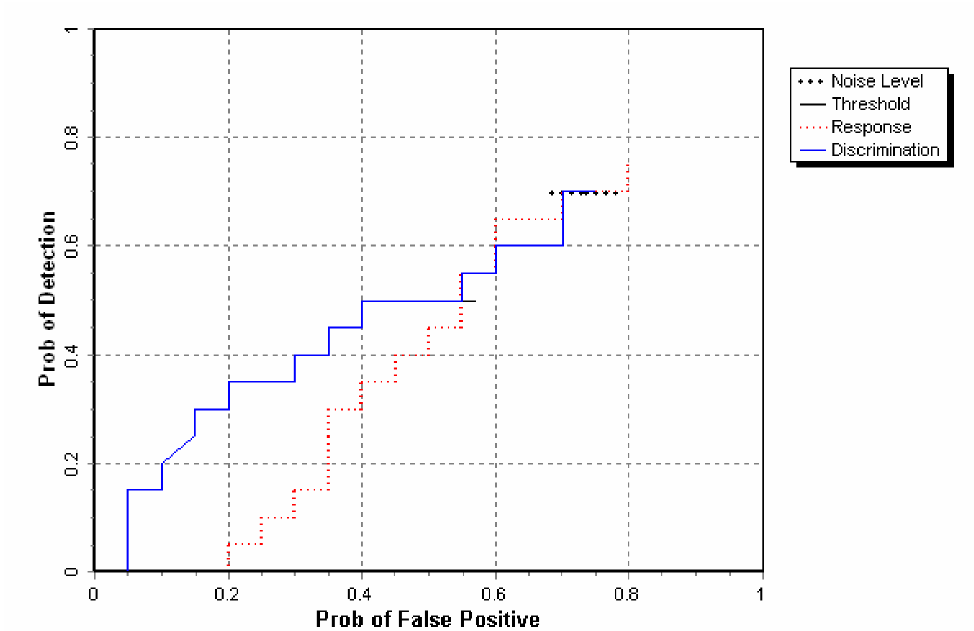

Figure A-1. GEM-5/man-portable dynamic blind grid probability of detection for response and discrimination stages versus their respective probability of false positive over all ordnance categories combined.

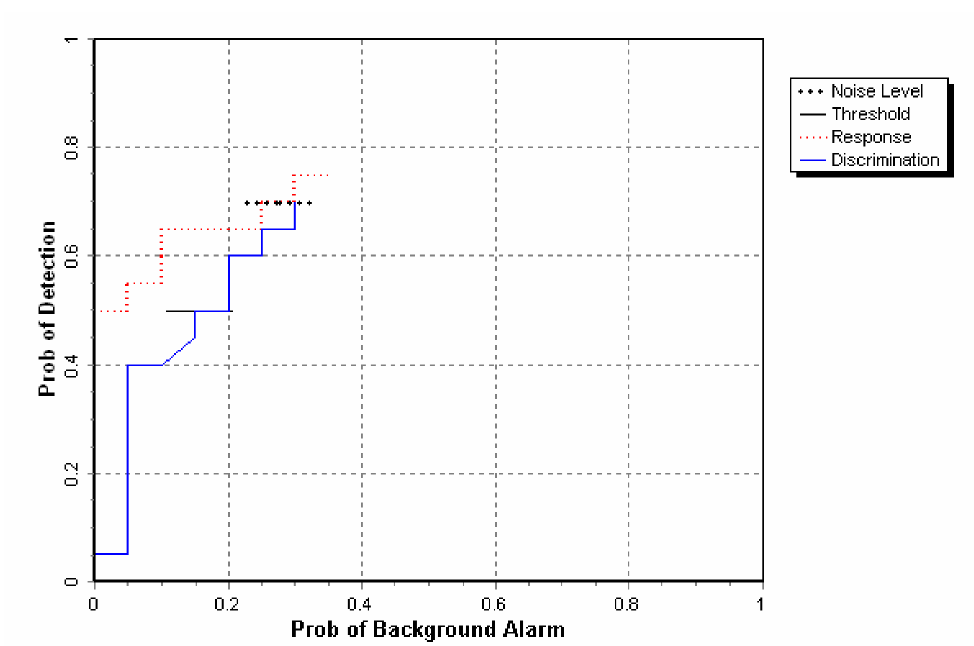

Figure A-2. GEM-5/man-portable dynamic blind grid probability of detection for response and discrimination stages versus their respective probability of background alarm over all ordnance categories combined.

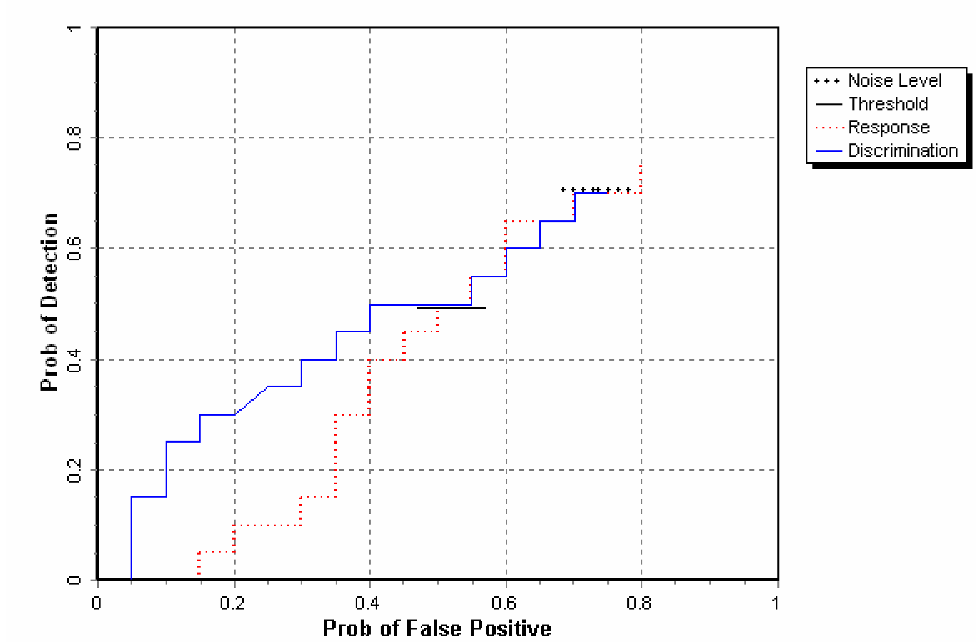

Figure A-3. GEM-5/man-portable dynamic blind grid probability of detection for response and discrimination stages versus their respective probability of false positive for all ordnance larger than 20 mm.

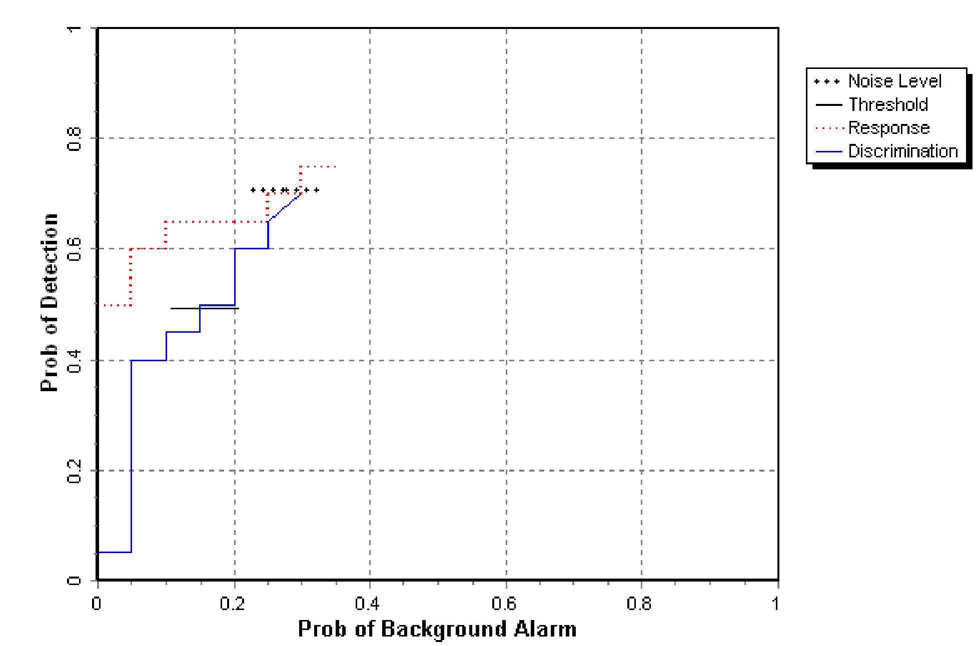

Figure A-4. GEM-5/man-portable dynamic blind grid probability of detection for response and discrimination stages versus their respective probabilities of background alarm for all ordnance larger than 20 mm.